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First Test Results of the 1 to 15 kW Coaxial HEMP 30250 Thruster

Norbert Koch, Hans-Peter Harmann and Günter Kornfeld
THALES Electron Devices GmbH, 89073 Ulm, Germany

We present a new type of HEMP (High Efficiency Multi Stage Plasma) thruster with a coaxial discharge channel. While maintaining the extreme throttle ability of the cylindrical HEMP thruster concept, the extension towards a coaxial geometry will allow for scaling up to high power and thrust levels as required for orbit raising and station keeping of medium to large geostationary satellites.

The first version of a laboratory model named HEMP30250 shall provide a nominal thrust and specific impulse of 250mN and 3000s at an anode efficiency of 55%, respectively. Based on the experience made with our cylindrical HEMP3050 type thrusters models, we expect a wide operational range in applicable discharge voltages from 200 to 2000 V and xenon propellant mass flows from 1 to 15 mg/s, resulting in anode power levels from below 1 up to 15 kW and thrust values of up to 500 mN with only small variations in thrusters efficiency. This is mainly due to the effective plasma confinement provided by the HEMP thruster specific magnetic field topology, where by means of a system of periodically arranged permanent magnets a high density discharge is maintained along the median of the coaxial discharge channel keeping the plasma off the channel walls. As a consequence, thermal losses typically amount only 10% of the electrical input power and are mainly dissipated at the anode rather than at the discharge channel which in addition is kept free from erosion.

At this conference we will review the concept of a coaxial HEMP thruster and show design aspects of our HEMP30250 laboratory model DM1. First operational characteristics will be presented and an outlook to future works will be given.

I. Introduction

Ion propulsion, where propellant is ionised and the ions are electrostatically accelerated, allows for high specific impulses of typically a factor 5 to 15 higher compared to chemical propulsion and therefore becomes of increasing interest for commercial communication satellite and space probe manoeuvring. The obvious benefits of an increased specific impulse are a reduction of spacecraft launch mass, an increase of payload or an increase in mission lifetime, respectively.

Established technologies for the thrust range from a few mN to several 100mN are grid ion thrusters (GITs) and Hall effect thrusters (HETs), typically operated with Xenon gas as propellant. In both cases propellant is ionised in a plasma discharge. GITs employ a grid system to shield the plasma electrons and to extract the propellant ions. Since the extractable ion current density is space charge limited, the operational domain of GITs typically is restricted to high specific impulses beyond 3500s. In case of a HET, ion extraction occurs directly form a space charge neutralized plasma, and ions are accelerated by means of a self-consistent electric field formed by the magnetically impeded plasma electrons. Consequently, HETs provide 10 times higher thrust densities compared to GITs, which makes them low-weight compact devices. However, since HETs exhibit pronounced ion sputtering of their acceleration channel wall, appropriate lifetime seems only achievable if HET operation is restricted to specific impulses below 2000s.

The so-called “high efficiency multi-stage plasma” (short: HEMP) thruster, invented at THALES Electron Devices GmbH, represents a new concept for ion propulsion [1,2]. In case of HEMP thrusters, the propellant plasma is confined by several magnetic cells, which provide effective propellant ionisation, prevent from plasma-wall contact and confine the electrons to form an appropriate electrostatic lens to extract and accelerate the propellant ions. HEMP thrusters have demonstrated a uniquely wide operational range in thrust, power and specific impulses, and are very compact devices due to their typically 10 times higher thrust densities compared to Hall effect thrusters. HEMP thruster models developed so far have aimed towards a thrust range of several mN up to 100mN and exhibit a cylindrical discharge channel[*]. In order to scale up the HEMP thruster concept to thrust ranges of several 100mN

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[*] The performance of our current state-of–the-art model HEMP thrusters models will be presented in a dedicated presentation at this conference.

as required for orbit topping and North-South station keeping of large geo-stationary satellites, a thruster geometry with a coaxial discharge channel is preferable [3]. In this case, basic design aspects with respect to channel width and magnetic field pattern can be overtaken from the cylindrical geometry, and assuming similar thrust densities, higher thrust levels are achieved by the increased exhaust surface. Scaling of a coaxial HEMP thruster is provided by increasing the radius of the coaxial channel median.
In this paper we will present our coaxial HEMP thruster, named HEMP30250, which is aimed towards a nominal thrust and specific impulse of 250mN and 3000s, respectively. In section II the operational principle of a coaxial HEMP thruster shall be reviewed. In section III design aspects for our first laboratory model HEMP30250-DM1are presented. First results on observed operational characteristics of DM1 are shown in section IV, and section IV gives an outlook to future work.

