20th International Workshop
Complex Systems of Charged Particles and Their Interactions with Electromagnetic Radiation

Prokhorov General Physics Institute
of the Russian Academy of Sciences

Moscow, Russia, April 8-12, 2024

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Prokhorov General Physics Institute of the Russian Academy of Sciences (Moscow, Russia)

Complex Systems of Charged Particles and their Interaction with Electromagnetic Radiation

20th INTERNATIONAL WORKSHOP, April 8-12, 2024

http://cscpier.org/

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Sections

1. Basic Aspects of Plasma Science
2. Complex Plasmas
3. Laser Plasmas
4. General Plasmas
5. Solid State Plasmas

Venue

The 20th Workshop on Complex Systems of Charged Particles and their Interaction with Electromagnetic Radiation will be held in Prokhorov General Physics Institute of the Russian Academy of Sciences, Vavilov street 38, Moscow, Russia

20th International Workshop

Complex Systems of Charged Particles and Their Interactions with Electromagnetic Radiation

***Moscow, Russia, April 8-12,* 2024**

PROGRAM

20th International Workshop

Complex Systems of Charged Particles and Their Interactions with Electromagnetic Radiation

Moscow, Russia, April 8-12, 2024

20th International Workshop
Complex Systems of Charged Particles and Their Interactions with Electromagnetic Radiation

Moscow, Russia, April 8-12, 2024

PROGRAM

April 8, 2024

9:30-10:00 Gathering of the Workshop participants

10:00-10:30 Opening Ceremony of the CSCPIER-2024

SECTION-1 April 8 BASIC ASPECTS OF PLASMA SCIENCE (GPI RAS)

10:30-11:00
PLASMADYNAMIC PROCESSES IN QUASI-STATIONARY HIGH-CURRENT PLASMA ACCELERATORS OF A NEW GENERATION (*Invited*)
V.M. Astashynski, O.G. Penyazkov
The A.V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus, Minsk, Belarus

11:00-11:15
FORMATION AND COLLISION IN LOW PRESSURE AIR THE PLASMA DIFFUSE JETS WITH DIFFERENT DIAMETERS
V.F. Tarasenko, V.A. Panarin, V.S. Skakun, N.P. Vinogradov
Institute of High Current Electronics SB RAS, Tomsk, Russia

11:15-11:30
IONIZATION-DISSOCIATION PHASE TRANSITIONS OF THE FIRST ORDER. (ON A NEW CLASS OF FIRST-ORDER PHASE TRANSITIONS)
G.E. Norman[1,2,3], I.M. Saitov[2,3]
[1]*National Research University Higher School of Economics, Moscow, Russia*
[2]*Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*
[3]*Moscow Institute of Physics and Technology (National Research University), Dolgoprudny, Moscow region, Russia*

11:30-11:45
ON COLLISIONLESS DAMPING OF ELECTROMAGNETIC WAVES IN A CLOUD OF PLASMA ELECTRONS
V.M. Somsikov
IETP Al-Farabi Kazakh National University, Almaty, Kazakhstan

11:45-12:00 Coffee Break

12:00-12:30
PUMPING OF PLASMA WAVES BY A REB IN A MAGNETIZED PLASMA COLUMN FOR PLASMA HEATING AND RADIATION FLUX GENERATION (*Invited*)
A.V. Arzhannikov[1, 2]
[1]Budker Institute of Nuclear Physics of Siberian Branch Russian Academy of Sciences (BINP SB RAS), Novosibirsk, Russia
[2]Novosibirsk State University, Novosibirsk, Russia

12:30-12:45
ON THE CORRESPONDENCE OF A RADIATION FLUX FREQUENCY SPECTRUM FROM A BEAM-PLASMA SYSTEM TO THE SPECTRUM OF PLASMA ELECTRONIC OSCILLATIONS PUMPED BY A BEAM
D.A. Samtsov[1], A.V. Arzhannikov[1,2], S.L. Sinitsky[1], S.S. Popov[1], P.V., Kalinin[1,2], E.S. Sandalov[1,2], M.G. Atluhanov[1], V.D. Stepanov[1,2], K.N. Kuklin[1], I.V. Timofeev[1]
[1]Budker Institute of Nuclear Physics of Siberian Branch Russian Academy of Sciences (BINP SB RAS), Novosibirsk, Russia
[2]Novosibirsk State University, Novosibirsk, Russia

12:45-13:00
DIPOLE EFFECTS IN THE VLASOV KINETIC EQUATION
P.A.Andreev
Department of General Physics, Faculty of physics, Lomonosov Moscow State University, Moscow, Russian Federation

13:00-13:15
ON THE PHYSICS OF DENSE PLASMAS
A.D. Rakhel
Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia

13:15-13:30
KINETIC THEORY OF PLASMA EXPANSION IN VACUUM DIODE
A.O. Kokovin, V.Yu. Kozhevnikov, A.V. Kozyrev, N.S. Semeniuk
Institute of High Current Electronics SB RAS, Tomsk, Russia

13:30-13:45
ON THE PROTON-BORON FUSION IN OSCILLATING PLASMAS OF NANOSECOND VACUUM DISCHARGE
Yu.K.Kurilenkov[1,2], A.V. Oginov[1], S.Yu.Gus'kov[1], I.S.Samoylov[2]
[1]P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
[2]Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia

13:45-14:00
ION-ACOUSTIC SOLITON IN A COLLISIONLESS NONISOTHERMAL PLASMA
S.V. Kuznetsov
Joint Institute for High Temperature of the Russian Academy of Science, Moscow, Russia

14:00-15:00 Lunch

15:00-15:30
MEASUREMENT OF ELECTRIC FIELD IN ATMO SPHERIC PRESSURE DISCHARGES USING STARK POLARIZATION SPECTROSCOPY (*Invited*)
B.M. Obradović[1], N. Cvetanović[2], S.S. Ivković[1], G.B. Sretenović[1], V.V. Kovačević[1], I.B. Krstić[1], and M. M. Kuraica[1]
[1]*Faculty of Physics, University of Belgrade, Belgrade, Serbia*
[2]*Faculty of Transport and Traffic Engineering, University of Belgrade, Belgrade, Serbia*

15:30-15:45
FEATURES OF THE DYNAMICS OF MICROWAVE DISCHARGES IN ATOMIC AND MOLECULAR GASES
A.I. Saifutdinov[1], A.A. Saifutdinova[1]
[1]*Kazan National Research Technical University named after A.N. Tupolev – KAI, Kazan, Russia*

15:45-16:00
FEATURES OF THE KINETICS OF FAST ELECTRONS IN A PLASMA OF NEGATIVE GLOW OF A SHORT GLOW DISCHARGE AND ITS APPLICATIONS
A.I. Saifutdinov[1], S.S. Sysoev[2]
[1]*Kazan National Research Technical University named after A.N. Tupolev – KAI, Kazan, Russia*
[2]*Saint-Petersburg State University, St Petersburg, Russia*

16:00-16:15
ON MODELING ELECTRON RUNAWAY IN GASES BY THE PARTICLE METHOD
S. A. Maiorov [1,2], R.I. Golyatina[3], and G.K. Omiraliyeva[2]
[1]*Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*
[2]*Institute for Experimental and Theoretical Physics, Al-Farabi Kazakh National University, Almaty, Kazakhstan*
[3]*Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia*

16:15-16:30
PATTERNS OF THE IONIZATION POTENTIALS OF MULTICHARGED IONS
G.V. Shpatakovskaya
Keldysh Institute of Applied Mathematics, Russian Academy of Sciences, Moscow, Russia

16:30-16:45 Coffee Break

16:45-17:15
64 YEARS OF PLASMA CRYSTALLIZATION STUDIES IN WHITE DWARFS *(Invited)*
D.A. Baiko
Ioffe Institute, Saint Petersburg, Russia

17:15-17:30
JEANS INSTABILITY IN THE SYSTEM WITH DIFFERENT GRAVITATIONAL MASSES AND THE ALPHA-G EXPERIMENT
S.A. Trigger
Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia

17:30-17:45
TREATMENT OF QUANTUM NUCLEAR EFFECTS VIA PATH INTEGRAL MOLECULAR DYNAMICS
N.D. Kondratyuk[1,2,3]
[1]*Moscow Institute of Physics and Technology (National Research University), Dolgoprudny, Moscow Region, Russian Federation*
[2]*Joint Institute for High Temperatures RAS, Moscow, Russian Federation*
[3]*HSE University, Moscow, Russian Federation*

17:45-18:00
ON THE MOST PROBABLE ENERGY RELEASE IN STRUCTURED MEDIA
M.Yu.Romanovsky [1,2,3]
[1]PI "Science and Innovation", Moscow, Russia
[2]National Center for Physics and Mathematics, Moscow, Russia
[3]Pirogov Russian National Research Medical University, Moscow, Russia

SECTION-2 April 9 COMPLEX PLASMAS (GPI RAS)

10:00-10:30
COMET DUSTY PLASMAS (*Invited*)
S.I. Popel, A.P. Golub', L.M. Zelenyi
Space Research Institute of the Russian Academy of Sciences, Moscow, Russia

10:30-10:45
LUNAR DUSTY PLASMAS: BASIC PHYSICS PROCESSES AND EXPERIMENTAL DATA OF LUNA-25
S.I. Popel, L.M. Zelenyi, A.V. Zakharov, I.A. Kuznetsov, G.G. Dol'nikov, A.N. Lyash, I.A. Shashkova, A.A. Kartasheva, M.E. Abdelaal, Yu.S. Reznichenko
Space Research Institute of the Russian Academy of Sciences, Moscow, Russia

10:45-11:00
NONLINEAR PERIODIC WAVE STRUCTURES IN THE EARTH'S DUSTY IONOSPHERE
Yu.N. Izvekova, S.I.Popel, T.I. Morozova, S.I. Kopnin
Space Research Institute of the Russian Academy of Sciences, Moscow, Russia

11:00-11:15
ELECTROSTATICALLY FORMED DUSTY PLASMAS ABOVE THE SURFACE OF ENCELADUS
D.V. Shokhrin[1], S.I. Kopnin[2], S.I. Popel[2]
[1]National Research University Higher School of Economics, Moscow, Russia
[2]Space Research Institute of the Russian Academy of Sciences, Moscow, Russia

11:15-11:30
VIBRATIONAL MODEL OF TRANSPORT PROPERTIES IN YUKAWA FLUIDS (COMPLEX PLASMAS)
S. A. Khrapak
Joint Institute for High Temperatures of the Russian Academy of Sciences, 125412 Moscow, Russia

11:30-11:45 Coffee Break

11:45-12:15
DUSTY PLASMA IN AN INDUCTIVE RF DISCHARGE IN A MAGNETIC FIELD (*Invited*)
V.Yu. Karasev, E.S. Dzlieva, M.S. Golubev, M.A. Gasilov, L.A. Novikov, S.I. Pavlov
Saint Petersburg State University, Saint Peterburg, Russia

12:15-12:30
THE VELOCITY OF SPIN-MOTION OF DUST PARTICLES DEPENDING ON THE TYPE OF INERT GAS
L.A. Novikov, E.S. Dzlieva, V.Yu. Karasev, S.I. Pavlov
Saint Petersburg State University, Saint Peterburg, Russia

12:30-12:45

ULTRAFAST ROTATION OF DUST STRUCTURES IN GLOW DISCHARGES UNDER THE MAGNETIC FIELD INFLUENCE

L.G. Dyachkov[1], E.S. Dzlieva[2], L.A. Novikov[2], S.I. Pavlov[2], V.Yu. Karasev[2]
[1]*Joint* Institute *for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*
[2]*Saint Petersburg State University, Saint Petersburg, Russia*

12:45-13:00

INFLUENCE OF WAKE FIELD INHOMOGENEITY ON THE VIBRATION SPECTRA OF TWO DUST PARTICLES IN A RF DISCHARGE

E.A. Sametov, E.A. Lisin, R.A. Syrovatka, M.M. Vasiliev, O.F. Petrov
Joint Institute *for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*

13:00-13:15

NUMERICAL STUDY OF THE PARAMETERS OF DUST PARTICLES CHAINS LEVITATED IN A GAS DISCHARGE PLASMA

A.V. Fedoseev[1], M.V. Salnikov[2]
[1]*Joint Institute for High Temperatures RAS, Moscow, Russia*
[2]*Institute of Termophysics SB RAS,. Novosibirsk, Russia*

13:15-13:30

DISPERSION OF LATTICE WAVES IN A TWO-LAYER CRYSTAL IN A COMPLEX DUST PLASMA

A.V. Zobnin, A. M. Lipaev, V. N. Naumkin, R. A. Syrovatka, A. D. Usachev
Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia

13:30 -13:45

OBTAINING A PLASMA-DUST CLOUD FROM ILMENITE CONCENTRATE USING A MICROWAVE DISCHARGE

V. D. Borzosekov[1, 2], N. S. Akhmadullina[3], A. S. Sokolov[1], T. E. Gayanova[1], A. D. Rezaeva[1, 2], V. D. Stepakhin[1], D. V. Malakhov[1], E. V. Voronova[1], V. P. Logvinenko[1, 2], A V. Knyazev[1], E. A. Obraztsova[1, 4], N. N. Skvortsova[1]
[1]*Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia*
[2]*RUDN University, Moscow, Russia*
[3]*Baikov Institute of Metallurgy and Materials Science of the Russian Academy of Sciences, Moscow, Russia*
[4]*Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region, Russia*

13:45 -14:00

CHAIN REACTIONS IN A PROCESSES INITIATED BY MICROWAVE OF HIGH POWER GYROTRON: STRUCTURE AND CYTOTOXICITY

N.N. Skvortsova[1,5], E.A. Obraztsova[1,2], V.D. Stepakhin[1], E.M. Konchekov[1], D.A. Skvortsov[3] , D.A. Lukianov[3], N.G. Gusein-zade[1], N.S. Ahmadullina[4], O.N. Shishilov[1,5]
[1]*Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia*
[2]*Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region, Russia*
[3]*Moscow State University, Faculty of Chemistry, Moscow, Russia*
[4]*A.A. Baikov Institute of Metallurgy and Material Science of Russian Academy of Sciences, Moscow, Russia*
[5]*MIREA – Russian Technological University, Institute of Fine Chemical Technologies, Moscow, Russia*

14:00-15:00 Lunch

15:00-15:30
TECHNIQUES FOR TWO- AND THREE-DIMENSIONAL DIAGNOSTICS OF MICROPARTICLES IN COLLOIDAL PLASMAS (*Invited*)
R.A. Syrovatka, K.B. Statsenko, A.S. Svetlov, M.M. Vasiliev, D.A. Zamorin, O.F. Petrov
Joint Institute for High Temperatures of Russian Academy of Sciences, Moscow, Russia

15:30-15:45
EVOLUTION OF THE TRAJECTORY OF A COLLOIDAL PARTICLE IN A CHAIN IN DC-DISCHARGE
X.G. Koss[1,2], A.V. Erilin[2], E.A. Kononov[1,2], M.M. Vasiliev[1,2], O.F. Petrov[1,2]
[1]Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia
[2]Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region, Russia

15:45-16:00
ACTIVITY MECHANISM OF CHARGED GLOBS OF COMPLEX COMPOSITION IN COLLOIDAL SYSTEMS UNDER THE EXTERNAL INFLUENCE
R.V. Senoshenko[1,2], E.A. Kononov[1], M.M. Vasiliev[1], O.F. Petrov[1]
[1]Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia
[2]Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region, Russia

16:00-16:15
STRUCTURAL TRANSITION IN STRONGLY COUPLED COULOMB CLUSTERS
D.I. Zhukhovitskii, E.E. Perevoshchikov
Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia

16:15-16:30
EXTERNAL ELECTRIC FIELD INFLUENCE ON THE MOTION OF COULOMB STRUCTURES IN A LINEAR ELECTRODYNAMIC TRAP
M.S. Dobroklonskaya
Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia

16:30 -16:45 Coffee Break

16:45-17:15
TWO-DIMENSIONAL BROWNIAN MOTION OF ACTIVE PARTICLE ON THE FREE SURFACE OF SUPERFLUID HELIUM (*Invited*)
R.E. Boltnev, M.M. Vasiliev, O.F. Petrov
Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia

17:15-17:30
MULTISCALE SELF-CONSISTENT SIMULATION OF COMPLEX PLASMA SYSTEM WITH ION FLOW
D.A. Kolotinskii[1,2], A.V. Timofeev[1,2]
[1] Joint Institute for High Temperatures of Russian Academy of Sciences (JIHT), Moscow, Russia
[2]Moscow Institute of Physics and Technology (National Research University), Dolgoprudny, Moscow Region, Russia

17:30-17:45
GENERALISED EQUIPARTITION THEOREM AS A NATURAL MEASURE OF NON-RECIPROCITY IN COMPLEX PLASMAS
D.A. Kolotinskii[1,2], A.V. Timofeev[1,2]
[1]Joint Institute for High Temperatures of Russian Academy of Sciences (JIHT), Moscow, Russia
[2]Moscow Institute of Physics and Technology (National Research University), Dolgoprudny, Moscow Region, Russia
[3]National Research University Higher School of Economics, Moscow, Russia

17:45-18:00
WAVES AND INSTABILITIES IN PLASMA OF METEOROID TAILS
T.I. Morozova, S.I. Popel
Space Research Institute of the Russian Academy of Sciences, Moscow, Russia

SECTION-3 April 10 LASER PLASMAS (GPI RAS)

10:00-10:30
TOWARDS INTENSE ATTOSECOND XUV PULSES PRODUCTION: FROM HIGH-HARMONIC GENERATION TO HIGH-ORDER FREQUENCY MIXING (*Invited*)
V. V. Strelkov[1], S. A. Bondarenko[2,1], M. A. Khokhlova[3]
[1]*Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia*
[2]*National Research Nuclear University "MEPhI", Moscow, Russia*
[3]*King's College London London, United Kingdom*

10:30-10:45
GUAGE EFFECTS IN HIGH HARMONIC GENERATION CHARACTERISTICS OF GA+ IONS IN LASER FIELD
A.I. Magunov[1,2], S.N. Yudin[3]
[1]*Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia*
[2]*Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia*
[3]*Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia*

10:45-11:00
IMPACT OF HIGH-POWER BEAM ON SECOND HARMONIC GENERATION IN COLLISIONLESS MAGNETIZED PLASMA
T. Singh
Department of Physics, DAV University, Jalandhar, India

11:00-11:15
EMISSION OF TERAHERTZ PULSES FROM NEAR-CRITICAL PLASMA SLAB UNDER ACTION OF P-POLARIZED LASER RADIATION
A.A. Frolov
P.N. Lebedev Physical Institute RAS, Moscow, Russia

11:15-11:30
MODELLING THE ELECTRON WAKEFIELD FOR ULTRA-RELATIVISTIC LASER INTENSITIES TAKING IONISATION INTO ACCOUNT
M.V. Sedov[1], S.N. Ryazantsev[1], I.Yu. Scobelev[1,2], S.A. Pikuz[1,2]
[1]*Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*
[2]*National Research Nuclear University MEPhI, Moscow, Russia*

11:30-12:00 Coffee Break

12:00-12:30
EXPERIMENTS AND MODELING ON LASER ACCELERATION OF ELECTRONS AND X-RAYS GENERATION AT VARIOUS PARAMETERS OF LASER-PLASMA INTERACTION (*Invited*)
N.E. Andreev[1,2]
[1]*Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*
[2]*Moscow Institute of Physics and Technology, Dolgoprudny, Russia*

12:30-12:45

ON THE ROLES OF DIFFERENT FREEDOM DEGREES IN THE WATER COULOMB EXPLOSION INITIATED BY A INTENSE X-RAY PULSE

S.N. Yudin, A.V. Bibikov, M.M. Popova, M.D. Kiselev, E.V. Gryzlova, A.N. Grum-Grzhimailo
Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

12:45-13:00

ULTRASHORT PULSE LASER TECHNOLOGIES: FROM OPTICAL TO X-RAY

N.A. Inogamov[1,2,3], V.V. Zhakhovsky[2,3], Y.V. Petrov[1], V.A. Khokhlov[1], S.S. Makarov[3], T.A. Pikuz[4]
[1]*Landau Institute for Theoretical Physics, RAS, Chernogolovka, Russia*
[2]*L.N. Dukhov All-Russia Research Institute of Automatics, Moscow, Russia*
[3]*Joint Institute for High Temperatures, RAS, Moscow, Russia*
[4]*Institute for Open and Transdisciplinary Research Initiatives, Osaka University, Osaka, Japan*

13:00-13:15

NOTES ON INVERSE COMPTON SCATTERING

Yu.V.Popov[1,2], I.P.Volobuev[1], K.A.Bornikov[3]
[1]*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
[2]*Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, Russia*
[3]*Physics Faculty, Lomonosov Moscow State University, Moscow, Russia*

13:15-13:30

IONIZATION OF HELIUM ATOMS BY METAL TRIPLY-CHARGED IONS IN LASER PLASMA

R.E. Boltnev[1, 2], A.V. Karabulin[1, 3], I.N. Krushinskaya[2], A.A. Pelmenev[2], and V.I. Matyushenko[2]
[1] *Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia*
[2] *Branch of Semenov Federal Research Center for Chemical Physics, Russian Academy of Sciences, Chernogolovka, Moscow region, Russia*
[3] *Federal Research Center for Problems of Chemical Physics and Medicinal Chemistry, Russian Academy of Sciences, Chernogolovka, Moscow region, Russia*

13:30 -13:45

ELECTRON BEAM GENERATION IN LASER-PLASMA INTERACTION WITH LIQUID TARGET

S.A. Shulyapov[1], K.A. Ivanov[1,2], I.N. Tsymbalov[1,3], D.A. Gorlova[1,3], R.V. Volkov[1], I.P. Tsygvintsev[4], A.B. Savel'ev[1,2]
[1]*Faculty of Physics, M.V. Lomonosov MSU, Moscow, Russia*
[2]*P.N. Lebedev Physical Institute, RAS, Moscow, Russia*
[3]*Institute for Nuclear Research, RAS, Moscow, Russia*
[4]*Keldysh Institute of Applied Mathematics, RAS, Moscow, Russia*

13:45-14:00

GENERATION OF ELECTRON-POSITRON PLASMA IN SELFSUSTAINED QED CASCADES WITH ULTRA-HIGH INTENSITY LASERS

A.A. Mironov
LULI, Sorbonne Université, CNRS, CEA, École Polytechnique, Institut Polytechnique de Paris Paris, France
Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia

14:00-15:00 Lunch

15:00-15:30

CHARACTERIZATION OF HOT ELECTRONS GENERATED BY LASER–PLASMA INTERACTION AT SHOCK IGNITION INTENSITIES (*Invited*)

E. D. Filippov[1], M. Khan[2], A. Tentori[3], P. Gajdos[4], A. S. Martynenko[1,5], R. Dudzak[4,6], P. Koester[7], G. Zeraouli[8], D. Mancelli[9,10], F. Baffigi[7], L. A. Gizzi[7], S. A. Pikuz[1,11], Ph.D. Nicolaï[3], N. C. Woolsey[2], R. Fedosejevs[12], M. Krus[4], L. Juha[6], D. Batani[3], O. Renner[4,6,13] and G. Cristoforetti[7]
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[3] Université de Bordeaux, CNRS, CEA, CELIA, Talence, France
[4]Institute of Plasma Physics of the CAS, Prague, Czech Republic
[5]Plasma Physics Department, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
[6]Institute of Physics of the CAS, Prague, Czech Republic
[7]Intense Laser Irradiation Laboratory, INO-CNR, Pisa, Italy
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[9]Institute of Plasma Physics and Lasers - IPPL, Centre of Research and Innovation, Hellenic Mediterranean University, Rethymnon, Greece
[10]Department of Electronic Engineering, Hellenic Mediterranean University, Chania, Greece
[11]National Research Nuclear University MEPhI, Moscow, Russia
[12]University of Alberta, Edmonton, Alberta, Canada
[13]The Extreme Light Infrastructure ERIC, ELI Beamlines Facility, Dolní Brezany, Czech Republic

15:30-15:45

CONCEPTUAL DESIGN AND SCIENTIFIC PROGRAM OF THE EXPERIMENTAL STATION "MATTER IN EXTREME CONDITIONS" FOR THE RUSSIAN XFEL (PROJECT "SYLA")

S.S. Makarov[1,2], K.F. Burdonov[2,3], A.V. Lobanov[2,4], V.V. Kravchenko[2,4], G.S. Lagodich[2,4], A.V. Targonsky[2], S.A. Pikuz[1]
[1]Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia
[2]National Research Center "Kurchatov Institute", Moscow, Russia
[3]Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia
[4]Institute of Laser and Plasma Technologies, National Research Nuclear University MEPhI, Moscow, Russia

15:45-16:00

GENERATION OF EXTREME QUASI-STATIC MAGNETIC FIELDS IN PLASMA TARGETS IRRADIATED BY CROSSED PETAWATT LASER BEAMS

T.V. Liseykina[1], E.E. Peganov[2], S.V. Popruzhenko[2,3]
[1]Institute of Computational Mathematics and Mathematical Geophysics of Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russia
[2]National Research Nuclear University Moscow Engineering Physics Institute, Moscow, Russia
[3]Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia

16:00-16:15

ANGULAR MOMENTUM TRANSFER IN THE INTERACTION OF INTENSE CIRCULARLY POLARIZED LASER PULSES WITH STRUCTURED TARGETS

E.G. Gelfer[1], E.E. Peganov[2], S.V. Popruzhenko[2,3]
[1]ELI-Beamlines, Dolni Brezany, Czech Republic
[2]National Research Nuclear University Moscow Engineering Physics Institute, Moscow, Russia
[3]Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia

16:15-16:30

ANALYSIS OF L-SPECTRA OF MULTIPLY CHARGED IRON IONS FORMED IN EXPERIMENTS WITH INTENSE LASER PULSES

M.A. Alkhimova, I.Yu. Skobelev, S.S. Makarov, S.N. Ryazantsev and E.D. Filippov
Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia

16:30 - 16:45 Coffee Break

16:45-17:15

TABLE TOP LASER PLASMA ELECTRON ACCELERATION (*Invited*)

A.B. Savel'ev, I.N.Tsymbalov, K.A.Ivanov, D.A.Gorlova, A.Yu.Zavorotny, R.V.Volkov, S.A.Shulyapov
Faculty of Physics, Lomonosov Moscow State University, Moscow, Russia

17:15-17:30

ACCELERATION OF NEUTRAL ATOMS BY STRONG SHORT-WAVELENGTH SHORT-RANG ELECTROMAGNETIC PULSES

V.S. Melezhik, S. Shadmehri
Joint Institute for Nuclear Research, Dubna, Moscow Region, Russia

17:30-17:45

EFFICIENT LASER ACCELERATION OF ELECTRONS AND IONS FROM TARGETS WITH CONTROLLED PREPLASMA

A.V. Brantov[1,2], M.A. Rakitina[1], S.I. Glazyrin[1]
[1]*Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*
[2]*Dukhov Research Institute of Automatics (VNIIA), Moscow, Russia*

17:45-18:00

LASER PULSE POLARIZATION INFLUENCE ON EMISSION BY AN ELECTRON FROM THE FOCUS

A.V. Borovskiy [1], A.L. Galkin [2]
[1]*Baikal State University, Irkutsk, Russia*
[2]*Prokhorov General Physics Institute, Russian Academy of Sciences, Moscow, Russia*

SECTION-3 April 11 LASER PLASMAS (GPI RAS)

10:00-10:30

EFFECTS OF QUASI-PHASE MATCHING IN COHERENT RADIATION GENERATION BY ATOMIC SYSTEMS IN TWO-COLOR LASER FIELDS (*Invited*)

S.Yu. Stremoukhov[1,2]
[1]*Moscow State University, Moscow, Russia*
[2]*National Research Center "Kurchatov Institute", Moscow, Russia*

10:30-10:45

CONDUCTION BAND DYNAMICS IN SOLIDS INDUCED BY NEAR- AND MID-IR FEMTOSECOND LASER FIELDS

K.V. Lvov[1,2], S.Yu. Stremoukhov[1,2]
[1]*Moscow State University, Moscow, Russia*
[2]*National Research Center "Kurchatov Institute", Moscow, Russia*

10:45-11:00

EXPERIMENTAL INVESTIGATION OF OPTICAL ANISOTROPY DURING FEMTOSECOND LASER-INDUCED AIR BREAKDOWN IN NARROW INTENSITY RANGE

A.A. Ushakov[1], P.A. Chizhov[1,2,3], V.V. Bukin[1], T.V. Dolmatov[1], S.V. Garnov[1]
[1]*Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia*
[2]*Moscow Institute of Physics and Technology (National Research University), Dolgoprudny, Russia*
[3]*Russian Institute for Scientific and Technical Information ofthe Russian Academy of Sciences, Moscow, Russia*

11:00-11:15
VECTOR PARAMETERS IN ATOMIC IONIZATION BY TWISTED BESSEL RADIATION
[1]*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
[2]*School of Physics and Engineering, ITMO University, Saint Petersburg, Russia*
[3]*Laboratory for Modeling of Quantum Processes, Pacific National University, Khabarovsk, Russia*

11:15-11:30
NUMERICAL MODELLING OF PLASMA PERIODIC SUBWAVELENGTH STRUCTURES UNDER THE FOCUSED ULTRASHORT LASER PULSE EXPOSURE IN THE VOLUME OF SOLID DIELECTRICS
A.V. Bogatskaya[1,2], E.A. Volkova[3], A.M. Popov[1,2]
[1]*Physics Department, Moscow State University, Moscow, Russia*
[2]*Lebedev Physical Institute, Russian Academy of Sciences, Moscow, Russia*
[3]*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*

11:30-11:45 Coffee Break

SECTION-5 April 11 SOLID STATE PLASMAS (GPI RAS)

11:45-12:15
DEMIXING IN NANOCOMPOSITES OF HIGHLY POLARIZABLE INCLUSIONS (*Invited*)
E. Allahyarov[1,2,3] and H. Löwen[1]
[1]*Institut für Theoretische Physik II: Weiche Materie, Heinrich-Heine Universität Düsseldorf, Düsseldorf, German*
[2]*Theoretical Department, Joint Institute for High Temperatures, Russian Academy of Sciences (IVTAN), Moscow, Russia*
[3]*Department of Physics, Case Western Reserve University, Cleveland, Ohio, United States*

12:15-12:30
ANALYTICAL DESCRIPTION OF CYCLOTRON PLASMA RESONANCES IN MONOLAYER GRAPHENE
V.P. Krainov
Moscow Institute of Physics and Technology (National Research University), Dolgoprudny, Russia

12:30-12:45
EDGE PLASMON MODE EXCITATION IN GRAPHENE RECTANGLES BY INCIDENT TERAHERTZ WAVE
K.V. Mashinsky[1], V.V. Popov[1], D.V. Fateev[1,2]
[1]*Kotelnikov Institute of Radio Engineering and Electronics of the Russian Academy of Sciences (Saratov Branch), Saratov, Russia*
[2]*Saratov State University, Saratov, Russia*

12:45-13:00
ELECTRON-HOLE PLASMA, FREE EXCITONS AND ELECTRON-HOLE LIQUID IN SYNTHETIC DIAMOND UNDER ULTRAVIOLET LASER EXCITATION
E.I. Lipatov[1,2], D.E. Genin[1,2], D.S. Voitenko[1], A.S. Popova[1]
[1]*Tomsk State University, Tomsk, Russia*
[2]*Institute of High-Current Electronics, Tomsk, Russia*

13:00-13:15
MECHANISM OF ULTRAFAST DECAY CAUSING PERIODIC DAMAGE OF METALS BY FEMTOSECOND LASER PULSES
I.V. Oladyshkin, D.A. Fadeev
Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia

13:15-13:30
FORMATION OF SOLID-STATE PLASMA IN FERROELECTRIC SEMICONDUCTORS NEAR THE PHASE TRANSITION TEMPERATURE
D.V. Kuzenko
Federal State Budgetary Scientific Institution "Scientific Research Institute "Reaktivelectron", Donetsk, Russia

13:30-13:45
EXCITATIONS IN SOLID-STATE PLASMA WITHIN THE POLAR MODEL
L.M. Svirskaya[1,2]
[1]South Ural State Humanitarian and Pedagogical University, Chelyabinsk, Russia
[2]South Ural State University (National Research University), Chelyabinsk, Russia

13:45-14:00
SOLID-STATE PLASMA MODEL OF ELECTRICAL BREAKDOWN OF POLYMER DIELECTRICS
V.A. Pakhotin[1], N.T. Sudar[2], S.E. Semenov[1]
[1]Ioffe Institute, Saint-Petersburg, Russia
[2]Peter the Great Saint-Petersburg Polytechnic University, Saint-Petersburg, Russia

14:00-14:15
HYDROGEN DIFFUSION ALONG THE BOUNDARIES OF TUNGSTEN GRAINS IN CONTACT WITH HYDROGEN
M.G. Urazaliev
M.N. Mikheev Institute of Metal Physics of the Ural Branch of the Russian Academy of Sciences, Ekaterinburg, Russia

14:15-15:00 Lunch

SECTION-4 April 11 GENERAL PLASMAS (GPI RAS)

15:00-15:30
EXPERIMENTAL INVESTIGATION OF AN ANOMALOUS ABSORPTION OF THE ORDINARY WAVE IN THE PULSE DISCHARGE PLASMA FILAMENT (*Invited*)
E.Z. Gusakov[2], A.Yu. Popov[2], L.V. Simonchik[1], M.S. Usachonak[1]
[1]Stepanov Institute of Physics of NAS of Belarus, Minsk, Belarus
[2]Ioffe Institute, Saint-Petersburg, Russia

15:30-15:45
PLASMA AND GAS-DYNAMIC PROCESSES IN A NANOSECOND DISCHARGE IN AIR AT ATMOSPHERIC PRESSURE IN THE GAP WITH THE "PIN-TO PLATE" GEOMETRY
S.A. Maiorov[1], G.B. Ragimkhanov[2], A.A. Trenkin[3]
[1]Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia
[2]Dagestan State University, Makhachkala, Russia
[3]Russian Federal Nuclear Center, All Russia Research Center of Experimental Physics, Sarov, Russia

15:45-16:00
NUMERICAL MODELING OF A CAPACITIVE RADIOFREQUENCY DISCHARGE WITH LARGE ELECTRODES
Z.A. Qodirzoda[1], S.A. Dvinin[2]. D.K. Solikhov[1]
[1]Tajik National University, Faculty of Physics,
[2]Lomonosov Moscow State University, Faculty of Physics, Moscow, Russia

16:00-16:15

EXPLOSIVE ELECTRON EMISSION IN HIGH-CURRENT FIELD CATHODES BASED ON DIAMOND GRAPHITE FILM STRUCTURES

R.K. Yafarov

Saratov Branch of the Kotelnikov Institute of Radioengineering and Electronics of the Russian Academy of Sciences, Saratov, Russia

16:15 - 16:30 Coffee Break

16:30-16:45

UNEXPECTED EFFECT OF RARE-EARTH ORGANOMETALLIC COMPOUNDS ON THE DEVELOPMENT OF PLASMA CHEMICAL PROCESSES IN THE MIXTURES OF METAL AND DIELECTRIC POWDERS

A.S. Sokolov[1], N.S. Akhmadullina[1,2], V.D. Borzosekov[1], T.E. Gayanova[1], A.K. Kozak[1], A.E. Petrov[1], D.O. Pozdnyakov[3], V.D. Stepakhin[1]

[1]Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia
[2]A.A. Baikov Institute of Metallurgy and Material Science of Russian Academy of Sciences, Moscow, Russia
[3]MIREA — Russian technological university, Moscow, Russia

16:45-17:00

DEPOSITION OF SILVER NANOPARTICLES ON DIELECTRIC SURFACES IN A PLASMA-CHEMICAL PROCESS INITIATED BY GYROTRON RADIATION

E.A. Obraztsova[1,2], N.N. Skvortsova[1], V.D. Stepakhin[1], V.D. Borzosekov[1], A.V. Sokolov[1], V.D. Malakhov[1], A.V. Knyazev[1], E.G. Voronova[1], N.K. Kharchev[1], N.S. Akhmadullina, O.N. Shishilov[3], N.G. Gusein-zade[1]

[1]Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow 119991, Russia, Vavilova st. 38
[2]Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region, Russia
[3]A.A. Baikov Institute of Metallurgy and Material Science, Russian Academy of Sciences, Moscow, Russia
[4]MIREA – Russian Technological University, Institute of Fine Chemical Technologies, Moscow, Russia

17:00-17:15

PLASMA CHEMICAL SYNTHESIS OF OXYNITRIDE CERAMICS DOPED WITH TB^{3+} IONS USING A MICROWAVE DISCHARGE

N.S. Akhmadullina[1], S.N. Gusein-zade[2], N.N. Skvortsova[3], V.D. Stepakhin[3], V.D. Borzosekov[3], N.G. Gusein-zade[3], T.É. Gayanova[3], A.S. Sokolov[3], A.D. Rezaeva[3], A.K. Kozak[3], D.V. Malakhov[3], E.V. Voronova[3], A.V. Knyazev[3], O.N. Shishilov[2]

[1]A.A. Baikov Institute of Metallurgy and Material Science of Russian Academy of Sciences, Moscow, Russia
[2]MIREA – Russian Technological University, Institute of Fine Chemical Technologies, Moscow, Russia
[3]Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia

17:15-17:30

EXCITONIC NATURE OF PLASMA PHASE TRANSITION KINETICS IN DENSE MOLECULAR FLUIDS

I.D. Fedorov[1,2,3], V.V. Stegailov[1,2,3]

