

Design and optimization of a Ring Cusp thruster with simulated beam extraction

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Abstract:

A ring cusp discharge chamber is currently under development at Mars Space Limited. Two activities are running in parallel for the experimental characterization of a breadboard discharge chamber and the development of a numerical tool to simulate the plasma discharge. The optimization was carried out by testing different magnet positions and strengths, varying the cathode position along the axis or changing the discharge chamber volume. Throughout the test campaign, the plasma properties at the grid exit were measured using a Langmuir probe. In parallel, a 2D-axisymmetric code is developed for future design. The model includes PIC method and finite volume solver for the different species. This paper presents the experimental characterization and model mainline.

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Nomenclature

α	=	Masking area coefficient
γ	=	Transparency coefficient
ε_b	=	Ion cost production [eV/ion]
$\hat{I}_{acc}$	=	Accel grid current without beam [A]
I_{acc}	=	Accel grid current with beam [A]
$\hat{I}_{beam_dc}$	=	Residual beam current without beam [A]
I_B	=	Ion beam current [A]
$\hat{I}_D$	=	Discharge current without beam [A]
I_D	=	Discharge current with beam [A]
I_e	=	Primary current from the hollow cathode [A]
$\hat{I}_{scr}$	=	Screen grid current without beam [A]
I_{scr}	=	Screen grid current with beam [A]
I_{tot}	=	Total ion current collected [A]
$\dot{m}_{beam}$	=	Total mass flow rate with beam [kg/s]
$\dot{m}_{dc}$	=	Total mass flow rate without beam [kg/s]
M_i	=	Atoms mass [kg]
T_{dc}	=	Ion grids transparency without beam
T_{beam}	=	Ion grids transparency with beam
T_{eV}	=	Electron Temperature [eV]
V_D	=	Discharge Voltage [V]
q	=	Elementary electric charge [C]
η_p	=	Mass utilization efficiency

I. Introduction

COMMERCIAL spacecraft operators are now actively proposing the adoption of electric propulsion (EP) for significant orbit raising maneuvers on GEO telecom satellites in addition to NSSK maneuvers. The duration of these maneuvers is strongly influenced by the thrust level and, since the total available power is limited by array sizing for the payloads, ultimately by the specific power (W/mN) of the EP system. The W/mN of the EP system is therefore increasingly recognized as a key technology selection discriminator.

The Kaufmann type ion engines that have been historically developed and flown in the UK (e.g. the QinetiQ T5 and T6 [1]) operate at a relatively high specific powers, in the order of 32 W/mN, which is driven by the specific impulse at which these systems operate. They were originally designed for this performance as they were primarily targeted for scientific missions and also because commercial applications at the time were limited solely to north-south station-keeping (NSSK) operations, which do not require high thrust levels and hence are less influenced by the W/mN. Reducing the W/mN requires the SI to be reduced, which in-turn requires the beam voltage to be decreased. Reducing the beam voltage in isolation is relatively simple, however it is also required to increase the thrust level. This means that a higher ion beam current density and extracted beam current are necessary, which also means higher discharge plasma densities and, hence, higher discharge powers for a given discharge chamber design. The discharge efficiency, defined as discharge energy required to generate a beam ion (eV/ion), becomes a critical design parameter.

The existing Kaufman discharge chamber configurations currently operate at a discharge efficiency of about 260 eV/ion [2], whereas ring-cusp discharge chambers (RCDC) have been designed and successfully operated at discharge efficiencies of ~ 150 eV/ion [3], thus significantly reducing the discharge power.

For this reason, Mars Space Limited (MSL) is developing a RCDC breadboard model in the frame of an ESA funded activity with the target of achieving an ion production cost below 160 eV/ion for an extracted ion beam current between 1 and 4 A. A thruster with these discharge chamber performances should be able to operate at 23 W/mN in a thrust range from 55 mN to 220 mN for a maximum ideal specific impulse of 4100 s.

To achieve this level of performances, the design and experimental characterization of a RCDC and the development of a 2D axisymmetric model to simulate the plasma discharge are currently being carried out in parallel at MSL. For what concerns the experimental development, a modular breadboard RCDC has been designed and manufactured based on the information currently available in the literature and from the indication provided by the 0D model described in [3] and [4].

The design modularity allows to investigate and optimize the DC performance by varying critical design parameters, such as cathode position or the magnetic cusps positions and strengths. In addition, a second larger DC has been manufactured to investigate the influence of the DC volume on the performances. It has to be noticed that within the frame of this project the DC was tested without beam extraction, therefore its performance was characterized using the simulated beam extraction method described by Brophy in [5]. The discharge plasma properties, i.e. the plasma density and the electron temperature, and their spatial distribution have also been assessed with a series of Langmuir Probe (LP) measurements.

For what concerns the numerical simulations, a 2D axisymmetric model of the DC is currently under development. The model is largely based on what proposed by Wirz in [6]. Once validated against the experimental results, the model will be used as an optimization tool to identify possible modifications to the DC configuration that would result in an improvement of the overall performance.

The RCDC design and the experimental apparatus are described in section II of this paper, whereas some key results from the experimental investigation are discussed in section III. A general description of the 2D model is given in section IV together with a comparison of the preliminary results, while section V summarizes the current performances and presents concluding remarks and future work.

II. Ring Cusp Discharge Chamber Design

The historic reason for the development of a “ring cusp” magnetic field was the need to reduce the ion production cost in the DC. The first experimental study describing the effort to optimize a RCDC configuration is reported in 1982 by J. Sovey [7]. Most of this investigation was carried out without ion beam extraction. The optics were replaced by a single stainless steel grid and the ion beam current was measured with three planar probes that were mounted along the grid radius to monitor the radial current distribution. The underlying assumption in this work was that the DC performance trends would not be affected significantly by the extraction of an ion beam. Efforts to develop the RCDCs continued throughout the following decade and are probably best represented by the study by Beattie and Matossian in [8], which illustrated the performance optimization of a mercury ring cusp ion thruster starting from Sovey’s initial design and investigating seven different magnetic configurations. These two studies laid the foundation for the development of modern ring cusp technology, including the NSTAR [9], XIPS [10] [11] [12], NEXT [13] [14] [15] and NEXIS [16] [17] thrusters.

A. Design of Mars Space Limited Ring Cusp Discharge Chamber 1 (MSL_RCDC1)

The design of MSL RCDC1 started at the beginning of 2016. Three main requirements drove the DC design:

- Sizing DC requirements to achieve an ion cost production below 160eV/ion for an extracted ion beam current between 1 and 4A.
- Have modularity to explore and optimize the DC configuration.
- Characterization of DC performances without beam extraction in MSL propulsion laboratory.

Based on the information available in the literature, it was decided to set the grid extraction diameter to 30 cm. At 4 A of ion beam current this results in an average extraction current density of about 5.6 mA/cm², hence in line with the figure found for the XIPS 25 thruster when operated at 3 A (6 mA/cm²) [11]. The radius of the DC was made larger than the grid extraction to add a masking area around the active grid diameter.

The number of magnets is similar to the T6RC thruster [18]. Three magnet rings are positioned along the straight part of the DC and one on the bottom part around the DC hollow cathode.

To help the modularity design, a fully cylindrical geometry has been selected. The modularity of the DC is designed by allow moving ring cusp strength and position, cathode position Figure II-1.

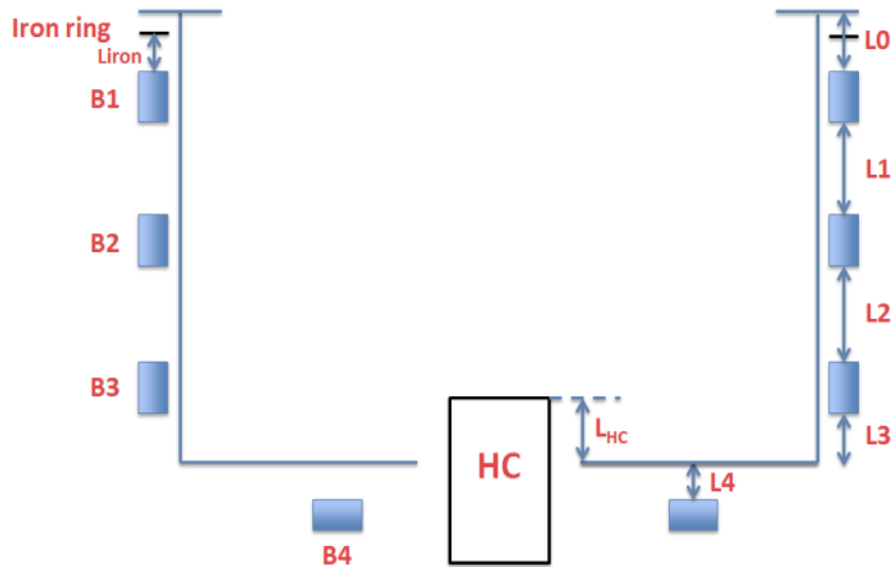


Figure II-1 DC chamber modularity

An initial magnetic field topology of the DC was designed to have a last closed contour value between 50 and 60G. An iron ring is placed at the exit of the DC close to the downstream magnet ring to “pull” the magnetic field lines away from the DC at this exit plane.

Figure II-2 shows the initial magnetic field topology with the HC magnet ring placed as close as possible to the DC upstream wall.

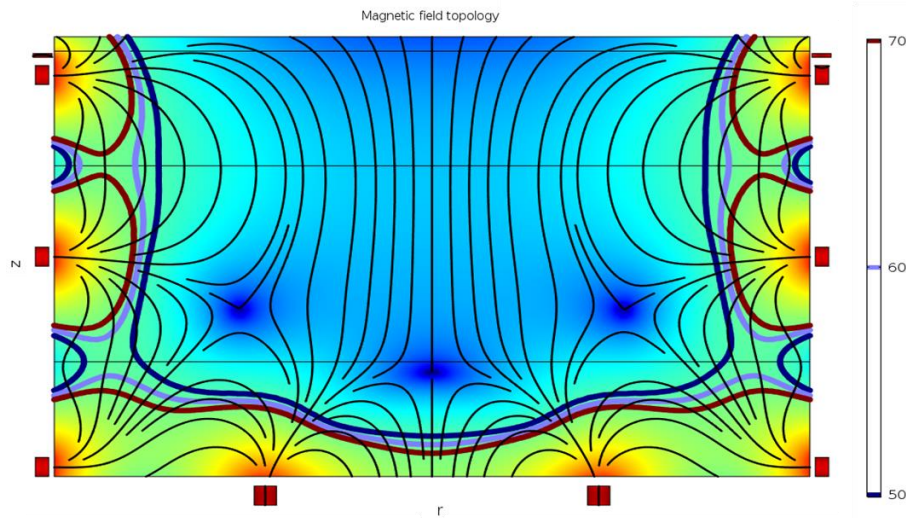


Figure II-2 Initial magnetic field topology

Finally, the ions optic is designed with holes distributed in a hexagonal pattern with a center to center distance of 2.45 mm. The grids are manufactured using photoetching. The accel grid has a thickness of 1.4mm and an aperture diameter of 1.6 mm diameter. The screen grid has a thickness of 0.3 mm and an aperture diameter of 2 mm resulting in a geometrical transparency of 0.8. The grids are spaced using alumina spacers to a distance of 1 mm.

The hollow cathode is connected to the DC via an alumina flange to avoid shorting. Three keeper orifice positions can be selected relative to the upstream wall (0, 25 and 50mm). It is a LaB6 cathode with Mars Space heater technology and a cathode orifice diameter of 2 mm.