II. Principle of Operation

A coaxial HEMP thruster consists of a coaxial discharge channel embedded in an inner and outer magnet system. An anode, which serves also as propellant feed, is mounted at the upstream end of the channel. A scheme of the coaxial HEMP thruster is given in fig. 1.

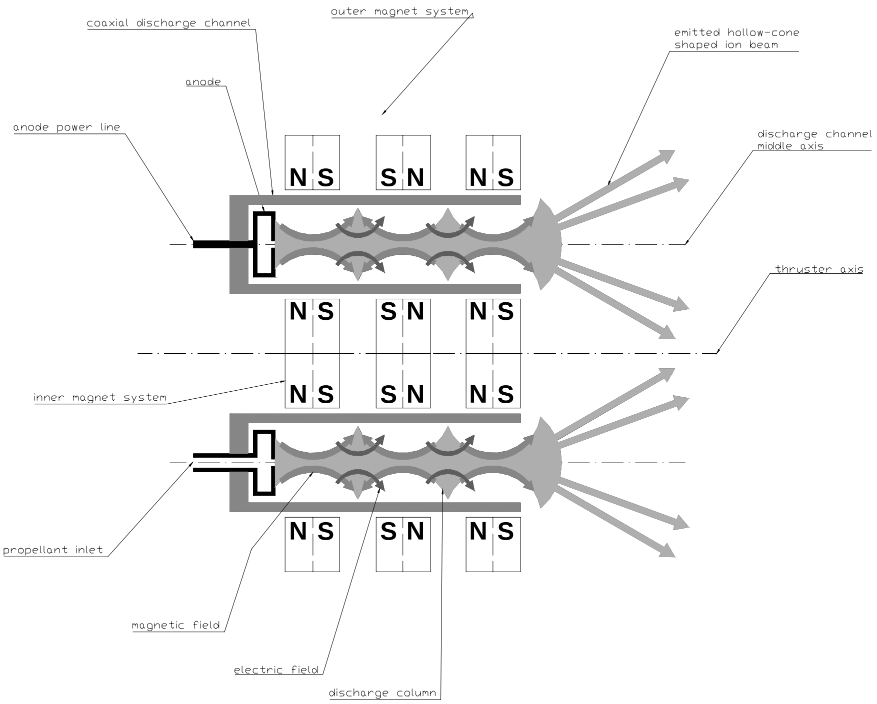

Figure 1: Schematic cross view of a coaxial HEMP thruster.

Alike in case of a cylindrical HEMP thruster, the magnets are arranged as a PPM (permanent periodic magnet) system, such that magnetic cusps are formed. Field strengths are chosen such that the electron Larmor radius is much smaller than the width of the discharge channel, whereas propellant ions are basically not affected by the magnetic field due to their high mass. The magnetic cusps act as magnetic cells, which provide an effective confinement of the plasma electrons. In the cusp zone, where the radial magnetic field becomes maximal, electron flow towards the anode is largely impeded and a voltage drop is induced. This voltage drop energizes the electrons leading to enhanced propellant ionization and on the other hand accelerates the created ions towards the thruster exit. In the entire discharge channel the magnetic field is shaped such that electrons are prevented from contacting the channel walls. In addition, appropriate arrangement of the magnetic cells provides that most of the propellant ions are created on high potential close to the applied anode voltage. Consequently, our multi-stage design, where each of the magnetic cusps represents an acceleration and ionization stage, allows for high beam power and ionization efficiency[†] and a minimum amount of wall losses. As experienced from our cylindrical

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[†] Beam power efficiency denotes the quotient of mean energy of the emitted ion beam and the applied anode voltage.

HEMP thruster models, electron confinement can be improved such, that no cathode is needed to operate the thruster discharge in a grounded test chamber.

III. Design Aspects of Thruster Laboratory Model

A first laboratory model DM1 of a coaxial HEMP30250 thruster has been set up in March 2005. Photographs of the DM1 thruster model during the set up phase and when installed in our test vacuum chamber are shown in fig. 2.

