

Министерство науки и высшего образования Российской Федерации

САНКТ-ПЕТЕРБУРГСКИЙ  
ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ ПЕТРА ВЕЛИКОГО

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# ДОСТИЖЕНИЯ И ПРИМЕНЕНИЯ ФИЗИКИ ПЛАЗМЫ

Сборник тезисов  
международной научной конференции

Санкт-Петербург  
18–20 сентября 2019 года



**ПОЛИТЕХ-ПРЕСС**

Санкт-Петербургский  
политехнический университет  
Петра Великого

Санкт-Петербург  
2019

ББК 22.333

Д70

**Достижения и применения физики плазмы** : сб. тез. междунар. науч. конф., С.-Петербург, 18–20 сентября 2019 г. – СПб. : ПОЛИТЕХ-ПРЕСС, 2019. – 118 с.

Представлены тезисы докладов участников международной научной конференции «Достижения и применения физики плазмы» (“Advances and Applications in Plasma Physics”). Конференция проводится совместно Санкт-Петербургским политехническим университетом Петра Великого и редакциями журналов Nature Communications, Nature Physics и Nature Reviews Physics.

Конференция включает в себя сессии по четырем направлениям: управляемый термоядерный синтез, космическая плазма, низкотемпературная плазма, взаимодействия лазер–плазма. Несмотря на достигнутый за последние десятилетия впечатляющий прогресс в понимании плазмы, физики по-прежнему сталкиваются с множеством интересных задач, особенно когда речь идет о конструкторских разработках для ряда практических применений. Содержатся тезисы устных и постерных докладов участников.

Сборник предназначен для широкого круга научных работников, студентов и аспирантов.

Ответственный за выпуск – *В. М. Якубсон*.

**ISBN 978-5-7422-6677-8**

doi: 10.18720/SPBPU/2/id19-184

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PETER THE GREAT  
SAINT-PETERSBURG POLYTECHNIC UNIVERSITY

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# ADVANCES AND APPLICATIONS IN PLASMA PHYSICS

Abstract book

Saint-Petersburg  
September 18–20, 2019



**POLYTECH-PRESS**

Peter the Great  
St. Petersburg Polytechnic  
University

Saint-Petersburg  
2019

**Advances and Applications in Plasma Physics** : abstract book, St. Petersburg, september 18–20, 2019. – SPb. : POLYTECH-PRESS, 2019. – 118 p.

The present book contains abstracts of talks and posters presented at the international scientific conference “Advances and Applications in Plasma Physics”. The conference is held by the Peter the Great St. Petersburg Polytechnic University in cooperation with Nature Communications, Nature Physics and Nature Reviews Physics.

The conference brings together experts and young scientists from various plasma subfields, including nuclear fusion; low-temperature plasmas; astrophysical plasmas; laser-plasma interactions. In spite of tremendous progress over the past decades in understanding plasmas, there are many challenges that still confront plasma physicists, especially when it comes to the design and development of potential applications.

The book is intended for broad audience of researchers and students.

E d i t o r:  
*Yakubson Vera*

**ISBN 978-5-7422-6677-8**  
doi: 10.18720/SPBPU/2/id19-184

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# Advances and Applications in Plasma Physics

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**September 18 – 20, 2019**

Big conference hall  
Science and Research  
Building

Peter the Great St.  
Petersburg Polytechnic  
University  
29 Polytechnicheskaya str.  
Saint-Petersburg, Russia

### **Organizing committee:**

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Vladimir Rozhansky (Peter the Great St.  
Petersburg Polytechnic University, Russia)

Bart Verberck (Nature Research,  
Germany)

# Conference Program

## September 18

08:30 - 09:30 Registration  
09:30 - 09:45 Welcome Remarks

### *Session 1: Fusion*

Chair: Michael Tendler, KTH, Royal Institute of Technology, Sweden,  
and Dr.h.c. SPbPU

09:45 - 10:30 *“Mechanisms of Impurity Transport in Edge Tokamak Plasma and Solar Chromosphere”*  
**Vladimir Rozhansky (Peter the Great St Petersburg Polytechnic University, Russia)**

**10:30 - 10:45 Coffee break**

10:45 - 11:30 *“Muon Catalyzed Fusion, Present and Future”*  
**Atsuo Iiyoshi (Chubu University, Japan)**

11:30 - 12:15 *“Simulating and optimising turbulence in stellarators”*  
**Josefine Proll (TU Eindhoven, the Netherlands)**

12:15 - 13:00 *“Fusion-Fission Hybrid Systems - Yesterday, Today and Tomorrow”*  
**Boris Kuteev (National Research Centre “Kurchatov Institute”)**

**13:00 - 14:00 Lunch**

***Session 2: Laser-plasma interactions***

Chair: Osamu Motojima, Chubu University, Japan

- 14:00 - 14:45                    *“Laser-driven relativistic plasma optics and ion acceleration in ultrathin foils”*  
**Paul McKenna (University of Strathclyde, UK)**
- 14:45 - 15:30                    *“Recent Advances in the Laser-Plasma Physics of High Energies”*  
**Valery Bychenkov (Lebedev Institute, Russia)**
- 15:30 - 16:00                    Coffee break**
- 16:00 - 16:45                    *“Manipulating relativistic electrons with intense lasers”*  
**Victor Malka (Weizmann Institute of Science, Israel, and Laboratoire d’Optique Appliquée, CNRS, Ecole Polytechnique, ENSTA, France)**
- 16:45 - 17:30                    *“High-Energy Density Physics in Pulsed Laser Experiments”*  
**Vladimir Rogachev (Russian Federal Nuclear Center, Russia)**
- 17:30 – 19:00                    Poster Session**
- 20:30 – 22:30                    Reception & Boat trip**

## September 19

8:30 - 9:00 Registration

### *Session 3: Cold/dusty plasmas and applications*

Chair: Irina Kumkova, IEE RAS, Russian Academy of Sciences, Russia

9:00 - 9:45                    “*Complex/Dusty Plasma Physics – from Laboratory to Space*”  
**Hubertus Thomas (German Aerospace Center (DLR), Germany)**

9:45 - 10:30                “*Interfacial Low-Temperature Plasmas for Directing Chemistry: Perspectives from Plasma-Liquids and Plasma-Catalysis*”  
**David Go (Notre Dame University, US)**

**10:30 - 11:00                Coffee break**

11:00 - 11:45                “*CO<sub>2</sub> plasmas: from solar fuels to oxygen production on Mars*”  
**Vasco Guerra (IST Lisbon, Portugal)**

11:45 - 12:00                **Short talk**  
“*Plasma Technologies based on High-Voltage AC Plasma Torches*”  
**Victor Popov (Institute for Electrophysics and Electric Power of the Russian Academy of Sciences, Russia)**

12:00 - 12:15                **Short talk**  
“*Constriction and Stratification of the Positive Column of a Glow Discharge in Inert Gases*”  
**Aleksei Siasko (St Petersburg State University, Russia)**

12:15 - 12:30                **Short talk**  
“*About Some Peculiarities of Interferometry for Micron Objects of the Pre-Breakdown Stage Air Discharge*”  
**Alexandra Khirianova (P.N. Lebedev Physical Institute, Russia)**

**12:30 - 13:30                Lunch**

***Session 4: Astrophysical plasmas***

Chair: Vasco Guerra, Instituto Superior Técnico, Lisbon, Portugal

- 13:30 - 14:15                    *“Dusty plasma at the Moon. Challenges of modeling and measurements”*  
**Sergei Popel (Space Research Institute, Russia)**
- 14:15 - 15:00                    *“Wave-particle interactions in earth’s inner magnetosphere across different timescales”*  
**Clare Watt (University of Reading, UK)**
- 15:00 - 15:30                    Coffee break**
- 15:30 - 16:15                    *“High-performance Computing in Application to Solar System Plasma Dynamics”*  
**Andrey Divin (Saint Petersburg State University, Russia)**
- 16:15 - 16:30                    **Short talk**  
*“Hybrid simulations of collisionless shocks in astrophysical plasma”*  
**Julia Kropotina (Ioffe Institute, Russia)**
- 16:30 – 16:45                    **Short talk**  
*“Hall - MHD regimes of plasmoid instability”*  
**Grigory Vekstein (University of Manchester, UK)**
- 17:00 – 18:00                    Public lecture**  
**Matteo Barbarino (IAEA, Austria)**
- 18:00 – 19:30                    Poster Session**

## September 20

8:30 - 9:00 Registration

### *Session 5: Fusion*

Chair: Vladimir Rozhansky, Peter the Great St. Petersburg Polytechnic University, Russia

9:00 - 9:45 *“Progress of the Large Helical Device (LHD) Project toward Understanding Plasma Confinement by 3D External Coils”*  
**Naoki Tamura (National Institute for Fusion Science, Japan)**

9:45 - 10:00 **Short talk**  
*“Modeling of Globus-M connected double-null discharge”*  
**Elena Vekshina (Peter the Great St. Petersburg Polytechnic University, Russia)**

10:00 - 10:15 **Short talk**  
*“Study of turbulence in the Globus-M tokamak plasma during the transition to the ELM-free H-mode”*  
**Alexander Yashin (Peter the Great St. Petersburg Polytechnic University, Russia))**

10:15 - 10:30 **Short talk**  
*“Faster Fusion: ST40, engineering, commissioning, first results”*  
**Mikhail Gryaznevich (TE Ltd, UK)**

10:30 - 10:45 **Short talk**  
*“The 1D - Calculations of Thermonuclear Ignition Margins of Direct – Drive Targets for MegaJoule Facilities with Laser Wavelength of 0.35 and 0.53  $\mu\text{m}$ ”*  
**Vladimir A. Lykov (Russian Federation Nuclear Center, Russia)**

- 10:45 - 11:00      *“Review of recent advances and new ideas in development of the open magnetic traps”*  
**Elena Soldatkina (Budker Institute of Nuclear Physics, Russia)**
- 11:00 - 11:30**      **Coffee break**
- 11:30 - 12:00      *“The ITER Project - On the Way to Fusion Energy”*  
**Alexander Alekseev (ITER, France)**
- 12:00 - 12:30      *“Fusion Technologies: from ITER to the next step in Russia”*  
**Anatoli Krasilnikov (ITER Russian Domestic Agency, Russia)**
- 12:30 - 13:15      *“High Temperature Plasma Physics and Fusion Research in Ioffe Institute”*  
**Evgeniy Gusakov (Ioffe Institute, Russia)**
- 13:15 – 13:30**      **Closing Remarks**
- 13:30 - 15:00**      **Lunch**
- 15:00 - 16:45**      **A guided tour of Ioffe Institute and Peter the Great St. Petersburg Polytechnic University’s research laboratories**

## KEY SPEAKERS

### **Vladimir Rozhansky**

*Peter the Great St. Petersburg Polytechnic University, Russia*

Researcher ID: Q-9759-2016

Homepage: <https://plasmaphys.spbstu.ru>



V. Rozhansky is professor of Peter the Great St. Petersburg Polytechnic University at Plasma Physics Department.. He is a head of the group, which studies transport phenomena in plasmas. The main activity of the group is focused on theoretical investigations (both analytical and numerical) of transport phenomena in tokamak, including transport phenomena in the edge plasmas. The emphasis is made on the role of self-consistent electric fields and current systems, which are generated in plasmas. The group has also experience in studying evolution of plasma clouds in the vicinity of a pellet injected into a tokamak or into space plasmas, and transport phenomena in partially ionized plasmas. His group was one of the developers of SOLPS-ITER code for edge plasma of a tokamak. V. Rozhansky as an outstanding scientist in 1997 was awarded the stipendium of the Academy of Sciences of Russia. In 1998-2004 he was nominated by International Soros Science Educational Program by a title "Soros Professor".

### **Atsuo Iiyoshi**

*Chubu University, Japan*

Scopus ID: 35354801800



Professor Atsuo Iiyoshi is currently a chairman of the Board of Trustees at Chubu University Educational Foundation and also a Chancellor of Chubu University in Japan. He is reknown as one of the pioneers of plasma physics and nuclear fusion. After his PhD from Keio University in Japan, he spent some time in Princeton Plasma Physics Lab in the United States and Culham Centre for Fusion Energy in England in mid-1960s. After professorship at Kyoto University where he was involved in Heliotron D and E, Prof. Iiyoshi became the first Director General of National Institute for Fusion Science (NIFS) in Japan in 1989, where the LHD (Large Helical Device) was constructed and is successfully operated currently. After the retirement from NIFS, he moved to Chubu University as the President in 1999, and later as the Chancellor served there for more than 18 years. Last year Professor Iiyoshi was awarded The Order of the Sacred Treasure, Gold Rays with Neck Ribbon, one of the most honorable awards given by the Emperor of Japan.

## **Josefine H.E. Proll**

*Eindhoven University of Technology,  
The Netherlands*

Scopus ID: 55251013000

Homepage:

<https://www.tue.nl/en/research/researchers/josefine-proll/>



Josefine Proll is an Assistant Professor in the department of Applied Physics at Eindhoven University of Technology. She obtained her PhD at the Max Planck Institute for Plasma Physics in Greifswald, Germany. In her thesis she investigated how the geometry of the confining magnetic field can reduce the turbulence-driving instabilities, in particular in fusion devices of the stellarator type. A postdoctoral grant obtained from the Helmholtz Society allowed her to spend time at the Princeton Plasma Physics Laboratory at Princeton, USA, to investigate optimizing stellarators for reduced turbulent transport. She collaborates with the advanced stellarator Wendelstein 7-X in Germany to test her theories via comparing her numerical findings with experimental turbulence data. Ultimately, this will help understand the mechanisms behind turbulence and will lead to advanced optimization strategies.

## **Boris V. Kuteev**

*National Research Center “Kurchatov Institute”,  
Moscow, Russia*

ORCID: 0000-0002-7514-5111



Boris V. Kuteev is the Deputy Head of Tokamak Division in the Kurchatov Complex of Fusion Energy and Plasma Technologies at the National Research Center and the professor in the Plasma Physics Chair at the National Research Nuclear University “MEPhI”, Moscow, Russia. He has published widely in the areas of plasma science and controlled fusion research, design and engineering of tokamak devices and enabling technology systems, and fusion nuclear science, with recent focus on Fusion-Fission Hybrid Systems, intense Fusion Neutron Sources, and fusion energy applications. He has authored or co-authored over 100 journal articles, nearly 100 conference papers and presentations, and holds more than 30 patents. Prof. Kuteev has been recognized with the Silver Medal Research Award of USSR Exhibition of Achievements of National Economy for the pellet injection technique. He is a member of Fusion Section of Research Council of SC “Rosatom” and the Russian representative in the International Fusion Research Council of IAEA, a corresponding member of the Academy of Engineering Sciences named after A.M. Prokhorov.

## **Paul McKenna**

*University of Strathclyde, United Kingdom*

ORCID: 0000-0001-8061-7091

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Professor Paul McKenna's research interests are in high power laser-plasma physics, including laser-driven ion acceleration and applications, relativistic laser-plasma interactions, high field physics at the focus of ultra-intense laser pulses, and plasma optics. He received his PhD from Queens University Belfast, before becoming a postdoctoral fellow at the University of Glasgow and a Royal Society of Edinburgh Personal Research Fellow at the University of Strathclyde. He was appointed a Lecturer at Strathclyde in 2006, a Reader in 2008 and a Professor in 2011. He held an EPSRC Leadership Fellowship from 2012-17. He has served on numerous UK and international advisory committees, including STFC's Science Board and ESPRC's Strategic Advisory Team for Infrastructure, and the Scientific Advisory Committees for the APOLLON 10-Petawatt laser facility in France and the HIBEF facility at DESY in Germany. He is presently Head of the Department of Physics at the University of Strathclyde.

## **Valery Yu. Bychenkov**

*Lebedev Physics Institute of Russian Academy of Sciences, Russia*

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Professor, Chief Scientist; Head of High Energy Laser-Plasma Physics Lab in Lebedev Physics Institute and Head of Plasma Physics Lab in Center for Fundamental and Applied Research, Dukhov Research Institute, ROSATOM.

Summary of Research Activity:

- Nonlinear laser-plasma interaction;
- Plasma turbulence;
- Transport phenomena in a hot plasma;
- Nonlinear vortical dynamics of a plasma;
- Physics of ultrashort laser pulses and laser-triggered particle acceleration

## **Victor Malka**

*Weizmann Institute of Science, Rehovot, Israel*

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Victor Malka (57), Professor at the Weizmann Institute of Science in Israel, has obtained his PhD thesis at Ecole polytechnique in 1990. He was until September 2019 a CNRS Research Director at LOA, and a Professor at Ecole Polytechnique. He worked on different topics such as atomic physics, inertial fusion, laser plasma interaction, and now on relativistic laser plasma interaction and on laser plasma accelerators, in which he makes several breakthrough contributions. He has published about 350 articles and has been invited in more than 175 international conferences. He got several prizes (including the Grand Prix d'Etat of the French Academy of Sciences, the Julius Springer prize, the F. Holweck prize from the SFP and IOP, the QEOD prize from EPS, and the Alfven prize from EPS in 2019). Victor Malka, fellow of APS and EPS, is member of the European Academy of science and officer of physic division.

## **Vladimir Rogachev**

*Russian Federal Nuclear Center, Russia*

Scopus ID: 7003280062



Vladimir G. Rogachev (born in 1946) graduated from Moscow Institute of Physics and Technology in 1969 and was employed at VNIIEF, where he held a number of scientific and managerial positions. Since 2013 he has been working as the Deputy Director of the Institute of Laser Physics Research, directly manages the Theoretical Department and conducts research. In 1979 Rogachev V. G. was awarded the degree of a candidate of phys.-math. sciences, and in 2007 – the degree of a doctor of phys.-mat. sciences.

The sphere of research interests includes the following: gas dynamics, physical kinetics, plasma physics, laser physics, numerical simulation and experimental modeling of complex processes. Rogachev V. G. is one of the leading scientists of VNIIEF in the areas of high-energy density physics and controlled thermonuclear fusion.

## **Hubertus Thomas**

*German Aerospace Center (DLR), Germany*

ORCID: 0000-0001-8358-2023



Hubertus M. Thomas is group leader at the DLR-Institute of Materials Physics in Space in Oberpfaffenhofen, Germany. He received his Diploma in physics from the University of Cologne in 1992, and his PhD degree from Ludwig-Maximilians Universität in Munich in 1996. He was working at the Max-Planck-Institut für extraterrestrische Physik in Garching from 1992 to 2013. Since 2014 he is leading the Working Group on Complex Plasmas at the Institute of Materials Physics in Space of the German Aerospace Center DLR. His research interests are low temperature plasmas and especially complex plasmas, but also atmospheric plasmas for application in hygiene and medicine. He was the responsible scientist for the long-term complex plasma projects PKE-Nefedov and PK-3 Plus, the first and second generation labs, respectively, continuously operated on the International Space Station from 2001-2013 in a German-Russian program. He is the PI of the present facility PK-4 in the Columbus Module of the ISS operational since 2014. Beside the microgravity research a complementary program in the ground lab, in theory and simulation is performed in his group at DLR. Hubertus Thomas is author/co-author of more than 200 publications.

## **Vasco Guerra**

*Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Portugal*

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Vasco Guerra is Associate Professor at the Department of Physics of IST and member of the N-PRiME group of Instituto de Plasmas e Fusão Nuclear, where he is head of the Modelling and Simulation activities. His research focuses on the modelling of the non-equilibrium kinetics of low-temperature molecular plasmas, the modelling of gas-surface reactions, as well as on the foundations of thermodynamics and of special relativity. In 2016 he was awarded the William Crookes Plasma Prize, co-sponsored by the European Physical Society and the Institute of Physics Publishing, "for the outstanding contribution to the modelling of molecular low-temperature plasmas."

## **David B. Go**

*University of Notre Dame, United States*

ORCID: 0000-0001-8948-1442

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David B. Go is the Rooney Family Collegiate Professor in the Department of Aerospace and Mechanical Engineering with a concurrent appointment in the Department of Chemical and Biomolecular Engineering at the University of Notre Dame. He has published widely in the areas of plasma science and gas discharges, heat transfer and fluid dynamics, and chemical analysis, with recent focus on microplasmas, plasma-liquid interactions, and plasma-catalysis. He has authored or co-authored over 70 journal articles, nearly 100 conference papers and presentations, one book, and multiple book chapters and holds three patents. Prof. Go has been recognized with the Air Force Office of Scientific Research Young Investigator Research Award, the National Science Foundation CAREER award, an inaugural winner of the Electrochemistry Society Toyota Young Investigator Fellowship, the inaugural winner of the Electrostatics Society of America Rising Star Award, and the IEEE Nuclear & Plasma Sciences Society Early Achievement Award. He is a Fellow of the American Society of Mechanical Engineers (ASME).