[1]Joint Institute for High Temperatures of the Russian Academy of Sciences, Moscow, Russia
[2]Moscow Institute of Physics and Technology National Research University, Dolgoprudny, Russia
[3]National Research University Higher School of Economics, Moscow, Russia

SECTION-4 April 12 GENERAL PLASMAS (GPI RAS)

10:00-10:30

OBLIQUE MAGNETOSOUND SOLITONS (*Invited*)

A.M. Ignatov

Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia

10:30-10:45

THE INFLUENCE OF EDGE LOCALIZED MODES ON THE SPECTRUM OF ELECTROMAGNETIC RADIATION SCATTERED BY PLASMA FLUCTUATIONS ON THE GLOBUS-M2 TOKAMAK

A.Yu. Tokarev[1], A.Yu. Yashin[1,2], K.A. Kukushkin[1], G.S. Kurskiev[2], V.B. Minaev[2], Yu.V. Petrov[2], A.M. Ponomarenko[1], N.V. Sakharov[2], N.S. Zhiltsov[2]
[1]*Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia*
[2]*Ioffe Institute, St. Petersburg, Russia*

10:45-11:00

GENERATION OF A HIGH-ENERGY SPECTRUM OF IONS AT THE FINAL STAGE OF THE Z-PINCH COMPRESSION

A.Yu. Chirkov, E.A. Morkhova, A.Yu. Frolov
Bauman Moscow State Technical University, Moscow, Russia

11:00-11:15

INFLUENCE OF NUCLEAR QUANTUM EFFECTS ON THE EQUATION OF STATE OF FLUID HYDROGEN AT HIGH PRESSURES

N.D. Kondratyuk[1,2,3], V.G. Lukianchuk[1,2], I.M. Saitov[1,2]
[1]*Joint Institute for High Temperatures RAS, Moscow, Russia*
[2]*National Research University Higher School of Economics, Moscow, Russia*
[3]*Moscow Institute of Physics and Technology (National Research University), Dolgoprudny, Russia*

11:15-11:30

ELECTRON-ION RELAXATION IN NONIDEAL PLASMAS: MOLECULAR DYNAMICS SIMULATIONS

I.V. Morozov, Ya.S. Lavrinenko, I.A. Valuev
Joint Institute for High Temperatures of Russian Academy of Sciences, Moscow, Russia

11:30-11:45

ON THE PHYSICAL NATURE OF SUBHARMONICS OF THE ELECTRON EMISSION FROM ULTRACOLD PLASMAS

Yu.V. Dumin[1,2]
[1]*Lomonosov Moscow State University, Sternberg Astronomical Institute, Moscow, Russia*
[2]*Space Research Institute of the Russian Academy of Sciences, Moscow, Russia*

11:45-12:00 Coffee Break

12:00-12:30

FORMATION OF EXTENDED TUBULAR PLASMA IN ARGON AT LOW PRESSURE AND IN A WEAK LONGITUDINAL MAGNETIC FIELD (*Invited*)

Yu.S. Akishev, V.P. Bakhtin, A.B. Buleyko, O.T. Loza, A.V. Petryakov, A.A. Ravaev, E.A. Fefelova
SRC «Troitsk Institute for Innovative and Thermonuclear Research», Moscow, Russia

12:30-12:45

MICROWAVE METHOD FOR MEASURING PLASMA CONCENTRATION IN A TUBULAR PLASMA SOURCE FOR A PLASMA MASER

A.V. Ponomarev, D.K. Ul'yanov
Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia

12:45-13:00

NUMERICAL SIMULATION: HIGH CURRENT IN A PLASMA RELATIVISTIC GENERATOR WITH INVERSE GEOMETRY

S.E. Andreev, I.L. Bogdankevich, N.G. Gusein-zade
Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia

13:00-13:15

NONLINEAR DYNAMICS OF BEAM-PLASMA INSTABILITY IN A PLASMA MICROWAVE AMPLIFIER IN THE PRESENCE OF AN ABSORBER

I.N. Kartashov, M.V. Kuzelev, A.V. Tumanov
Faculty of Physics, Lomonosov Moscow State University, Moscow, Russia

13:15-13:30

MULTI-WAVE AMPLIFICATION OF ELECTROMAGNETIC WAVES IN COAXIAL DIELECTRIC WAVEGUIDES

A.V. Ershov, M.V. Kuzelev
Faculty of Physics, Lomonosov Moscow State University, Moscow, Russia

13:30-13:45

SIMULATION OF A MINIATURE VIRCATOR AS A THZ SOURCE

R. Zamani[1], B. Shokri[2]
[1]*Faculty of Physics, Shahid Beheshti University, Tehran, Iran*
[2]*Physics Department and Laser-Plasma Research Institute Shahid Beheshti University Evin, Tehran, Iran*

13:45-14:00

MUTUAL INFLUENCE OF PLASMA ANTENNAS WITH DIFFERENT EXCITATION FREQUENCIES

I.M. Minaev, Sergeichev., Tikhonevich O.V., Karfidov D.M., Zhukov V.I.
Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia

14:00-14:15

NUMERICAL PIC SIMULATION OF THE EFFECT OF PLASMA ON THE CHARACTERISTICS OF THE PLASMA ANTENNA

N.N. Bogachev , I.L. Bogdankevich, V.P. Stepin, S.E. Andreev, N.G. Gusein-zade
Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia

14:15-15:00 Lunch

15:00-15:30

COMPARATIVE ANALYSIS OF ELECTROMAGNETIC PHENOMENA IN THE ATMOSPHERES OF EARTH, MARS, AND VENUS (*Invited*)

M.E. Abdelaal[1,2], A.V. Zakharov[2]
[1]*Moscow Institute of Physics and Technology, Dolgoprudny, Russia*
[2]*Space Research Institute of the Russian Academy of Sciences, Moscow, Russia*

15:30-15:45

EFFECT ON THE IONOSPHERIC PLASMA TO POWERFUL HIGH-FREQUENCY RADIO EMISSION AS A METHOD FOR STUDYING OF THE NEUTRAL ATMOSPHERE

N.V. Bakhmetieva, G.I. Grigoriev, I.N. Zhemyakov, E.E. Kalinina
Radiophysical Research Institute, Lobachevsky State, University of Nizhny Novgorod, Nizhny Novgorod, Russia

15:45-16:00

RADIO OCCULTATION STUDIES IN THE EARTH'S IONOSPHERE DURING STRONG MAGNETIC STORMS IN MARCH AND JUNE 2015

V.N. Gubenko, V.E. Andreev, I.A. Kirillovich
Kotelnikov Institute of Radio Engineering and Electronics RAS, Fryazino, Moscow region, Russia

16:00-16:15
PRODUCTION OF ARTIFICIAL BALL LIGHTNING USING A CAPILLARY PLASMA GENERATOR
V.L. Bychkov, D.E. Sorokovykh, D.V. Bychkov
Lomonosov Moscow State University, Moscow, Russia

16:15-16:30
A MODEL OF BALL LIGHTNINH WITH A CHARGED SOLID SHELL AND A GASEOUS CORE
V.L. Bychkov, D.E. Sorokovykh, D.V. Bychkov
Lomonosov Moscow State University, Moscow, Russia

16:30 - 16:45 Coffee Break

16:45-17:15
DIELECTRIC BARRIER DISCHARGES IN CONTACT WITH LIQUIDS (*Invited*)
V.V. Kovačević, G.B. Sretenović, B.M. Obradović, M.M. Kuraica
University of Belgrade, Faculty of Physics, Belgrade, Serbia

17:15-17:30
EXPERIMENTAL STUDY OF THE TRANSFER PROCESSES FROM THE SPHERICAL WATER DROPLET SURROUNDED BY SPARK DISCHARGE PLASMA CHANNEL FLOW
I.A. Shorstkii
Advanced technologies and new materials laboratory, Kuban State Technological University, Russia

17:30-17:45
PARAMETERS OF THE MULTISPARK HIGH-VOLTAGE DISCHARGE WITH GAS INJECTION THROUGH THE GAP BETWEEN DURALUMIN ELECTRODES
M.A. Zimina[1,2], K.V. Artem'ev[1], A.M. Davydov[1], I.V. Moryakov[1], V.D. Borzosekov[1,2], V.V. Gudkova[1,2]
[1]Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia
[2]Peoples' Friendship University of Russia (RUDN University), Moscow, Russia

17:45-18:00
ELIMINATING MATRIX EFFECTS IN AN INDUCTIVELY COUPLED PLASMA MASS SPECTROMETER
T.K. Nurubeyli[1,2], N.Sh. Cafar[1]
[1]Institute of Physics of the Ministry of Science and Education, Republic of Azerbaijan, Baku, Azerbaijan
[2]Azerbaijan State University of Oil and Industry, Baku, Azerbaijan

18:00-18:15 Closing Ceremony of the CSCPIER-2024

20th International Workshop
Complex Systems of Charged Particles and Their Interactions with Electromagnetic Radiation

Book of Abstracts

20th International Workshop

Complex Systems of Charged Particles and Their Interactions with Electromagnetic Radiation

Moscow, Russia, April 8-12, 2024

PLASMADYNAMIC PROCESSES IN QUASI-STATIONARY HIGH-CURRENT PLASMA ACCELERATORS OF A NEW GENERATION

V.M. Astashynski, O.G. Penyazkov

The A.V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus, 220072, Belarus, Minsk, Brovki str., 15

Quasi-stationary high-current plasma accelerators, operating in the ionic current transfer mode and performing ion-drift acceleration of magnetized plasma, are of great interest for creating high-energy plasma flows. In these systems, acceleration of plasma is accompanied by its compression due to interaction between longitudinal components of electric current and its own azimuthal magnetic field [1]. As a result, created at the outlet of the plasma accelerator is the compression plasma flow with plasma parameters significantly superior to those in the discharge device. To realize ionic current transfer it is necessary to organize ion supply from the anode side into the accelerating channel of the discharge device. For this purpose, the external electrode (anode) is made rod-shaped, as a result of which ions can enter the accelerating channel through the gaps between the anode rods. Replacing a solid external electrode on a rod-shaped one almost completely eliminates anode erosion [1].

For quasi-stationary plasma accelerators operating in the ion current transfer mode, criterions have been experimentally obtained that establishes the conditions for realizing maximum plasma parameters with a relatively small amount of impurities, depending on the macroscopic discharge parameters (peak value of discharge current and mass flow rate of the working gas). It was shown that the maximum values of the plasma velocity and thermodynamic parameters of the compression flow are observed in such a region of the integral parameters of the accelerator when the dependence of the amplitude value of the current on the mass flow rate of the working gas has a minimum.

The ideas about the determining influence of ion-exchange processes in the accelerating channel of quasi-stationary plasmadynamic systems with electrodes permeable to plasma and magnetic field on the character of discharge current distribution providing the formation of compression flow with high thermodynamic parameters are discussed. Based on local measurements of the azimuthal component of a magnetic field the spatial-temporal pattern of electric current contours distribution in two stage quasi-stationary high-current plasma accelerator QHPA P50M type was obtained. In addition to “slippage” of current along cathode, two further types of current distributions in accelerator’s channel were first obtained. These are quasi-radial current distribution and distribution with “anti-slippage” of current. As follows from our studies, in order to obtain any one of these modes of current distribution it is necessary correlate Morozov’s exchange parameters in the near-anode and near-cathode regions according to established relations. It should be noted here, that exchange parameter ξ is equal to the ratio of total discharge current to the total number of ions in accelerator’s channel [2].

To characterize the degree of "stationarity" of plasmadynamic systems, the dynamic coefficient $\eta(t)$, which shows the ratio of the parameter under study (e.g., temperature or plasma electron concentration, etc.) to the total discharge current $I_p(t)$, was introduced into the analysis.

Designed and developed at the Institute are the quasi-stationary plasma accelerators operating in a mode of ion-current transfer such that magnetized plasma is accelerated through the ion-drift mechanism. These plasmadynamic systems generate high-energy compression plasma flows of a specified composition, on a set of parameters (plasma velocity – up to 200 km/s, temperature and electron concentration – up to 10–15 eV and 10^{17}–10^{18} cm^{-3}, accordingly, discharge duration – 100 to 500 μs) surpassing all other types of plasma accelerators.

References

[1]. Morozov A. I. *Introduction to plasma dynamics* (2013, CRC Press).

[2]. Morozov A. I., Solov’ev L. S. *Questions of Plasma Theory* **8**: 3-87 (1974, Moscow).

FORMATION AND COLLISION IN LOW PRESSURE AIR THE PLASMA DIFFUSE JETS WITH DIFFERENT DIAMETERS

V.F. Tarasenko[1], V.A. Panarin[2], V.S. Skakun[2], N.P. Vinogradov[2]

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[2] *Institute of High Current Electronics SB RAS, Akademichesky Ave., 2/3, Tomsk, 634055, Russia*

Over the past three decades, considerable attention has been paid to the study of pulsed atmospheric discharges that occur at altitudes of more than 20 km above sea level. The greatest interest is shown in the study of sprites that are predominantly red in color and observed in the altitude range of 40–100 km. Sprite photography and other measurements are carried out in ground-based laboratories, as well as from aircraft, satellites and the International Space Station. In parallel, analogues of high-altitude discharges are being studied in laboratory conditions. For this purpose, various discharge modes are used at low air pressures.

In our works [1–3], it was shown that by creating plasma in tubes filled with atmospheric air to pressures of a fraction of a unit of Torr, it is possible to form plasma diffuse jets (PDJs) of red color. As the pressure decreases, the length of the jets exceeds 1 meter and their front reaches the end flanges. The initiation of the PDS was carried out due to the plasma of a pulse-periodic capacitive discharge. The electrodes were located on the outer surface of the dielectric tube; accordingly, the capacitive discharge plasma did not contact the metal electrodes.

The purpose of this work is to study the formation and collision of diffuse plasma jets with different and identical frontal polarities, as well as to determine the emission spectra in different parts of the discharge.

An example of the discharge glow during a collision of a PDS in a tube with an internal diameter of 14.2 cm is shown in Fig. 1.

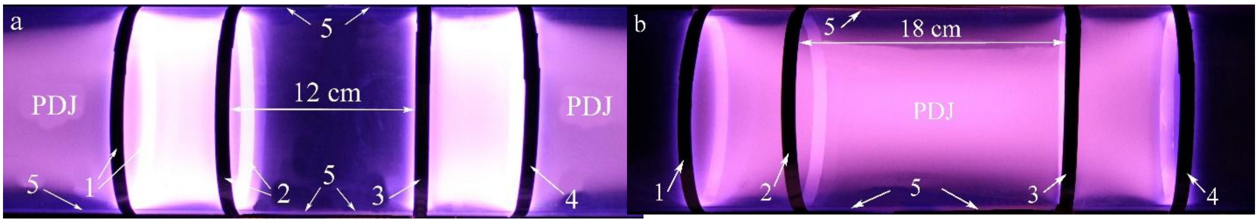

Fig. 1. Photographs of the discharge glow when voltage pulses from two generators of the same (a) and different polarity (b) are applied to high-voltage electrodes 1-2 and grounded electrodes 3-4. 5 – ESALUX TX polycarbonate tube with an outer diameter of 15 cm and a wall thickness of 4 mm. $/U/ = 7$ kV, $f = 21$ kHz. $p = 2$ Torr.

It has been established that when the PDS is formed by voltage pulses of different polarities, the radiation intensity in the central part of the tube between the grounded electrodes increases and exceeds the radiation intensity between each pair of electrodes connected to the generators.

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IONIZATION-DISSOCIATION PHASE TRANSITIONS OF THE FIRST ORDER. (ON A NEW CLASS OF FIRST-ORDER PHASE TRANSITIONS)

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Plasma phase transition was theoretically predicted in 1968. The type of metastable states that could arise during this phase transition was qualitatively proposed in [1], where some of their exceptional features were revealed. In this work, we consider the phase diagram for the fluid-fluid phase transition in warm dense hydrogen at megabar pressures. As in [1], we use the coordinates pressure P – specific volume V. Within both chemical models and quantum approaches, we have identified three features of the $P(V)$ isotherms of pressure versus specific volume in the region of the fluid-fluid phase transition in warm dense hydrogen.

These three features distinguish the obtained isotherms from the Van der Waals (VdW) type $P(V)$ isotherm: (1) the function $P(V)$ is single-valued for the VdW type; accordingly, the metastable and equilibrium branches of different phases are separated according to the ranges of their specific volume; in our case, in a certain range of specific volume, there is an overlap of the metastable branch of one phase with the metastable and equilibrium branches of another phase; (2) the critical temperature has the highest pressure among all VdW-type isotherms and, conversely, the lowest in our case; (3) since the function $P(V)$ is in our case three-valued in the range of overlapping branches of the isotherm, in our case in this range of specific volume, an isolated section of metastable states appears.

We provide examples of phase diagrams for several chemical models, including those provided by V.K. Gryaznov, A.V. Filippov and A.S. Shumikhin, who kindly calculated these drawings based on data from their archives at our request. Chemical models with both ionization and dissociation without ionization are considered. For the fluid-fluid phase transition in warm dense hydrogen, we also consider phase diagrams obtained by ab initio approaches: quantum molecular dynamics and path integral molecular dynamics methods.

We argue in favor of the plasma nature of the fluid-fluid phase transition in warm dense hydrogen. We make a comparison with experimental data.

Preliminary results were published in [2]. We thank V.K. Gryaznov, A.V. Filippov and A.S. Shumikhin for providing materials that were not previously published anywhere.

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ON COLLISIONLESS DAMPING OF ELECTROMAGNETIC WAVES IN A CLOUD OF PLASMA ELECTRONS

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In plasma physics, considerable attention is paid to the study of the propagation *of electromagnetic waves* (EMW) [1, 2]. The study of the mechanisms of their propagation, for example in the ionosphere, is carried out within the framework of the material equations of electrodynamics. In this case, the concept of dielectric constant is used [1]. A more in-depth study of the propagation of EMW in plasma is carried out within the framework of kinetic theory based on the plasma distribution function [2]. A further opportunity has emerged to study the propagation of EMW in plasma using the *structured bodies* (SB) motion equation, that is, bodies consisting of interacting elements. It takes into account that in the general case, the work of external forces acting on a system goes not only to its acceleration, as is the case in classical mechanics for a material point (MP), but also to a change in its internal state. This equation has a form [3, 4]:

$$M_N \dot{V}_N = -F_N^0 - \mu V_N, \tag{1}$$

where $F_N^0 = \sum_{i=1}^N F_i^0$; F_i^0 is external force acted on i - th MP; $F_{ij}^0 = F_i^0 - F_j^0$; $m_i = m_j = 1$; $M_N = Nm_i$; $V_N = (\sum_{i=1}^N v_i)/N$; $\dot{E}_N^{\text{int}} = \sum_{i=1}^{N-1}\sum_{j=i+1}^N v_{ij}(m\dot{v}_{ij} + F_{ij}^0 + NF_{ij})$; $\mu = \dot{E}_N^{\text{int}} / (V_N^{max})^2$; F_{ij} -is a force between i and j MP; $V_N^{max} = -\dot{E}_N^{\text{int}} / F_N^0$.

According to eq. (1), when the SB moves in a non-uniform field of forces, a change in its internal energy occurs. Such a field of forces for charged plasma particles can be EMW. It can heat up due to the increase in the energy of the chaotic motion of charged particles due to the energy of the EMW. Substituting the EMW force into eq. (1), we obtain:

$$N\dot{V}_N = -\sum_{i=1}^N e_i E_0 e^{i(\omega t - kr_i)} - \frac{1}{NV_N}\sum_{i=1}^{N-1}\sum_{j=i+1}^N v_{ij}[\dot{v}_{ij} + 2eE_0 e^{i(\omega t - k(r_i + r_j)/2)}\sin(kr_{ji}/2) + Ne^2 / r_{ij}^2]. \tag{2}$$

Here e is electron charge, $E = E_0 \exp[i(\omega t - kr_i)]$ is harmonic of EMW in point r_i .

The second term on the right-hand side of the eq. (2) determines the dissipative forces that lead to plasma heating due to EMW. This heating is similar to the excitation of oscillators placed in a non-uniform field of external forces. Their excitation is proportional to the difference in forces acting on the elements of the oscillator. As in the case of collisionless Landau damping [5], this EMW damping is collisionless, although it has a completely different mechanism.

Thus, according to the SB motion equation, when EMW passes through plasma, its attenuation occurs. This is caused by gradients of forces acting on charged particles created by EMW. That is, attenuation occurs at EMW scales at which the difference in forces acting on plasma particles is significant. It is logical to call such attenuation **electromagnetic friction,** since its nature is associated with the work of the EMW forces, which goes towards increasing the energy of the chaotic motion of plasma particles.

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PUMPING OF PLASMA WAVES BY A REB IN A MAGNETIZED PLASMA COLUMN FOR PLASMA HEATING AND RADIATION FLUX GENERATION

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The first experiments on pumping plasma oscillations during relaxation of a relativistic (~ 1 MeV) electron beam (REB) with a kiloampere current in a magnetized plasma column were carried out at the Institute of Nuclear Physics of the Siberian Branch of the USSR Academy of Sciences in the early 70s of the last century [1,2]. These experiments were carried out at a beam pulse duration of 100 ns. These studies focused on the problem of plasma heating due to the transfer of energy from the beam to plasma electrons through highly nonlinear processes occurring at a high energy density of pumped plasma oscillations [3]. The highest energy transfer from the REB with a duration of 100 ns to plasma electrons reached a level of ~ 30% [4]. The results of studies of the beam-plasma system, carried out with beams of the above duration, made it possible to achieve nuclear fusion parameters of heated plasma using the GOL-3 installation with a beam current of 20 kA and a pulse duration of about 10 μs [5].

Along with collisionless heating of the plasma, an important effect of intense beam-plasma interaction is the generation of radiation at plasma frequencies. Experiments in this direction were started on GOL-3 [6] in 2010. In subsequent experiments at the GOL-PET installation, a power level of 10 MW was achieved with a microsecond duration at the frequency of upper hybrid oscillations (0.2-0.3 THz) in a directed flow released into free space [7]. The mechanisms of generation of radiation at plasma frequencies lying in the terahertz region of the spectrum were proposed and analyzed in detail in works [8-9].

The above-mentioned stages of research into plasma heating and generation of radiation during relaxation of a kiloampere REBs in a plasma column will be described in the present report.

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ON THE CORRESPONDENCE OF A RADIATION FLUX FREQUENCY SPECTRUM FROM A BEAM-PLASMA SYSTEM TO THE SPECTRUM OF PLASMA ELECTRONIC OSCILLATIONS PUMPED BY A BEAM

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The interaction of a relativistic electron beam with plasma is a complex physics process in frame of scientific research. One of the manifestations of this interaction process is the generation of electromagnetic radiation fluxes, observed at the propagation of the electron beam with kiloampere current through a magnetized plasma column [1]. It should be mention, that the first attempt to involve theoretical description of radiation flux emission by a beam-plasma system was done a long time ago for the explanation of radio frequency bursts from the solar corona [2]. Currently, studying the physical mechanism of the radiation flux generation due to the intense interaction of a beam with a plasma is of great importance. This mechanism is especially promising to create a multi-megawatt source of the radiation in the frequency range (0.1–1) THz [3]. This fundamentally new method to generate terahertz radiation is realized in experiments caring out at the GOL-PET facility in the Budker Institute of Nuclear Physics SB RAS (see [3]).

In these experiments, a directed radiation flux in the frequency range 0.2-0.3 THz was successfully generated with the energy content of 10 J per microsecond pulse. Given result was obtained in case of propagating the beam at the current density (1–2) kA/cm^2 in a plasma column with the density (6-8) 10^{14} cm^{-3} [4]. An important task of these and further studies is the establishing of a connection between the radiation flux spectral characteristics and the spectrum of the plasma electronic oscillations pumped by the electron beam. This report is devoted to comparison of the spectral density of the radiation flux measured in experiments in case of uniform plasma density in the column cross section with the radiation spectrum calculated in numerical simulation based on the model considering electron beam pumping the upper-hybrid plasma oscillations [5]. The spectrum of these upper-hybrid plasma oscillations was calculated in the theoretical model under suppose of the transformation of the oscillations propagating in synchronous with the beam electrons into the waves with turbulent spectrum of wave vectors (see [5]). Comparison measurement results with the results of the theoretical study demonstrates good agreement. Thus, we got well conformation on promising of the beam-plasma system to generate radiation in the frequency area of plasma oscillation and the possibility to obtain multi-megawatt radiation fluxes in the frequency range of 0.1-1 terahertz.

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DIPOLE EFFECTS IN THE VLASOV KINETIC EQUATION

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We consider microscopic deterministic derivation of the Vlasov kinetic equation in terms of classical mechanics. In the beginning we present the microscopic definition of the distribution function

$$f(\mathbf{r},\mathbf{p},t) = \frac{1}{\Delta}\cdot\frac{1}{\Delta_{\mathbf{p}}}\cdot\int_{\Delta,\Delta_{\mathbf{p}}} d^3\xi\cdot d^3\eta\cdot\sum_{i=1}^{N}\delta\big(\mathbf{r}+\boldsymbol{\xi}-\mathbf{r}_i(t)\big)\cdot\delta\big(\mathbf{p}+\boldsymbol{\eta}-\mathbf{p}_i(t)\big), \qquad (1)$$

where $\mathbf{r}$ is the coordinate space variable, $\mathbf{p}$ is the momentum space variable, t is the time, Δ is the physically infinitesimal volume in the coordinate space, $\Delta_{\mathbf{p}}$ is the physically infinitesimal volume in the momentum space, $d^3\xi$ ($d^3\eta$) element of volume in the coordinate (momentum) space, $\boldsymbol{\xi}$, , $\boldsymbol{\eta}$, , , $\mathbf{r}_i(t)$ is the coordinate of a particle, $\mathbf{p}_i(t)$ is the momentum of a particle. Here we follow concept suggested in Ref. [1].

Definition (1) allows us to consider the evolution of this function. Since we consider an averaging over volume of space

$$\begin{gathered}\partial_t f + \mathbf{v}\cdot\nabla_{\mathbf{r}} f + q\left(\mathbf{E}+\frac{1}{c}[\mathbf{v},\mathbf{B}]\right)\cdot\nabla_{\mathbf{p}} f + \nabla\cdot\mathbf{F} \\ +q\left(\partial^\beta\mathbf{E}+\frac{1}{c}[\mathbf{v},\partial^\beta\mathbf{B}]\right)\cdot\nabla_{\mathbf{p}} d^\beta + \frac{q}{c}\varepsilon^{\alpha\beta\gamma}B^\gamma\left(\partial^\alpha_{\mathbf{p}}F^\beta\right) = 0\end{gathered}. \qquad (2)$$

A generalized Vlasov equation (2) contains three additional terms, each of them contains one of two additional vector distribution functions. Here we present the explicit definitions of these functions

$$\mathbf{d}(\mathbf{r},\mathbf{p},t) = \frac{1}{\Delta}\cdot\frac{1}{\Delta_{\mathbf{p}}}\cdot\int_{\Delta,\Delta_{\mathbf{p}}} d^3\xi\cdot d^3\eta\cdot\sum_{i=1}^{N}\boldsymbol{\xi}\cdot\delta\big(\mathbf{r}+\boldsymbol{\xi}-\mathbf{r}_i(t)\big)\cdot\delta\big(\mathbf{p}+\boldsymbol{\eta}-\mathbf{p}_i(t)\big), \qquad (3)$$

$$\mathbf{F}(\mathbf{r},\mathbf{p},t) = \frac{1}{\Delta}\cdot\frac{1}{\Delta_{\mathbf{p}}}\cdot\int_{\Delta,\Delta_{\mathbf{p}}} d^3\xi\cdot d^3\eta\cdot\sum_{i=1}^{N}\boldsymbol{\eta}\cdot\delta\big(\mathbf{r}+\boldsymbol{\xi}-\mathbf{r}_i(t)\big)\cdot\delta\big(\mathbf{p}+\boldsymbol{\eta}-\mathbf{p}_i(t)\big). \qquad (4)$$

Appearance of equation (2) and the distribution functions (3) and (4) is presented in Ref. [2]. The suggested model includes the equations for evolution of the distribution functions (3) and (4). Equations for the evolution of the dipolar distribution functions (3) and (4) contain the additional tensor quadrupole distribution functions. The method of truncation of this chain of equations is presented. It is made in a way so the physically infinitesimal volume of the coordinate/momentum space appears explicitly in the coefficients. Finally, the application of the extended set of the kinetic equations to the plasma waves is made. Corresponding dispersion dependencies are obtained.

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ON THE PHYSICS OF DENSE PLASMAS

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Recently, using the exploding foils experiments [1] the measurements of thermodynamic functions and the electrical resistivity of dense plasma of lead (Pb) were carried out [2]. A comparison of the results with those obtained by a chemical model of the classical plasma has shown that the model essentially underestimates the energy of ionization of the plasma and overestimates its temperature (for given values of the specific volume and internal energy) [2]. At present there is no consistent theory of dense plasmas, so that to interpret these results it is necessary to estimate accurately the coupling parameter and for this one needs to know the temperature and the ionization degree. None of these quantities is measured in the experiments.

In the present work an estimate of the range of the coupling parameter values for the plasma investigated in the experiments [1,2] is made and some effects of nonideality in the thermodynamic functions and the resistivity behavior are interpreted.

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Kinetic theory of plasma expansion in vacuum diode

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The phenomenon of vacuum breakdown has been widely studied both experimentally and theoretically [1,2]. One of the key problems of the vacuum breakdown theory is the process of plasma motion. Experiments convincingly show that the velocities of cathode plasma expansion and characteristic values significantly exceed the thermal velocities of plasma components [3]. The phenomenon why do ions move towards the increasing electric potential (from cathode to the anode) and arriving at anode gain kinetic energy (> 100 eV) exceeding the operating voltage of a vacuum arc discharge (< 80 eV) is called an “anomalous ion acceleration” [4]. There are many hypotheses aimed to explain this phenomenon (e.g., explosive, collisional and electrodynamic theories [5]), but it still has no commonly accepted explanation.

The paper presents a theoretical explanation of the causes of the phenomenon of “anomalous ion acceleration”. Based on the kinetic equations for charged particles and field equation, the motion of multi-component electron-ion plasma in a self-consistent electric field is described. The proposed theoretical interpretation convincingly proves that the main mechanism of anomalous acceleration of cathode plasma ions is the collisionless motion of ions in a self-consistent electric field. The key factor having an effect on the dynamics of collisionless plasma is the formation of a virtual cathode with a potential drop depth of tens of volts due to fast removal of electrons to the anode. The simulation also indicates that the plasma expansion mechanism has a purely electrodynamic nature, not associated either with the specific geometric inhomogeneity of the gap, or with the influence of elastic scattering electron-ion and ion-ion collisions [6-8].

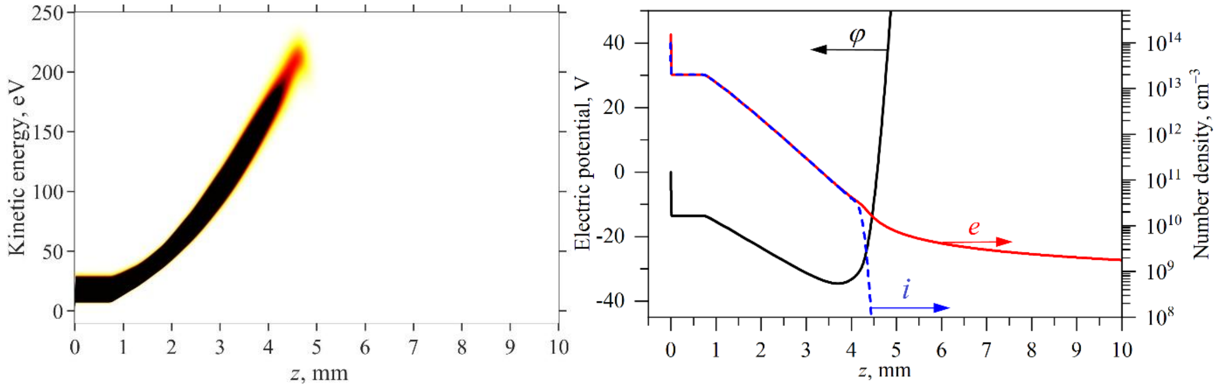

Fig. 1. Typical density plots of ion distribution function as well as number density and electric potential distribution in vacuum diode.

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ON THE PROTON-BORON FUSION IN OSCILLATING PLASMAS OF NANOSECOND VACUUM DISCHARGE

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Earlier, experiments on the aneutronic proton-boron (pB) fusion $p + {}^{11}B \rightarrow \alpha + {}^{8}Be^{*} \rightarrow 3\alpha + 8.7$ MeV in a plasma of a miniature nanosecond vacuum discharge (NVD) were presented [1]. In the cylindrical geometry of the NVD, a well-known inertial electrostatic confinement (IEC) scheme, but with reverse polarity, was implemented [1]. In this scheme, PiC modeling in the electromagnetic code KARAT revealed the formation of a virtual cathode (VC) in the anode space of the NVD and a corresponding potential well (PW) with a depth of ≈ 100 kV. A quasi-stationary PW with a size of several millimeters plays the role of a micro-accelerator of protons and boron ions to energies of hundreds keV, when the yield of the pB reaction in the field of particle energies near the secondary resonance (≈ 150 keV) becomes already noticeable [1]. In the process of ion oscillations in PW, head-on collisions of a part of protons and boron ions with energies of ~100-500 keV lead to a proton–boron reaction and the appearance of α particles [1]. Earlier, in the same scheme of deuterons confinement and oscillations in the PW, nuclear DD synthesis was previously studied, where both a single and pulsating yield of 2.45 MeV neutrons was observed in oscillating plasma [2].

PiC modeling revealed the optimal geometry of the electrodes for the maximum yield of α particles from the proton–boron reaction in the NVD scheme [1,3]. However, the proton-boron nuclear fusion experiment was conducted earlier with an old anode of a slightly different geometry, which turned out to be convenient for filling it with boron nanoparticles due to the developed microrelief of the surface in previous experiments on DD synthesis. In this report, we present the results of PiC modeling in the KARAT code of the processes leading to the proton-boron reaction for the real geometry of the anode. In particular, it follows from them that the total yield of α particles was accumulated in the experiment due to just single convergence of protons and boron ions to the discharge axis with each shot [4]. In addition, some features of scaling of the proton–boron fusion power by the size of the virtual cathode are discussed.

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ION-ACOUSTIC SOLITON IN A COLLISIONLESS NONISOTHERMAL PLASMA

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The process of propagation of an ion-acoustic soliton in a collisionless non-isothermal plasma is studied analytically in one-dimensional geometry. To describe the electronic component of the plasma, a kinetic approach is used taking into account the motion of the soliton. The movement of ions is described by the equations of hydrodynamics.

It is shown that in this model the Vlasov kinetic equation for electrons and hydrodynamics for ions admit solutions in the form of a solitary ion-acoustic wave. It was found that the main parameter determining the possibility of the existence of an ion-acoustic soliton is the value of its propagation speed in the plasma. A soliton is possible only at supersonic propagation speeds, and the greater the speed of the soliton, the greater its amplitude reaches. The limit to the increase in soliton amplitude is determined by the phenomenon of breaking the ion component of the plasma.

It was found that in the laboratory coordinate system, along with the transfer of trapped electrons in the direction of soliton propagation, there is a flow of transit electrons directed in the opposite direction. The physical explanation for the appearance of the current of transit electrons is the absence of symmetry in velocities in the distribution function of electrons interacting with the field of a soliton moving in space. There are fewer electrons that fall into the potential well of the soliton, overtaking it, than electrons, which are overtaken by the soliton. Electrons catching up with the soliton, passing over the well, increase their speed, and the latter slow down. As a result, an integral flow of electrons appears in the direction opposite to the direction of soliton motion. Taking into account the sign of the charge, this corresponds to the appearance of an electron current in the direction of soliton motion.

The current of trapped electrons is always negative, so the current of transit electrons reduces the total electron current. It is shown that over the entire range of ion-acoustic soliton velocities these currents are comparable in magnitude. Consequently, taking into account the motion of the soliton when determining the electron velocity distribution function is of fundamental importance when studying electron currents flowing in the soliton region.

It has also been established that, integral over the time of interaction of the soliton with the plasma, the total current of all charges passing through any cross section in the laboratory coordinate system is equal to zero. Consequently, the quasineutrality of the plasma volume is maintained after the ion-acoustic soliton passes through it.

MEASUREMENT OF ELECTRIC FIELD IN ATMOSPHERIC PRESSURE DISCHARGES USING STARK POLARIZATION SPECTROSCOPY

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A short overview of the emission spectroscopy methods for measuring the macroscopic electric field in discharges with helium (at low and at high pressures) is given. The occurrence of macroscopic electric field is a consequence of the space charge buildup. It is a common feature of discharge sheaths, streamer heads and double layers. The spectroscopic methods are based on polarization-dependent Stark splitting and shifting of atomic lines in the presence of a relatively strong electric field. The polarization dependent Stark emission spectroscopy is a powerful and practical tool for investigating the macroscopic field in electric discharges [1-3]. Several experimental examples of the use of helium line Stark effect are presented, see Figure 1. The line He I 492.2 nm is the best choice for measuring of the electric field spatiotemporal distribution in high pressure discharges. The important advantage of this noninvasive method is its ab initio nature, making it independent of plasma parameters and fulfillment of special conditions. Special attention should be paid to the optical path effects when setting up the experiment and analyzing the results. For measurement in conditions where the Stark method cannot be used, a method based on helium line intensity ratio is recommended. This second method relies on the local field approximation and therefore can only be used at a relatively high (atmospheric) pressure.

