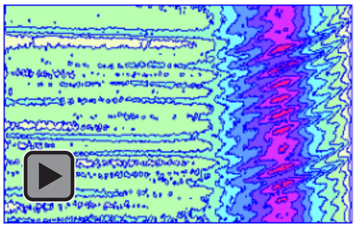

# PROGRAM and Abstracts EXB – 2017

## EXB Plasmas for Space and Industrial Applications

*21-23 June 2017,Toulouse (France)*

## EXB 2017 WORKSHOP

The EXB-2017 workshop is focused on charged particle transport and instabilities in various low pressure magnetized plasma devices with large EXB or ∇PXB drift of magnetized electrons and weakly magnetized ions. These devices include Hall thrusters, magnetron discharges such as those used for High Power Impulse Magnetron Sputtering - HiPIMS, Penning sources, cusped-field thrusters, etc…). Magnetic nozzles in partially magnetized plasmas will also be discussed.

The aim of the workshop is to review and discuss the present state of knowledge that has been obtained from diagnostics, theory, and simulations. In order to enhance interactions among the participants, each half-day session will focus on a specific topic and will include three 30-minutes or four 20-minutes talks followed by a moderated discussion session where participants are encouraged to present short (2-3 minutes) questions/comments.

The workshop is organized by Jean-Pierre Boeuf (LAPLACE, Univ of Toulouse, France), and Andrei Smoylakov (Univ of Saskatchewan, Canada)

## SPONSOR

The workshop is organized in the framework of the IMPULSE project ( https://www.impulse-stae.net/ ) sponsored by the RTRA STAE Foundation.

The aim of this project is to improve the basic knowledge and the predictive capabilities of the models of low pressure partially magnetized plasmas applied to space propulsion.

Several Toulouse laboratories are involved in the IMPULSE project:

- LAPLACE (LAboratoire PLAsma et Conversion d'Energy)
- IMT (Institut de Mathématiques de Toulouse)
- CERFACS (Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique)
- ONERA (the French Aerospace Lab)
- CNES (Centre national d'Etudes Spatiales)

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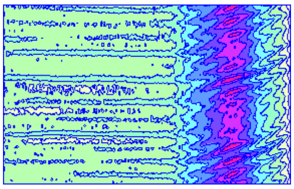


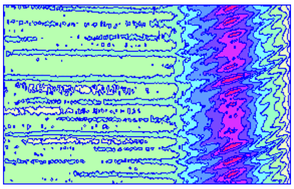


## Tuesday, June 20

| | |
|---|---|
| 19:30 | Reception/Diner |

## Wednesday, June 21

| **09:00 – 12:30** | **Session 1** | **Instabilities and turbulence in partially magnetized plasmas : theory, diagnostics, and modeling** |
|---|---|---|
| 08:15 – 08:45 | Welcome | |
| 08:45 – 09:00 | Introduction | **Jean-Pierre BOEUF & Andrei SMOLYAKOV** |
| 09:00 – 09:30 | Lecture 1<br>Abstract | **Benjamin JORNS** (University of Michigan)<br>An overview of instabilities capable of inducing cross-field transport in low -temperature, partially magnetized discharges |
| 09:30 – 10:00 | Lecture 2<br>Abstract | **Edgar CHOUEIRI** (Princeton University)<br>*Software and diagnostics for the study of instabilities in partially magnetized plasmas* |
| 10:00 – 10:30 | Lecture 3<br>Abstract | **Igor KAGANOVICH** (PPPL, Princeton Plasma Physics Laboratory)<br>*Electron-wall interactions and their consequences on transport* |
| 10:30 – 11 :00 | Pause | |
| 11:00 – 12:30 | Discussion | Moderators : **Andrei SMOLYAKOV** & **Stéphane MAZOUFFRE** |
| 12:30 – 14:00 | Lunch | |
| **14:00 – 17:30** | **Session 2** | **Magnetic Nozzles – Kinetic models** |
| 14:00 – 14:30 | Lecture 4<br>Abstract | **Rod BOSWELL** (Australian National University)<br>*Beam plasma discharges and the adiabatic expansion of an electron gas : the role of electric and magnetic fields* |
| 14:30 – 15:00 | Lecture 5<br>Abstract | **Eduardo AHEDO** (UC3M, Universitad Carlos III de Madrid)<br>*Physics and open issues on magnetized plasma plumes* |
| 15:00 – 15:30 | Lecture 6<br>Abstract | **Ralf-Peter BRINKMAN** (Ruhr-Unversität Bochum)<br>*Kinetic description of magnetized technological plasmas* |
| 15:30 – 16 :00 | Pause | |
| 16:00 – 17:30 | Discussion | Moderators : **Trevor LAFLEUR** & **Ioaniss MIKELLIDES** |





## Thursday, June 22

| **09:00 – 12:30** | **Session 3** | **The Electron Cyclotron Drift Instability** |
|---|---|---|
| 09:00 – 09:30 | Lecture 7<br>Abstract | **Bertrand LEMBEGE** (LATMOS, Univ. de Versailles-ST-Quentin-en-Yvelines)<br>*The electron cyclotron drift instability in space plasmas* |
| 09:30 – 10:00 | Lecture 8<br>Abstract | **Sedina TSIKATA** (ICARE, CNRS, Orléans)<br>*The electron cyclotron drift instability : thruster studies and physical interpretations* |
| 10:00 – 10:30 | Lecture 9<br>Abstract | **Trevor LAFLEUR** (LPP, Ecole Polytechnique)<br>*Electron drift instabilities in EXB plasmas : kinetic theory and PIC simulations* |
| 10:30 – 11 :00 | Pause | |
| 11:00 – 12:30 | Discussion | Moderators : **Edgar CHOUEIRI** & **Andrei SMOLYAKOV** |
| 12:30 – 14:00 | Lunch | |
| **14:00 – 17:30** | **Session 4** | **HiPIMS and other devices** |
| 14:00 – 14:30 | Lecture 10<br>Abstract | **Fabrice DOVEIL** (PIIM, Aix-Marseille University)<br>*Instabilities in the linear plasma MISTRAL* |
| 14:30 – 15:00 | Lecture 11<br>Abstract | **Achim von KEUDELL** (Ruhr-Unversität Bochum)<br>*Instabilities and anomalous transport in HiPIMS* |
| 15:00 – 15:30 | Lecture 12<br>Abstract | **Jón Tómas GUDMUNDSSON** (University of Iceland, Reykjavik)<br>*Consequences of EXB transport on electron heating in HiPIMS* |
| 15:30 – 16 :00 | Pause | |
| 16:00 – 17:30 | <br>Abstract<br>Abstract<br>Abstract<br>Abstract<br>Abstract | Poster Session<br>**Fabrice DELUZET** et al., IMT, Toulouse<br>**Valentin JONCQUIERES** et al., CERFACS, Toulouse<br>**Dennis KRUEGER** et al., Ruhr Univ Bochum<br>**Sarah SADOUNI** et al., LAPLACE, Toulouse<br>**Marc VILLEMANT** et al., ONERA, Toulouse<br>Some other posters (not listed here) summarize the work presented in oral sessions |

