FIRST TEST RESULTS OF THE HEMP THRUSTER CONCEPT

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Acknowledgement
The authors would like to thank:
Jean Bonnet for his continuous and encouraging professional support from the beginning of our feasibility study to the thrust measurements in his lab at ONERA in Palaiseau, France
Eberhard Hartmann, Horst Neumann, Steffen Jankuhn, Frank Scholze for the efficient cooperation within the DLR feasibility study, for revising this paper and particularly for the excellent characterisation of the ion beam angular and energy distribution performed at IOM (Institut für Oberflächenmodifizierung) in Leipzig, Germany
Grégory Emsellem from Ecole Polytechnique in Palaiseau, France for his enthusiasm in developing the HEMP 1-D 4 fluid theory
Hans Meusemann from DLR in Bonn, Germany for his engagement to support this feasibility study of a new thruster concept and to provide the DLR funding means over a 33 months period
Anne Cadiou and **Franck Darnon** from CNES in Toulouse, France for their supporting interest and the funding of the thrust test campaigns at ONERA.
For their encouragement to consider the HEMP concept in a real study we thank **Prof. M. Auweter–Kurtz** from IRS, University of Stuttgart; **Prof. A. Bouchoule** from GREMI, Université d' Orleans; **Prof. J.M. Rax** from Ecole Polytechnique Palaiseau and **E. Rosencher** and his team at ONERA in Palaiseau.
The management, colleagues and workshop members in Thales Electron Devices for their engaged and substantial support which enabled this work.

Abstract:

The paper reports the first test results of a new High Efficient Multistage Plasma thruster (HEMP thruster) concept, unique by its potential for extremely low wall losses and low sputter erosion, its high thrust densities and extremely wide operational ranges.

The highest thrust and thrust density (thrust per channel exit area) of 43 mN and 16.9 mN/cm² were measured so far with demonstrator model DM3a MS2 on the thrust balance of ONERA in July 02 at 30 sccm Xe flow, 500 V and 2.88 A, respectively. This operational limit was not set by the device, but the limited test time and power supply capabilities.

At the same test campaign another demonstrator model DM3a MS1-2 having a slightly lower apparent ion beam angle and delivering a thrust of 24 mN provided within the smaller operational stability range the best combination of total efficiency and specific impulse with 31% and 1682 s, respectively, at a Xe flow of 15 sccm, an anode voltage of 550 V and an anode current of 1.16 A. For brevity, the details are not given here.

A further improved version, DM3a MS1-3, was tested in Oct. 02 at IOM at Leipzig with respect to angular and energy distribution of the ion beam at one selected operating point of 8 sccm, 500 V and 0.505 A. The performed measurements provided insight into the distribution of the multistage plasma potentials and the ionisation probabilities inside the thruster channel and confirmed the ideas the HEMP thruster concept is based upon. The integration over the angular and the energy distribution resulted in a thrust value of 12 mN, a total efficiency of 38% and an effective swallow tail beam angle of 43°. Another surprising feature of DM3a MS1-3 has been its ability to turn on and off the neutraliser cathode with practically no impact on the thruster operational characteristics and its performance.

At present a new HEMP thruster layout DM6 is under test. Current measurements on DM6 MS1 performed at TED Ulm by means of an own developed thermal diagnostic indicated further significant improvements. At 14 sccm, 600 V and 1.3 A, thrust, total efficiency and specific impulse were determined to be well above 30 mN, 55 % and 2300 s, respectively. For Xe flows up to 8sccm DM6 MS1 could be stably operated at anode voltages of up to 1800 V, providing specific impulses well above 3500 s. Also operation of DM6 MS1 required no neutraliser cathode.

It is intended to confirm these thermal diagnostic results on DM6 versions in the course of thrust balance tests to be performed at ONERA in February 03 the results of which shall be presented at the conference.

1. Introduction

The basic, multiply patented HEMP thruster concept was inspired by the focusing method of electron beams through delay lines and Multistage Depressed Collectors (MDC) in Travelling Wave Tubes (TWT's) with Permanent Periodic Magnet (PPM) systems. Their application to plasma discharge channels lead in the presence of an axial electrostatic field to a well confined discharge plasma ionising neutral propellants and accelerating the produced ions with negligible wall losses in multistage magnetic cusp structures. A feasibility study, funded by DLR, was started in June 2000. First thrust tests on a Demonstration Model DM3 using an external neutraliser cathode were performed at ONERA in Palaiseau in April 02. They showed low but promising performance features. 1.4 mN thrust and 13 % total efficiency were achieved at a Xe flow of 0.55 sccm with anode circuit 320 V and 0.47 A. Due to thermal limitations the device could only be operated for few minutes. Three months later, with a similar PPM system but improved channel properties and an additional liquid cooling system, the DM3a Magnet System MS2 and MS1-2 versions operated already much more efficiently and completely stable over long periods and wide voltage and Xe flow ranges. Especially the MS2 version impressed by applicable Xe flows from 3 sccm to 30 sccm, anode voltages from 200 V to 1000 V and resulting thrust range values from 1 mN to 43 mN. Its performance data are reported in detail below.

During the feasibility study several design improvements towards a higher total efficiency, that means lower effective ion beam angle and higher ionisation efficiency, could be realised. These development steps were supported by several theoretical activities which gave some insight in the physical processes in the thruster channel.

- In a cooperation with Gregory Emsellem from the Ecole Polytechnique in Palaiseau an unpublished 1-D 4 fluid theory for primary and secondary electrons, ions and neutrals of the periodically magnetised plasma could be developed. It describes the thrust efficiency obtained in multistage magnetic cusp structures. The theory is based on the empirical first Townsend coefficient of the magnetised Xe plasma, characterised by the Hall parameter. A limitation of this theory is its lack to predict the angular dependence of the ion beam.
- More details are revealed with the help of an Object Oriented Particle In Cell (OOPIC) code developed at Berkeley university and introduced in the HEMP thruster simulation studies in cooperation with IOM Leipzig. A limitation still is given by relatively small computation capacity of even modern PCs. Attempts are undertaken to overcome the shortcoming.
- The magnetic properties of the HEMP thruster are simulated with the commercial Maxwell code, providing the 3-D B field patterns of the tested PPM structures, which in turn can be fed into the 2.5-D OOPIC code.

The paper is structured as follows: chapter 2 gives insight into the HEMP thruster concept, chapter 3 reports on thrust measurements, chapter 4 on measurements of the ion beam energy and angular intensity distribution and in chapter 5, the HEMP thruster status is summarised.

