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EDITED AND REVIEWED BY
XinPei Lu,
Huazhong University of Science and Technology, China

*CORRESPONDENCE
Filippo Cichocki,
filippo.cichocki@istp.cnr.it

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Editorial: Numerical simulations of plasma thrusters and/or related technologies

Filippo Cichocki[1]*, Francesco Taccogna[1] and Laurent Garrigues[2]

[1]Institute for Plasma Science and Technology (ISTP-CNR), Bari, Italy, [2]LAPLACE, CNRS, Université de Toulouse, Toulouse, France

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Editorial on the Research Topic
numerical simulations of plasma thrusters and/or related technologies

In the last few decades, electric propulsion has become in high demand on modern spacecrafts, from very small nano-satellites to large communications orbital platforms. The difficulty of experimentally characterizing the plasma discharge channels and the operative in-space conditions of plasma thrusters make simulations a real game changer in this advanced technology/research field. In this respect, the rapid growth of high-performance computing and esa-scale flops of modern architecture supercomputers has enabled tackling more and more complex and computationally costly scenarios. With the use of different numerical approaches, typically based on kinetic, hybrid or fluid plasma models, a large number of applications can be covered: thruster physics and performance estimation, plasma thruster plume interaction with the spacecraft, synthetic simulations of plasma diagnostic tools, *etc.*

This Research Topic aimed to investigate, from a numerical point of view, plasma propulsion applications or physical phenomena. When possible, in order to validate and/or tune the numerical tools, simulation results were compared with real experiments. The numerical simulation techniques employed belong to the three categories mentioned above and span over all possible dimensions, from 0-D global models to 3-D ones. Several applications and/or technologies were covered: (i) air-breathing propulsion; (ii) Hall thrusters; (iii) magnetic nozzles of electrode-less thrusters; (iv) retarding potential analyzers (RPAs); and (v) a test thruster called MS4. Below, the research results achieved are discussed.

Air breathing propulsion is a new propulsion concept that consists in utilizing the upper atmosphere air atoms and molecules as a “free” propellant for an electric thruster unit, which ionizes and accelerates them to high exhaust velocities, thus counteracting the atmosphere drag effect on the satellite. If this technology were demonstrated in-orbit, it would enable enormous propellant mass savings, thus increasing the lifetime of satellites operating at relatively low altitude orbits around the Earth (150–250 km). This concept is elaborated in depth in an article of this Research Topic, namely in Ferrato et al., where a feasibility study is carried out, with the use of a 0-D global model that couples the rarefied air-intake and the thruster physics. The model takes as inputs the transmission coefficients and the residence times of ions and neutrals through the different stages of an air-breathing propulsion unit: the intake, the ionization and the acceleration stages. These are obtained with 3-D Monte Carlo simulations of ions and neutrals trajectories, assuming static electric and magnetic fields. The main outcomes of this work are the identification of the performance requirements for the electric thruster unit and their sensitivity to different compositions of the air. It will serve as a reference study for future works in this field.

A direct application of air-breathing propulsion is then presented in Taccogna et al., where a 2D Particle-in-Cell (PIC) model with Monte Carlo Collisions, is used to investigate the effects of using alternative propellants, such as N_2, O_2, or N_2/O, in a Hall thruster, one of the most mature electric thruster technologies, normally operated with Xe. The inclusion of non-conventional propellants adds a great complexity in the simulation, since new collisional processes appear when molecules are considered, such as dissociation, dissociative ionization and attachment. For a fixed thruster geometry, the authors find that the thruster performance degrades in all alternative propellant cases due to reduced ionization cross-sections, larger gas ionization mean free paths (due to lighter elementary mass species), and additional electron collisional power losses. These findings confirm the need of re-designing the thruster geometry for air-breathing applications, considering longer channel lengths, by factors between 4 and 10, depending on the considered propellant.

Still in the field of Hall thrusters, Leporini et al. presents a numerical study on the breathing mode instability, an oscillation in the tens of KHz frequency range of the discharge characteristics, caused by predator-prey dynamics between propellant neutrals and electrons. In this work, a 1-D fluid model of the discharge chamber is used to analyze the mechanisms that are responsible for the origin of the breathing mode and for its self-sustenance. A positive feedback mechanism that sustains the instability is identified. As neutral density decreases because of ionization, the electric field increases and produces a raise in electron temperature, thus further enhancing ionization. When neutral density reaches its minimum, on the other hand, the electric field is at its maximum and accelerates ions downstream, thus reducing the quasi-neutral plasma density and ionization rate, and promoting neutrals replenishment.

Another technology that was investigated in this Research Topic is that of plasma thrusters with magnetic nozzles. These thrusters have an imposed convergent-divergent magnetic field, which is used to channel the plume expansion, maintaining a low plume divergence, while converting the electron thermal energy (and heat flux) into ion directed kinetic energy. Their great advantage compared to ion thrusters or Hall thrusters is that they do not require external electrodes (like a cathode) to sustain the discharge and/or neutralize the emitted plasma plume. A first numerical study of an RF thruster with magnetic nozzle is presented in Emoto et al., where energy loss channels are investigated through 2-D PIC simulations. These seem to indicate that plasma energy wall losses are dramatically reduced by increasing the magnetic field strength, and that, divergence and collisional losses are almost independent of the magnetic field strength. Another work by Cichocki et al. focuses, on the other hand, on the divergent part of the magnetic nozzle of a Helicon plasma thruster. This is studied through a 3-D hybrid plasma plume simulator, which treats ions and neutrals as particles of a PIC sub-model and electrons as a magnetized fluid. The expansion up to a distance of about 40 cm from the source is simulated and compared with experiments, finding a relatively good agreement and two separate ion populations in terms of energy, a high energy population due to source ions, and a low-energy population due to ions produced by charge-exchange collisions in the very near plume.

Cichocki et al. also presents small scale simulations, carried out again with a hybrid code, of the interaction of the Helicon plasma plume with the retarding potential analyzer (RPA) used in the experiments. Relevant parasitic effects due to RPA geometry, that can contaminate the measurements, are identified and discussed. The RPA is also the main subject of the work by Nicolle et al., where a new RPA performance model is presented that accounts for the view angle between the RPA entrance surface and the incoming ion flux direction, the internal RPA electric fields, and masking effects due to RPA walls. Using a simplified 3-D fluid transport model from the plasma source (a Hall thruster) to the RPA, located on the solar arrays, this model is tested against real RPA measurements aboard the Express-A spacecraft, finding a good match.

Finally, Lewerentz et al. presents a kinetic study, through a 2-D PIC model, of the plasma discharge of the MS4 test

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thruster concept, developed by Thales Deutschland GmbH. This device features a beam formation and acceleration process occurring outside of the thruster, thus enabling a non-intrusive experimental characterization of the discharge through optical measurements. The experimentally observed emission patterns in the plume are consistently reproduced by the PIC model, which therefore shows an interesting potential for thruster design optimization.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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