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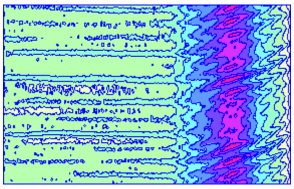
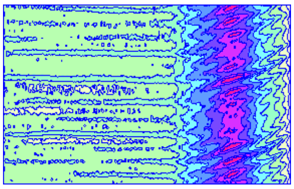
| 19:30 | Workshop Diner |





## Friday, June 23

| 09:00 – 12:30 | Session 5 | Fluid modeling and theory of instabilities in partially magnetized plasmas |
|---|---|---|
| 09:00 – 09:30 | Lecture 13<br>Abstract | **Alejandro LOPEZ ORTEGA and Ioannis MIKELLIDES** (NASA JPL)<br>*Electron transport by the EXB-driven ion acoustic instability in a Hall thruster based on r-z multi-fluid simulations* |
| 09:30 – 10:00 | Lecture 14<br>Abstract | **Gerjan HAGELAAR** (LAPLACE, CNRS & Univ of Toulouse)<br>*Fluid simulation of instabilities in partially magnetized plasmas* |
| 10:00 – 10:30 | Lecture 15<br>Abstract | **Andrei SMOLYAKOV** (Univ Staskatchewan)<br>Instabilities in EXB plasmas – Theory, dispersion relations, fluid models |
| 10:30 – 11 :00 | Pause | |
| 11:00 – 12:30 | Discussion | Moderators : **Ben JORNS** & **Igor KAGANOVICH** |
| 12:30 – 14:00 | Lunch | |
| **14:00 – 17:30** | **Session 6** | **Spokes and their control** |
| 14:00 – 14:30 | Lecture 16<br>Abstract | **Yevgeny RAITSES** (PPPL, Princeton Plasma Physics Laboratory)<br>*Controlling of spokes and breathing oscillations in partially ionized EXB plasmas* |
| 14:30 – 15:00 | Lecture 17<br>Abstract | **Francesco TACCOGNA** (CNR NANOTEC, Bari)<br>*Examples of EXB instabilities predicted by PIC simulations* |
| 15:00 – 15:30 | Lecture 18<br>Abstract | **Konstantin MATYASH** (University of Greifswald)<br>*3D PIC simulations of rotating spokes in wall-less thrusters* |
| 15:30 – 16 :00 | Pause | |
| 16:00 – 17:30 | Discussion | Moderators : **Rod BOSWELL** & **Yevgeny RAITSES**<br>Discussion includes topics of session 4 and session 6 |
| 17 :30 – 18:00 | Conclusion | |





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2. **Edgar CHOUEIRI,** *Software and diagnostics for the study of instabilities in partially magnetized plasmas*
3. **Igor KAGANOVICH,** *Electron-wall interactions and their consequences on transport*
4. **Rod BOSWELL,** *Beam plasma discharges and the adiabatic expansion of an electron gas : the role of electric and magnetic fields*
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# An overview of instabilities capable of inducing cross-field transport in low -temperature, partially magnetized discharges

Benjamin Jorns

*Department of Aerospace Engineering*
*University of Michigan*
*Ann Arbor, MI 48109 USA*
*e-mail: bjorns@umich.edu

An overview is presented of select plasma instabilities capable of inducing cross-field electron transport in two types of plasma devices, the Hall effect thruster and the Penning discharge. In most cases, the cross-field electron current in these devices---the current in the direction of the applied electric field---is orders of magnitude higher than what can be explained by classical effects such as interspecies collisions. This suggests that there are other, non-classical mechanisms that dominate this process. A fluid-formalism is presented that demonstrates how propagating modes with a wavevector component in the Hall direction can induce enhanced cross-field electron current. A summary is then presented of plasma instabilities that both satisfy this criterion and have been experimentally-observed in these low-temperature devices. These instabilities are examined in the context of their dispersion relations, stability criteria, numerical simulations, and experimental observations. Where applicable, data is also presented on the magnitude of current that these instabilities can conduct in the cross-field devices. Special attention is paid to two of the most popular modes currently being examined in the Hall thruster community: large-scale spoke-like oscillations and short length scale turbulence.

# Software and diagnostics for the study of instabilities in partially magnetized plasmas

Edgar Y. Choueiri and Sebastián Rojas Mata

*Electric Propulsion and Plasma Dynamics Laboratory*
*Princeton University*
*Princeton, NJ 08540 USA*
*email: choueiri@princeton.edu

This talk overviews the ongoing development of two exploratory tools whose goal is to aid researchers characterize dispersion relations in plasma discharges. The first is the Plasma Rocket Instability Characterizer (PRINCE), a versatile software tool that numerically characterizes linear plasma waves and their dependence on operational parameters by solving for the zeros of relevant dispersion relations. PRINCE combines a root-bracketing algorithm based on Cauchy's Argument Principle to find the zeros of a user-selected dispersion relation with an iterative root-tracking algorithm to characterize the zeros in frequency-wavenumber $(\omega, \mathbf{k})$ space. The software is wrapped as a stand-alone application with an intuitive graphical user interface for specifying input data numerically and governing dispersion relations analytically. We describe the structure of Prince and illustrate its use with examples that are relevant to waves in Hall thruster plasmas.

The second tool is an active wave injection (AWI) experimental diagnostic which excites plasma waves in order to conduct interferometric measurements of the waves' dispersion relation in a plasma discharge. Through spectral analysis of time-varying ion saturation currents, the AWI diagnostic can be used to carry out experimental plasma wave studies with high signal-to-noise measurements and direct control over the harmonic content of the probing wave modes.

We also describe an experiment designed to validate both tools using, for reference, laser induced fluorescence (LIF) measurements of the dispersion relation of excited electrostatic ion cyclotron (EIC) waves in an RF argon plasma source.