2. The HEMP thruster concept

German and international patents are filed for the HEMP thruster concept. The principle is shown in fig. 1. The plasma chamber is separated by the PPM cusp structure into several stages with decreasing electric potentials towards the open exit at ground potential. The scheme shown in figs. 1 and 2 has four potential stages formed by metallic ring electrodes. A primary electron beam produced in a standard electron gun is injected through a small diameter hole to start the ionisation in the plasma chamber. Also neutral propellant gas is fed into the chamber and ionised by primary and secondary electron bombardment.

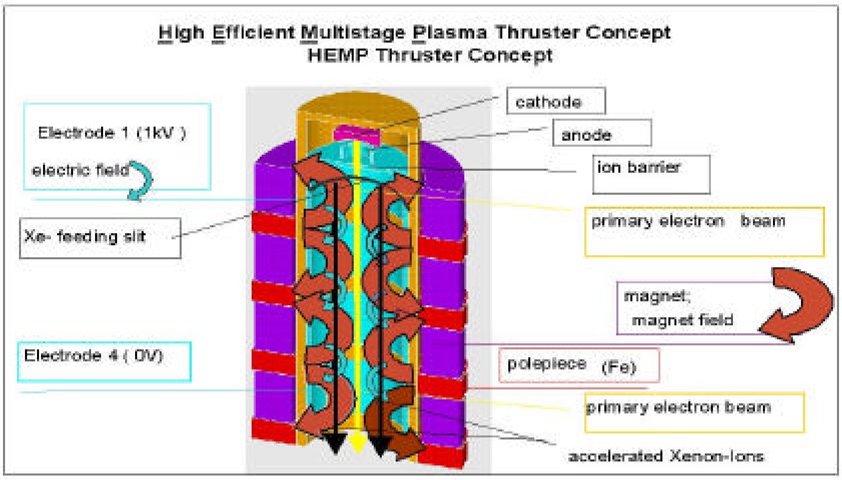


Fig. 1: Basic design of a HEMP thruster.

The electrodes create with their applied potentials inside the chamber an essentially axial electric field, which accelerates positive ions (e.g. Xe^+, Ar^+, He^+) towards the chamber exit and decelerates the primary electrons, which are then used to neutralise the exiting positive ions.

The magnet rings, stacked in PPM manner, form inside the chamber a quasi periodic magnetic field configuration (cf. figs.1 and 2), which is almost perpendicular to the electric fields. In that respect the HEMP thruster is a quasi periodic E x B device with closed-drift azimuthal Hall currents in the magnetic cusp regions (see figure 2).The operational principle of the HEMP-thruster is further explained in fig. 2:

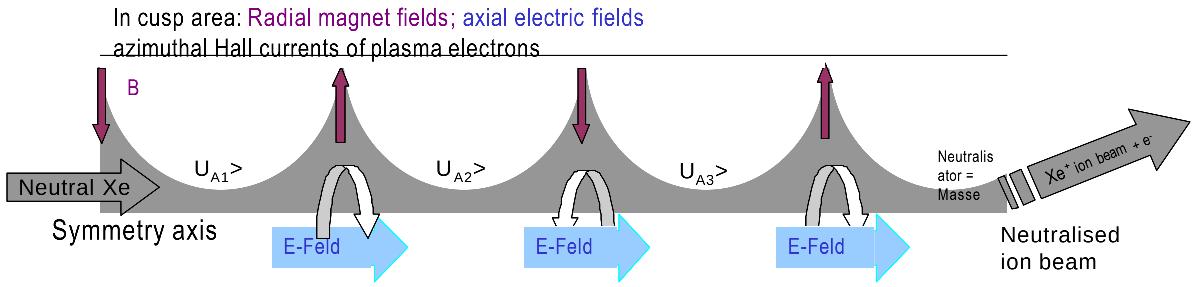


Fig. 2: Operational principle of a HEMP–thruster.

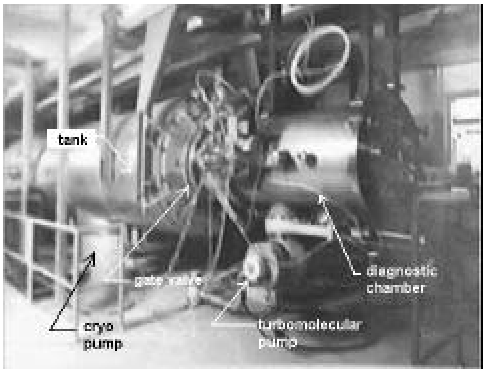
As in a TWT, an almost periodic permanent magnet structure focuses the Xe plasma on the axis and thus prevents losses to the ionisation chamber walls. The plasma potentials U_{Ai} between the cusps decrease towards the exit. The resulting electrical fields accelerate the Xe ions. Due to the crossed electric and magnetic fields in the cusp area the plasma electrons are orbiting and mirrored in closed azimuthal Hall current loops, which maintain a quasi neutral space charge distribution in the plasma chamber and lead to a very high ionisation rate.

Instead of the primary electron beam of an electron gun, a neutraliser cathode at the exit may provide the electrons for neutralisation of the positive ion beam current. In the 1-D 4 fluid theory we could prove the equivalence of both neutralisation principle variants.

Furthermore, in our empirical studies it could be found that the magnetic configuration of the HEMP thruster can confine the plasma electrons throughout the accelerated ion beam so effectively that the positive ion beam space charge is compensated and the applied electrostatic potentials are maintained even when no equivalent external electron current is provided by a near cathode neutraliser. In that case the positive ion beam current is neutralised at the grounded chamber walls.

Though this operational feature of the new HEMP thrusters is so far proven only in closed vacuum tanks, it is expected that similar to the grounded vacuum tank walls the free space environment with its diluted plasma will provide the final current compensation by an electron dislocation current at the far space boundary of the ion beam and an equivalent positive ion current of low energetic ions to the grounded spacecraft walls. We therefore speculate that if the HEMP thruster can operate without a neutraliser in a vacuum tank, it could operate without a neutraliser also in free space. Therefore, in future, it might be for some applications an effective method to avoid the propellant and energy losses of a hollow cathode neutraliser.