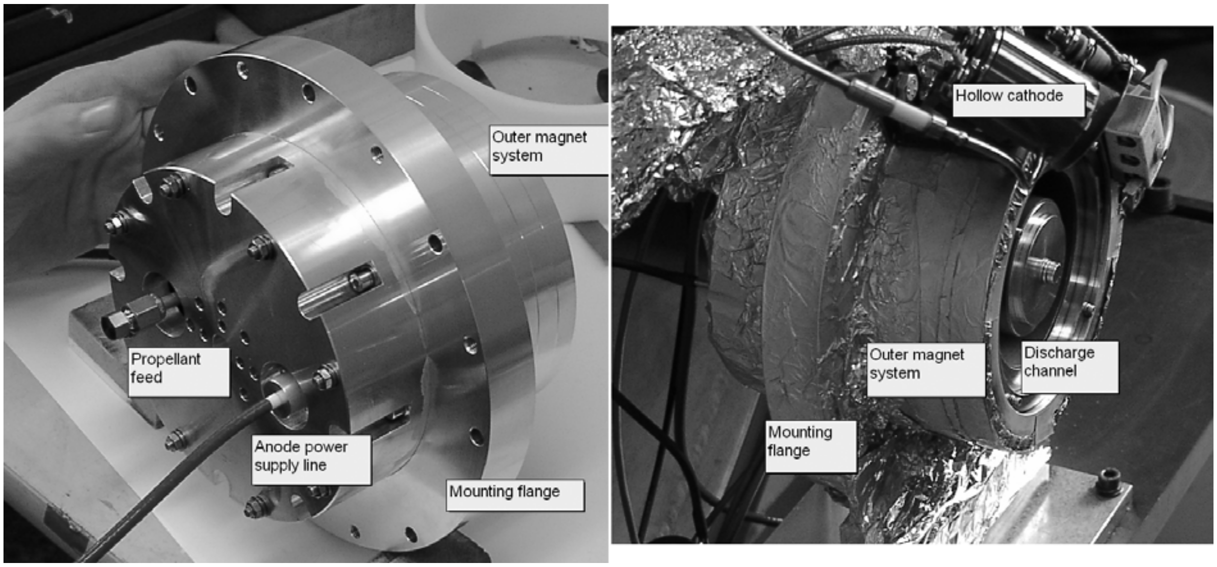

Figure 2: First HEMP3250 laboratory model DM1. Left photograph: rear side of the thruster. Right photograph: side view into exhaust plane (thruster mounted in vacuum test chamber).

The concepts for the thruster gas inlet and connection of the anode power line have been overtaken from our latest cylindrical HEMP3050 thruster model and provide high voltage insulation up to 5kV for Xenon gas flows from 1 to 300sccm at a maximum operational temperature of up to 250°C[‡].

In order to provide azimuthally symmetric gas distribution in the discharge channel, gas is fed from the anode via multiple holes, and in the anode itself a two-stage flow impedance allows for a azimuthally homogeneous gas pressure already in front of the holes.

Purpose of our first laboratory model DM1 was to demonstrate in how far the thruster operational parameters and discharge behavior are comparable to what is typically observed in cylindrical HEMP thruster models. Therefore we have chosen a very simple magnetic field pattern with only one main magnetic cell. The width of the discharge channel is small in order to provide sufficient ionization yields already at low propellant mass flows[§]. However, from our experience with cylindrical geometries, the small channel width would result in a non-negligible plasma-wall contact. In order to compensate for this effect we increased the magnetic field strengths, but, nevertheless, results from our P(article) I(n) C(ell) simulations of the thruster plasma have predicted a certain amount of wall losses.

Taking into account, that our first coaxial HEMP thruster model is the basis for a 10kW thruster, its geometry is very compact. The thruster outer diameter amounts 140mm (the mounting flange with a diameter of 200mm is not taken into account), the length 150mm and the thruster weight is below 6kg.

[‡] The temperature limit is due to the limited operational temperature of the high voltage cable.

[§] Due to the limited pumping speed and chamber size in our current vacuum test facility, a sufficiently low background pressure in vicinity of the thruster exhaust can only be provided for Xenon mass flows below 3mg/s.

IV. First results

The first HEMP30250 laboratory model, DM1, has been mounted in our test vacuum chamber end of March 2005. The test chamber has a diameter by length of 1m × 1m and an effective pumping speed for xenon of 8,000l/s provided by means of two turbo-molecular and a cryo pump.

The thruster has been operated at anode voltages between 150 and 1500Vand Xenon mass flows of up to 3mg/s. The maximum anode power applied was 3kW. A photograph of the thruster in operation is shown in fig. 3.