A 0D model was developed in MSL based on Goebel and Katz [3] description. It has been used to evaluate the discharge curves performance of the designed RCDC for the ion beam requirement. Figure II-3 is the ion cost production as a function of the mass utilization efficiency (discharge curves) of the pre-sizing design for a discharge voltage of 25V and a cathode potential at 10V. The discharge curves follow the common trends of the ion cost as a function of the mass utilization efficiency. From these curves, the 0D confirm that the proposed design is able to achieve the desired performances (below 160eV/ion from 1 to 4A beam current) for a reasonable mass utilization efficiency (90%).

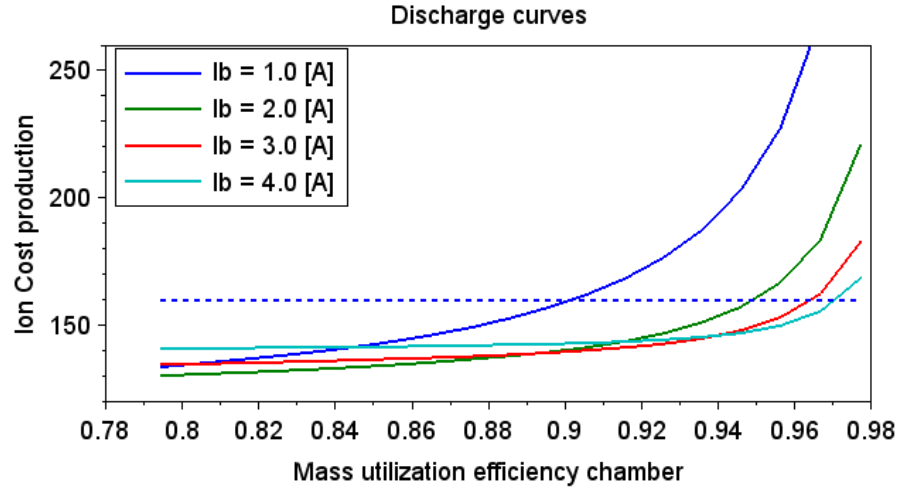


Figure II-3 Discharge curves performances estimated with 0D model

With the results provided by the 0D model and modularity of the designed DC to optimize efficiency, the RCDC has been manufactured and assembled to make experimental campaign characterization and performances measurement, Figure II-4.

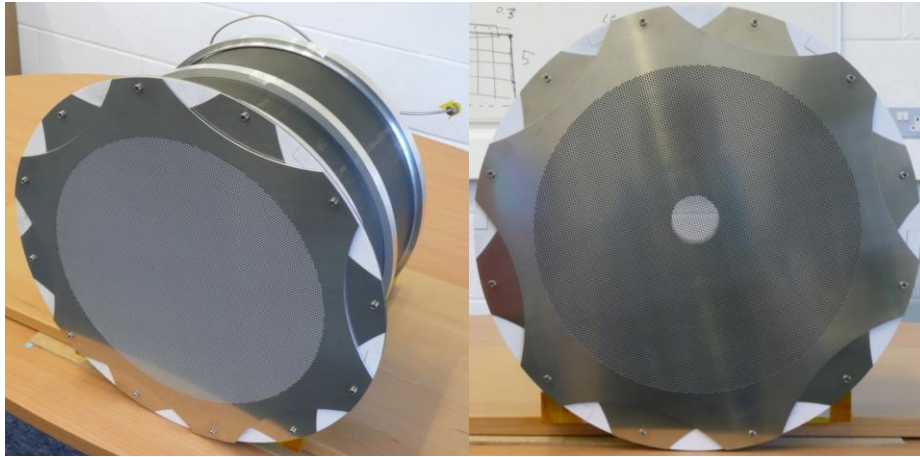


Figure II-4 assembled RCDC

B. Experimental Setup, Simulated Ion thruster and probes measurement

1. Vacuum Facility

The experimental test campaign was carried out in Mars Space Limited Propulsion Laboratory in Vacuum Chamber 2, shown in Figure II-5. The vacuum chamber is provided with a pumping system composed of the following parts:

A Low Vacuum Pumping System which consists of an Edwards 35 m³/h scroll pump, used to bring the chamber pressure down to 5×10^{-2} mbar. This pump is also used as backing pump for the High Vacuum Pumping System.

A recently upgraded High Vacuum Pumping System which includes a turbo-molecular pumping system, which can bring the chamber base pressure below $7 \cdot 10^{-7}$ mbar. It consists of two Edwards STP-iXA4506C, each one with a pumping speed of 4400 l/s of N₂. An effective xenon pumping speed of about 6500l/s is obtained.

It should be noted that the DC is designed to run in simulated ion beam mode, no neutralization of the beam is necessary and the mass flow rate injected through the DC is reduced and allows to use this facility. Ingested gas from the background pressure is evaluated at 10% of the total mass flow rate injected through the DC during the experiment [3].

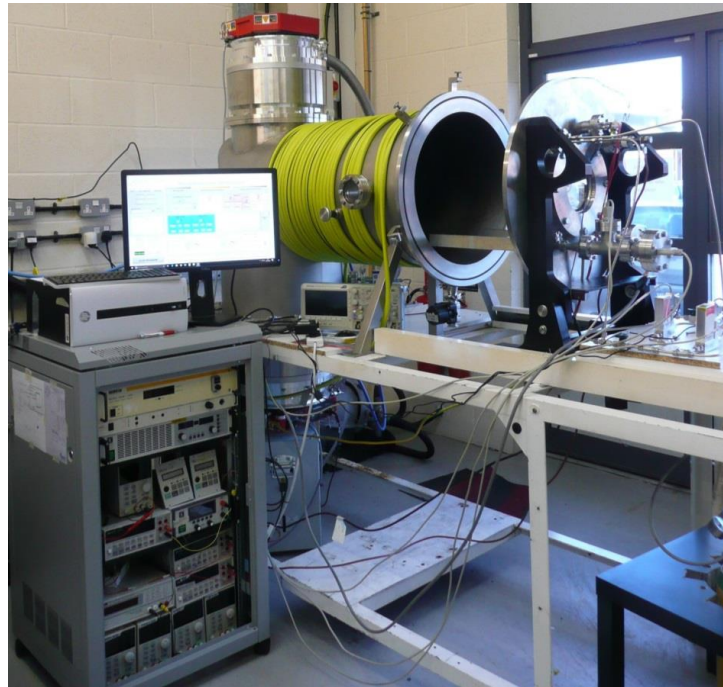


Figure II-5 – MSLC-2 vacuum chamber with the GSE in MSL propulsion laboratory

2. Electrical discharge chamber setup without beam extraction

The electrical scheme of the DC is presented in Figure II-6, it is the same used by Brophy in [5]. This scheme allows to operate without ion beam extraction and by measurement of the ion current grids collection and through the engine bias supply to estimate the expected performances with beam extraction.

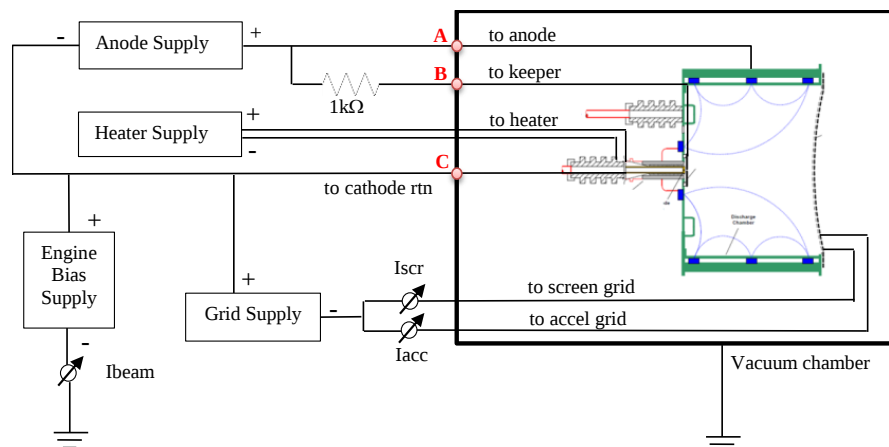


Figure II-6 – Electrical DC scheme without beam extraction

The DC body is electrically isolated from the vacuum chamber, which is connected to facility mains ground. The anode and the hollow cathode are connected to the anode supply. The cathode keeper is connected to the anode via a 1kOhm resistor. The cathode heater is floating and powered by a dedicated heater supply. The screen grid and the accel grid are connected to a grid supply that can be used to repel electrons allowing the measurement of the ion current they collect.

The cathode (negative of the anode supply) is connected to an “engine bias” supply used to bias the engine to 20V positive with respect to ground. This is made in line with what reported in [5] to avoid the escape of electrons from the DC volume. There will still be a residual ion beam leaving the DC generating that is expected to be less than 50mA.

All voltages are read from DMMs independently of power supplies apart from the keeper voltage which is read across the B terminal and ground using an oscilloscope and a differential low voltage probe reading the anode voltage noise between A and C. The anode current is read from the PS whereas the residual ion beam, screen and accel grids currents are read using DMMs.

All the DC control command and data acquisition are done using a LabVIEW program which communicates to the DMMs, oscilloscope and power supplies using either USB or RS323 connections.

3. Simulated ion thruster operation without beam extraction

The simulated ion thruster procedure is described by Brophy in [5]. Ion thruster operation without beam extraction results in decreasing ions optics transparency that induces two important modifications.

- Many more ions recombine on the grids and more neutral atoms re-enter in the DC. Then to simulate the discharge conditions with beam extraction, the propellant flow rate into the chamber must be reduced accordingly.
- A larger ion current is collected on the grids. Hence, to simulate the discharge current conditions with beam extraction, the simulated ion beam should be subtracted from the discharge current without beam.

To estimate ion beam I_B with beam extraction, the total ions current I_{tot} reaching the grid plane and leaving the DC is measured.

$$I_{tot} = \alpha \hat{I}_{scr} + \hat{I}_{acc} + \hat{I}_{Beam_dc}$$

where $\hat{I}_{scr}$ is the ion current collected by the screen grid, $\hat{I}_{acc}$ is the ion current collected by the accel grid and $\hat{I}_{Beam_dc}$ is the residual ion beam produce in DC only mode, it should be note that the residual ion beam is negligible to compare of the other. The coefficient α is used to take in count the masking area surface on the screen grid area. The current collected by the masking area does not contribute to the ion beam. The results given below are presented with $\alpha = 1$, considering the collected current one the masking part is negligible to compare with the current collect on the active grid region. From the total ions current collected, the simulated ion beam is deduced from the ion optics transparency T_{beam} with beam extraction. In our case, the value of T_{beam} is obtained from FFX simulations [19].

$$I_B = I_{tot} T_{beam}$$

Then the simulated discharge current I_d is deduced by from conservation of the discharge current without beam extraction $\hat{I}_D$

$$\hat{I}_D = I_e + \hat{I}_{scr} + \hat{I}_{acc}$$

where I_e is the electron current from the cathode. Without beam extraction, the collected current on the grid $\hat{I}_{scr}$ and $\hat{I}_{acc}$ are equal to current collected to screen grid and the ion beam I_B with beam extraction as

$$\hat{I}_{scr} + \hat{I}_{acc} \approx \hat{I}_{scr} + \hat{I}_{acc} + \hat{I}_{Beam_dc} = I_{scr} + I_{acc} + I_B \approx I_{scr} + I_B$$

Then, the simulated discharge current I_D is deduced as

$$I_D = I_e + I_{scr} \leftrightarrow I_D = \hat{I}_D - I_B$$

Then equivalent discharge cost in beam on mode can be calculated as

$$\varepsilon_b = \frac{I_D V_D}{I_B} = \frac{(\hat{I}_D - I_B) V_D}{I_B}$$

The simulated total mass flow rate $\dot{m}_{beam}$ is deduced as:

$$\dot{m}_{beam} = \frac{\dot{m}_{dc}}{1 - \eta_p \left(1 - \frac{T_{dc}}{T_{beam}}\right)}$$

where $\dot{m}_{dc}$ is the reduced total mass flow rate in discharge only mode, η_p is the mass utilization efficiency and T_{dc} is the grid transparency in discharge only mode. It should be noted that $\dot{m}_{dc}$ takes into account the ingested flow from the background pressure of the vacuum chamber. The mass utilization efficiency can be calculated as:

$$\eta_p = \frac{I_B}{q \frac{\dot{m}_{dc}}{M_i} + I_B \left(1 - \frac{T_{dc}}{T_{beam}}\right)}$$

And grid transparency in discharge only mode can instead be calculated experimentally by measuring the ion currents reaching the grid plane as:

$$T_{dc} = \frac{\hat{I}_{Beam_dc} + \hat{I}_{acc}\gamma}{\hat{I}_{Beam_dc} + \hat{I}_{scr} + \hat{I}_{acc}}$$

where γ is the ratio of ions impacting on the accel grid that leaves the grids as neutrals, here γ is defined at 0.55 as described in [5].