# Electron-wall interactions and their consequences on transport

I. D. Kaganovich(1), D. Sydorenko(2), A. V. Khrabrov(1), A. T. Powis(1), J. Carlsson(1), Y. Raitses(1)
*(1) Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ, USA)*
*(2) University of Alberta, Edmonton, Alberta, Canada*
*e-mail: ikaganov@pppl.gov

The purpose of the talk is to give an overview of accomplishments at PPPL in predictive control of electron kinetics in low-pressure plasmas relevant to ExB discharges. We show using specific examples that this progress was made possible by synergy between full-scale particle-in-cell simulations, analytical models, and experiments. For low-pressure devices, the electron velocity distribution function (EVDF) is non-Maxwellian and, correspondingly, the wall potential is strongly modified. Electron emission strongly influences the wall potential and also leads to the enhanced ExB transport [1]. Nonlinear coupling between EVDF and the wall potential causes additional kinetic instabilities and can cause the relaxation sheath oscillations [2]. We also studied electron beam interaction with the plasma and collisionless transfer of the beam energy to plasma electrons [3]. When secondary electron emission (SEE) needs to be controlled, special surfaces can be used for the SEE mitigation [4]. Our current work includes implementing modern Poisson solvers into the Large Scale Plasma (LSP) particle-in-cell (PIC) code [5] which enables multidimensional PIC simulations. This enhanced PPPL-modified LSP code is being applied to study several low-temperature plasma technologies, including anomalous transport in closed drift ExB devices [6,7].

**References:**

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# Adiabatic expansion of an electron gas.

[1]Kazunori Takahashi, [2]Rod Boswell and Christine Charles

*1 Tohoku University, Sendai, Japan. 2 Australian National University, Canberra, Australia.*

A specially constructed experiment is described that shows the near perfect adiabatic expansion of an ideal electron gas resulting in the measurement of a polytropic index greater than 1.4, approaching the adiabatic value of 5/3. The measurements were made on electrons in an argon plasma expanding in a magnetic nozzle where the potential of the expanding plasma was forced to be zero by externally setting the potential of the source plasma to be zero resulting in an electric current in the system. By changing the magnitude of the current, the plasma potential can be changed and either an isothermal or adiabatic expansion can be achieved. In all cases, the collision length of all processes is greater than the scale length of the expansion meaning the system cannot be in thermodynamic equilibrium, yet thermodynamic concepts can be used, with caution, in explaining the results. A Lorenz force, created by inhomogeneities in the radial plasma density, does work on the expanding magnetic field reducing the internal energy of the electron gas.

# Physics and open issues on magnetized plasma plumes

E. Ahedo* and M. Merino

*Plasmas and Space Propulsion Team (EP2),Universidad Carlos III de Madrid, Spain*

*e-mail: eduardo.ahedo@uc3m.es

This talk summarizes EP2's work on a magnetic nozzle(MN) for space propulsion. A two-fluid, steady-state model with fully-magnetized electrons but partially-magnetized ions (DIMAGNO) is used as the basis to assess the main phenomena on the divergent magnetized expansion of a plasma jet. While electrons admit simple first-integrals laws, ions behave as a supersonic fluid. The ambipolar electric field controls the conversion of the electron internal energy into ion kinetic energy and the development of a highly-supersonic plasma jet. The model explains the magnetic thrust and detachment mechanisms and the central role of azimuthal plasma currents (both diamagnetic and paramagnetic). Extensions of the base model assess the effects of plasma collisionality, electron-inertia, and induced-magnetic field in increasing jet divergence. A fully-magnetized-ion model, although more restrictive, allows to complete the physics discussed by DIMAGNO. Furthermore, that model has been extended to analyze a 3D steerable MN and show its capacity of control the thrust vector.

Moving into issues left unsolved by DIMAGNO, a first one is the correct model for electron thermodynamics of the very-rarified jet, where local thermodynamic equilibrium and the subsequent adiabatic law fail. A Vlasov-based, steady-state kinetic model of a paraxial MN has unveiled and assessed that electron collisionless cooling is due to the partial depletion of its distribution function. At present, a time-dependent version of this model is being studied in order to characterize doubly-trapped electrons and their relevance on the electron density. A second important issue, still fully open, is the final region of the jet expansion, where electrons become demagnetize: a consistent transition model from a magnetized to an unmagnetized electron formulation appears at present as very challenging.

**References:** M. Merino and E. Ahedo, 'Space Plasma Thrusters: Magnetic Nozzles for', in 'Encyclopedia of Plasma Technology', J. Shohet Ed., Taylor & Francis, New York, Vol. 2, 1329-1351, (2016).

# Kinetic description of magnetized technological plasma

R.P. Brinkmann and Dennis Krüger

*Ruhr University, Bochum, Germany*

Plasma processes like magnetically enhanced reactive ion etching (MERIE), plasma ion assisted deposition (PIAD), and conventional and high power im-pulse magnetron sputtering (dcMS/HiPIMS) employ magnetized high den-sity plasmas at relatively low pressures. (Typical values are $p \approx 0.1 - 1\,\mathrm{Pa}$, $B \approx 10 - 100\,\mathrm{mT}$, $n_\mathrm{e} \approx 10^{15} - 10^{20}\,\mathrm{m}^{-3}$.) Such plasmas are, at least in their active regions, characterized by a peculiar ordering of the dynamic length and corresponding time scales: $\lambda_D \ll s \ll r_\mathrm{L} \ll L \sim \lambda \ll \lambda^*$, with $\lambda_D$ Debye length, $s$ sheath thickness, $r_\mathrm{L}$ gyroradius, $L$ system length, and $\lambda$ and $\lambda^*$ elastic and inelastic electron mean free path, respectively. This regime is very difficult to analyze. Fluid models do not apply and numerical kinetic approaches like particle-in-cell are rather expensive. An alternative may be “gyrokinetics”. This theory - actually more a class of theories - was designed and successfully employed in the field of fusion plasmas. It relies on the insight that the fast gyro motion of magnetized particles can be mathemat-ically separated from the slower drift motion and be integrated out, leaving only the dynamics on slower time scales and larger length scales. Unfor-tunately, however, magnetized technical plasmas are considerably different from fusion plasmas: Differences concern the magnetic field topology, the the desired wall interactions, collisions with neutrals, the fact that only elec-trons are magnetized, etc. Direct application of theories developed for fusion is thus not possible. We will present a gyrokinetic theory for magnetized technical plasmas that is based on first principles. The outset is a general kinetic description of the electron component which incorporates the scaling mentioned above. A multi-time scale formalism is employed which results in four separate levels. Explicitly solving the first two levels and substituting into the last two gives the desired self-consistent transport theory on the slowest time and largest length scales. The approach shares features both with “bounced averaged gyrokinetics” (of fusion theory) and with “nonlocal theory” (of low temperature plasma physics).