## **Sergei I. Popel**

*Space Research Institute of the Russian Academy of Sciences, Russia*

Scopus ID: 7004783855

Researcher ID: M-3165-2019



Sergey I. Popel graduated with honours from the Moscow Institute of Physics and Technology (MIPT) in 1988. He defended his PhD thesis at MIPT in 1991 and DSc thesis at the General Physics Institute of the Russian Academy of Sciences in 1998. At present, he is a head of Laboratory of Dusty Plasma Processes in Space Objects at the Space Research Institute of the Russian Academy of Sciences. He is also full professor at the Moscow Institute of Physics and Technology and at the National Research University Higher School of Economics. He is an expert in the fields of plasma physics and chemistry, planetary sciences, nano- and microscale objects in nature, self-organization, etc. He was awarded with Humboldt fellowship (Germany), awards of the Moscow Government and the Dynasty Foundation, Prize of International Academic Publishing Company “Nauka/Interperiodica” for the best publication in the journals published by the Company, Yu. A. Gagarin Medal of the Federation of Cosmonautics of Russia for services to cosmonautics, etc.

## **Clare E. J. Watt**

*University of Reading, U.K.*

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Dr Clare Watt is a space plasma physicist specializing in kinetic physics and wave-particle interactions. Her work at the British Antarctic Survey in Cambridge, UK, targeted current-driven instabilities in Earth's magnetosphere, and led to the Royal Astronomical Society's Blackwell Thesis Prize in 2002. At the University of Alberta, Canada, she developed a new drift-kinetic simulation to study the acceleration of electrons by ultra-low frequency shear Alfvén waves above Earth's auroral regions. During her time in Canada, she won the European Geophysical Union "Young Talent in Geosciences" award. She has built Vlasov simulations, drift-kinetic simulations, phase-space diffusion models and designed methods to estimate wave energy density of electromagnetic waves propagating through inhomogeneous plasma environments. Now based at the University of Reading, her focus is the study of wave-particle interactions in Earth's Radiation Belts and the growth of electromagnetic waves at substorm onset.

## **Andrey Divin**

*St. Petersburg State University, Russia*

ORCID: 0000-0002-5579-3066



Andrey Divin is Senior Researcher at the Earth's Physics Department of St. Petersburg State University. During his Ph.D. studies in KU Leuven, Belgium, he participated in development of the massively parallel simulation code iPIC3D. He is currently focused on numerical simulations of plasma dynamics on kinetic (sub-ion) scales using high-performance computing techniques. His research interests include, but not limited to: collisionless magnetic reconnection and plasma instabilities, interaction of the solar wind with minimagnetospheres, and numerical simulation of weak cometary atmospheres.

## **Matteo Barbarino**

*International Atomic Energy Agency, Austria*

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Matteo Barbarino is a Nuclear Plasma Fusion Specialist at the International Atomic Energy Agency (IAEA), Division of Physical and Chemical Sciences, Department of Nuclear Sciences and Applications, where he organizes and implements the IAEA's activities on fusion energy research and development, mainly the ones related to plasma physics.

He graduated at Texas A&M University and received his PhD degree in Physics in 2015.

His work focuses on promoting and supporting existing and novel applications of plasma physics and plasma fusion technology, enhancing international cooperation among small laboratories and main facilities working on fusion and plasma physics.

## **Naoki Tamura**

*National Institute for Fusion Science, Japan*

Scopus ID: 57200763397



My research seeks to understand the transport of impurities in order to control them in magnetically-confined high-temperature plasmas, allowing the realization of a cost-effective magnetic confinement fusion reactor. This research is necessary because the impurities can detrimentally impact the fusion reaction due to fuel dilution, etc. I developed a sophisticated diagnostic tool, Tracer-Encapsulated Solid Pellet (TESPEL), which inserts a 3D-localized impurity source inside the plasmas for more precise measurement of the diffusivity of impurities in the plasmas. We can also utilize TESPEL, owing to its flexibility of impurity payload, to study atomic and molecular processes, which is an important issue not only in fusion plasma, but also in e.g. astrophysics. I have received domestic awards for the development and utilization of the TESPEL technique.

## **Evgeniy Gusakov**

*Ioffe Institute, St. Petersburg, Russia*

Researcher ID: E-2032-2014

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Professor Evgeniy Gusakov is the Head of High Temperature Plasma Physics laboratory in Ioffe Institute. His research focuses on investigation of wave-plasma interaction including nonlinear phenomena; development of microwave plasma diagnostics and studying of RF plasma heating and confinement in tokamaks. In 1981 he was awarded the all-USSR national prize for young scientists. In 2012 he was awarded the Russian and Belorussian Academies of Science prize.

## **Alexander Alekseev**

*ITER International Fusion Energy Organization,  
France*

Scopus ID: 7202891020

Homepage: <https://www.iter.org>



Alexander Alekseev is the Head of Tokamak Engineering Department at the ITER Organization. Alexander Alekseev received the MS degree with honor of Mechanical Engineer-Researcher in the field of dynamics and strength of machine from the St.-Petersburg State Polytechnical University, St.-Petersburg, Russia, in 1986. He received the degree of Candidate of Physico-Mathematical Science (Ph.D.) and the degree of Doctor of Engineering Science from the Efremov Institute, St.-Petersburg, Russia, in 2003 and 2010, respectively. Both works are devoted to the engineering problems of the tokamak superconducting magnet system. He started his career working on engineering of Russian tokamaks at the Efremov Institute and from the very beginning was involved in ITER project activities. At the ITER EDA he coordinated the Efremov Design Office (1995 – 2002) providing engineering support to the Naka JWS. From 2001 to 2003 he was the Responsible Officer for design and analysis for KSTAR project in the frame of the agreement between KBSI and the Efremov Institute. Within the collaboration with IPP (Greifswald) he led supporting design and analysis works for the W7-X magnet system. He is a co-author of the ITER Magnet Structural Design Criteria. Since 2011 he works at the ITER Organization as the Director of Tokamak Directorate and after reorganization in 2015 as the Head of Tokamak Engineering Department. The Department is responsible for development and procurement of ITER Magnet System, Vacuum Vessel, In-vessel Components, Plasma Diagnostics and Current Drive and Heating systems.

## **Anatoly Krasilnikov**

*Institution “Project Center ITER”, Moscow, Russia*

Scopus ID: 35355613200



Anatoly Krasilnikov is doctor of physics and mathematics, director of the Institution “Project Center ITER”, member of the ITER Organization Execution Project Board. His activity and research focused on the ITER construction, magnetically confined plasma physics and diagnostics. In 2018 he was awarded as “Person of the year” in nomination “Science” in scientific town Troitsk and “Honorary member of Ioffe Institute”.

# **SPEAKER ABSTRACTS** In order of presentation

## **DAY 1**

### **Session 1: Fusion**

Vladimir Rozhansky  
Atsuo Iiyoshi  
Josefine Proll  
Boris Kuteev

### **Session 2: Laser-plasma interactions**

Paul McKenna  
Valery Bychenkov  
Victor Malka  
Vladimir Rogachev

## **DAY 2**

### **Session 3: Cold/dusty plasmas and applications**

Hubertus Thomas  
David Go  
Vasco Guerra  
Victor Popov  
Aleksei Siasko  
Alexandra Khirianova

### **Session 4: Astrophysical plasmas**

Sergei Popel  
Clare Watt

Julia Kropotina  
Grigory Vekstein

### **Public lecture**

Matteo Barbarino

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### **Session 5: Fusion**

Naoki Tamura  
Elena Vekshina  
Alexander Yashin  
Mikhail Gryaznevich  
Elena Soldatkina  
Vladimir A. Lykov  
Alexander Alekseev  
Anatoli Krasilnikov  
Evgeniy Gusakov

## **MECHANISMS OF IMPURITY TRANSPORT IN EDGE TOKAMAK PLASMA AND SOLAR CHROMOSPHERE**

**V. Rozhansky, I. Senichenkov, E. Kaveeva**

Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia

In the past years many measurements of the relative element abundances in the solar wind with respect to the chromospheric abundances of the Sun were performed. It was demonstrated that an abundance ratio depends on the first ionization potential (FIP) of an element. As was observed for low FIP elements the ratio of the element density to the hydrogen density in the solar wind is larger than that in the chromosphere. Several models for 'enrichment' have been put forward. However, many explanations invoked completely different physics and different assumptions and none of them looked satisfactory enough.

On the other hand, the impurity species transport has been studied recently in detail for edge plasma of thermonuclear devices such as tokamaks, where the situation is essentially similar to that in the chromosphere. In the edge tokamak plasma understanding of impurity extraction from the divertor regions is of vital importance. At present various impurities (N, Ne, Ar, Xe etc) are used as "radiants" to organize a so-called "detached regime". In this regime the main part of the power coming from the core of a tokamak is radiated before reaching the material surfaces (divertor plates) to protect them from being destroyed by large heat flux density coming from upstream. The injected impurities should be kept in the divertor without significant "leakage" along the magnetic field lines, otherwise the main tokamak plasma would go to the radiation collapse and fusion reactions would not be possible. However, in spite of importance of the problem, lot of experiments and modeling efforts, up to now understanding of the mechanism of impurity extraction was practically absent.

In the present paper a unified mechanism for the impurity extraction along the magnetic field lines is suggested. The key element of the model is the difference in elements ionization potentials, and the suggested mechanism could explain different retention/leakage of impurities both in the chromosphere of the Sun and stars and in the divertor regions of a tokamak. In both situations FIP effect determines level of impurity fluxes directed away from the Sun or divertor region of a tokamak.

## MUON CATALYZED FUSION, PRESENT AND FUTURE

**Atsuo Iiyoshi<sup>1</sup>, Yasushi Kino<sup>2</sup>, Motoyasu Sato<sup>1</sup>, Yoshiharu Tanahashi<sup>1</sup>, Norimasa Yamamoto<sup>1</sup>, Shin Nakatani<sup>1</sup>, Osamu Motojima<sup>1</sup>**

<sup>1</sup>Chubu University, Kasugai, Aichi, Japan; <sup>2</sup>Tohoku University, Sendai, Miyagi, Japan

In 1993, Kino and Kamimura (KK) considered another type of muon catalyzed fusion (MCF) by the non-adiabatic calculations of muonic atom-nucleus in the wide collision energy range from  $10^{-3}$  eV to 100 eV, in which they discussed about the “fusion in flight, via the formation of muonic molecular resonances”. In 1994, Froelich independently calculated up to 2 keV, and found resonance like behavior in the cross section. In 1996, KK examined the resonances, and concluded that the resonances were not suitable for MCF. In 2015, the ImPACT research, financed by Japanese government, called up a Renaissance. Thence, we discussed a possibility of non-resonant fusion in flight and calculated the muonic atom-nucleus collision with much precision within an optical model for nuclear reaction. Calculated fusion cross section was 2000 barns at 1.4 keV which was large enough to use as a neutron source. In order to confirm the results, a new research program support from JSPS/MEXT KAKENHI grant is ongoing both theoretically and experimentally.

Theoretically, a strict few-body computer code has been developed to treat the nuclear reaction as a nucleon transfer reaction. Experimentally, these cross sections are going to be measured using the muon facility in the J-PARC.

Muon catalyzed fusion will be realized first as a neutron source for transmutations of long-lived fission products (LLFP). Chubu University has been studied theoretically by the way of irradiation of fusion neutrons. The flux of neutrons is required to reach  $10^{19} \text{ m}^{-2} \text{ s}^{-1}$  with the initial energy of 14.1 MeV to convert 10-100 kg of LLFP for 10 years to stable nuclei or short-lived radioactive isotopes.

We have proposed the innovative concept of reactor based on In-flight muon catalyzed fusion. The injection of muon to  $\text{D}_2$  and  $\text{T}_2$  gas target confined aerodynamically by Mach shock wave in supersonic stream in Laval nozzle. It generates power of 27 MW with  $10^{19} \text{ cm}^{-3} \text{ s}^{-1}$  of fusions by supplying fresh muons of  $10^{16} \text{ cm}^{-3} \text{ s}^{-1}$  providing 1000 times of catalyzed actions. For getting net Q values  $> 1$ , assuming the 30 % of conversion efficiency from thermal to electric power, the supply energy for a muon production shall be as low as 8 GeV / muons.

## **SIMULATING AND OPTIMISING TURBULENCE IN STELLARATORS**

**Josefine H.E. Proll<sup>1</sup>, Per Helander<sup>2</sup>, Pavlos Xanthopoulos<sup>2</sup>, Harry E. Mynick<sup>3</sup>, Samuel A. Lazerson<sup>3</sup>**

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Stellarators, the twisted siblings of the axisymmetric fusion experiments called tokamaks (with ITER being the most prominent example), have historically suffered from confining the heat of the plasma insufficiently compared with tokamaks and were therefore considered to be less promising candidates for a fusion reactor. This has changed, however, with the advent of stellarators like Wendelstein 7-X, in which the collisional transport is reduced by shaping the magnetic field accordingly. As in tokamaks, the turbulent transport remains as the now dominant transport channel.

In this talk I want to give a brief overview of what we know about turbulence and the underlying instabilities in the - rather complicated - geometry of stellarator plasmas. I will show that some stellarators with a particular magnetic field are more stable towards the turbulence-causing instabilities than others, and discuss what is still missing before these findings can be translated into accurate turbulence predictions for general geometry. Ultimately, these predictions will be necessary to allow us to optimise stellarators not only for laminar, but also for turbulent transport.

## **FUSION-FISSION HYBRID SYSTEMS - YESTERDAY, TODAY AND TOMORROW**

**B.V. Kuteev**

National Research Center "Kurchatov Institute", Moscow, Russia

Combining nuclear fusion and fission reactions in a single design opens up the possibility of achieving fundamentally new characteristics and parameters in energy systems and special applications. Fusion-Fission Hybrid Systems (FFHS) very quickly (in less than 10 years) and effectively solved problems in the field of nuclear weapons. The peaceful use of FFHS in the energy sector, which was also foreseen by the creators of nuclear weapons, has proved to be much more difficult. This report discusses FFHS development: the initial stage in the first 50 years till 2000, the current stage 2000 - 2020 and the long-term targets for 2020-2050.

The first stage is associated with the names of A. Sakharov, E. Teller, H. Bethe, V. Orlov, V. Blinkin, who revealed the potential of FFHS in the energy sector and identified potential applications. Interest in these applications increased and faded as the parameters of thermonuclear systems increased, reaching a maximum in the construction of the largest tokamaks TFTR and JET, which demonstrated the achievement of DT fusion power exceeding 10 MW.

The modern stage can be associated with the names of P. Rebut, E. Velikhov, V. Stacey, Yu. Wu. After the decision, made in 2006, to build ITER with 500 MW DT fusion power, it became clear that the fusion part of FFHS is approaching the parameters of energy systems. Simultaneously the research society started to search for new applications of neutron sources for solving problems of materials science and fundamental physics (neutron scattering). Activities in this direction were supported by the IAEA because the sources of MW-level meet the requirements of energy systems and FFHS created on their basis might use fast reactors materials. The further development is associated with the optimization of neutrons generation and nuclides transmutation. There is increasing interest in breeding tritium by FFHS for launching thermonuclear power plants. Current forecasts indicate the feasibility of industrial FFHS by 2050.

# LASER-DRIVEN RELATIVISTIC PLASMA OPTICS AND ION ACCELERATION IN ULTRATHIN FOILS

**Paul McKenna**

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There is intense international interest in the development of high power laser-driven ion sources due to the unique properties of the ion beam, including its short temporal duration, and the potential to make these sources compact for applications. This has motivated research into new ion acceleration mechanisms, mainly involving ultrathin foils, to increase the maximum energies achieved and to control the spectral and divergence properties of the ion beam. The range of intensities within the laser focus and fast evolving nature of the interaction, means that typically more than one acceleration mechanism occurs in the interaction with a thin foil target. Here we show experimental and numerical results on the interaction of linearly polarized, picosecond-duration, ultra-intense laser pulse interactions with ultrathin foils, in which record proton energies near to 100 MeV are achieved. It is shown that this occurs via a hybrid scheme involving both radiation pressure and sheath acceleration, and that the acceleration field is boosted by the onset of relativistic self-induced transparency in the expanding foil. This occurs due to the super-thermal heating of plasma electrons by the propagating laser pulse. The range of laser and target parameters over which this scheme works is discussed.

We also report on experimental and 3D particle-in-cell simulation results on the collective motion of plasma electrons and ions responding to the propagation of an intense laser pulse through an expanding ultrathin foil which becomes relativistically transparent. It is shown that spatial structure within the beam of energetic electrons produced can be controlled by variation of the laser pulse parameters. Static and rotating electron beam profiles can be induced by variation of the degree of ellipticity of the laser polarisation. The resulting modulation of the charge-separation-induced electrostatic field means that the ion motion can also be manipulated.

## RECENT ADVANCES IN THE LASER-PLASMA PHYSICS OF HIGH ENERGIES

**V.Yu. Bychenkov<sup>1,2</sup>**

<sup>1</sup>P. N. Lebedev Physics Institute, Moscow, Russia; <sup>2</sup>Center for Fundamental and Applied Research, Dukhov Research, ROSATOM, Moscow, Russia

Theoretical-simulation studies of laser-driven charged particle acceleration mechanisms with relativistically intense pulses of ultrashort duration are reviewed for innovative nanosized foil targets, low-density targets either of near critical or near relativistically critical densities, nano/micro-structured targets, and clusters. These targets being optimized over their parameters for given laser intensity allow generate electrons with maximum total charge and protons with maximum energy.

We have proposed new schemes of charge particle acceleration such as so-called SASL (synchronized acceleration by slow light) mechanism for ion acceleration and self-trapping regime for acceleration of electrons. Our analytical and simulation study shed light on the intrigue experimental results on laser-cluster interaction for many years remained controversial.

A theoretical basis for new methods of high-intensity ultrashort laser pulse diagnostics via vacuum charged particle acceleration is proposed.

Our findings constitute important approaches to laser-based radiation and radioactive sources: multi-keV x-ray betatron emission of high brightness, MeV-gamma generation for deep gamma-radiography of dense samples, ultra-broadband THz pulse production providing extreme field strength, neutron generation, production of positrons and mesons. These approaches are illustrated with several examples for multi-TW and PW lasers.

The studies completed were supported by the Russian Science Foundation (the Grants Nos. 14-12-00194 & 17-12-01283).

# MANIPULATING RELATIVISTIC ELECTRONS WITH INTENSE LASERS

**Victor Malka**<sup>1,2</sup>

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Laser Plasma Accelerators (LPA) rely on the electrons motion control with intense laser pulses [1]. The manipulation of such relativistic electrons with lasers allows a fine mapping of the longitudinal and radial components of giant electric fields with values that can exceed hundreds of GV/m [2]. This control is crucial to optimize laser plasma accelerators for delivering ultra-short and ultra-bright energetic particle or radiation beams.

To illustrate the beauty of laser plasma accelerators I will show some concepts that give improvements the quality of the electron beam, its stability [3] and its energy gain [4], and its divergence [5].

I'll then show how by controlling the quiver motion of relativistic electrons intense and bright X-rays beam are produced in a compact and elegant way [6-8]. Finally I'll show some examples of applications.

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## **HIGH-ENERGY DENSITY PHYSICS IN PULSED LASER EXPERIMENTS**

**S.G. Garanin, V.G. Rogachev**

Russian Federal Nuclear Center, All-Russian Research Institute of Experimental Physics, Sarov, Russia

The presentation describes the status and data obtained as a result of activities pursued in the area of pulsed laser high-energy density physics in the All-Russian Research Institute of Experimental Physics.

The data on «ISKRA-5" and “LUCH” fully functional lasers are presented. Some experimental and computational data are provided with respect to LCF inverted corona targets (ICT) allowing reaching extremely high ion plasma temperatures and neutron yields.

As an example of the pulsed laser applications, the research data on rheological properties of moderately loaded materials are presented.

With regard to experimental astrophysics, it is exemplified the physical modeling method for a nuclear explosion impact on an asteroid with the help of a laser pulse focused on the surface of a mini-model. The experimental data and evaluation of the stone asteroid destruction criterion are discussed.

## **COMPLEX/DUSTY PLASMA PHYSICS – FROM LABORATORY TO SPACE**

### **Hubertus M. Thomas**

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A dusty plasma is a plasma containing small solid particles in the range from nanometers to millimeters. Historically, dust in plasma was first observed by Langmuir in his pioneering work on plasma discharges in the 20ies of the last century. Nevertheless, dusty plasma research was concentrated on theoretical aspects of dust in space plasmas, like in cometary tails, Saturn rings, interstellar matter or star and planet forming clouds for a long time. Only in the late 1980ies laboratory research started since the plasma processing industry found the growth of dust particles in their production devices – a growth which diminished the efficiency of their processes.

However, the biggest step in the dusty plasma research happened 25 years ago when in 1994 the Coulomb crystallisation of particles, charged in the plasma – the so-called plasma crystal – was discovered.