4. Probes measurement

In addition to the telemetry from the electrical and fluidic setup, two further types of probes have been used to monitor behavior and performance of the RCDC: thermocouples and Langmuir probes.

As shown in Figure II-7, thermocouples were installed all along the discharge chamber sidewall and backplate, alternatively on the magnet ring support or in the space between rings. The electric signals from the thermocouples were also recorded by a LabView® routine via a dedicated acquisition card.

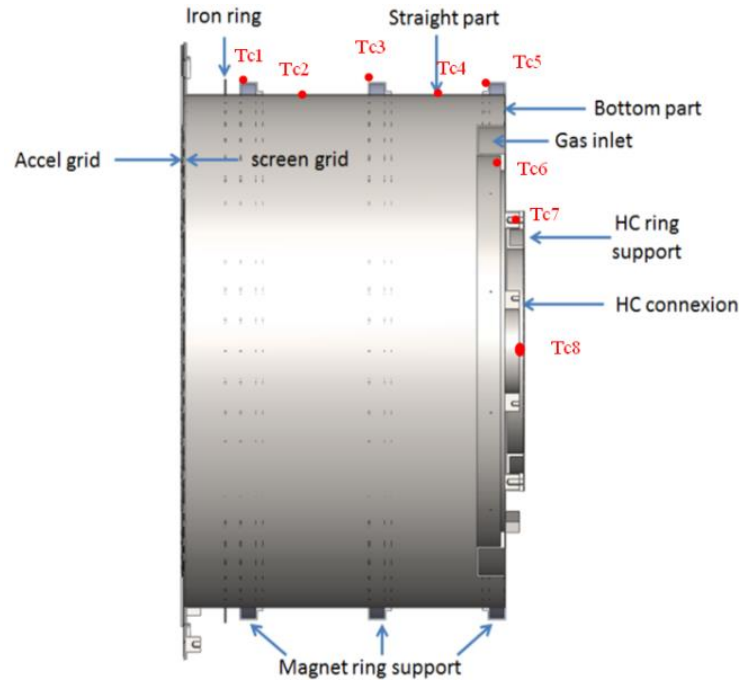


Figure II-7 - Thermocouples location

A single cylindrical LP is used inside the DC to measure plasma properties as close as possible to the grid plane. The LP consists of a 0.125 mm diameter tungsten wire that is exposed to the plasma for a length of 1.25 mm and then runs inside a thin L-shaped alumina. The Langmuir probe is connected to a motorized rotation stage located behind the thruster that allows to change the probe angular position inside the discharge chamber. As shown in Figure II-8, the probe's axis of rotation is off the thruster axis, such that the possible scan radius will move from engine periphery to engine periphery via the central hole (note that when performing a Langmuir probe voltage scan the probe position is fixed). In order to minimize any gas leak, the alumina tube is inserted into the chamber through another short alumina tube fixed to the DC bottom part.

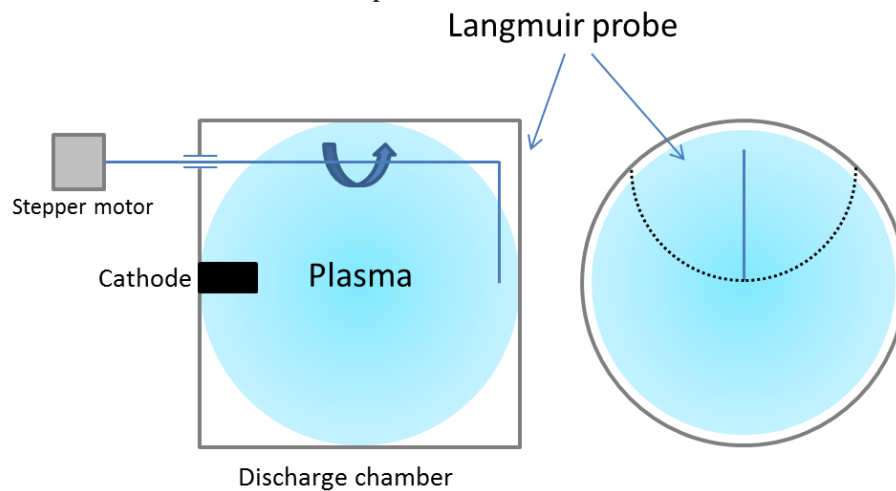


Figure II-8 – Langmuir probe setup

During a measurement, the LP is biased with respect to cathode potential using a dedicated power supply and the current collected by the probe is measured by a DMM. The bias voltage is swept from cathode potential to few volts above the discharge voltage to measure the probe I-V characteristic, from which the electron energy distribution

function and ultimately, using the Druyvesteyn technique [20], the electron temperature and plasma density can be calculated.

The rotation stage motor, the probe bias voltage and the DMM current measurement with the DMM are controlled by a LabView® routine to produce an automated measurement system.

III. Characterizations of Mars Space Limited Ring Cusp Discharge Chamber

The experimental campaign started at the end of 2016. The modularity of the MSL RCDC1 allows characterizing different configurations and then optimizing a RCDC in respect of ion thruster performances, thermal behavior and plasma properties. As of September 2017, 20 configurations have been thermally and electrically characterized and 5 configurations have been characterized using the LP.

Each RCDC configuration has been characterized in a range of operating conditions defined by the cathode mass flow rate, the main mass flow rate and the discharge current. It should be noted that the DC operates in discharge current $\hat{I}_D$ control from the anode supply. Figure III-1 shows the RCDC MSL1 in operation with xenon in MSL propulsion laboratory.



Figure III-1 RCDC MSL1 in operation with xenon at Mars Space Ltd propulsion laboratory

The data acquisition of the electrical performances generates an important number of information allowing to optimize chamber configuration and operating conditions. The presented results give the general observed trends and results obtain with the MSL RCDC1 during test campaign. The main mass flow rate (MFR) on graph is the actual flow rate used without beam extraction $\dot{m}_{dc}$ and the mass utilization efficiency η_p is the one that we should be have with beam extraction.

A. Experimental optimization

Major component providing the performances of a RCDC is the magnetic field topology. It allows to distribute primaries (electron emitted from the cathode) in the DC and reducing losses to the wall (confinement). For what concerns the primaries, they are highly energetic and magnetize, the magnetic streamline defined their distribution inside the discharge chamber. For the plasma, the ambipolar diffusion is strongly correlated to the magnetic field topology and strength.

1. Magnet position

The first example of topology effect is about the magnet position. For both configuration the operating conditions are similar, the thermal equilibrium is reached after more than 1.5 hours. Only the magnet B3 (see Figure II-1) position is changed of 2cm. This modification allows changing the magnetic line close the B3 cusp and eliminating these to cross the gas distributor wall inside the discharge chamber. Figure III-2 is the recorded

temperature on thermocouple number 6 placed on the bottom part of the DC. The temperature recorded by moving the magnetic line from the gas distributor is lower than 30deg Celsius in the configuration 2. The reduction of the temperature indicates that less flux is flowing on this wall and then less loss.

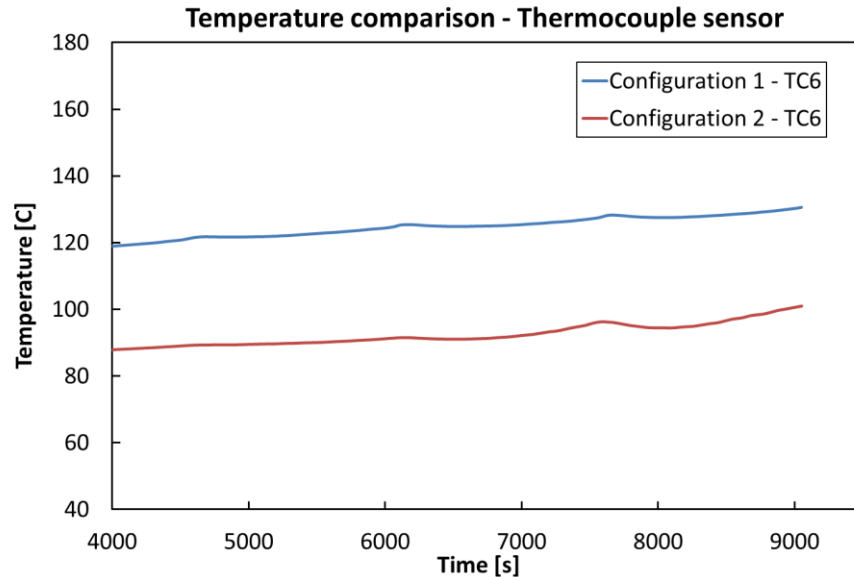


Figure III-2 Temperature measurement on TC6 – Comparison between 2 magnet positions

Then from ion thruster performances comparison, the simulated ion beam current for each configuration recorded at the same time is much improved in configuration 2 as shown in

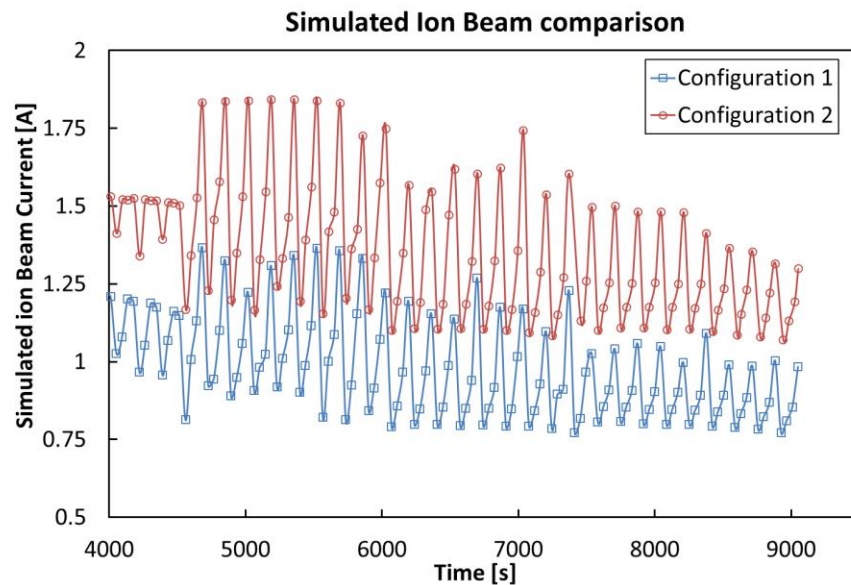


Figure III-3. In this case, the modification of the magnetic line shape allows to improve the discharge efficient to ionized and then extract more ion beam. It should be noted that the oscillation shown in Figure III-3 is due to the sweeping of the cathode, main mass flow rate and discharge current control.