# The Electron Cyclotron Drift Instability in space plasmas.

**B. Lembège[1] and L. Muschietti [1, 2]**

(1) LATMOS-UVSQ-IPSL-CNRS, Guyancourt, F-78280 France, email:lembege@latmos.ipsl.fr
(2) SSL, University of California, Berkeley, CA-94720, USA, email:laurent@ssl.berkeley.edu

Abstract:

When the solar wind (in supersonic regime) hits a magnetized obstacle such as a planetary magnetized environment (so called magnetosphere), a permanent shock wave forms upstream of the magnetosphere, allowing a transition of the flow from super- to sub-sonic regime. Such shocks are frequently observed around different planets (Uranus, Earth, Mercury, Jupiter etc..). This shock is called 'collisionless' since its characteristic spatial scale is much lower than the free mean path which is of the order of the 1 Astronomical Unit (1 AU= 146 x 10 **6 kms). Collisionless shocks are also frequently met in solar physics, interplanetary physics, heliospheric physics (interaction of the insterstellar wind with the obstacle formed by the heliosphere) etc..In a first approach, collisionless shocks can be classified into 2 main groups : (i) the quasi-perpendicular and quasi-parallel shocks when the angle between the shock normal and the upstream magnetostatic field is varying between (90°, 45°) and (45°, 0°) respectively, and (ii) the subcritical and supercritical shocks.

Super/sub-critical quasi-perpendicular shocks are characterized by a noticable/poor fraction of the incoming ions which is reflected at the steep front, stream across the magnetic field and form a foot upstream of the ramp. While gyrating, reflected ions accumulate within the foot and have several impacts : (i) these carry a significant amount of energy and play a key role in transforming the directed bulk energy (upstream) into thermal energy (downstream) and (ii) are source of microturbulence within the shock front itself. Indeed, the relative drift between the reflected ion beam and the incoming electrons within the foot can easily destabilize waves (electron cyclotron drift instability or ECDI) in the electron cyclotron frequency range. By means of linear analysis, several Bernstein harmonics are shown to be unstable, their number being proportional to the drift, yet limited by the ion beam’s temperature. Separate electromagnetic PIC simulations restricted to all ions and electrons populations present in the foot region have been performed in order to investigate the nonlinear characteristics of these waves with a high spatial resolution and a high statistics, which will be presented.

# The electron cyclotron drift instability: thruster studies and physical interpretations

Sedina Tsikata

e-mail: sedina.tsikata@cnrs-orleans.fr

The electron cyclotron drift instability (ECDI) has been studied in various contexts since the 1970s, including collisional shocks and θ-pinch devices[1, 2, 3]. In recent years, its role as a likely contributor to anomalous electron current in Hall thrusters was made evident in PIC (particle-in-cell) numerical simulations performed by Adam, Héron and Laval[4]. This work was the first to establish a clear link between the presence of a particular thruster instability and the anomalous electron current. PIC simulation efforts were also later pursued by Coche and Garrigues[5].

The existence of the instability in the Hall thruster plasma was confirmed in recent years by special coherent Thomson diagnostic measurements[6]. Combined experimental and theoretical studies[7,8] on the mode have provided detailed insights regarding its features. Subsequent PIC studies[9] have also provided an improved understanding of subtle effects, including the interaction between the instability and electron wall emission.

This talk discusses experimentally-determined insights into the ECDI and the relationship between such results and numerical studies in axial-azimuthal and radial-azimuthal geometries. The broader challenges associated with determining the level of electron current attributable to this instability, in the light of recent results, are discussed.

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# Electron drift instabilities in ExB plasmas: kinetic theory and PIC simulations

Trevor Lafleur[1,2], Pascal Chabert[1]

[1]Laboratoire de Physique des Plasmas, CNRS, Sorbonne Universités, UPMC Univ Paris 06, Univ Paris Sud, Ecole Polytechnique, F-91128 Palaiseau, France
[2]Centre National d'Etudes Spatiales (CNES), F-31401 Toulouse, France
*e-mail: trevor.lafleur@lpp.polytechnique.fr

In this work, we present particle-in-cell (PIC) simulations and kinetic theory that demonstrate the importance of electron drift instabilities (EDIs) in typical **E**x**B** discharges, such as Hall-effect thrusters (HETs). Kinetic theory [1-2] predicts that these EDIs produce an enhanced electron-ion friction force that acts as an additional electron momentum loss mechanism. This momentum loss can be orders of magnitude higher than that due to electron-neutral or electron-ion Coulomb collisions, and can explain the "anomalous" electron cross-field transport observed in HETs. The instability-enhanced friction also leads to ion rotation and heating.

Predictions from kinetic theory are compared with results from different 1D (azimuthal) and 2D (radial-azimuthal and axial-azimuthal) PIC simulations where good agreement is found. In particular, the observed instability spectrum in the simulations matches the dispersion relation for EDIs, and "anomalous" electron and ion transport is found to result entirely from an instability-enhanced friction force. The amplitude of electron density fluctuations in the 2D (axial-azimuthal) PIC simulations is found to decrease sharply just downstream of the exit in HETs, and reaches levels almost identical to those measured experimentally [3]. Clear evidence of ion-wave trapping is observed in all simulations, and plays an important role in saturation of the instability.

**References:**

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# Instabilities in the linear plasma device Mistral

A. Escarguel, R. Baude, P. David, Y. Camenen, N. Claire, F. Doveil

PIIM, UMR 7345 CNRS/Aix-Marseille Université,
Campus St. Jérôme, case 321, F13397 Marseille, France

Plasma transport across magnetic field lines has been experimentally studied in the linear machine Mistral to address the physics of plasmas encountered in the scrape-off layer of controlled magnetic fusion machines. The transport in the scrape-off layer is still far from being completely understood and needs to be studied in laboratory plasmas, where parameters can be easily controlled. The Mistral device is dedicated to study cross-field plasma instabilities in the presence of a magnetic field, essentially by optical diagnostics [1, 2]. The linear magnetized plasma column is created by the injection of energetic ionizing electrons (primary electrons) through a diaphragm and is limited at both ends by two planar conducting grids. We mainly focus on the study of plasma flute instabilities regularly rotating around a central plasma. The crucial role of primary electrons has been shown by retarding field analyzer [3] and spectroscopic measurements [1]. The complex radial/azimuthal evolution of the ionic velocity distribution function in the presence of a coherent rotating mode is measured by Laser induced Fluorescence (LIF) [5]. More recently, a fast optical tomographic diagnostic of the plasma emission was installed and is used to measure the 2D profile of the light emitted in a section of the plasma column [4]. The experimental measurements demonstrate a steady rotation of the plasma column, confirming an assumption frequently used to reconstruct the 2D cross-section from a series of single Langmuir probe measurements. Considering the momentum equations for ions and electrons, a physical model has been developed to interpret the experimental data [6]. The solutions are in qualitative agreement with the experiments and the physics is discussed.