Starting with this, the research broadened from plasma physical aspects to classical condensed matter physics relying on the special properties of investigation of phenomena like melting or crystallisation, defect motion, or wave propagation in solids and liquids on the most fundamental - the individual particle level. Soon, it was recognized that strongly coupled dusty plasma is a new form of soft matter with many similarities to complex fluids. This was the reason to create the new field of “complex plasmas” to distinguish natural or by chance occurring dusty plasmas from plasmas where dust particles – in most cases monodisperse and spherical microparticles – were introduced on purpose.

Due to the large mass of the microparticles gravity becomes the dominating force in the laboratory. To overcome this complementary research under microgravity conditions has been performed right from the beginning of the research, starting with parabolic flights and a sounding rocket in 1996, experiments on the Russian MIR Space Station in 1998 and followed by the long-term program on the International Space Station ISS from 2001 until now. The presentation will overview and highlight the research on complex plasmas from the laboratory to space over the last 25 years.

# **INTERFACIAL LOW-TEMPERATURE PLASMAS FOR DIRECTING CHEMISTRY: PERSPECTIVES FROM PLASMA-LIQUIDS AND PLASMA- CATALYSIS**

**David B. Go**

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One of the primary features of low-temperature plasmas is that they generate an abundance of reactive species that can be used to produce useful chemistry. Such chemistry has played an important role in scientific and industrial history, from the dielectric barrier discharge used to discover ozone and arc plasmas to produce fertilizer to the reactive plasmas using modern microfabrication applications. Two areas where there has been significant advances over the past several decades are plasmas in contact with liquids to drive liquid chemistry and plasmas in contact with catalysts to drive gas chemistry. In both cases, multi-phase interfacial phenomena are critical to understanding the underlying plasma physics and the ensuing chemistry.

This talk will overview both of these areas, highlighting recent advances by our group and pointing to opportunities for future developments. One of the primary challenges in plasma-liquid systems is understanding the coupling between the plasma and liquid, including the electrostatics and charge transfer that are essential to maintaining the plasma in contact with the liquid. In our work, we have extensively studied how electrons are transferred from the plasma and dissolve into the liquid, becoming solvated and leading to a wide variety of reduction reactions. In addition to directly detecting the solvated electron in the liquid, we have also shown how the plasma sheath and liquid double layer are electrostatically coupled, such that the plasma itself depends on liquid properties.

In plasma-catalysis, there are a wide variety of unknowns about how plasma species and plasma physics couples to a catalytic material. Typically, reactor design and optimization has been based on trial-and-error approaches, often starting from known quantities from thermal catalysis. In our recent work, we showed how the non- equilibrium nature of the plasma environment is fundamentally different from the equilibrium environment in thermal catalysis, and how this necessitates rethinking catalyst design in these systems.

Measurements of catalytic conversion and plasma properties point strongly to the conclusion that the plasma alters the catalyst activity but that the catalyst does not alter the chemistry that occurs in the plasma itself.

## CO<sub>2</sub> PLASMAS: FROM SOLAR FUELS TO OXYGEN PRODUCTION ON MARS

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CO<sub>2</sub> plasmas constitute a very active field of research nowadays, due to their potential use in several carbon dioxide valorisation strategies, where CO<sub>2</sub> is considered as a viable resource rather than a waste. One of the most noticeable is the production of solar fuels from the conversion of renewable electricity, which always involves a step of reduction of CO<sub>2</sub> into CO [1]. This is the bottleneck of the process, as CO<sub>2</sub> is a very stable molecule, quite difficult to activate efficiently. The interest of CO<sub>2</sub> plasmas for in-situ resource utilisation (ISRU) on Mars has also been recently advocated [2].

This work discusses the similarities and differences between CO<sub>2</sub> plasmas to produce solar fuels on Earth and oxygen on Mars. The investigation comprises a theoretical study based on simulations from a detailed kinetic model, and an experimental campaign to address the influence of Martian conditions in CO<sub>2</sub> dissociation. The theoretical predictions suggest that Mars has excellent conditions for in-situ resource utilisation on Mars by plasmas [2]. In particular, the cold Martian atmosphere may enhance vibration-vibration (V-V) up-pumping and hinder vibration-translation (V-T) deactivation, thus leading to a higher degree of non-equilibrium, the pressure on Mars (~4.5 Torr) is very suitable for plasma operation and small additions of the trace gases Ar and N<sub>2</sub> act as energy savers and can increase CO<sub>2</sub> dissociation. The experimental results corroborate the conjecture of a positive effect of the Martian atmospheric composition on dissociation advanced in [2], confirming the potential of plasma technologies for oxygen production on Mars.

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This work was partially funded by Portuguese FCT - Fundação para a Ciência e a Tecnologia, under projects UID/FIS/50010/2019 and PTDC/FISPLA/1420/2014 (PREMiERE) and grant PD/BD/114398/2016 (PD-FAP- PLAuSE), and by LabEx Plas@par receiving financial aid from the French National Research Agency (ANR) under project ANR-16-CE06-0005-01 (SYCAMORE).

## PLASMA TECHNOLOGIES BASED ON HIGH-VOLTAGE AC PLASMA TORCH

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Most organic compounds are extremely toxic and it directly affects the ecosystem, and their uncontrolled burning leads to the formation of ecotoxicants (for example, benzpyrene and dioxins). One of the possible methods of processing these substances is plasma technology. In most cases, for this purpose air thermal plasma is used. However, when using air as an oxidizing agent, the gaseous products volume increases significantly, which leads to an increase in capital and operating costs. Steam has a significantly higher chemical activity than air at high temperatures.

The report discusses a plasma-chemical facility containing a high-voltage AC plasma torch and 70 liters lined reactor. Steam (3 g/s) and carbon dioxide (3 g/s) are used as plasma-forming media. Chlorobenzene was chosen as a model organic compound (boiling point is 131 ° C). The plant capacity of the chlorobenzene was 3 g/s. It was fed to the plasma torch in a gaseous form to improve its mixing with steam and carbon dioxide. The plasma reactor was preheated to 1250 ° C. The analysis of the products composition of the plasma-chemical process was carried out using a mass spectrometer (gaseous products) and a gravimetric method (for soot). Hydrogen chloride was the only chlorine-containing substance in gaseous products. Soot was a mixture of higher aromatic compounds containing chlorine and oxygen. The carbon soot was 1.31% of raw materials, the chlorine content in soot was 1.61% wt.

The considered plasma torch has several drawbacks: the short lifetime of the electrodes (up to 300 hours) and limitations on power and electric current. To solve these problems, a three-phase high-voltage AC plasma torch with hollow copper electrodes has been developed. Currently this plasma torch operates in air and has the following characteristics: the power is up to 450 kW, the air flow rate is 110 g/s, electrode life is more than 2000 hours, electric arc length is up to 3 m. This model of plasma torch allow to increase the plants capacity and to increase the term of its continuous work.

## CONSTRICTION AND STRATIFICATION OF THE POSITIVE COLUMN OF A GLOW DISCHARGE IN INERT GASES

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The constriction and stratification of a glow discharge is one of the fundamental problems in the physics of the non-equilibrium gas discharge plasma. Today, two different points of view on the nature of constriction have formed. Firstly, the inhomogeneous heating of the neutral gas may cause a compression of the positive column. The redistribution of neutrals along the radius leads to an increase of the reduced electric field  $E/N(r)$  and to a compression of plasma due to the exponential dependence of the ionization frequency on the reduced electric field. Secondly, the competition of the electron – atom and the electron – electron collisions can lead to the depletion of the EDF (electron distribution function) in the high-energy region. This, in turn, results in a compression of the ionization zone due to the exponential dependence of the ionization frequency on the electron density, which decreases from the center to the wall. Experiments show that there is an abrupt transition from the diffuse to the constricted state, which is accompanied by the development of ionization waves of high amplitude (striations). Current paper presents the results on studying the constriction and stratification of a positive column of a glow discharge in neon and argon in the absence of the inhomogeneous heating of the neutral gas. The gas temperature was controlled by interferometric measurements of the refractive index. It is shown that the inhomogeneous heating of the neutral gas is not the primary mechanism during the constriction and stratification of a discharge, but plays a secondary role. At the same time, the inhomogeneous heating in argon is more notable than in neon, leading to the emersion of the plasma cord due to convective fluxes. Detailed modeling also confirms the priority of the kinetic mechanism of an abrupt constriction. The study of the diffuse and constricted discharges for stability with respect to the wave disturbances showed that the diffuse discharge is stable to such disturbances. Constricted column exists in the regime of propagation of essentially two-dimensional ionization waves. Thus, both constriction and stratification arise due to a nonlinear (exponential) dependence of the ionization frequency on the electron density.

# **ABOUT SOME PECULIARITIES OF INTERFEROMETRY FOR MICRON OBJECTS OF THE PRE-BREAKDOWN STAGE OF AIR DISCHARGE**

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Plasma formations with characteristic sizes of  $\sim 50\text{-}100\ \mu\text{m}$ , arising in the discharge after the breakdown of  $\sim 1\ \text{mm}$  air gap with the characteristic tip-plane geometry of electrodes are investigated.

The processing of the results of multi-frame laser probing of an object, in particular, the interferograms of an object obtained with a spatial resolution of  $3\text{-}4\ \mu\text{m}$ , is described. The method involves taking into account the correction of the diffraction effect due to defocusing by solving the Helmholtz equation in the Rytov approximation. The features of processing interference frames in the cathode region and the cathode shadow region, which is difficult to process, are described. A two-dimensional map of the phase delay on the object is reconstructed, layer-by-layer processing of the obtained distribution is carried out to get a two-dimensional map of the object density assuming cylindrical and spherical symmetry of the object in different zones of the spark channel. Verification of the results obtained is carried out by processing the schlieren frames of the object.

The experimental study is partially supported by the Russian Foundation for Basic Research (grant no. 18-32-00566). The plasma analysis and interferogram processing is partially supported by the Russian Foundation for Basic Research (grant no. 18-32-00012).

## DUSTY PLASMA AT THE MOON. CHALLENGES OF MODELING AND MEASUREMENTS

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Investigations of the Moon got new momentum nowadays. The Luna-25 and Luna-27 missions are being prepared in Russia. At the same time, in connection with the future lunar missions, theory investigations of dust and dusty plasmas at the Moon are being carried out. Here, the corresponding results are reviewed briefly. We present the main theory results of these investigations concerning the lunar dusty plasmas. We show, in particular, the absence of the dead zone near a lunar latitude of  $80^\circ$  where, as was assumed earlier, dust particles cannot rise over the surface of the Moon. This indicates that there are no significant constraints on the Moon landing sites for future lunar missions that will study dust in the surface layer of the Moon. We demonstrate that the electrostatically ejected dust population can exist in the near-surface layer over the Moon while the dust appearing in the lunar exosphere owing to impacts of meteoroids present everywhere. The calculated values of number densities at high altitudes of the particles formed as a result of the impacts of meteoroids with the lunar surface are in accordance (up to an order of magnitude) with the data obtained by the recent NASA mission LADEE. Finally, we formulate new problems concerning the dusty plasma over the lunar surface.

A feature of the circumlunar space is the presence of a dusty plasma system. This system is an object of current lunar studies. The Luna-25, Luna-26, Luna-27, Luna Sample Return missions are under preparation in Russia. The landing modules of the Luna-25 and Luna-27 spacecrafts are planned to be equipped with instruments for studying the properties of the dusty plasma over the surface of the Moon. Piezoelectric shock sensors (IS) are supposed to be used for direct detection of dust particles over the surface of the Moon while electric field sensors (ES), operating analogously to a classical Langmuir probe, will record primarily the parameters of the dusty plasma environment. Optical observations of dust will be performed with the aid of stereo camera (Cam S) and surveillance cameras (Cam O).

In connection with the future lunar missions Luna-25 and Luna-27, where measurements of dust and dusty plasmas are planned to be carried out at

heights that do not exceed several meters, self-consistent studies have been carried out which consider dusty plasma system in the near-surface layer of the Moon. Furthermore, theory research of dusty plasmas at high altitudes over the lunar surface has been performed. Here, we present a brief review reflecting the results of these studies.

The lunar surface at the illuminated part of the Moon is charged under the influence of the solar electromagnetic radiation, the solar wind plasma, and the plasma of the terrestrial magnetosphere tail. Upon interacting with the solar radiation, the lunar surface emits photoelectrons due to the photoelectric effect. This leads to the emergence of a layer of photoelectrons above the surface. Additional photoelectrons are emitted by the dust particles levitating above the lunar surface when these particles interact with the solar electromagnetic radiation. The dust particles located on the lunar surface or in the near-surface layer absorb photoelectrons, photons of the solar radiation, electrons and ions of the solar wind, and (if the Moon is located in the terrestrial magnetosphere tail) electrons and ions of the magnetosphere plasma. All these processes promote charging of the dust particles, their interaction with the charged lunar surface, and the dust levitation and motion.

The distributions of the dust and electrons in the near-surface layer of the illuminated part of the Moon are calculated using the theoretical model, in which the charging of dust grains over the lunar surface is determined within the orbit-limited probe model with allowance for the influence of photoelectrons, solar wind electrons and ions, and solar radiation.

# **WAVE-PARTICLE INTERACTIONS IN EARTH'S INNER MAGNETOSPHERE ACROSS DIFFERENT TIMESCALES**

**Clare Watt**

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The Earth's Outer Radiation Belt is a highly-variable region of high-energy electrons that forms a torus spanning 2.5-7 Earth radii from our planet. In this region of the inner magnetosphere, the number flux of electrons of energies between 100keV to a few MeV can vary by orders of magnitude in a matter of hours. It is now widely understood that a large contribution to the variability in the Outer Radiation Belt is wave-particle interactions in the collisionless natural plasma environment of the Earth's magnetosphere. Many different wave modes, across a large frequency range, are important for the dynamics of the Outer Radiation Belt, but here we focus on the physics of the whistler-mode interaction with electrons in all its different manifestations.

The whistler-mode wave is a right-hand polarised electromagnetic wave mode with frequency between the proton and electron gyrofrequency that displays different characteristics in different parts of the magnetosphere. Evidence of temperature anisotropy and beam-driven instabilities both exist, but some magnetospheric whistler-mode waves are generated in the terrestrial atmosphere during lightning strikes (true "whistlers"), and some from man-made VLF transmitters on Earth's surface.

The wave-particle interaction between whistler-mode waves and electrons in the inner magnetosphere is governed by kinetic plasma physics. Our challenge is to include the kinetic physics of the interaction in models that span time and length scales that are >4 orders of magnitude greater than the time and length scales of the wave-particle interaction.

We use observation, linear and quasilinear theory and fully nonlinear numerical experiments to study both acceleration and loss of electrons in the Outer Radiation Belt of Earth as a result of all the different manifestations of whistler-mode waves. We compare and contrast the observational evidence for different types of whistler-mode waves in the magnetosphere and discuss the theoretical approaches suitable to bridge the gap between the millisecond timescale of the whistler-mode wave, and the many days timescale required to model the behaviour of the Earth's Outer Radiation Belt.

# HIGH-PERFORMANCE COMPUTING IN APPLICATION TO SOLAR SYSTEM PLASMA DYNAMICS

## A. Divin

St. Petersburg State University, St. Petersburg, Russia

In various environments of interest, like the Earth's magnetosphere or the solar wind, plasma can be considered fully collisionless. From theoretical viewpoint, collisionless plasma is described by the Vlasov-Maxwell coupled system of equations, making formation of fine structures in the velocity space possible. Numerically, the velocity space adds 1,2 or 3 extra dimensions to the 1D, 2D or 3D spatial problem, therefore the amount of resources, needed for a simulation, is significantly increased if compared to the fluid treatment. The most comprehensive account of plasma dynamics is provided by the evolution of the particle distribution function (the so-called "Vlasov approach"). A more robust and widely used approximation is to use macroparticles which move in self-consistent electromagnetic field ("Particle-in-Cell", PIC methods). The task is extremely challenging from computational point of view, stressing the need of supercomputing resources.

We discuss results produced by a semi-implicit, fully kinetic, electromagnetic code iPIC3D. The code solves the Vlasov-Maxwell system of equations for both ions and electrons using the implicit moment method allowing large-scale domains in three dimensions. iPIC3D keeps properties of a full kinetic model but lifts such typical explicit code stability constraints as the necessity to resolve the Debye length or light waves. The code was used previously at various supercomputer facilities (Pleiades, Curie, Lomonosov, Beskow, Marconi supercomputing machines) with up to 100'000 cores. Three main applications of iPIC3D are reviewed: magnetic reconnection, ion-scale interaction of the solar wind with Lunar Magnetic Anomalies (LMAs) and solar wind-weak comet (67P/Churyumov-Gerasimenko at  $\sim 3$  AU) interaction.

## **HYBRID SIMULATIONS OF COLLISIONLESS SHOCKS IN ASTROPHYSICAL PLASMA**

**Julia Kropotina, Andrei Bykov**

Ioffe Institute, Saint Petersburg, Russia

The results of kinetic hybrid simulations of collisionless shocks with various parameters are presented. The collisionless nature of the shocks leads to plasma instabilities, magnetic field amplification, particle acceleration and long lived non-maxwellian distributions of ions. The hybrid kinetic ions-liquid electrons approach allows to study all these effects on ion scales from the first principles. The applications for the Solar wind, Supernova remnants and galaxy clusters shocks are discussed.

## **HALL – MHD REGIMES OF PLASMOID INSTABILITY**

### **Grigory Vekstein**

Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, University of Manchester, Manchester, UK

Magnetic reconnection is a fundamental process allowing fast release of excess magnetic energy accumulated in a magnetohydrodynamic system. It plays a pivotal role in various phenomena occurring in space and laboratory plasmas (solar flares, magnetic sub-storms, tokamak disruptions, etc.). Although history of its investigation spans for more than half a century, some important details of this process are still not fully understood. The major outstanding issue is to explain why the pace of magnetic reconnection is almost insensitive to a magnitude of the plasma resistivity (or other effects) that makes breaking of magnetic field lines possible in the first place.

This problem prompted renewed interest in the so-called plasmoid instability, which is the tearing mode developing in an evolving current sheet. A large body of observations and numerical simulations clearly indicates that this instability is crucially involved in the transition to fast reconnection. In this context the important issue is revealing the fastest mode (a mode with the maximal growth rate), which kick-starts the subsequent process of nonlinear interaction of plasmoids eventually leading to the onset of fast magnetic reconnection.

However, the standard MHD theory of the tearing instability is not applicable to highly elongated current sheets that are likely to form in a hot plasma. In this case the two-fluid plasma model should be explored, which brings about the Hall effect. Thus, here we review a comprehensive description of the Hall-mediated tearing instability, which could be relevant to the study of magnetic reconnection and magnetic turbulence in MHD objects with a large Lundquist number.

## **THE IAEA'S ACTIVITIES IN SUPPORT OF FUSION ENERGY RESEARCH, PLASMA PHYSICS AND TECHNOLOGY**

**Matteo Barbarino, Sehila M. Gonzalez de Vicente, Danas Ridikas**

International Atomic Energy Agency, Vienna, Austria

The objective of fusion power development is to bring to the world a safe, economical and essentially unlimited energy source. While considerable progress has been made during the last few years, there is still a great deal of R&D needed. The International Atomic Energy Agency (IAEA) fosters international collaboration and coordination to help close the existing gaps in physics, technology and safety and move forward in developing the peaceful use of fusion energy. The IAEA activities in this field cover, among others, plasma physics and fusion energy research, technologies and materials, and take place under the guidance of the International Fusion Research Council and the Subcommittee on Atomic and Molecular Data for Fusion, with the objective of encouraging the development of new technologies and science for ITER and contributing to the roadmap for a DEMO fusion power plant. The IAEA promotes international research and exchange of information on fusion specifically through its series of Fusion Energy Conferences, Coordinated Research Projects, Technical Meetings and Workshops, and publishing the leading scientific journal in the field, Nuclear Fusion, to enhance the awareness of the potential benefits of fusion as a long-term energy option and support R&D activities to the development of nuclear fusion reactors and to a global readiness to tap this form of energy when available. As R&D priorities are moving towards nuclear technology for fusion energy and industrial applications, plasma physics stays at the heart of present and future research, and the IAEA keeps supporting much of the research into plasma science and applications playing an important bridging function between the 35 ITER members and the other IAEA Member States. In this talk, an overview of the IAEA's activities in support of fusion energy research, plasma physics and technology will be presented. Besides, recent advances in this field call for the IAEA to adjust its focus in a way to encourage technological and safety-related developments that need to keep up with the pace of scientific knowledge advances. Future plans and priorities in this new area will be presented and placed in context as part of the wider fusion R&D effort.