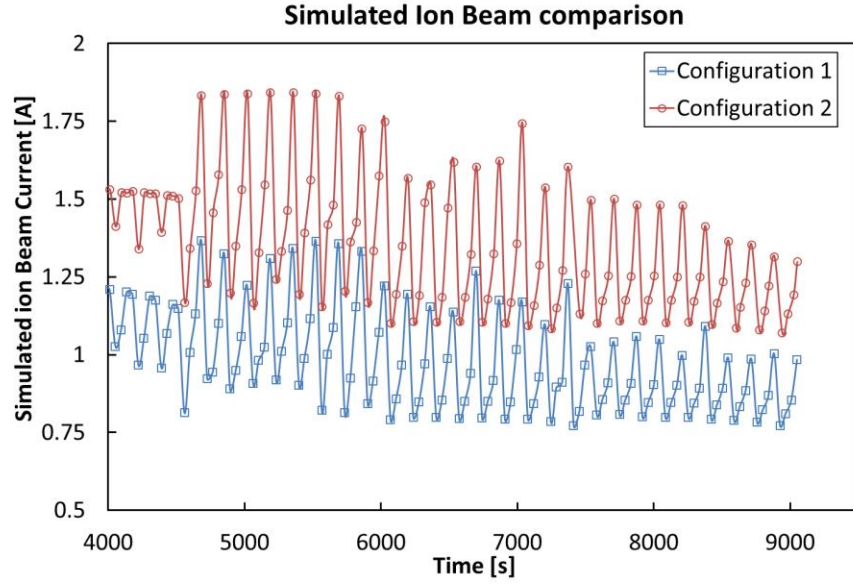


Figure III-3 Simulated ion beam measurement – Comparison between configuration 1 & 2

2. Cathode positions

The second example of the parametric study is realized by changing the cathode position along the z-axis inside the DC. Figure III-4 presents the three positions characterized for a given magnetic field. It should be noted that changing the cathode position is the DC corresponds by changing the location of the primaries injection.

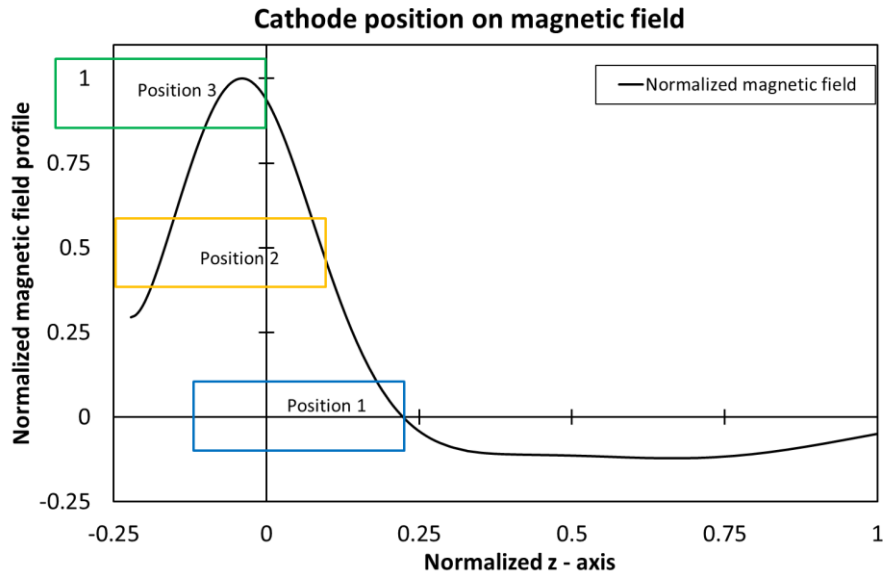


Figure III-4 Cathode position along the magnetic field on the discharge chamber axis

Figure III-5 shows the simulated ion beam current for the three cathode positions. The simulated ion beam is much improved in the position 1 and 2 to compare with the position 3. The discharge voltage between each configuration, not shown, is lower than 1V and is not the first responsible for the lower ion beam in position 3. As described above the modification of the primaries injection location influences their distribution inside the DC. The position 1 injected primaries nearly a null magnetic point that means the primaries are randomly injected in the DC and the cathode orifice is worst confined for the bulk plasma. The cathode position 2 and 3 is better to inject magnetized primaries, allows well distribute through the magnetic line and the cathode orifice is placed above the

last close contour, well confine from the bulk plasma. The smaller performances of the position three to compare with the second might be due to the uncertainty of the location of the magnetic field maximum relative to the cathode orifice.

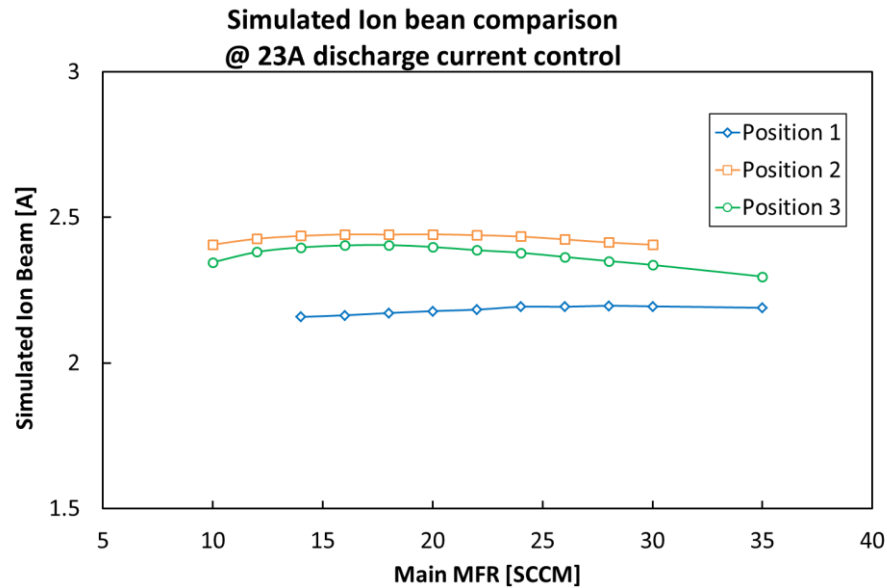


Figure III-5 Simulated ion beam measurement comparison for 3 cathode positions

3. Magnetic field profile along axis

The third example is the influence of the magnetic field profile along the z-axis of the DC chamber. This modification is realized by changing the HC magnet radius and position. The profile 1 is the original magnetic field with a null point along the axis and the second profile remove the null point along and keep a decreasing magnetic field from the cathode exit to the exit. In both profile, the cathode orifice is above the last closed contour.

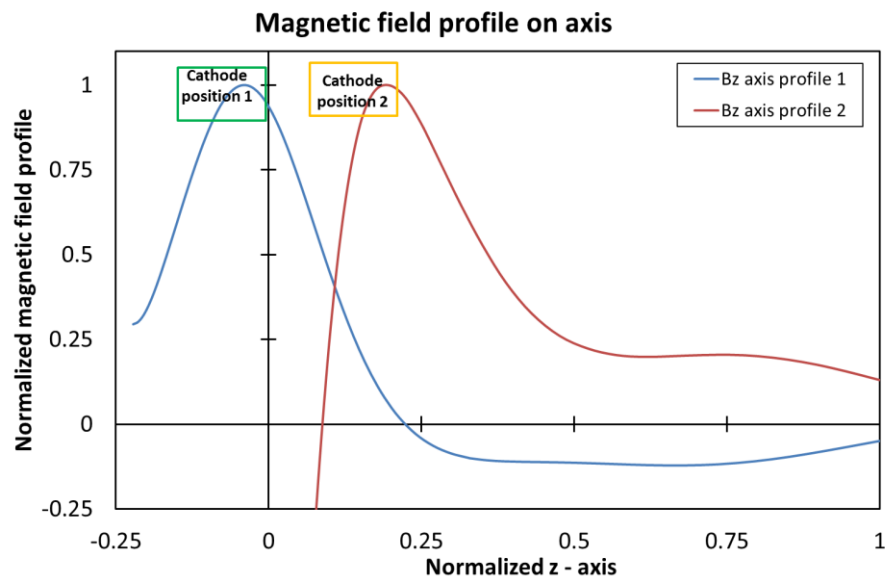


Figure III-6 Magnetic field profile along z axis

Figure III-7 is the comparison of simulated beam current for both profiles. The beam current for the profile 2 is much higher than profile 1. The profile 2 allows to well distribute primaries through the entire streamline without random trajectories by crossing a null magnetic point.

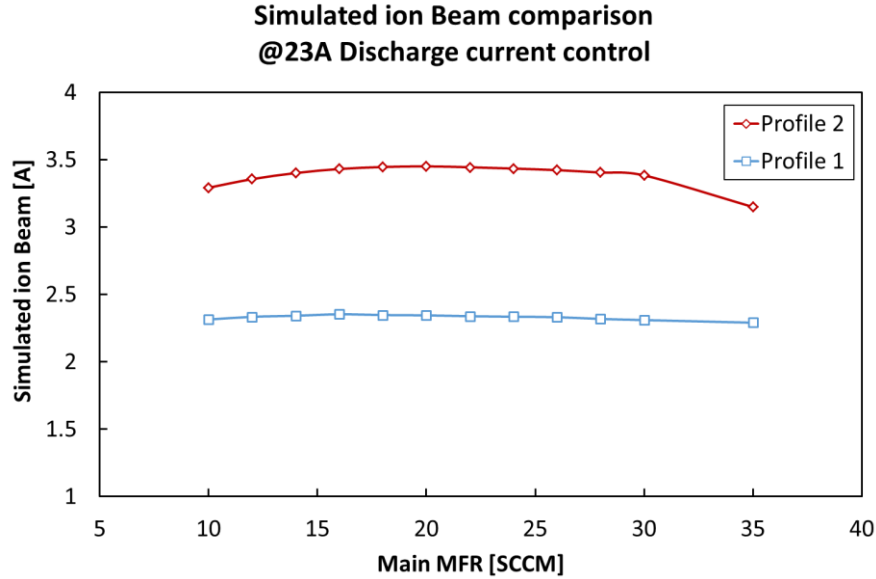


Figure III-7 Simulated ion beam comparison for two different magnetic fields along axis

The discharge voltage difference, no show, is about 3V higher for the profile 2. By balancing the gain in beam current and the highest discharge voltage the discharge curves of the RCDC are strongly improve by this modification, see Figure III-8. The simulated ion cost production for the profile 2 is at the expected level for the discharge chamber (160eV/ion). The results providing by this modification are in accord with design rules providing by D. Goebel and R. Wirz in [21]. From the cathode to the grid, the magnetic field on the axis should be monotonically decreasing.