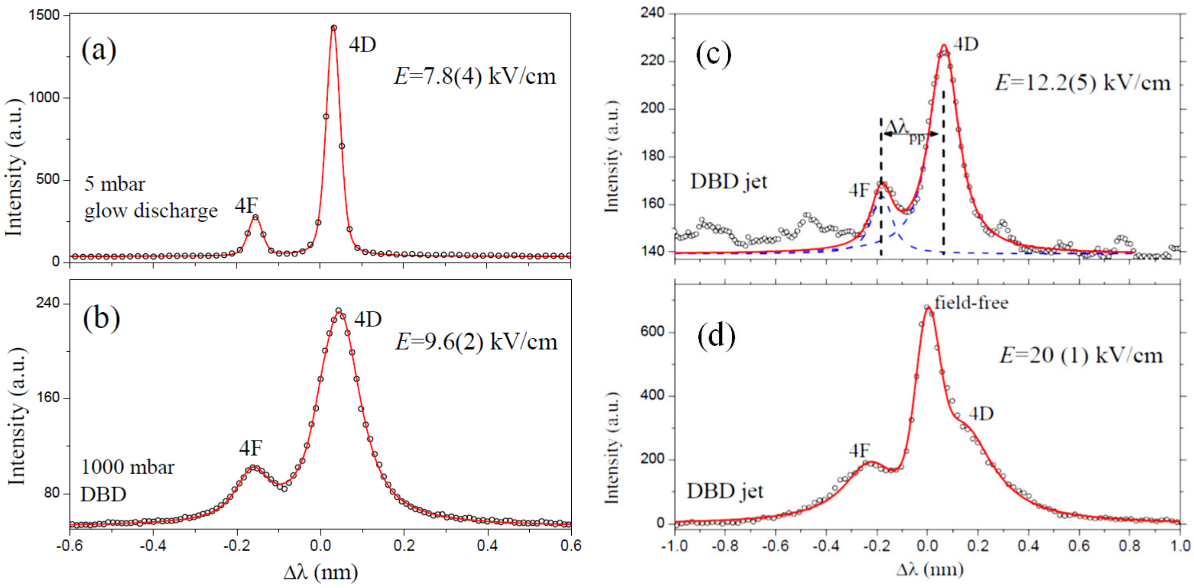

Fig. 1. Examples of He I 492.2 nm line (a) from a low pressure DC glow discharge, near the cathode, (b) from a dielectric barrier discharge at atmospheric pressure, near the cathode, (c); fit for each component and the overall fit are shown. (d) from atmospheric plasma jet; example of spectrum with strong field-free component. Corresponding fits are shown as line graphs.

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FEATURES OF THE DYNAMICS OF MICROWAVE DISCHARGES IN ATOMIC AND MOLECULAR GASES

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This paper presents the results of numerical calculations of plasma dynamics in a microwave discharge in nitrogen and helium under the experimental conditions from [1].

The model is based on the balance equations of charged and excited particles, the balance equations for the energy of electrons and the heavy component of the plasma, as well as the system of Maxwell's equations for describing the electromagnetic field of the microwave [2,3]. To describe the discharge in helium, a set of plasma-chemical reactions taken from [4] was used. Two excited atomic and one excited molecular states of helium, as well as two types of ions, were taken into account. In addition, a detailed set of elementary processes taken from the work [5] and [6] was considered. 2 types of ions and 5 excited states of the helium atom and two excited molecular helium were taken into account.

To describe the microwave discharge in nitrogen, a set of reactions from [2,3] was considered. In addition, the model took into account the balance equation for the vibrational energy of nitrogen, and the kinetics of elementary processes included the mechanisms of rapid gas heating [2,3] and vibrational-translational relaxation. The rates of inelastic processes involving electrons were determined using the Maxwellian EDF and the EDF obtained within the framework of the local Boltzmann kinetic equation.

As a result of numerical calculations, the dynamics of the breakdown of a microwave discharge and its elongation along an oscillating electric field are presented.

A transition from a diffuse form of microwave discharge to a contracted (thread-like) form has been demonstrated. Quantitative agreement of the gas temperature and electron density with experimental data at times longer than 7 μs has been shown [2,3].

For a discharge in helium, it is shown that it is more accurately described within the framework of a detailed set of elementary processes, which is apparently due to taking into account the excitation of various states and taking into account the loss of electron energy due to this. As a consequence, the electron concentration values turned out to be closer to the experimental data.

For a discharge in nitrogen, the influence of a small oxygen admixture leads to agreement with experiments over a larger interval of time studied.

In addition, for a discharge in nitrogen, an analysis was carried out on the sensitivity of the reaction constants to the formation of a discharge.

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FEATURES OF THE KINETICS OF FAST ELECTRONS IN A PLASMA OF NEGATIVE GLOW OF A SHORT GLOW DISCHARGE AND ITS APPLICATIONS

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The paper presents the results of studies of plasma parameters and kinetics of fast electrons in the region of negative glow (NG) of a short glow discharge at low pressures and a discharge with a microhollow cathode at high pressures based on a hybrid model [1,2], including a kinetic description of electrons and fluid description of heavy plasma components.

The results of numerical calculations are compared with the results of probe studies. It is shown that the hybrid model well describes the plasma parameters in the NG region of the glow discharge: temperature and electron density. In addition, the hybrid model makes it possible to quite accurately describe the formation of peaks in the EEDF from fast electrons produced as a result of Penning ionization reactions and second-order impacts. The possibility of recording small fractions of impurities of hydrocarbons, silane and other molecules has been demonstrated [3-5].

The reliability of determining the concentration of excited helium atoms in NG plasma is shown by analyzing the experimental high-energy part of the EEDF, namely peaks from fast electrons generated in Penning ionization reactions between two metastable helium atoms and Penning ionization of impurity atoms and molecules of low concentration. The above technique can be successfully applied to determine the absolute values of the concentration of impurity atoms and molecules by eliminating the second derivative of the ion current on the probe and analyzing the high-energy part of the EEDF.

This technique can be in demand both in gas analytical applications and in applications related to the synthesis of various types of nanostructures.

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ON MODELING ELECTRON RUNAWAY IN GASES BY THE PARTICLE METHOD

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Modeling of diffusion and drift of electrons in gases by the particle method allows us to obtain almost all kinetic characteristics: mobility and diffusion coefficients, ionization coefficient, etc. When drifting in weak homogeneous electric fields (for inert gases E/N <10 Td), electron transfer is very well described in the diffusion-drift approximation with diffusion and drift coefficients depending on the field strength.

In strong fields, due to ionization and the appearance of new electrons in a real physical system, the situation becomes more complicated. There is a need to adequately take into account the appearance and loss of electrons. In moderately strong fields (for inert gases E/N < 200 Td), the following problem statements can be used:

1) Avalanche mode – new electrons are added to the system and the average velocity and energy of electrons in the system are determined (Townsend stationary experiment [1]);
2) Time–of–flight experiment - electrons arising during ionization are not taken into account, i.e., according to the ergodic hypothesis, it is assumed that the ensemble average coincides with the time average [1, 2];
3) We have proposed a modification of the avalanche mode, in which instead of the electron added to the system during ionization, the most energetic electron is removed from it. This determines the value of the energy barrier for electrons to leave the system - wall potential (wall model) [3].

In ultra-strong fields (for inert gases above 1000 - 10000 Td), electrons can go into a constant acceleration mode, which for real physical conditions leads to the appearance of electrons with very high energy, limited by the size of the physical installation.

In this work, for all inert gases, the results of calculations are presented for regimes of weak and moderate fields (0.001 - 10 Td), and strong and ultra-high fields up to 10000 Td. For strong fields, a definition of the electron runaway coefficient is given by analogy with the ionization coefficient. Its value was calculated for two modes: avalanche and recombination on the wall. It is shown that, starting from a certain critical value of E/N, the runaway coefficient exceeds the ionization coefficient, and in this case the existence of an independent discharge is impossible. That is, the electron formed during the ionization event will, on average, go into the runaway mode without producing a single act of ionization.

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PATTERNS OF THE IONIZATION POTENTIALS OF MULTICHARGED IONS

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For elements of the periodic system with atomic numbers 18 ≤ Z ≤ 110, the available data [1] on the ionization potentials of ions $I_N^{(Z)}[eV]$ in isoelectronic sequences with the number of electrons $N_e \leq Z - 5$ are analyzed. Presented in special, semiclassical, coordinates:

$$e_N(\sigma) = I_N^{(Z)}\, Z^{-4/3}/E_H, \quad \sigma = \pi Z^{-1/3}, \; E_H = 27.21\, eV. \qquad (1)$$

these data form smooth monotonic dependences on the atomic number Z (see Fig.) allowing their approximation by simple polynomials: $\lg e_N(\sigma) = \sum_{i=0}^{i_{max}} a_i(N)\sigma^i$. It is optimal to divide the range of elements into 3 groups: medium, 18 ≤ Z ≤ 54 [2], heavy, 55 ≤ Z ≤ 85 [3] and super-heavy, 85 ≤ Z ≤ 110 [4]. In this case, $i_{max} \leq 3$, and small tables of polynomial coefficients make it possible not only to approximate known ionization potentials with an accuracy of about one percent or higher, but also to estimate missing ones.

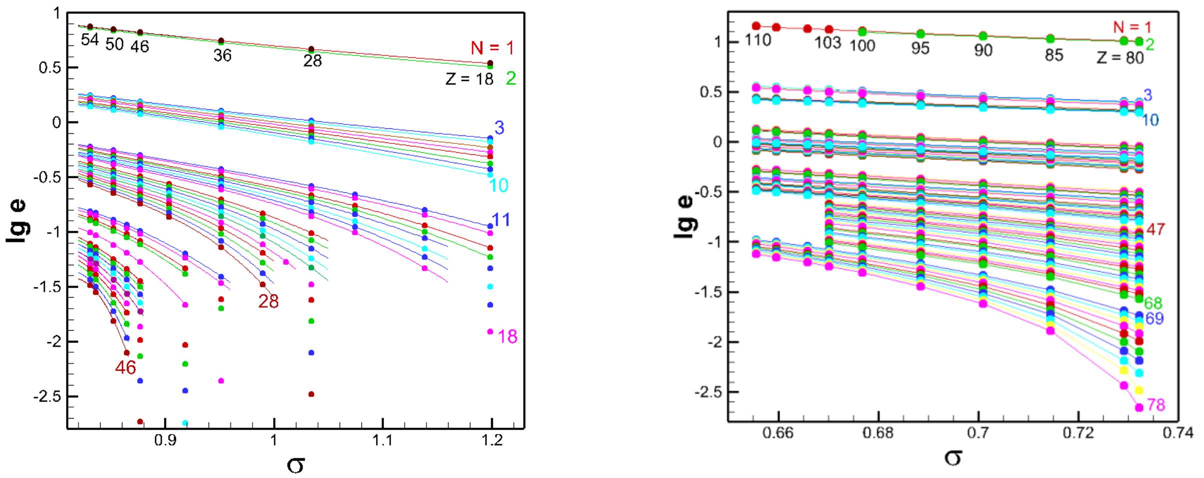

Fig. Ion ionization potentials of medium (left) and superheavy (right) elements in the special coordinates (1).

It is important that in multielectron ions in the ground state, the shells are filled in a hydrogen-like order. In this case a piecewise continuous dependence of the polynomial coefficients $a_i(N)$ on the number of electrons N reflects the shell structure of the electronic spectra in the ions. Their approximation by polynomials of the form $a_i(N) = \sum_{\kappa=0}^{k_{max}} b_{ik} N^k$ makes it possible to determine with good accuracy the ionization potentials (in eV) of more than five thousand ions using several tables of b_{ik} coefficients by the formula:

$$I_N^{(Z)} = Z^{4/3} 10^{\lg e_N(\sigma)} E_H, \quad \lg e_N(\sigma) = \sum_{i=0}^{i_{max}} \sum_{k=0}^{k_{max}} b_{ik} N^k \sigma^i. \qquad (2)$$

The general pattern becomes simpler and transparent with increase in atomic number *Z*.

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64 YEARS OF PLASMA CRYSTALLIZATION STUDIES IN WHITE DWARFS

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After a brief summary of dense plasma properties with a focus on phase diagrams of crystallizing fully ionized mixtures, their types, representations, and astrophysical significance, a review is given of extensive theoretical efforts to understand the physics of the ion-plasma crystallization in compact stars undertaken over the past 64 years since the first suggestion of this possibility by David Kirzhnits in 1960. We describe the already classic sequence of one-component plasma studies; various first-principle and semi-analytical methods; the impressive progression in understanding the phase diagram of the C/O mixture, most relevant for the inner layers of white dwarf stars; the importance of ternary systems and theoretical approaches to their analysis; the effects of ion motion quantization; the research on multicomponent plasmas anticipated in accreted neutron star crusts; and more. While the main aspects of plasma crystallization physics seem to be understood, several remaining issues are outlined. These include detailed properties of random lattices (whether they are in fact random and whether they are necessarily of the body centered cubic type), self-consistent and eventually quantum thermodynamics of binary and ternary plasmas, liquid-like low-Z ions within the lattices, kinetics of the crystallization process and resulting macrostructures (eutectic systems, phase separation in the solid phase, possibility of the epitaxial crystal growth).

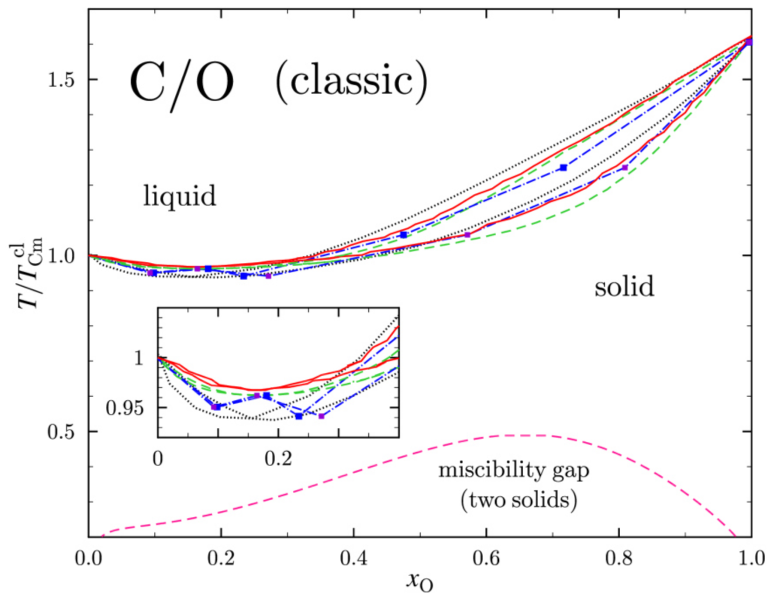

Fig. 1. Phase diagram of fully ionized classic C/O plasma according to Ref. [1] dotted black, Ref. [2] dashed green, Ref. [3] dot-dashed blue, Ref. [4] solid red. Dashed pink: miscibility gap according to Ref. [5]

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JEANS INSTABILITY IN THE SYSTEM WITH DIFFERENT GRAVITATIONAL MASSES AND THE ALPHA-G EXPERIMENT

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The hypothesis of a repulsive gravitational interaction of elementary particles and antiparticles [1],[2] is applied in the present report to consider Jeans instability in the Early Universe. Application of this hypothesis to the evolution of the Early Universe (see, e.g., [3] and references therein) could solve the difficult problems of λ-CDM standard model which uses to describe the Big Bang cosmology: dominating and unknown - directly unobserved components - Cold Dark Matter (CDM) and Dark Energy (DE), filling more than 95 percent of the Universe, it baryonic asymmetry and recently discovered accelerating expansion of the Universe on its large scale [4], [5]. In the recent brilliant experiment [6] on the repeal gravity of matter and antimatter the surprising result for the gravity acceleration of antihydrogen g_{AG} ~ 0,75 g in the Earth gravitational field has been found. The attempt to explain the result of this experiment is proposed in [7] on the basis of the detail consideration of the inner structure of proton. The statement about positive contribution of the gluon binding energy (BE) to the proton and antiproton masses under charge conjugation [2] in combination with the hypothesis on the repulsive gravity of quarks and antiquarks leads to the difference of the net gravitational masses of proton and antiproton and, respectively, hydrogen and antihydrogen. Due to big value of the gluon BE the gravitational charge of antiproton has a positive sign but possesses lower mass than proton. We use the two-component hydrodynamic model of point gravitational objects with the different "gravitational charges" to describe the Jeans instability in the system of electrically quasineutral objects (considered as point particles). In general case the gravitational masses of two species of particles (objects) are the same or different [1]-[3]. We use the masses of purely gravitationally attractive particles M and antiparticles M. The last ones have the fraction of repulsive antimatter f, where $0 \leq f \leq 1$. The dispersion relation and the modes are found. The particular case $f = 0$ corresponds to Jeans instability [8], $f = -1$ was considered in [9].

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TREATMENT OF QUANTUM NUCLEAR EFFECTS VIA PATH INTEGRAL MOLECULAR DYNAMICS

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The quantum nuclear effects play a role in the prediction of plasma properties. These effects are treated using the path integral molecular dynamics methods [1]. In this approach, a Hamiltonian is determined as [2]:

$$H_q = \sum_{k=1}^{P}\left[\sum_{j=1}^{N}\frac{[p^k]_j^2}{2m_j{}'} + \sum_{j=1}^{N}\frac{1}{2}m_j\omega_P^2(r_j^k - r_j^{k+1})^2 + \frac{V(r_1,\dots,r_N)}{P}\right],$$

where P is a number of beads (Trotter slices) in the quantum polymer, $[p^k]_j$ and $m_j{}'$ are a fictitious momentum and mass correspondingly, $\omega_P^2 = \sqrt{P}k_BT/\hbar$ and $V(r_1,\dots,r_N)$ is an interaction potential between beads with the same i. The schematic view of approach is presented on Fig. 1.

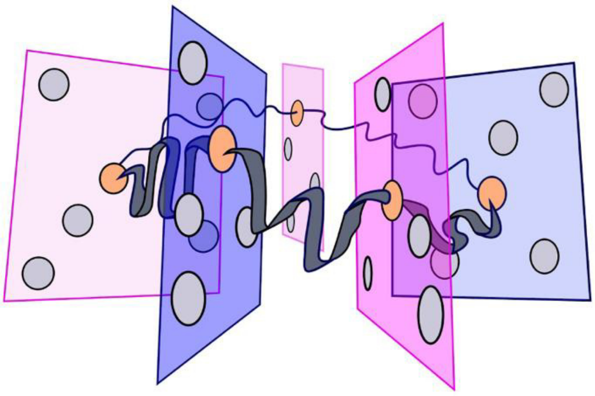

Fig. 1. The scheme of cyclic polymers, that represent the path integral molecular dynamics approach. Each plane schematically demonstrates the interacting particles with the specific bead number *i*. The neighboring planes (*i-1*, *i*, *i+1*) interact with each other via the harmonic potential.

The report is devoted to the formulation of quantum theory through Feynman path integrals, as well as the application of this method in calculations of physicochemical properties. The report will consider both theoretical aspects and numerical implementations. The capabilities of the method for calculating structural properties, equations of state, vibrational spectra, transport coefficients will be demonstrated.

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ON THE MOST PROBABLE ENERGY RELEASE IN STRUCTURED MEDIA

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The problem of energy release in hierarchically structured media that are "pieces" of matter of various sizes, contained large quantity of reacting particles, for example, molecules, is investigated. The extremes media here are single–molecular (non-clustered) gases of these substances on the one hand, and homogeneous condensed substances on the other.

Under natural assumptions about the different quantity of a substance that can enter into an energy release reaction (combustion, explosion, etc.) due to their location on the surface / inside the structure, the dynamics of access to reacting molecules and the obvious probabilistic nature of the process, a combinatorial procedure is carried out to determine the most probable distribution of energy release. In some simple approximation, the energy release is determined by a single parameter of the combinatorial scheme. The most probable distribution is coincided with the distribution of the unconditionally minimum values of energy release

The result may be used for quantitative interpretation of the difference in the values of the heat of combustion, explosion and other processes under various conditions

COMET DUSTY PLASMAS

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We present a description of dusty plasma processes in the vicinity of comets. We show that they can substantially impact, in particular, formation of the shock wave as a result of interaction of the comet coma with the solar wind. They can also reveal themselves in the situations when the comet is far from the Sun.

(1) The shock wave can sometimes be interpreted as a variety of the ion-acoustic shock wave. The presence of charged dust leads to another important type of interaction, namely, interaction of protons of the solar wind with dust particles in the comet coma. For a typical comet nucleus with a radius of ~1 km and relatively dense coma (dust number densities exceeding 10^6 cm^{-3}), anomalous dissipation caused by charging of dust particles plays an important role in shock wave formation. Apparently, the nature of such a shock wave is similar to that of the ion-acoustic shock waves.

(2) For a comet exhibiting parameters of the nucleus close to those of the nucleus of the Halley's comet, the dusty plasma in the vicinity of the nucleus forms due to electrostatic interactions, i.e., analogous to dusty plasma formation near other bodies without atmosphere (e.g., Mercury [1], the Moon [2], Mars satellites [3, 4]), provided that the distance from the comet to the Sun is at least ~3.5 AU. On the contrary, if the comet is closer to the Sun, the dynamics of dust particles is determined by the gas flow from the comet nucleus.

Although the history of studying comet dusty plasmas is relatively long, there are still unresolved problems, and successful solution of some of them requires accumulating new knowledge about the studied space objects. This goal can be achieved only in the course of future space missions.

This work was supported by the BASIS Foundation for the Development of Theoretical Physics and Mathematics.

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LUNAR DUSTY PLASMAS: BASIC PHYSICS PROCESSES AND EXPERIMENTAL DATA OF LUNA-25

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Basic physics processes related to dusty plasmas at the Moon are described. Experimental data on dust observations by Luna-25 spacecraft are discussed.

It is currently generally accepted [1] that dust above the lunar surface represents a constituent part of the dusty plasma system. The surface of the Moon becomes charged as a result of action of electromagnetic radiation of the Sun, the solar-wind plasma, and plasma of the Earth's magnetotail. Upon interaction with the radiation, the lunar rocks emit electrons due to the photoelectric effect, which leads to formation of a layer of photoelectrons above the surface. Photoelectrons are also supplied by the dust particles levitating above the Moon (they also absorb the solar light). Dust particles above the surface of the Moon and in the near-surface layer not only emit photoelectrons, but they also absorb them, along with photons of the solar radiation, electrons and ions of the solar wind. When the Moon crosses the Earth's magnetotail, they also absorb electrons and ions of the magnetospheric plasma. All these processes result in charging of the dust particles, their interaction with the charged surface of the Moon, dust rising and motion.

Several conclusions can be drawn based on the analysis of the dusty plasma processes near the Moon (see, e.g., [1-4]). In particular,

(1) Electrostatic processes lead to charging of dust particles, their interaction with charged surface of the Moon, dust rising and motion. In the process, characteristic size and number density of charged dust particles in the near-surface layer of the illuminated part of the Moon are on the order of 100 nm and 10^3 cm^{-3}, respectively.

(2) Meteoroid impacts play an important role in detachment of dust particles from the lunar surface. Adhesion the effect of which is weakened by the surface roughness should be taken into consideration when analyzing processes of this kind. High velocities (exceeding 10 m/s) and micrometer size are the distinguishing characteristics of particles that appear in the dusty plasma system above the surface of the Moon as a result of meteoroid impacts.

(3) Characteristic magnitude of the electric field in the region of lunar terminator that is induced by the dusty plasma processes can reach $E \sim 300$ V/m. In the process, dust particles with a size of 2–3 μm can rise to the altitude of about 30 cm above the surface of the Moon, which is sufficient to explain the glow above the lunar-terminator region observed during the Surveyor mission.

Luna-25 performed successful measurements of dust in a circular lunar orbit at the altitude of 100 km in August 17, 2023. In particular PmL instrument onboard Luna-25 detected 4 events which can be interpreted as the interaction with the instrument of the particles of meteoric origin. The PmL instrument experimental design included a charge-sensitive grid and piezoceramic plates that record the passage and impact of a dust particle, respectively, as well as the time marks of both signals.

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NONLINEAR PERIODIC WAVE STRUCTURES IN THE EARTH'S DUSTY IONOSPHERE

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During high-speed meteor showers like Perseids, Orionids, Leonids, and Geminids, ablation of the meteors in the lower ionosphere and subsequent condensation of the evaporated substance results in the formation of dusty ionospheric plasmas. It is well known that the process of dusty ionospheric plasma formation is accompanied by the following manifestations related to possible observations: the existence of low-frequency ionospheric radio noise at the Earth's surface; the generation of infrasonic waves in the ionosphere; an increase in the intensity of the green radiation of the night sky at a wavelength of 577.7 nm; modulational excitation of inhomogeneities of electrons and ions in the ionosphere. Here, we discuss another possible manifestation of dusty ionospheric plasmas during high-speed meteor showers, namely, the formation of periodic ionospheric structures, the so-called dunes, which were observed in the altitude range of 90-110 km during the period of Draconid meteor shower. The appearance of the dunes is associated here with the formation of a nonlinear dust acoustic wave.

ELECTROSTATICALLY FORMED DUSTY PLASMAS ABOVE THE SURFACE OF ENCELADUS

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It is shown that in the near-surface layer above the illuminated part of Saturn's moon Enceladus, dusty plasmas are formed due to photoelectric and electrostatic processes. Based on a physical and mathematical model for a self-consistent description of photoelectrons and dust particles above the surface of the illuminated part of Enceladus, the distribution functions of photoelectrons near its surface are determined, the altitude dependences of the number density of dust particles, their charges and sizes, as well as electric fields are found. It is noted that in spite of the distance of Enceladus from the Sun is large, the photoelectric effect turns out to be an important process in the formation of dusty plasmas. It is shown that the number density of photoelectrons above the surface of Enceladus can be one order of magnitude higher than the number density of electrons and ions in the solar wind, and the sizes of levitating dust particles exceed the characteristic sizes of dust particles rising above the surface of the Moon.

This work was supported by the BASIS Foundation for the Development of Theoretical Physics and Mathematics.

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VIBRATIONAL MODEL OF TRANSPORT PROPERTIES IN YUKAWA FLUIDS (COMPLEX PLASMAS)

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Vibrational model of transport properties has been recently shown to describe rather well transport coefficients of various simple fluids [1]. The purpose of this talk is to demonstrate how this model applies in a plasma-related context, using a complex (dusty) plasma fluid as an important relevant example. Assuming screened Coulomb (Yukawa) interaction potential between the charged particles immersed in a plasma, we will analyze existing results on the diffusion, shear viscosity, and thermal conductivity coefficients of the particles. The accuracy of the vibrational model and its applicability limits will be discussed.

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DUSTY PLASMA IN AN INDUCTIVE RF DISCHARGE IN A MAGNETIC FIELD

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We present the first observations of dust structures created under conditions of an RF inductive type discharge (RFI) in a weak and moderate magnetic field. The created structure itself must be voluminous for detailed study. Since there are instabilities in a magnetic field in a direct current discharge usually used for volumetric dust traps it was decided to use an electrodeless RF discharge, which is free from a number of such problems.

It was selected conditions under which a volumetric dust structure is formed in the diffuse region of the discharge in a magnetic field of up to 700 Gauss and begins to rotate. In this magnetic field range a strong dependence of the size of the dust structure on the radius of the discharge chamber and the type of particles used were discovered. A linear dependence of the rotation speed on magnetic induction was recorded. A significant velocity gradient along the magnetic field vector was discovered.

A qualitative interpretation is proposed for the results obtained - the conditions and dimensions of particle levitation and angular velocity of rotation. This interpretation and qualitative assessments make it possible to compare the results with data on other types of discharges: the DC discharge in the stratum [1] and in the region of narrowing of the current channel [2], as well as in the RFE electrode discharge [3-5]. For this comparison, an analysis of recent results on the dynamics of bulk dust structure in various inert gases and in a strong magnetic field is presented.

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THE VELOCITY OF SPIN-MOTION OF DUST PARTICLES DEPENDING ON THE TYPE OF INERT GAS

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At the moment, quite a lot of experimental material on the study of self-rotation, both in a direct current discharge and in an RF discharge has been collected [1-4]. It was shown that the magnetic field does not have a significant effect on the velocity of the dust particle's own rotation [5], contrary to theoretical estimates made by the authors earlier. Also, the expected dependence of the rotation velocity on the type of inert gas was not revealed.

This work proposes a modified model that explains the appearance of own rotation of dust particle depending on the discharge current (or the power put into the discharge in an RF discharge) and the pressure of gas. According to the new concept, there should be no noticeable change in the angular velocity of the dust particle's own rotation depending on the mass of the inert gas, which is consistent with experimental data.

The work was supported by the RSF, grant No. 22-72-10004.

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ULTRAFAST ROTATION OF DUST STRUCTURES IN GLOW DISCHARGES UNDER THE MAGNETIC FIELD INFLUENCE

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In a DC glow discharge, a dielectric insert is used to stabilize the striations, narrowing the current channel. Inside such an insert, a volumetric trap for dust particles was discovered, in which the rapid rotation of these particles was recorded. The structure of this trap is not yet completely clear. But we can draw some analogy with a trap that arises in the striation head. At the same time, there is a certain difference between them, which manifests itself in particular in the dust particle rotation peculiarities in these traps under the influence of a magnetic field. In our report at 19th Workshop CSCPIER-2023 [1], we have explained the significant discrepancy between theoretical and experimental results on the dust structure rotation velocities in magnetic fields of 0.7 − 1 T in our paper [2]. In [2], we assumed that rotation occurs only as a result of ion drag. In [1], we assumed that inside the dielectric conical insert the current channel begins to expand and a radial current component appears. Its action can be considered by analogy with the action of eddy currents in striations, which lead to the rotation of the neutral gas, and with it the dust structure, around the discharge axis [3]. In this report, a similar mechanism is used to explain the rapid rotation of the dust structure inside the insert in fields $B > 1$ T. In such fields, this rotation mechanism becomes the main one. In fields $B \approx 2$ T, we observed rotation of dust structures inside the insert at velocities of more than 50 rad/s. To explain such rotation velocities, a calculation model is proposed, based on the specified mechanism and taking into account some movements of the dust structure inside the insert along the discharge axis when the magnetic field changes. It should be noted that a sufficiently small radial component of the current can lead to such rapid rotation of the dust structure inside the insert.

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INFLUENCE OF WAKE FIELD INHOMOGENEITY ON THE VIBRATION SPECTRA OF TWO DUST PARTICLES IN A RF DISCHARGE

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An experimentally observed feature of plasma-dust systems is the significantly higher kinetic energy of particles compared to the temperatures of all components of the surrounding nonequilibrium medium. In addition, there is a significant difference between the average horizontal and vertical energy. This difference can be explained by an increase in energy due to the influence of the degrees of freedom of the dust particle on each other. The proposed mechanism for energy transfer between vertical and horizontal vibrations is based on the dependence of the particle charge on the relative position arising from the ion wake. Such a wake is formed behind a dust particle as a result of a disturbance in the flow of ions drifting in the electric field of a gas discharge.

An analytical description of this effect is presented using the spectral density of vibrations. Using the example of a vertical pair of interacting microparticles in a rf discharge, various mechanisms of anomalous kinetic heating of particles were experimentally studied using an improved method of spectral response to stochastic processes [1]. It was found that the effect of horizontal vibrations on vertical vibrations can account for more than 60% of the kinetic energy of the movement of microparticles in the vertical direction.

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NUMERICAL STUDY OF THE PARAMETERS OF DUST PARTICLES CHAINS LEVITATED IN A GAS DISCHARGE PLASMA

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Structural characteristics of the chains of dust particles suspended vertically in a gas discharge plasma were studied with the help of a multi-block model based on the mean field approximation. The model describes the movement of ions and dust particles under the action of external electric field, electric field (Coulomb) of each charged dust particle, and the field of bulk plasma charge (ions and electrons) that screens the charges of dust particles. The gravity and the ion drag forces acting on the dust particles were also taken into account. Self-consistent chains parameters (dust particles charges and inter-particle distances) and space distributions of the bulk charge and electric potential have been calculated and analyzed for the chains with different number N = 1, 3, 5, 7 of dust particles.

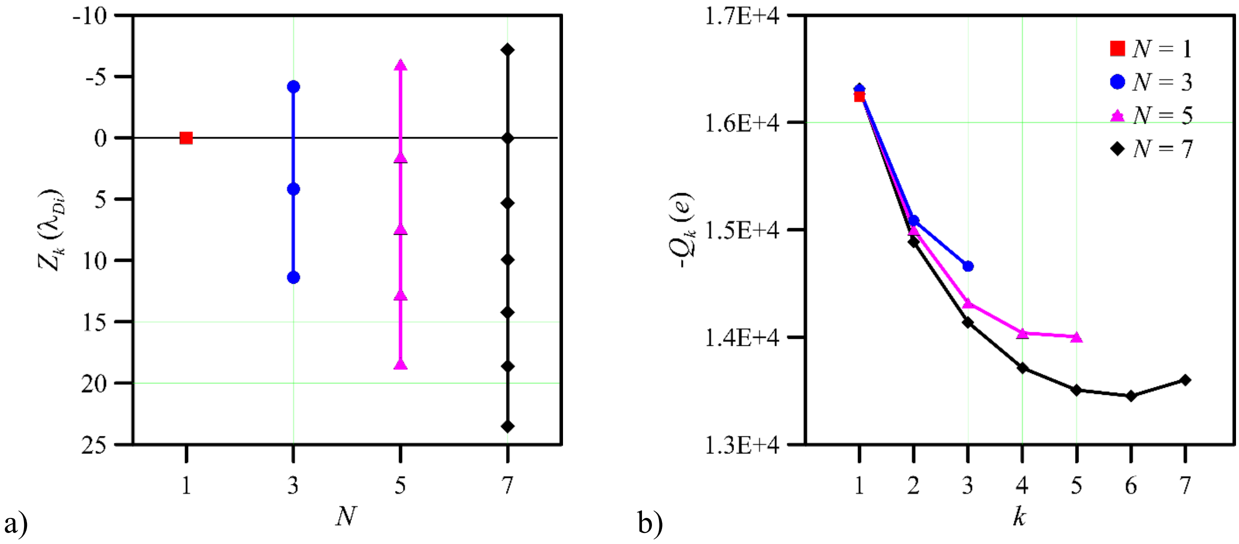

Fig. 1. a) Dust particles vertical positions Z_k depending on the total number N of the particles in the chain, b) The particles charges Q_k depending on their order number k in the chain for different number N.

It was obtained that an "ion wake" is formed behind the dust structures, and it grows with the number N of dust particles. With an addition of new particles into the chain, the newly added particles find its position above the previously added particle due to the repulsion between the particles, but the summarized gravity force leads to the fact, that the chains as a whole, i.e. centers of the chains, move down to lower electrode (see Fig. 1a). Due to electrostatic lensing of the ions by the first dust particle of the chain, the charges of the subsequent particles in the chain decrease that is confirmed by the experimental data (see Fig. 1b). With an increase in the number N of dust particles the charge of the first (top) dust particle of the chain increases (see Fig. 1b).

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DISPERSION OF LATTICE WAVES IN A TWO-LAYER CRYSTAL IN A COMPLEX DUST PLASMA

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Dispersion of in-plane waves in a bilayer binary strongly coupled dusty plasma system in a sheath of an rf discharge was experimentally investigated by the analysis of spontaneous velocity fluctuations. Microparticles of two different sizes were aligned into vertical pairs due to plasma wakes just under the upper particles in the ion flow towards the bottom electrode. The pairs were ordered into 2D hexagonal crystalline structure. The structure is presented in the Fig.1 . The dark area in the figure indicates the high-ordered cluster taken for our analysis.

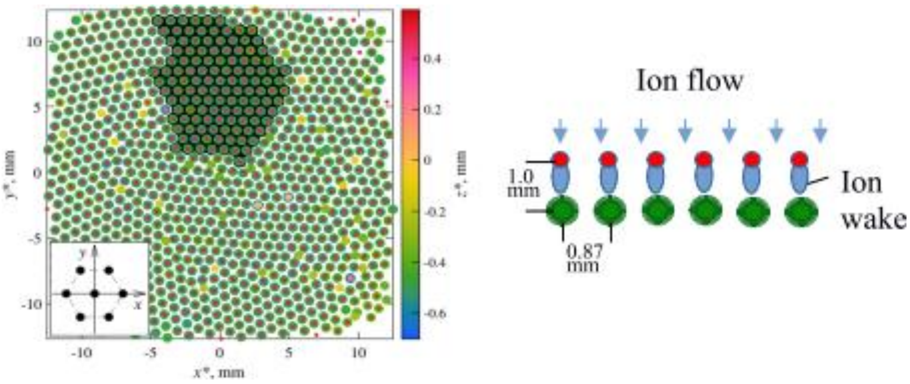

Fig. 1. Microparticle crystalline structure and scheme of the microparticle paring.

The collective mode dispersion relations were obtained by Fourier analysis of the microparticle velocities for both layers separately. Splitting of the modes in the bilayer lattice was observed and theoretically described [1]. The spectra of longitudinal waves determined for each microparticle layers as well as the theoretical curves are presented in the Fig. 2. The relative intensities of the mode branches reflect non-reciprocal features of the wake-mediated interaction between the microparticles.