3. Thrust measurements at ONERA



3.1 Thrust Stand:

Fig.3 shows the ONERA test facility. The thrust stand consists of two vacuum chambers separated by a 0.5 m diameter gate valve. In the first chamber, 1.0 m long by 0.6 m diameter, the thrust balance is mounted. A turbo molecular pump provides an effective pumping speed for Xenon of about 1200 l/s. The second chamber is formed as a 4 m long by 1.0 m diameter tank pumped by a cryogenic pump with an effective pumping speed for Xe of 8000 l/s.

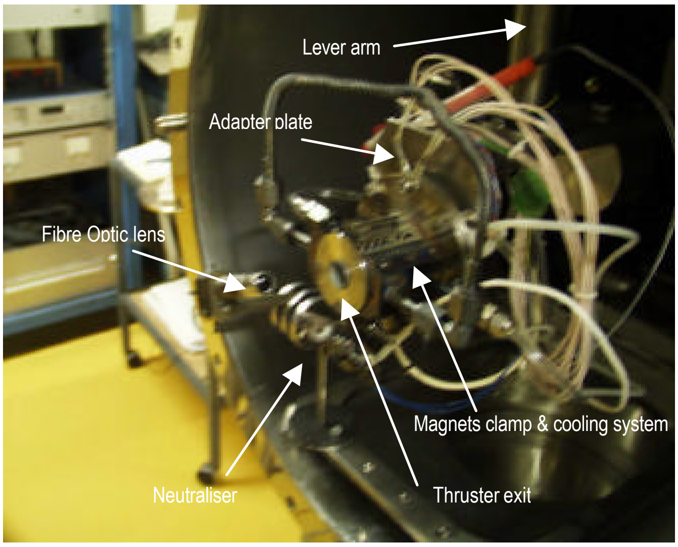
Fig.3: ONERA thrust stand.

For thrust measurements the separating gate valve between the two chambers is opened and the tank is pumped either by the turbo pump of the diagnostic chamber or in addition by its cryogenic pump. View ports at the diagnostic chamber allow for visual inspection of the plasma behaviour of the thruster mounted at the thrust balance.

The thrust balance is capable to perform direct thrust measurements in the range of 0.1 to 100mN. Thrust is balanced by an electromagnet in order to keep the balance in zero position during thruster operation with the zero-point signal taken from a capacitive reference measurement. Hence, the current flow through the magnet for the balance kept in steady state is a measure for the thrust. Calibration occurs by means of a 40 mN calibrated weight pulling at the balance.

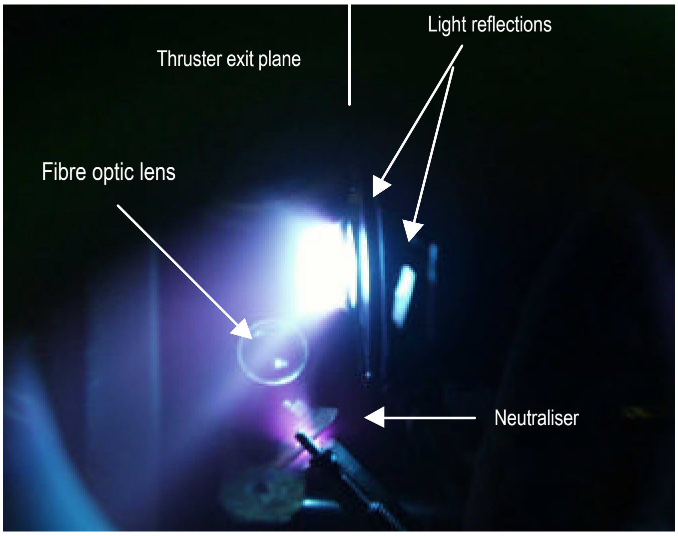
3.2 Measurements on Thrusters DM3a in July 02

Thrust measurements have been performed on HEMP thrusters DM3a with two different magnetic field configurations MS2 and MS1-2, respectively, employing a liquid cooling of the different magnet systems which allowed continuos and stable operation at input power levels of as high as 1.4 kW. Though the magnetic designs differed, both essentially consisted of three stages with magnetic cusps confining the plasma electrons..



An external Xenon-fed hollow-cathode based neutraliser has been applied for neutralisation. In addition a fibre optic system was installed to take a spectrum analysis of the light emitted at the thruster axis. As shown in fig. 4, the thruster has been mounted on the thrust balance lever arm by means of an adapter plate, all electrical, gas and cooling lines are fed through the lever arm to the corresponding vacuum feedthroughs.

Fig. 4: DM3a MS2 thruster mounted onto the ONERA thrust balance in the diagnostic chamber.



In fig. 5 a view on the ion beam exit plane of HEMP thruster DM3a MS2 operated at a Xe flow of 8 sccm and an anode voltage of 510 V is given. Under these operational parameters the apparent beam angle amounts to about 40 degrees.

For thrust measurements, both chambers have been pumped over night by means of the turbo molecular and cryogenic pump providing a base pressure below $1x10^{-6}$ mbar prior to testing. The neutraliser conditions were adjusted to a Xenon gas flow of about 2.5 sccm and neutraliser current levels between 1 A and 1.6 A yielding keeper voltages of about 38 V to 25 V, respectively.

Fig. 5: DM3a MS2 thruster in operation at 8 sccm Xe flow and anode voltage of 510 V.

The anode voltage was chosen as adjustment parameter. For each selected Xe flow in the range from 3 sccm to finally 30 sccm thrust measurements were performed at anode voltages increasing from low to high values. Owing to test time restrictions the limits of possible operation were not systematically determined. The overall range of applied anode voltage was between 200 V and 1000 V.

Low systematic uncertainties have been achieved by calibrating the thrust balance at each operating condition before turning on the thruster. Thrust has been noted once a stable discharge current and voltage situation has been achieved and, after turning off the thruster, the balance has been again calibrated.
By applying this method, the systematic error in measured thrust values is estimated to be below 0.25mN.
The calibrated thrust values were electronically recorded by the ONERA thrust measurement system. An example at medium Xe flow of 11.2 sccm is shown in figure 6, where thrust values in mN were plotted versus measurement time in seconds. Balance calibrations are indicated by the 40 mN peaks after each thrust measurement. Small instabilities and drifts in the thrust values up to +/- 0.25 mN occurred versus time. They are believed to be related to the thrust measurement system since the same disturbance levels can be noted when the thruster is turned off.

Discharge voltage, current and temperature of the adapter plate at the anode were recorded in parallel to thrust measurements by means of a data recorder. An evaluation of these data for the DM3a MS2 is presented in the following figs. 7 through 14.