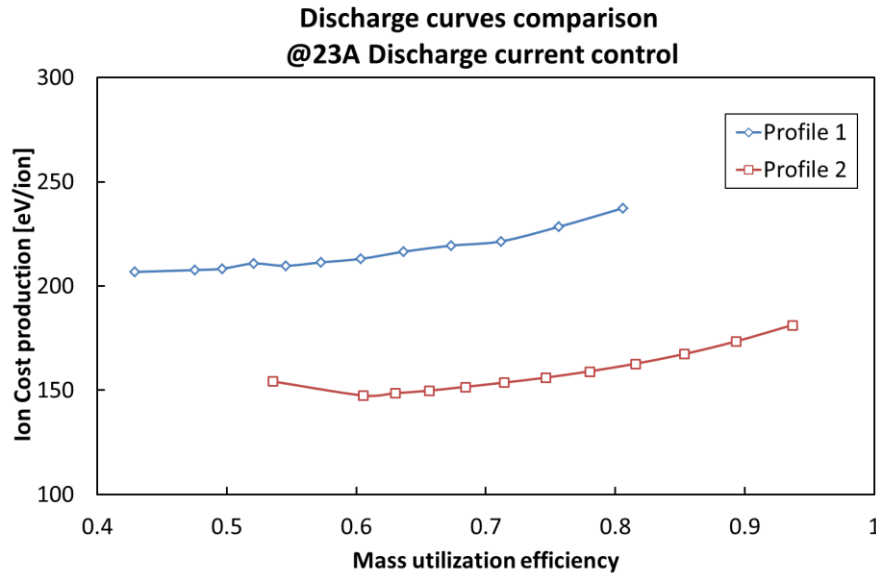


Figure III-8 Discharge curves comparison for two different magnetic fields along the axis

4. Magnet strength

The next example of RCDC design optimization is realized by changing the magnet strength. The compared performances are realized with three different configurations. The denomination of the configuration is realized with “1” for the simple layer and “2” for a double layer of magnet inducing a twice strength to compare with the simple layer. The magnet position and operating conditions are similar. Figure III-9 is the simulated ion beam comparison for three configurations. The configuration 1222 record less ion beam regardless of the other configurations. One of the reasons for this difference is induced by the lower discharge voltage Figure III-10 and then the primaries have less energy to ionize neutral atoms.

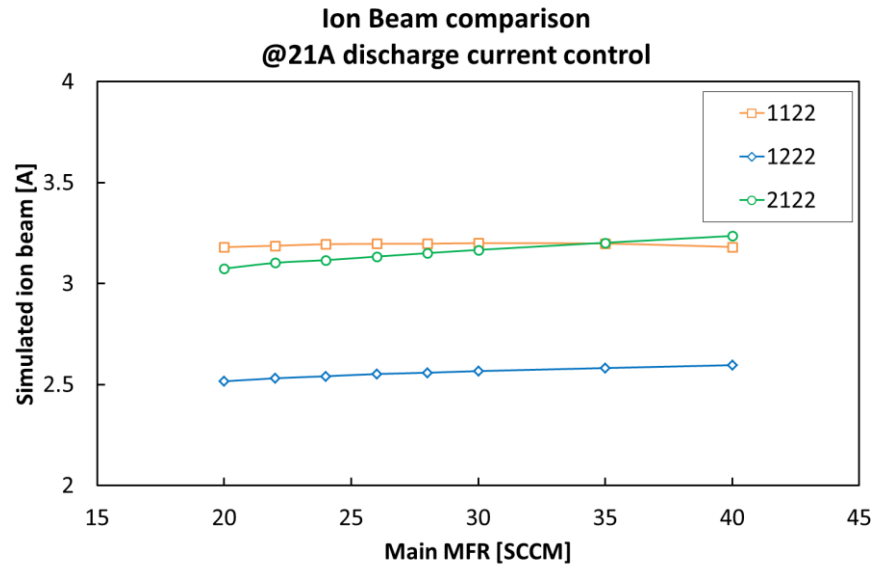


Figure III-9 Simulated ion beam measurement comparison for 3 magnet configurations

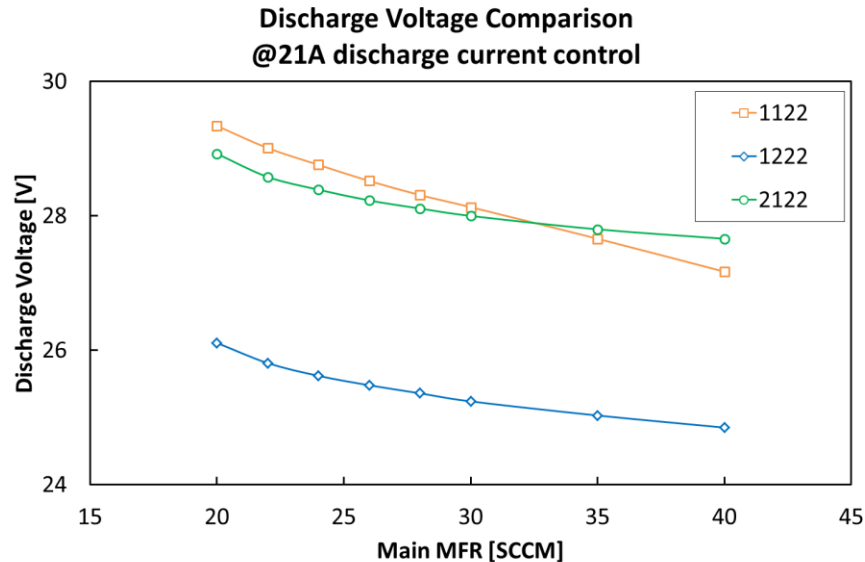


Figure III-10 Discharge voltage measurement comparison for 3 magnet configuration

The modifications of the magnet strength change the last closed contour shape, value and then modified the confinement volume of the plasma inside the discharge chamber. The lower voltage needed to sustain a plasma discharge in 1222 is lower and then the ionization is lower. Discharge curves performances for these three

configurations are shown Figure III-11. Regardless a lower discharge voltage, the discharge curve of configuration 1222 is above the other configurations which present an efficient ion cost production.

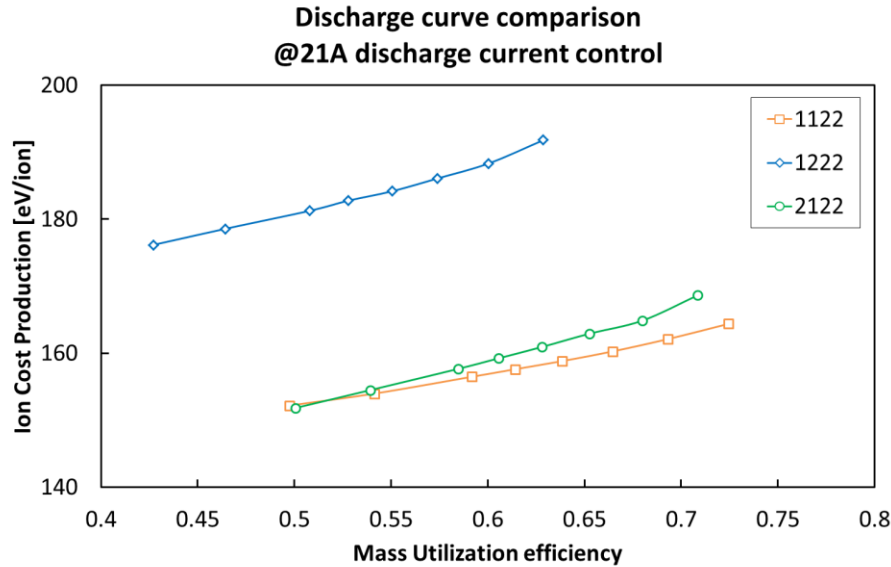


Figure III-11 Estimated discharge curves performances comparison for 3 magnet configurations

5. Discharge Volume

The last example of parametric RCDC is realized by changing the discharge volume itself with a longer length. The volume 1 and 2 corresponds to respectively a length of 23 and 30cm. Figure III-12 is the discharge voltage comparison at similar conditions. The temperature recorded on each magnet for the volume 2 is recorded 20% lower than the volume 1 and the temperature between each magnet is similar (less of 5% difference). That means the flux going to the anode in volume 2 is lower than volume 1 and the plasma is more confined in volume 2.

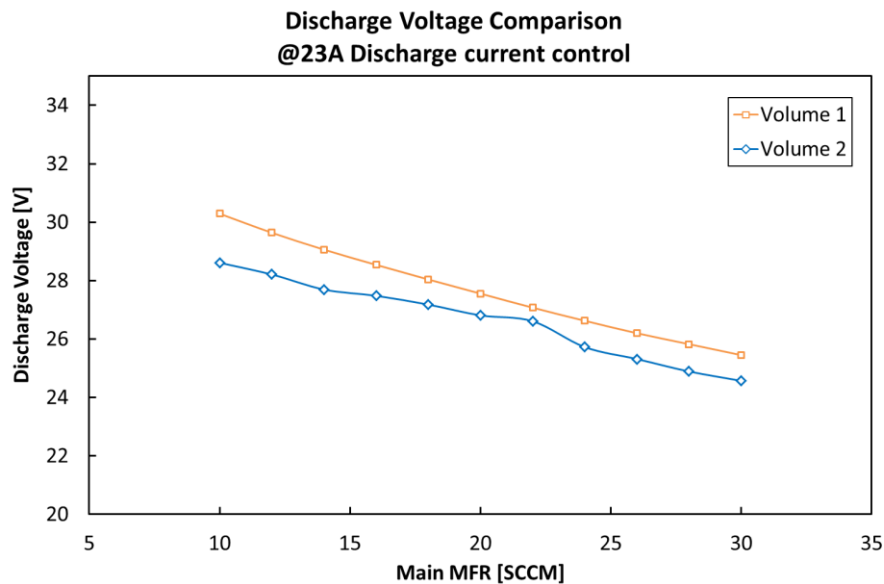


Figure III-12 Discharge voltage comparison for 2 discharge chamber volumes

Figure III-13 is the simulated ion beam comparison between each volume. The ion beam for the volume 1 is highest of 4% at similar operating conditions and finally, the discharge curves performances show Figure III-14 present a relative difference of 3%.

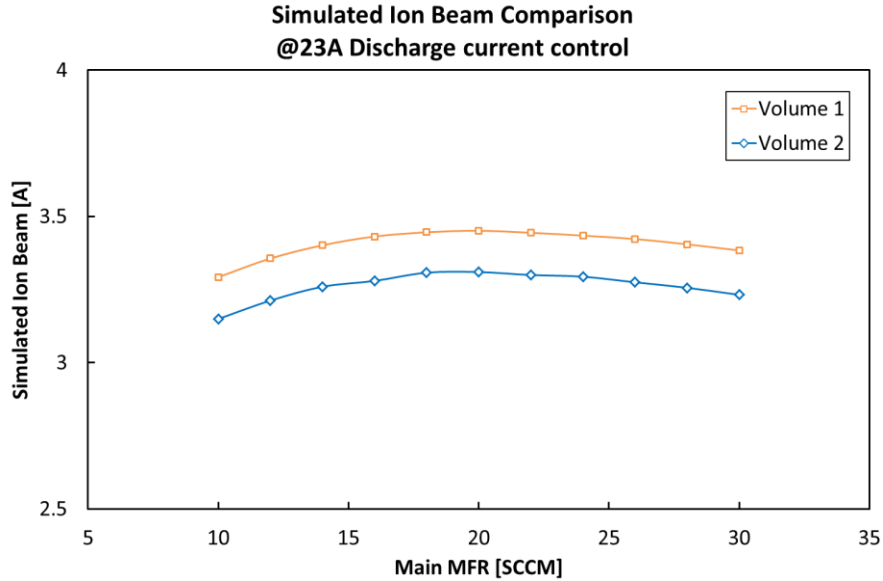


Figure III-13 Simulated ion beam measurement comparison for 2 discharge chamber volumes