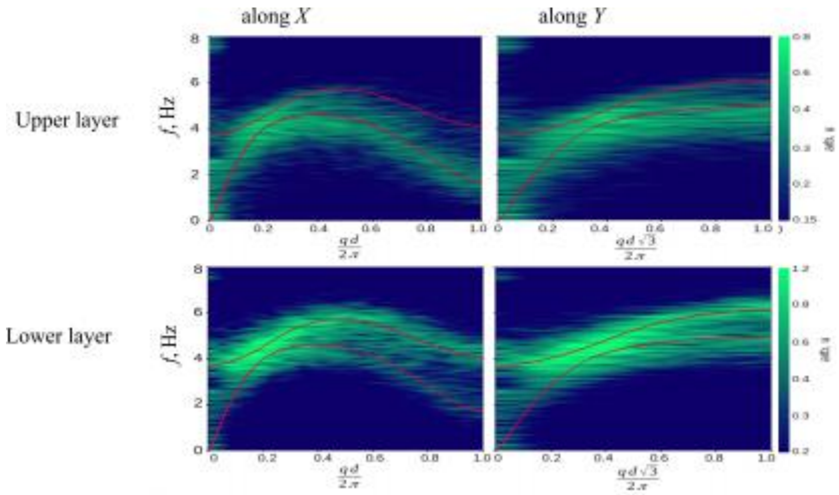

Fig. 2. Spontaneous oscillation spectra.

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OBTAINING A PLASMA-DUST CLOUD FROM ILMENITE CONCENTRATE USING A MICROWAVE DISCHARGE

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The chemical and plasma-chemical synthesis and modification of substances of cosmic bodies occurs in a plasma-dust environment such as impact events and hyper-velocity motion. To investigate this processes microwave gas discharge in a powder sample was used in our work. This experimental setup has already been used in [1,2] for the synthesis of nano- and microparticles. The sample chosen was ilmenite concentrate, a common mineral in the soils of cosmic bodies, such as lunar regolith. This mineral has semiconducting properties, so a microwave discharge can be initiated in a powder medium without the addition of metal particles. In the experiment, we did obtain plasma-dust clouds from the substance of ilmenite concentrate. We used a commercially available ilmenite concentrate (ilmenite 95%, rutile 3%, zircon 0.4%) with particle sizes of no more than 100 μm. The microwave radiation power was 300–400 kW, the pulse duration was 6–8 ms. The powder was exposed to five microwave pulses with a total energy of 11.4 kJ. Almost immediately at the front (~100 μs) of the microwave pulse, a discharge was initiated in the powder medium. The dynamics of the development of the discharge with the appearance of a plasma-dust cloud and it's relaxation at the end of the microwave pulse were recorded. From the emission spectra of the plasma and the surface of a solid body, the temperatures of the gas (T_r = 5500 ± 1500 K), electrons (T_e = 5000 K) and surface (T_s = 1500–3000 K) were determined. Micrographs of the sample were taken before and after the experiment using a scanning electron microscope (SEM) equipped with X-ray microanalysis system. Based on the results of scanning electron microscopy, it can be concluded that spheroidization of initially angular and irregularly shaped particles occurred, which is a known effect of the action of gas discharge plasma on micro- and nanoparticles. The sizes of some spherical particles are larger than the linear sizes of particles in the original sample. A comparison of the elemental composition of the initial samples and samples after exposure showed that there was no significant change in the composition.

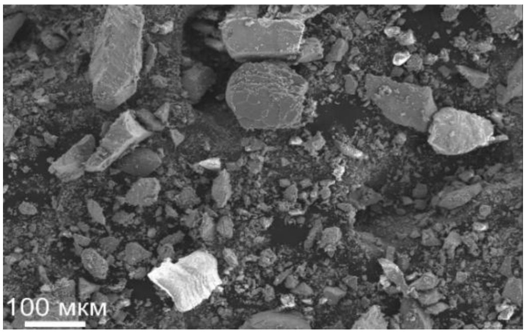

Fig.1. Microphotographs of a prepared sample of ilmenite concentrate.

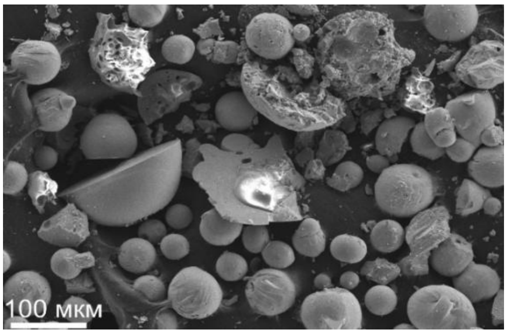

Fig.2. Microphotographs of ilmenite concentrate after the impact of microwave discharge.

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MICRODISPERSED TI / B / N AND PT / AL_2O_3 MATERIALS SYNTHESIZED IN CHAIN REACTIONS IN A PROCESSES INITIATED BY MICROWAVE OF HIGH POWER GYROTRON: STRUCTURE AND CYTOTOXICITY

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Synthesis of substances was carried out on a specialized stand using a powerful pulsed gyrotron (microwave radiation power up to 0.8 MW, pulse duration up to 12 milliseconds, frequency 75 GHz). The description of the experiment, the conditions for the development of a microwave discharge, and the evolution of process parameters in the reactor are described in detail in [1,2]. In the chain plasma-chemical reactions, initiated by gyrotron, in mixtures of metal and dielectric powders resulting in formation of microdispersed materials [3,4]. In mixtures Ti/B and Ti/BN powders the synthesized materials consisted of several types of nano- and microparticles with modified chemical composition. The synthesized particles were represented by conglomerates of micrometer-sized titanium oxides, borides and nitrides particles with highly developed surface with nanometer-sized particles of boron oxides and nitrides. In the mixtures of Pt/Al_2O_3 the synthesized materials consist of aluminum oxide micrometer-sized particles on which platinum nanoparticles are deposited [5].

In order to analyze hazardless of the materials, cytotoxicity tests were necessary [6]. The study of the obtained samples for cytotoxicity against human cells (lines HEK293T, MCF7, A549, VA13) showed toxic effects only at concentrations of tens of mg/L and the absence of detectable toxic effects in bacterial system (E. coli). It can be assumed that, at the level of cellular models, their cytotoxicity does not exceed that of the starting materials.

The data on the absence of strong cytotoxic effects in cell models and size control by the collection of particles from different height of reactor open the perspective of its use in a wide range of applications.

The work was carried out within the framework of the State Assignment GZ BV10–2024 “Study of innovative synthesis of micro- and nanoparticles with controlled composition and structure based on a microwave discharge in gyrotron radiation”.

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TECHNIQUES FOR TWO- AND THREE-DIMENSIONAL DIAGNOSTICS OF MICROPARTICLES IN COLLOIDAL PLASMAS

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Active Brownian particles are particles capable of converting environmental energy into their own propulsive motion [1,2]. Active Brownian particles are of great interest due to their possible use for the delivery of medicinal substances, the creation of new structural materials, etc. The fundamental interest of the study of active systems is in the development of physics of nonequilibrium systems; physics of dissipative structures; principles of self-organization, self-assembly. Colloidal plasma, such as a suspension of microparticles levitating in an RF or DC discharge, is a convenient object for studying active Brownian particles. On the one hand, in plasma, compared to electrolytes, chemical reactions play a much smaller role, which makes it possible to more accurately control the process parameters. On the other hand, the significantly lower plasma viscosity allows microparticles to be sensitive to relatively weak sources of active motion.

In studies of active systems, diagnostics of microparticle dynamics plays an important role. In some cases, such as two-dimensional melting studies [3], it is often sufficient to use simple two-dimensional diagnostics. In this case, the system of microparticles is simply recorded by a video camera located perpendicular to the plane of the monolayer. In more complicated cases, such as investigation of the dynamics of three-dimensional systems of active particles levitating in the strata of the DC discharge [4], it is necessary to use three-dimensional diagnostics.

This work provides a review of known methods for two-dimensional and three-dimensional diagnostics of microparticles. The recent results on the study of active colloidal plasma using these techniques are presented, such as an analysis of the root-mean-square displacements of active Brownian particles, phonon spectra in a two-layer structure consisting of particles of different sizes, and structural instability accompanied by a transition to a square lattice in a quasi-two-dimensional plasma crystal [5].

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EVOLUTION OF THE TRAJECTORY OF A COLLOIDAL PARTICLE IN A CHAIN IN DC-DISCHARGE

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Active Brownian particles are the particles that can convert the energy coming from the environment into the energy of their own directed motion [1]. The motion of active particles can be both independent and collective. The average kinetic energy of active particles can significantly exceed the average kinetic energy (temperature) of the ambient particles, which is a sign of a substantially non-equilibrium process. Examples of active particles are many bacteria, moving cells, micro- and nanorobots [1], dust particles in discharge plasma [2] and superfluid helium [3].

The results of the experimental study of the dynamics of chain structures in a DC glow discharge under the influence of laser radiation are presented. The structures were formed from active Brownian particles. Spherical monodisperse melamine-formaldehyde (MF) particles coated with copper were used. Absorption of laser radiation by the metal surface of the particles led to heating of their surface and the emergence of thermophoretic force. As a result, an increase in the intensity of microparticle motion was observed.

Two high-speed video cameras placed at an angle of 90 degrees relative to each other were used to register the particles. As a result of processing the experimental video data, there were obtained the following data for each particle in the structure: trajectories and their fractal dimensions, dependences of the mean first-passage time dynamic entropy [4] on the coarsening parameter, the mean kinetic energy of the particles. These parameters were calculated both for three-dimensional motion and for the projection of motion on each of the cameras.

Throughout the experiment, the evolution of the obtained structure was observed: the particles could change their position and even leave the trap of the stratified DC discharge. It is experimentally shown that the effect of laser radiation on quasi-one-dimensional (chain) structures of active Brownian particles affects them. With increasing laser intensity, the dynamic entropy and fractal dimension of particle trajectories varied.

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COMPLEX SYSTEMS OF CHARGED PARTICLES AND THEIR INTERACTIONS WITH ELECTROMAGNETIC RADIATION

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Active systems are thermodynamically non-equilibrium and are able to convert external energy into their own motion [1]. Colloidal system consists of tiny particles distributed in a continuous medium. In liquid-phase colloidal systems, solid particles stabilized by a surfactant have a surface charge and can show phenomenas, similar to a complex plasma [2]. Many properties of colloidal systems appear in both natural and artificial systems. Such active particles in colloidal systems are able to exhibit various collective phenomena, including swarming and vortex formation. Vortex structures are also typical of both living systems and artificial active colloidal structures.

The transition in the dynamics of a system of 3000 surface-charged stabilized melamine-formaldehyde particles with partial copper coating in a liquid medium of high viscosity (mineral oil) was experimentally observed. The system was fully exposed to the laser beam the whole time of observation. The initial structure after turning on the laser came to rotate in one direction. After some exposure time to radiation, the system of colloidal particles separated into two differently rotating vortices.

The coordinates of particle motion in time were obtained and their trajectories were reconstructed. For both types of motion, the velocities and kinetic energies of particles were calculated and their MSD curves were obtained.

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STRUCTURAL TRANSITION IN STRONGLY COUPLED COULOMB CLUSTERS

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The Coulomb cluster is a system of massive charged point particles on the uniformly distributed background charge confined in a sphere. Such systems are encountered in dusty plasma, ion traps, and in astrophysics; they are also an object of fundamental research. In study [1], strongly coupled Coulomb clusters comprising up to $N = 350$ particles were investigated both experimentally and theoretically. It was shown that their structure is a set of nested spherical shells. Molecular dynamics (MD) simulation performed in [2] demonstrates that these shells undergo a diffuse 2D crystal–liquid transition at the Coulomb coupling parameter Γ from 60 to 90. Although the maximum cluster size N in this work was 1100, no crystal core was found in the clusters even in a very strong coupling regime ($\Gamma = 500$). The question arises if the strongly coupled Coulomb clusters have a thermodynamic limit as N tends to infinity, i.e., starting from which N the cluster core structure changes from shell to crystalline. The Monte Carlo simulation investigation [3] of the Coulomb clusters was performed for a large size $N < 51201$ but in the weak-coupling regime $\Gamma < 1$, where no structural transition is possible. Similar simulation in the range $1 < \Gamma < 190$ was performed in [4] for the maximum size $N = 3200$, however, the cluster structure was not uncovered.

We performed MD simulation of the equilibrium Coulomb clusters in the range $150 < \Gamma < 500$ for N up to 5000. For the first time, we found that at $\Gamma > 210$, formation of a crystalline core inside a cluster is a crossover occurring in the cluster size range from ca. 2400 to 5000. The cluster structure proved to be a crystal core surrounded by a set of nested shells, whose number decreases from 5 to 2 as Γ is increased. Crystallographic analysis showed that a core consists predominantly of hcp lattice slabs comprising from several hundred to thousand particles. Comparison between the internal energies of a set of spherical shells and hcp lattice revealed that they are very close, and their relative difference decays rapidly as $1/N$. This account for a high threshold of the structural transition in the Coulomb clusters. Thus, existence of thermodynamic limit for this system was principally demonstrated.

Investigation of the cluster core crystallization and melting at $N > 2400$ shows that this is also a crossover taking place in the interval $150 < \Gamma < 210$, whose center corresponds to known threshold of crystallization for the bulk one-component plasma. Hence, at $\Gamma < 150$, a cluster consists of a liquid core surrounded by the surface layer of spherical shells that form 2D crystal.

In the range of Γ and N specified above, we studied the particle pressure determined in our MD simulation by calculation of the virial. In the entire parameter range, irrespective of N, we could not distinguish the resulting compressibility factor from zero. This makes it to possible to apply the result to thermodynamic limit and draw an important conclusion that the compressibility factor must vanish in this limit, i.e., for the bulk one-component plasma. It is shown that this vanishing follows straightforwardly from the Wigner–Zeits cell model.

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EXTERNAL ELECTRIC FIELD INFLUENCE ON THE MOTION OF COULOMB STRUCTURES IN A LINEAR ELECTRODYNAMIC TRAP

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Management of behaviour and determination of statistical properties of the Coulomb structure of micron-sized singly charged dust particles in an electrodynamic trap is one of the main tasks in the experimental study of single-charged plasma, in the creation of filtration and purification devices and in the development of new technologies. In the previous works we have determined the boundaries of retention regions and the emergence of instability of charged particle motion; we have shown the dependence of the particle motion not only on the ratio of its charge to its mass, as follows from the system of Mathieu equations, but also on the friction force, which is proportional to the size of the moving particle and is a component of the Langevin equation describing the particle motion in the medium. In the case of imposing an additional electric field, charged particles located on both sides of the stability boundary can react in two ways, depending on the polarity and phase of the applied voltage. The particle inside the trap can either leave the trap or remain in it. A particle beyond the stability boundary without an additional electric field will leave the trap, however, when an additional influence is applied, it may start to move along the stable trajectory.

In this work, a two-dimensional trajectory of a charged particle of micron dimensions in a horizontal quadrupole linear electrodynamic trap under the influence of an alternating external electric field in air at atmospheric pressure has been computer modelled. The trajectories of stable motion of the particle in the trap at the stability boundary are obtained and the corresponding parameters of the alternating external electric field are determined. The obtained results are important for further investigation of the influence of external influences on the Coulomb structures of charged dust particles in electrodynamic traps in air at atmospheric pressure.

TWO-DIMENSIONAL BROWNIAN MOTION OF ACTIVE PARTICLE ON THE FREE SURFACE OF SUPERFLUID HELIUM

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We report an experimental study of the 2D dynamics of active particles driven by quantum vortices on the free surface of superfluid helium at T = 1.45 K. The particle mean-square displacement and the energy dissipation within a vortex bundle were measured directly through the observation of translational and rotational motion of an active particle. The rotational energy and angular momentum of the particle captured by a quantum vortex were determined as $\sim 10^{-15}$ J and $\approx 2.6\cdot10^{-17}$ kg·m^2/s, correspondingly, in good accordance with the energy and total angular momentum of the quantum vortex were estimated as $\approx 6.1\cdot10^{-14}$ J and $\approx 2.6\cdot10^{-15}$ kg·m^2/s, respectively. A translational motion of the particle at short times (< 25 ms) related to anomalous diffusion mode typical for active particles, while for longer times it corresponded to normal diffusion mode. The values of the rotational and translational kinetic energies of the particle allowed us to determine for the first time the intensity of the particle-vortex interaction and the dissipation rate of the vortex bundle energy. The interaction of a particle with quantum vortices revealed a very efficient energy transfer from a vortex tangle to a particle due to coupling of the normal and superfluid components of superfluid helium [1].

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MULTISCALE SELF-CONSISTENT SIMULATION OF COMPLEX PLASMA SYSTEM WITH ION FLOW

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The simulation of a system containing multiple charged micron-sized particles in a flowing plasma is essential for various scientific and technological applications like microelectronics, controlled fusion, and thin film deposition. However, this poses a significant challenge in modern computational physics and high-performance computing due to its computational complexity. Various simplifying methods, including PIC modeling, Monte Carlo methods, and molecular dynamics approaches, are used to address this challenge.

This study evaluates the advantages and disadvantages of different approaches for the self-consistent simulation of plasma-dust systems in plasma flow. An open-source GPU-based code named OpenDust [1] is introduced to enable rapid and accurate simulation of charged micron-sized particles in a flowing gas discharge plasma commonly seen in laboratory experiments. OpenDust significantly reduces simulation time to seconds, surpassing previous methods that required hours of computation. By leveraging multiple GPUs, modern high-performance computing techniques have proven to be more efficient than traditional CPU-based methods for solving these complex problems.

The complexity of simulations using OpenDust scales almost linearly with the size of the computational domain, allowing researchers to simulate large systems of dust particles that were previously inaccessible. This tool is designed to support the work of both theoretical and experimental complex plasma physicists, providing a valuable resource for advancing research in this field.

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GENERALISED EQUIPARTITION THEOREM AS A NATURAL MEASURE OF NON-RECIPROCITY IN COMPLEX PLASMAS

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Nowadays, active matter is one of the fastest growing fields of research. The term "active matter" refers to any set of objects that individually utilise the free energy of the environment for their own motion and forces [1]. Active systems can be observed in living biological systems such as bacterial colonies, cells and flocks of birds, or in special types of non-living systems such as complex plasmas or colloids. A particular focus in the study of active matter is on nonreciprocal effects. For example, the interaction between charged colloidal or dust particles does not satisfy Newton's third law of actio=reactio. This effective violation of the fundamental principle is explained by the transfer of energy and momentum from the nonequilibrium medium to the interacting particles [2]. In addition to active matter, non-reciprocity in interactions is also inherent in nonequilibrium systems, networks of neurons and metamaterials. In turn, the arising nonreciprocity at the level of individual interactions leads to symmetry breaking already at mesoscopic scales.

For example, a consequence of nonreciprocity at the level of individual interactions is the violation of the equipartition theorem in an equilibrium dynamical system. In this report we consider ordered nonreciprocal systems in which the interaction forces are a linear function of the particle displacements. We show how the equipartition theorem can be generalised to a certain subclass of such systems, which are called pseudo-Hamiltonian [3]. Based on a deviation from this generalised equipartition theorem, we develop a natural measure of non-reciprocity for ordered active systems. We demonstrate the performance of this measure on a nonreciprocal system with three degrees of freedom. The developed measure of nonreciprocity can be used to determine how far an active system is from pseudo-Hamiltonian, and is a step towards building a theory of nonreciprocal systems in general. Moreover, we show that for the chain structure of active particles this measure of nonreciprocity grows with increasing contribution of long-range interactions.

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WAVES AND INSTABILITIES IN PLASMA OF METEOROID TAILS

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There are a lot of wave modes and instabilities can be excited in plasma of meteoroid tails. Such waves as dust acoustic waves, lower-hybrid waves, langmuir waves, ion acoustic waves and cyclotron waves can lead to the development of instabilities which cause arising of low-frequency perturbations from meteoroid tail. It connects with electrophonic noises and magnetic field fluctuations.

Electrophonic noises from meteoroid flight are very interesting and mysterious phenomena which still do not have definite explanation. In this work it is explained buy the development of modulational interaction of different wave modes that can explain the arising of electrophonic noises and magnetic field fluctuations during meteoroid flight.

Modulational instability of different wave modes in meteoroid tails is described. It can lead to a number of observational effects in meteoroid tails, such as electrophonic noises [1-3] and arising of fluctuations of magnetic fields. In particular, this can be the modulation instability of electromagnetic waves from the shock wave of a meteoroid associated with the dusty sound mode, as well as the modulation instability of lower hybrid and Langmuir waves. In the first case, waves can be born, which are then transformed into sound waves when they reach the Earth's surface. In the last two cases, magnetic fields can arise, the magnitudes of which are comparable with the observed magnetic fields during experiments with magnetometers, and transverse electromagnetic oscillations can also propagate, which, reaching the Earth's surface, can be perceived as electrophonic noises heard simultaneously with passage of meteoroids. The influence of meteor flares on the parameters of the dusty plasma of meteoroid tails is considered depending on the height of the passage of meteoroids. The characteristic concentrations of dust particles in meteoroid tails during flares with height are estimated. Using the example of the modulation instability of electromagnetic waves associated with the dusty sound mode, it is shown how the concentration of dust particles increased during flares will affect the magnitude of the instability increments and the conditions for its development.

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TOWARDS INTENSE ATTOSECOND XUV PULSES PRODUCTION: FROM HIGH-HARMONIC GENERATION TO HIGH-ORDER FREQUENCY MIXING

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The generation of bright, coherent XUV light via frequency conversion of intense laser pulses in gases and plasma is a problem of both fundamental and technological importance. We identify the dominant mechanism limiting the high-harmonic generation (HHG) conversion efficiency – the combined effect of phase matching and the blue shift of the driving field during its propagation through a rapidly ionising generating medium [1,2]. We introduce the blue-shift length, which sets the upper bound for the quadratic intensity growth of the high harmonics.

We study analytically and numerically (solving the propagation equation coupled with the time-dependent Schrödinger equation, TDSE) the behavior of the macroscopic HHG signal with propagation distance. We show that its quadratic growth is limited by the shortest of three lengths: absorption, coherence or blue-shift length. Thus, we define three regimes of HHG, corresponding to the dominant limiting mechanisms.

Moreover, we show that this seemingly fundamental restriction can be overcome by using an additional generating weak mid-IR field. For suitable combinations of frequencies of the generating fields, the corresponding high-order frequency-mixing (HFM) process does not suffer from the blue shift of the drivers and phase mismatch [1], and thus its efficiency grows quadratically with propagation up to much longer distances, than for HHG. The macroscopic efficiency of HFM in laser plasma can be up to three orders of magnitude higher than the efficiency of HHG [5].

Our results open a new route for highly efficient generation of XUV light, the first step of which has been taken already via an observation of high-order parametric generation [3]. Moreover, HFM offers new handles for XUV control such as the control of the carrier envelope phase of the emitted attosecond XUV pulses [4,5].

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GUAGE EFFECTS IN HIGH HARMONIC GENERATION CHARACTERISTICS OF GA$^+$ IONS IN LASER FIELD

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Usually, when theoretical studying the spectra of high harmonic generation by an atomic system, a semiclassical approach is applied, based on the Fourier transform of the dipole moment induced by an intense laser pulse and averaged over the solution of the time-dependent Schrödinger equation (TDSE). From fist principles, the results should not depend on the unitary transformation of the exact solution of the TDSE. In reality, there is a violation due to approximations, especially for multielectron atoms. The degree of the difference may be a sign of the accuracy of the method used.

We consider two expressions (in atomic units) for the laser-atom interaction operator in the TDSE $\hat{V}(t) = -\mathbf{D}\cdot\mathbf{F}(t)$ (length gauge) and $\hat{V}'(t) = c^{-1}\hat{\mathbf{P}}\cdot\mathbf{A}(t) + A^2(t)/(2c^2)$ (velocity gauge), where $\mathbf{D}$ is the atomic dipole moment operator, $\hat{\mathbf{P}}$ is the total electron momentum operator, $\mathbf{F}(t)$ and $\mathbf{A}(t)$ are the classical field strength and the vector potential of the laser field, respectively, coupled by the relation $\mathbf{F}(t) = -c^{-1}\partial\mathbf{A}/\partial t$. The corresponding solutions of the TDSE are related by the unitary transformation $\Psi'(t) = \exp[-i\mathbf{D}\cdot\mathbf{A}(t)/c]\Psi(t)$.

In our study, we expand the TDSE solution of the Ga$^+$ ion in a femtosecond laser field over a finite superposition of discrete stationary states of an unperturbed target obtained in the Hartree-Fock method [1]. The time-dependent expansion coefficients referred to the population amplitudes of the basis states during laser-ion interaction obey a set of coupled ordinary differential equations. By comparing the results obtained in both gauges, we control the expansion basis with respect to its completeness and the approximation of the basis states.

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IMPACT OF HIGH-POWER BEAM ON SECOND HARMONIC GENERATION IN COLLISIONLESS MAGNETIZED PLASMA

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The present work explores the Second harmonic generation of high-power beam in Collisionless magnetized plasma. When the incident beam is propagating along the direction of externally applied static magnetic field. Now alterations in the static magnetic field's strength have an impact on the redistribution of carriers. Because of ponderomotive force, there is redistribution of carriers in the plasma in a plane transverse to the beam propagation and a transverse density gradient is formed in the plasma which in turn generates an Electron plasma wave (EPW) at the pump frequency. This EPW further interacts with the incident laser beam and a second harmonic is generated. The nonlinear differential equation for the beam width parameters of incoming laser beam, expression for density perturbation associated with the EPW and the second harmonic yield will be set up and solved numerically. Effects of change in laser and plasma parameters and an externally applied magnetic field on the beam width parameter of main beam and second harmonic yield will be analyzed.

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EMISSION OF TERAHERTZ PULSES FROM NEAR-CRITICAL PLASMA SLAB UNDER ACTION OF P-POLARIZED LASER RADIATION

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Increasing the energy of terahertz (THz) pulses and improving the efficiency of their generation is an important and actual scientific problem. One of the possible mechanisms for the increase in the THz pulse energy and conversion rate was theoretically proposed in [1], where the action of *p*-polarized laser radiation on low-density targets was considered in the model of a semi-limited plasma. In the present article, we show that the more significant increase in the THz energy compared to [1] occurs at the almost normal incidence of ultra-short, tightly focused *p*-polarized laser radiation on the plasma slab with a near-critical density and a small thickness [2].

The incidence of the focused *p*-polarized laser pulse on the boundary of the plasma slab is considered and the boundary value problem for electromagnetic fields is solved and the ponderomotive potential of laser radiation in the plasma slab is calculated. The excitation of THz fields in the plasma slab under the action of laser radiation ponderomotive forces and there emission into vacuum is considered. The total energy of THz radiation is calculated and it is shown that it increases extremely at the almost normal incidence of the ultra-short tightly focused laser pulse on the boundary of the thin plasma slab (Fig.1) with the near-critical density and rare electron collisions. The spectral composition of THz radiation has been studied and it is established that the radiation spectrum contains the broad maximum, the position of which in the case of tight focusing of the laser pulse is determined by its reciprocal duration. The THz radiation pattern is studied and it is shown that the direction THz signal emission weakly depends on the thickness of the plasma slab and is determined mainly by the degree of laser pulse focusing. The decrease of the laser pulse focal spot size leads to the increase of the radiation angle with respect to the plasma boundary normal, and in the limiting case of tight focusing the THz signal is emitted almost along the boundaries of the plasma slab.

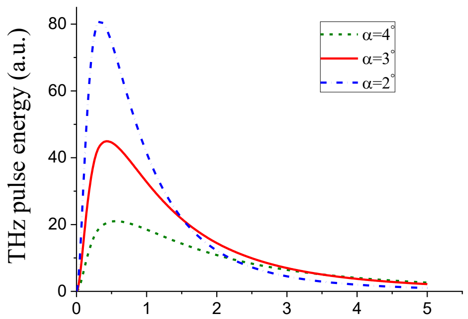

Fig. 1. THz signal energy as function of the plasma slab thickness d for the different laser pulse incidence angles α, λ_0 is the laser wavelength

The applicability conditions of the presented theory are discussed, and the estimates are given for the parameters of the THz pulse under the conditions of modern laser-plasma experiments. The estimates show the possibility of the generating high-power THz pulses with millijoule energy and the sufficiently high conversion rate up to 10% under the action of ultra-short tightly focused *p*-polarized mid-infrared laser radiation at its almost normal incidence on the slab of near-critical plasma with rare electron collisions.

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MODELLING THE ELECTRON WAKEFIELD FOR ULTRA-RELATIVISTIC LASER INTENSITIES TAKING IONISATION INTO ACCOUNT

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Laser-plasma electron accelerators based on laser wakefield acceleration (LWFA) or direct laser particle acceleration (DLA) make it possible to generate high-energy electrons at short distances. The acceleration of electrons to energies of several gigaelectronvolts is already regularly observed experimentally. This process has been theoretically studied quite well for a wide range of laser intensities (10^{18}-10^{22} W/cm^2) and electron densities (0.01 -0.5 n_{cr}). However, the vast majority of numerical studies assume a fully ionised gas target. When using light elements such as helium, this is justified, but when calculating heavier elements (argon, krypton), ionisation can have a significant effect. To evaluate this effect, a series of PIC calculations were performed simulating the passage of a laser pulse through a gas jet containing only neutral argon atoms taking ionisation into account and only $Ar^{+16\text{-}18}$ atoms without taking ionisation into account. We calculate the interaction of laser radiation with a gas-cluster medium using 3D PIC code EPOCH [1] with extended modules including both collision and collisionless ionization. The resulting electron spectrum for a laser intensity of 10^{20} W/cm^2 and an ion density of 10^{19} cm^{-3} for various electron scattering angles at 100 fs. interaction of a laser pulse with a gas jet is shown in Figure 1.

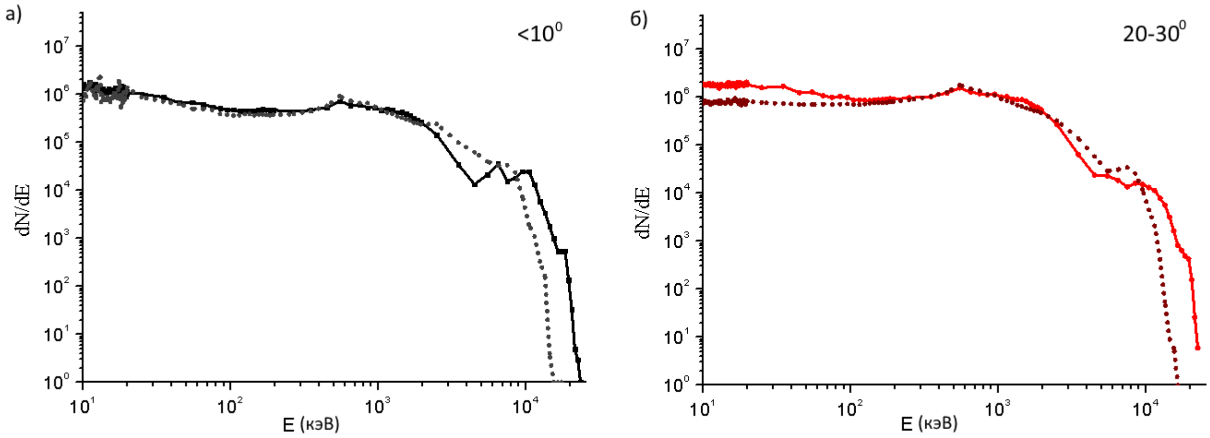

Fig. 1. Electron spectrum for Ar+16 ions (solid line) and neutral gas (dashed dots). A) – electrons falling into a spatial cone with a solution θ < 100; b) electrons falling into a cone with a solution of 100 < θ < 300, where θ is the deviation of the electron pulse from the axis of propagation of the laser pulse

Figure 1 shows that the electronic spectra agree well up to ≈ 2 MeV; small discrepancies begin at higher energies. the main difference: the cut-off energy for the neutral gas was 16.5 MeV, for the initially ionised gas 23 MeV. From this we can conclude that a laser prepulse, which ionises the gas before the main pulse arrives, generally increases the efficiency of electron acceleration.

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EXPERIMENTS AND MODELING ON LASER ACCELERATION OF ELECTRONS AND X-RAYS GENERATION AT VARIOUS PARAMETERS OF LASER-PLASMA INTERACTION

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Laser sources of high-energy particles and hard radiation are of great interest due to their widespread use in the creation and diagnosis of extreme states of matter. The concept of creating efficient laser sources of hard radiation based on the generation of relativistic electrons in the direct laser acceleration mode is discussed. As was confirmed in experiments [1], PW-class laser systems generating subpicosecond and femtosecond pulses of relativistic intensity are capable of creating high-current beams of ultrarelativistic electrons in an extended plasma of a near-critical density [2, 3].

The results of experiments and modeling of the dependence of the parameters of laser-generated electron bunches and hard radiation on the parameters of laser pulses and targets are obtained and analyzed [2 - 7]. The developed approach shows ways to increase the efficiency of a wide class of secondary laser sources for various applications [8].

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ON THE ROLES OF DIFFERENT FREEDOM DEGREES IN THE WATER COULOMB EXPLOSION INITIATED BY A INTENSE X-RAY PULSE

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When a molecule irradiated with an intense X-ray pulse like the ones generated by the modern free-electron lasers or synchrotron sources, the prime process to occur is photoeffect, followed by a complex evolution involving Auger-decay, fluorescence, vibration and dissociation. Finally the molecule obtains essential charge with further Coulomb explosion. For the processes occurring in high-frequency domain typically inner-shell ionization dominates over valence-shell, and as result exotic hollow states of the molecules such as SCH (single core-hole) and DCH (double core-hole) are created. Note that while ground states of H_2O^+, H_2O^{2+} were explored in a very detail the investigation of these dications with 1s-vacancie(s) are very restricted. The lack of these data are caused by the problem with convergence for hollow states taking place in some numerical approaches.

This work was stimulated by the recent investigation [1], where the moments of water decay fragments were measured in coincidence with Oxygen ion charge. Additionally measured values are charge distribution and kinetic energy release (KER). Calculations were performed by solving the system of classical dynamical equations with the surface of potential energy obtained by the original code [2].

We consider water molecule irradiated by the X-Ray pulse with frequency 1 KeV. After first inner-shell ionization there is a competition between subsequent Auger-decay and ionization. In first case $H_2O(z=+2)$ the ion relax to the equilibrium linear geometry; in second case there is no stable configuration and the ion decays (if ionization occurs from 1s shall) or dissociates (if ionization occurs form valence shell). Let us emphasize that opening the molecule is crucial to reproduce some experimental finding especially protons observed in the same hemiplane as oxygen ion.

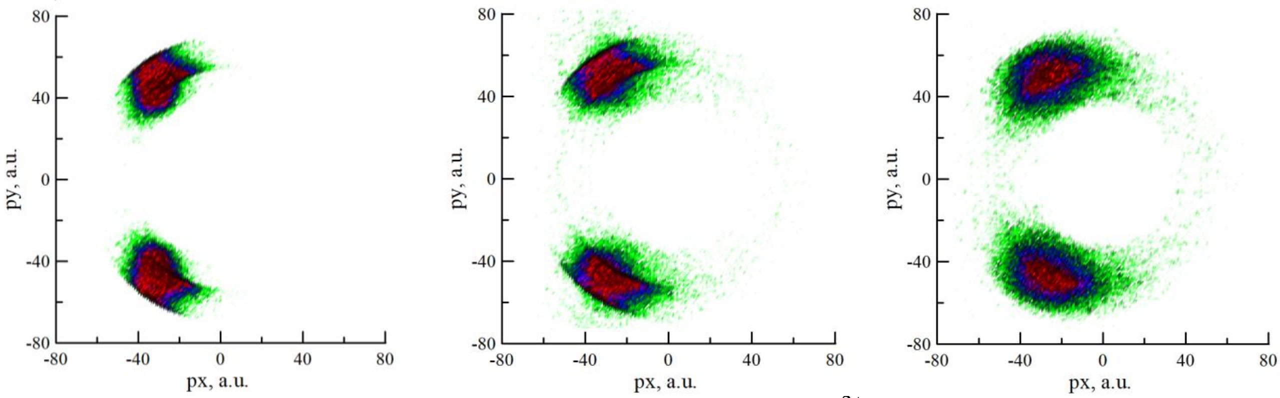

Fig.1 Newton diagram for protons detected in coincidence with O^{2+} simulated for the neutral H_2O in the equilibrium position (a); in the position accounting scissors vibration (b); in the position accounting all vibration modes (c).

In figure 1 there is simulation of the Newton diagram accounting different vibration modes for the initial geometry of neutral water molecule.

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ULTRASHORT pulse laser technologies: from optical to x-ray

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The results of papers [1–4] are reported. In [1], we consider the effect of a femtosecond (fs) laser pulse of hard X-ray (9 keV) on a LiF dielectric. Hard photons have a long attenuation length d_{att} in all materials (metals, dielectrics, semiconductors) except heavy metals with many-electron shells. This dramatically differentiates metal ablation with a spot larger than the optical wavelength and a small skin layer thickness from the situation with a hard X-ray laser with a well collimated beam (spot down to small fractions of a micron) and a huge length d_{att}, see Figure. In [2], the propagation of a two-jump elastic/fracture laser-induced shock in diamond is considered. In [3], the melting/crystallization of titanium by a multi-megabar shock is described. Such a shock is generated by a fs laser pulse. The problem has applications in LSP (laser shock peening)—there is a refinement of large crystallites (tens of microns) to nanosize. In [4] the coefficients of electron-phonon interaction and thermal conductivity in gold with strongly excited electron subsystem were determined.