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# Dynamic of HiPIMS plasmas - the transport from target to substrate

A. von Keudell*, C. Maszl, W. Breilmann, Julian Held,
V. Schulz-von der Gathen, A. Hecimovic
*Ruhr University Bochum, Germany*
*e-mail: Achim.vonKeudell@rub.de

The dynamic of high power pulsed magnetron plasmas is analysed using various diagnostics ranging from optical emission spectroscopy, probe diagnostics to mass spectrometry. It is shown that structure formation in these plasmas is driven by the Simon-Hoh instability leading to the appearance of rotating spokes along the racetrack of the magnetrons. The plasma parameters in these rotating ionization zones are measured using time resolved optical and mass spectrometry indicating that the energy distribution of the ions reaching the substrate are directly connected to the appearance of the spokes. By using various triggering mechanism, the plasma parameter of an isolated spoke are determined. The underlying mechanisms are discussed to explain the good performance of HiPIMS plasmas for material synthesis

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# On electron heating in magnetron sputtering discharges

J. T. Gudmundsson[1,2], D. Lundin[3], M. A. Raadu[1], C. Huo[1], T. M. Minea[3], and N. Brenning[1,4]

*1 Department of Space and Plasma Physics, KTH-Royal Institute of Technology, SE-100 44, Stockholm, Sweden*
*2 Science Institute, University of Iceland, Dunhaga 3, IS-107 Reykjavik, Iceland*
*3 Laboratoire de Physique des Gaz et Plasmas - LPGP, UMR 8578 CNRS, Université Paris-Sud, Université Paris-Saclay, 91405 Orsay Cedex, France*
*4 Plasma and Coatings Physics Division, IFM-Materials Physics, Linköping University, SE-581 83, Linköping, Sweden*

The magnetron sputtering discharge is a highly successful tool for deposition of thin films and coatings.
It has been applied for various industrial applications for over four decades. Sustaining a plasma in a magnetron sputtering discharge requires energy transfer to the plasma electrons. In the past, the magnetron sputtering discharge has been assumed to be maintained by cathode sheath acceleration of secondary electrons emitted from the target, upon ion impact. These highly energetic electrons then either ionize the atoms of the working gas directly or transfer energy to the local lower energy electron population that subsequently ionizes the working gas atoms. This leads to the well-known Thornton equation, which in its original form [1] is formulated to give the minimum required voltage to sustain the discharge. However, recently we have demonstrated that Ohmic heating of electrons outside the cathode sheath is typically of the same order as heating due to acceleration across the sheath in dc magnetron sputtering (dcMS) discharges [2]. The secondary electron emission yield γ_see is identified as the key parameter determining the relative importance of the two processes. In the case of dcMS Ohmic heating is found to be more important than sheath acceleration for secondary electron emission yields below around 0.1. For the high power impulse magnetron sputtering (HiPIMS) discharge we find that direct Ohmic heating of the plasma electrons is found to dominate over sheath acceleration by typically an order of magnitude, or in the range of 87 – 99 % of the total electron heating. A potential drop of roughly 80 - 150 V, or 10 - 20 % of the discharge voltage, always falls across the plasma outside the cathode sheath [3]. We compare discharges with Al and Ti targets and find that for high currents the discharge with Al target develops almost pure self-sputter recycling, while the discharge with Ti target exhibits close to a 50/50 combination of self-sputter recycling and working gas-recycling [4]. We also explore the effect on the magnetic field strength on the electron heating mechanism [4]. In the discharge with Ti target the B-field was reduced in steps from the nominal value, which resulted in a corresponding stepwise increase in the discharge resistivity.

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# Asymptotic-Preserving methods for the efficient resolution of anisotropic equations arising in magnetized plasma physics.

Fabrice DELUZET, Jacek Narski

*Université de Toulouse; UPS, INSA, UT1, UTM, CNRS UMR 5219,*
*Institut de Mathématiques de Toulouse,*
*F-31062 Toulouse.*

*e-mail: fabrice.deluzet@math.univ-toulouse.fr, jacek.narski@math.univ-toulouse.fr

We present a class of numerical methods design to address efficiently the resolution of elliptic or diffusion equations arising in magnetized plasma simulation. Standard discretizations of these problems give rise to system matrices with a condition number increasing with the anisotropy strength. This difficulty can be explained by the singular nature of these problems. Indeed in the limit of infinite anisotropy, these equations degenerate into a system with an infinite amount of solutions. The principle of Asymptotic-Preserving (AP) methods is to manufacture a set of reformulated equations, equivalent to the original problem, in which this limit is regular [1]. The reformulated system remains well posed irrespective of the anisotropy. The matrices issued from standard discretizations of this system have a condition number bounded with respect to the anisotropy strength [2,3,4]. This permits the construction of numerical methods with a computational cost and a precision roughly independent of the anisotropy.

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# An unstructured HPC parallel 3D code for numerical simulations of a Hall effect thruster

Joncquieres Valentin, Pechereau François, Vermorel Olivier, Puigt Guillaume, Cuenot Bénédicte

*CERFACS (Centre Européen de Recherche et Formation Avancée pour le Calcul Scientifique), Toulouse, France*

*e-mail: joncquieres@cerfacs.fr, pechereau@cerfacs.fr

Hall effect thrusters have been used for spatial propulsion since the 1970's. However, complex physical phenomena such as erosion or instabilities which may lower thruster efficiency and lifetime, are not yet fully understood. Unfortunately experiments for the design of Hall thrusters are long and expensive and numerical simulations are now considered to understand and control plasma behavior and predict system efficiency. With the renewed interest for such electric propulsion to supply light satellites, the industry needs accurate numerical solvers.

