SORBONNE UNIVERSITÉ

PROGRAMME INSTITUTS ET INITIATIVES

Appel à projet – campagne 2021

Proposition de projet de recherche doctoral (PRD)

IPhyInf - Initiative Physique des infinis

Projet soumis avec l'accord de la direction du laboratoire

Intitulé du projet de recherche doctoral (PRD): Extended magnetohydrodynamics simulations of strongly magnetized plasmas for space propulsion

Directeur.rice de thèse porteur.euse du projet (titulaire d'une HDR) :

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Unité de Recherche :

Intitulé : LERMA
Laboratoire d'Etudes du Rayonnement et de la Matière en Astrophysique et Atmosphères

Code : UMR 8112

École Doctorale de rattachement de l'équipe (future école doctorale du.de la doctorant.e) : ED 127 Astronomie et Astrophysique

Doctorant.e.s actuellement encadré.e.s par la.e directeur.rice de thèse (préciser le nombre de doctorant.e.s, leur année de 1e inscription et la quotité d'encadrement) :

1. Alexis Marret, 2018, Directeur de Thèse, encadrement 50% (soutenance Oct. 2021)
2. Victor Tranchant, 2019, Directeur de Thèse, encadrement 20%
3. Jean Carlos Porto, 2018, Directeur de Thèse, encadrement 20% (soutenance Oct. 2021)

Co-encadrant.e :

NOM : KHIAR Prénom : Benjamin

Titre : Ingénieur de recherche HDR Non

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Unité de Recherche :

Intitulé : ONERA - Office National d'Etudes et de Recherches Aérospatiales

École Doctorale de rattachement ED 127 Astronomie et Astrophysique

Doctorant.e.s actuellement encadré.e.s par la.e directeur.rice de thèse (préciser le nombre de doctorant.e.s, leur année de 1e inscription et la quotité d'encadrement) : Non

Cotutelle internationale : Non

Selon vous, ce projet est-il susceptible d'intéresser une autre Initiative ou un autre Institut ? Non

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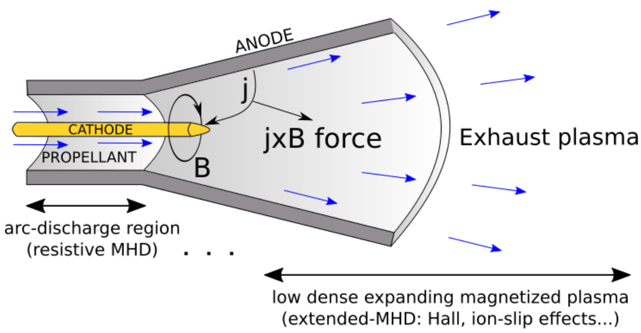
Context of the project

Electric propulsion is a class of space propulsion that makes use of electromagnetic forces to accelerate plasmas to high velocities (> 10 km/s). Compared to classical chemical thrusters, where the exhaust velocity is limited to a few km/s, electric propulsion has the advantage of requiring very little mass. Whereas not suitable for launching spacecraft from Earth surface, it represents nowadays an attractive option for in-space missions for which the fuel mass is very limited. Electric propulsion technologies are frequently cited as one of the leading candidates for long duration, manned space missions farther in the solar system (Choueri 2009), in particular for missions to Mars.

A mature propulsion technology capable of efficiently processing hundreds of kilowatts of power could potentially revolutionize deep space travel by shortening interplanetary transfer trajectories. However current “mainstream” electric propulsion technologies (ion drivers, Hall thrusters...) have major shortcomings related, for example, to the limited amount of thrust force per unit area they can produce. Crucially, the physical mechanisms at the core of these devices become inoperational as the input power is increased, thus limiting their interest for high-power systems.

Magnetoplasmadynamic thrusters (MPDT) circumvent these current limitations by accelerating a collisional neutral plasma using the Lorentz force. A MPDT typically consists of a central cathode sitting within a larger cylindrical anode between which a gas (lithium, argon…) is pumped and then ionized by the anode-cathode radial current (see Figure). This current is additionally responsible for inducing an azimuthal magnetic field generating the thrust-producing Lorentz force **jxB**. MPDT are designed to process up to about a megawatt in regimes where tens of newtons are produced for specific impulses reaching tens of thousand of seconds in a device the size of a standard rocket nozzle.