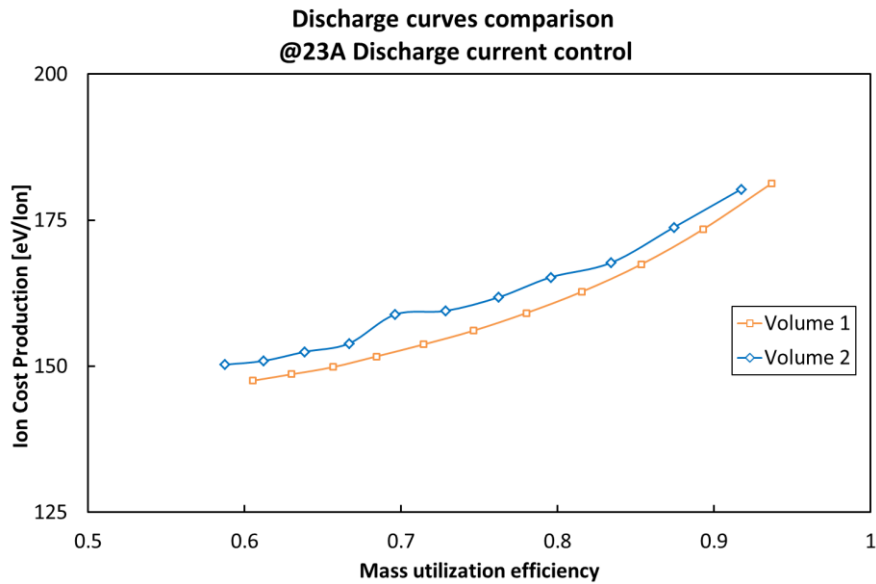


Figure III-14 Estimated discharge curves performances comparison for 2 discharge chamber volumes

These first comparative trends between discharge volumes are the preliminary result. Further magnetic field topologies would be tested by increasing the effective discharge volume and an enough last close contour to confined plasma.

B. Langmuir probe measurements

For ion thrusters, the uniformity of the plasma at the grid exits is an important parameter for ions optics design and performances. The Langmuir probe setup described in II-4 is used to characterize different plasma properties.

Figure III-15 shows the Langmuir probe inside the DC during an acquisition. In the following part, the plasma density measurements are compared as a function of the mass flow rate and function of the magnetic field. The presented data are estimated from I-V post-processed by using Druyvesten technique [20].

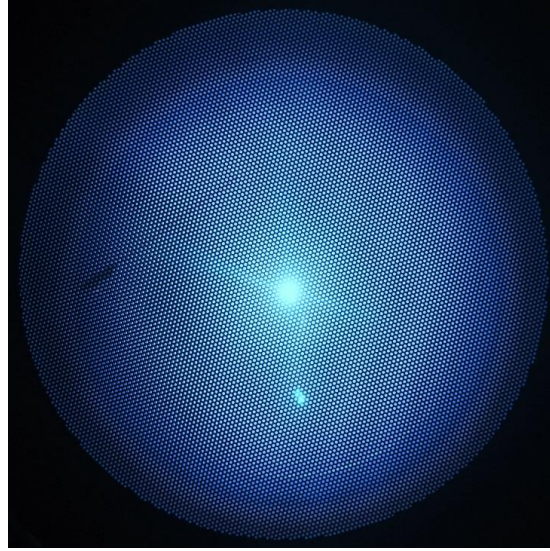


Figure III-15 – Langmuir probe in the discharge chamber

1. Comparison with mass flow rate

The first comparison shows in Figure III-16 is realized between 3 different mass flow rate operating conditions through the main and the cathode. The higher plasma density is obtained for the lowest cathode mass flow rate and highest main mass flow rate. The lower plasma density is obtained for the highest mass flow rate in the cathode. Lower mass flow rate in the cathode allows to have more energy for the primaries and finally to ionize more the neutral atoms and obtain plasma density.

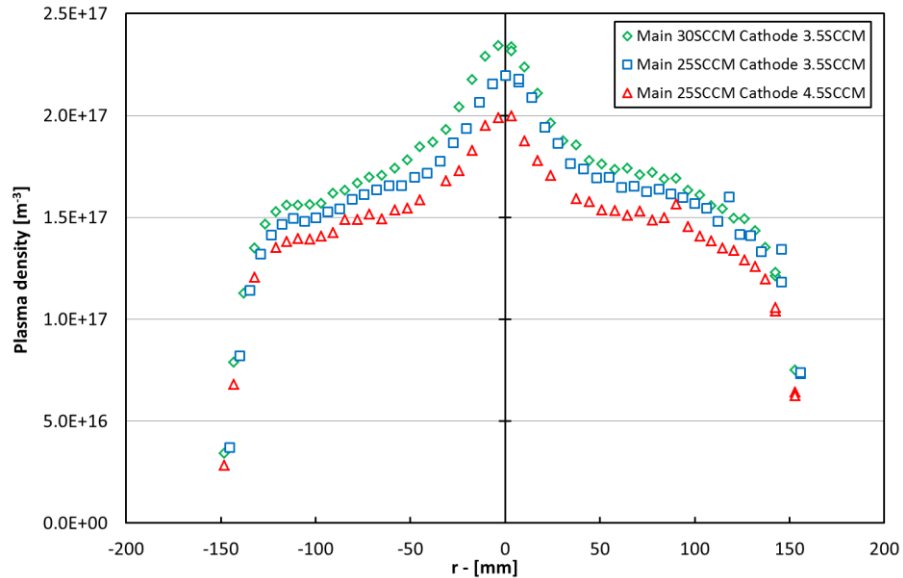


Figure III-16 Plasma density comparison – Langmuir probe measurement

These three profiles are normalized Figure III-17, their shape are strictly identical. It can be deduced that the mass flow rate is not responsible about the beam flatness on the first order. It should be noted that the plasma density drop

on the edge of the density profile. The proportion of the current flowing to the grid on the masking area is negligible to compare with the beam in active grid area.

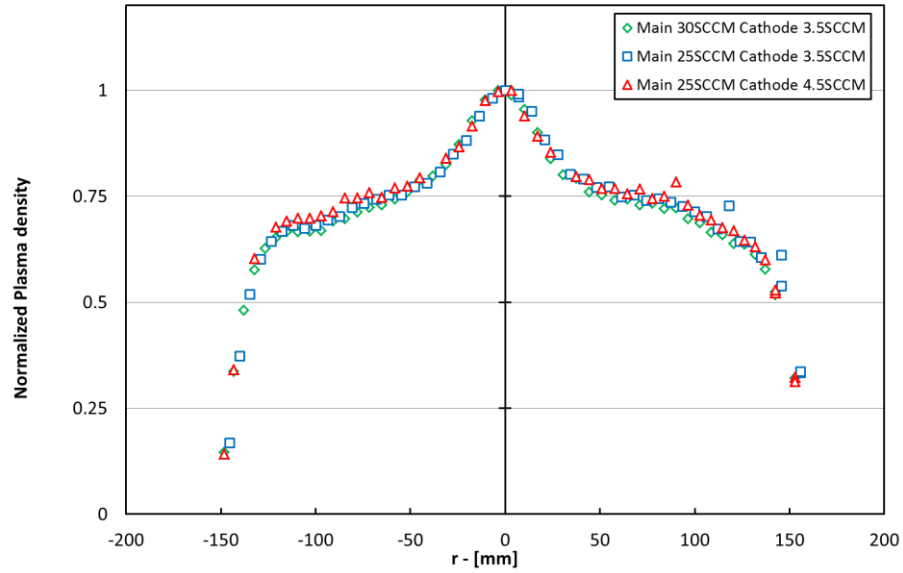


Figure III-17 Normalized Plasma density comparison – Langmuir probe measurement

2. Comparison with magnetic field

Figure III-18 presents comparison on normalized density profile for two different magnetic field profiles. The measurements are realized in the same operating conditions. The shape of the plasma density is different and the middle, magnetic field 2 present a center more peaked than magnetic field 1. Similarly to the previous comparisons, the plasma density drops to a negligible value at the masking area region. The beam flatness F_B ratio defined below, is respectively 0.38 and 0.44 for the magnetic field 1 and 2.

$$F_B = \frac{2\pi q \int_0^R n(r)u_B(r)rdr}{q\pi R^2[nu_B]_{max}}$$

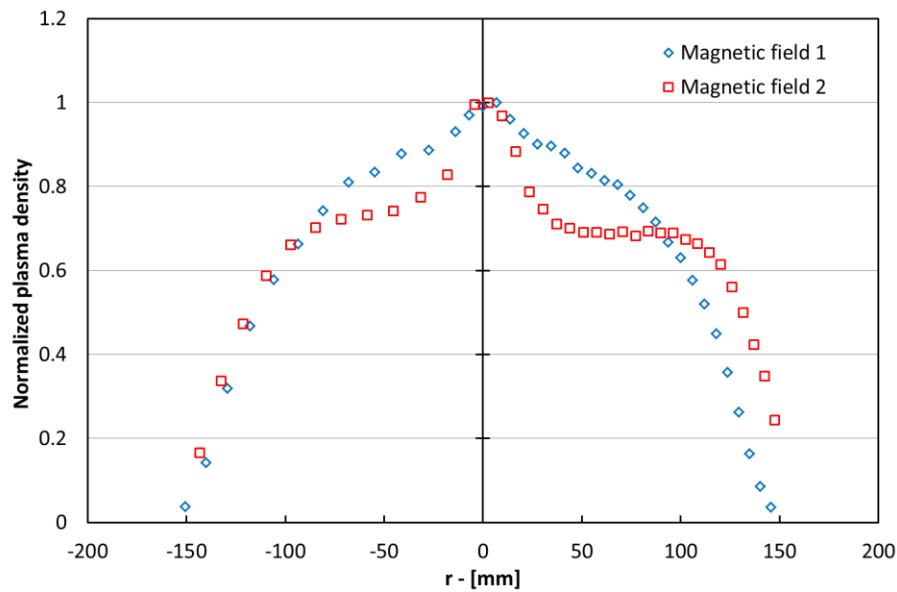


Figure III-18 Normalized plasma density comparison for two magnetic field

The difference of plasma density profile can be explained by the magnetic field on low order. The ambipolar diffusion of the plasma is strongly affected by the magnetic field topology. One of the important parameters is the diffusion coefficient ratio defined as $\frac{D_{||}}{D_{\perp}}$. The diffusion coefficient ratio is presented Figure III-19, the shape similarity with the plasma density measurement is important and confirm the magnetized ambipolar effect on the plasma distribution.

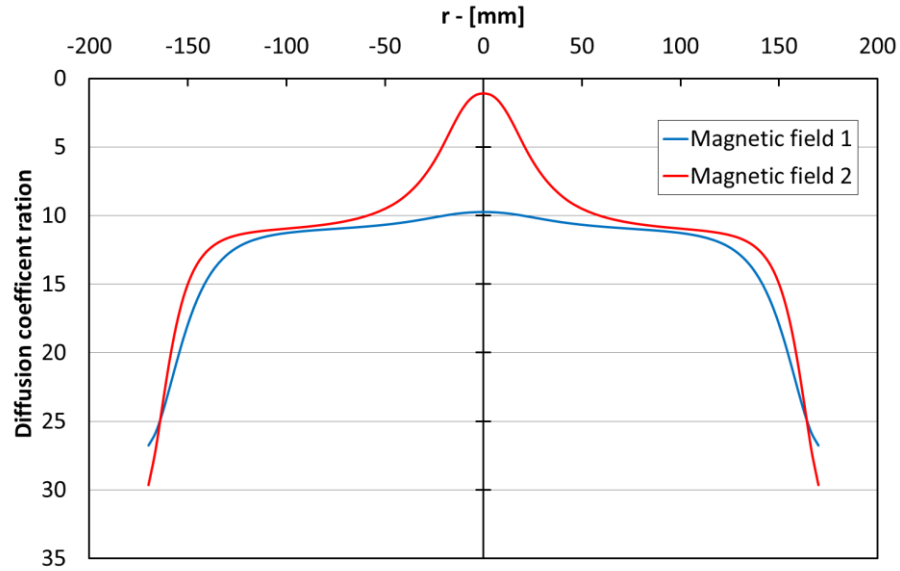


Figure III-19 Simulated diffusion coefficient ratio at discharge chamber exit

The experimental characterization and optimization of MSL RCDC1 is still ongoing as of the end of September 2017. An important part of the optimization realized on the RCDC was presented in this section. The best configuration found provides already good performances to achieve requirements Figure III-20. A simulated ion beam at 3.5A was recorded with an ion cost production 158eV/ion cost at 20A simulated discharge current. Recent measurement shows a simulated ion beam at 3.9A below 160eV/ion. Further measurements are ongoing to confirm and map the DC performances.