## **PROGRESS OF THE LARGE HELICAL DEVICE (LHD) PROJECT TOWARD UNDERSTANDING PLASMA CONFINEMENT BY 3D EXTERNAL COILS**

**Naoki Tamura on behalf of LHD Experimental Group**

National Institute for Fusion Science, National Institutes of Natural Sciences,  
Toki, Japan

Large Helical Device (LHD), which is one of the world's largest magnetic confinement fusion experiment devices, solely employs three-dimensionally(3D)- shaped external superconducting magnetic field coils to confine high-temperature plasmas in the magnetic cage. LHD is based on a heliotron (non-axisymmetric 'stellarator'-like) concept that differs from the axisymmetric 'tokamak' concept, which requires a large current in the plasma to produce part of the magnetic field. Stellarators thus have an inherent advantage for steady-state operation. Over the recent two-decade-long experiment, LHD has demonstrated the capability of stellarators. Accordingly, high-performance and steady-state plasmas, which are comparable to those in tokamaks, have been obtained. Moreover, LHD has also yielded significant findings, such as non-diffusive and non-local transport in the physics of toroidally confined plasmas. In LHD, the D-D (deuterium-only) operation has been launched from March 2017. This allows us to further deepen our physical understanding of toroidally confined plasmas, such as isotope effect on bulk ions, electrons, impurities, and energetic ion transport, as well as to open the stellarator frontier toward the reactor-relevant regime.

Recent studies in tokamaks suggest that application of a non-axisymmetric 3D magnetic field to the tokamak configuration is effective for controlling magnetohydrodynamic instabilities, such as edge-localized modes. Therefore, knowledge and information obtained from the LHD project can contribute to the ITER project, in particular regarding 3D field effects (e.g., impact of 3D field on the energetic ion confinement) and the establishment of a database for designing a cost-effective steady-state helical fusion reactor. In this conference, the progress of the LHD project will be presented in further detail.

## MODELING OF GLOBUS-M CONNECTED DOUBLE-NULL DISCHARGE

**Elena Vekshina<sup>1</sup>, Vladimir Rozhansky<sup>1</sup>, Elizaveta Kaveeva<sup>1</sup>, Ilya Senichenkov<sup>1</sup>, Nickolay Khromov<sup>2</sup>**

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<sup>2</sup>Ioffe Institute, Saint Petersburg, Russia

Two Ohmic H-mode discharges of tokamak Globus-M with similar parameters and different magnetic configurations were simulated with SOLPS-ITER code. One of the discharges has two separatrixes and active low X-point – disconnected double null (DDN). The second discharge has connected double null configuration (CDN). The modelled plasma parameters were matched to the experimental ones. Scrape-off Layer (SOL) width and energy loads on the divertor targets have been analysed for both cases. It is demonstrated that for the Globus-M CDN configuration energy peak load at the lower outer divertor plate halves. It is also shown that the electric currents flowing from the plasma to the target plates change the energy flux to the plates in both cases with respect to the flux one would expect for the floating potential at the plates. Two types of electric currents flowing to the plates were observed. The first one is a well-known thermoelectric current flowing between magnetically connected plates with different electron temperature. This current is more pronounced in the DDN case and is strongly reduced in the CDN case, where the difference between the temperatures at the lower and upper plates is modest. In addition, a new second type of electric currents to the plates is obtained which might be called plate closing currents (PCC). These currents close radial currents in the SOL and private region (PR). For DDN case the PCC currents are comparable with the thermoelectric ones, while for CDN case the PCC currents dominate.

## **STUDY OF TURBULENCE IN THE GLOBUS-M TOKAMAK PLASMA DURING THE TRANSITION TO THE ELM-FREE H-MODE**

**A.Y. Yashin<sup>1</sup>, V.V. Bulanin<sup>1</sup>, A.V. Petrov<sup>1</sup>, E.A. Zhivulin<sup>1</sup>, V.K. Gusev<sup>2</sup>, G.S. Kurskiev<sup>2</sup>, V.B. Minaev<sup>2</sup>, M.I. Patrov<sup>2</sup>, Y.V. Petrov<sup>2</sup>**

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One of the most important issues in the tokamak's path to a thermonuclear power plant is the implementation of a high plasma confinement mode (H-mode) without large pulsed thermal loads on the wall, which are usually the result of instabilities caused by the high edge pressure gradient. These periodic emissions of heat and particles from the plasma core are caused by magnetohydrodynamic instabilities known as edge localized modes (ELMs). As was recently shown, it is possible to operate tokamaks in the H-mode without ELMs.

The transition from the ELMy H-mode to ELM-free H-mode was found on the Globus- M tokamak. The paper is devoted to the study of the dynamics of turbulence during this transition. The main method of turbulence studying was Doppler backscattering. Studies have been performed at different radii (in areas with different plasma parameters). It was found that during the transition from H-mode with edge localized modes (ELMs) to the improved confinement mode without ELMs, both turbulent fluctuations of the plasma density and velocity fluctuations are suppressed, which apparently leads to a decrease in anomalous transport.

The work was supported by the grant from the Russian Science Foundation (project number 18-72-10028).

## **FASTER FUSION: ST40, ENGINEERING, COMMISSIONING, FIRST RESULTS**

### **M. Gryaznevich and Tokamak Energy team**

Tokamak Energy Ltd, Milton Park, Oxon, UK

Spherical Tokamak (ST) path to Fusion has been proposed in R Stambaugh et al, Fus. Tech. 33(1998) 1, and experiments on STs demonstrated feasibility of this approach. Advances in High Temperature Superconductor technology (M Gryaznevich et al, Fus. Eng. & Design 88 (2013) 1593); allows significant increase in the Toroidal field which was found to improve confinement in STs. The combination of the high  $\beta$ , which has been achieved in STs (M Gryaznevich et al, Phys Rev Lett 50 (1998) 3972), and high TF that can be produced by HTS TF magnets, opens a path to lower-volume fusion reactors, in accordance with the fusion power scaling proportional to  $\beta^2 B_t^4 V$ . Modular approach then becomes an alternative to high power, GW-scale Fusion reactors. Feasibility of low-power compact ST reactor module and physics and engineering challenges of the ST path to Fusion Power will be discussed. High field spherical tokamak ST40 (R=0.4-0.6m, R/a=1.6-1.8, I<sub>p</sub>=2MA, B<sub>t</sub>=3T, k=2.5,  $\tau_{\text{pulse}} \sim 1-10$ sec, 2MW NBI, 2MW ECRH/EBW, DD and DT operations) is the first prototype on this path and is now operating. TF Cu magnet in ST40 will be LN<sub>2</sub> cooled and research is on-going on development of full-HTS magnets. TF of 3T in ST makes ST40 to have 3 times higher field than in any operational or upgraded STs and is an important step on the ST path to Fusion. 1.5T has been already achieved in ST40, which is the record for STs. Temperatures in 1-2keV range and plasma current up to 400kA have been already achieved in the first experimental campaign. Experiments on ST40 are already demonstrating improvement in performance at high field in ST. Details of engineering design, diagnostics, heating systems, results of commissioning, of first experiments and experimental plans will be presented.

# **THE 1D-CALCULATIONS OF THERMONUCLEAR IGNITION MARGINS OF DIRECT – DRIVE TARGETS FOR MEGAJOULE FACILITIES WITH LASER WAVELENGTH OF 0.35 AND 0.53 MKM**

**Vladimir Lykov, Ekaterina Bakurkina, Valerian Chernyakov, Nicolai Karlykhanov, Ivan Khimich, George Rykovanov**

RFNC-VNIITF named after academician E.I. Zababakhin, Snezhinsk, Russia

The results of a comparative calculations of cryogenic direct-drive targets for a megajoule facilities with laser wavelength  $\lambda = 0.35$  and  $\lambda = 0.53 \mu\text{m}$  are presented. Calculations were performed with the using of the 1D - radiation hydrodynamics code ERA with the account for non-local electron transport and laser light absorption model that takes into consideration stimulated Brillouin scattering (SBS), the generation of fast electrons in processes of two - plasmon decay (TPD) and stimulated Raman scattering (SRS). The ignition margin ( $W_Q$ ) of nonuniform thermonuclear targets with allowance for energy losses from hot spot due to electron heat conductivity has been accepted as the objective function at carrying out of a target numerical optimization. The ERA code simulations have shown that a preheat of targets by fast electron generated in processes of TPD and SRS would fatally lower a possibility to achieve thermonuclear ignition of direct - drive targets with CH-ablator in future experiments at megajoule facility with laser wavelength  $\lambda = 0.53 \mu\text{m}$ .

The ignition margin of targets increases about twice with the  $\sim 1.6$ -fold increase of CH-shell aspect ratio, or at the using of glass ablator.

However, they remain considerably lower the threshold of the ignition for laser radiation with wavelength  $\lambda = 0.53 \mu\text{m}$ . The ignition margins increase by 2-3 times at the transition of a MJ-laser facility from the 2<sup>nd</sup> to the 3<sup>rd</sup> harmonic of the Nd-laser radiation. It is noted that introduction of a shifts between a centers of laser emission lines in the neighboring channels by  $\Delta\lambda \approx 10 - 20\text{\AA}$  can significantly decrease the SBS effects. In this case the ignition margin  $W_Q \sim 1,7$  and fusion energy yield  $\sim 50$  MJ were obtained in the 1D-calculations of cryogenic direct – drive targets with glass ablator for laser radiation energy about of  $\sim 2$  MJ with laser wavelength  $\lambda = 0.35 \mu\text{m}$ .

## REVIEW OF RECENT ADVANCES AND NEW IDEAS IN DEVELOPMENT OF THE OPEN MAGNETIC TRAPS

**Anton Sudnikov and Elena Soldatkina on behalf of the scientific council of the Budker INP on plasma physics**

Budker Institute of Nuclear Physics, Novosibirsk, Russia

Advanced plasma confinement in magnetic mirrors features high relative pressure ( $\beta \approx 60\%$ ), mean energy of hot ions of 12 keV and electron temperature of up to 0.9 keV in quasistationary regime today. These parameters in gas-dynamically confined plasma exceed both the design parameters of the GDT device and the parameters, which can be obtained in linear plasma with classical longitudinal thermal conductivity. The progress in confinement became possible due to the implementation of new techniques, such as vortex confinement, electron losses suppression by the expanders and moderate power of the local ECR heating.

In modern concepts, mirror ratios of  $\sim 15\text{--}20$  and improved longitudinal confinement are proposed. The existing method of multiple-mirror suppression of the axial flux combined with a gas-dynamic central cell can provide an effective mirror ratio of the order of 100, which gives fusion gain appropriate for neutron sources and hybrid fusion-fission reactors in a  $\sim 50$ -meter-long linear machine. Pure fusion reactors with DD and, under some assumptions,  $p^{11}\text{B}$  fuels are presumably possible.

Helical and diamagnetic confinement are two new possible ways of further improvement of the longitudinal confinement. The idea of the helical confinement considers a flow of a rotating plasma through a linear magnetic system with helical symmetry. Periodical variations of the helicoidal magnetic field, which move upstream in plasma's frame of reference transfer momentum to plasma. The diamagnetic confinement considers plasma with the relative pressure  $\beta \sim 1$ . Low magnetic field inside a «diamagnetic bubble» leads to the sufficiently higher mirror ratio compared to the vacuum magnetic field one. This report sums up the experiments on magnetic mirrors in the Budker INP and their contribution to the next-step linear machine efforts. GDT (gas-dynamic), GOL-NB (multiple-mirror), SMOLA (helical) and CAT (diamagnetic) programs will be presented, as well as the next-generation GDMT project, which includes all the discussed ideas.

## **THE ITER PROJECT – ON THE WAY TO FUSION ENERGY**

**Alexander Alekseev**

ITER Organization, St. Paul-lez-Durance, France

ITER – designed to demonstrate the scientific and technological feasibility of fusion power – will be the world's largest experimental fusion facility. Fusion is the process that powers the Sun and the stars: when light atomic nuclei fuse together to form heavier ones, a large amount of energy is released. Fusion research is aimed at developing a safe, abundant and environmentally responsible energy source. ITER is also a first-of-a-kind global collaboration. Europe is contributing almost half of the costs of its construction, while the other six Members to this joint international venture (China, India, Japan, the Republic of Korea, the Russian Federation and the USA), are contributing equally to the rest. The ITER Project is under construction in Saint-Paul-lez-Durance, in the south of France. In this presentation we will report about the progress made until today and what lies ahead in the coming months and years.

## **FUSION TECHNOLOGIES: FROM ITER TO THE NEXT STEP IN RUSSIA**

### **Anatoly V. Krasilnikov**

Institution “Project Center ITER”, Moscow, Russia

The tokamak plasma configuration was invented and research at several first tokamaks started in “Kurchatov institute” at the beginning of 1950s. More than 200 tokamaks have been constructed in scientifically and technologically developed countries up to now. 11 and 17 MW of fusion power were produced at TFTR (USA) and JET (EU) in 1994 and 1997, respectively. In 1986, following the proposal of the Soviet Union, design of the International Thermonuclear Experimental Reactor ITER with project value of fusion power of 500 MW was started. At the moment all ITER systems including 25 of RF responsibility are being manufactured in scientific centers and industrial plants of 7 ITER Partners.

In the frame of the ITER project in Russia the following items have been created:

- manufacturing of superconductors (JSC «TVEL», JSC «ChMZ», JSC VNIKP, JSC “Bochvar institute”, IPHE, NRC «Kurchatov institute», JSC «Efremov institute”, JSC «SNSC»);
- technologies and semi-industrial plants for first wall and divertor manufacturing (JSC “Efremov institute” and JSC “Dollezhal institute”);
- experimental benches and technologies to perform first wall and divertor component tests (JSC “Efremov institute”, JSC “Dollezhal institute”, and JSC SRC RF TRINITI);
- gyrotrons (invention and successful manufacturing in IAP RAS and JSC “Gykom”);
- atom beam injectors with parameters: 1000 keV, 5 MW, 1000 s. (INP SB RAS);
- and the following are being created:
- methods and equipment for stationary non-inductive plasma current

- generation (NRC «Kurchatov institute», «Ioffe institute»);
- port-plugs (INP SB RAS) and port plug test facilities (JSC «Cryogenmash»);
- methods and equipment for plasma diagnostics (NRC «Kurchatov institute», «Ioffe institute» INP SB RAS, Institution «Project center ITER», «Fusion-center» JSC SRC RF TRINITI).

In accordance with the Joint Implementation Agreement for the creation of ITER Organization, Russian Federation has the right for free licenses for applications in the national fusion program for all technologies created in the frame of ITER project, as well as information about world fusion industry. However ITER technologic platform does not include all technologies required for fusion reactor creation, namely Li first wall, methods of non-inductive plasma current generation, HTSC coils, radiation hardness test technologies of reactor components, etc. To provide a successful creation of a fusion reactor in Russia it is necessary to arrange an efficient participation of Russian scientists and specialists in ITER construction and experiments in 2025-2045 and to create in Russia an experimental scientific and technological basis (technological platform) – Tokamak with Reactor Technologies (TRT) – prototype of the plasma part of a hybrid (fusion-fission) reactor. Main technical solutions and components of TRT that could be created by Russian scientific centers and industrial companies today will be presented in report.

## **HIGH TEMPERATURE PLASMA PHYSICS AND FUSION RESEARCH IN IOFFE INSTITUTE**

**Evgeniy Gusakov, FT-2 team, Globus-M2 team, TUMAN-3M team, Plasma theory group, ITER diagnostics group**

Ioffe Institute, St.Petersburg, Russia

Status of high temperature plasma physics and fusion research in Ioffe Institute is described with a brief insight into history. Studies traditionally oriented to the investigation of stability, transport, heating, current drive and diagnostics of high temperature tokamak plasmas are described. Results obtained at three actively functioning small research tokamaks with significantly different parameter spaces: FT-2 ( $B=2-3$  T,  $I_p=20-40$  kA,  $R=55$  cm,  $a=8$  cm), Globus-M(M2) ( $B=0.4 - 1$  T,  $I_p=200-500$  kA,  $R=36$  cm,  $a=24$  cm), TUMAN-3M ( $B=0.5-1.2$  T,  $I_p=120-180$  kA,  $R=53$  cm,  $a=22$  cm) are presented. Peculiarities of lower hybrid, ion cyclotron and electron cyclotron heating and current drive experiments are discussed in the context of results provided by the plasma-wave interaction theory producing the basis for experiments and diagnostics development. A wide variety of fast particle physical effects accompanying neutral beam injection experiments are presented. The progress of ITER diagnostics development is followed.

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## **MODELING OF GLOBUS-M2 SPHERICAL TOKAMAK EDGE WITH NITROGEN SEEDING**

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The reduction of heat fluxes to the tokamak divertor targets is a crucial problem of future thermonuclear devices, like ITER, DEMO and beyond. According to a present understanding of the Scrape-Off Layer (SOL) physics, such devices should operate in a detached divertor regime, when most of the exhaust power coming to a divertor region is dissipated by the radiation. Recent experiments at ASDEX Upgrade, JET and other tokamaks demonstrated that the transition to the detachment might be achieved by the intensive puff of radiative impurity. Spherical tokamaks can give a contribution to the understanding of mechanisms, which defines the impurity circulation in the tokamak volume. Fusion neutron source for a hybrid fusion–fission reactor is considered to be based on a spherical tokamak, and in a steady state can face the problem of critical heat loads. Simple estimates of power fluxes to the divertor of Globus-M2 tokamak (which is an upgraded Globus-M tokamak) results in that they will exceed the limit of 10 MW/m<sup>2</sup> at both inner and outer divertor targets, so the impurity seeding might be required. In the present paper the modeling of different regimes of Globus-M2 tokamak is performed by the SOLPS-ITER code with varying nitrogen seeding rate. It is demonstrated that with seeding rate almost equal to the deuterium puff (as measured in electrons/sec) a significant reduction of the peak power density at the outer target plate may be achieved, while the inner target plate goes to a detachment with a formation of High Field Side High Density (HFSHD).

This result is similar to what is observed in the experiments at ASDEX Upgrade (AUG). However, in contrast to AUG, further increasing of the seeding rate leads to a radiative collapse rather than to a formation of the radiative spot near the X-point.

This is caused by a smaller machine size, which allows the impurity neutrals to penetrate easier into the confined region.

## **ENERGY RELEASE IN BE, C AND W DUE TO IRRADIATION WITH D AND T ATOMS**

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Projected energy losses of hydrogen isotopes bombarding Be, C and W surfaces were calculated for the typical plasma particle energy range in the ITER tokamak-reactor (0.1 - 20 keV). It was shown that for energies less than 50 keV the energy release maximum occurs near the surface. Binary collision approximation was used in this work. To describe particle scattering, we chose DFT potential, obtained in the framework of density functional theory, which predicts the presence of an attractive potential well. The attractive well impacts surface scattering coefficients. Thermal vibrations of the target atoms were taken into account. Electronic stopping data was obtained from the NDS data base. Nuclear stopping was calculated directly using collision kinematics. Due to charge exchange and photorecombination, atoms leaving the plasma will be produced in the deuterium-tritium plasma inside the ITER tokamak. We calculated energy spectra of D and T atoms bombarding the first wall at different angles.

Inductive scenario was used in the calculation. Using these energy spectra, we estimated the heating of the near-surface layers of the walls. The contribution of reflected particles was also taken into account. As in the case of a monoenergy beam, the maximum of the energy release is observed near the surface. Tritium atoms, on average, penetrate deeper into the material of the wall, which can lead to their accumulation.

## **GLOBUS-M2 EXPERIMENTS IN SCOPE OF FUSION-FISSION REACTOR DEVELOPMENT**

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Globus-M2 is a new one-Tesla spherical tokamak, located in Ioffe institute, Russia. It was launched in 2018; first full-scale experimental campaign starts this year.

Globus-M2 keeps size of the predecessor Globus-M: plasma major radius  $\approx 36$  cm, minor radius  $\approx 24$  cm, elongation  $\approx 2$ ; however, toroidal magnetic field and plasma current are increased two times up to 1 T and 500 kA respectively. Auxiliary heating systems and diagnostics have also been upgraded. Globus-M2 is expected to demonstrate sustenance of a plasma discharge in a Tesla range magnetic field with the extreme heating power density (up to 5 MW/m<sup>3</sup>) under a record mechanical stress level in a compact machine.

Given report is focused on the role of Globus-M2 in Russian hybrid fusion-fission program and describes the role of the machine in the present world fusion studies. First Globus-M2 experimental campaign is considered. It is centered on the experiments, unique for the spherical tokamaks (Lower Hybrid Current Drive and minority Ion Cyclotron Resonance heating) and reactor-relevant issues: current drive, energy and fast ion confinement, non-inductive plasma current start-up, divertor and SOL plasma studies. Finally, Globus-3 – intermediate step between present facilities and future hybrid reactors – is discussed.