State-of-the-art in magnetoplasmadynamic thrusters physics



Despite its promise, the MPDT technology still faces several important challenges. Early experimental investigations in the high-power regimes (> 100 kW) have shown puzzling plasma behavior that is still poorly understood. In particular, the so-called *onset phenomena* is responsible for an important reduction in the thruster performance above a certain critical value of the driving electric current (typically > 12-15 kA), as well as greater electrode erosion that can be crucial in terms of MPDT lifetime achievements (Andrenucci 2010). Several different physical processes are thought to be responsible for the *onset phenomena*, such as the generation of microinstabilities triggering anomalous resistivity (Choueiri 1999) or more classical magnetohydrodynamic (MHD) instabilities (Paganucci et al 2012). Moreover, it has also been demonstrated that non-ideal MHD effects, such as Hall and ion-slip effects, could play an important role in the flow dynamics of a MPD thruster (Niewood et al 1991).

On the theoretical side and within the framework of magnetohydrodynamics, a large number of 1D fully analytical or semi-empirical models have been proposed. While useful for thruster operation at *relatively low power*, these models are incapable of accurately reproducing the experiments in the high-power regime (Coogan et al 2017). Similarly, two-dimensional numerical MHD simulations were shown to give relatively consistent results with experiments as long as the discharge current stays below the critical value (C. C. Mayigué 2018, Parma 2011, Sankaran 2005). In general, the failure to model the high-power regime of MPDT is thought to be the results of the simplified MHD models employed, the numerical challenges associated with simulating the vast range of plasma parameters (e.g. from low to high Reynolds numbers and plasma-beta) and the reduced dimensionality, for an otherwise inherently 3D plasma dynamics. To the best of our knowledge, there are no published works reporting numerical simulations of the *onset phenomena*. Thus, despite an active experimental research on MPDT at high-powers (Princeton, Stuggart, ...), a comprehensive understanding of the physics leading to the *onset phenomena* and how to mitigate its effects to obtain thrust efficiencies (> 50%) at high-powers is still lacking. Further theoretical work and new multi-dimensional and multi-physics modelling capabilities are needed to unlock the promising potential of this technology.

Objectives, methodology and risk assessment.

Summary. The main goal of the proposed PhD project is to perform the first 3D non-ideal MHD simulations of a MPD thruster in the high-power regime and to advance our understanding of the *onset phenomena*. Using our existing code, the student will first model the arc-discharge region to validate a newly implemented EOS and transport coefficients, and then move to modelling the full 3D MPDT system exploring the effects of anomalous resistivity. In terms of major code developments, the student will extend the-MHD solver to include Hall and ion-slip effects and explore under more realistic conduction the critical high-power regime.

The main research tool. The project will be based on extending our state-of-the-art code GORGON. The code solves the two-temperature, single fluid resistive MHD code on a 3D Cartesian grid. The code is massively parallel and, importantly for this project, the code includes among several other packages, anisotropic thermal conduction and LTE Thomas-Fermi ionization. In addition, the code is capable of modelling solid electrodes and (quite uniquely) it can model a plasma-vacuum interface. The code includes an anomalous resistivity model and it has been extensively used to model laser and pulsed-power produced plasmas.

Workplan

0-9 months The student will address the **physics of the dense plasma in the arc-discharge region** (see figure) by adapting the existing equations-of-state and transport coefficients in GORGON to include additional internal energy modes using tabulated or fitted data from our equilibrium plasma properties code. Given the plasma conditions, resistive MHD is an adequate model for this part of the work. Code validation will be done by comparing simulations with existing experimental data of arc-discharges produced by the plasma group at ONERA. ***Low risk.*** *This part is relatively straightforward and part of the coupling will be undertaken during an upcoming M2 internship.*