In this context, CERFACS is developing, in collaboration with the LPP (Laboratoire de Physique des Plasmas), the AVIP code which solves plasma physics in real industrial geometries using an unstructured parallel-efficient 3D fluid/particle methodology. The particle solver uses a Particle-In-Cell (PIC) method to solve the dynamic of ions neutrals and electrons combined with a Monte-Carlo approach for collisions. A Poisson equation is considered for the electric field resolution and the magnetic field is supposed constant. The PIC algorithm has been validated against benchmarks of helium discharges[1]. Similarly to the work of Futtersack[2] and Hakim[3,4], the fluid approach includes a detailed plasma model where species are ruled by a system of Euler equations with source terms representing electric field, ionization or other chemical processes. The fluid part is being validated on different classical benchmarks. Both PIC and fluid solvers are developed in parallel with the idea of building a hybrid solver that will describe the dynamics of ions and neutrals with the PIC solver and electrons with the fluid method.

In this poster, numerical methods and models developed in the AVIP solver will be presented. A particular attention is paid to the choice and validation of the fluid model and numerical schemes. Comparisons of benchmarks between PIC and fluid solvers will be shown. Specifically the influence of the heat flux[4] will be discussed.

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# Investigation of the electron drift dynamics at the boundary of magnetized low temperature plasmas

Dennis Krüger, Jan Trieschmann and Ralf Peter Brinkmann

*TET, Ruhr-University Bochum, Bochum, Germany*
*e-mail: dennis.krueger@rub.de

Magnetized low temperature plasmas have many applications in research and industry. High power impulse magnetron sputtering (HiPIMS) geared to deposit thin films of superior quality and Hall-effect thrusters used for spacecraft propulsion are two important examples. One peculiar phenomenon in such discharges are rotating patterns, sometimes called spokes, which develop under certain conditions. As self-organized symmetry breaking structures, these patterns can only be understood by 3d models. To formulate a consistent 3d model, an appropriate boundary condition at the plasma walls must be utilized. Therefore, we investigate the interaction of magnetized electrons with the plasma boundary sheath by means of a 3d kinetic single electron model, thereby focusing on the drift of the guiding center. For this particular aspect of the interaction dynamics we can observe a good agreement between applying a specular reflection model and a more physical Bohm sheath model.

This work is supported by the German Research Foundation (DFG) in the frame of the transregional collaborative research center SFB-TR 87.

# Numerical simulations and linear analysis of Simon-Hoh type instabilities in magnetized plasmas

Sarah Sadouni, Gerjan Hagelaar

*LAPLACE (Laboratoire Plasma et Conversion d'Energie), Université de Toulouse, INPT, CNRS,UPS, 118 route de Narbonne, 31062 Toulouse Cedex 9, France*
*e-mail: sarah.sadouni@laplace.univ-tlse.fr

Low-temperature magnetized plasmas, submitted to some specific conditions, show an interesting phenomenon: the emergence and growth of instabilities. In this study, the focus is made on the Simon-Hoh instabilities, developing when an electric field and a plasma density gradient occur both in the same direction across the magnetic field [1].

The LAPLACE laboratory in Toulouse elaborated its own self-consistent fluid code called "MAGNIS", previously used for the study of instabilities occurring in the negative ion source ITER. This code considers the plane perpendicular to the magnetic field for its simulations, and can describe the **E**x**B** (crossed electric and magnetic fields) plasma configuration.

The purpose of this study is to compare the instabilities described by MAGNIS to the results of an analytical linear analysis. For this, the fluid equations (continuity and momentum equations) are linearized to the first order and then solved by injecting linear solutions such as existing solutions for the linearized system, to finally end up with a linear dispersion relation. In a second phase, MAGNIS is configured to describe exactly the same system as the analytical analysis, with periodic boundary conditions in one direction and a voltage and density gradient imposed in the other direction. The MAGNIS results are Fourier analyzed in order to measure the growth rate, frequency and wave numbers of the simulated instabilities, which can then be compared with the results from the analytical dispersion relation.

Through this analysis we are able to verify the numerical capabilities of the MAGNIS code and to better understand the behavior of the instabilities over a wide range of the model parameters (electric field, density gradient, magnetic field, ion and electron inertia).

This study is carried out in collaboration with Andreï Smolyakov of the University of Saskatchewan.

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# Plasma-wall interaction: a new model of electron emission experimentally validated

Marc Villemant,[1,a] Pierre Sarrailh,[1,b] Laurent Garrigues,[2,c] Mohamed Belhaj,[1,d] and Claude Boniface[3,e]

[1]*ONERA - The French Aerospace Lab, 31055 CEDEX , France*
[2]*LAPLACE Laboratory, Toulouse University, CNRS, INPT, UPS,France*
[3]*CNES - French National Space Agency, Propulsion Pyrotechnic and Aero-thermodynamic Service, France*

[a]Electronic mail: marc.villemant@onera.fr
[b]Electronic mail: pierre.sarrailh@onera.fr
[c]Electronic mail: laurent.garrigues@laplace.univ-tlse.fr
[d]Electronic mail: mohamed.belhaj@onera.fr
[e]Electronic mail: claude.boniface@cnes.fr

Hall Thrusters (HTs) plasma modelling is a major topic of research for space industry as it could have a determining impact on HTs design and optimization, which currently depend on empirical reasoning and onerous experiment without determining results. Numerous attempts have been made to reliably model HT plasma, but they are not able to explain all physical phenomena in HTs plasmas (e.g. electrons abnormal transport). Nonetheless, it is known that wall material has a non negligible influence on HTs performances [1, 2] and numerous modelling show that Electron Emission (EE) in HTs channel could have a determining impact on plasma behaviour (abnormal transport, etc.) [3, 4].

A new EE model suitable for HT plasma modelling is presented at this workshop. This model describes electron emission yield, emitted electrons angular distribution (EEAD) and emitted electrons energetic distribution (EEED) and differentiate secondary and backscattered electrons. This model is based on physical reasoning and not only fitted experimental data. It also depends on several physical parameters (material, incident electron angle, incident electron energy, material work function). This allows extrapolating results to a large range of physical environments. This model is being validated thanks to experimental measurements made at ONERA. These measurements concern Total Electron Emission Yield (TEEY, cf. Figure 1), EEED and energetic efficiency of electron/wall interaction (cf. Figure 2).

This model will be implemented in a Particle In Cell model developed at Laplace in order to determine the influence of EE on global HTs plasma behaviour.