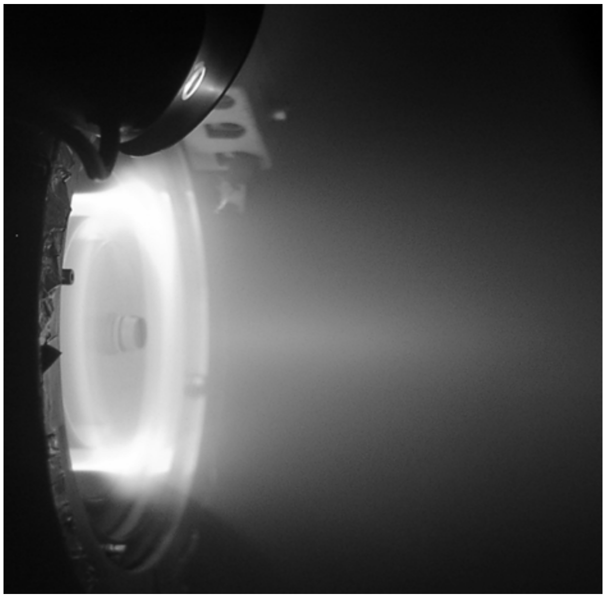

Figure 3: First laboratory model of a coaxial HEMP30250 thruster in operation.

In contrast to our advanced cylindrical HEMP thruster models, a cathode was required to operate the thruster discharge. The cathode leakage current to the anode current amounted between 10 to 15% of the total anode current. At constant thruster mass flow the leakage current increased when the background pressure was increased or at increased anode voltage, respectively.

A strong dependence of the total anode current on residual chamber pressure has been observed. As an example, at a given operational point the anode current has increased by a factor of 4 when the background pressure has been increased from 2×10^{-3} Pa to 2×10^{-2} Pa, whereas in case of our latest cylindrical HEMP thruster models the increase in anode current amounts only a factor of 1.1 to1.2.

In addition we have observed variations and a tendency towards an increase of anode current with increased anode voltage, whereas in case of cylindrical HEMP thrusters the anode current showed nearly no variations for anode voltages above 400V.

Measurements of the polar angle distribution of the ion beam power density by means of our thermal diagnostics show a peak of ion beam power density on axis but also a relatively wide angular spread.

Due to the insufficient test environment, HEMP30250-DM1 could only be tested at a few operational points. As a result of the large exhaust surface of the thruster, the small vacuum chamber and the short distance of our thermal diagnostics to the thruster exit of only 450mm, the diagnostics provide rather qualitative than quantitative results. Nevertheless, it could be shown that the cylindrical HEMP thruster concept can be scaled to a coaxial geometry. However, the observations made with our first laboratory model HEMP30250-DM1 indicate an insufficient magnetic confinement of the plasma electrons.

V. Summary and Outlook

A first laboratory model, HEMP30250-DM1, has been set up to demonstrate the scalability of the cylindrical HEMP thruster concept towards a coaxial discharge channel. Due to the increased exhaust surface, coaxial HEMP thrusters shall provide increased thrust levels in the range of several 100mN. Despite the restrictions arising from our testing environment, the observations made so far show principal feasibility of the coaxial HEMP thruster concept. Although, in case of DM1, the arrangement of the magnetic cusps and the chosen geometry of the discharge channel do not provide sufficient electron confinement, a peaked ion beam distribution on axis could be observed.

Future efforts are directed towards an improved electron confinement of our next laboratory model, HEMP30250-DM2. Currently, simulations of the discharge plasma with a modified magnetic field pattern and discharge channel are performed, which indicate a clear improvement potential.

In order to improve our diagnostics to fully characterize all of our HEMP thruster models, we are about to set up a large thruster test facility consisting of a 2.4m diameter × 4m length vacuum chamber with an effective Xenon pumping speed of 100,000l/s equipped with a thrust balance, and various ion beam diagnostic tools[**].

[**] Our new thruster test facility will be subject of a dedicated talk at this conference.

Acknowledgments

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[1] Kornfeld G. et al. Plasma Accelerator Arrangement PCT/DE99/01708 filed 11.June 99; Priority Germany No.198 28 704.6 filed 26th June 98

[2] Kornfeld G., Koch N.,. Harmann H.-P; "New performance and reliability results of the Thales HEMP thruster";4th International Space Propulsion Conference, Cagliary 2004.

[3] US Patent 10/239272, Multistage Hall Plasma Thruster; G. Kornfeld, W. Schwertfeger; priority 22.03.2001