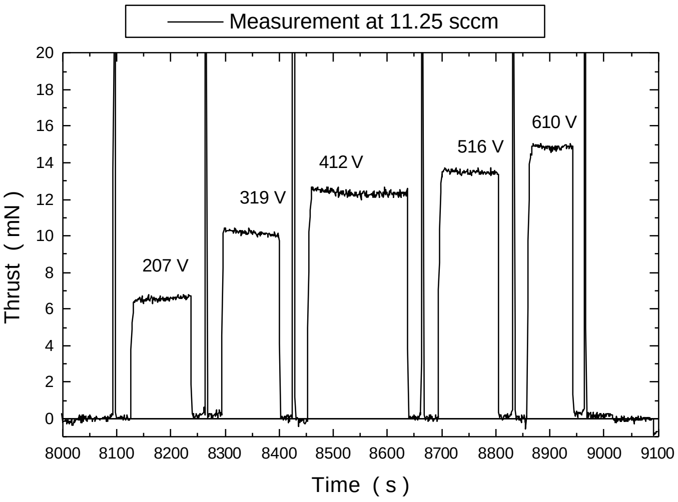


Fig. 6: Thrust versus time of DM3a MS2 at 11.2 sccm Xe flow in operation at different anode voltages.

In general we note an almost linear increase of thrust with Xe flow up to 30 sccm, which indicates that no severe saturation effect occurs. This means that the device might have been used at an even higher Xe flow than 30 sccm. Despite of this linearity the physics in the thruster channel is changing. As shall be shown below, the ionisation efficiency and effective beam angle are increasing with Xe flow but almost compensating its opposing effects.

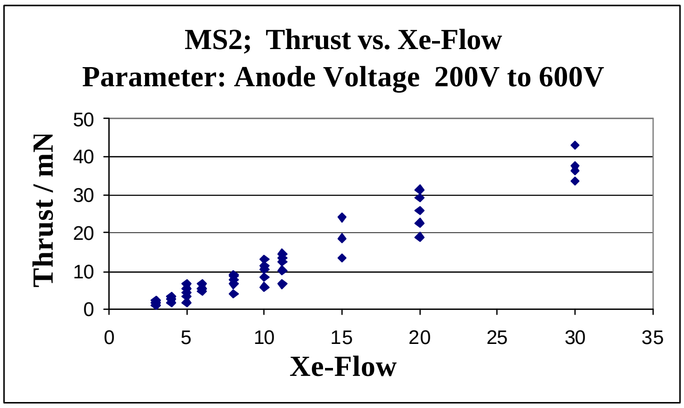


Fig. 7: Thrust of DM3a MS2 vs. Xe flow. Parameter is the anode voltage U_a ,which varies mostly from 200, 300... to 600 volt..

Fig. 8 gives thrust as function of anode voltage for various Xe flow values. It can be seen that thrust fits roughly to the expected square root dependence with anode voltage U_a for all Xe flow levels. Higher and lower anode voltages and Xe flows than those shown were not yet tried in the restricted available time of about 1 day. Therefore the stable operation range of DM3a MS2 is probably much higher.

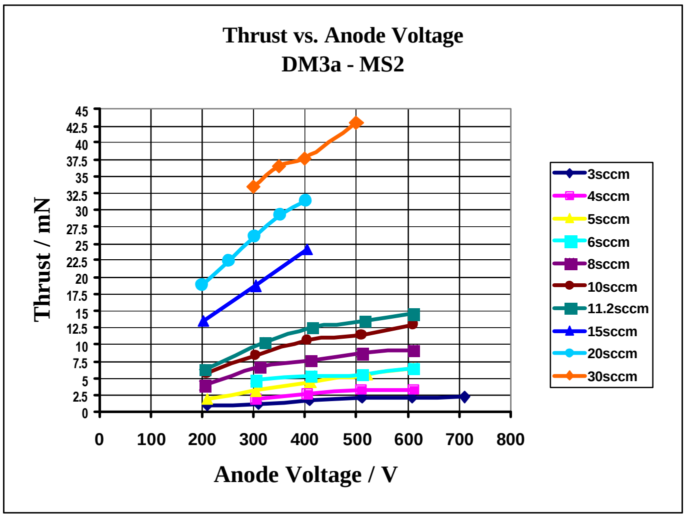


Fig. 8: Thrust of DM3a MS2 vs. anode. voltage U_a. Parameter is the Xe flow.

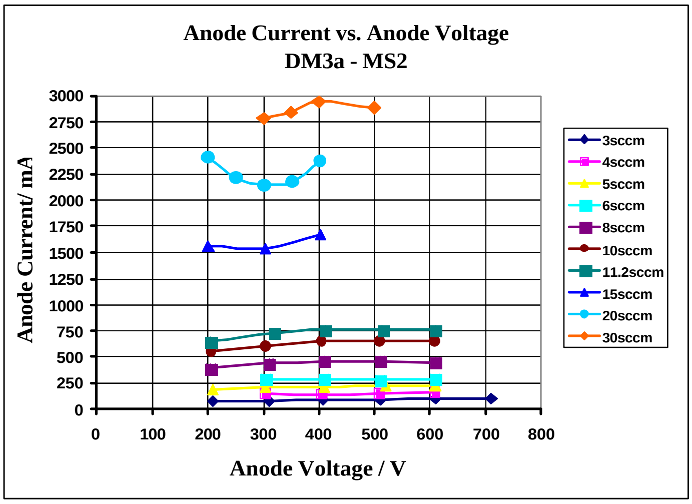
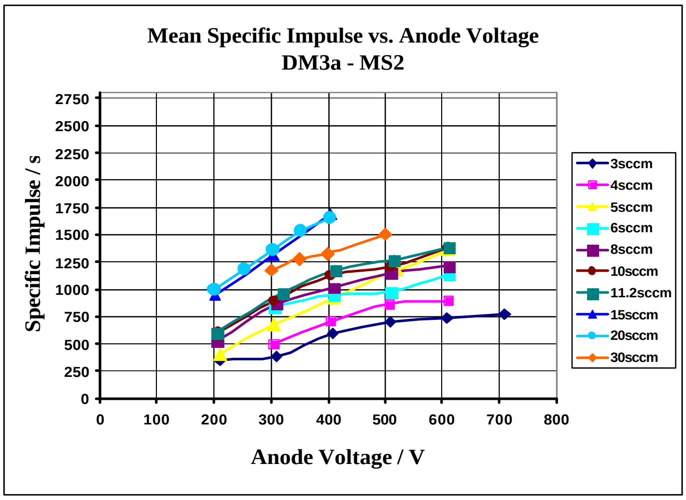


Fig. 9 shows the dependence of anode current on anode voltage for different Xe flows. Obviously the anode current is essentially determined by the Xe flow and to a lesser extend by the anode voltage. The over proportional of current with Xe flow indicates, that also ionisation efficiency is mainly an increasing function with Xe flow.