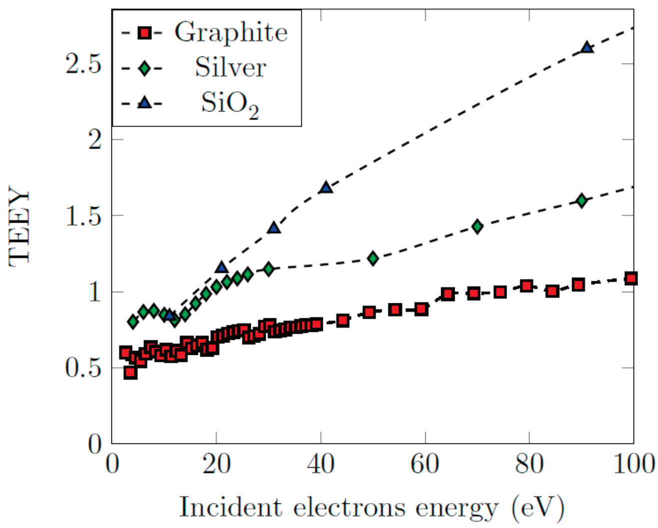


*Figure 1 : TEEY measurement at low energy[5,6]*

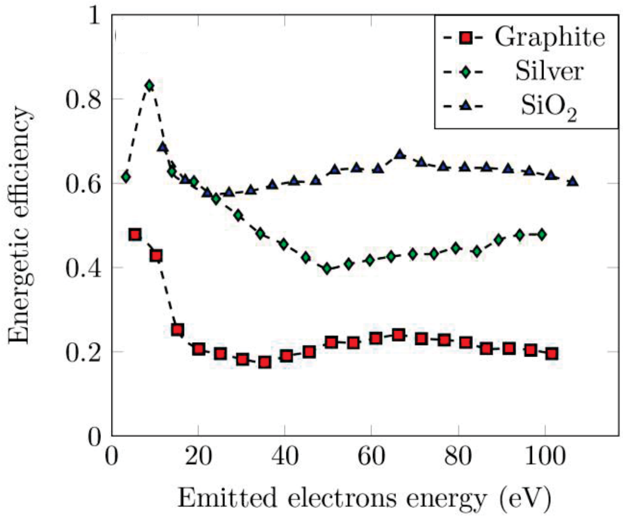


*Figure 2: Energetic efficiency of electron/wall interaction at low energy*

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# Electron Transport by the EXB-Driven Ion Acoustic Instability in a Hall Thruster Based on r-z Multi-Fluid Simulations with Hall2De

Alejandro Lopez Ortega and Ioannis G. Mikellides

*A Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109*
*e-mail: Ioannis.G.Mikellides@jpl.nasa.gov

After several years of effort with the r-z code Hal2De the spatial variation of the anomalous collision frequency needed in Ohm's law to produce the observed thruster behavior has now been isolated for a lab Hall thruster called H6. This numerical solution was used recently to test the validity of a first-principles model of the anomalous transport in these devices. The model was based on the hypothesis that the Electron Cyclotron Drift Instability (ECDI) excites ion acoustic turbulence that, in turn, enhances the effective collision frequency in these devices. We found that an idealized model of the ECDI with Maxwellian velocity distributions for electrons and singly-charged, main-beam, cold ions was insufficient to explain the expected variation of the anomalous collision frequency. When warm ions (~0.5-3 eV) were accounted for, the ECDI model in the channel interior appeared more promising but failed by orders of magnitude in the near plume region due to the much higher Landau damping of the ion acoustic waves there. We concluded that either (a) one or more processes allow the ECDI instability to remain uninhibited by classical Landau damping or, (b) that a different instability (or instabilities) altogether, also insusceptible to Landau damping, is/are active in this region. Part I of this presentation provides a brief overview of this work which, in part, led to the effort presented in Part II.

In Part II, we first explore the possibility that the discrepancies between the "theoretical" and "needed" growth rates are due to waves of different wave-lengths grow, that saturate and decay at different locations in the plasma. Here we also account for the anomalous heating produced by the ion acoustic instability. We conclude that these two mechanisms cannot decrease the growth rate to values that would be required to self-consistently produce an anomalous collision frequency profile similar to expected profile. We finally present the hypothesis that in the acceleration region, the waves of the ion-acoustic instability do not produce additional drag of the electrons in the azimuthal direction. We justify this assumption by comparing the energy associated with the electron azimuthal drift with the energy carried by the waves. Full self-consistent simulations that account for this hypothesis produce results that agree remarkably well with the expected solution.

# Fluid simulation of instabilities in partially magnetized plasmas

Gerjan Hagelaar

*LAPLACE (Laboratoire Plasma et Conversion d'Energie), Université de Toulouse, INPT, CNRS,UPS, 118 route de Narbonne, 31062 Toulouse Cedex 9, France*
*e-mail: gerjan.hagelaar@laplace.univ-tlse.fr

Fluid simulations are widely used in research on low-temperature plasma applications. They can be very valuable tools to obtain a qualitative picture of the plasma device operation and to predict trends, but they sometimes fail to capture essential physics. A particularly problematic case is that of magnetized plasma devices such as Hall thrusters or magnetrons, featuring magnetized electrons and non-magnetized ions. These plasmas are sensitive to turbulent instabilities, often involving kinetic effects and enhancing the transport of electrons across the magnetic field lines. Fluid models usually take this into account by ad hoc "anomalous" transport coefficients, which strongly reduces their predictive capabilities. Yet, when solved properly in the 2D plane perpendicular to the magnetic field lines, or in 3D, even very basic fluid models of these plasmas turn out to predict certain types of instabilities and anomalous transport in a self-consistent manner. This poses the following questions. Do these fluid instabilities represent any physical reality, to what extent are they affected by the fluid approximations, and how does this depend on the plasma conditions and configuration? Can the fluid model closures be improved to make these instabilities more realistic and consistent with kinetic theory? How to keep control of numerical discretization errors in the presence of these instabilities and make sure they are not in fact numerical artefacts?

In this presentation, we discuss the above questions on the basis of simulation results from a fluid code developed at the LAPLACE laboratory in Toulouse in the context of different magnetized plasma applications. This code solves standard fluid equations for continuity, momentum and energy of (magnetized) electrons and (non-magnetized) ions, coupled by quasineutrality, with boundary conditions derived from classical sheath theory. We show and discuss magnetized plasma instabilities arising in fluid simulations of different ion source configurations, and make links with particle in cell simulations and linear stability analysis.