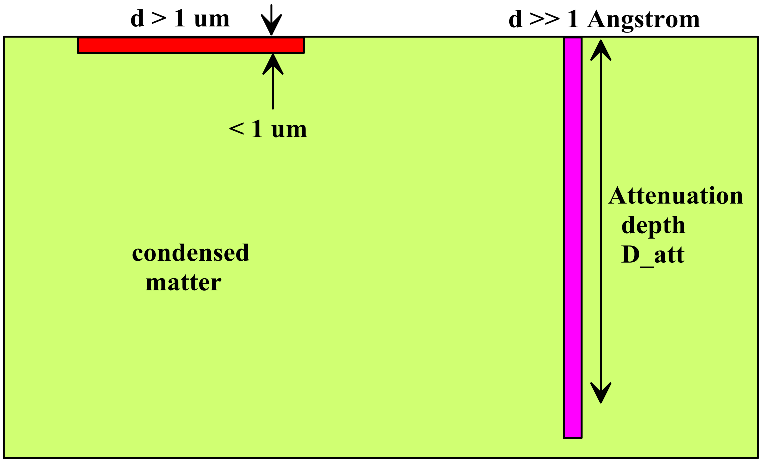

Fig. 1. Principle difference between the laser effects: on the left an optical fs laser (shallow water mode), on the right a hard photon source from an X-ray free electron laser (deep piercing mode).

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NOTES ON INVERSE COMPTON SCATTERING

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We examine how the kinematic conditions of the inverse Compton scattering of photons by relativistic electrons, as well as the polarizations of the colliding particles, affect the differential cross section of the process as a function of the angle of the scattered photon. It is found that the cross section is significantly influenced by the helicities of the electron and photon. In the case, where the initial photon momentum is transverse to the electron momentum, it was found that, in the ultrarelativistic limit, there is a surprising almost twofold increase in the cross section compared to the case of the head-on collision. In both cases the scattered photon moves in the direction of the electron beam. The increase in the photon energy is almost the same as in the head-on collision [1]

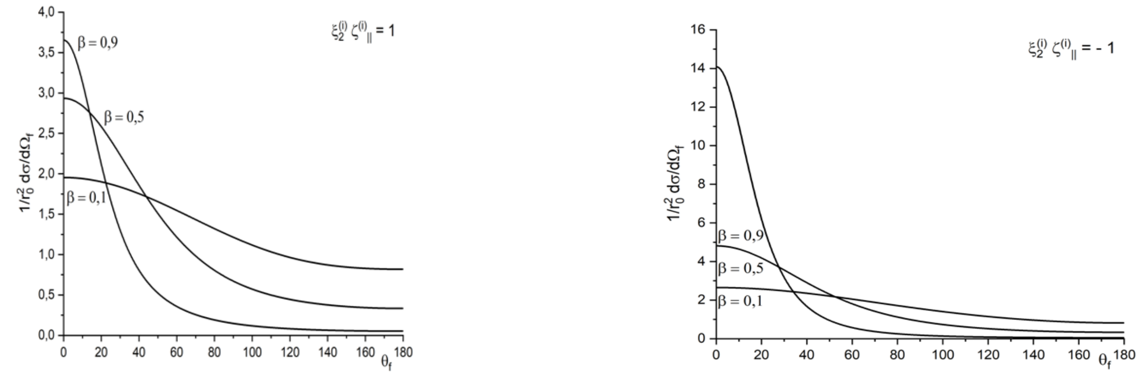

Fig. 1. Differential cross section of the head-on Compton photon-electron collision versus the photon scattering angle for several values of the parameter β=v/c. The incident photon energy is ω_i = 150 keV. Left panel: helicities of particles are of the same sign; right panel: signs are opposite.

As an example, in Fig. 1, the cross sections are displayed for the cases, where the electron and photon helicities are either the same (left panel) or have opposite signs (right panel). The photon energy is 150 keV and the collision is head-on. In the figures, the parameter $\beta = v/c < 1$ is the ratio of the electron speed to the speed of light. For large β, the difference in the values of the cross section at the peak is nearly quadrupled.

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IONIZATION OF HELIUM ATOMS BY METAL TRIPLY-CHARGED IONS IN LASER PLASMA

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It is known that the binding energy of complexes of a helium atom bound to a triply-charged metal ion can be rather strong, > 1 eV, for $HeCu^{3+}$, $HeMn^{3+}$, $HeFe^{3+}$, and $HeCo^{3+}$ [1]. In this case, HeM^{3+} complexes can be metastable or even stable if the potential energy curves for pairs $He + M^{3+}$ and $M^{2+} + He^{+}$ intersect at a sufficiently high energy barrier to prevent rapid exothermic dissociation.

We have analyzed the luminescence spectra of a plasma plume during laser ablation of a metal target immersed in superfluid helium. An appearance of excited neutral helium atoms points to formation of helium ions in laser plasmas. The main channel for the formation of helium ions in plasma at the laser power density below the breakdown threshold of liquid helium has been determined [2]. It occurs in two steps through the formation of an ionic complex from a helium atom and a triply-charged metal ion,

$M^{3+} + He \rightarrow HeM^{3+}$

followed by dissociation of the complex caused by its interaction with the neutral metal atom,

$HeM^{3+} + M \rightarrow He^{+} + M^{2+} + M^{+} + e.$

The helium atom luminescence during laser ablation of the targets was observed exclusively for Ni, Co, Ga, Au, and Ag, the metals with a positive balance $IE^{2+} - 24.59 - IE > 0$,

where IE and IE^{2+} are the ionization energies of neutral metal atom and doubly-charged ion, correspondingly.

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ELECTRON BEAM GENERATION IN LASER-PLASMA INTERACTION WITH LIQUID TARGET

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Femtosecond laser plasma is well-known source of high energy electrons. Various mechanisms can be used for the generation of the collimated electron beams, such as Laser Wakefield Acceleration (LWFA), Direct Laser Acceleration (DLA), etc. Depending on the acceleration mechanism, gaseous, solid [1], film [2] or other types of targets can be used.

One of the most promising types of targets are liquid targets created with the help of a piezocapillary. Possessing solid-state electron density, they allow the generation of high charge electron beams. On the other hand, the self-regenerating surface of liquid targets and their high stability, allow operate at high repetition rates of laser pulses. In this work we present liquid target configurations that are promising for electron acceleration: continuous jet and single drop modified by additional ns pulse on the μs time scale. Also we present results of electron beam generation (divergence – 0.1rad, charge – 10pC, energies – up to 10MeV) on a continuous jet previously ablated by a ns pulse on a ns time scale.

In our experiments we used Ti:Sa laser system (pulse duration – 50fs, intensity – $5\cdot10^{18}$ W/cm^2, wavelength – 805nm, repetition rate – 10Hz, ASE level – 10^{-7}). The drops (diameter ~10-100μm) and the continuous jet (diameter ~40-60μm) were created by a MicroFab MJ-SF-02 capillary. The liquid is ethyl alcohol. The liquid target modification on the μs time scale was made by a ns pulse of a Nd:YAG laser ($5\cdot10^{8}$ – 10^{10} W/cm^2, 532 and 1064nm), and the ablation on the ns time scale was made by another ns pulse (10^{12} W/cm^2, 1064nm).

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GENERATION OF ELECTRON-POSITRON PLASMA IN SELFSUSTAINED QED CASCADES WITH ULTRA-HIGH INTENSITY LASERS

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It is predicted that in selfsustained (also called avalanche-type) QED cascades — long chains of non-linear processes of hard photon emission by electrons and electron-positron pair creation by photons in a strong electromagnetic field — an exponential amount of particles can be produced in the interaction of an ultra-strong electromagnetic field with seed particles [1,2]. For this, the field should satisfy specific conditions [3] that can be met at the focus of two counterpropagating laser pulses. Self-sustained QED cascades generated with laser fields can open a path to recreating high-density relativistic electron-positron plasma in a laboratory.

We revisit the theory of selfsustained QED cascades in the context of the laser-based setup. We propose a new model for the cascade growth rate generalizing previous findings [4]. The model allows analytic treatment of cascades in realistic field configurations, e.g. a standing wave formed by two counterpropagating laser beams, and accounts for the particle migration effect leading to the reduction of the cascade multiplicity. We validate our considerations by full-scale PIC-MC simulations.

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CHARACTERIZATION OF HOT ELECTRONS GENERATED BY LASER–PLASMA INTERACTION AT SHOCK IGNITION INTENSITIES

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At laser intensities relevant to shock ignition conditions ($I>10^{16}$ W/cm^2), the heating and transport of hot electrons were studied by using several complementary diagnostics, i.e., Kα time-resolved imaging, hard x-ray filtering (a bremsstrahlung cannon), and electron spectroscopy. Ablators with differing composition from low Z (parylene N) to high Z (nickel) were used in multilayer planar targets to produce plasmas with different coronal temperature and collisionality and modify the conditions of hot-electron generation. The variety of available diagnostics allowed full characterization of the population of hot electrons, retrieving their conversion efficiency, time generation and duration, temperature, and angular divergence. The obtained results are shown to be consistent with those from detailed simulations and similar inertial confinement fusion experiments. Based on the measured data, the advantages, reliability, and complementarity of the experimental diagnostics are discussed.

The present results provided an electron temperature of ~35 keV and a laser-to-HE conversion efficiency of 1%–2%. These values are consistent with detailed simulations done with the CHIC code at $\lambda = 1.315$ μm and, as well as with experimental data collected under similar conditions from the front and rear sides of the target. Implementing a comprehensive set of multiple diagnostics as reported herein is very important for future studies focused on understanding HE generation and transport in ICF-scale targets and their relationship to laser plasma instabilities.

CONCEPTUAL DESIGN AND SCIENTIFIC PROGRAM OF THE EXPERIMENTAL STATION "MATTER IN EXTREME CONDITIONS" FOR THE RUSSIAN XFEL (PROJECT "SYLA")

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The rapid development of laser technologies towards the creation of high-power laser complexes around the world has made it possible to generate and study plasmas at extremely high temperatures and densities in the laboratory. The related field of research, High Energy Density Physics (HEDP), is a new, comprehensive branch of physics that has the potential to revolutionize various areas of traditional science and technology, including astrophysics, particle acceleration, nuclear fusion and the properties of condensed matter under extreme conditions. HEDP is closely linked to plasma and condensed matter physics, relativistic physics, the physics of lasers and charged particle beams, nuclear, atomic and molecular physics and astrophysics.

"Matter in Extreme Conditions" (MEC) experimental station is being developed as part of the Russian X-ray free electron laser XFEL (“SyLa” project – Synchrotron and Laser). The key feature of the station is that this state of matter will be created by optical lasers. It is planned to have two optical channels – ns (kJ) and fs (sub/PW). Similar stations are already in operation at three international XFELs (European XFEL – Germany, SACLA XFEL – Japan. LCLS – USA).

Traditionally, it is assumed that a substance is in a state of “high energy density” if the energy density is above 10^{11} J/m^3, which corresponds to a pressure of 1 Mbar (0.1 TPa) or a magnetic pressure of 500 T. This state of matter can be determined under laboratory conditions. This state of matter can be generated under laboratory conditions when optical laser radiation of high and ultra-high peak power is applied to material targets. The combination of an X-ray free-electron laser with a source of powerful optical radiation in a laboratory experiment opens enormous possibilities for studying matter in an extreme state.

Our report highlights the scientific program of the MEC station as well as the current state of development of the target and laser halls of this station.

GENERATION OF EXTREME QUASI-STATIC MAGNETIC FIELDS IN PLASMA TARGETS IRRADIATED BY CROSSED PETAWATT LASER BEAMS

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Inverse Faraday effect (IFE) induced by the radiation reaction force was theoretically predicted in [1] as resulting from an irreversible angular momentum transfer (AMT) between a strong circularly polarized infrared laser field and a dense plasma slab. Conversion of a number of infrared photons into a single X-ray quantum – the process taking place when the plasma electrons emit synchrotron-like radiation – explains this AMT within the microscopic picture, while the macroscopic description relies on the concept of radiation friction [1]. The AMT leads to the excitation of a quasi-static magnetic field pointed along or opposite to the propagation direction of the laser pulse. For laser fields of extreme intensity exceeding 10^{24}W/cm^2, the magnetic field fills the focal volume with spatial size of several wavelengths in each direction, exists during more than 100fs and reaches several Giga-Gauss in its peak value.

Intensities ~10^{24}W/cm^2 and higher remain out of the experimental reach so far. New high-power laser sources under construction [2] will combine several multi-petawatt linearly polarized beams superimposed in the focal area. Therefore it is of interest to model the IFE induced by radiation friction in a multi-beam configuration.

In this work, we present results of particle-in-cell (PIC) simulations of the plasma dynamics in the focal area, where two or four linearly polarized femtosecond laser pulses overlap. The simulation was performed by two PIC-codes with the radiation reaction force included into the equation of motion [3,4]. Each beam had intensity ~10^{23}W/cm^2, and the polarization directions were mutually orthogonal so that the resulting field was close to a circularly polarized one when the crossing angles of the beams remained small, up to ~20^{O}. We show that the IFE remain quite robust with respect to the relative phase shift between the beams, the crossing angle value (provided it is sufficiently small) and the relative amplitude variation. In the last case the IFE is induced by an elliptically polarized field. These results justify the idea to reach the radiation-dominated regime of laser-plasma interactions using several beams of 10-20PW power each and to demonstrate the radiation reaction impact on the plasma dynamics by observing Giga-Gauss magnetic fields. These parameters are realistic to reach within the nearest decade.

Preliminary results were published in [5]. The work was supported by the Russian Science Foundation (project No. 20-12-00077).

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ANGULAR MOMENTUM TRANSFER IN THE INTERACTION OF INTENSE CIRCULARLY POLARIZED LASER PULSES WITH STRUCTURED TARGETS

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Electromagnetic fields carry angular momentum (AM), which can be separated into the spin and the orbital parts [1]. The spin part is associated with the circularly polarized (CP) component of the field, and CP Gaussian-type beams, if not extremely tightly focused, mostly carry spin momentum. In this case, the orbital momentum is on the level of a few percent of the spin. Irreversible absorption of AM by plasmas opens a way to the excitation of strong electronic currents, which generate high quasi-static magnetic fields. Different mechanisms of AM deposition can lead to similar consequences. In the extreme field regime, i.e. for intensities 10^{24}W/cm^2 and higher the Inverse Faraday Effect (IFE) induced by the radiation reaction force was theoretically shown to be the main mechanism of the AM transfer and magnetic field generation [2].

However, intensities $>10^{24}$W/cm^2 required for a clear demonstration of the IFE currently remain out of the experimental reach, while realistic expectations promise the peak intensity to be a few times of 10^{23}W/cm^2 at the operating laser facilities of the multi-petawatt class including ELI-Beamlines, Apollon or CoRelS [3,4]. Numerical simulations show that the IFE induced by radiation friction is too week at such intensities, however, a strong magnetic field can still be excited in the interaction of CP pulses with dense plasma targets.

In this work, we examine possible mechanisms of the AM transfer at intensities $\sim 10^{23}$W/cm^2. We show that the space structure of the plasma surface can play a crucial role in this process. In particular, for dense targets with a cylindric hole, a CP laser pulse with a transverse width comparable to the hole diameter can lead to a very efficient AM transfer and magnetic field excitation in the case when it propagates along the hole axis. The underlying physical mechanism is a strong lateral inhomogeneity of the plasma, which makes possible the generation of a surface cylindric current. The observed physics is similar to that examined by Park et al. [5] with a considerable difference in polarization: in our case CP radiation generates circular currents and an extremely strong longitudinal magnetic field. Results of our particle-in-cell simulations made with the help of SMILEI code [6] show a quasi-static magnetic field of Giga-Gauss strength at a laser intensity not exceeding 10^{23}W/cm^2 .

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ANALYSIS OF L-SPECTRA OF MULTIPLY CHARGED IRON IONS FORMED IN EXPERIMENTS WITH INTENSE LASER PULSES

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We discuss the possibility of using L-spectra of multiply charged ions to study the physical effects which take place in laboratory experiments carried out on modern laser facilities of nano-picosecond duration at relativistic laser intensities on target. One of these physical phenomena is magnetic reconnection (MR), or reconnection of magnetic field lines. It is a fundamental physical process that occurs when a sharp change in the topology of the plasma magnetic field results in the release and conversion of magnetic energy into the kinetic energy of plasma particles. The MR takes place in many plasmas. It is of interest both for applied problems, for example, inertial thermonuclear fusion, and fundamental problems, for example, for a better understanding of the evolution of various astrophysical objects and phenomena. Here we consider the opportunity to investigate MR in laboratory astrophysical experiments, discuss possible schemes for MR formation in laser plasma and consider how x-ray spectroscopy can be useful for MR studying.

It is shown that x-ray spectroscopy makes possible to determine with sufficiently high accuracy the parameters of the plasma formed during the interaction of a laser pulse with a target, as well as in a localized reconnection region, for example, when using 2D registration schemes using spherically curved crystals. Plasma parameters determined from X-ray emission spectra play a key role in subsequent numerical calculations and PIC modeling, which makes it possible to reconstruct the picture of the generated magnetic fields and describe the reconnection process in more detail.

Using atomic kinetic calculations have been performed for the spectra from the L-shells of Ne- and F-like iron ions (Fe, Z=26), we demonstrate the high sensitivity of the spectra to plasma parameters variation. It is shown that the spectra of Ne-like multi-charged ions are a convenient tool for diagnosing plasma parameters in experiments studying MR.

TABLE TOP LASER PLASMA ELECTRON ACCELERATION

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Production of directed electron beams through the interaction of a femtosecond laser pulse of relativistic intensity with subcritical plasma is one of the most actively developing areas at the intersection of laser physics and plasma physics. The most impressive results were obtained using unique laser systems with a peak power from 0.5 to several PW. At the same time, the low pulse repetition rate of such systems determines the low average beam current. In addition, many application areas require not so high electron energies around 10 MeV, but the charge of the electron pulse and the average beam current are important. It is precisely these electron pulses that can be obtained using femtosecond laser complexes with a terawatt peak power level and capable of operating at kilohertz repetition rates.

We present results of computational and experimental studies of several schemes for accelerating electrons with a femtosecond laser pulse with a peak power of 1-2 TW, the possibility of scaling the developed approaches to high powers (tens of TW and PW), as well as the use of these beams for generating secondary radiation in a wide electromagnetic field ranging from terahertz to gamma. In particular, we have obtained electron beams with an energy of up to 15 MeV, a charge of hundreds of picoculombs, and a divergence of about 0.1 rad. Original approaches will be presented that provide effective control of the energy spectrum of the beam at a high repetition rate, generation of quasi-unipolar pulses of terahertz radiation, gamma flares and photonuclear reactions.

ACCELERATION OF NEUTRAL ATOMS BY STRONG SHORT-WAVELENGTH SHORT-RANG ELECTROMAGNETIC PULSES

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Non-dipole corrections in the interaction of an atom with laser radiation, which arise when taking into account the spatial inhomogeneity **kr**=ky of the electromagnetic wave and the presence of a magnetic component in it, lead to “entanglement” of the variables of the center of mass (CM) and electrons in a neutral atom and, as a consequence, to its acceleration. We studied this effect, as well as the accompanying processes of excitation and ionization of the hydrogen atom in strong (10^{12} - 2×10^{14}) W/cm^2 linearly polarized short-wave (5 eV ≤ hν ≤ 27 eV) electromagnetic pulses with a duration of about 8 fs. The study was carried out within the framework of a hybrid quantum-quasiclassical approach [1], in which the coupled time-dependent Schrödinger equation for the electron and the classical Hamilton equations for the CM of the atom are simultaneously integrated [2]. A strong correlation was discovered between the velocity (momentum) of the CM of the atom V_y (MV_y) at the end of the laser pulse and the total probability P_{ex}+P_{ion} of excitation and ionization of the atom (see Fig. 1). Two mechanisms of atomic acceleration have been established: through single-photon and two-photon excitation of the atom. It is shown that the one-photon mechanism leads to a linear dependence of the atomic velocity at the end of the laser pulse on the laser intensity, and the two-photon mechanism leads to a quadratic dependence (see Fig. 1). Optimal conditions for the frequency and intensity of the electromagnetic wave were found for the acceleration of atoms without their noticeable ionization in the studied range of changes in laser parameters [2].

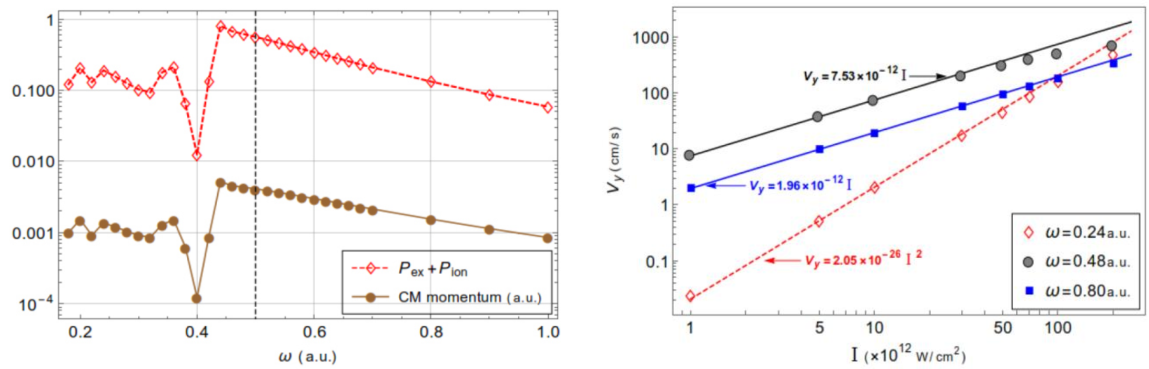

Fig. 1. Calculated dependencies of the total probability P_{ex} + P_{ion} of excitation and ionization and the momentum of the CM of the atom MV_v on the laser frequency ω at I=10^{14} W/cm^2 (left figure) and the velocity of the CM of the atom V_v on the laser intensity I for single-photon (ω=0.48a.u. and 0.8a.u.) and two-photon (ω=0.24a.u.) mechanisms of atomic acceleration (right figure) [2].

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EFFICIENT LASER ACCELERATION OF ELECTRONS AND IONS FROM TARGETS WITH CONTROLLED PREPLASMA

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It is well known that preplasma is one of the most important parameters for the acceleration of charged particles from a solid target irradiated with an ultrashort laser pulse [1]. Here the impact of preplasma scale length on electron/ion acceleration is studied.

The hydrodynamic modeling performed by FRONT code [2] shows that the density profile of an expanding target can be described by the sum of two exponentials with two characteristic density gradients in the region of near-critical and low plasma densities. The near-critical plasma density gradient with increasing laser fluence quickly reaches saturation in the region of ~0.15 microns. The low-density plasma gradient, weakly dependent on the target thickness, varies from 7 microns to 20 microns with an increase in laser fluence from 0.2 kJ/cm^2 to 25 kJ/cm^2 (cf. [3]). Using the obtained density profiles, a series of 3D PIC simulations of the acceleration of electrons and ions from an Al target (with thickness of 2 microns and 100 nm proton layer on rear side) with preplasma by a laser pulse with a power of 0.8 J and a duration of 40 fs was carried out.

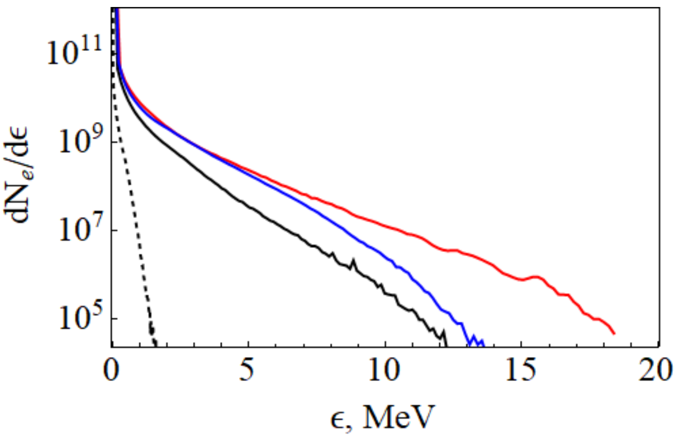

Fig. 1. Spectra of electrons accelerated by a 0.8 J laser pulse with a duration of 40 fs from a solid Al target without preplasma (dashed line) and with preplasma on the irradiated side created by a prepulse with a duration of 5 ns and intensity of 10^{11} W/cm^2 (black line), 10^{12} W/cm^2 (red line) and 5×10^{12} W/cm^2 (blue line).

As expected, an increase in the preplasma density gradient leads to an increase in the efficiency of electron acceleration. Some reduction in maximum electron energy at the maximum density gradient used is due to laser pulse filamentation and can be avoided by adjusting the laser focusing position. The optimal preplasma density gradient of 10-15 microns corresponds to the maximum temperature of electrons and the highest energy of protons accelerated from the contamination layer on the back side of the target. In general, the efficiency of electron and ion acceleration depends not only on the preplasma gradient, but also on the position of the laser pulse focus on the gradient.

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LASER PULSE POLARIZATION INFLUENCE ON EMISSION BY AN ELECTRON FROM THE FOCUS

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For a short circularly polarized laser pulse, the time course of the power emitted by the electron per solid angle and the total power, as well as the energy emitted by the electron from the trajectory, are determined. A comparison is made with the characteristics of radiation in a linearly polarized field. In backscattering in a circularly polarized field, the direction of radiation of maximum intensity is tilted due to the circular motion of the electron in the focal plane, but due to the small radius this does not lead to a difference in the energy emitted from the trajectory compared to a linearly polarized field, as in the case symmetrical trajectories. It is shown that the law of growth of peak intensity in a linearly polarized field discovered in [1] also applies to the case of a circularly polarized field. The characteristics of radiation for elliptical polarization are predicted.

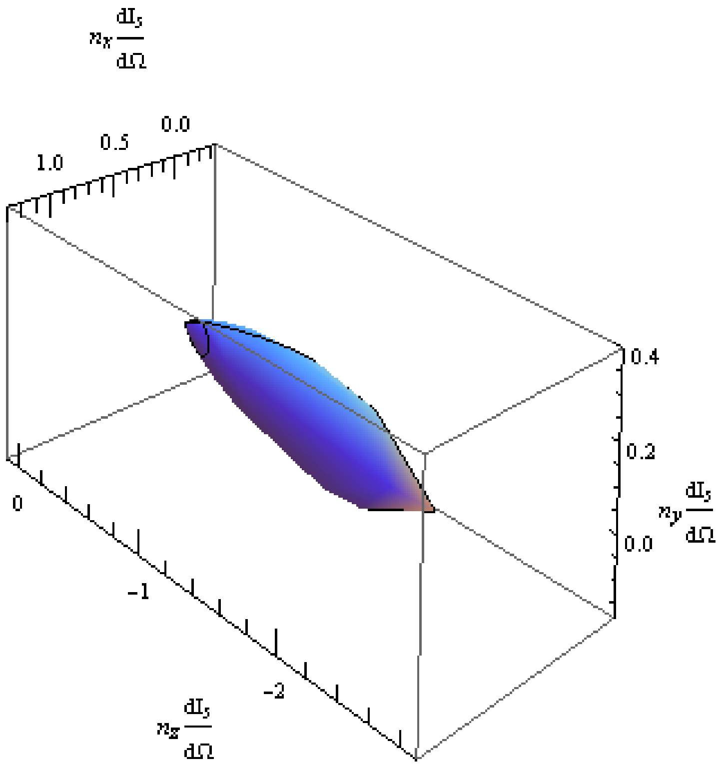

Fig. 1. Tilted emission diagram of electron colliding velocity $v_{z,0}/c = 0.968$ in a circularly polarized laser pulse.

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EFFECTS OF QUASI-PHASE MATCHING IN COHERENT RADIATION GENERATION BY ATOMIC SYSTEMS IN TWO-COLOR LASER FIELDS

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Non-linear optical response of a matter under the intense laser fields is one of the methods used to produce pulsed coherent radiation in wide range of spectrum: from terahertz (THz) [1] and up to the ultraviolet and X-ray ranges (due to the high-order harmonic generation (HHG) phenomenon) [2]. One of the classical and still popular mediums for the coherent radiation generation is atomic gas [3]. The low conversion efficiency due to the low concentration of atoms in the gas can be considered a disadvantage of generating in gas jets, while an advantage is the relatively simple experimental setup. To overcome relatively low efficiency of generated radiation methods based on quasi-phase matching (QPM) are developed [4]. The QPM affects significantly when multi-color laser field propagates through a gas medium consisting of a set of gas jets separated by vacuum gaps [5-7].

Here we demonstrate the resent results of numerical studies of the coherent radiation parameters (efficiency and degree of ellipticity) control in short-wavelength (due to HHG) and long-wavelength (THz) parts of spectra generated by a set of gas jets interacting with two-color femtosecond laser fields. For this study, we have used the interference model presented in [8] and non- perturbative theory of the single-atom response calculation discussed in [9].

Methods for control over the parameters of the generated radiation by varying both the parameters of the laser field and medium (sizes of gas jets, their number, gas pressure) are proposed.

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CONDUCTION BAND DYNAMICS IN SOLIDS INDUCED BY NEAR- AND MID-IR FEMTOSECOND LASER FIELDS

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There are several models of electrons dynamics in solids induced by femtosecond laser field: based on Boltzmann transport equation [1] or on rate equations: SRE [2], MRE [3]. The latter model is a tradeoff between physical correctness and computing complexity. Since the rate of electrons laser heating band increases with wavelength, it might become higher than the impact ionization rate in near- and mid-infrared spectral ranges, that is forbidden in the MRE model.

We propose an extension for this model – EMRE model [4], which makes it possible for electrons to acquire kinetic energy above the critical level and therefore to modify the total impact ionization rate. As in the MRE model, it is considered the conduction band as a finite number of electron energy levels separated from each other by photon energy. The features of the EMRE model are the following [4]: 1) the rate of one-photon absorption α_{1ph} depends on time and an electron energy level; 2) to account for possible electron heating above the critical energy we introduce an averaged energy level above the critical one.

To underline the benefit of the EMRE model we conducted a set of calculations of electron dynamics for various wavelengths (from 1.25 to 4.5 μm) and laser fluences (up to 0.1 J/cm^2) in silicon and retrieve deposited energy density (DED) – an integral over time of the laser energy density absorbed by electrons (Fig. 1). As follows from the calculations, DED calculated in the context of the EMRE reaches the melting threshold (the dotted horizontal line in Fig. 1) at laser fluences approximately equal to $F_{melt} \approx 0.05$ J/cm^2, which is in accordance with numerous experiments on silicon bulk micromodifications [5, 6]. This fact directly points out a need for use the EMRE model to correctly describe matter excitation by laser field.

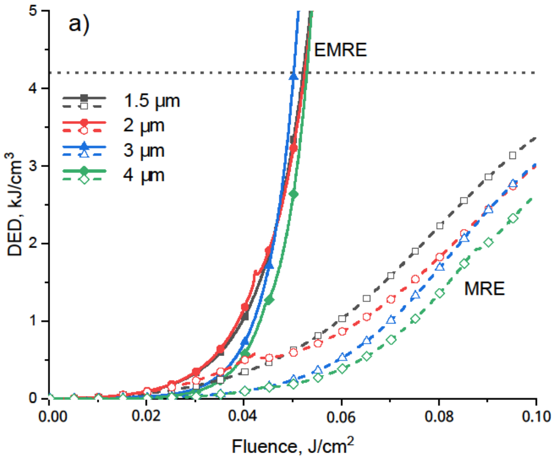

Fig. 1. Deposited energy density in silicon calculated using the EMRE (solid lines) and MRE (dashed lines) models.

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EXPERIMENTAL INVESTIGATION OF OPTICAL ANISOTROPY DURING FEMTOSECOND LASER-INDUCED AIR BREAKDOWN IN NARROW INTENSITY RANGE

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We report on experimental observation of the ultrafast depolarization induced by propagation of an intense laser pulse through the ionizing gas media. It has been previously demonstrated that during filamentation in gases a birefringence occurs that could also lead to depolarization [1,2]. Here we show that the depolarization is strongly dependent on the intensity of the laser pulse. The experiment is based on pump-probe scheme with transverse directions of the beam paths. The pump pulse (2.5 mJ, 50 fs, 12 mm dia. 1/e2) is focused by a 5 cm focal length parabolic mirror producing ~2 mm long plasma channel. The polarization of the beam is vertical. The probe beam goes through a controllable delay line and thereafter through the region of plasma formation. To visualize the depolarization, the probe beam polarization is turned to 45 degrees. It passes a 45 degrees oriented polarizer, the plasma region and an analyzer rotated in the vicinity of 135 degrees (crossed polarizers). The plasma channel region (and depolarization) is imaged on a CMOS-camera by a telescope. By changing of the delay we can scan the position of the pump pulse in the focusing region and so the intensity conditions. The depolarization pattern changes from the spotlike to ring-like structures with the increase in the intensity. The most intense depolarization occurs in the vicinity of ionization threshold. Based on the theory of Gaussian beam focusing and the dynamics of changes in the depolarization structure, it was determined that the depolarization pattern corresponds to a narrow range of intensities. Using the formula for the dependence of the refractive index on intensity, the value of the addition to the refractive index corresponding to the 5th order Kerr effect was determined based on the measurement results.

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VECTOR PARAMETERS IN ATOMIC IONIZATION BY TWISTED BESSEL RADIATION

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The electron and ion properties observed in photoionization inherit the symmetry properties of both a target and radiation. Involving symmetry violation in the photoionization process, one can expect to observe a noticeable variation of the vector correlation parameters of either an outgoing photoelectron or a residual ion. We present an extension of the approach developed in [1] for photoelectron angular distribution to the other vector correlation parameters, specifically, spin polarization of the photoelectron, and residual ion orientation and alignment [2].

In the present study we derive general expressions for the statistical tensors of photoelectron and photoion when target, which consists of randomly and uniformly distributed unpolarized atoms, is irradiated by Bessel beam. There are no restrictions on multipoles number and on atom imposed. We show that in such expressions one can separate out photon statistical tensor, dynamical parameters (which do not depend on polarization parameters and remains the same in any coordinate system) and geometrical factor in a form of a small Wigner D-function responsible for effects of radiation “twistedness”. Further one can construct expressions for component of photoelectron spin and photoion orientation and alignment.

We illustrate the developed approach with the case of 4*p*-shell ionization of neutral krypton by circularly and linearly polarized Bessel light in dipole approximation within *jj*-coupling scheme. It was found that photoelectron spin components are dynamically connected with the cone angle of the Bessel beam. Moreover, in case of linearly polarized Bessel beam a component oriented along the polarization vector, which does not exist in the conventional plane-wave case, appears.

Specific results will be presented at the conference.

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NUMERICAL MODELLING OF PLASMA PERIODIC SUBWAVELENGTH STRUCTURES UNDER THE FOCUSED ULTRASHORT LASER PULSE EXPOSURE IN THE VOLUME OF SOLID DIELECTRICS

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Femtosecond laser writing of birefringent subwavelength nanopatterns in solid dielectrics has been studied for almost two decades since it reveals a number of applications for optical memory devices, optical waveguides, microfluidic channels etc [1,2]. Despite the large number of works in this field, there is still no universal theoretical model explaining the self-consistent dynamics of field and plasma subsystems in a particular regime of laser exposure, which prevents further progress in the field of laser writing of such nanostructures.

In this work a 3D numerical study of the formation of plasma periodic subwavelength structures in the volume of fused silica exposed by a tightly focused sub picosecond laser pulse is carried out. The parameters of focused laser radiation are chosen according to the experiments carried out in Lebedev Physical Institute RAS [3,4]. It is shown that the laser beam creates in the pre-focal region a bunch of dense plasma having an almost spherical shape. This bunch provides an effective reflection of at incident wave field. The interference of an incident plane wave and reflected from the near-spherical plasma object wave in the beam focal region provides two-directional periodic subwavelength modulations of plasma density both along the wave vector of propagated pulse and along the radial coordinate. It is numerically demonstrated that the best implementation of such 2D modifications is possible under the tight focusing conditions which agrees with the recent experimental data.

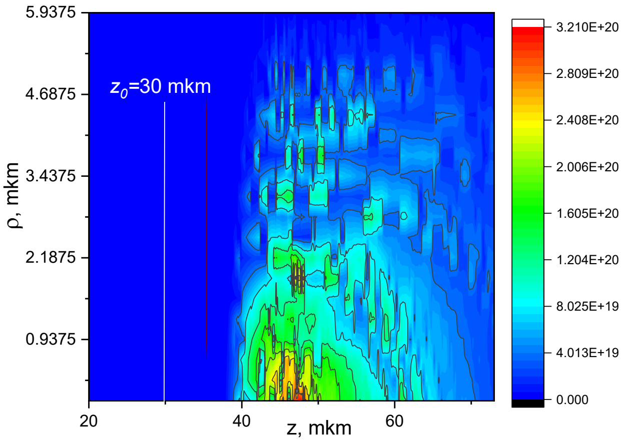

Fig. 1. Plasma density distribution after the focused laser pulse exposure. The colormap indicates the value of electron density. The laser wavelength is 1030 nm, the intensity is 1.3×10^{14} W/cm^2 , the pulse duration is 50 fs, the radius of focal spot is ~ 2.5 mkm.