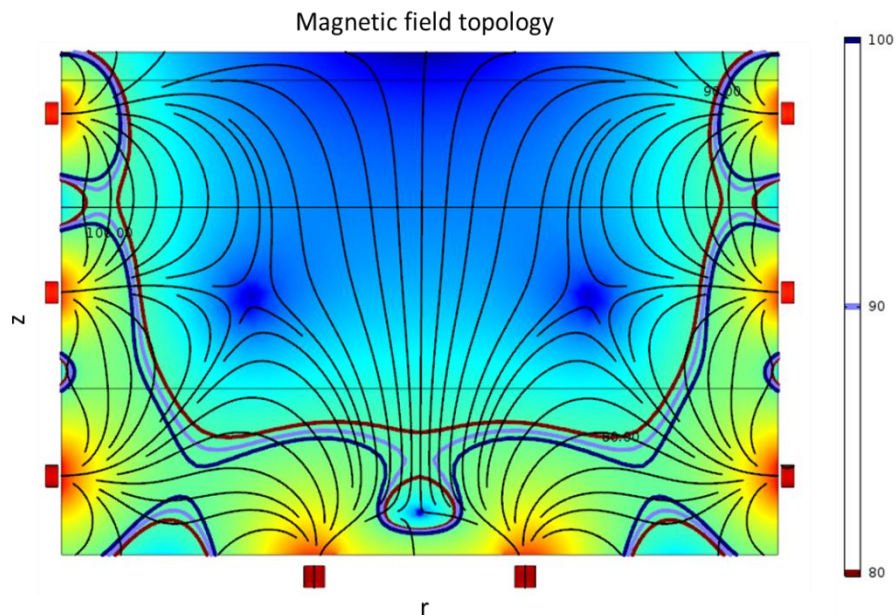


Figure III-20 Optimized magnetic topology end of September

From the initial configuration presented Figure II-2, general rules on magnetic topology design were established to optimize performances.

- The magnetic line should allow to a proper distribution of the primary in the DC
- The magnetic field profile on the axis should be monotonically decreasing from the cathode orifice to the grid.
- The last close contour should be sufficient to confine enough the plasma
- The magnetic field cross diffusion plays an important role for the plasma uniformity.

The 0D model wasn't able to capture these different effects on the discharge chamber performances, to design properly an RCDC from numerical tools, a model more sophisticated should be used.

Main [SCCM]	Cathode [SCCM]	V DC [V]	Equiv DC[A]	Ibeam [A]	Mass Efficiency	Ion cost [eV/ion]	Equiv MFR [SCCM]
20	2.5	28.1	19.5	3.5	75%	158	64
12	2.5	27.7	19.6	3.4	89%	162	52
35	2.5	24.8	19.6	3.4	56%	145	84

IV. 2D-axisymmetric model development of Ring Cusp Discharge Chamber

In parallel of experimental campaign, a 2D-axisymmetric model is developed in MSL. The model is based on the work proposed by R. Wirz [6]. The purpose of this discharge model is to have numerical tools to design an ion thruster in the future. The model is solved in the 2D axisymmetric structured-mesh domain and should capture more physics and design elements than the 0D. The model is developed in Matlab software. The overall model uses only elementary functions and loops. Figure IV-1 shows the general flow chart of the model. The objective of this part is to present an overview of the simulated physics and preliminary results of the discharge model.

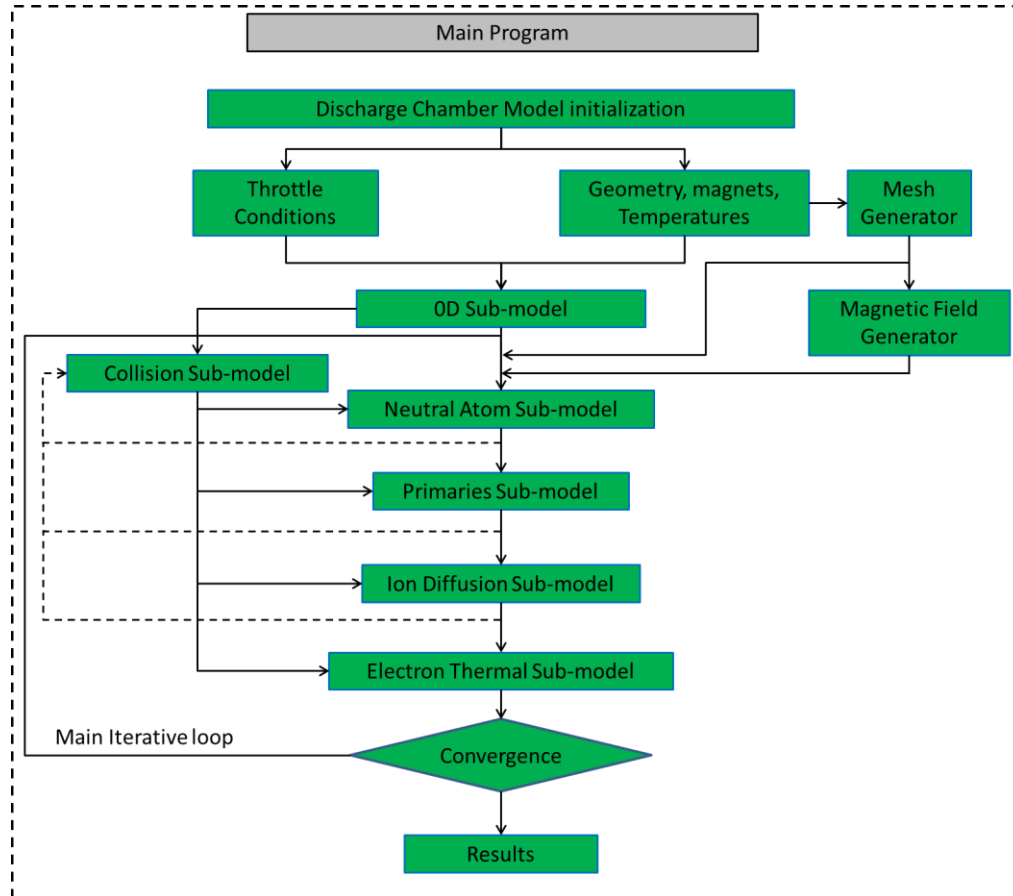


Figure IV-1 2D-Model general flow chart

A. General description

The 2D-axisymmetric model is organized in a main program, it loads and executes several sub-models in sequence. The model is initialized by defined throttle conditions, geometry, and magnetic field on the meshed domain. From these input data, the 0D model is used to initialize parameters at first iteration.

The model described four species inside the domain and electromagnetic fields of the discharge chamber. The four species described are the neutral, the primary electrons, the secondary electrons and the ions.

- The neutral are coming from the mass flow rate injected through the cathode, the main gas injection, the gas ingestion and the ion recombination on the walls. The gas used for the model is xenon and it is described at thermodynamic equilibrium.

- The primary electrons are coming from the hollow cathode, they are injected from cathode orifice. In the following description, the primary electrons are called “primaries”. They are described as full-magnetized and are heated by the plasma potential.
- The secondary electrons are the electrons of the plasma itself, they originate from the primaries ionization, excitation and thermalization and from plasma collisions. In the following description, the secondary electrons are called “secondaries”.
- The ions are coming from the plasma, they are created by ionization collisions between neutral and primaries or secondaries.

The plasma is described as quasi-neutral, Maxwellian, magnetized and the flux leaving the plasma is at the Bohm conditions. The sheath between the plasma boundary and the discharge wall is not solved. Through the different sub-models, the discharge chamber model solves the mass, current and energy conservations at steady state.

1. Collisions sub-model

The collision sub-model describes the collision processes between each species inside the DC. It determines rate coefficients, frequencies collisions and sources terms creation.

- The primaries are described mono-energetic, the rate coefficients for the primaries interaction with neutral atoms are estimated as follow,

$$K_{elp,excp,izp} = \langle \sigma_{el,exc,iz} v_p \rangle$$

where $\sigma_{el}, \sigma_{exc}, \sigma_{iz}$ are respectively the elastic, excitation and ionization cross sections and are function of primaries energy and v_p is the primaries velocity.

The primaries relaxation and thermalization times is defined as the residence time τ_{ep_slow} of the primaries before becoming secondaries by elastic collision reported in [3]. The rate coefficient for thermalization is defined as,

$$K_{slow} = \frac{1}{n\tau_{ep_slow}}$$

The secondaries source terms from the interaction between primary, neutrals atom and plasmas are defined as,

$$\begin{aligned}\dot{n}_{exp} &= n_p n_0 K_{excp} \\ \dot{n}_{izp} &= n_p n_0 K_{izp} \\ \dot{n}_{slow} &= n_p / \tau_{ep_slow}\end{aligned}$$

Where n_0 is the neutral density and n_p the primaries density. The depleted flux of primary is calculated as,

$$\Gamma(t + dt) = \Gamma(t) \left[1 - \exp \left(-dt (n_0 K_{excp} + n_0 K_{izp} + \tau_{ep_slow}^{-1}) \right) \right]$$

- The secondaries are described as Maxwellian. The rates coefficients for secondaries that interact with neutral atoms are described as follows.

$$K_{iz,exc,el} = \left(\frac{m_e}{2\pi q T_{eV}}\right)^{3/2} \int_0^\infty \sigma_{iz,exc,el}(v) \exp\left(-\frac{m_e v^2}{2q T_{eV}}\right) 4\pi v^3 dv$$

The plasma source term from the secondaries is defined as,

$$\dot{n}_{iz} = n n_0 K_{iz}$$

where n is the plasma density

- Other collisions taken into consideration are
 - Ion-neutral charge exchange
 - Ion-neutral collision
 - Electron – Ion collision
 - Electron – Electron collision
 - Ion – Ion collision
 - Ion-Electron Collision

- The total ions creation rate coefficient is defined as,

$$\dot{n}_i = \dot{n}_{iz} + \dot{n}_{izp}$$

- The total secondaries creation rate is defined as,

$$\dot{n}_e = \dot{n}_{exp} + 2\dot{n}_{izp} + \dot{n}_{slow} + \dot{n}_{iz}$$

- The depleted flux of neutral is calculated as,

$$\Gamma(t + dt) = \Gamma(t) \left[1 - \exp\left(-dt(v_{izp} + v_{iz})\right)\right]$$

2. Neutral and Primaries Sub model -PIC Algorithm

The neutral atoms and primaries densities in the DC are estimated by using PIC method. The particles are described by super-particle (SP). The trajectory of each SP is iterated by using particle mover and boundary conditions. At each iteration, the SPs are depleted by collisions. By moving a large number of SP, the density of each species can be estimated by probability.