# Instabilities and transport in ExB plasma discharges

A. Smolyakov[1], . Chapurin[1], S. Janhunen[1], . oshkarov, I. Romadanov[1], . Raitses[2], I.D. aganovich[2]

*[1]University of Saskatchewan, Saskatoon, SK, S7N 5E2, Canada*
*[2]Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ, 08543, USA*

andrei.smolyakov usask.ca

We describe an hierarchy of nonlinear fluid models describing fluctuations and instabilities in plasma discharges supported by ExB electron current. For typical parameters, partially magnetized plasma with magnetized electrons and non-magnetized ions is considered. The nonlinear e uations for electrons are reduced using the low-fre uency approximation $\omega << \omega_{ce}$ while the ion e uations include full dynamics. The resulting e uations describe several fundamental modes of partially magnetized plasma: ion sound mode, lower-hybrid mode and anti-drift mode due to plasma density gradient. Density and magnetic field gradients and the electron current result in complex coupling of various modes destabilized by the interplay of ExB drift, ion beam velocity, density and magnetic field gradients, collisions and ionization. The nonlinear simulations have been performed to investigate the nonlinear saturation of the instabilities and resulting nonlinear transport. The simulations demonstrate highly intermittent electron current with magnitudes generally consistent with typical experimental parameters. It is shown that while the most unstable are small scale modes, the dominant contribution to the anomalous transport is provided by the large scale modes. The nonlinear energy transfer to large scale modes is demonstrated in nonlinear simulations. Role of parallel electron dynamics and sheath boundary conditions is studied. It is shown that the boundary sheath can screen bulk plasmas so that the effective parallel wave-vector turns out to be much smaller than the na ve geometric estimate $k \approx 1/L$, where $L$ is the plasma length along the magnetic field. The role of electron-cyclotron instabilities detected in PIC simulations is also discussed.

# Controlling of Spokes and Breathing Oscillations in Partially-Ionized EXB plasmas

Y. Raitses[1], I. Romadanov,[1,2] V. Skoutnev,[1] A. Smolyakov,[2] J. Carlsson,[1] A. Diallo,[1] and I. D. Koganovich[1]

[1]*Princeton Plasma Physics Laboratory, Princeton, NJ, 08543, USA*
[2]*University of Saskatchewan, Saskatoon,* SK, S7N 5E2, *Canada*
*e-mail: yraitses@pppl.gov

Spoke mode and breathing mode are main modes of low frequency oscillations (from a few kHz to a few tens kHz) commonly observed in Hall thrusters, Penning discharges, helicon plasma sources etc. In addition, spoke oscillations of higher frequency (~ 100 kHz) are also observed in magnetron discharges. Since spoke and breathing oscillations are most powerful modes, which can be up to 100% of the applied power (e.g. breathing oscillations in Hall thrusters), they may have profound effect on operation of these ExB discharges. In this talk, various effects of input parameters, including magnetic field, gas pressure, gas type, wall materials and discharge geometry on both modes of oscillations are analyzed to identify dominant mechanisms of these oscillations using frequency scaling relationships for several instabilities predicted in theoretical studies [1]. We will also discuss results on suppression and driving of these oscillations. Using segmented anode and a feedback control, we demonstrated the suppression of rotating spoke in a cylindrical Hall thruster (CHT) [2]. The same segmented anode approach can also be used to drive this mode by applying a wave voltage between to the anode segments with successive phase shifts. For the CHT, driving at the natural spoke frequency in the E×B direction was shown to enhance the coherence of the spoke, while driving at other frequencies generally suppresses the coherence of the spoke [3]. A qualitatively similar behavior was observed with driving breathing oscillations [4]. Responses of breathing oscillations to the driving signal will be discussed.

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# Anomalous electron transport inside Hall thruster as result of correlation among azimuthal drift, electron-wall interaction and axial acceleration.

Francesco Taccogna, Pierpaolo Minelli

*CNR-Nanotec_PLasMI lab, via Amendola 122/D 70126-Bari (Italy)*
*e-mail: francesco.taccogna@nanotec.cnr.it

There are still many missing elements to complete the physical picture at the basis of the Hall thruster functioning. The origin of the anomalous electron cross-field transport ascribed to electron-cyclotron drift instability remains decoupled from the strong electron-wall interaction and ion acceleration. The radial dynamics induces sheath instability, which is often represented as local phenomena and represented in reduced radial dimensional models, while the ion acceleration is responsible for instability saturation. This study represents the first attempt to correlate these different mechanisms contributing to the electron transport by means of a fully kinetic and self-consistent 3D particle simulation the Hall thruster channel.

# 3D PIC simulations of rotating spoke in a wall-less Hall thruster

K. Matyash[1*], R. Schneider[1], S. Mazouffre[2], S. Tsikata[2] and L. Grimaud[2]

[1]*Greifswald University, Greifswald, D-17487, Germany*
[2]*CNRS, ICARE, EP team, 1c avenue de la recherche scientifique, 45071 Orléans, France*
[*]knm@ipp.mpg.de

In this work, the self-consistent 3D-3V Particle-in-Cell simulation code STOIC (electroSTatic Optimized particle In Cell) [1,2] has been applied to simulate the low-frequency rotating plasma instabilities in the ISCT200 thruster [3,4] operating in the wall-less configuration [5,6].

The model utilizes an equidistant Cartesian grid which explicitly assures momentum conservation and absence of self forces in the PIC algorithm. The simulation includes electrons, $Xe^+$ ions and neutral Xenon atoms. All relevant collisional processes are included in the model: Coulomb collisions between charged particles; electron-neutral elastic, ionization and excitation collisions; ion-neutral momentum transfer and charge exchange collisions and neutral-neutral elastic collisions. The dynamics of the background neutral gas is self-consistently resolved with direct simulation Monte Carlo (DSMC).

The simulation domain represents a rectangular slab with dimensions 70x70x50mm. The total number of computational particles in the simulation was about $20*10^6$. The simulations were carried on a 16-processor Intel Xeon workstations. The duration of a typical computation run was about 20 days. About 12 millions time steps were performed which corresponds to a simulated time of 960 microseconds.

In the simulations spokes rotating with the velocity of about 3-5 km/s were observed. For the most of the simulated regimes the m = 1 mode was present with a few occurrences of m = 2 mode. The spokes rotating both in the *ExB* and counter-*ExB* directions were detected. In the cource of the simulations it was found that the spoke rotation direction can be changed by the variation of the anode voltage and the neutral gas injection parameters.

The detailed discussion of the simulation outcomes with regard to the spoke dynamics and the origin as well as comparisons between the simulation and the experimental results will be presented at the workshop.

**Acknowledgments:** This research was funded by the EOARD under Grant FA9550-15-1-0281.

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