Fig. 9: Anode current vs. anode voltage. Parameter is Xe flow.



The specific impuls averaged over all Xe particles (including neutrals) is for a given anode voltage not constant, but rising with Xe flow, due to an increasing ionisation efficiency. Also it rises with the anode voltage. The relative high swallow tail beam angle of DM3aMS2 is a reason for generally low Isp.

Fig. 10: Specific impuls of all Xe particles vs. anode voltage according to Parameter is Xe flow.

Whereas the total efficiency and the specific impuls can be directly determined from thrust, Xe flow and power via:
$\eta_{tot} = T^2 / (2 \cdot Q_{Xe} \cdot U_a \cdot I_a)$ and $Isp = T / (Q_{Xe} \cdot 9.81\ m/s^2)$ with Q_{Xe} = Xe mass flow, the other, more refined parameters η_{ion} , η_{beam} , η_{thr} need additional information on the ion current, the energy and the velocity distribution of the ions in the beam. To describe the angular distribution, as a minimum, the effective beam angle α is required. It can be related to the apparent beam angle of a swallow tail beam, but needs obviously corrections as our angular analysis at IOM in Leipzig has shown (see next chapter). Typically the apparent beam angle for the HEMP thrusters is about 10° lower. The beam efficiency η_{beam} as ratio of the total kinetic beam power to the thruster electrical input power was determined by the thermal diagnostic tests performed in Ulm. They typically range between 70% and 80%. In the case of a HEMP thruster operated without neutraliser, the ionisation efficiency is simply approximated by $\eta_{ion} = (I_a /e) / (Q/M_{xe})$. Here e/M_{xe} is the charge to mass ratio of single charged Xe ions. At the time of evaluation of the ONERA July 02 thrust tests, this simple η_{ion} definition was not justified since the thruster was operated with neutraliser. Therefore another slightly different approximate determination $\eta_{ion} = \eta_{tot} / \eta_{thr}$ has been used for the evaluations via the identity
$\eta_{tot} = \eta_{thr} \cdot \eta_{ion} = \eta_{beam} \cdot \cos^2\alpha \cdot \eta_{ion}$ with
$\eta_{thr} = T \cdot (2 \cdot e \cdot (U_a - U_k)/M_{xe})^{0.5} \cdot \cos\alpha / (2 \cdot U_a \cdot I_a)$;
U_k = Keeper voltage (Plasma potential of beam at exit).

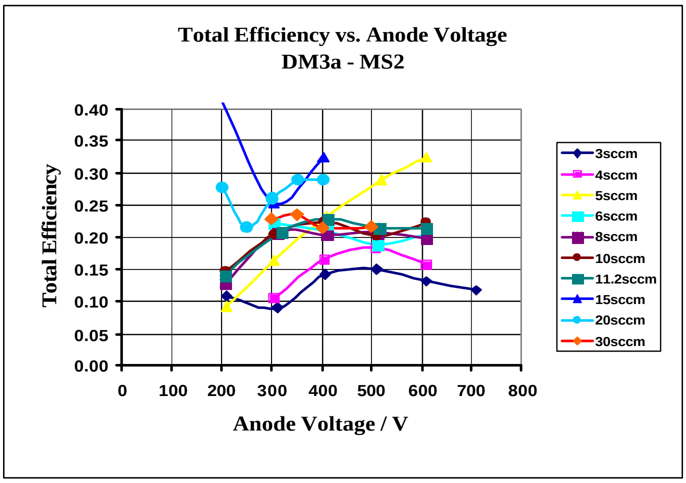
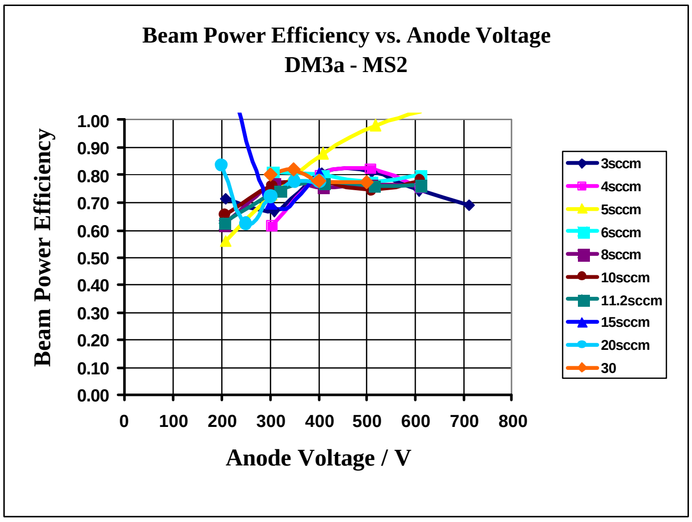


Fig. 11: Total efficiency vs. anode voltage. Parameter is Xe flow.

Table 1: Estimated dependence of the effective beam angle on DM3a MS2 from Xe flow

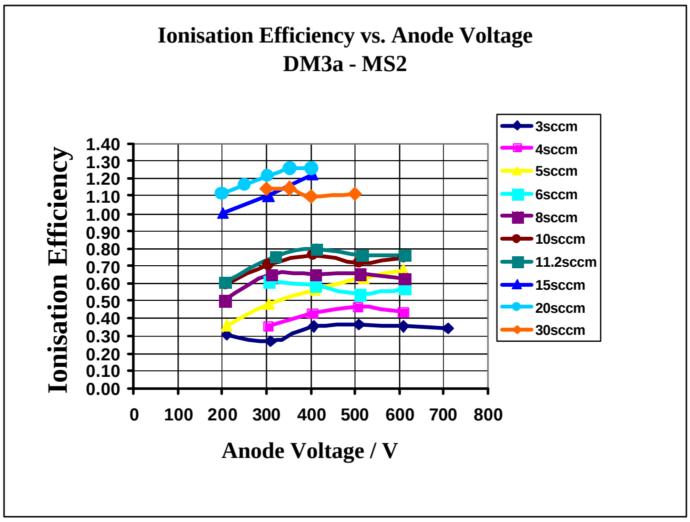
Xe flow / sccm	3	4	5	6	8	10	11.2	15	20	30
Effective angle α /°	45	46	47	48	50	52	52.5	55	57	60



Except the always same escaping values at 5 and 15 sccm, which are obviously not correct (drift of thrust value or Xe flow), most of the beam power efficiency data fit under the definition of fig.12 with the beam power efficiencies of about 70% to 80%, determined by our direct thermal measurements in Ulm and the measurements at IOM Leipzig. The rather high beam power efficiency (or sometimes thermal efficiency) is in agreement with the observation of very low channel wall losses in the HEMP thruster.