Reported studies were supported by RSF research project № 17-72-20076

## **SOLPS-ITER MODELING WITH BE IMPURITY FOR ITER INCLUDING WALL COMPOSITION DYNAMICS MODEL**

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Beryllium transport modeling was carried out by SOLPS-ITER code for tokamak ITER using new surface composition dynamic model for divertor tungsten plates. This advanced wall interaction model included beryllium redeposition and resputtering, which were not considered in SOLPS-ITER code before. TRIM reflection model and Roth-Bogdanskii formula sputtering model were applied. SOLPS-ITER code has key advantage comparing to other codes, which study beryllium transport, because it describes the main plasma and impurities self-consistently. Therefore, if beryllium affects the background plasma, only this code can take this effect into account. Two regimes were modelled: 1) 11.1Pa neutral pressure under Dome and 1.2% Ne at the separatrix; 2) 7.4Pa neutral pressure under Dome and 0.6% Ne at the separatrix. In the latter case the outer target is in weaker detachment regime. In the first case significant Be deposition appears above the strike point (near- SOL) at the outer target, while in the second case there is no deposition above the strike point at the outer target. The main cause of this difference is higher ion and electron temperatures in the weaker detachment regime, which leads to higher energy of impinging ions and more effective resputtering. Inner target strike point remains in deep detachment in both cases and big Be deposition remains above the strike point. For the second case Be trace impurity run was carried out to compare with standard case and find out Be impact on the background plasma. The difference between the standard case and the case where beryllium is present only as a trace impurity is very small showing that sputtered beryllium impact on main plasma is not significant.

## **FIRST RESULTS FROM THE THOMSON SCATTERING DIAGNOSTICS ON GLOBUS-M2**

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Thomson scattering is considered as a key diagnostics in all fusion devices. In this work first results of measurements of spatial distributions of  $n_e$  and  $T_e$  in Globus-M2 are presented.

Globus-M2 is a spherical tokamak constructed in Ioffe Institute in Saint-Petersburg ( $R = 0.36$  m,  $r = 0.24$  m,  $I_p < 500$  kA,  $B_t < 1$  T). The Thomson scattering system has the following distinctive features: it contains 13 polychromators with an analogue output connected to the A/D converter and the digitizer CAEN. Two devices of new generation with an integrated A/D converter and a power unit have been exploited simultaneously. New generation polychromators allow obtaining spatial distributions of electron temperature and density online, also they are equipped with thermal compensation system, that alters voltage.

Measurements are made simultaneously by means of two lasers: 1055 nm NdGlass laser 30 ns time of pulse and 1064 nm NdYag 3 ns time of pulse. This work presents results of time evolution of spatial distributions  $T_e$  и  $n_e$  in Globus- M2 in plasma with increased toroidal magnetic field. As well as discussion of the signal processing methods, both technical specifications of the diagnostics and the first results obtained by it.

## LH-TRANSITION INITIATION AND DYNAMICS IN A CONVENTIONAL TOKAMAK

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Radial electric field shear is crucial for the drift-wave turbulence suppression and transition to the H-mode, although the high shear value alone may not be sufficient for the LH-transition initiation. Effectiveness of turbulence suppression depends on spatial and temporal parameters of radial electric field perturbation; also in some cases depending on particle source value LH-transition occurs if no strong  $E_r$  perturbation is applied and vice versa, there is no transition even if  $E_r$  shear is high.

The model of particle density and ion temperature profiles evolution was applied to GAM scenarios in TUMAN-3M and FT-2, to pellet injection scenarios in TUMAN-3M and to high density regimes in FT-2 to calculate the dynamics of confinement; turbulence parameters and data on diffusion coefficient modulation were provided by ELMFIRE gyrokinetic code. Possibility of LH-transition for the observed scenarios was analyzed according to quantity of stable solutions of non-linear diffusion equation with shear-dependent diffusion coefficient.

Modeling and analysis results show that temporal and spatial structure of perturbed  $E_r$  shear and turbulence level play significant role in LH-transition initiation. The particle source was shown as a factor determining if H-mode existence is possible.

The work is supported by Ioffe institute (experiments on TUMAN-3M and FT-2 tokamaks) and Russian Science Foundation (numerical modeling works, project №18-72-10028).

## COMPARATIVE ANALYSIS OF LITHIUM DIVERTORS FOR TOKAMAK OF FUSION-FISSION HYBRID SYSTEMS

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The divertor power exhaust is the essential issue affecting both steady state tokamak operation and transients in fusion reactors and fusion-fission hybrid systems. A variety of techniques were implemented to reduce the power flux onto the divertor target below the engineering limit of 10 MW/m<sup>2</sup>. Two approaches utilizing lithium vapor boxes (LVB) were proposed by Nagayama et al., and by Goldston et al. and are currently developed. The SOL power entering the divertor is consumed in LVBs by lithium evaporation, ionization and radiation with cold and hot inner wall temperature of boxes correspondingly.

To make a choice of the divertor design for the fusion-fission project DEMO-FNS a comparative analysis of these divertor approaches is presented. Main physical processes involved are discussed with uncertainties of their input in estimations of the lithium flux entering the main plasma. The hot wall approach had been calculated from 2 to 4 vapor boxes. In the case of 2 or 3 boxes the Li flux from the divertor into plasma is too high. The system with 4 boxes provides sufficiently low Li flux, but its scale cannot fit the contemporary DEMO-FNS vacuum chamber design. Therefore, the Nagayama divertor concept was adopted for the DEMO-FNS tokamak. The ionization shielding, the geometrical shielding, and the shielding by the ablation material had been estimated. The first process plays the major role. The resulting Li flux to the main plasma is in 10-100 times smaller than the deuterium flux from plasma to divertor so it will not disturb the main plasma significantly. Main elements of the loop lithium system for its circulation in the machine are also presented and discussed.

## **PIC-MCC CALCULATIONS OF THE ION ENERGY-ANGULAR DISTRIBUTION FUNCTION AT GLANCING INCLINATION ANGLES OF THE MAGNETIC FIELD LINES TO THE WALL**

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Sputtering erosion of the beryllium walls and tungsten divertor is one of the key issues in performance of the future fusion reactors. Sputtered atoms may affect the plasma and the sheath parameters as well as deposit on the surfaces of optical elements in plasma diagnostics and cause their properties degradation. An accurate calculation of sputtered atoms flux from the walls is based on the information about energy and angular distribution functions for impinging ions from the plasma bulk. A present work is focused on the numerical study of the  $D^+$ ,  $Be^+$  ions transport in the limited region near the wall using Particle-In-Cell Monte-Carlo Collisions (PIC- MCC) techniques. The one-dimensional computational domain covers more than five ion cyclotron radiuses including the magnetic presheath and the space charge sheath. Both elastic and charge exchange collisions are taken into account. Magnetic field of  $\sim 6$  tesla is considered to be spatially uniform, and the magnetic field lines are inclined at  $\sim 88^\circ$  to a normal of the wall surface. Electrons are considered to be distributed in space according to the Boltzmann law with electron temperature. The values of charged and neutral particles flux, temperature and density were obtained from numerical simulation in SOLPS-ITER code.

First PIC-MCC simulation results show, that potential drop from plasma to the wall is 12.5 V and 0.46 V for the one point at the left and the right from the separatrix, respectively. The broadening of ion energy distribution function peak is caused by initial ion temperature of several eV and the ion collisions with hot neutrals within the magnetic presheath and space charge sheath. A large number of ions reaches the wall with the incidence angles in the range  $40 \div 80^\circ$ , while the magnetic field lines are inclined at  $\sim 88^\circ$  to a normal of the surface. One of the next steps will be a study of the sputtered atoms effect on the magnetic presheath, space charge sheath properties and, thus, ion energy-angular distribution function.

## **CALCULATIONS OF BERYLLIUM SPUTTERING RATE IN CAPACITIVE RF DISCHARGE IN STRONG OBLIQUE MAGNETIC FIELD**

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Erosion and re-deposition of beryllium walls in tokamaks lead to a contamination of mirror surfaces in diagnostic systems. Front-end diagnostics in large-scale fusion reactors like ITER will require a cleaning technique adopted for the in-vessel environmental conditions. He<sup>+</sup> ion bombardment in capacitive radio frequency (rf) discharge is considered to be a promising technique for the sputtering of the deposited beryllium films during the maintenance periods in scenarios with the strong oblique magnetic field. An accurate calculation of the beryllium sputtering rate requires the information about energy and angular distribution functions for impinging He<sup>+</sup> ions, which significantly depend on the magnetic field lines inclination to the mirror surface.

This work presents a numerical study of magnetized He<sup>+</sup> ion motion within a collisional rf sheath of capacitive rf discharge using one-dimensional three velocity coordinate Particle-In-Cell Monte-Carlo Collision simulations. Oblique magnetic field of 1 ÷ 5 tesla is considered to be spatially uniform with inclination angles in the range 60 ÷ 85° to a normal of mirror surface. The effect of the magnetic field, gas pressure and discharge frequency on the ion energy-angular distribution functions as well as the Be and Mo sputtering rates is analyzed. First simulation data demonstrates that the increase in the inclination angle and gas pressure lead to a significantly broadened energy and angular distribution functions and shift to the small incidence energy and angle, respectively. The energy spectrum He<sup>+</sup> ions impinging on the electrode consists of a series of large peaks in low energy part, while the primary peak is significantly reduced. Be and Mo sputtering rates are calculated based on the He<sup>+</sup> energy and angular distribution functions.

## THE ELM TRIGGERING BY SAWTOOTH OSCILLATIONS

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The Globus-M tokamak edge plasma was investigated for the interaction of the large scale magnetohydrodynamics (MHD) instabilities with the edge-localized mode (ELM). At Globus-M tokamak, ELM bursts have been measured by  $D\alpha$  diagnostics, and the filament structure has been seen on the Doppler reflectometry diagnostic and the fast camera, but these bursts are irregular and depend on the MHD perturbations magnitude.

It was seen that in the presence of the sawtooth oscillations, ELM bursts become synchronized with the onsets of sawtooth. The presence of tearing modes with  $m/n=2/1$  also was synchronized with the appearance of the filament structure. In the presented research we investigate the causes of this synchronization. The two possible mechanisms: an increasing of the pedestal pressure gradient and consecutive destabilization of the ballooning mode instability or an increase in the current density near the separatrix and kink/peeling mode destabilization.

Previous researchers successfully have shown that the coupling between the continuous  $m/n=3/2$  NTM and ELM caused the broadening of the current density profile due to flux pumping or radial transport of fast ions.

We used the local peeling-ballooning code to investigate the  $s-\alpha$  stability of the pedestal plasma, and to compare the steady-state the  $s-\alpha$  stability with the  $s-\alpha$  during the sawtooth and NTMs. The non-local codes were used to verify the mode structure of the instabilities and their actual localization.

## **GLOBUS-M2 PLASMA EDGE MODELING WITH NEON SEEDING**

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One of the areas of study on the tokamak Globus-M2 is the development of a prototype of the thermonuclear neutron source. For the neutron source steady state regime is preferable. Material constraints of such tokamak requires the energy fluxes to divertor targets to be below  $10\text{MW/m}^2$ . Experiments on ASDEX-Upgrade, JET and other tokamaks show that radiative impurity seeding decreases the peak energy flux to the divertor target. Recent plasma edge modeling for Globus- M2 spherical tokamak with nitrogen seeding demonstrated that presence of this impurity leads to heat loads reduction on the divertor target. Unfortunately, nitrogen can react with hydrogen to form ammonia, which is undesirable for the neutron source because of tritium radioactivity.

Neon does not react with hydrogen, so it is better as a radiative impurity. This work presents the result of Globus-M2 modeling with neon as a radiative impurity. Simulations have been done with SOLPS- ITER code. Neon seeding rate was changed from  $5.2 \times 10^{17}$  to  $1.3 \times 10^{19}$  particles per second. Low values of neon puff do not result in energy load reduction. The increasing of impurity puff leads to increase of effective charge inside the separatrix. Consequently, radiation losses increase and the electron temperature decreases inside the confinement region. Thus, the use of neon as radiative impurity shown to be inefficient.

# **A GENERALIZED FOKKER-PLANCK THEORY OF CHARGED PARTICLE STOPPING POWER IN A STRONGLY COUPLED PLASMA OF INERTIAL FUSION**

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Stopping power of charge particles describes its energy loss dynamics while passing through a medium. During last decades, the various analytical models of ion stopping power have been proposed which did not fully satisfy the plasma features we have in a burning plasma of inertial confinement fusion. In 1993, Li and Petrasso proposed their analytical stopping power based on the formalism previously developed by Rosenbluth et al (Phys. Rev. 107, 1 (1957)). It has been derived by modifying the Fokker-Planck (FP) equation accounting higher order terms (third order) in collision operator Taylor expansion. It was included the large coulomb angle scattering, quantum properties as well as the plasma collective effect. It initially examined the stopping power of alpha-particle released by DT nuclear reaction in a moderately coupled igniting DT plasma condition. However, recent studies indicate that at different plasma conditions ( $T$  and  $\rho$ ), this stopping power prediction results in an overestimate of as much as 20 percent than other competitors. Moreover, it is hardly match with experimental measurements of the energy loss in dense and strongly coupled plasmas, such as those in ICF experiments. In a strongly coupled plasma the macroscopic transport properties, such as diffusion or temperature relaxation are important which is usually difficult to estimate them directly. Moreover, the screening or correlation effects of plasma components is unavoidable.

Here, in a strongly coupled plasma using the effective potential kinetic theory (EPKT) and FP equation, an analytical expression of the modified stopping power model was then proposed. Moreover, we have employed higher terms up to fifth term in collision operator expansion in FP equation. Our initial results showed that EPKT will decrease the ion and electron stopping power about 42% and 30%, respectively in moderately coupled plasma, compared with LP calculation. This will be more pronounced in low projectile velocity regime. Furthermore, we have calculated the stopping power for a strong coupling plasma either. It has been shown that the strong coupling will improve the stopping power curve. Under this condition, the Bragg peak shifts to higher energies up to 12% in contrast to moderated coupling.

## **NBI HEATING STUDY IN THE GLOBUS-M/M2 SPHERICAL TOKAMAK AT-LIKE MODE**

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The first application of spherical tokamaks (STs) is foreseen to be an intense fusion volume neutron source. The examples of such a device are the compact fusion neutron source (CFNS), component test facility and two-energy component spherical tokamak-reactor. A critical requirement for these applications of spherical tokamaks is good fast particle confinement, since fast ion losses can cause plasma facing material damage and can lead to deterioration of plasma heating, neutron yield and current drive, reducing commercial efficiency.

It is important to create the model of plasma for prediction, analysis and creating full scale CFNS. One of the promising modes for CFNS is advanced tokamak with reversed shear (or AT mode). AT-like modes are usually obtained with early NBI-heating, when the neutral beam injection (NBI) starts at the plasma current ramp-up phase.

A small aspect ratio Globus-M2 tokamak, which is result of Globus-M modernization, with the major radius  $R_0=0.36$  m, minor radius  $a=0.24$  m, aspect ratio  $R/a\sim 1.5$  and vertical elongation  $k\sim 1.8-2$ . The upgrade allowed to increase the plasma current up to 500 kA and the toroidal magnetic field up to 1 T.

The original technique of the NBI-heating modelling using NUBEAM is discussed. Obtained fast particle distribution function was used to estimate neutron emission and NPA signal with FIDASIM. Comparison with experimental data is presented. The reason for including anomalous fast ion diffusion in the model is discussed.

## 3D SIMULATION OF PARTICLES SPUTTERING, TRANSPORT AND DEPOSITION IN RARIFIED AND LOW-IONIZED GASES

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Transport of particles in rarified gases and low-ionized plasmas is of key importance in many applications such as optics contamination by eroded materials in plasma machines e.g. in fusion devices or a surface treatment by energetic ions and/or activated species in the vapor phase, which are now employed for deposition (sputtering, ion plating, activated reactive evaporation, and plasma polymerization) and also for etching (sputtering and plasma etching).

The presentation discusses implementation of Monte-Carlo code KITE optimized for modeling sputtered particles transport in rarified and low-ionized gases as well as for processes of surface sputtering/deposition. The code provides correct simulation of particle-particle and particle-surface interaction in a wide range of energy from a few eV (energy of sputtered atoms) to a thermal energy using neutral-neutral collision model based on realistic attractive-repulsive potential of any complexity whether experimentally obtained one or an *ab initio* simulated potential. The surface sputtering and particles reflections are modeled in binary collision approximation. The features providing the code applicability for computer-aided engineering are as follows:

- Simulation of acceleration using databases of pre-calculated neutral-neutral collision and particle-surface interaction data;
- 3D simulations of particle transport in complex-geometry mesh imported from CAD-models;
- Massively parallel implementations; test launches on up to 1000 CPU.

A few applications of the KITE software for sputtered particles transport simulation are presented and validation against the experimental data are made in different background conditions.

## NEUTRAL BEAM STOPPING AND SHINE-THROUGH CALCULATIONS FOR FUSION NEUTRON SOURCES

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Neutral beam injection (*NBI*) based on deuterium beams is particularly important in fusion neutron sources (*FNS*), as it provides a steady state heating and current drive under the high density and relatively low magnetic field conditions.

BTR code (“*Beam Transmission with Reionization*”), which is generally used for NBI beamlines design and optimizations, is applied to calculate the injected beam decay in plasma, the beam ionization imprints, and the shine-through power maps. 3D calculations are performed for a fusion neutron source DEMO-FNS tokamak with  $R = 3.2\text{m}$ ,  $a = 1\text{m}$ ,  $k = 2$ ,  $B = 5\text{T}$ ,  $ED = 500\text{keV}$ , NBI power  $\approx 30\text{MW}$ . BTR beam-plasma model produces the detailed beam spatial and angular distributions, uses the available cross-section models (*Janev-Suzuki*) and delivers the penetrated beam axial and normal footprints, including the shine-through power deposition onto the tokamak first wall.

The influence of beam-plasma mutual geometry (beam targeting and inclination) and the effect of the injected beam angular structure (individual focusing and scattering) on the effective ionization and losses are shown. The calculations are made for thin, rectangular and focused beam shape options. For tangential beam injection through toroidal plasma, the effective plasma target thickness varies across the beam resulting in power decay aberrations, and this effect has proved to be mostly essential for the beam cross-dimensions comparable with the plasma minor radius.

## **FULL WAVE MODELING OF DOPPLER BACKSCATTERING FROM FILAMENTS**

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It is recognized that the filaments have a significant effect on the anomalous energy and particle transport in the tokamak periphery. They are actively investigated using various diagnostics in this regard. Recently three studies of filaments using the Doppler backscattering (DBS) method have been performed in Globus-M and ASDEX-Upgrade. Backscattering from filaments manifests itself in approximately the same way as a burst of quasi-coherent oscillations of the signals of IQ detectors. Such signals are easy to describe in the Born approximation using the diagnostic weighting function. However, the filaments in tokamaks differ noticeably in their size and intensity. With an increase in the amplitude of the filaments, it is necessary to consider the transition from linear scattering to nonlinear scattering up to the transition from backscattering to reflection from a moving filament. This problem can be solved only using a full wave code. Our simulation was carried out using finite-difference time-domain code IPF-FD3D in slab geometry. We did not resort to using well-known non-linear MHD codes to determine filament parameters. In the simulation artificial filament-like perturbations were used, the parameters of which varied over a wide range. Modeling DBS signal was focused on the identification of the influence of the amplitude of the filament and its size on the shape and size of the DBS output signal. The results obtained largely explain the similarity of the IQ detector data registered in different tokamaks.

The work is supported by RSCF grant 18-72-10028 and Ioffe Institute.

## REACTIVE COLLISIONS BETWEEN ELECTRONS AND $\text{BeD}^+$

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Dissociative recombination (DR), elastic collisions (EC), vibrational excitation (VE), vibrational de-excitation (VdE) and dissociative excitation (DE) are major elementary processes in numerous cold ionized gases. Using Multichannel Quantum Defect Theory (MQDT)[1] cross sections and rate coefficients have been obtained for reactions induced on  $\text{BeD}^+$ .

In order to model and diagnose the low-temperature edge plasma, a complete database for electron impact collision processes is required for molecular species containing beryllium and hydrogen. We have expanded our studies on  $\text{BeH}^+$  [2] to  $\text{BeD}^+$ [3] and  $\text{BeT}^+$  cations. Our calculations show cross sections and state-to-state rate coefficients for the vibrational transitions of  $\text{BeD}^+$ .

A complete set of vibrationally resolved rate coefficients for  $\text{BeD}^+$  cation reactive collisions with electrons below the ion dissociation threshold is provided. Similar calculations on  $\text{BeT}^+$ , are object of ongoing work.

The resulting data are useful for the magnetic confinement fusion edge plasma modelling and spectroscopy, in devices with beryllium based main chamber materials, such as ITER and JET, and operating with the deuterium-tritium fuel mix.