9-24 months The student will investigate **the role of anomalous resistivity and MHD instabilities on the *onset phenomena*.** The 3D capabilities of the GORGON code to model unstable magnetized plasmas (z-pinch, laser produced plasmas...) will be leveraged to model a full MPDT. Different models and variations of the current anomalous resistivity implementation will be explored. For this step, a direct comparison with existing 3D-reconstructed experimental data (Paganucci 2005) will be performed. This work should lead to an article. ***Low risk.*** *The code capabilities are well established, similar setup to the MPDT have been extensively explored by the coordinators to model z-pinch experiments and plasma focuses.*

9-24 months The student will implement **extended-MHD physics in GORGON** (Hall effect and ion slip). This work will allow a more realistic modelling of the low dense magnetized expanding plasma (see figure). ***Medium risk.*** *The coordinators have expertise in including this type of physics in MHD codes (see Supervision and scientific expertise section below). However, unforeseen numerical issues may slow down the code development, and that is why ample time is dedicated to this task.*

24-36 months The student will run the **first full-3D extended-MHD simulations of MPDT** and explore the critical current regime to shed further light on the *onset phenomena*. Successful completion of this objective would set a new state-of-art modelling tool not only for high-power MPDT but also for a whole family of MHD-based accelerators with a wide range of applications (Pulsed Plasma Thrusters, arcjets, plasmoid thrusters...). We expect an article to be written on this part of the work. ***Medium risk.*** *The risk is linked to the extended MHD code not being fully operational and/or exploration of its effects being limited in scope because of time constraints. In any case, the work performed here will still represent an advancement of the current state-of-the-art in the field and will lead to a publication.*

Supervision and scientific expertise

The student will be based at LERMA in Jussieu, but will spend approximately half-the-time (or more as needed) at ONERA in Palaiseau.

Andrea Ciardi (directeur de these, encadrement at 50%) is one of the main developers of the 3D resistive MHD code GORGON. The code has been extensively used to model high-energy density plasmas. He has published over 60 articles related to laser and pulsed-power produced plasmas, as well as astrophysical plasmas.

Benjamin Khiar (co-encadrant at 50%) has recognised expertise in high energy density and aerospace-relevant plasmas, and has published articles related to MHD instabilities, laboratory astrophysics plasmas and electric propulsion. He was a postdoctoral researcher at the University of Chicago in the FLASH Center for computational science where he was responsible for implementing extended-MHD physics in the publicly available, multiphysics code FLASH (http://flash.uchicago.edu/site/).

Full list of publications A. Ciardi https://sites.google.com/site/andreaciardihomepage/publications
Full list of publications B. Khiar https://www.researchgate.net/profile/Benjamin-Khiar

Benefits for the Initiative Physique des Infinis

This research project joins the forces of the plasma physics group of the LERMA laboratory and the "Foudre, plasma et applications" group at ONERA to develop a powerful computational tool whose applications go well beyond space propulsion. The new developments will be generally useful to model a wide range of laboratory plasmas. In particular, we will use it for the experiments on strongly magnetized laser-produced plasmas done in collaboration between the LERMA, LPP and LULI and for the modelling of the upcoming pulsed-power, plasma focus experiments hosted on the Jussieu Campus and shared between the LERMA and the LPP.

Profile of the candidate

The candidate will have a Master 2 in physics, applied mathematics or a closely related field. The candidate will be keen to work on analytical theory, as well as on high-performance programming, simulations, analysis and 3D visualization.

Relevant publications from the project coordinators

→ Revet, G., Khiar, ..., Ciardi, A., Fuchs, J. (2021). Laboratory disruption of scaled astrophysical outflows by a misaligned magnetic field. *Nature communications*, *12*(1), 1-10.
→ Khiar, B., Revet, G., Ciardi A., et al. (2019) "Laser-produced magnetic-Rayleigh-Taylor unstable plasma slabs in a 20 T magnetic field", Physical Review Letters 123. https://arxiv.org/abs/1910.13778
→ Vaudolon, J., Khiar, B., & Mazouffre, S. (2014). Time evolution of the electric field in a Hall thruster. *Plasma Sources Science and Technology*, *23*(2), 022002.
→ Ciardi, A., et al., (2013) "Astrophysics of Magnetically Collimated Jets Generated from Laser-Produced Plasmas", Physical Review Letters, 110, 02500

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cd_instituts_et_initiatives@listes.upmc.fr avant le 20 février.