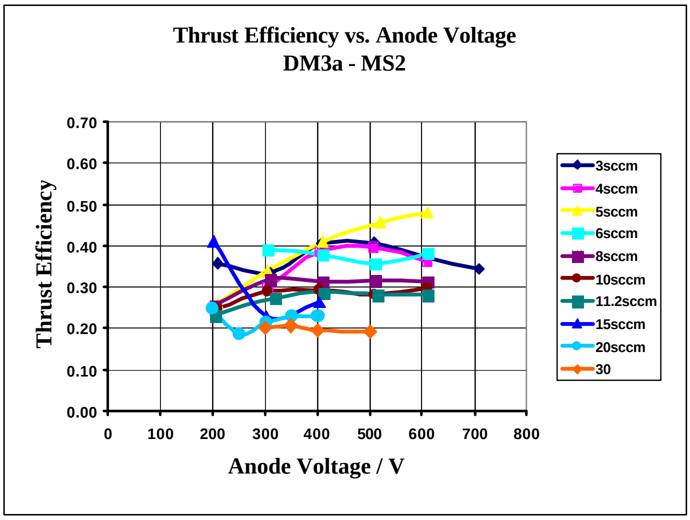
Fig. 12: Beam power efficiency vs. anode voltage according to $h_{beam} = h_{thr}/(\cos a)^2$ *and* a *given in table 1.*

The residual losses are essentially caused by the impact of high kinetic energy secondary electrons at the anode electrode. Those electrons are created downstream the channel at lower plasma potential (see evaluation of IOM Leipzig data on DM3a MS1-3).



According to fig. 13, the ionisation efficiency increases steadily with the Xe flow and depends only weakly on anode voltage. This can be understood considering the increased neutral gas pressure inside the channel at higher Xe flows. Ionisation efficiencies above 1 are due to multiply charged Xe ions. This finding was evidenced by spectral analysis of the light emitted by the exiting plasma beam.

Fig. 13: Ionisation efficiency vs. anode voltage according to $h_{ion} = h_{tot}/h_{thr}$ *.*



The overall decrease in thrust efficiency at higher Xe flows, shown in fig. 14, is mainly caused by an increased effective swallow tail beam angle α. The dependence on the anode voltage is generally weak.

Fig. 14: Electrical thrust efficiency vs. anode voltage.

4. Measurement of ion beam energy and angular distribution at IOM Leipzig

4.1 Experimental set up

The energy selective mass spectrometer EQP 300, of Hiden, was installed at the front plate of a cylindrical vacuum tank evacuated with two 2000 l/s turbo-molecular pumps. The thruster was mounted within the tank on a table which can be rotated around a vertical axis through the centre of the DM3a MS1-3 thruster exit. In zero angle position the thruster axis is directed towards the 445 mm distant entrance of the EQP 300 mass spectrometer. The principle assembly of the mass spectrometer is sketched in fig. 15.

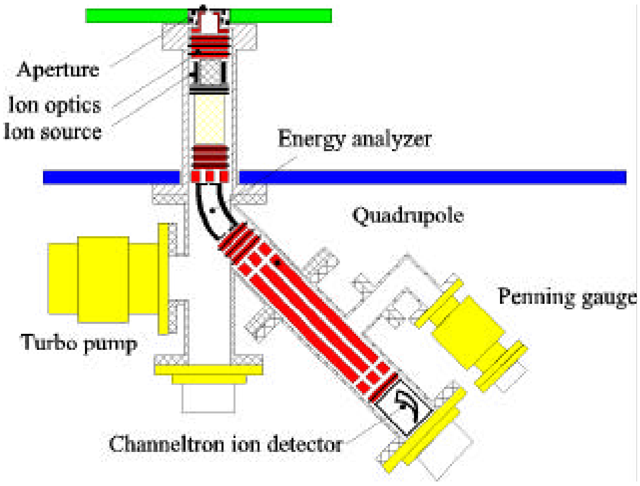


Fig. 15: Schematic assembly of EQP 300

4.2 Measurements on HEMP thruster DM3a MS1-3

After calibration of the mass spectrometer to maximal signals for the major Xe isotope at amu 131.8 the following series of tests was performed with the DM3a MS1-3 operated at 8 sccm of Xe flow with an anode voltage of 500 V resulting in about 505 mA anode current:

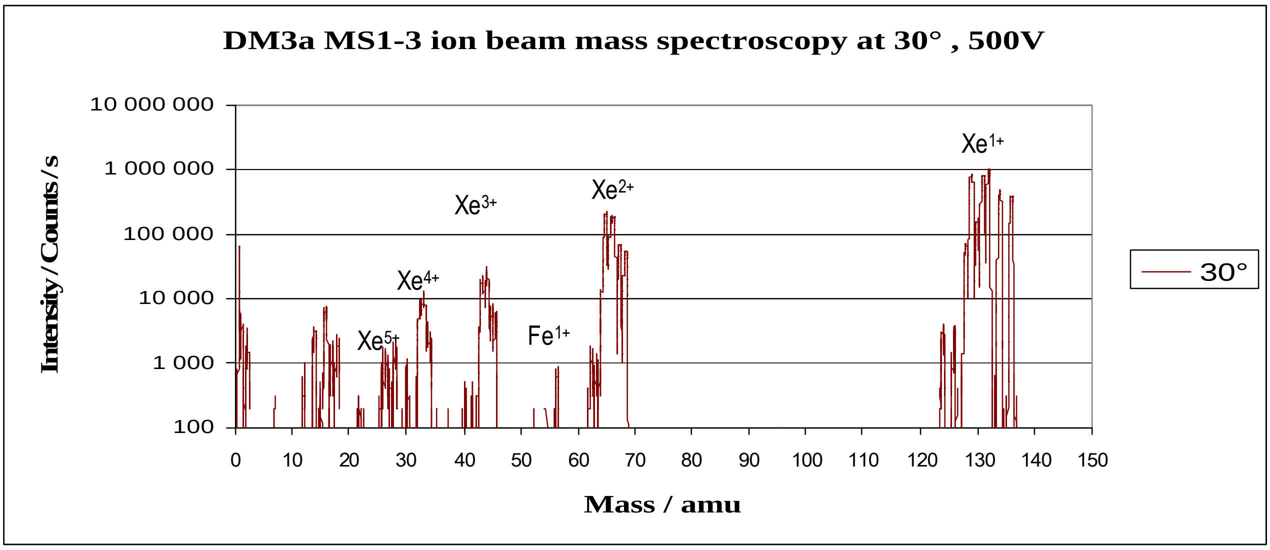


Fig. 16: DM3a MS1-3 ion beam mass spectroscopy in an angle of 30° at kinetic energy of 500 eV.