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DEMIXING IN NANOCOMPOSITES OF HIGHLY POLARIZABLE INCLUSIONS

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A nanocomposite film containing highly polarizable inclusions in a fluid background is explored when an external electric field is applied perpendicular to the planar film. For small electric fields, the induced dipole moments of the inclusions are all polarized in field direction, resulting in a mutual repulsion between the inclusions. Here we show that this becomes qualitatively different for high fields: the total system self-organizes into a state which contains both polarizations, parallel and antiparallel to the external field such that a fraction of the inclusions is counter-polarized to the electric field direction. We attribute this unexpected counter-polarization to the presence of neighboring dipoles which are highly polarized and locally revert the direction of the total electric field. Since dipoles with opposite moments are attractive, the system shows a wealth of novel equilibrium structures for varied inclusion density and electric field strength. These include fluids and solids with homogeneous polarizations as well as equilibrium clusters and demixed states with two different polarization signatures. Based on computer simulations of an linearized polarization model, our results can guide the control of nanocomposites for various applications, including sensing external fields, directing light within plasmonic materials, and controlling the functionality of biological membranes.

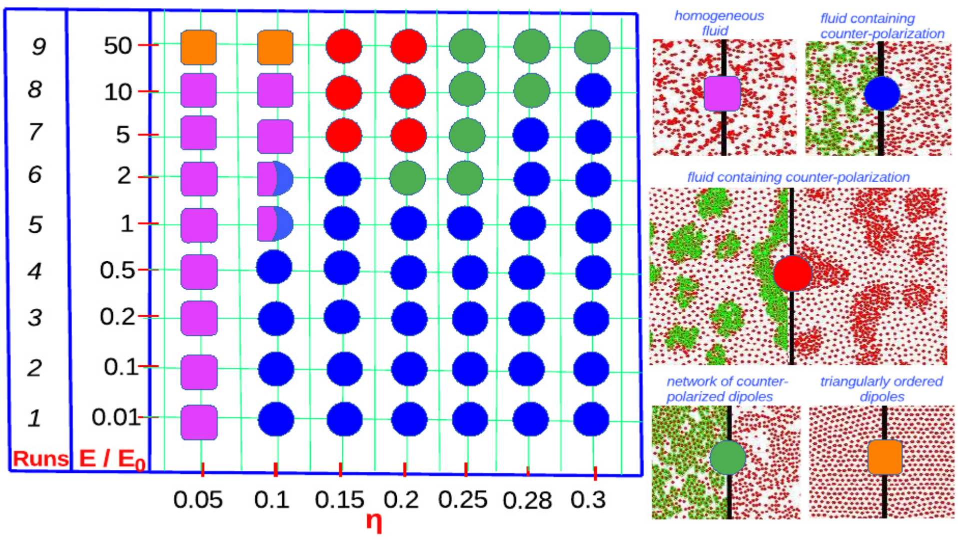

Fig. 1. The predicted phase diagram of the polarized 2D nanocomposite on the (log(E/E0), η) plane. Magenta squares are for the classical dipolar system with no dipole-dipole association. Blue circles are for systems with partially associated and counter-polarized dipoles without any clustering. Red circles are for fluid-gas demixed systems featuring high particle density clusters of counter-polarized dipoles surrounded by low density liquid of positively oriented dipoles. Green circles are for systems with voids filled with a few positively oriented dipoles surrounded by a high density crystalline network of counter-polarized dipoles. Orange squares are for homogeneous systems with triangular ordering for positively oriented dipoles.

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ANALYTICAL DESCRIPTION OF CYCLOTRON PLASMA RESONANCES IN MONOLAYER GRAPHENE

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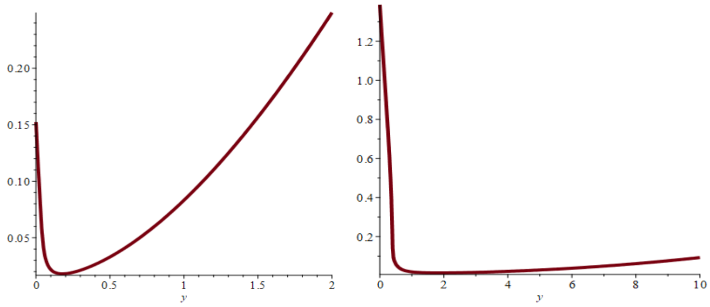
We consider propagation of longitudinal surface plasma waves in graphene in the presence of external magnetic field H. The linear electron energy spectrum of the graphene is of the form $\varepsilon = \pm v|\mathbf{p}|$. It follows from the solution of the kinetic Boltzmann equation the inexplicit dispersion equation for the dependence of the plasma frequency ω on the wave number k in the longwave limit:

$$1 = \frac{e^2 kT}{\hbar^2} \int_{-\infty}^{\infty} \frac{\left(\omega^2 + \omega_L^2\right)}{\left(\omega^2 - \omega_L^2\right)^2 + \gamma^2} \frac{|x|\,dx}{\cosh^2\left(x - \dfrac{\mu}{2T}\right)}; \quad \omega_L = \frac{ev^2 H}{2Tcx}.$$

Here T is the temperature, μ is the chemical potential, ω_L is the Larmour frequency, γ is the relaxation constant for cyclotron resonance. When the magnetic field is absent, the plasmon spectrum is of the simple form $k \propto \omega^2$ [1-3].Typical dependence of the wave number k on the ω^2 is shown in Fig.1 for the case of the moderate magnetic field. It is seen that at the large frequency the role of the magnetic field is diminished, and again $k \propto \omega^2$ (straight line). The conclusion can be made that the magnetic field changes significantly the magneto-plasmon spectrum at the low frequencies.



a *b*

Fig. 1. The wave number k of the magneto-plasma wave as a function of $y \propto \omega^2$.
a) moderate magnetic field; *b*) strong magnetic field.

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EDGE PLASMON MODE EXCITATION IN GRAPHENE RECTANGLES BY INCIDENT TERAHERTZ WAVE

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Graphene plasmon structures is promising platform for planar terahertz (THz) optoelectronics [1]. Its advantages include field localization at lengths shorter than the electromagnetic wavelength [2], nonlinear properties useful for THz detection [3] and amplification [4].

The majority of theoretical studies consider a graphene structures that is homogeneous and infinite in the direction perpendicular to the plasmon wave vector [5]. Consideration of full 3D plasmonic problems with 2D plasmonic cavity confined in two perpendicular directions, made it possible to reveal edge effects of plasmon modes [6] that localize THz field deeply below the diffraction limit [7].

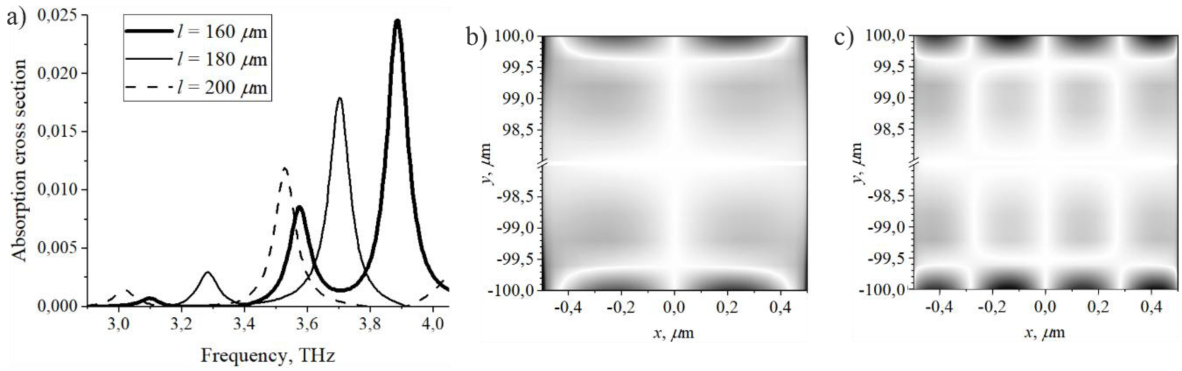

Fig. 1. (a) Spectrum of absorption cross-section normalized to the geometric area of graphene rectangle for $w = 1$ μm and different values of l. The value of the attenuation cross section for an infinite graphene strip 1 μm wide is subtracted from the value of the spectrum of the attenuation cross section. The instantaneous spatial distributions of the oscillating charge density modulus over the area of graphene rectangle with $l = 200$ μm in the plasmon resonances excited near frequencies (b) 3.5 THz and (c) 3 THz.

In this work the problem of the incidence of a THz wave on a rectangular graphene cavity is solved. The rectangle lies on a flat interface between two media with different dielectric constants; the width of the rectangle is $w = 1$ μm and the length is l. A linearly polarized THz wave is normally incident on the graphene rectangle, scatters on it and excites plasmon modes in it (fig. 1, a). The electric field vector of the incident wave is polarized along the short side w of the rectangle. Instantaneous spatial distributions of the oscillating charge density in the graphene rectangle with $l = 200$ μm in the plasmon resonances excited near frequencies 3.5 THz and 3 THz are plotted in figs. 1, b, c. The charge oscillations are strongly localized near the longitudinal edges of graphene rectangle in crucial contrast from the well-known fundamental *sheet* plasmon mode in which the charge oscillations exist over the entire area of graphene cavity.

The work was supported by the Russian Science Foundation grant No. 22-19-00611.

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ELECTRON-HOLE PLASMA, FREE EXCITONS AND ELECTRON-HOLE LIQUID IN SYNTHETIC DIAMOND UNDER ULTRAVIOLET LASER EXCITATION

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Diamond is characterized by the high binding energy of free excitons (~80 meV), therefore, after interband transitions during absorption of deep UV photons and subsequent thermalization, it is energetically advantageous for electrons and holes to form free excitons even at room and elevated temperatures. In the low temperature region, as the excitation intensity increases, the formation of exciton complexes and further condensation of free excitons into droplets of an electron-hole liquid are observed. However, at temperatures above 200 K at high excitation densities, bands of apparently electron-hole plasma are observed in the edge luminescence spectra.

Electron-hole liquid (EHL) was previously observed in almost all direct- and indirect-band bulk semiconductors, as well as in quantum wells (Fig. 1). Diamond is characterized by the high critical condensation temperature of EHL ~ 200 K [1]. However, even more interesting is the high-temperature EHL in two-dimensional materials such as MoS_2 [2] and thin films of <111> diamond [3]. It is assumed that a high-temperature EHL (close to room or elevated temperature) will be used in promising semiconductor devices.

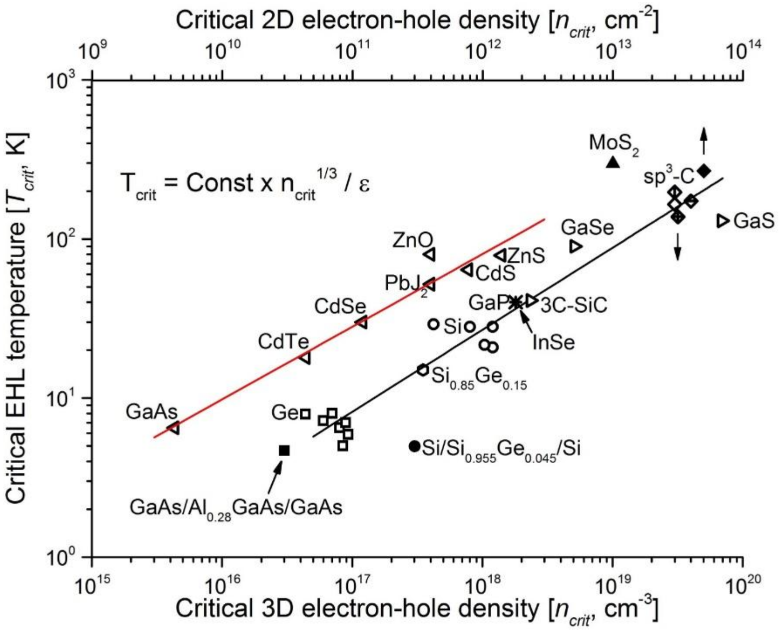

Fig. 1. Electron-hole liquid in various semiconductors. Open symbols are bulk materials; solid symbols are thin materials; ehe black line is for indirect-band semiconductors; the red line is for direct-band semiconductors

However, the questions of the conditions of existence of an electron-hole plasma of charge carriers in diamond, its radiative recombination in photoluminescence spectra and differences from an electron-hole liquid still remain open. The report reveals the current state of research on electronic excitations in diamond, as well as the fundamental and practical significance of these studies for carbon electronics and photonics.

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MECHANISM OF ULTRAFAST DECAY CAUSING PERIODIC DAMAGE OF METALS BY FEMTOSECOND LASER PULSES

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We propose the mechanism of optical pulse decay into a pair of surface plasmon-polaritons (SPPs) and analyze the process both analytically and numerically [1,2]. It is proved that the rapid growth of electronic collision frequency provides the positive feedback for the development of electromagnetic instability, which occurs to have femtosecond timescale at damaging laser fluences of about several J/cm^2. This process is an important stage of laser ablation and periodic surface structuring, or LIPSS formation [3], since it leads to inhomogeneous light absorption.

We model femtosecond laser pulse interaction with a rough metallic surface in 2D geometry, using the full system of Maxwell equations for the electromagnetic field and the Euler equations for electrons inside the metal. Electron gas heating, thermal energy redistribution and electronic pressure were taken into account. The positive feedback between heating and electromagnetic wave transformation to SPPs was introduced through the dependence of the electron collision frequency on the thermal energy, which was extracted from experimental data for gold [4].

Typical picture of nonlinear diffraction at the rough metallic surface obtained in numerical modelling is shown in Fig. 1. The incident optical pulse propagates along x-axis being linearly polarized along z-axis. Upper panel shows the spatial distribution of the electric field component E_x (above the metal surface) and the electronic temperature (below the metal surface) in the middle of the interaction process. Lower panel shows the set of graphs $E_x(z)$ at the surface ($x = 0$) plotted at several moments of time during a single optical period; φ denotes the optical wave phase. The formation of SPPs standing wave was observed from a random noise.

To sum up, the development of ultrafast electromagnetic instability which manifests in the incident pulse decay to the pair of SPPs was demonstrated. As a result, the standing wave of SPPs causes periodic (striped) heating of electrons with high contrast between the neighboring areas.

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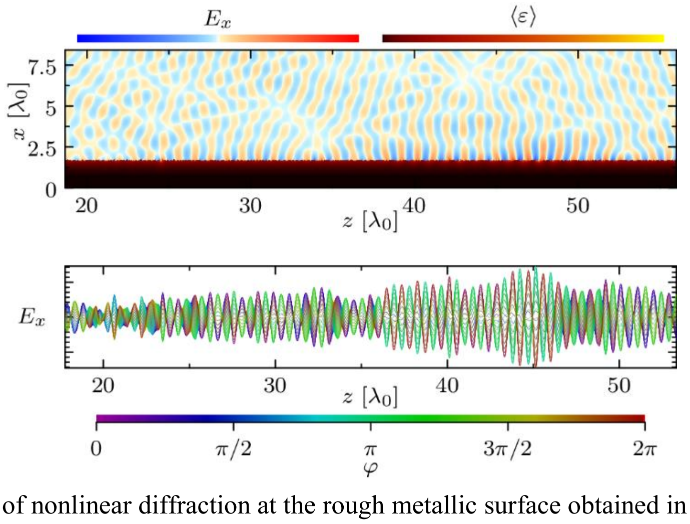

Fig. 1. Typical picture of nonlinear diffraction at the rough metallic surface obtained in numerical modelling.

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FORMATION OF SOLID-STATE PLASMA IN FERROELECTRIC SEMICONDUCTORS NEAR THE PHASE TRANSITION TEMPERATURE

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In solids, the presence of an electronic subsystem characteristic of the plasma state is a fact that is theoretically justified and confirmed experimentally [1]. Of particular interest among solids in which plasma can arise are ferroelectric semiconductors. These are, for example, SbSI single crystals, in which the phase boundaries are similar to electrical domains in semiconductors [2]. Ferroelectric plasma cathodes for electron emission based on $BaTiO_3$ and $Pb(Zr,Ti)O_3$ have found practical application [3, 4]. In a number of ferroelectric semiconductors, this can lead to a critical increase in the electron concentration and the emergence of electrical domains necessary for the formation of solid-state plasma. The combination of internal and external plasma electron generation mechanisms makes it possible to increase the cathode current density.

In this work, it is proposed to investigate the possibility of the emergence of solid-state plasma in ferroelectrics at a certain temperature preceding the phase transition, and which is characterized by an increase in the mobility of the domain structure, dielectric constant and electrical conductivity of the ferroelectric.

Using the example of a ceramic ferroelectric $(Pb_{0.95}Sr_{0.05})(Zr_{0.53}Ti_{0.47})O_3$, it is shown that an inflection occurs in the temperature dependence of the residual polarization $P_r(T)$ near the Curie temperature T_C at the point T_d (Fig. 1) [5]. This leads to an extremum of the derivative dP_r/dT and a maximum release of current I due to ferroelectric polarization. This provides a promising opportunity to create a ferroelectric pulsed cathode with an increased current density. But because at a temperature T_d the domain structure of the ferroelectric decays, then for the cathode to operate it is necessary to provide the following cyclic mode: pulsed heating of the cathode to a temperature T_d and subsequent exposure to an external electric field to restore the domain structure of the ferroelectric.

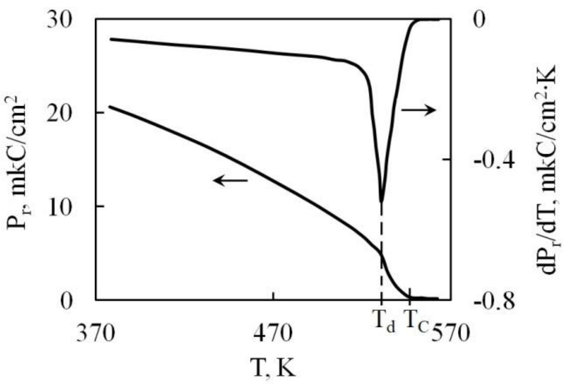

Fig. 1. Temperature dependence of the remnant polarization P_r and its derivative dP_r/dT of the ceramic ferroelectric $(Pb_{0.95}Sr_{0.05})(Zr_{0.53}Ti_{0.47})O_3$ [5]. T_d – depolarization temperature (531 K). T_C – Curie temperature (553 K).

The work was carried out as part of the fundamental research of the Ministry of Science and Higher Education of the Russian Federation "Activation mechanisms of phase transitions in ferroelectric materials", scientific topic code FREU-2023-0001.

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EXCITATIONS IN SOLID-STATE PLASMA WITHIN THE POLAR MODEL

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Specific solid-state collective excitations characteristic of the polar Shubin–Vonsovsky crystal model are considered [1]. To determine the laws of dispersion of excited states, the Hubbard Hamiltonian is used [2], which is a reduced Hamiltonian of the polar theory

$$\widehat{H} = \sum_{g_1,g_2,\sigma} t_{g_1g_2}\,\hat{c}^{+}_{g_1\sigma}\hat{c}_{g_2\sigma} + U\sum_{g}\hat{n}_{g\uparrow}\,\hat{n}_{g\downarrow}. \quad (1)$$

It takes into account the hopping integral $t_{g_1g_2}$between neighboring lattice sites and the integral U of Coulomb repulsion of the electrons in couples (that is, pairs of electron with opposite spin projections occupying the same lattice site).

Excited states with zero average electric charge of a crystal lattice site are considered $(\bar{q}_g = 0)$. In this case, three types of excitations are possible [3]:
1) homeopolar state, in which there are no couples and holes and fluctuations in the number of couples and electric charge are equal to zero; 2) a completely polar state at site g, when it is charged with equal probability positively (hole) or negatively (couple); 3) excited not completely polar state.

The excited state can propagate throughout the crystal, forming a homeopolarity wave, a polarity wave, and a wave with a changed ratio of polar and neutral states compared to the ground state. The corresponding quasiparticles can be called in case 1) homeopolarons, and in cases 2) and 3) – ionisons. Their effective masses are determined by the integrals $t_{g_1g_2}$ end U:

$$m^* = \frac{\hbar^2}{a^2\left(|t| \mp \frac{U}{4}\right)}, \quad (2)$$

the minus sign is for a homeopolaron, the plus sign is for a completely polar ionison.

In some cases, characteristic energy losses of fast electrons in thin metal and dielectric films have better agreement with the energies of elementary excitations in the polar model compared to plasmons. For example, for metals with narrow energy bands, for which the identification of characteristic loss lines with plasmons is not entirely obvious [4].

The considered quasiparticles can be excited not only from the outside (electrons, light, neutrons, etc.), but also virtually through various interactions inside a solid. Their discovery would mean the possibility of the existence of specifically solid-state collective excitations with an energy gap depending on non-gas parameters – integrals $t_{g_1g_2}$ end U.

Polar waves may be important for the theory of high conductivity states in low-dimensional systems [5].

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SOLID-STATE PLASMA MODEL OF ELECTRICAL BREAKDOWN OF POLYMER DIELECTRICS

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Currently, the field ionization of macromolecules in polymer dielectrics is considered as a possible cause determining the development of electrical breakdown in them [1]. In strong electric fields in polymers, charge carriers can occur in a local volume due to field ionization of macromolecules during the tunneling transition of an electron from the highest occupied orbital of a macromolecule (HOMO) to the lowest unoccupied orbital (LUMO) of a neighboring molecule. From this point of view, the field strength at which intense ionization of macromolecules begins ($\sim 10^9$ V/m) can be associated with the limiting (theoretical) electrical strength of polymers.

Finally, the ionization of macromolecules caused by the HOMO→LUMO transitions will lead to the accumulation of a certain equilibrium concentration of electrons and holes in the considered local region of the polymer, the value of which is determined by the balance between the rate of the ionization process and the outflow of charge carriers from this region. When macromolecules decay, new macroions and chemically active free radicals are formed, which enter into chemical reactions with neighboring molecules. As a result, chemical defects of macromolecules arise – new atomic groups with positive electron affinity that can serve as deep electron traps. Their appearance and accumulation in a strong electric field accelerates the appearance of macroins in the polymer, since it becomes possible to tunnel an electron from the level of the HOMO macromolecule to a deep trap (HOMO→TRAP transition). The probability of such transitions exceeds the probability of HOMO→LUMO transitions.

The accumulation of positive molecular ions and electrons in the local polymer region (both located in the LUMO zone and trapped in deep traps) can be considered as the formation of a solid-state non-ideal plasma, in which the Debye effect of shielding charges occurs, leading to a decrease in the ionization potential of neutral molecules [2].

The course of two interconnected self-accelerating processes, i.e. processes whose speeds increase over time, eventually leads to an explosive increase in the concentration of quasi-free charges in the polymer and, consequently, to a sharp increase in the current flowing through the polymer dielectric.

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HYDROGEN DIFFUSION ALONG THE BOUNDARIES OF TUNGSTEN GRAINS IN CONTACT WITH HYDROGEN

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Simulation of the diffusion of atomic hydrogen along grain boundaries was carried out using the method of classical molecular dynamics. To simulate interatomic interaction, the potential of an embedded atom is used. The LAMMPS package [1] was used. Grain boundary diffusion of hydrogen within the grain boundaries of metals can be accompanied by accelerated diffusion channels, the so-called short-circuited ones. But in addition to this, diffusion can also be hindered. It is known that there are traps for atoms within grain boundaries. Light atoms can accumulate in them and thus prevent further passage of the diffusion substance. It is interesting to look at this situation under various temperature conditions. The Arrhenius pattern of diffusion usually expected at moderate temperatures, that is, in the presence of point defects, may not be observed.

Another important consequence of increasing temperatures is a change in the structure of the boundary, which can also affect the Arrhenius dependence.

Diffusion in the presence of a free surface on the inner wall of the bubble is also considered.

MD modeling of grain boundary diffusion of hydrogen within grain boundaries was. The list of references follows the report text.

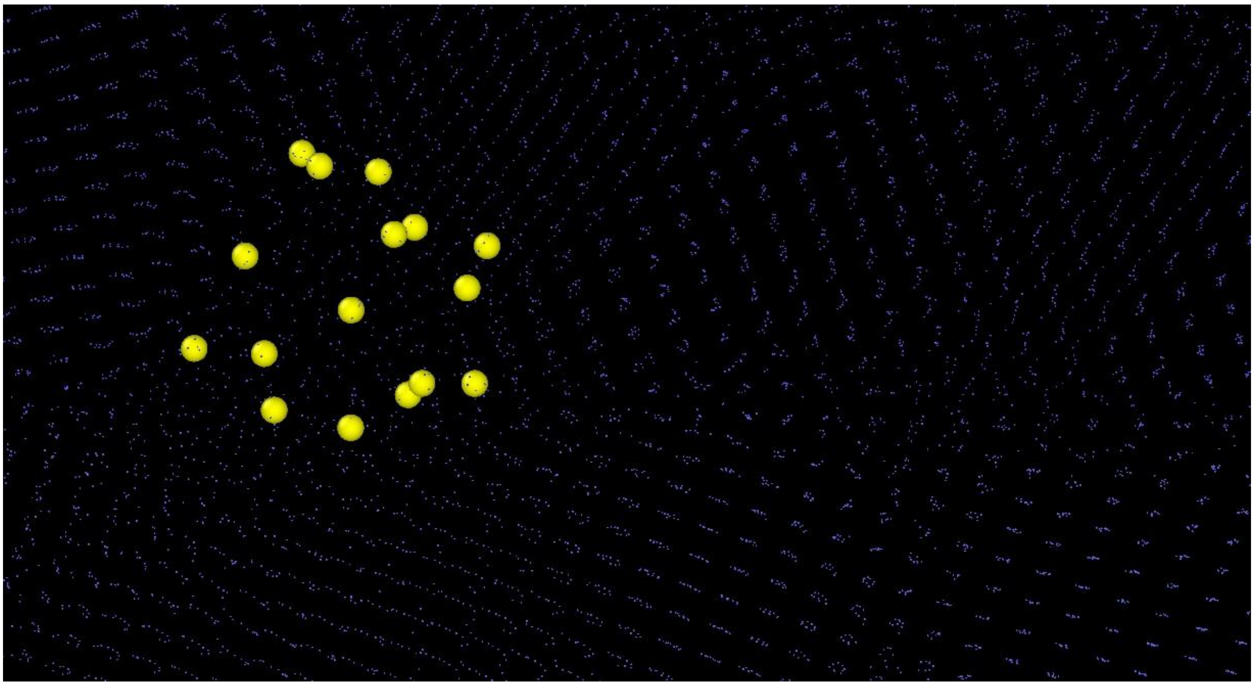

Fig. 1. Hydrogen distorts the symmetrical grain boundary structure. For convenience, the hydrogen atoms are expanded.

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The work was carried out using the Uran supercomputer at IMM UB RAS

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EXPERIMENTAL INVESTIGATION OF AN ANOMALOUS ABSORPTION OF THE ORDINARY WAVE IN THE PULSE DISCHARGE PLASMA FILAMENT

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A large number of various anomalous effects (anomalous backscattering, anomalously accelerated ions) observed in experiments on electron-cyclotron resonant heating (ECRH) [1-2] are not explained within the conventional linear theory. The theoretical model proposed in [3] explains the anomalous backscattering as a result of the two upper-hybrid (UH) plasmon parametric decay (TUHPD) instability possessing very low threshold due to trapping of excited plasmons in the vicinity of the density maximum. Model experiments [4] of the TUHPD instability shown that the anomalous absorption can reach 80%. A similar situation with the excitation of low-threshold instabilities may also appear for waves with ordinary polarization. In present work anomalous absorption of the ordinary wave in the plasma filament is under investigation.

A plasma filament is created by pulse discharge in a quartz tube (inner diameter 22 mm) filled with argon at a pressure of about 4 Pa and placed in magnetic field of up to 45 mT. The maximal average plasma density in the filament is slightly exceeded 2×10^{10}cm^{-3} and electron temperature is about 1 eV. The tube with plasma passes through a waveguide with a cross section of 72×34 mm^2 perpendicular to wide walls. Pulses of microwave power (up to 200 W) at a frequency of 2.35 GHz significantly exceeded the ECR and UH frequencies are supplied to the plasma by this waveguide. Thus, there is an ordinary polarized wave in plasma. The presence effect of ananomalous absorption of incident power in a plasma depending on the magnetic field, plasma density and microwave power is demonstrated. This effect has a threshold nature and appears at incident power level of about 30 W. The absorption efficiency of pump power is about 30-35%. Estimations of electron density and temperature temporal evolutions were performed. At maximal absorption, the electron energy did not exceed 3 eV. As the magnetic field increases, the occurrence moment of maximal absorption shifts towards the beginning of microwave pulse.

The obtained effect can be explained by the excitation of a parametric decay instability.

Work is supported by SCST-St.-Petersburg grant №F24StP-005 (Ф24СПбГ-005).

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PLASMA AND GAS-DYNAMIC PROCESSES IN A NANOSECOND DISCHARGE IN AIR AT ATMOSPHERIC PRESSURE IN THE GAP WITH THE "PIN-TO PLATE" GEOMETRY

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In work, a spark discharge in the gap between the tip (cathode) and a plane 1.5 mm long in air at atmospheric pressure was studied using a two-frame version of the shadow photography technique. The design of the experimental stand and research methods are described in detail in our previous works [1]. The electrode system had a “point-plane” geometry. An axisymmetric stainless steel electrode with a length of 19 mm, a diameter of 14 mm, an apex angle of 36° and a radius of curvature of 0.15 mm was used as a tip. An electrode made of an aluminum alloy with a working part similar in shape to a spherical segment with a diameter of 4.5 cm and a thickness of 1.5 cm was used as a flat electrode. The interelectrode gap was 1.5 mm. The working gas is air under normal conditions. Voltage pulses of negative polarity with an amplitude of 25 kV and a rise time of about 7 ns at the level of 0.1–0.9 were applied to the discharge gap.

From the discharge shadowgrams (Fig. 1), the time dependences of the expansion rate of the spark channel and the shock wave were determined. The initial phase of growth in the expansion rate of the spark channel and the shock wave has been established, the duration of which is about 5 ns. After reaching a maximum value of ~5 km/s, the expansion rate tends to decrease. Near the surface of the tip electrode, in the time interval from 10 to 50 ns, bright extended regions were detected extending from the cathode surface, which can be identified with cathode shock waves.

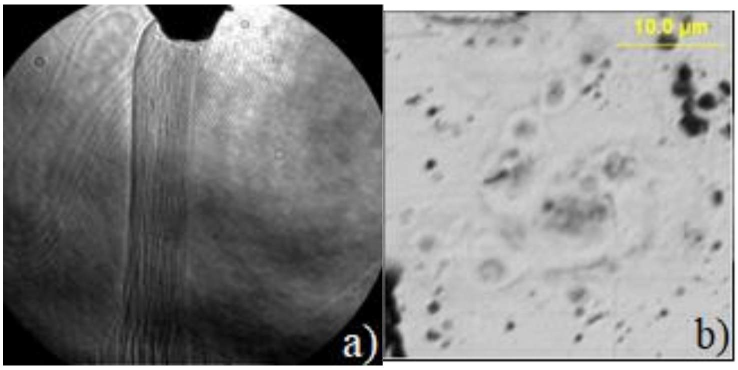

Fig. 1. A characteristic shadowgram of the discharge at a time instant of 20 ns relative to the breakdown (a) and a fragment of the channel autograph on the anode (b)

To study the effect of a spark discharge on the surface of the electrode, typos left by the discharge on the surface of a flat electrode (anode) were studied. Electrodes (anode) made of iron, aluminum and copper were used. The surface morphology was studied on a scanning electron microscope PSEM eXpress from Aspex with an EDX analyzer “Omega Max”, which allows for express analysis of the morphology and elemental composition of the surface, as well as an optical microscope - a modular inverted microscope “Olympus GX53”. In particular, Figure 1b shows electron microscopic images of a fragment of the autograph of the discharge channel on a flat anode (material: copper)

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NUMERICAL MODELING OF A CAPACITIVE RADIOFREQUENCY DISCHARGE WITH LARGE ELECTRODES

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High-frequency capacitive (HF) low-pressure discharges are widely used for dry etching of thin films and plasma chemical deposition [1-3]. An electrodynamic model of a symmetric discharge was constructed in [2]. This work is devoteв to 3D simulation of this discharges using the Comsol Multiphysics software. The shape of the vacuum chamber is described in [2].

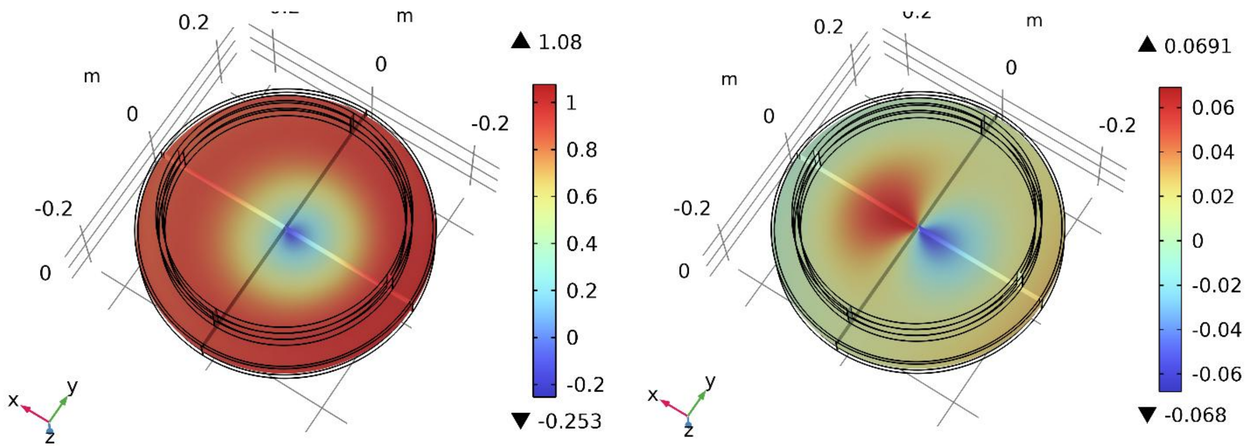

Fig. 1. Spatial distribution of the real (left figure) and imaginary (right one) components of the azimuthal magnetic field in the discharge. The field frequency is 137 MHz, the electron density is 10^9 cm^{-3}. The dimensions of the discharge chamber in the figure are in m. The ratio of the frequency of collisions of electrons to the frequency of the field one is 0.1.

Plasma electrodynamics was described in the framework of a cold plasma model, and the density distribution of charged particles was described using a drift-dissipative model. The thickness of sheath was determined using a phenomenological ratio. Calculations have shown that the occurrence of azimuthal plasma inhomogeneity is accompanied by the excitation of an azimuthal surface wave propagating along the plasma boundary and the spatial charge layer. The amplitude and phase of the wave depended on the plasma density, that is, on the ratio of the field frequency and the resonance frequency for this wave in the discharge chamber. Under certain conditions, the phase of the excited wave corresponded to an increase in the initial density disturbance, i.e. the development of ionization-field instability.

A comparison of the calculations with the "global" discharge model shows their qualitative agreement.

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EXPLOSIVE ELECTRON EMISSION IN HIGH-CURRENT FIELD CATHODES BASED ON DIAMOND GRAPHITE FILM STRUCTURES

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A low-temperature technology for microwave plasma-chemical synthesis (MPCVD) of diamond-graphite film structures (Fig. 1) has been developed with a long-term service life and a current density of blade field electron sources based on them above 1000 A/cm2 [1,2]. At electric field strength of about 35 V/μm, cathode glow is observed at the end of the diamond-graphite film (Fig. 2). At a field current of 5.8 mA, its spontaneous increase was recorded at a constant voltage of the power source. Over time, the growth rate increased. In 5-7 minutes the current reached a value of about 10 mA. At the same time, the residual pressure in the vacuum measuring device increased from $3{\cdot}10^{-5}$ to $7{\cdot}10^{-5}$ Pa. The maximum current densities at an anode field strength of 170 V/μm were 2300 A/cm^2. The explosive emission current density during end-to-end current collection with a double-sided diamond-graphite coating on a polycor substrate exceeded $3.5{\cdot}10^5$ A/cm^2. The maximum breakdown current was 2.1A.

A study of the elemental composition of the anode surface after a plasma discharge showed the presence of a carbon phase on it. When the polarity of the voltage in the circuit changed, a current was recorded, the magnitude of which was commensurate with the pre-breakdown current of the cathode. Subsequent direct switching of the diode structure showed an improvement in the emissivity of the cathode. The positive effect was manifested in a decrease in the field emission threshold and an increase in the slope of the current-voltage characteristic. The discovered effect can be used to restore the emissivity of field cathodes during long-term operation as part of high-power EECs [2].

The achieved field current densities are more than an order of magnitude higher than the best world achievements of electron sources with ultra-high current densities obtained by the world's leading laboratories based on carbon nanotubes and hybrid carbon film structures, which, according to various sources, range from 20 to 40 A/cm^2. Obtaining field sources of electrons with a high current density opens up the possibility of creating a new electronic component base for power radiation-resistant vacuum-plasma microelectronics, energy-efficient white light sources, flat cathodoluminescent screens and displays, high-power EVP microwave and sub-terahertz frequency ranges with microsecond readiness time for satellite communication systems, radar, electronic countermeasures, etc.

