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Plasma diagnostic with inductive probes in the discharge channel of a pulsed plasma thruster

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ABSTRACT

Research of magnetoplasmadynamic Pulsed Plasma Thrusters (PPTs), or iMPDs, at the Stuttgart Institute of Space Systems (IRS), led to the thruster design ADD SIMP-LEX. For optimization of the thruster's discharge behavior and of the plasma acceleration, the magnetic self-field is measured. Inductive miniaturized probes are introduced and used to acquire data at points of the volume inside of the thruster's discharge channel. The results are used for analysis to identify the extend of the discharge zone along the discharge channel of the PPT. Measured magnetic field signals along the centerline of the discharge channel are presented. The underlying distribution of the dynamic discharge current is deduced from Amperes circuital law and interpreted in a two-dimensional plot against camera images for the current-plasma-interaction, current motion and validity of today's discharge models. The evaluation of the calculated integral discharge current in a plane of the discharge channel against the recorded thruster discharge current is presented and discussed.

1. Introduction

The pulsed magnetoplasmadynamic thruster (iMPD), represents a robust and simple design for secondary propulsion needs of satellites, for example target pointing, attitude control, formation flight, and drag compensation. Relatively high mean exhaust velocities c_e and efficient propellant utilization are achieved through the pulsed operation mode. This beneficially limits power consumption and allows for thrust adjustment without losses in Δv. The common choice of propellant is solid Polytetrafluoroethylene (PTFE), or Teflon™. Without the need for injection, feed lines, valves and tanks, the weight and system complexity are exceptionally low. The overall low complexity is main criteria for minimum operational risk and high affordability, with cost savings of one to two orders of magnitude in comparison. The easy handling and long flight heritage also justify primary propulsion tasks for iMPDs, under the condition of increase of the generally low thrust efficiency of this type of electric thruster.

The development of ADD SIMP-LEX (Advanced Stuttgart Impulsing MagnetoPlasmadynamic thruster for Lunar EXploration) tackled this problem, by achieving world leading thrust efficiencies around 30%, together with the APPT thrusters developed at the RIAME and Kurchatov Institutes in Moscow, Russia [1–4]. This was made possible through a close technology exchange as part of a cooperation contract. Beyond the demonstrated performance, the ADD SIMP-LEX also invites continued efforts, to even further increase the thrust efficiency. For this, the common approach of electrical and geometric parameter variation was found to require extension to the level of discharge formation and energy transfer mechanisms. The relatively poor universal validity and qualitative character of discharge models also suggest the rethinking of the thruster's working principle and idealized model of a moving current sheet [5]. This model has been extended and refined by the work of many researchers, yet never led to a universally satisfying and applicable solution.

The goal is to utilize the observed trends derived from data of experimental parametric studies at IRS, to focus the experimental efforts on observations, which are not mirrored by current models. At first, this leads towards the extraction of possible explanations, deeper insight into the physical mechanisms and possibly, even towards a new and more unified theory. The second output is the development of new and more effective optimization methods, i.e. the shaping and design of the electric and magnetic self-fields. With more data on the formation, progression and interaction of the fields, new ways to optimize the energy transfer to the propellant and to balance the ratio of ablation energy and kinetic energy of the plasma can be identified. This is also important to identify and to introduce better technologies to the thrusters and for thruster scaling.

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This process requires the united efforts of researchers and data in the field from around the world, to generate the output in the near term and to ensure universal validity and applicability of the results. For this reason, the members of the International PPT-and-iMPD-Working Group, founded at the IRS in Stuttgart, are concentrating their expertise on the matter and consolidate in this point to continue in refining the thrusters towards space application.

2. Theory

The discharge model usually employed for treatment of the working principle of an iMPD is the slug model introduced by Jahn [5]. The model itself will only briefly be described herein, as far as necessary for the analysis and presentation of the experimental data and the resulting implications with respect to the discharge current density distribution. A thorough discussion of the model would go beyond the scope of this paper. The reader is therefore referred to literature for a more in-depth description.

2.1. Discharge model

A pulsed magnetoplasmadynamic thruster uses energy stored in a capacitor bank to create and to ionize plasma from a block of solid propellant in a very high current discharge pulse. After charging the capacitors, controlled thruster ignition is realized using a spark plug. Upon initiation, a breakdown occurs across the face of the propellant. The resulting high pulse current transfers energy to create and sustain the plasma.