## **FEASIBILITY OF DEVELOPING NON-DESTRUCTIVE MAGNETS WITH MEGAGAUSS FIELD FOR CONTROLLED THERMONUCLEAR FUSION**

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Using the example of a solenoid in a coaxial cylindrical screen, the possibility of developing a quasi-force-free double-layer coil that is balanced along the entire length is shown. It has been shown previously that such magnet is characterised by significantly reduced mechanical stresses. In particular, it has been demonstrated by means of axisymmetric computations that the mentioned stresses are about an order less than the magnetic pressure of the generated field. However, the strength of actually manufactured multi-turn coils is inevitably less than predicted by axisymmetric simulations due to the inter-turn gaps filled with dielectric medium and due to the effect of magnetic flux density components that are normal to the coil. The influence of these factors was analysed in 3D simulations and confirmed by experiments with thin-wall magnets. It is shown in the paper that application of high-modulus dielectrics and field correction by split screens allow one to reduce the role of these factors and to develop a magnet in which the stresses do not exceed 1 GPa. That opens up possibilities of using such field for the confinement of hot dense plasma in controlled thermonuclear fusion reactors.

# TOKAMAK PLASMA STEADY FLOWS IN VISCO-RESISTIVE MAGNETOHYDRODYNAMICS WITH JET AND ITER-LIKE GEOMETRIES

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Experimentally, there are many observations of spontaneous rotation in tokamaks especially in the toroidal direction. This rotation of the plasma proves to have very important effects on the improvement of the confinement and on the entrance into the H mode of improved confinement. To clarify the experimental observations, we propose to determine numerically the steady states of the visco-resistive MHD equations including the non-linear  $(\mathbf{v} \cdot \nabla) \mathbf{v}$  term. We take into account the external electric field in the toroidal direction used to create the toroidal current required in a tokamak to create the poloidal component of the magnetic field.

We present numerical results in JET and ITER geometries obtained using the programming language FreeFem++ focused on solving partial differential equations using the finite element method. We consider realistic values of the resistivity  $\eta$  and vary the viscosity,  $\nu$ , of which the realistic order of magnitude is poorly known. The axisymmetric steady-state visco-resistive MHD equations are solved using a continuation method on  $\nu$  and a Newton-Raphson scheme to handle the nonlinearity.

All other things being equal, the maximal toroidal velocity is an increasing function of the plasma temperature and is greater in ITER than in JET. For no-slip boundary conditions, this maximal toroidal velocity is attained within a thin viscous boundary layer at the border of the toroidal device that is accurately resolved using mesh refinement.

# CONTROLLING THE ENERGY DISTRIBUTION OF ACCELERATED PARTICLES BY CHOOSING THE RELIEF PARAMETERS OF THE TARGET IRRADIATED BY A SHORT LASER PULSE OF RELATIVISTIC INTENSITY

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Presence of a relief on the target surface changes the absorption coefficient and electron parameters. Propagation of hot electrons inside the target is accompanied by the appearance of a return current and the formation of a cold electron ensemble. At the end of the laser pulse with several tens of fs, an energy distribution between cold and hot electron ensembles is established. Therefore, the increase of the absorption coefficient with the help of surface structuring does not lead to a proportional increase in electron ensemble energies. First of all, the optimum relief for the given laser intensity increases the temperature and the number of hot electrons. With the laser intensity increasing at the same relief, the energy exchange between the groups of hot and cold electrons also increases, which leads to the fact that the cold electron temperature (tens of keV) at the end of the laser pulse increases more strongly with intensity than the hot electron temperature (several MeV). The contribution from hot and cold electron components leads to a characteristic non-monotonic K- $\alpha$  yield dependence on laser intensity. From the corresponding inflection points, the temperature of cold electron ensembles can be estimated. Our model incorporating two main different groups of electrons and their different dynamics allows us to trace the observed differences in the K- $\alpha$  yield and ion energies as a function of laser intensity. If the target parameters are chosen such that laser absorption is maximum, the temperatures and numbers of the hot electrons will be maximum, and, accordingly the numbers and energy of the protons will be maximized, while the cold electron temperature may not correspond to the maximum K-shell ionization cross section. In this case, the K- $\alpha$  yield will not be maximum despite subsequent cooling of hot electrons and their transformation into cold electrons. Thus, changing of the relief parameters allows to selectively influence hot and cold electron ensembles of energy distribution function, achieving the maximum energy of protons or maximal K- $\alpha$  yield. The K- $\alpha$  yield and proton spectrum can be used to determine electron distribution function and establish the nature of laser plasma conductivity.

## **ELECTRON DISTRIBUTION FUNCTION STRUCTURE NEAR THE STEEP TEMPERATURE GRADIENT IN LASER-PRODUCED PLASMA**

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In laser heated plasmas such features as steep temperature gradients, nonlocal heat transport and suprathermal electrons are commonly accepted and have been an ongoing interest for inertial confinement fusion (ICF). The kinetic theoretical studies and corresponding numeric simulations demonstrate significant deviation of the non-equilibrium electron distribution function (EDF) from Maxwellian, what is of particular importance for such effects as: heat wave propagation, hot spots relaxation in a plasma with speckled laser beam, plasma preheat by hot electrons, Langmuir wave damping, return current instability, nonequilibrium radiation and density fluctuations.

In this work we present the results of numerical simulation of the steep electron temperature gradient relaxation in a low-density laser-produced plasma. Simulations have been performed with the original finite difference 1D2V Fokker-Planck kinetic code. The temperature, heat flux profiles and EDF in the velocity space have been studied in details as functions of space and time at the multi-ps time scale. The results of kinetic simulations significantly differs from the hydrodynamic simulations. Appearance of nonthermal tails of fast electrons is similar to the previously theoretically found algebraic EDF's tails. We also make an estimate of the hot electrons contribution to the particle number density and mean energy, their influence on plasma preheating and plasma wave Landau damping that is important for ICF laser-plasma interactions.

# STUDY OF RADIATION SPECTRA PRODUCED DURING LASER INDUCED THOMSON SCATTERING IN XENON CLUSTERS

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The interaction of lasers with atomic clusters ionizes the cluster atoms and produces plasma medium containing energetic ions and electrons. This interaction find applications in various fields, depending on the experimental parameters and conditions. If the laser pulse interacting with the cluster is a low intensity multi-cycle pulse, the electrons oscillate in the field of the laser and the radiation emitted by these electrons consists of higher order harmonics generated due to Thomson scattering of electrons in the field. However, when the laser pulse interacting with the cluster has just few cycles and is highly intense ( $>10^{18} \text{W/cm}^2$ ), the interaction of laser field with the clusters becomes relativistic. The electrons now experience a significant magnetic field as well, due to which the  $\mathbf{v} \times \mathbf{B}$  force comes into play and alters the trajectory of electrons significantly. Due to this, higher order harmonics emitted by electrons are also altered.

This radiation spectrum has diagnostic potential, depending on the kind of interaction taking place. For instance, in case of the high intensity laser-cluster interaction, electrons cause distinct emission of radiation in a particular direction due to the ponderomotive force acting on them, which in turn depends on laser intensity. Thus, the study of angular distribution of radiated power can serve as a diagnostic tool to measure intensity of the incident laser directly. In case of the low intensity, prolonged interaction of laser with the cluster, ionization dynamics and intra-cluster fields affect the harmonics spectra and can potentially provide information about the intrinsic dynamics occurring inside the cluster.

In this study, we have used both few-cycles multi-cycles pulses with intensity ranging from  $10^{16}$ - $10^{21} \text{W/cm}^2$  to interact with Xenon clusters in order to explore the diagnostic potential of the radiation spectra produced in this process. We have used molecular dynamics to study the interaction of lasers with clusters and the Thomson scattered radiation emitted by electrons is studied using standard Liénard-Wiechert potentials.

**RESONANT LASER-ASSISTED PROCESS OF THE  
ULTRARELATIVISTIC ELECTRON-POSITRON PAIR CREATION  
BY A GAMMA QUANTUM IN THE NUCLEUS FIELD**

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The resonant laser-assisted process of creation of the ultrarelativistic electron-positron pair by a gamma quantum in the nucleus field was studied theoretically. Unlike the processes in absence of laser field, the laser-assisted processes can occur both non-resonant and resonant way. This is explained by the fact that in the field of laser the processes of first order in the fine structure constant are able to take a place. Due to that the process of second order effectively reduces to two successive processes of the first order. The resonant kinematics was studied in details. It was shown that the process has characteristic threshold energy. Resonant differential cross section of studied process was obtained. It is magnitude significantly exceed the corresponding resonant differential cross section without a laser field. The project calculation can be experimentally verified by the scientific laser plasma facilities of pulsed radiation (SLAC, FAIR, XFEL, ELI, XCELS).

## **Resonant Laser-assisted Process of the Electron-Positron Pairs Annihilation and Production**

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A resonant laser-assisted process of the electron-positron pairs annihilation and production is studied theoretically. The second order in fine structure constant process in the laser field transforms into two consistent processes of first order in the fine structure constant: laser-assisted annihilation of initial electron-positron pair into intermediate photon and laser-assisted production of final electron-positron pair by intermediate photon under resonant conditions when virtual photon becomes real. It is demonstrated that the resonant conditions for initial pair include the excess of certain combination of the electron and positron energies over threshold energy and narrow angle between momenta of electron and positron. The same holds true for the final pair. Also, final positron emission angle can vary from zero to some maximum value. It is shown that energies of the final particles depend on this angle and can take from one to two values. A resonant differential cross section of the studied process is obtained. It is shown that the resonant differential cross section can significantly exceed the corresponding cross section without an external field (Bhabha cross section). The project calculations may be experimentally verified by the scientific facilities of pulsed laser radiation (SLAC, FAIR, XFEL, ELI, XCELS).

## **RESONANT LASER-ASSISTED PROCESS OF ULTRARELATIVISTIC ELECTRONS BREMSSTRAHLUNG IN THE FIELD OF A NUCLEUS**

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The contemporary academic examination represents the scrutiny of the resonant laser-assisted bremsstrahlung (LAB) of ultrarelativistic electrons in the field of a nucleus. The kinematics of the explored process indicate a possibility to develop within two probable channels. Therefore, a couple of Feynman diagrams illustrate the phenomenon frameworks. Thus, for the first channel – an electron radiates a spontaneous photon and subsequently scatters on a nucleus. In contrast, for the second channel – an electron scatters on a nucleus and consequently emits a spontaneous photon. It is important to underline, that with the presence of the external laser field the ultrarelativistic electron in the intermediate state emerges to the mass shell and transforms into the real particle. Furthermore, the second order effect functionally transmits into two sequential first order procedures (implementing the laser-stimulated Compton process and the laser-assisted Mott scattering) with respect to the fine structure constant. The research evaluates the fluctuation of the spontaneous photon resonant frequency for the various initial parameters criteria. As a result, the investigation highlights a specific diapason of the resonant frequency modification for the second reaction scheme when the ultrarelativistic electron at first scatters on a nucleus and then radiates a spontaneous photon. The designated interval consists of three frequency levels in alternative to the first channel interaction pattern. Moreover, the study delineates the occurrence of the particles propagation within a narrow angle cone in the vector direction parallel to the initial electron momentum. To summarize, the article estimates that the magnitude of the differential cross-section in the resonant ambience substantially exceeds the cross-section of the process without the external field. In addition, pulsed laser radiation laboratories (SLAC, FAIR, XFEL, ELI, XCELS) maintain the ability to verify the project calculations.

## INVESTIGATION OF THE ROLE OF RADIAL ELECTRIC FIELDS ON PROPAGATION OF FAST IONIZATION WAVES

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Breakdown of screened dielectric tubes and capillaries under nanosecond voltage pulses takes the form of a fast ionization wave (FIW). Basic properties of FIWs (such as propagation velocity, electric fields and charged particle densities) can be obtained theoretically using a quasi- one-dimensional approach which is based on assumption on their negligible radial. However, spatial distributions of emission intensity, obtained recently using Intensified Charged Coupled Device (ICCD), have shown much brighter areas in the vicinity of the tube walls, which could be connected with significant radial electric fields. Moreover, experimental observations performed in the 1-24 Torr pressure range revealed a transition of plasma density from the tube axis to the walls with increasing gas pressure, which was correlated with results of 2D simulations showing a similar transition. Neither experimental methods typically used for investigation of FIWs, such as capacitive probes, nor one-dimensional numerical simulations cannot provide much information regarding the role of radial electric fields in propagation of the wavefront. Nevertheless, quasi-one- dimensional simulations have, surprisingly, shown excellent agreement with experiment for the case when radial inhomogeneity of emission intensity was observed. In this regard it is of particular interest to investigate the role of radial electric field in wave propagation for conditions when a more pronounced radial inhomogeneity can be expected, such as higher gas pressures, materials with high dielectric permittivity, and negative polarity of voltage pulses.

In this work, we have performed detailed comparison of simulation results of a FIW using quasi-one-dimensional and fully self-consistent two-dimensional models in a broad range of external parameters (voltage pulse polarity and shape, gas type and pressure, geometric and material properties of the dielectric tube). The comparison allowed distinguishing main factors influencing propagation dynamics and establishing a range of applicability for the quasi-one- dimensional model.

# INVESTIGATION OF INITIATION, DEVELOPMENT, AND FILAMENTATION OF SPARKS IN AN ATMOSPHERIC DISCHARGE BY USING MULTI-FRAME LASER PROBING

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Formation of a millimeter-sized spark discharge in ambient air is studied on a nanosecond time scale by using multi-frame laser probing with an exposure time of 70 ps and spatial resolution as high as 3–4  $\mu\text{m}$ . In order to implement the laser probing a six-frame optical system is employed. The system provides a means to simultaneously record interferograms, shadowgrams, and schlieren images of the studied discharge gap. We find that the gap breakdown is associated with fast ( $\ll 1$  ns) explosive formation of a micron-sized ( $\sim 10$   $\mu\text{m}$ ) cathode spot constituting a plasma with an electron density of  $n_e \sim 10^{19}$   $\text{cm}^{-3}$ . The spot gives rise to further spark channel having an electron density of  $n_e \sim 10^{19} - 10^{20}$   $\text{cm}^{-3}$ . It is demonstrated that within  $\sim 1$  ns after the breakdown the dynamics of the highly ionized near-cathode plasma governs the initial current rise rate. We also find that the growing spark channel develops in the form of multiple filaments that appear as plasma channels with micron-sized ( $\sim 10 - 50$   $\mu\text{m}$ ) diameters, the electron density of  $n_e \sim 10^{19} - 10^{20}$   $\text{cm}^{-3}$ , and subnanosecond characteristic evolution time. It is demonstrated that first filaments are formed at the top of the developing homogenous spark channel and their number is increasing over time. The features of the observed filaments are their pronounced directivity towards the anode and high propagation velocities ( $\sim 10^8 - 10^9$   $\text{cm/s}$ ) that are more typical to strong ionization waves, e.g., streamers. Our findings indicate that the spark channel filamentation is one of the important mechanisms governing the resistivity of the discharge gap after the breakdown.

The experimental study is partially supported by the Russian Foundation for Basic Research (grant no. 18-32-00566). The plasma analysis and interferogram processing is partially supported by the Russian Foundation for Basic Research (grant no. 18-32-00012).

## **ATMOSPHERIC PRESSURE PLASMA SYNTHESIS OF NANOCOMPOSITES**

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The study of the formation of nanostructured coatings and thin films is one of the relevant objectives of modern materials science. Nowadays, formation of nanocoating with desired properties is at the stage of accumulation and systematization of experimental results which achieved by variation of different parameters. Therefore, promising way is to establish fundamental physicochemical laws which allow to use self-organization predisposition of nano-objects.

Low-temperature plasma induced by high-frequency electrical discharges in a reaction atmosphere is successfully used to activate chemical deposition processes. The usage of atmospheric pressure discharges represents a great practical interest due to some advantages: simplicity of implementation, high concentration of reagents, high yield of the final product, low thermal effects on the substrate due to the possibility of low-temperature gas-discharge plasma generation, potential capability usefull for controlling the topology of the formed nanocomposite.

Low pressures plasma-chemical synthesis technologies traditionally require to use several stages in separate processes of matrix formation and embedded particles. However, this approach causes the emergence of uncontrolled parameters that may adversely affect the efficiency and functionality of the composite.

The possibility of the nanocomposite synthesis sequentially in a single process is an essential technological advantage of the proposed atmospheric pressure plasma- enhanced chemical vapor deposition formation process.

## **CHARACTERISTICS OF A DUSTY PLASMA PRODUCED IN A PLASMA EXCITED AT ELECTRON-CYCLOTRON RESONANCE**

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Dusty plasmas produced at electron cyclotron resonance (ECR) were studied. Using a movable Langmuir probe, the spatial distributions of plasma characteristics were obtained in argon and acetylene plasma, the latter leading to the formation of dust particles.

The effect of the magnetic field on the curvature of the current-voltage characteristics (CVC) of the Langmuir probe was evaluated. During the CVC process the probe sheath length was calculated and taken into account. At high magnetic field the strong difference was found between plasma concentration calculated from ion and electron currents. Correction of the influence of a magnetic field reduces the difference between the above concentrations, but does not fully equate them.

In argon, the spatial distribution of electron and ion densities are, as classically described in the literature, with a maximum in the electron-cyclotron resonance region. This behavior is classical and related to the efficient magnetic confinement of charged species.

In acetylene, the spatial distribution is highly modified. Indeed, in contrast with argon, the plasma densities reach minimal values in the high magnetic field region, the maximal one being shifted to the walls. This behavior suggests that chemical processes such as nucleation and growth of dust particles take place in the high magnetic field region. Also in the acetylene discharge a temporal evolution of plasma parameters with time was found. This may also indicate the presence of dust particles. While in the argon discharge there was no time evolution.

## **INVESTIGATION OF THE STRUCTURE OF CURRENT CHANNELS IN THE PREBREAKDOWN PHASE OF THE ATMOSPHERIC DISCHARGE IN LONG GAPS**

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In this work the formation of current channels of atmospheric discharge in the long gap was studied. The parameters of the discharge were closed to the parameters of the lightning one. The discharge was forming in the gap between the tip cathode and the mesh anode in the shape of a hemisphere. The length of the discharge gap was 60 cm. A voltage pulse with an amplitude of - 1.2 MV and a rise time of 200 ns was applied to the cathode. The electrical breakdown of the interelectrode gap of the setup was characterized by the formation of a bright luminous channel connecting the electrodes and the current rise up to 10 kA.

In previous experiments, it was found that on the front of the voltage rise the current up to 500 A appears. This pre-breakdown phase is accompanied by luminescence and X-ray flashes from the discharge gap. To study this phase of the formation of a high-current channel, laser probing methods were implemented: interferometry, schlieren and shadow photography. By the laser probing was investigated a cathode region with character size of 2 cm. Due to the precise focus on the tip of the cathode, the structure of current channels was obtained with high spatial resolution ( $\sim 10 \mu\text{m}$ ). The time resolution was corresponded to the laser pulse length and was about  $\sim 7$  ns.

The experimental part of the study was supported by the Russian Foundation for Basic Research (grant no. 17-08-01690 and 19-02-00465). The plasma analysis was partially supported by the Russian Foundation for Basic Research (grant no. 18-32-00566). The interferogram processing was partially supported by the Russian Foundation for Basic Research (grant no. 18-32-00012).

**OPTIMIZATION OF THE ICP PLASMA TORCH PARAMETERS  
BASED ON MATHEMATICAL SIMULATION FOR PLASMA  
SPHEROIDIZATION OF THE HIGH ALLOYED STEEL POWDER**

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This paper presents the results of the optimization of the parameters of an argon- hydrogen inductively coupled plasma for the process of spheroidization a high-alloy steel powder. The influence of the ICP plasma torch power, temperature, plasma-gas flow rate on the spheroidization process was studied. As a result of the mathematical simulation and the experiment, the parameters that ensured the maximum yield and high-sphericity of the powder were obtained.

## SELEVTIVE SIN/SIO2 ETCHING BY SF6/H2/AR/HE PLASMA

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Silicon nitride (SiN) spacer is used as the encapsulated materials for a ferroelectric during ferroelectric random-access memory (FRAM) production. Anisotropic dry etch process is used for selective SiN removal over SiO<sub>2</sub>. The mechanism of enhanced SiN etching in the presence of F-atoms have been proposed using quantum chemistry modeling. It was predicted that H-atom and HF molecule increase SiN etch rate reacting with fluorinated SiNF<sub>x</sub> surface. Here we present the experimental data about SiN and SiO<sub>2</sub> direct plasma etching. SF<sub>6</sub> and H<sub>2</sub> are chosen for F-atom and H-atom production in plasma discharge. Small amount of Ar is added for actinometry measurements. It has been shown that SiN etch rate nonmonotonically depends on amount of He gas added to plasma mixture. At the same time the Balmer lines intensities normalized on Ar line (750 nm) monotonically increase at He flow rate rise. It can be explained by the fact that He gas promote H-atom production. We proposed two mechanisms of He affects on the H-atom production. The first mechanism describes H-atom production via  $\text{He} + \text{H}_2^+ \rightarrow \text{HeH}^+ + \text{H}$  reaction. H- atoms are produced during reaction of H<sub>2</sub> molecule with metastable He\* atom according to second mechanism. On the other hand, dissociation degree of SF<sub>6</sub> does not depend on He concentration. Moreover, F-atom concentration decreases at He concentration rise due to dilution. Thus, the SiN etch rate peak appears due to the fact that F-atom concentration drops and H-atom concentration increases according to our assumption. It should be note that SiO<sub>2</sub> etch rate has no peak therefore the highest selectivity is achieved at the point where SiN etch rate has the maximum.