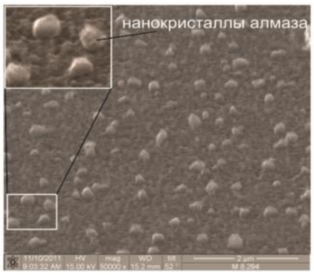

Figure 1. SEM image of a composite diamond-graphite film structure.

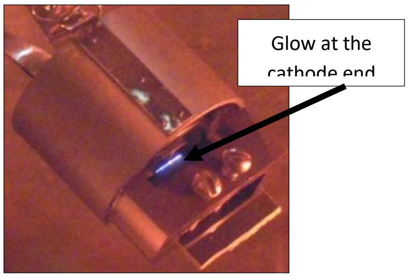

Figure 2. Glow from the end of a diamond-graphite cathode at a field current density of 1450 A/cm^2.

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UNEXPECTED EFFECT OF RARE-EARTH ORGANOMETALLIC COMPOUNDS ON THE DEVELOPMENT OF PLASMA CHEMICAL PROCESSES IN THE MIXTURES OF METAL AND DIELECTRIC POWDERS

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In the last decade we have been developed a new approach to preparation of ceramic materials utilizing a microwave discharge in the mixtures of metal and dielectric powders initiated with a short pulse from high-power gyrotron. Recently we have applied the approach for preparation of aluminum oxynitrides doped with rare-earth metal ions, which are promising phosphors showing emission in a broad spectral range. The initial mixtures included aluminum and aluminum oxide powders and melamine was added as a source of nitrogen to promote reductive nitridation and formation of oxynitride phases. Rare-earth metals (REM; Eu, Ce, Tb) were added in the forms of both oxides and organometallic compounds, e.g. acetylacetonates. Microwave breakdown in the mixtures led to the scattering of particles into the free volume of the specially designed reactor and development of chain processes in the plasma-gas media [1,2].

Although the content of REM was only up to 3 at. % vs. Al, we observed a dramatic difference in the duration of plasma chemical processes and dynamic of particles scattering depending on the initial form of REM. For example, plasma chemical process was found to last an order of magnitude longer when Ce(acac)$_3$ was added compared to CeO_2 (fig. 1). In fact, the process is so intense with the addition of Ce(acac)$_3$ that counting of number of particles and plotting of their tracks are possible no more with the regular technique developed for other mixtures [3]. One can assume that is a result of turning the process into autothermic mode due to an additional heat released when REM is incorporated into the oxide or oxynitride matrices.

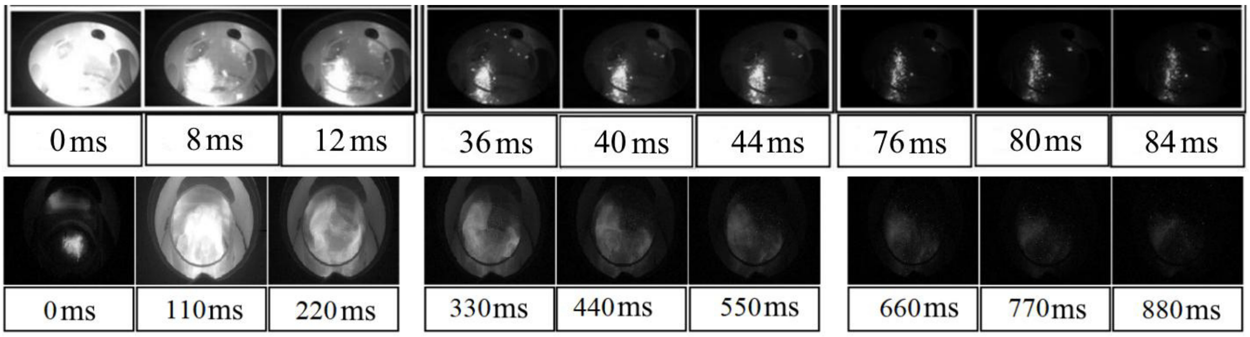

Fig. 1. Clouds of luminous particles for the mixtures of Al/Al_2O_3/melamine + 3% CeO_2 (top) or Ce(acac)$_2$ (bottom)

This work was carried out with the support of the grant of Russian Science Foundation № 23-79-01078.

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DEPOSITION OF SILVER NANOPARTICLES ON DIELECTRIC SURFACES IN A PLASMA-CHEMICAL PROCESS INITIATED BY GYROTRON RADIATION

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Nanostructured silver coatings are perspective for a wide range of applications. Well-known antimicrobial activity of silver makes it especially attractive for development of bio-medical materials. Among its perspective industrial applications are silver-based catalysts. In this work we suggest a procedure of nanosized Ag particles deposition on a dielectric surfaces or micrometer-sized particles in a plasma-chemical process. We illustrate it by deposition of silver nanoparticles on aluminum oxide microparticles in a plasma-chemical process initiated by gyrotron in a mixture of precursor powders. Synthesis was carried out on a specialized stand using a powerful pulsed gyrotron. The description of the experiment, the conditions for the development of a microwave discharge, and the evolution of process parameters in the reactor are described in detail in. [1-4]. In this work, materials were obtained from mixtures of silver and aluminum oxide precursor powders. The size of the synthetized nanostructured silver could be controlled through the synthesis conditions and varied from tens of nanometers to micrometers as shown in Figure 1.

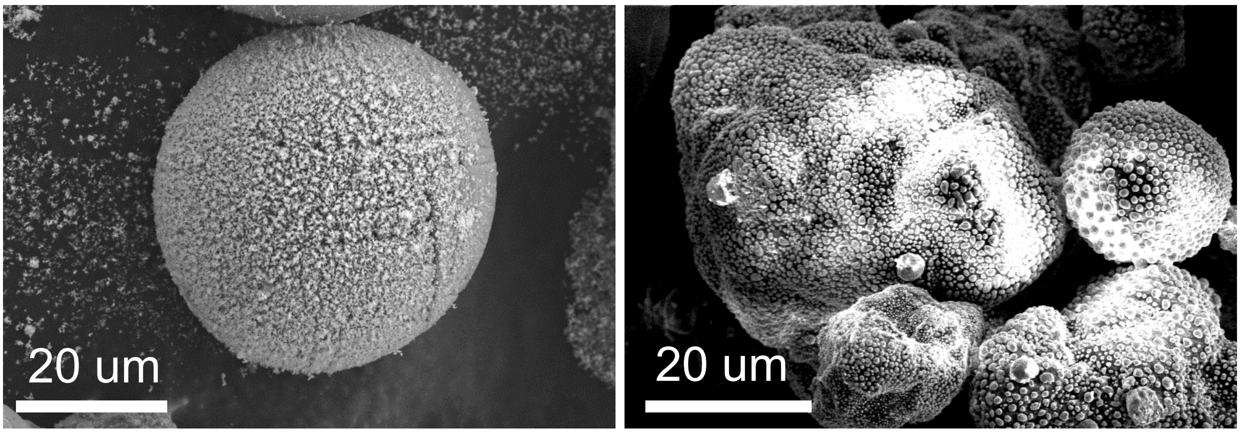

Fig. 1. Scanning electron microscopy images of aluminum oxide particles covered by nanostructured silver in different experimental conditions.

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PLASMA CHEMICAL SYNTHESIS OF OXYNITRIDE CERAMICS DOPED WITH TB^{3+} IONS USING A MICROWAVE DISCHARGE

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For the last decade we have been developed a new approach for plasma chemical synthesis of micro- and nanodispersed materials of different types. The approach is based on the use of microwave discharge, which occurs in the mixtures of metal and dielectric powders when they treated with short (2-8 ms) and high-power (up to 350 kW) pulses of microwave irradiation (75 GHz). The experimental setup consists of the high-power gyrotron, plasma-chemical reactor and diagnostic complex, which includes the optical emission spectrometers and high-speed camera as described in [1] (fig. 1a). Recently we have applied the developed approach to synthesis of phosphor materials containing ions of rare-earth metals.

The mixtures of metal aluminum, aluminum oxide and terbium oxalate with an addition melamine were used as starting mixtures. Melamine was added as a source of nitrogen to facilitate formation of aluminum oxynitride, which is considered to be one of the most promising matrices for phosphors. The Al:Al_2O_3:melamine molar ratios were set to 1:2:1, 2:2:1 and 4:2:1. The content of terbium was 0.1, 0.5, 1.0 and 2.0 at. % vs. aluminum. The breakdown did not observed even for 6 ms and 400 kW pulses, so stainless steel sponge was set up to initiate a non-self-sustaining breakdown (fig. 1a). The product material was collected from the wall of quartz tube and characterized with XRD analysis and pulsed cathodoluminescence (PCL) spectroscopy.

XRD data confirm formation of aluminum oxynitride (fig. 1a), which is consistent with the results obtained earlier [2]. The highest content of AlON ranges from 20 to 30 v/v %. PCL spectra show typical pattern for Tb^{3+} ions in the AlON matrices (fig 1b) [3].

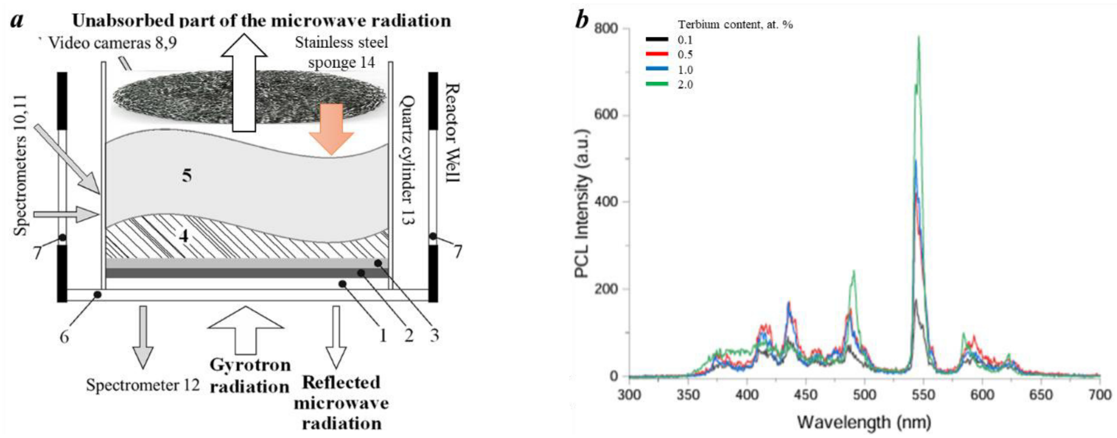

Fig. 1. (a) Plasma chemical reactor; (b) PCL spectra of the samples with Al:Al_2O_3:melamine ratio 1:2:1.

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EXCITONIC NATURE OF PLASMA PHASE TRANSITION KINETICS IN DENSE MOLECULAR FLUIDS

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The transition of warm dense fluid hydrogen from an insulator to a conducting state at high pressures (20-400 GPa) and temperatures (500-5000 K) has been extensively studied, but a consistent theoretical description remains elusive.

This work applies the restricted open-shell Kohn-Sham (ROKS) method within density functional theory (DFT) to model the formation and dissociation of localized excitons in dense hydrogen during thermal excitation to the first singlet excited state [1-3]. Analysis of the exciton dynamics using the Wannier localization method reveals that a key mechanism driving the phase transition is the dissociation of electron-hole pairs, irreversibly transferring energy from the ions to electronic excitations. The model quantitatively explains several key experimental observations, including the large latent heat of transition, the isotope effect, and differences in the onset of optical absorption versus reflectivity. Calculated threshold temperatures and pressures for exciton dissociation at different densities agree well with experimental data for the insulator-metal transition. The exciton dissociation mechanism helps resolve discrepancies between prior experimental and theoretical studies of this important phase transition in dense hydrogen. In this talk, we will also analyze this exciton mechanism in the dense liquid nitrogen and discuss the differences between these two dense molecular liquids.

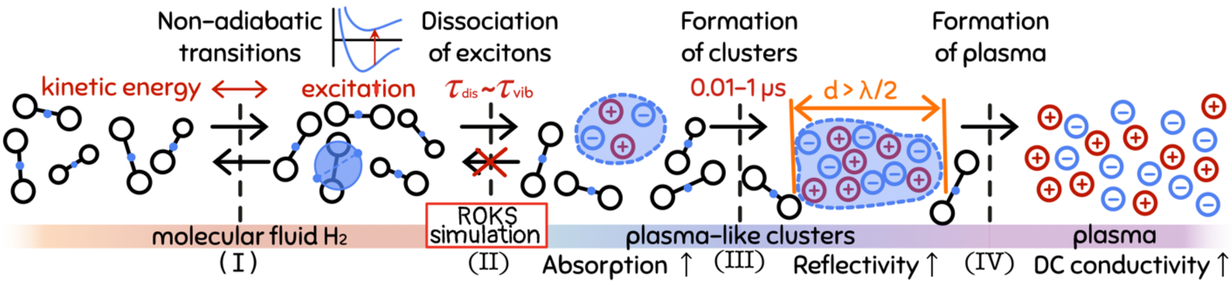

Fig. 1. Proposed transition mechanism.

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OBLIQUE MAGNETOSOUND SOLITONS

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Properties of nonlinear low-frequency waves in magnetized plasmas were studied for many decades (for the review see, e.g. [1]). It was established that there exist wave patterns in the form of solitons propagating at non-zero angle to the guiding magnetic field. On the other hand, separate treatment shows that there are no solitons propagating strictly along the magnetic field. Instead, there appear the envelope solitons describing modulation of nonlinear monochromatic waves.

To resolve the controversy, we derive a set of nonlinear equations for the slowly varying magnetic field. Assuming that the perturbation of the magnetic field is of the order of $\sqrt{\varepsilon}$, where $\varepsilon \ll 1$, and making use of the multiscale expansion ($z,t \sim \varepsilon,\ x,y \sim \varepsilon^{3/2}$) we arrive at

$$b_{\alpha,t} = -\left[b_\alpha(\mathbf{b}^2 + \mu b_z) - \mathrm{T}_{\alpha\beta} b_{\beta,z}\right]_{,z} + \frac{1}{2}\left[\mu \mathbf{b}^2 + b_z\right]_{,\alpha} \qquad \alpha = x, y$$
$$b_{z,z} + b_{x,x} + b_{y,y} = 0 \tag{1}$$

Here b_i are the components of the magnetic field variations and the guiding magnetic field is aligned along the z axis. Eq. (1) is written in appropriate dimensionless variables in the reference frame moving at Alfven velocity, V_A, and $\mu = \sqrt{1 - V_A^2 / c^2}$.

With the help of Eqs. (1) we address two problems. First, we investigate solutions in the form of plane nonlinear wave propagating oblique to the z axis, $b_i = b_i(z\cos\phi - x\sin\phi - ut)$. It is shown that solitary wave solutions to Eq. (1) decaying at $z \to \pm\infty$ exist. The shape of the solutions depends on the phase velocity, but the shape is independent of the propagation angle, ϕ. However, with decreasing ϕ the amplitude of the solution also decreases and solitary-wave solutions disappear at $\phi = 0$.

Second, we show that there exist solutions to Eqs. (1) in the form of three-dimensional self-localized pattern propagating at super Alfven velocity. We develop a numeric procedure based upon the minimization of the action functional for Eqs. (1). It was found that with same phase velocity several local minima of the action functional may exist which are associated with the ground and the excited states of the solitary wave (Fig. 1).

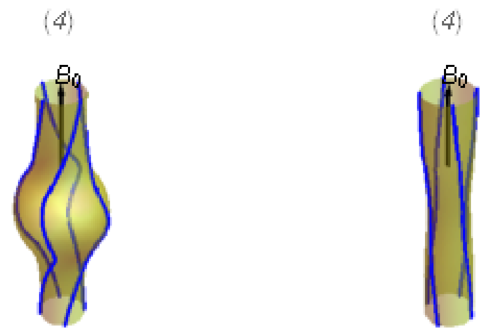

Fig. 1. Magnetic field lines for the ground (left) and the exited (right) states of a solitary wave

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THE INFLUENCE OF EDGE LOCALIZED MODES ON THE SPECTRUM OF ELECTROMAGNETIC RADIATION SCATTERED BY PLASMA FLUCTUATIONS ON THE GLOBUS-M2 TOKAMAK

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The main mode of operation of tokamaks is the H-mode [1], characterized by a large pressure gradient at the periphery, which leads to the appearance of edge localized modes (ELMs) [2]. They lead to pulsed emissions of particles and energy from the plasma, which can damage the device. Therefore, ELMs research is an important task. One of the methods that allows us to study the processes inside the confinement region, where the origin and development of ELMs takes place, is the probing of plasma with electromagnetic waves.

This report presents the results of using Doppler backscattering (DBS) diagnostics for studying edge localized modes on the spherical tokamak Globus-M2. This diagnostic is based on the study of electromagnetic radiation backscattered off fluctuations of plasma density [3].

It has been observed that the spectrum of scattered radiation is strongly shifted during ELM bursts. The maximum of the spectrum is shifted to the region of higher frequencies. Such a shift corresponds to an increase in the plasma rotation velocity and is observed simultaneously at many radii – from the separatrix to half of the minor radius. An averaged profile of the plasma rotation velocity between and during the ELM bursts was constructed from the spectra of signals corresponding to different probing frequencies. It is shown that the rotation velocity increases by 1.5-2 times at all studied radii.

In addition, narrow spectral components that periodically occur during ELMs were detected in the backscattered radiation spectrum for the edge plasma region. They correspond to the appearance of quasi–coherent oscillations in the plasma - filaments. They are a manifestation of the developed peeling-ballooning instability. It turned out that the values of the Doppler shift of the signal, and hence the rotation velocities corresponding to the filaments, differ significantly. To study this phenomenon, it was decided to use full-wave modeling of the scattering process of electromagnetic radiation on filaments in the geometry of the Globus-M2 tokamak [4]. It is shown that 2 cases of scattering of electromagnetic radiation off density fluctuations are possible – linear and nonlinear. Linear scattering corresponds to small density perturbations and leads to a small Doppler shift of the signal. Density fluctuations of a large amplitude lead to nonlinear scattering and an overestimated value of the rotation velocity of the filaments. Both types of scattering were observed in experiments.

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GENERATION OF A HIGH-ENERGY SPECTRUM OF IONS AT THE FINAL STAGE OF THE Z-PINCH COMPRESSION

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The mechanism of generation of high-energy ions in Z-pinches (including non-cylindrical configurations, such as a plasma focus) does not yet have an unambiguous explanation within the framework of any one physical mechanism that would take into account the features of the spectrum of fast ions [1]. Previously, to simulate the spectrum of fast ions in Z-pinches, we developed a kinetic approach based on the Fokker–Planck equation [2]. In general, this approach showed effectiveness, with the exception of the very last moments of compression of the neck of the pinch. A multi-group kinetic model was also developed [3], which in a certain sense is equivalent to the above approach, but is simpler for the last moments of compression (in collisionless regime). The betatron mechanism was used as the basis for modeling acceleration during the quasi-adiabatic compression. Due to the peculiarity of betatron acceleration, it practically did not change the initial Maxwellian character of the ion distribution. The integral spectrum of ions in this case corresponded to the predictions of the hydrodynamic model (self-similar solution), but only up to relatively moderate energies (hundreds of keV) [4]. Correspondence of the number of ions with energies of the order of 1 MeV with experimental data within the framework of such a model requires an unreasonably large increase in the plasma density and temperature. As is known from MHD calculations, the increase in density is limited.

Apparently, significant acceleration of ions occurs at the final stage of development of neck instability, immediately before its destruction. Considering that the final stage proceeds very quickly (~ 1 ns), it can be assumed that a strong electric field associated with charge separation arises within a short time. For example, a small group of fast electrons can leave the neck region. Estimates show that with such acceleration, ions can get energies of several tens of MeV and higher. Instability leads to intense turbulence and mixing of the magnetic field and plasma, and significant electric fields can be induced. It is estimated that such fields can accelerate particles to energies of ~1 MeV. In addition, estimates have shown that the anisotropy of the ion spectrum (observed in experiments on the spatial distribution of the neutron yield) can be associated with such induced fields. Thus, there may be several reasons for the strong acceleration at the final stage. In this work we do not attempt to develop a complete model of these processes. We consider ion kinetics within the framework of an approximate compression scenario. At the first stage, a quasi-adiabatic compression mode of the neck is realized. Then it is replaced by a non-adiabatic regime, in which the acceleration value is set, and the change in the neck radius is not taken into account (accordingly, the density does not increase). Calculations performed within the multi-group framework showed a connection between the features of the ion spectrum at high energies and the magnitude of acceleration at the non-adiabatic stage. In the future, the acceleration value can be used to verify models of the non-adiabatic stage. Note that the developed model includes effect of collisions.

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INFLUENCE OF NUCLEAR QUANTUM EFFECTS ON THE EQUATION OF STATE OF FLUID HYDROGEN AT HIGH PRESSURES

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Path Integral Molecular Dynamics (PIMD) within the framework of the Finite Temperature Density Functional Theory (FTDFT) is applied for the calculation of the equation of state including metastable states of fluid hydrogen. It should be noted that hydrogen atom is “light” particle with de Broglie wavelength close to 1°Å at temperature 1000 K. Therefore, it is necessary to consider quantum properties of this atom. The PIMD approach allows to take into account the influence of Nuclear Quantum Effects (NQE) to the thermodynamic and structural properties of fluid hydrogen. The PIMD calculations are performed in the i-PI [1] and PIMD [2, 3] software packages. The FTDFT calculations of the electronic structure and forces acting on hydrogen atoms are performed in the VASP package [4, 5]. The authors of the work carry out verification for hydrogen fluid, available from the work of Morales and colleagues [6], at a density of 0.88 g/cm^3 and a temperature of 1000 K. Metastable states on the isotherm are calculated with using of the method suggested in [7]. Both molecular and non-molecular metastable branches are obtained along the 700 and 1000 K isotherms. Proton-proton pair correlation functions (PCF) and conductivity are calculated to diagnose metastable states. Taking zero-point oscillations into account within the PIMD leads to a noticeable decrease in the phase equilibrium pressure from 180 to 137 GPa at temperature 1000 K. At the same time, the value of the region of metastable states of molecular fluid hydrogen also decreases from ΔP=32 GPa to 15 GPa. For 1000 K isotherm we reached the spinodal border which corresponds to the smoothing of the dependence pressure on density (where the derivative $(\partial P/\partial\rho) = 0$).

Comparison of the 700 K isotherms (calculated within the framework of PIMD) and 1000 K (calculated using MD) gives close values of both the region of metastable states of the molecular hydrogen fluid and the phase equilibrium pressure. Therefore, on the one hand quantitively the influence of nuclear quantum effects is equivalent to the down shift of the temperature by the value of about 300 K. On the other hand, qualitatively the results are similar to those obtained without considering NQE.

The resulting isotherms have inclined shape with a strong overlap of equilibrium and metastable branches and a rather small difference in specific volumes between the branches. The detected overlap corresponds to the prediction for the plasma phase transition. A small jump in the specific volume during a phase transition does not allow the resolution of metastable states at higher temperatures.

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ELECTRON-ION RELAXATION IN NONIDEAL PLASMAS: MOLECULAR DYNAMICS SIMULATIONS

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Shock waves, the interaction of laser pulses, and particle beams of moderate intensities with condensed targets lead to the appearance of nonideal plasmas where temperatures of elections and ions can differ significantly at the initial time moment. Therefore, the electron-ion relaxation rate becomes an important parameter for theoretical and computational models of such plasmas. The existing relaxation rate theories typically require pre-knowledge of the electron-ion correlation functions and effective interaction potentials, which makes non-equilibrium classical and quantum molecular dynamics (MD) simulations a crucial stage in studying this phenomenon.

We begin by revisiting the classical MD simulations of the system of equally charged particles with different masses on a neutralizing background. We accurately simulate this simple ab-initio (parameterless) system with controlled precision in terms of the number of particles, mass ratio, and energy convergence. The predictions for the equally charged system are compared to the previous simulations and theories, which are reproduced with higher accuracy.

We also perform a series of high-accuracy classical MD simulations of the system of oppositely charged particles with the corrected Kelbg potential based on the quantum statistical approach. The differences and similarities between the same-charge and opposite-charge systems are analyzed. The obtained dependence on the relaxation rate normalized by the period of electron plasma oscillations on the plasma nonideality parameter is shown in Fig. 1, compared with the results by other authors.

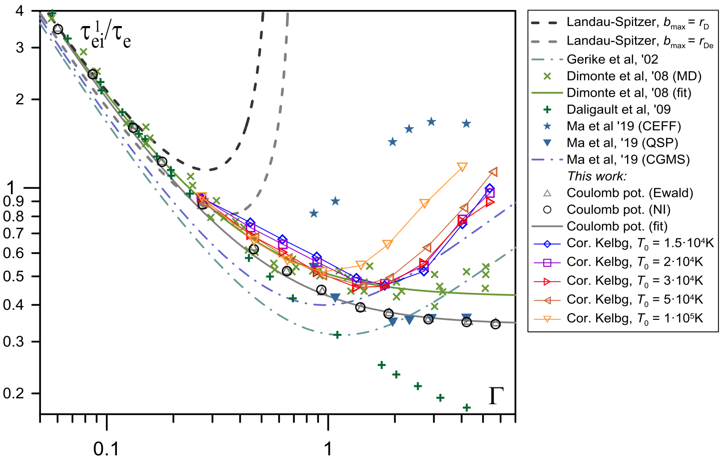

Fig. 1. Electron-ion temperature relaxation time depending on the plasma nonideality: circles and black triangles are the results for like charges, rhombus, squares and colored triangles correspond to the simulations with the corrected Kelbg potential; other results are taken from literature (see [2]).

Although the method of classical MD is a powerful tool for studying non-equilibrium nonideal plasmas, it relies on the pseudopotential interaction model and lacks pure quantum effects such as exchange-correlation energy. One of the goals of this work is to support the forthcoming studies of the electron-ion relaxation rate by quantum simulations with the help of the recently developed WPMD-DFT approach [3].

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ON THE PHYSICAL NATURE OF SUBHARMONICS OF THE ELECTRON EMISSION FROM ULTRACOLD PLASMAS

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One of the interesting phenomena in ultracold plasmas are multiple subharmonics of the electron emission caused by the microwave (MW) irradiation (left panel in Fig. 1). Although this effect was found quite a long time ago [1], its theoretical interpretation remains poorly understood. The most popular point of view is that the above-mentioned subharmonics are similar to the so-called Tonks–Dattner resonances [2, 3], i.e., actually the standing plasma waves. Unfortunately, such an interpretation encounters a number of serious problems, for example, a lack of the adequate boundary conditions in the freely-expanding plasma cloud. Besides, according to the experimental data, the subharmonics of electron emission become more pronounced with decreasing electron temperature, while just the opposite behavior should be expected in the case of Tonks–Dattner resonances.

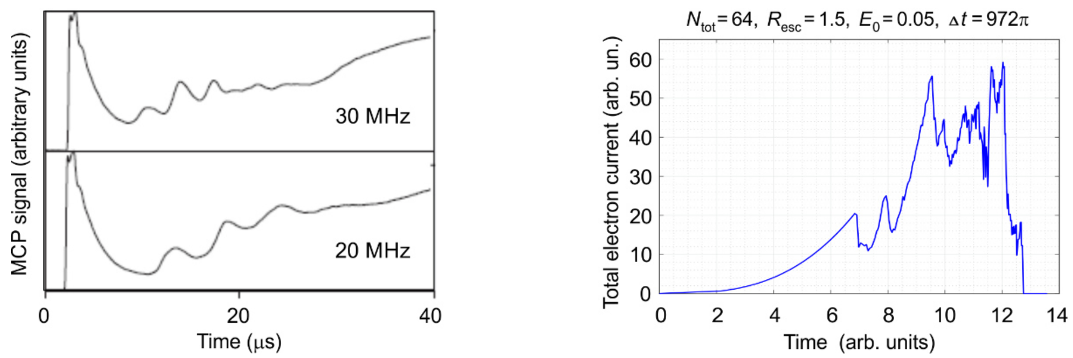

Fig. 1. Experimental profiles of the electron emission [1] (left panel) and the results of their theoretical simulation under assumption of MW ionization of the “secondary” Rydberg atoms (right panel).

It is the aim of the present work to show that a promising alternative interpretation can be based on the MW ionization of the “secondary” Rydberg atoms, formed due to recombination in the expanding plasma cloud. In general, the total current of electron emission I can be written as

$$I(t) \propto \eta(n^* \omega^{1/3})\, N_e^{\,3}\, T_e^{-9/2} R^3 \propto \eta(n^*(t))\, t^3,$$

where η is the efficiency of multiphoton MW ionization (i.e., percentage of the ionized atoms), N_e is the concentration of electrons and ions, T_e is the electron temperature, R is the radius of the plasma cloud, ω is the frequency of the external electromagnetic wave, and $n^*(t) \propto t$ is the principal quantum number of the Rydberg state into which the recombination predominantly occurs. As follows from our numerical simulations, the efficiency of ionization η exhibits a number of sharp peaks, resulting in the quasi-periodic modulation of electrons escaping from the expanding plasma cloud (right panel in Fig. 1).

As distinct from the Tonks–Dattner resonances, the proposed mechanism is evidently irrelevant to the boundary conditions. Besides, it gives a correct dependence on the initial plasma temperature.

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FORMATION OF EXTENDED TUBULAR PLASMA IN ARGON AT LOW PRESSURE AND IN A WEAK LONGITUDINAL MAGNETIC FIELD

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The creating extended tubular plasma is of great interest for development of plasma masers [1]. The results of experimental studies on the formation and subsequent evolution of extended (l = 300 mm) and thin-walled (Δr ≈ 10 mm) tubular (2r ≈ 110 mm) plasma in a weak longitudinal magnetic field (*B* = 175 Gs) without the use of a thermionic cathode are presented (Figs 1 and 2a). The cylindrical chamber in which the tubular plasma was formed was pumped with high purity argon (99.998%) at an average velocity of about 1 m/s at a pressure of $P = 10^{-3}$-10^{-2} Torr. Two methods of creating seed electrons initiating the development of ionization avalanches were used. A difference inherent to these methods has been established in the dynamics of breakdown, completing in the formation of a tubular discharge. In the first of them, a pulsed discharge preceding the high voltage supply of the main discharge created gas preionization in a small area around the sectioned cathodes. In the second method, seed electrons were created in the entire working area of the discharge chamber by an RF discharge with a frequency of 85 kHz and duration of about one second. High-speed shooting with a 4-frame ICCD camera allowed us to establish the dynamics of tubular discharge formation at all its stages. Measurements of the longitudinal and radial discharge current were carried out. The results obtained showed the possibility of spatial isolation of an extended tubular plasma from the close located metal wall of the discharge chamber by using a weak longitudinal magnetic field (B ≈ 0.02 T) (Fig.2b).

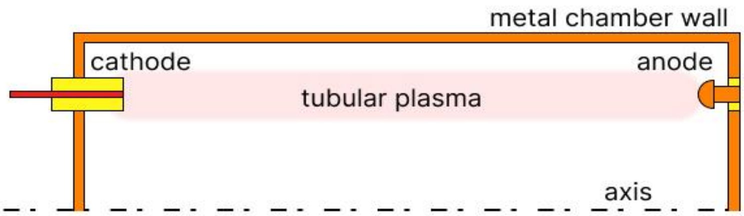
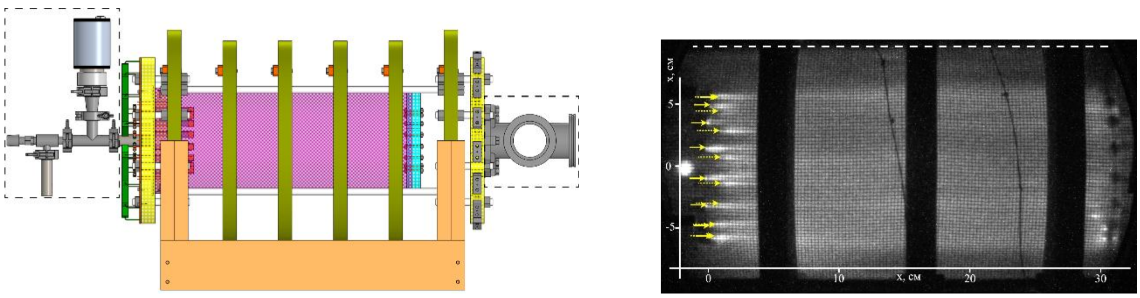


Fig. 1. The cross-section sketch of a discharge chamber with long tubular plasma



a) b)

Fig. 2. a) The side view of the discharge chamber placed into 6 Helmholtz coils; b) the image (side view) of long tubular plasma in a weak longitudinal magnetic field (three black vertical strips are the Helmholtz coils

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MICROWAVE METHOD FOR MEASURING PLASMA CONCENTRATION IN A TUBULAR PLASMA SOURCE FOR A PLASMA MASER

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A plasma maser is a powerful source of microwave operating on the basis of the Cherenkov interaction of a relativistic electron beam with slow waves in plasma. The presence of plasma as a slowing structure makes it possible to obtain a very wide spectrum of maser radiation and the possibility of adjusting the average frequency of radiation by changing the plasma concentration. Therefore, knowledge of plasma parameters is important for understanding the processes occurring in plasma masers and improving their operation. Unfortunately, traditional methods of plasma diagnostics - probe measurements, optical interferometry, microwave diagnostics, do not work in the presence of a relativistic electron beam, intense light from an explosive emission cathode and powerful microwave radiation in the system. Therefore, there are two ways left - either an indirect estimation of plasma concentration by comparing the emission spectra of a plasma maser with numerical models, or plasma parameters measurement by traditional methods in the absence of a relativistic electron beam and related interfering factors. This work follows the second path and is a continuation of the work [1].

This work presents the results of microwave measurements of the concentration of tubular plasma in the source used in plasma masers [2,3]. It is shown that at the moment of the plasma maser switching on the plasma concentration is $(3\pm0.3)\times10^{12}$ cm^{-3} for a discharge current of 5 A, $(5.5\pm0.6)\times10^{12}$ cm^{-3} for a discharge current of 9 A and $(9.5\pm1)\times10^{12}$ cm^{-3} for a discharge current of 20 A. In addition, it grows approximately in proportion to the growth of the discharge current, which makes it possible to estimate the plasma concentration by the value of the discharge current measured during the experiment. A comparison with previously performed probe measurements, as well as numerical calculations of the plasma maser performed using the KARAT code, showed a good correspondence (error less than 15%) of the results of microwave measurements with numerical calculations. Probe measurements give a significantly greater deviation from the results of microwave measurements due to the presence of a strong magnetic field in the plasma source, which is not taken into account in the standard Langmuir theory.

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NUMERICAL SIMULATION: HIGH CURRENT IN A PLASMA RELATIVISTIC GENERATOR WITH INVERSE GEOMETRY

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In relativistic microwave electronics, there are problems of using high currents of relativistic electron beams (REB) at a given electron energy. According to the analytical theory [1,2], a plasma relativistic microwave generator (PRG) can operate effectively at currents not exceeding 0.4-0.5 of the limiting vacuum current. In [3], the results of experimental studies were published on a setup in which the REB was output to the wall of a metal waveguide, and the plasma was deposited on the collector (inverse geometry). The experiment in [3] was accompanied by numerical simulation, where the plasma was described within the framework of the Drude model. As indicated in [3], the results of experiment and simulation differed significantly. One of the possible reasons is that the calculations in [3] assumed that the properties of the plasma remain unchanged during the interaction of plasma-beam subsystems. In this work, the authors, getting as close as possible to the experimental parameters, used both an analytical model of inverse geometry and numerical modeling, where the plasma, like the REB, was considered as an ensemble of large particles [4]

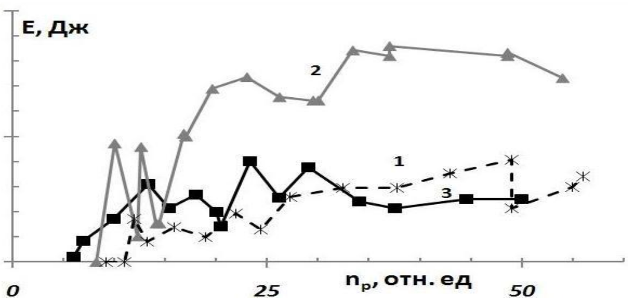

Fig.1 Experimental dependence of energy microwave pulse on plasma concentration and current REB. 1- 2.5 kA, 2 – 4 kA, 3- 6 kA.

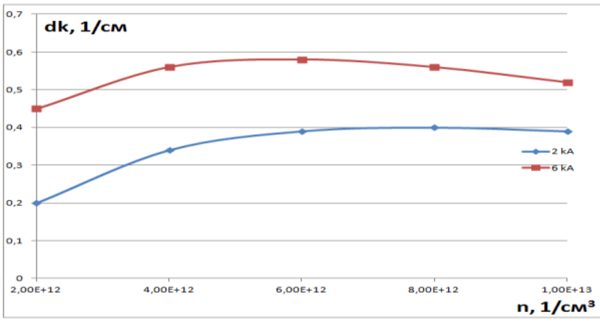

Fig.2 Analytical dependence of the growth rate on plasma concentrations blue – 2kA, red – 6kA.