- Mass spectroscopy at 500 V at the angles 0°, 5°, ..., 30° with a resolution of 0.1 amu. Due to their similarity, except for the count rate, only the mass distribution at 30° is shown in fig. 16.

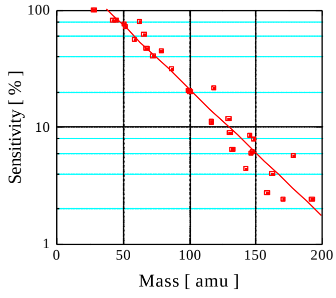


Fig . 17: Mass sensitivity curve of the EQP 300.

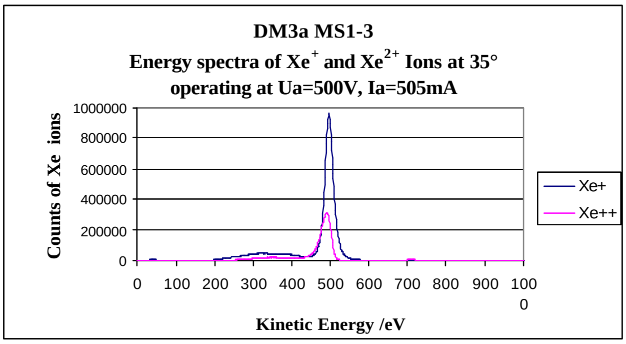


Fig. 18: Energy spectrum of single and double charged Xe ions in 35° angle sector of the ion beam.

The mass spectrometer is sensitive to the mass to charge ratio, and hence the double charged Xe isotopes group occurs around 66 amu instead of 132 amu. Having this in mind we can unambiguously identify in fig. 16 the other isotope groups up to the fifth ionisation stage Xe^{5+}. Except the standard residual gases of a vacuum tank and the sputtered Fe/Ni tank walls no other materials particularly no thruster wall material can be detected by mass spectroscopy. Once again this stresses the extremely low sputter rate of wall materials of the HEMP thruster.

Taking the factor 6 higher detection sensitivity from the sensitivity curve of the EQP 300 mass spectrometer given in fig. 17 we can calculate the non negligible amount of Xe^{2+} ions to be 5% of the Xe^{1+} ions in the 30° sector of the ion beam.

- Energy spectra of Xe^{1+} and Xe^{2+} ions are taken at 0°, 5°,...,75°. The contribution of the Xe^{1+} and Xe^{2+} ions, is shown in fig. 18 by their energy spectra at the angle of 35°, at which maximum intensity is observed for the single charged ions.

  A surprisingly sharp peak near the applied anode potential of 500 V is observed for both species. The small deviation from 500 V corresponds closely to the different ionisation energies of the species. A broader shoulder can be recognised around 350 V, which is interpreted as plasma potential drop across the first cusp downstream from the anode.