## SPHERODIZATION OF ALUMINOSILICATE PARTICLES IN THERMAL PLASMA FLOW

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Currently, hollow microspheres are widely used in the development of new technologies of constructional materials and coatings. Hollow microspheres possess high thermophysical and mechanical properties. Aluminosilicate hollow particles are the most common type of microspheres in the industrial applications. They are coal combustion by-products remaining in boiler furnaces of thermal power plants (TPP) after 1500 K heating. In this case, the microsphere formation is chaotic and uncontrolled, with a large amount of ash residual. The microsphere concentration in it is not over 5÷8 % that does not meet the industrial requirements. It is important to note that the phase composition of aluminosilicate microspheres is comparable to that of ash residual. This type of material is a combination of refractory oxides and silicates having the high melting temperature (over 1850 K). Refractory oxides and silicates is an important source of raw materials in the microspheres production. The microspheres production from ash residual using the highly-concentrated thermal plasma provides the intensification of physical processes in condensed media that cannot be achieved by the traditional heating sources. The main physical parameters of microspheres include the diameter  $D_{p,m}$ , density  $\rho_p$  and relative wall thickness  $\delta/D_{p,m}$ . The optical images of the plasma treated agglomerated powders based on the ash residual. The particle size is 90÷100  $\mu\text{m}$  at different gas rates (0.5÷1.5 g/s). At the lowest gas rate of 0.5 g/s, the particles overheat with the subsequent formation of dense microspheres ( $D_{p,m}=65\pm 3 \mu\text{m}$ ,  $\rho_p=1.98 \text{ g/cm}^3$ ) in the surface layer. The rational heating is performed at a 1.0 g/s gas rate, resulting in the formation of hollow microspheres ( $D_{p,m}=110\pm 2 \mu\text{m}$ ,  $\rho_p=0.83 \text{ g/cm}^3$ ). Their wall thickness varies between 4÷5  $\mu\text{m}$ . With the increase in the gas rate up to 1.5 g/s, the agglomerate surface vitrifies, thereby forming a thin film  $\leq 1 \mu\text{m}$  thick. The particle diameter and density are in their initial state ( $D_{p,m}=95\pm 2 \mu\text{m}$ ,  $\rho_p=1.36 \text{ g/cm}^3$ )

The reported study was funded by RFBR according to the research project № 18-48-703004r\_mol\_a

## ELECTRON ENERGY RELAXATION LENGTH IN XENON, CHLORINE AND THEIR MIXTURE

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The ability to predict the degree of locality of electron energy distribution function (EEDF) can be very important in the modeling and design of gas discharge devices, for instance ecological powerful sources of ultraviolet radiation with a moderate pressure glow discharge in mixtures of inert gases and halogens, as an example — in a mixture of Xe and Cl<sub>2</sub>. In particular, if relaxation length of electron energy  $W_e$  —  $\lambda_W(W_e)$  — turns out to be much less than discharge tube radius  $R_0$  for all  $W_e$ , the EEDF may be considered as local.

Let us define the fact of electron energy relaxation after  $k$   $e$ - $a$ -collisions as  $e$ -time reduction in the probability of *maintaining* the initial electron energy  $W_e$ . Then the number of  $e$ - $a$ -collisions  $k(W_e)$  needed for electron energy relaxation can be expressed as the solution of following equation (rounded to

nearest integer): 
$$\left[ \frac{N_{\text{Xe}}\sigma_{\text{Xe}}^{\text{el}}(W_e) + N_{\text{Cl}_2}\sigma_{\text{Cl}_2}^{\text{el}}(W_e)}{N_{\text{Xe}}\sigma_{\text{Xe}}^{\text{full}}(W_e) + N_{\text{Cl}_2}\sigma_{\text{Cl}_2}^{\text{full}}(W_e)} \right]^{k(W_e)} = \frac{1}{e}. \text{ Here } \sigma_j^{\text{el}}(W_e) \text{ — cross}$$

section of elastic  $e$ - $a$ -collisions of an electron having energy  $W_e$ ,  $\sigma_j^{\text{full}}(W_e)$  — full cross section of any  $e$ - $a$ -collisions,  $N_j$  — density of the  $j$ -th component of neutral gas. The small electron energy losses in elastic  $e$ - $a$ -collisions are neglected here, but for pure xenon they should be taken into account.

We express the electron free path length as

$$\lambda_e(W_e) = [N_{\text{Xe}}\sigma_{\text{Xe}}^{\text{full}}(W_e) + N_{\text{Cl}_2}\sigma_{\text{Cl}_2}^{\text{full}}(W_e)]^{-1}.$$
 Since the electron motion in our plasma is a kind of Brownian motion, we obtain the desired length  $\lambda_W(W_e)$  as 
$$\lambda_W(W_e) = \sqrt{k(W_e)} \cdot \lambda_e(W_e) = \sqrt{k(W_e)} / [N_{\text{Xe}}\sigma_{\text{Xe}}^{\text{full}}(W_e) + N_{\text{Cl}_2}\sigma_{\text{Cl}_2}^{\text{full}}(W_e)].$$

Such calculations can help us to find out the conditions of EEDF locality. For instance, we would argue that the EEDF in a glow discharge in a mixture of several Torr Xe and chlorine may be assumed as local for  $R_0 \geq 6$  mm if partial pressure of Cl<sub>2</sub> is more than 0.2 Torr.

## THE PULSE PLASMA FLOWS APPLICATION PROGRESS IN MATERIAL SCIENCE AND NANOTECHNOLOGY

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A common and characteristic feature for all pulsed plasma installations is the pulsed nature of plasma formation. For use in technology, it is importance not the kinetic parameters of the plasma, but its total energy flux and time duration. According to these parameters, the installations differ significantly in the energy flux density of units from ones to several tens of J / cm<sup>2</sup>. In addition, the determining factor in the choice of these facilities was the geometry of the plasma formation and the conditions for flow generation. From this point of view, such processes as erosion and emission of electrodes, formation of a buffer plasma, acceleration and compression of the flow can have a significant impact on the technological result.

As for the technological part, the work mainly presents the results of researches on the use of a pulsed vacuum-arc unit VDU-1 in nano-engineering. Studies conducted to optimize the operation of this facility for the synthesis of nanomaterials in a low-pressure arc discharge plasma, plasma diagnostics and the obtaining of nanopowders. As a result, powder samples were obtained in the form of clusters, in the composition of which spherical particles were found. The uniformity and dispersion of the powder depended on the time course of the processes accompanying the precipitation. The following are the results of the deposition of spherical nanoparticles on the KPU-30 facility. In this experiment, the plasma flow was directed to a graphite target for its sputtering, and then the plasma was condensed onto a nearby steel substrate. The presence of precipitated graphite particles of spherical shape and dimensions of 110–900 nm is shown. The results of the study allow making a conclusion about the possibility of obtaining spherical particles with a controlled composition when using different targets. At the PF-4 installation, the processes of sputtering targets from constructional materials investigated; special attention was paid to the influence of the shape of the plasma formation on the pattern of erosion of the target surface.

## THE ROLE OF THE OXYGEN ATOMS IN CO<sub>2</sub>-O<sub>2</sub> PLASMAS

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The increase of the CO<sub>2</sub> concentration in the atmosphere is widely established as the main cause for global warming. One promising solution consists in recycling the CO<sub>2</sub> molecule, using it as a raw material to produce synthetic solar fuels. In this way, it would be possible to convert the temporary energy from renewable sources into stable chemical compounds. One important step in this process involves the CO<sub>2</sub> dissociation, which must be done in an efficient way in order to make it economically competitive. Low-temperature plasmas can be the answer, due to their strong non-equilibrium nature, which can efficiently enhance several chemical processes.

Therefore, fundamental studies of CO<sub>2</sub> plasmas, from both experimental and modelling points of view, are mandatory to find an efficient path for dissociation. Despite the studies developed in the last years, one topic is barely understood and requires further attention: the role of the atomic oxygen in the kinetics of CO<sub>2</sub> plasmas. Indeed, the atomic oxygen produced from dissociation can influence positively or negatively the dissociation efficiency. For example, O atoms can collide with an excited CO<sub>2</sub> molecule and dissociate it, enhancing dissociation, or oxidize CO producing again CO<sub>2</sub>, hindering it. This work is focused on the measurement of the oxygen atom density and loss frequency in CO<sub>2</sub>-O<sub>2</sub> plasmas, using a glow discharge and varying several parameters: gas pressure, current, wall temperature and fraction of CO<sub>2</sub>. Two diagnostic techniques were used: optical emission actinometry and Cavity Ring-Down Spectroscopy (CRDS). The variation with the gas pressure shows that the oxygen atom density is controlled by reactions in the surface and that there are two working regimes, with a transition around 1 torr. The results are compared to the dissociation fraction of CO<sub>2</sub> measured in previous works by infra-red absorption.

This work was partially funded by Portuguese FCT - Fundação para a Ciência e a Tecnologia, under projects UID/FIS/50010/2019 and PTDC/FISPLA/1420/2014 (PREMiERE), by LabEx Plas@par receiving financial aid from the French National Research Agency (ANR) under project ANR-16-CE06-0005-01 (SYCAMORE). TD was partially funded by the Institut Français du Portugal.

## **THE INCREASE OF CURRENT RISE RATE AND INPUT POWER DENSITY FOR Z- DISCHARGE USING NON-UNIFORM FORMING LINES**

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High-current Z-discharges are widely used as a source of radiation in a wide range, a source of neutrons, etc. The report deals with a high-current Z-discharge with a power supply system based on a high-voltage generator and inhomogeneous forming lines. Non-uniform lines allow to control the electrical characteristics (current, voltage, etc.) in pulsed plasma loads.

In the report the ways to increase the discharge current rise rate and the input power density in Z-discharge are analyzed on the base of calculation results for different distributions of inhomogeneous transmission line characteristics.

The calculations have been carried out using an electrophysical self-consistent model, where processes developing in an electrical circuit and a pulsed plasma load are described. To analyze the plasma dynamics in a Z-discharge, a modified “snow-plow” model is used, where different mechanisms of energy absorption are taken into account. It is shown that by choosing physically reasonable distributions of the inhomogeneous line characteristics, one can obtain the increase of current rise rate no less than 1.5 times.

## **CORONA DISCHARGE PLASMA APPLICATION FOR WOUND HEALING AND FIBROBLAST PROLIFERATION**

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Thermal plasma effects have long been employed for tissue coagulation, cutting, desiccation, and cauterizing for a long time. Nevertheless, there have been significant developments in cold atmospheric pressure plasma (CAP) with well-controlled temperatures below 40°C. Thereby, in the last decade, a new innovative field, often referred to as plasma medicine, has emerged. Effective using of a handheld portable custom designed plasma jet generator for biomedical applications is reported. Portable CAP-generator is powered by a 4-5 V DC battery and operated at atmospheric pressure air without any external feed gas. CAP-generator has diverse positive results in biomedical applications due to production of reactive oxygen and nitrogen species (RONS). This CAP is produced in self-repetitive nanosecond pulse corona discharges with current pulses of ~300 ns duration, current peak amplitude of ~ 60-100 mA and repetition rate of ~ 10-50 kHz. Various experiments of in vivo wound models with CAP treatment have been conducted. As a result of the research, control-group mortality was 80%, and in contrast to this it was 10% in the plasma treated group. In addition, in vivo experiments with human fibroblasts were carried out. As a result, the optimal plasma exposure time promoting maximum fibroblasts` proliferation was determined. Resulting from the points mentioned above, the custom designed CAP- generator can be used for wound healing, and for sterilization of contaminated areas.

## **ELECTRIC EXPLOSION OF THIN FILMS OF DIFFERENT METALS**

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Exploding-wire investigations have been conducted since the 1950s. The initial studies dealt with usual electrical fuse regimes and the modern experiments are carried out using high-voltage Marx generators. In electrical explosion, the electromagnetic energy transfers to radiation, heat, and shock waves that are used for creation of the UV and X power sources radiation, gas lasers, nanopowder production, plasma sources etc. Physical properties of metals at high-density energy are important for the extreme pressure and temperature conditions of the matter investigations. Fast heating of the exploding-wire up to 10 000 K allows for studying the metal-plasma transition. The achievements in experiments with Z-pinch of Al, Ti, and W wires as X-ray sources are important for inertial confinement fusion and other applications.

In numerous experiments, the efficiency of energy deposition into conductor is limited by the development of the spatial instabilities caused by MHD, electrothermal processes etc. Usually spatial instabilities represent a stratified pattern of conductor matter along its longitudinal axis.

We present the experimental results of the nanometer metal films electrical explosion in the air. The experiments were conducted on the thin (5-20 nm) aluminum, zinc, nickel and gold films deposited on a dielectric substrate – quartz glass. The applied voltage was up to 10 kV, maximum current being up to 1 kA (current density up to  $3 \times 10^{12}$  A/m<sup>2</sup>) and pulsewidth ranged from 10 ns to 5  $\mu$ s depending on the storage capacity.

It was found that the film destruction is accompanied with the stratification (the strata are formed in the transverse direction to the applied electric field) for all metals under investigation. This allows us consider this effect as the universal mechanism of thin metal film electrodynamic destruction. The initial strata growth can be explained by the electro-thermal instability development.

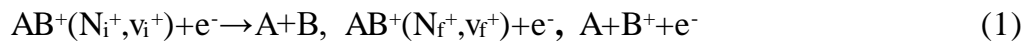
The strata propagation velocity reaches 10 km/s and depends on the current density. The pattern is formed during ~20-100 ns. During electrical explosion of conductors, the energy deposition value for all of the investigated regimes is less than the average metal melting level. This destruction mechanism can be significant in the modern investigation of electrical explosion wires.

# DISSOCIATIVE RECOMBINATION AND ELECTRON-IMPACT EXCITATION OF MOLECULAR CATIONS IN COLD PLASMA: APPLICATION TO $\text{BeH}^+$ , $\text{H}_2^+$ AND THEIR ISOTOPOMERS

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The detailed collisional-radiative modeling of cold plasmas requires accurate cross sections and rate coefficients of the major elementary processes, in particular of the dissociative recombination, ro-vibrational excitation and dissociative excitation:



where  $\text{N}^+/\text{v}^+$  stand for the rotational/vibrational quantum numbers of the cation. Using Multichannel Quantum Defect Theory (MQDT) cross sections and rate coefficients have been obtained for the above reactions involving the molecular cations  $\text{BeH}^+$ ,  $\text{BeD}^+$  and  $\text{BeT}^+$  relevant for the fusion edge plasmas (ITER project).

On the other hand, data for the processes involving  $\text{H}_2^+$  and  $\text{HD}^+$ , in order to model the same plasma, but also the excessively cold environments involved in the chemistry of the early Universe, interstellar molecular clouds, supernovae and planetary atmospheres, have been produced.

## **ELECTROPLASMIC PROCESSING OF COAL FLOTATION WASTE INTO ORGANO-MINERAL SORBENTS FOR WASTEWATER TREATMENT**

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The introduction of sorption technology in various industries requires an increase in the production of sorbents with a wide range of actions, involving the production of absorbers of substances of organomineral nature. Undoubtedly, a significant role among other types of sorbents belongs to carbon materials. Recently, organomineral sorbents based on thermally activated carbon-mineral raw materials (coal sludge, cake, coal-mineral pulp) are beginning to acquire special importance. Important factors of the use of these substances are their selectivity, achieved by the formation of active sorption centers formed by a highly developed organomineral surface, as well as the possibility of utilization of multi-ton dumps and, in addition, reducing the share of use in the production of sorbents of expensive hardwood trees or high-grade coal for sorbent briquettes. It is known that in the extraction of fossil coal, part of them in the process of coal enrichment inevitably goes into waste (coal sludge, pulp). However, the main limiting factor in the processing of organomineral coal residue in sorbents is its high humidity, sometimes up to 40%. The use of the method of thermoactivation electroplating allows significantly intensify the processes of obtaining sorbent from coal-mineral matter associated with its thermodestruction dehydration caused by the combined reactions occurring at the surfaces of particles at temperature exposure up to 3000 K, which contributes to reduction of production cost and significantly improves the environmental performance associated with involvement in the production of secondary raw materials, as well as the lack of emissions from the processing.

The article presents the results of studies of the structure and properties of the waste of carbon enrichment - cake, electroplasma treated to develop a technique for obtaining organo- mineral porous material to implement the possibility of its practical application as a sorbent for wastewater treatment. We conducted a study thermoactivation zone in the chamber electroplating reactor. The method of obtaining organomineral porous materials from coal cakes with the study of the elemental composition of raw materials before and after thermal activation is presented. Their most important physical and chemical properties are also

studied. The result of the conducted researches the ability of thermoactivation of the coal cake, changing its material composition, the occurrence of porosity and the related sorption capacity applied for wastewater treatment. Thus, the waste of flotation of the coal cake is fundamentally suitable for the production from it of porous substances by the method of thermal degradation in electroplating reactor.

## **LIGHTNING SHAPED CURRENT IMPACT ON COMPOSITE MATERIAL SURFACE FRACTURE**

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The distribution of current density in conductive composite materials under lightning impact is studied. The analysis of the experimental data and the results of numerical simulation have shown that configuration of electric field on the surface of composite materials under lightning impact is similar to configuration of electric field in the surface discharge geometry. Scenario of the effect of lightning current on the sample surface, taking into account the possibility of the surface discharge formation in the fast current phase is proposed. The estimation of mechanical stresses in the material area near the lightning channel shows that it is necessary to take into account the impulse strength characteristics of the material under pressure impacts with microsecond scale duration.

The opportunity of using of the magnetic pulse method of pressure formation for determination the dynamic strength and the fracture energy of the carbon fiber composite is shown. It is also shown that a magnetic field with amplitude of  $\sim 12$  T does not effect on the mechanical properties of the carbon fiber composite.

## FORMATION OF NANOGRAFITE FLAKES ON SiO<sub>2</sub> SUBSTRATE BY PLASMA DEPOSITION OF CARBON AND SUBSEQUENT ANNEALING

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The properties of nanographite flakes formed on the surface of silicon oxide by deposition of carbon in a plasma of methane (CH<sub>4</sub>) and subsequent annealing at a temperature of 650°C are investigated. Plasma treatments were performed in radiofrequency (13.56 MHz) inductively coupled plasma. Methane (30 sccm) was introduced in the reaction chamber and a plasma was ignited at a pressure of 0.04 mbar with a microwave power of 150 W to 200 W. Plasma treatment time was up to 12 min. Research using Raman spectroscopy, electron and atomic force microscopy showed that after plasma treatment in methane, an amorphous carbon film with characteristic Raman spectra is formed on the surface of the SiO<sub>2</sub> substrate. Measurements of current-voltage (I-V) characteristics showed that the sheet resistance of the film is hundreds of MΩ/sq. Heat treatments in an inert gas lead to the formation of thin graphitized films with a sheet resistance of up to several units of kΩ/sq and mobility of charge carriers up to hundreds of cm<sup>2</sup>V<sup>-1</sup>s<sup>-1</sup>. The temperature dependences of the I-V-characteristics show a sharp increase in resistance as the temperature decreases from room temperature to 77° K. In addition, the semi-logarithmic dependences of the resistance on temperature (T<sup>-1/3</sup>) show a linear dependence corresponding to the variable-range range (VRH) model of electrical conductivity. Based on these data and Raman spectroscopy, the sizes of the formed flakes were estimated. The paper analyzes and discusses the results.

## FUNDAMENTAL INHOMOGENEITY OF HARMONICALLY CONFINED YUKAWA PLASMAS

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In this work, we address the problem of homogeneity of Yukawa structures in a harmonic trap. In most works, Yukawa crystals in a trap are considered as spatially uniform and their properties are usually averaged over an entire structure. Only nonuniformity of density has been studied in detail while the problem of its influence on spectral properties and phase state has not been given enough attention. The subject of our interest goes beyond structural properties of Yukawa crystals and extends to dynamic properties. Among these are the amplitude of thermal oscillations, the Lindemann parameter, the spectra of oscillations and the non-ideality parameter of Yukawa crystals. We obtain explicit analytic formulas indicating that nonuniformity of density in Yukawa crystals directly leads to nonuniformity of all mentioned properties. We also demonstrate that inhomogeneity of inter-particle distance in a dusty plasma crystal may lead to the nonuniform heating of dust particles. Possibility of nonuniform driven melting in dusty plasma experiment is discussed. Developed analytic theory is verified by conducting molecular dynamics simulations and comparison with a glow discharge dusty plasma experiment. Obtained results are important for the theory of structure formation and phase transitions in systems of likely charged particles.