The ionized particles are accelerated by means of the electromagnetic Lorentz force, thus creating a small thrust force. The magnetic field is the self-field of the current. The schematic overview in Fig. 1, shows the current I in the form of an intermittent region of changing volume. The slug model however, assumes a current sheet of fixed geometry and mass. Sheet canting is neglected and the electrodes are considered to be of infinite width. This assumption is problematic, as it neglects edge effects and deformations of the electric field that are common in miniaturized or high efficiency thruster electrode designs. The current density is assumed to be homogeneously distributed over the current sheet and therefore only depends on the integral current I from the capacitors varying over time. The magnetic self-field strength remains constant behind the current sheet and can be calculated through amperes law, neglecting the displacement current term:

$$B = \frac{\mu_0 I}{d}. \tag{1}$$

here, B is the magnetic flux density, μ_0 is the magnetic permeability in vacuum and d is the width of the electrodes. The magnetic field ahead of the plasma is set to zero, assuming a linear drop over the sheet thickness. Considering Eq. (1) shows, that fields and the current are only treated on an integral level. The highly dynamic field configurations, interactions between fields and particles as well as the distributed current density remain unaccounted for. It becomes obvious, that computed results from such a model can be qualitative at best. Major model refining attempts were directed at modifications to introduce more complex field distributions, sophisticated electrode geometries and ablation models for estimation of the mass bit per pulse [6–11]. The additional data altered the obtained simulation results, but remained behind expectations and specific to the respective thruster development. This limits the model's applications towards the extraction of parameter trends and complicates the development and evaluation of engineering tools for preliminary thruster design.

A stifling issue is the understanding of the current as a progressing sheet. The concept of a sheet running along the electrodes of the thruster, like on rails, can hardly be observed in experimental thruster studies. This observation becomes all the more apparent, with increasing deviation of the electrode shape from the parallel plate configuration. It is also not suited to explain effects like late-time-ablation, uneven propellant mass ejection and thrust vector misalignment. A camera shot of the discharge channel of the thruster ADD SIMP-LEX, as shown in Fig. 2, does show little resemblance to the moving sheet theory.

The shot was taken with a DICAM-2 micro channel plate camera, with an exposure time of 50 ns and a spectral range between 380 and 900 nm.

The area between the electrodes in Fig. 2 can be divided into three zones of distinct brightness. The brightest zone (1) appears near the cathode, a darker zone (2) with a roughly triangular shape beneath it, and finally an almost completely dark zone (3) near the anode. It should be noted here, that this sectioning can only be of qualitative nature and does not represent a clear indicator of the current flow in the thruster. It does however demonstrate the lack of reason to assume a moving current sheet to explain this data. Only little is known about the complex fields and plasma distributions and interactions inside of the thruster during operation. Preliminary work with inductive magnetic field probes had shown very promising results in acquiring spatial and time resolved information of the magnetic field distribution between the thruster electrodes [6]. It was concluded, to use this approach to investigate the theory of a moving current sheet inside of ADD SIMP-LEX, by

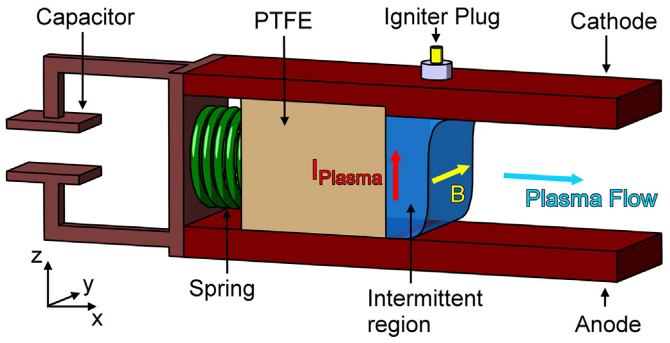

Fig. 1. Schematic overview of an iMPD-thruster.

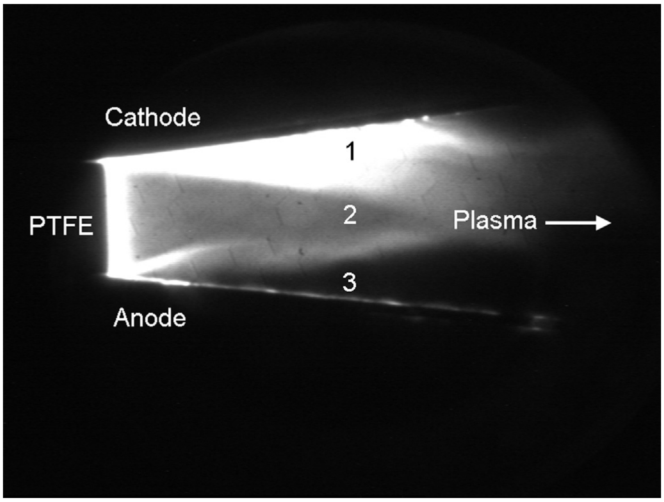

Fig. 2. Side view of ADD SIMP-LEX discharge channel at 2.7 μs after thruster ignition.