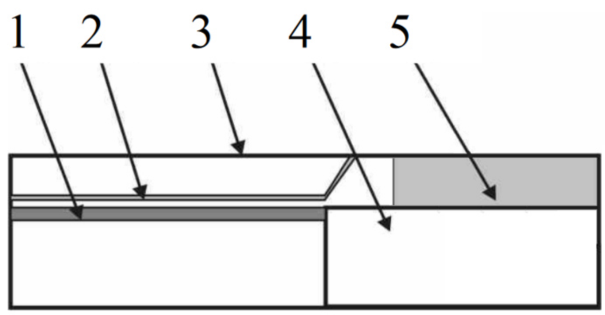

Fig.3 Scheme of the numerical experiment 1 - plasma, 2 - REB, 3 - waveguide, 4 - collector, 5 - absorber.

The analytical model suggests that the difference in linear gain from the current value decreases with increasing plasma concentration. Numerical modeling confirmed the complex relationship between the REB current and the plasma concentration on the output radiation power, which may be due to the fact that for different currents the transition from the single-particle to the collective regime occurs at different plasma concentrations.

The obtained dependences qualitatively correspond to the experimental data from [3].

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NONLINEAR DYNAMICS OF BEAM-PLASMA INSTABILITY IN A PLASMA MICROWAVE AMPLIFIER IN THE PRESENCE OF AN ABSORBER

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Nonlinear dynamics of beam-plasma instability in plasma microwave amplifier in geometry [1, 2] is considered at the presence of an absorber located along wall of waveguide of electrodynamic system. A system of nonlinear equations was obtained by the method of slowly changing amplitudes

$$\left(1-\alpha_p\hat{L}\right)\tilde{j}_p=\alpha_p\alpha_b\theta\hat{L}\tilde{j}_b,\quad \hat{L}=1-2i\gamma^2\frac{d}{d\xi},\tag{1}$$

$$\tilde{j}_b=\frac{1}{\pi}\int_0^{2\pi}e^{iy}dy_0,\tag{2}$$

$$\frac{dy}{d\xi}=\eta,\quad \frac{d\eta}{d\xi}=\frac{i}{2}\left(1+2\frac{u^2}{c^2}\gamma^2\eta\right)^{3/2}\left[\hat{L}\left(\tilde{j}_p+\alpha_b\tilde{j}_b\right)e^{-iy}-c.c.\right],\tag{3}$$

$$y(\xi=0)=y_0,\quad \eta(\xi=0)=0.\tag{4}$$

Eq. (1) is a cold hydrodynamics equation for plasma electrons moving in a self-consistent field and determines the spatial dynamics of the dimensionless plasma current amplitude $\tilde{j}_p$ by a dimensionless coordinate $\xi=z\omega/u$. The dimensionless amplitude of the electron beam current $\tilde{j}_b$ calculated by summing the contributions from the particles is determined by Eq. (2). Eq. (3) are equations of motion of particles in Lagrangian specification, where $y=\omega(t-z/u)$ and $\eta=(u-v_z)/u<<1$ are dimensionless local time and change in velocity of particle, respectively. Conditions (4) are conditions of entry corresponding to an unmodulated mono-velocity electron beam. The values $\alpha_{p,b}$, $k_{\perp p,\perp b}^{-2}$ and θ are determined by the parameters of the beam-plasma system. For the system of Eqs. (1)-(4), the law of conservation of energy flow is fulfilled

$$\frac{d}{d\xi}(P+W)=-Q,\tag{5}$$

where

$$P=\frac{1}{2\pi}\int_0^{2\pi}\left(1+\frac{2u^2}{c^2}\gamma^2\eta\right)^{-1/2}dy_0\tag{6}$$

is the energy flux of the beam particles (normalized to $mc^2\gamma$), Q determines the dissipation of energy in the absorber, and

$$W=\frac{u^2\gamma^4}{2c^2}\left(\frac{\left|\tilde{j}_p\right|^2}{\alpha_b\theta}+\alpha_b\left|\tilde{j}_b\right|^2+2\,\mathrm{Re}\,\tilde{j}_p\tilde{j}_b^*\right)\tag{7}$$

is energy flow of waves excited by the beam. The calculated value W gives the efficiency of converting the energy of the straight-line movement of the electron beam into the energy of electromagnetic waves.

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MULTI-WAVE AMPLIFICATION OF ELECTROMAGNETIC WAVES IN COAXIAL DIELECTRIC WAVEGUIDES

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A flat waveguide formed by two parallel ideally conducting planes $x = 0$ and $x = L$ is considered, a homogeneous dielectric layer adjoins one of the boundaries of the waveguide: ε_0-dielectric permittivity, x_0-layer thickness:

$$\varepsilon = \begin{cases} \varepsilon_1, & 0 < x < x_0 \\ \varepsilon_2, & x_0 < x < L \end{cases} \qquad (1)$$

The beam is assumed to be monospeed and completely magnetized by a strong external magnetic field directed along the z axis. The beam passes at a distance from the dielectric
$x_b > x_0$, ω_{b0}- Langmuir frequency of the electron beam, Δ_b- effective beam thickness, u - beam speed.

Dispersion equation for complex frequencies (or complex wavenumbers) of a planar dielectric waveguide with a magnetized ribbon electron beam:

$$D_0(L) = \frac{\chi_2 \Delta_b \omega_b^2 \gamma^{-3}}{\varepsilon_2(\omega - k_z u)^2} \frac{\sinh[\chi_2(L - x_b)]\sinh[\chi_2(x_b - x_0)] D_0(x_b)}{\sinh[\chi_2(L - x_0)]}, \qquad (2)$$

where $D_0(x) = \left(\frac{\varepsilon_1}{\chi_1} \frac{\cosh(\chi_1 x_0)}{\sinh(\chi_1 x_0)} + \frac{\varepsilon_2}{\chi_2} \frac{\cosh[\chi_2(x - x_0)]}{\sinh[\chi_2(x - x_0)]} \right)$, $\chi_{1,2}^2 = k_z^2 - \varepsilon_{1,2} \frac{\omega^2}{c^2}$,

The numerical solution of the equation (2) is shown in Fig. 1. In Fig. 1a $x_b = x_0$, in Fig. 1b $x_b > x_0$.

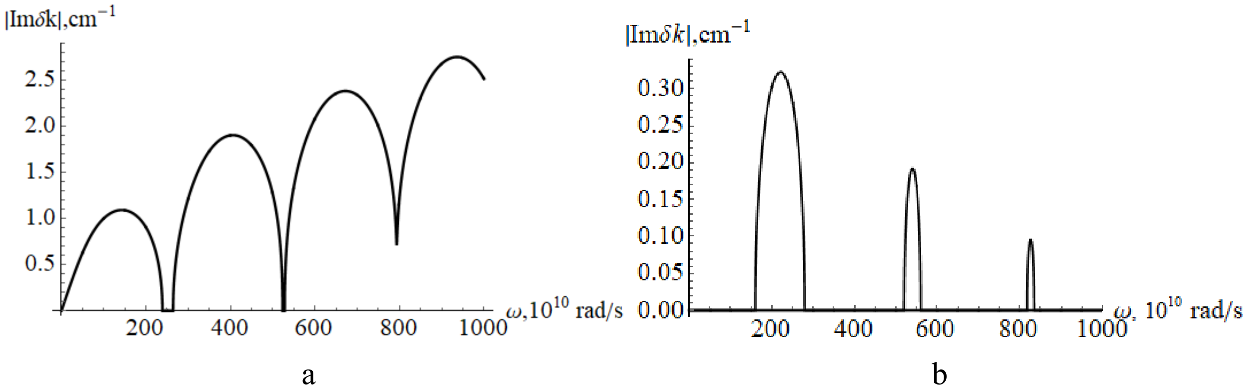

Fig. 1. Amplification factor in a planar waveguide with a dielectric layer and a ribbon beam, $L = 1\ cm$, $x_0 = 0.1\ cm$, $u = 2.2 \times 10^{10}\ cm/s$, $I_b = 0.5\ kA/cm$, $\varepsilon_1 = 2$, a - $x_b = 0.1\ cm$, b - $x_b = 0.11\ cm$

The amplification factor in the modes of single-particle and collective forced Cherenkov effects are calculated [1]. It is shown that in the single-particle mode and $x_b = x_0$ there is a single frequency domain of effective gain from zero to thousands of gigahertz. However, in the case of $x_b > x_0$, it can be seen from Fig. 1b that, with an increase of the number of the resonant mode, the efficiency of its interaction with the electron beam weakens, because the higher the frequency, the weaker penetration of the field into the vacuum region of the waveguide where the electron beam passes.

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SIMULATION OF A MINIATURE VIRCATOR AS A THZ SOURCE

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THz wave has many applications in imaging, plasma diagnostics, non-destructive tests, biology, and communications and attracted many researchers to itself. Therefore, it is essential to propose a THz wave source.

Vacuum electronic devices (VEDs) can be an affordable option for a wave generator in the THz range. A virtual cathode oscillator (vircator) is a kind of VED that its special characteristics like simplicity, compactness, and high output power are attractive to researchers. The operating frequency of vircators is usually in the order of GHz, and there are a few works for increasing it up to the THz band. However, in this study, a virtual cathode oscillator as a THz source was designed and simulated. Two different configurations were proposed and simulated using the particle-in-cell (PIC) method in CST software. The first design [1] is a low-voltage vircator with a third decelerating electrode (that helps to form a virtual cathode at lower currents). The radius of the outer waveguide is the most effective parameter for determining frequency. By altering the radius of the third electrode, the gap of the anode-cathode, and the distance of the anode to the thied electrode, we can optimize output power. The results of the simulation show 30 mW at 0.23 THz when the vircator is fed by a 3 kV and 300 mA electron beam. In addition, the effect of the magnetic field was examined, and as we expected, by adding an axial magnetic field, we can confine electrons and increase the efficiency of the device.

In the second proposed design [2], the virtual cathode oscillator is implemented in a coaxial configuration. For more performance, center rod and reflector were added. After optimization an output about 30 W at 0.25 THz with a 26 kV/100 mA electron beam can be obtained. Therefore, more efficiency in comparison to previous design and other similar works [3] was achieved.

A non-full-transparent anode is also simulated, and it was shown that both proposed devices can tolerate the real situation that a thin or meshed anode cannot pass all electrons. Furthermore, these devices are scalable and can be minimized or maximized for increasing or decreasing frequency.

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MUTUAL INFLUENCE OF PLASMA ANTENNAS WITH DIFFERENT EXCITATION FREQUENCIES

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The main advantage of plasma antennas on gas-discharge tubes compared to metal antennas is the ability to electronically control the antenna characteristics by changing the electron plasma density [1] and adjusting the effective length of the antenna radiation region [2-3]. The possibility of controlling the radiation pattern of a multi-element plasma antenna by turning off individual active elements is discussed in [2]. The study of the parameters of the antenna radiation region, the effective length of which is changed by changing the radiation power of the pump generator was carried out [3].

To study the characteristics of the plasma filling the gas-discharge tube partially or completely, the antenna was represented in the form of a plasma capacitor with a vacuum gap [4], the length of which varies depending on the transmitter power. The effective length of the radiation region can vary along the entire length of the gas-discharge tube if the pump generator operates at a frequency exceeding the maximum radiation frequency and a certain ratio of the plasma frequency and the frequency of the UHF radiation wave is satisfied [3]. This relationship is most simply fulfilled when using a pump generator at a frequency higher than the frequency of UHF radiation. The use of two sources of UHF radiation, one to create a plasma antenna of a given length, and the second as a transmitter at a wavelength corresponding to the length of the plasma antenna, leads to the fact that the parameters of the plasma will change depending on the radiation power of the transmitter. This paper presents the results of experimental studies of the degree of influence of the radiation of the transmitter, the radiation power of which varies from 5 to 20 W at frequency (F), on the parameters of the plasma created by the radiation of a generator with a power of 45 W at a frequency of ~ 3F. Figure 1 shows the results of measurements of the plasma density created in the discharge tube: 1 - low-frequency (160 MHz) transmitter curve; 2 - high-frequency (446 MHz) transmitter; 3 - when they work together, 4 - calculation. Plasma density measurements were carried out according to the method described in [5].

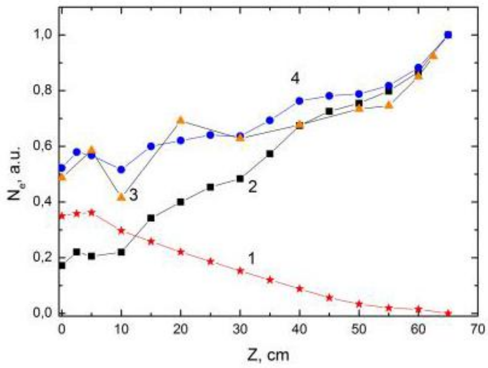

Fig. 1. Distribution of plasma density along the length of the plasma column

It is shown that when using two UHF oscillation generators, the plasma density in the column depends on the radiation power of both transmitters, which leads to a change in the parameters of the plasma column as an antenna (active and reactive resistance and effective length).

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NUMERICAL PIC SIMULATION OF THE EFFECT OF PLASMA ON THE CHARACTERISTICS OF THE PLASMA ANTENNA

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An important fundamental research task of an plasma asymmetrical dipole antenna with a gas-discharge tube is the construction of a physical model and a description of the processes occurring in it and affecting its operation. In this work, using numerical modeling in the KARAT code [1], the processes of ionization in a gas-discharge tube, the movement of electrons in the tube and their oscillations in the field of the incoming electromagnetic wave and their effect on the current in the antennas, the field distribution in the near zone and the spectra of the emitted signal were studied.

Two plasma antenna models were created in the KARAT code using the Particle - in - Cell method to describe the plasma. The numerical model considered a plasma asymmetrical vibrator antenna with an arm length (gas discharge tube with plasma) $l=\lambda/4$ and a metal disk screen. In both models, the initial distribution of equilibrium argon plasma with a concentration $n_e = 1\cdot10^{12}$ cm^{-3} was set in the gas discharge tube, uniform along its length and radius, and the gas pressure in the tube was set to 1 Torr. A monoharmonic signal was supplied to the antenna via a coaxial cable at a frequency f_0 = 450 MHz and varying powers from 9 to 353 W. In the first model, the ionization processes in the gas-discharge tube were turned off, and in the second model, the mechanism of ionization by electron impact in the field of the supplied electromagnetic wave was turned on.

In the first model, it was shown that the escape of plasma electrons to the dielectric wall and its charging has a strong interaction with the change in the profile of plasma concentration distributions along the radius of the tube and a strong violation of the monoharmonic of the plasma at times longer than 40 ns (the electron concentration drops by more than 30%), in this case, noise appears in the spectrum of the emitted signal of the plasma antenna in the band from the frequency of the input electromagnetic wave f_0 to the plasma frequency f_p. At low input signal power (~10 W) in the radiation spectrum, the detected noise in spectral density exceeds the signal at frequency f_0. At high input signal power (>200 W), the component at frequency f_0 is clearly visible in the spectrum of the emitted signal, and due to an increase in the amplitude of the input wave, the electrons move to the dielectric wall accelerates due to an increase in the amplitude of their oscillations in the wave field. It is important to note that in this model, multiple harmonics of the input signal, previously experimentally and numerically discovered in [2-4], are weakly expressed.

In the second model, additional ionization of the plasma in the field of the input electromagnetic wave does not completely compensate for the violation of the quasineutrality of the plasma in the gas-discharge tube. It is important to note that clearly visible multiple harmonics of the input signal frequency appear in the spectrum of the emitted signal ($2f_0$, $3f_0$, $4f_0$). We believe that the generation of multiple harmonics in the spectrum of the emitted signal is associated with the ionization process, which was previously described in [5].

The study was financially supported by the RCSI grant No. 20-58-04019 Bel_mol_a.

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COMPARATIVE ANALYSIS OF ELECTROMAGNETIC PHENOMENA IN THE ATMOSPHERES OF EARTH, MARS, AND VENUS

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This research presents a comprehensive overview of electromagnetic radiation phenomena in the atmospheres of Mars, Venus, and Earth. Utilizing data from space measurements, experiments in terrestrial conditions, and laboratory modeling, the study explores the generation and propagation of electromagnetic radiation in these planetary atmospheres. The Mars section focuses on the electrical effects of dust particles transported by wind, with insights from different experiments. Venus's atmospheric lightning is explored, and ongoing Venus’s exploration experiments are emphasized. Earth's distinct atmospheric conditions, spanning from the surface to the upper stratosphere, are analyzed for their varied electrical characteristics, influenced by phenomena like thunderstorms and dust activations. The comparative analysis aims to enhance our understanding of electromagnetic activities across the atmospheres of the terrestrial planets.

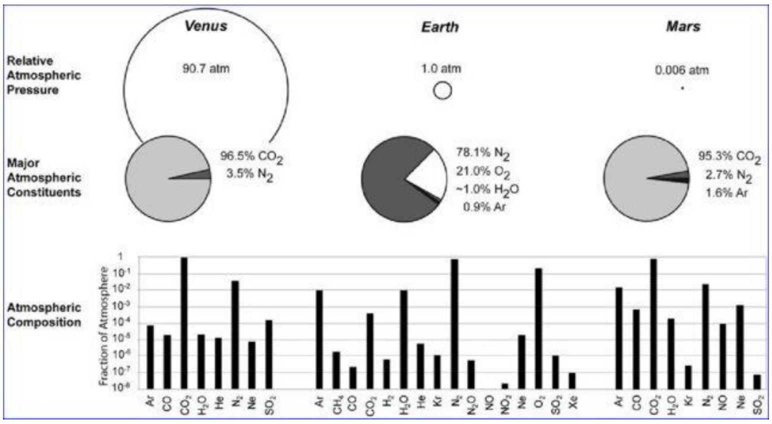

Fig. 1. Comparison of the atmospheres of Earth, Mars, and Venus. (Credit: Carie Frantz) [1,2]

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EFFECT ON THE IONOSPHERIC PLASMA TO POWERFUL HIGH-FREQUENCY RADIO EMISSION AS A METHOD FOR STUDYING OF THE NEUTRAL ATMOSPHERE

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The impact of powerful high-frequency radio emission from a ground-based heating facility on the ionospheric plasma causes the occurrence of plasma instabilities and the formation of plasma inhomogeneities of various sizes from several cm to tens of km [1]. One of the processes that occur during plasma disturbance is the creation of artificial periodic inhomogeneities (APIs) of the ionospheric plasma. For this purpose, we use the SURA mid-latitude heating facility (56.1°N; 46.1°E). In the field of a standing wave formed when a powerful radio wave is reflected from the ionosphere, uneven heating of the plasma occurs and periodic inhomogeneities in temperature and electron concentration are formed. They are formed in the altitude range from 50 km to the height of reflection of powerful waves from the ionosphere. API studies of the ionosphere are based on Bragg scattering of sounding pulse signals from an artificial periodic structure and measuring the amplitude and phase of the scattered signal [2]. The scattering of probe (weak) radio waves by the APIs makes it possible to determine the parameters of both the ionospheric plasma and its neutral component. These are the temperature and density of the atmosphere, the velocity of vertical movement of the environment, the level of turbopause and turbulent velocity, and the characteristics of atmospheric waves. Changes in temperature affect the rate of chemical reactions. Note that, despite the fact that the API technique assumes artificial disturbance of the ionospheric plasma; the parameters of the neutral atmosphere are determined at the relaxation stage of irregularities and they characterize the undisturbed environment.

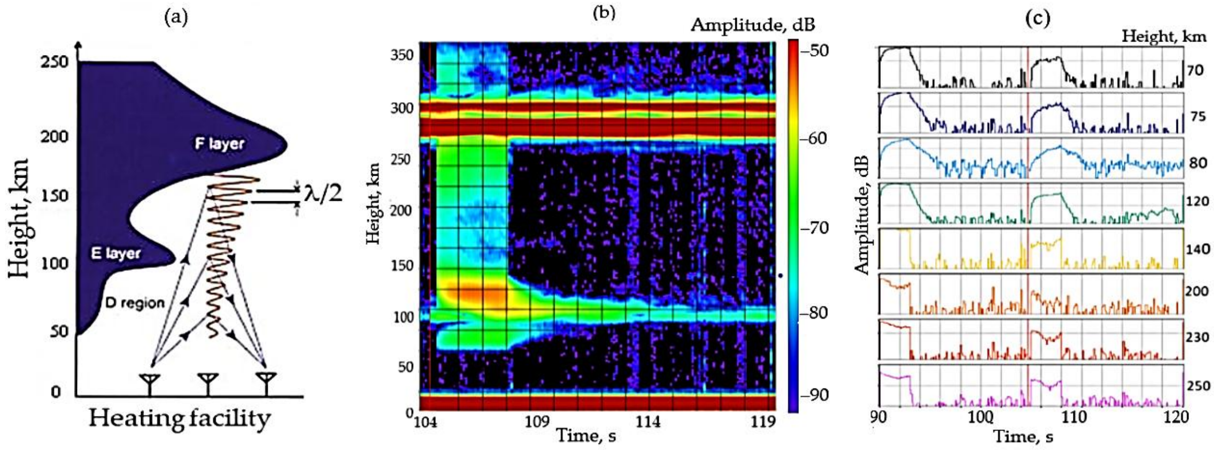

Fig. 1. APIs creation (a) and processes of the development and relaxation of the scattered signal (b,c)

The report contains the results of long-term research of the neutral atmosphere using the API technique [3-5]. The work was supported of the Ministry of Science and Higher Education of the Russian Federation under project no. 0729-2020-0057.

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RADIO OCCULTATION STUDIES IN THE EARTH'S IONOSPHERE DURING STRONG MAGNETIC STORMS IN MARCH AND JUNE 2015

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Satellite remote sensing methods are a universal and powerful tool for systemic studies in the Earth's atmosphere and ionosphere performed in real time. Regional and terrestrial networks of global navigation satellite systems (GNSS) and numerous navigation signal receivers located on low-orbit aircraft in space provide unique data about the atmosphere and ionosphere of the planet. The high accuracy and cost-effectiveness of radio occultation (RO) measurements, as well as their all-weather capability and long-term stability, are advantages of the RO methods.

In the spring and summer of 2015, the Sun experienced powerful coronal mass ejections (CMEs) towards the Earth. These events were recorded by many spacecraft and ionospheric stations. Coronal plasma ejections that reached the Earth's magnetosphere during the periods from March 17 to 18 and from June 22 to 23, 2015 provoked two strong magnetic storms of the G4-class in which the maximum values of the planetary K_p-index were equal to 8. We processed and analyzed ~100 RO sessions of *FORMOSAT-3/COSMIC* satellite measurements taken during a geomagnetic storm on June 22–23, 2015 in the Earth's ionosphere. The results of this analysis show that the storm in June 2015 caused significant fluctuations in the parameters of radio waves on the ionospheric sounding paths between navigational (*GPS*) and low-orbit (*FORMOSAT-3/COSMIC*) satellites in the high-latitude ionosphere of the planet. It was found that ionospheric disturbances of the radio wave characteristics are caused by both the storm geomagnetic conditions and the activity of powerful X-ray flares observed during the period of measurements.

A search for the absorption of decimeter (DM) radio waves (wavelength ~19 cm) at the GPS-carrier frequency of 1545.42 MHz was carried out. For the first time, the integral absorption of DM radio waves was found in the D- and E-regions of the Earth's high-latitude ionosphere. The absolute value of the integral absorption on radio occultation sounding paths is ~3 dB in the altitude range of ~60–90 km, and, in some cases, it reaches ~10 dB at levels from ~90 to ~95 km. Based on the results of solving the inverse problem of radio wave absorption, the altitude profiles of the absorption coefficient of DM radio waves in the lower ionosphere were reconstructed during the magnetic storm on June 22-23, 2015. The maximum value of the absorption coefficient of DM radio waves reached values of $(5.7\pm1.4)\cdot10^{-3}$ dB/km at altitudes from ~90 to ~100 km in the Earth's high-latitude ionosphere [1–6].

The purpose of this work is to analyze RO *FORMOSAT-3/COSMIC* measurements carried out during a strong magnetic storm in the period from March 17 to 18, 2015 in the D- and E-regions of the high-latitude ionosphere of the Earth. The results obtained are compared with similar data on the magnetic storm on June 22-23, 2015. Powerful periodic oscillations of the DM signal amplitude were discovered in the D-region (altitudes ~60–90 km) of the Earth's low-latitude (20.19°N) ionosphere, which may be associated with Joule heating at high latitudes due to a strong geomagnetic storm in March 2015. The work was carried out within the framework of the state order of the Kotelnikov Institute of Radio Engineering and Electronics of the RAS.

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PRODUCTION OF ARTIFICIAL BALL LIGHTNING USING A CAPILLARY PLASMA GENERATOR

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Successful experiments have been carried out to produce artificial ball lightning (ABL) at the interaction of a capillary plasma generator's jet with metal samples under different conditions. **I** Maximum current was 72 A, pulse time was 15-25 ms.

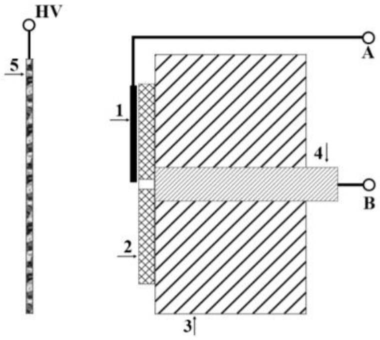

Fig. 1. Capillary plasma generator. 1,4 – electrodes, 2 – dielectric plate with capillary (discharge chamber), 3 – base of plasma generator (dielectric), 5 – metal sample (target)

At inputted energies of 0.2 -1.5 kJ, plasma interacted with metal in the plasma jet, which formed a luminous object with an internal vapor region and an oxide shell. Metal samples made of aluminum, copper, steel, lead and solder were used. The best results were obtained using aluminum, lead and solder, in which the formation of a shell from 20 to 100 microns width was observed. As the energy inputted increased, the size of the objects increased also. At an energy of 200-220 J, the formation of ABL with a diameter of up to 3 mm, with a shell thickness of up to 20 microns and a lifetime of up to 3-4 s was observed. At an energy input of about 15,000 J, the formation of ABL with a diameter of up to 1.0-1.5 cm, with a shell thickness of up to 100 microns and a lifetime of up to 7 s was observed. These ABL also exploded and left traces in the form of soot dots when they interacted with paper and explosion marks on paper. According to the parameters: long glow (long life time), the ability to jump, disintegration into several objects, high density of internal energy, they are analogs of real ball lightning.

A MODEL OF BALL LIGHTNINH WITH A CHARGED SOLID SHELL AND A GASEOUS CORE

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Based on observations of natural ball lightning and successful experiments to create long-lived luminous analogues of ball lightning using capillary discharge, a model of ball lightning is presented. In the model, the ball Lightning is a luminous charged sphere with a solid shell and a core filled with hot gas. The solid shell compresses the hot gas, and the electric charge on the surface causes the surface to stretch. The equations of the internal energy of this object are presented, due to the pressure of charges and the thermal expansion of a hot gas. Calculations of the internal energy of this object, the pressure of charges on the shell and the shell voltage caused by the pressure of hot gas inside the shell are carried out. Calculations show that the internal energy density of this object can reach a value of 10^9-10^{11} J/m^3, which is in agreement with observations.

Parameters and internal energy of BL as charged sphere

R, м	*Q*, C	10^{-5}	10^{-4}	10^{-3}
0.1	W_{el} , J/m^3	$2.15 \cdot 10^3$	$2.15 \cdot 10^5$	$2.15 \cdot 10^7$

Internal energy of BL with respect to weight of BL at shell width δ=100 μm, T=2000 K, μ=30 au.

R, м	M, kg	10^{-3}	10^{-2}	10^{-1}
0.1	W_{term} , J/m^3	$1.32 \cdot 10^5$	$1.32 \cdot 10^6$	$1.32 \cdot 10^7$

DIELECTRIC BARRIER DISCHARGES IN CONTACT WITH LIQUIDS

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The study of plasma-liquid interactions has evolved as a new interdisciplinary field driven by the development of plasma applications for water purification, biomedicine and agriculture. Understanding of the fundamental processes of the plasma-liquid interaction enables optimization of plasma chemistry in large-scale plasma devices with liquid electrodes [1]. Dielectric barrier discharges (DBDs) at atmospheric pressure are most commonly used for various applications due to their simple electrode arrangement, easy scaling to required capacity and stability against arcing. In this work we present diagnostics of complex plasma-liquid interaction in plasma sources based on dielectric barrier discharge: DBD helium plasma jet and water falling film DBD.

Helium plasma jet with liquid target is a convenient plasma source for spatially and temporally resolved studies of plasma-liquid interaction. Here we present discharge development, electric field measurement results, spatial distribution of excited species and Schlieren imaging of He plasma jet impinging on the liquid surface [2]. Influence of non-electrical parameters, such as target distance and the gas flow rate on the nature of the discharge is demonstrated.

Specially designed water falling film DBD reactor is suitable for water purification applications and studies of the bulk effect of plasma on treated liquid. We will show how discharge generated in different gases influence physical and chemical properties of the gas phase and the liquid phase [3]. The formation of hydroxyl radical ($^{\bullet}OH$) and long-living chemical species (H_2O_2, O_3, NO_3^- and NO_2^-) generated in the liquid phase of the reactor in dependence on the gas atmosphere (air, nitrogen, oxygen, argon and helium) is investigated. The examples of applications of water falling film DBD will be mentioned.

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EXPERIMENTAL STUDY OF THE TRANSFER PROCESSES FROM THE SPHERICAL WATER DROPLET SURROUNDED BY SPARK DISCHARGE PLASMA CHANNEL FLOW

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The influence of an external electric field on the evaporation processes of water microdroplets attracts the attention of many researchers due to a wide range of practical applications in electrical micro- and nanoelectromechanical systems. The electric field has a significant effect in many cases, ranging from heat transfer during film boiling [1] to the manipulation of ultra-small droplets using the ionic wind of a corona discharge [2]. For example, the presence of electric field has a significant impact on local heat transfer processes due to the formation of air bubbles and evaporation during boiling [3].

The purpose of this paper is to experimentally examine the features of the matter transfer from the surface of a water spherical droplet, when interacting with the oncoming flow of drifting and diffusing electrons emitted by a thermionic emission source, which are part of the plasma channel of a spark discharge.

To implement the experiment the laboratory set-up with an electrode system is used, see Fig. 1. A system consisting of function generator Agilent 33220A (Agilent Technologies, USA) and high-voltage amplifier Matsusada 20-B-20 (Matsusada Precision Inc, Japan) were used as a source of positive rectangular pulses.

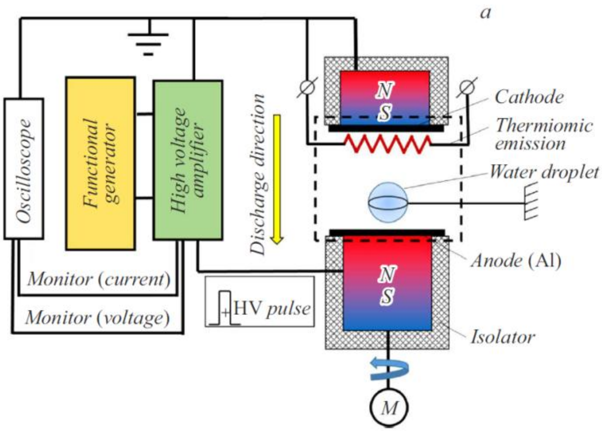

Fig. 1. Scheme of the experimental set-up (not to scale).

Based on the experimental data obtained, the rationale for the ”kangaroo effect” is determined by the presence of water molecules in the crater formation zone, as a result of the work of matter transfer near the side surface of the plasma channel. The dissociation of water molecules with pronounced optical radiation indicates that the water molecule received a portion of thermal energy in the microcrater zone, where the luminescence of the excited hydroxyl ion OH^- is evaluated visually in the form of the luminescence lying in the visible region of the spectrum.

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PARAMETERS OF THE MULTISPARK HIGH-VOLTAGE DISCHARGE WITH GAS INJECTION THROUGH THE GAP BETWEEN DURALUMIN ELECTRODES

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In this work we have studied the parameters of high-voltage pulse discharge (U ~ 2 kV, I ~ 300 A, pulse duration ~ 2 μs) [1] on the model of a linearly arranged electrodes at air and argon flow. This plasma source has shown its efficiency in the production of reactive oxygen and nitrogen forms when deionized water is treated, which is in demand for biological tasks to intensify plant growth and control phytopathogens.

In our case, the discharge was carried out in the presence of erosion of duralumin electrodes, which is confirmed by the presence of lines of neutral atoms and ions of aluminum and copper in the emission spectrum of the discharge. Metal atoms have a higher probability of ionization due to lower ionization potentials. The situation when a small concentration of metal vapor can significantly influence the ionic composition of the plasma becomes probable.

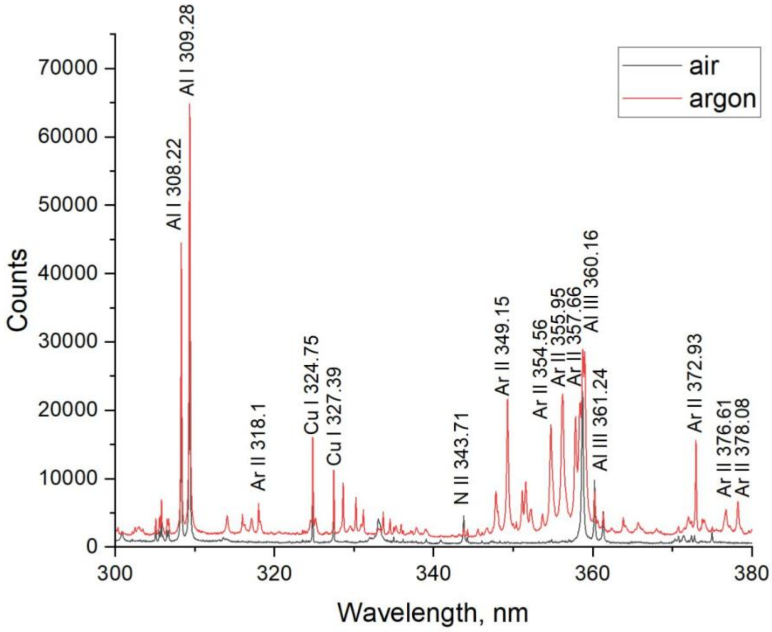

Fig. 1. Emission spectrum of the discharge.

Two temperatures of heavy particles (for argon 9900±500 K, 7000±200 K; for air 9600±180 K; 7900±100 K) were obtained from the emission continuum, indicating possible spatial inhomogeneity of the discharge. The plasma concentration using both plasma-forming gases was ~ 10^{17} cm^{-3} according to the Stark broadening of the H_α line caused by the collective influence of the microfields of charged particles in plasma. According to the relative intensities of the N^+ (in the case of air) and Ar^+ (in the case of argon) lines, as well as Al^+ (for both gases), the electron T_e temperatures were determined as 2.4±0.3 eV.

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IMPROVING THE RESULTS OF ANALYSIS OF BIOLOGICAL FLUIDS BY ELIMINATING MATRIX EFFECTS IN AN INDUCTIVELY COUPLED PLASMA MASS SPECTROMETER

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In the work, we studied the influence of matrix effects on the detection limit of individual components, and the dilution and mineralization method carried out a comparative analysis of the results of sample preparation (fig.1) [1]. The studies shown that during both sample preparations in biological fluids the concentration of some elements with low atomic mass does not change, and the concentration of elements with higher atomic mass increases by 2−3 times. In general, spectral matrix effects most often manifest themselves during sample preparation, and therefore, in most cases, to eliminate this effect the devices equipped with collision cells located after the ion-optical system of ICP-MS are used. Inductively coupled plasma mass spectrometry studied a number of elements in solutions for analysis. It was found that the decrease in the throughput of a number of parts of the analyzer is a decrease in the diameters of the sampler and skimmer holes due to organic solvents. Two methods to reduce the influence of organic components of analyzed solutions on the results of the analysis were proposed -microwave decomposition and simple decomposition [2-4]. We showed the advantage of simple dilution. However, in the analysis of biological fluids (mainly whole blood), oxidative mineralization can remove complex organic matrix and reduce biohazard. The paper also considers the possibility of using an internal standard in order to obtain correct results by eliminating matrix effects [5]. The paper may be useful for an experimental analyst to assess (even increase) the degree of accuracy of the results obtained and allow doctors to restore important elements lost during dialysis in the patient's body.

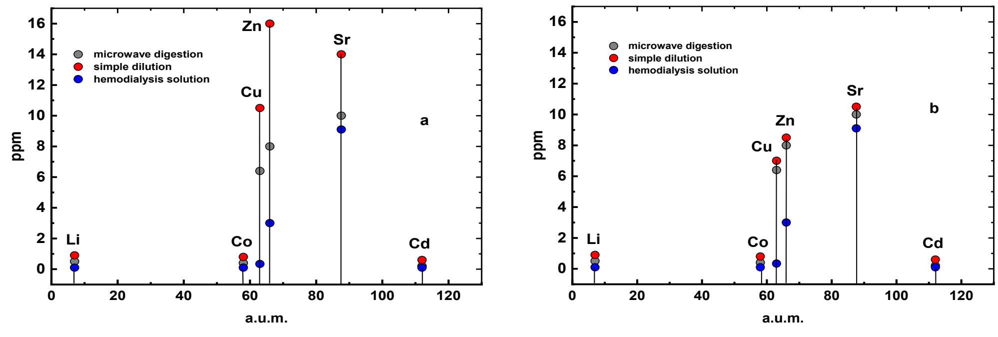

Fig. 1. Concentration of elements in biological fluids depending on the sample preparation conditions without (a) and with the use of the collision cell (b).

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