## KINETIC NUMERICAL ALGORITHM FOR WAKE POTENTIAL CALCULATION

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Dusty plasma is a weakly ionized gas which contains micron-sized particles of condensed matter. These particles are charged negatively due to the difference between the mobility of ions and electrons. In the absence of an external electric field, ions and electrons redistribute symmetrically in the radial direction around a particle and screen its electric potential. The resulting potential is likewise radially symmetrical and, in the linear approach, can be described by the Debye potential.

However, most experiments with dusty plasmas are ground-based and are carried out in the presence of an external electric field in order for dust particles to levitate against gravity. The presence of this field leads to deviation of ion distribution from the radial symmetrical case, and the potential around the dust particle becomes anisotropic. Anisotropy of the potential has a significant influence on the structural and dynamic properties of dusty plasma crystals. In this work, wake potential around a single dust particle in the presence of external longitudinal electric field is calculated numerically. For this purpose, the system of Vlasov equations with additional collision term in BGK form, which describes ion-neutral collisions, is used. As a result of this work, the limits of applicability of the method were established and the potential around the dust particle was calculated for various plasma flow parameters. Results were successfully compared with the limit analytical solutions obtained by other authors.

## MODELLING OF N<sub>2</sub>-H<sub>2</sub> CCRF DISCHARGES

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Capacitively coupled radio-frequency (ccrf) discharges in nitrogen-containing mixtures have been used in planetary studies to simulate, in laboratory environment, the reactivity of ionospheres. In this work, we present the results of simulations carried out for N<sub>2</sub>-H<sub>2</sub> low pressure, low power capacitively coupled radio-frequency discharges, for amounts of H<sub>2</sub> up to 5%. Simulations are performed using a hybrid code that couples a two-dimensional time-dependent fluid-type module, describing the transport of the charged particles, to a very complete zero-dimensional kinetic module for the nitrogen-hydrogen mixture. The fluid module solves the continuity and the momentum transfer equations for electrons, positive ions N<sub>2</sub><sup>+</sup>, N<sub>4</sub><sup>+</sup>, H<sup>+</sup>, H<sub>2</sub><sup>+</sup>, H<sub>3</sub><sup>+</sup>, HN<sub>2</sub><sup>+</sup>, NH<sup>+</sup>, NH<sub>2</sub><sup>+</sup>, NH<sub>3</sub><sup>+</sup> and NH<sub>4</sub><sup>+</sup>, and negative ions H<sup>-</sup> and NH<sub>2</sub><sup>-</sup>, the electron mean energy transport equations, and Poisson's equation for the rf electric potential. The space-time map of the electron transport and rate coefficients are obtained from the electron mean energy profile, using the local mean energy approximation. The kinetic module solves the two-term homogeneous and stationary electron Boltzmann equation (accounting for inelastic collisions from ground-state molecules and atoms, and inelastic and superelastic collisions involving vibrationally excited states), the rate balance equations of the ground-state vibrational excited states of N<sub>2</sub> and H<sub>2</sub>, the most relevant electronic excited states for N<sub>2</sub> and N, H, and the most important crossed-species NH<sub>y</sub> (y=1-3) and N<sub>2</sub>H<sub>y</sub> (y=2-4) resulting from interactions within the N<sub>2</sub>/H<sub>2</sub> systems. An extended surface chemistry is considered, taking in account adsorption, surface association and heterogeneous reactions, which are key to the formation of NH<sub>3</sub>. The electron impact chemistry of hydrogen has been updated using the latest set of cross sections available from LXCat. Simulations show that significant amounts of NH<sub>3</sub> are produced in the discharge, with a high dependence on the parameters for the surface kinetics. The abundances of positive ions are greatly affected by the neutral composition, with NH<sub>4</sub><sup>+</sup> quickly becoming the major ion when sufficient NH<sub>3</sub> is present.

# **DESIGNING A HYBRID PHYSICAL CHEMICAL VAPOR DEPOSITION (HPCVD) SYSTEM FOR DEPOSITION OF SUPERCONDUCTING MgB<sub>2</sub> THIN FILMS ON 3D SUBSTRATES**

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In this work we report a novel approach towards coating MgB<sub>2</sub> on 3D surfaces using Solenoid Magnetron based Hybrid Physical Chemical Vapor Deposition approach. The setup comprises of a Mg rod (1.6mm dia.) serving as the sputtering target and confined within a metallic cylinder, the three dimensional substrate. The substrate in turn is surrounded by a solenoid coil powered by a DC power supply (~80V, 2A) to provide a uniform magnetic field. One gas line is connected from the base to introduce H<sub>2</sub> gas to initiate the precursor decomposition reaction within the plasma. Boron is sourced from high purity BBr<sub>3</sub> injected into the system using high purity Ar as carrier gas. The plasma generated from Mg sputtering decomposes BBr<sub>3</sub> in presence of H atoms to liberate B in atomic form, followed by chemical reaction between Mg and B and ultimate deposition of MgB<sub>2</sub> on the substrate. The entire system is maintained at a temperature of 150<sup>o</sup>C to ensure uniform deposition and high adhesion of the coating to the substrate surface. Parameters such as the Ar and H<sub>2</sub> flow rate, input power and deposition time are varied to optimize the conditions necessary to maintain the desired Mg/B atomic ratio of 1:2.

# OPTIMIZATION OF Xe LPP SOURCE OF EUV RADIATION FOR LITHOGRAPHY. NEW METHOD OF SUPPRESSING PERIPHERAL ABSORPTION

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Until now, the 13.5-nm EUV lithography experiences difficulty to enter the high volume manufacture connected with its laser-plasma tin-target radiation source. Since 2013, an idea exists to use the wavelength 11.2-11.4 nm and the debrisless Xe laser plasma source for another branch of the EUV lithography hoping that its intensity will be satisfactory for industrial needs. The present paper describes a new method for suppressing the peripheral absorption of EUV radiation in a Xe gas-jet source. Using turnable Bragg mirrors, spectra of the Xe radiation power density of a laser plasma in the 11-14 nm band were measured. It is shown that using the developed method, the registered signal of EUV radiation in the wavelength band  $\lambda = 11 \div 11.8$  nm increased 4 times, and in the wavelength band  $\lambda = 12.7 \div 14.2$  nm – 10 times. The first for a source with Xe gas-jet target, the conversion coefficient  $\eta_{conv} = (3,65 \pm 0,35)\%$  was obtained.

## **NOVEL DISTRIBUTED AIR-BREATHING PLASMA JET PROPULSION CONCEPT FOR ALL-ELECTRIC HIGH-ALTITUDE FLYING WINGS**

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The paper describes a novel distributed air-breathing plasma jet propulsion concept for all-electric hybrid flying wings capable of reaching altitudes of 100,000 ft and subsonic speeds of 500 mph. The new concept is based on the recently achieved first breakthrough for air-breathing high-thrust plasma jet engines. Pulse operation with a few hundred Hertz will soon enable thrust levels of up to 5-10 N from each of the small trailing edge plasma thruster cells with one inch of core engine diameter and thrust-to-area ratios of modern fuel-powered jet engines. An array of tens of thrusters with a magnetohydrodynamic (MHD) fast jet core and low speed electrohydrodynamic (EHD) fan engine based on sliding discharges on new ultra-lightweight structures will serve as a distributed plasma “rocket” booster for a short duration fast climb from 50,000 ft to stratospheric altitudes up to 100,000 ft. Two electric aircraft engines with each 110 lb (50 kg) weight and 260 kW of power as recently developed by Siemens will make the main propulsion for take-off and landing and climb up to 50,000 ft. Especially for climbing up to 100,000 ft the propellers will apply sophisticated pulsed plasma separation flow control methods. The novel distributed air-breathing plasma engine will be only powered for a short duration to reach stratospheric altitudes with lowest possible power consumption from the high-density battery swap modules and special fuel cell systems with minimum 660 kW, all system optimized for a short one to two hours near-space tourism flight application. The shining Plasma Stingray can bring up to six space tourists to the edge of near-space in less than an hour, switch-off the plasma pulse detonation engine at 100,000 ft and come back as a glider or lifting body aerospace shuttle. Advanced plasma flow control methods will be used to increase the glide ratio and flight time. Wing mounted flexible solar cells based on optical rectenna technology can provide additional 50 kW or at least 25 kW using state-of-the-art solar cells with 30% efficiency. Possible near infrared, terahertz or microwave power transmissions to flexible underwing rectannas are additional onboard lightweight power tools.

## **PROBE RESEARCH OF THE CATHODE REGION OF THE GLOW DISCHARGE**

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An experimental investigation of the ion fluxes to the cathode of the glow discharges in nitrogen has been performed and is presented in this work. These were studied in a discharge tube with flat electrodes. A hole closed by a grid was located in the cathode center. Next to the hole, a collector was mounted. The study was conducted in nitrogen at discharge currents of 2.5–10 mA and gas pressure 0.3–3 Torr. The dependence of the collector current on the potential difference between the collector and the cathode was determined. In all cases, the voltage blocking (the collector current is equal to zero) is much less than the total voltage across the tube, which can be taken as the value of the cathode fall. The maximum energy of ions reaching the cathode significantly depends on the gas pressure. The alteration of the discharge current at a constant gas pressure does not affect the blocking voltage and the energy distribution of ions. The ion energy distribution functions were determined from the experimental characteristics. The analysis of the ion distribution functions shows that the main process determining the ions energy distribution is charge-exchange.

## **DEVELOPMENT OF 5-CM ION THRUSTER AND PRELIMINARY NUMERICAL SIMULATION OF PLASMA IN ITS DISCHARGE CHAMBER**

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Within the "Technology-SG" framework of the scientific and technical program of the Union State of Russia and Belarus a 180 W ion thruster with a direct current discharge chamber is being developed in Keldysh Research Center. To achieve high performance parameters, electric current density and operation lifetime a project of a hybrid magnetic system consisting of permanent magnets supplemented by electric magnetic coils was considered. This magnetic system configuration combines the advantages of energy savings and the possibility of the operation mode optimization. At the design stage, preliminary numerical modeling with a 3d axis-symmetric particle-in-cell model was used to confirm the theoretical assumptions used in the development of the magnetic system and to further improve magnetic system design. The simulation allowed to obtain the distributions of plasma parameters for various configurations of the magnetic field. In addition, the estimated data on the dynamics of the discharge chamber integral parameters and the ion beam current density distribution over the radius were obtained. These distributions confirmed the correctness of the chosen approach to the development of the magnetic system and were used to form the final thruster design.

## **NEW THERMO-PLASMA TECHNOLOGY FOR SELECTIVE $^{14}\text{C}$ ISOTOPE EXTRACTION FROM IRRADIATED REACTOR GRAPHITE**

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We propose new thermo-plasma technology for the selective extraction of the radioactive isotope  $^{14}\text{C}$  in the deactivation treatment of the irradiated reactor graphite surface. The proposed technology has several advantages compared with other decontamination methods as it provides effective extraction of highly radioactive nano-micro-size layer from the surfaces of the graphite bulk via cathode plasma inert ion sputtering and compact collecting of the radionuclides via diffusion to anode. Thus it avoids formation of the liquid secondary radioactive waste (“dry” technology), the method is relatively simple to implement and can be technically and economically effective. For the decontamination of the graphite surface and concentrate of  $^{14}\text{C}$  exploration under the heating and plasma sputtering, the design of the plasma spraying cell is described. One of the problem to be traversed in this way is the presence of a number of other radioactive isotopes which must be separated from  $^{14}\text{C}$  enriched final product. It may be reached by thermal separation of different atoms presenting in the irradiated graphite in accordance with their individual rates for condensation from inert gas to anode substrate. For this purpose plasma sputtering cell includes elongated ceramic heat insulator elements at the heated inert gas pumping out tube to provide a number of zones with different temperature for separate spatial condensation, as well as a vacuum thermal insulation of the anode (collector) for the maximum temperature zone. Model of energy release in this plasma discharge was considered, heat flux via and temperature of the cathode (sputtered surface) and the anode were estimated to ensure pure carbon condensation on the anode excluding other radionuclide impurities.

The reported study was funded by RFBR according to the research project № 18-32-00679 mol\_a.

## **MEASUREMENTS OF RELATIVE EROSION RATE OF CERAMIC INSULATORS IN HALL THRUSTER WITH EXTERNAL LAYER USING LOW-TEMPERATURE PLASMA SPECTRAL ANALYSIS**

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A specific operating mode was observed for Hall thrusters in the power range up to 5 kW when at least one of the following changes occurred: a decrease in gas flow rate, an increase in magnetic field magnitude, an extension of ceramics or a change in ceramics properties. The thruster operating in the observed mode has total efficiency from 5 to 20 % lower than in the design mode. In this paper, relative erosion rate of boron nitride (BN) ceramics was measured for a Hall thruster with external ionization and acceleration region for both operating modes using passive spectral analysis.

The Hall thruster has middle line diameter of 77mm and maximum power up to 2.5 kW. Estimations of the relative erosion rate were based on boron doublet linewidth with wavelengths of 249.677 and 249.773 nm. During the study, discharge voltage range was from 400 to 1000 V, gas flow rate range was from 2 to 6 mg/s. It was shown that the relative erosion rate for all operating conditions is lower for the operating mode with lower efficiency for chosen thruster.

## **THE NONLINEAR CHANGE IN DYNAMIC PROPERTIES OF A 2D YUKAWA HEXAGONAL CLUSTER UNDER AMPLITUDE INSTABILITY ONSET**

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Here we present the results of analytical and numerical investigation of the nonlinear change in dynamic properties of a two-dimensional Yukawa seven-particle cluster with the amplitude instability onset. Mechanisms for the onset and growth of instabilities in nonideal gases, plasmas, or complex plasmas are in the permanent focus of the researches. As particle displacement increases, the deviation of particles from their equilibrium positions (e.g., due to the rise in the kinetic temperature) can lead to a disruption of stability of a strongly coupled system.

We used an analytical approach, which is based on the pursuit of the energetically favorable inflection point of the potential energy function taking into the account displacements of each particle from its equilibrium positions as well as mutual displacements of particles. As a result, we obtained the assessment for the critical value of the coupling parameter indicating to the amplitude instability onset.

We produced a series of Langevin molecular dynamics simulations varying parameters for interparticle interaction and parameters of surrounding media. Our numerical simulations have shown drastic changes in structural and dynamical properties of the system near the critical value of the coupling parameter. The investigation of mass transfer processes allowed us to determine the coupling parameter with better accuracy in comparison to methods dealing with the pair correlation functions, or the dynamic entropy. The original analytical assessment gave a good agreement with our numerical data. We also have obtained that the amplitude instability onset in a hexagonal cluster has an obvious general correlation with the melting criteria for spatially homogeneous two-dimensional systems having primitive hexagonal packing.

## **EXPERIMENTAL STUDY OF THE WAKEFIELD BEHIND A DUST PARTICLE IN A DC DISCHARGE OF THE GAS MIXTURE**

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Experimental study of the wakefield behind a dust particle in a DC gas discharge containing an easily ionized impurity of heavy atoms was performed. The main buffer gas was helium, and inert krypton (Kr) was used as an impurity. During the experiment, the molar amount of impurity in the gas mixture ranged from 0 to 2.4 percent, while the pressure of the gas mixture was maintained at 50 pascals. Two monodisperse polystyrene particles were suspended under each other in a stratum of the positive discharge column. Video recordings of dust particle trajectories made it possible to study the interaction between dust particles, as well as the external electrical forces acting on the particles from the discharge. We found that a small fraction of the impurity of heavy ions in the plasma of a light gas significantly affects the wake structure which is formed due to the perturbation of the ion flux by the charged macroparticle.

## TOWARDS APPLICATION OF PLASMA BURNERS TO INDUSTRIAL PROCESSES

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The replacement of fossil fuel combustion in the heavy process industry (e.g. cement, iron ore) with plasma burners is considered as a potentially attractive approach in Sweden. One of the major concerns with the approach is that the introduction of the plasma gases into already hot industrial air stream will result in very high NO<sub>x</sub> levels. The objective of this work was to build up knowledge in the field of interaction of the plasma gas with hot air.

The experiments were made using a laboratory-scale chamber including the 18 kW plasmatron and electrical system for air preheating. The properties of plasma jet were studied using emission spectroscopy. New strategy for online in-situ quantitative broadband UV absorption diagnostics of the NO mole fraction and T was developed for application in the mixtures of plasma and coflow air. The emission experimental results indicate that the temperature in the middle of the plasma is not very sensitive to the choice of the plasma gas (Air or N<sub>2</sub>) and its flow and is mainly determined by the power of the plasma system. The centerline temperature is significantly higher than the mass averaged temperature of the plasma jet calculated using equilibrium program. The NO levels in the mixture of the plasma and coflow gases were higher than those typically observed for combustion of fossil oil. The NO<sub>x</sub> emission depended on the mixing of the plasma and coflow gases as well as temperature and composition of the plasma gas. The plasma operated with N<sub>2</sub> at high flows produces the lower NO amount in the mixture. The preheating of the air coflow up to 700 C does not lead to significant increase of the NO level. The addition of methane to air plasma reduces the plasma formed NO<sub>x</sub>. The NO reburning increases with the CH<sub>4</sub> addition reaching ~70 % in the experiments with N<sub>2</sub> used as a coflow.

This work has been conducted as part of the HYBRIT research project RP1. We gratefully acknowledge financial support from the Swedish Energy Agency. HYBRIT (Hydrogen Breakthrough Ironmaking Technology) is a joint initiative of the three companies SSAB, LKAB and Vattenfall with the aim of developing the world's first fossil-free ore-based steelmaking route.

# ON THE NATURE OF STABILITY OF SOLITONS IN A LINEAR AND NONLINEAR WEAKLY AND STRONGLY DISPERSIVE ADIABATIC ELECTRON-POSITRON-ION PLASMA

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Our objective is to study the linear and nonlinear behaviour of modulated envelope solitons in a Schrodinger equation along with contribution of higher order terms in the perturbation expansion for strongly dispersive case in a three component plasma with constituents electrons, positrons and warm ions. While the warm ions are treated as an inertial fluid, the electrons and positron beams are assumed to be in a Maxwellian state, described by a state of thermodynamic equilibrium in a solar flare environment. In the analysis, it is exhibited that the lower order terms is governed by nonlinear Schrodinger equation, while the higher order expansion is governed by the linear Schrodinger equation. The dynamical modulatory waves in the present plasma system is modelled via a varying dissipative Schrodinger equation, derived via the concept of a scale parameter  $g$  into a power series of the smallness parameter  $\epsilon$ , which includes a dissipative term associated with finite imaginary part of the nonlinearity term. Besides, it is found that with the inclusion of ion temperature and positron beam, the modulational instability sets in much earlier. Our work elucidates formation of progressive wave solution, steady state solution along with a class of periodic solutions for which the real and imaginary parts are linearly exhibited. Results of numerical simulation confirm predictions of stability and instability criteria, bright and dark solitons, breather like soliton, kink and anti-kink solitons and present explicit forms for these solutions from first to fourth order. The findings presented in this paper should be useful in understanding the effect of ionic temperature, positron beam and strong dispersiveness on the dynamical and structural characteristics (amplitude, width, velocity and wave number) of the solitons without having to incorporate Landau damping useful in Tokamaks, thereby, modifying stability of nonlinear and linear complex wave structures, along with possibilities for existence of different types of slow evolutionary excitations compared to that of the rapid carrier wave.

# **THEORETICAL ANALYSIS OF ELECTRON – ACOUSTIC SHOCK WAVES IN MAGNETIZED SUPERHERMAL PLASMA WITH ELECTRON BEAM**

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Small amplitude electron acoustic shock waves in magnetized four component plasma system consisting of cold electrons, superthermal hot electrons, electron beam and stationary ions are studied using reductive perturbation technique.

Two types of shock waves, namely, Slow mode and fast mode electron acoustic shock waves are formed. Interesting features are obtained for the study of shock wave structure depending upon the mode structures.

Numerical analysis show that amplitude is positive for slow shock structure and negative for fast shock structures. Beam density, beam temperature, beam velocity, kinematic viscosity has significant effect on the profile of shock waves. The present study may be helpful to explain some features of localized structures in the plasma sheet boundary.

# **ДОСТИЖЕНИЯ И ПРИМЕНЕНИЯ ФИЗИКИ ПЛАЗМЫ**

Сборник тезисов  
международной научной конференции

Санкт-Петербург  
18–20 сентября 2019 года

Налоговая льгота – Общероссийский классификатор продукции  
ОК 005-93, т. 2; 95 3004 – научная и производственная литература

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Подписано в печать 11.09.2019. Формат 60×84/16. Печать цифровая.

Усл. печ. л. 7,5. Тираж 120. Заказ 18159b.

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Отпечатано с готового оригинал-макета,  
предоставленного орг. комитетом конференции,  
в Издательско-полиграфическом центре Политехнического университета.  
195251, Санкт-Петербург, Политехническая ул., 29.  
Тел.: (812) 552-77-17; 550-40-14.