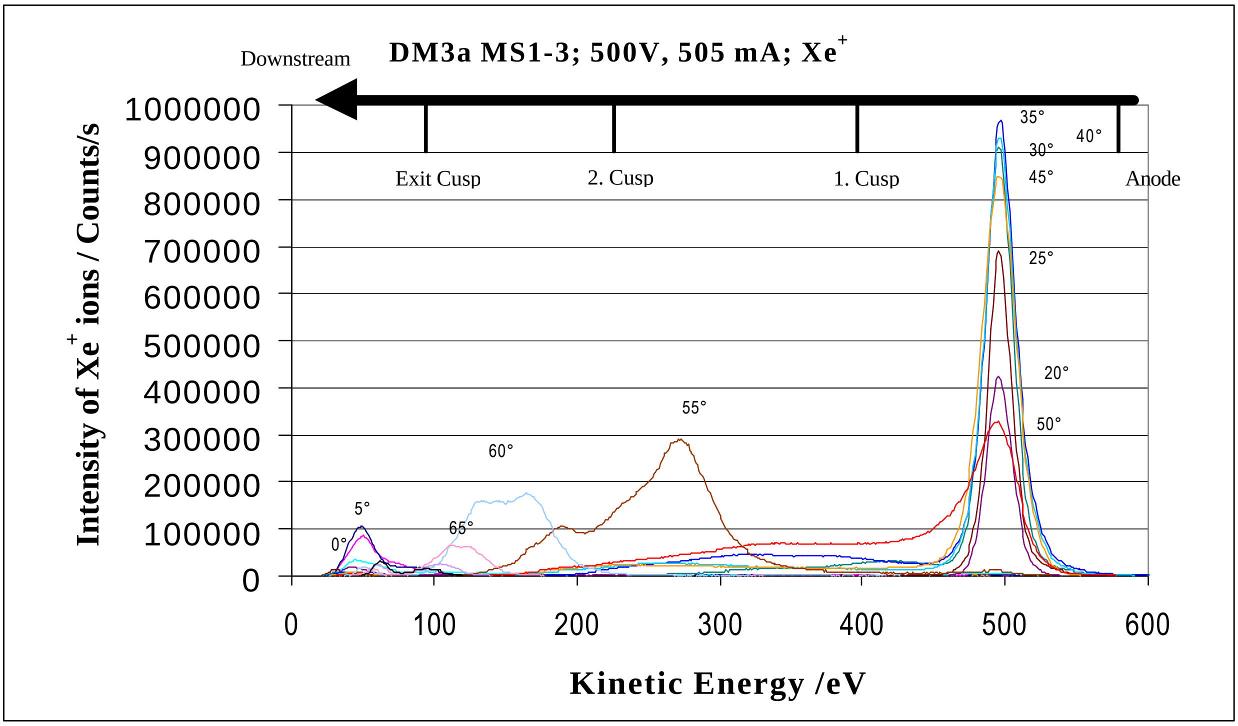
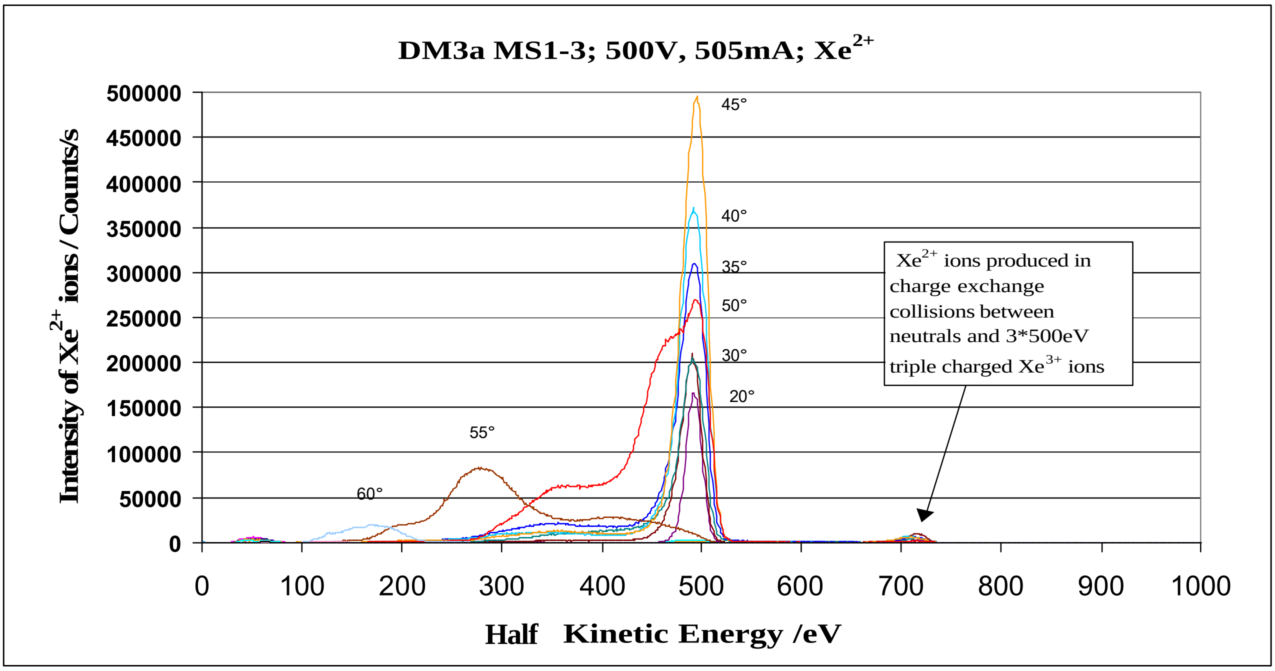


Fig. 19: Energy spectra of Xe^{1+} for all the various measured angles.

Fig. 19 shows the spectrum of Xe^{1+} for all angles (no significant intensity was measured above 70°). The structured energy spectrum of single charged Xe ions allows a clear interpretation in agreement with the HEMP thruster functional principle:

- Most of the ions are created at anode potential between first downstream magnetic cusp and anode as predicted by the 1-D 4 fluid theory and our OOPIC simulations. They finally are accelerated by the plasma electrostatic optics into angles from about 20° to 50° with an intensity peak at 35°.
- Ions emitted at around 55° originate from about 270 V between 1st and 2nd cusp.
- Ions at even higher beam angles of 60° to 65° originate between the 2nd and exit cusp close to the thruster exit from a plasma potential of approximately 150 V.
- There is negligible beam intensity into angles of 70° and higher.
- Also, at low beam angles from 0° to 15°, there is weak intensity except the slow ions with beam plasma potential energy of about 50 V, created as charge exchange ions beyond the exit.


DM3a MS1-3; 500V, 505mA; Xe^{2+}

Xe^{2+} ions produced in charge exchange collisions between neutrals and 3*500eV triple charged Xe^{3+} ions

Fig. 20: Energy spectra of Xe^{2+} *for all measured angles.*

The energy spectra of the Xe^{2+} ions are closely resembling the Xe^{1+} spectra apart from some particulars shown in fig. 20. This can be well understood, because charged particle trajectories do not depend on the e/M ratio in electrostatic potentials (magnetic fields have negligible effects on the massive Xe ions).

The energy spectra, taken for DM3a MS1-3 for single and double charged Xe ions, allowed integration over all space angles. Normalising the result to the anode current of 505 mA, allows for estimating the average performance parameters of the thruster operated at 500 V anode voltage and 8 sccm Xe flow. This values are given in the following table 2 and compared with the previous DM3a MS2 ONERA data and the DM6 MS1 thermal diagnostics data recently measured at TED in Ulm.

Table 2: Summary of the HEMP thruster achievements in 2nd half of 2002 at 8 sccm and 500 V.

8 sccm Xe flow	DM3a MS2 at ONERA July 02	DM3a MS1-3 at IOM Oct 02	DM6 MS1 at TED Dec 02
Anode voltage / V	510	500	500
Electric Power / W	234.6	252.5	245
Thrust / mN	8.7	12	(12.5)
Specific Impulse / s	1143	1600	(1635)
Total efficiency / %	21	38	(44)
Ionisation efficiency / %	(66)	90	88
Electrical efficiency / %	(32)	42	(50)
Beam efficiency / %	(76)	79.5	80
Effective beam angle / °	(50)	43	(38)

( ) indicate evaluations which are based on indirect methods due to lack of detailed beam distribution data.

The data in table 2 show a continuing fast performance improvement of the HEMP thruster concept.

5. Summary

The first characterisations and iterations of the HEMP thruster concept clearly demonstrated its unique potential for further improvements and its almost ideal suitability for spacecraft propulsion applications. With the advantages of nearly absent wall erosion, extremely high thrust density, light weight and stability over wide operating conditions, requiring no grids, no supply for magnet coils and (potentially) no neutraliser, the HEMP thruster concept promises to compete with the performances of standard Hall effect thrusters and grid ion engines without their particular shortcomings. Today the only exception is the still high effective ion beam angle of about 40°. It is a clear near term goal to improve this value significantly.