- The particles mover for the neutral assumes a straight movement of the SP ($dp = vdt$) until it is reflected at the boundaries or exits the DC through the grid. Figure IV-2 shows the normalized neutral density distribution over the DC. The highest density is coming at the cathode and main injection region. High density around the keeper wall is coming from the ion recombination.

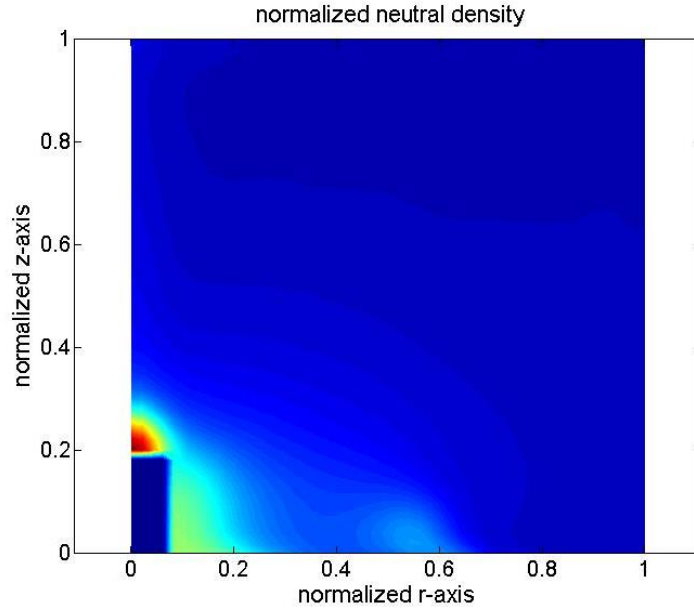


Figure IV-2 Example of normalized neutral density distribution from sub model

- The particles mover for the primaries solves the Lorentz force differential equation in cylindrical coordinates. The kinetic energy of the primaries injected from the cathode is at the cathode potential.

$$m_e \frac{d\vec{v}_p}{dt} = q\vec{E} + q\vec{v}_p \times \vec{B}$$

Figure IV-3 shows the normalized logarithm primary density in the magnetized discharge chamber. Injected from the cathode the primaries expand in the DC and are distributed along the magnetic line and attracted on the cusp regions.

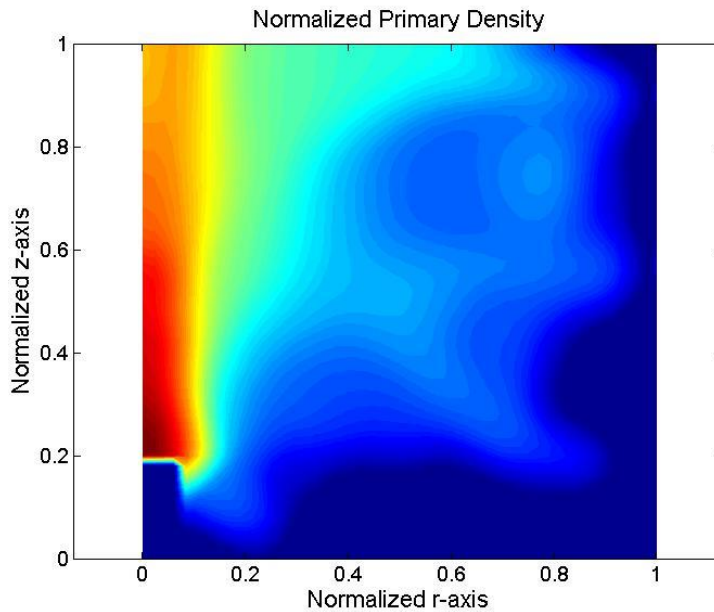


Figure IV-3 Example of normalized primaries density distribution in magnetized RCDC

The total mass inside the domain is conserved by re-injection of SP depleted, lost or collected on the anode. For a large number of SP, the steady-state condition in this method is reached when the total loss becomes constant.

3. Ion Diffusions – Finite volume method

The ion diffusion sub-model uses Fick law applied in a Finite volume method to simulate the ions density [3] [22]. The Fick laws are applied to the quasi-neutral magnetized plasma taking into account the ambipolar diffusion.

$$-\nabla \cdot (D_a \nabla n) = \dot{n}_i \Leftrightarrow \nabla \cdot \vec{\Gamma}_i = \dot{n}_i$$

where the ambipolar diffusion coefficient D_a is calculated parallel ($D_{a\parallel}$) and perpendicularly ($D_{a\perp}$) to the magnetic field and then projected on the r-z meshed domain. The source creation $\dot{n}_i$ of the ion plasma is described by primary and secondary ionization collisions.

Then the equation solved on each cell of the domain can be written as

$$-\nabla \cdot \left\{ \begin{bmatrix} D_{a\parallel} \sin^2 \theta + D_{a\perp} \cos^2 \theta & (D_{a\parallel} - D_{a\perp}) \sin \theta \cos \theta \\ (D_{a\parallel} - D_{a\perp}) \cos \theta \sin \theta & D_{a\parallel} \cos^2 \theta + D_{a\perp} \sin^2 \theta \end{bmatrix} \begin{bmatrix} \frac{\partial n}{\partial z} \\ \frac{\partial n}{\partial r} \end{bmatrix} \right\} = \dot{n}_{izp} + n v_{iz}$$

The boundaries conditions are defined at the Bohm flux nu_B . The systems equations are solved by direct sparse matrix inversion. The solution allows to conserve ion source terms and the ion flux leaving the plasma domain. Figure IV-4 is an example of the plasma density distribution obtained over the magnetized domain. The highest density is due to the high source terms creation from the primaries and neutral densities the exit of the cathode. The plasma diffusion across the magnetic field is observable and affect the uniformity at the exit.

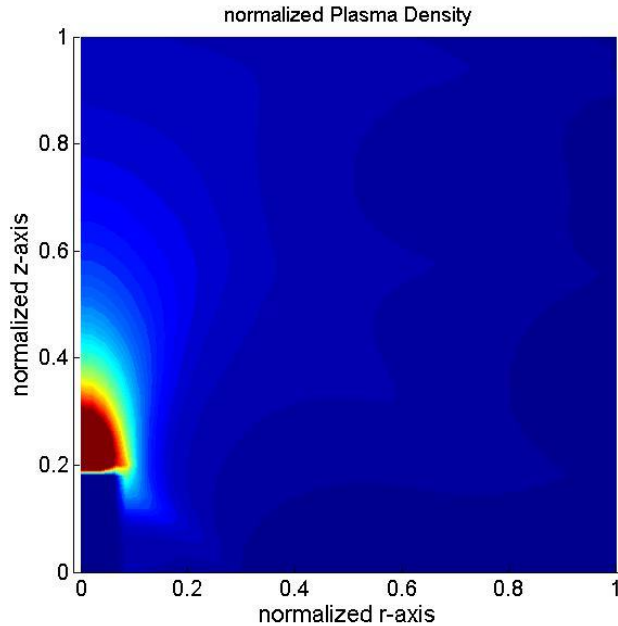


Figure IV-4 Example normalized plasma density distribution in magnetized RCDC

4. Electron thermal convection-diffusion – Finite Volume method

The electron thermal sub-model uses energy conservation from Boltzmann equation in a finite volume method [3]. The simplified form of the energy conservation can be expressed in a convective-diffusion form.

$$\nabla \cdot \left\{ \frac{5}{2} k_B T_e \vec{\Gamma} - \kappa \nabla T_e \right\} = Q$$

where $\vec{\Gamma}$ is the flux of secondaries, κ is electron thermal conductivity [23] and Q the energy exchange from primaries and secondaries.

- The flux of secondaries $\vec{\Gamma}$ is calculated from the electron continuity defined by the Fick law and the momentum equation as,

$$\dot{n}_e = -\nabla \cdot \vec{\Gamma}_e$$

$$\vec{\Gamma}_e = n\vec{u} = -\mu_e n \vec{E} - D_e \nabla n$$

- The energy exchange is described by the energy addition from primaries collisions to secondaries and energy losses from secondaries to neutral collisions

$$Q = (\dot{n}_w \varepsilon_w)|_p - (\dot{n}_i^s \varepsilon_c)|_s$$

$$(\dot{n}_w \varepsilon_w)|_p = q [\dot{n}_{izp}(V_k - \varepsilon_{iz}) + \dot{n}_{exp}(V_k - \varepsilon_{exc}) + \dot{n}_{slow} V_k]$$

$$(\dot{n}_i^s \varepsilon_c)|_s = q \left[\dot{n}_{iz} \varepsilon_{iz} + \dot{n}_{exc} \varepsilon_{exc} + n n_0 K_{el} \frac{3m_e}{m_i} T_{eV} \right]$$

where ε_{iz} ε_{exc} are ionization and excitation energies.

Then the equation solved on each cell of the domain can be written as

$$\nabla \cdot \left\{ \frac{5}{2} k_B T_e \begin{bmatrix} \Gamma_{ez} \\ \Gamma_{er} \end{bmatrix} - \begin{bmatrix} \kappa_{\parallel} \sin^2 \theta + \kappa_{\perp} \cos^2 \theta & (\kappa_{\parallel} - \kappa_{\perp}) \sin \theta \cos \theta \\ (\kappa_{\parallel} - \kappa_{\perp}) \cos \theta \sin \theta & \kappa_{\parallel} \cos^2 \theta + \kappa_{\perp} \sin^2 \theta \end{bmatrix} \begin{bmatrix} \frac{\partial T_e}{\partial z} \\ \frac{\partial T_e}{\partial r} \end{bmatrix} \right\} = Q$$

The boundaries conditions are fixed at the energy of the electron flux leaving at the plasma domain. The convection-diffusion is solved with an exponential scheme [24]. Figure IV-5 is an example of the electron temperature normalized in the domain. The high electron temperature on the axis allows to compensate the energy exchange from the primaries.

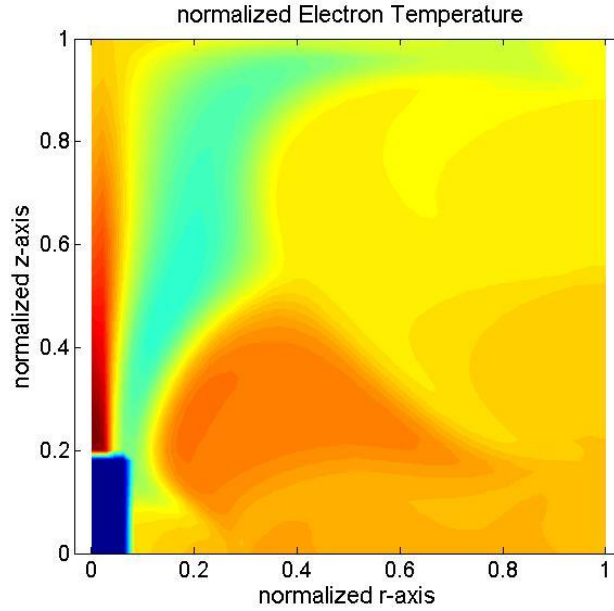


Figure IV-5 Example of electron temperature distribution in magnetized RCDC

End of September each sub models are finished and main loop iterations are under validation. The entire model should converge at the steady state when the mass utilization efficiency of the neutral and ion sub model are equal.

V. Conclusion

An ion thruster is under development in MSL. The experimental characterization of a RCDC allowed to optimize discharge efficiency and ion beam extraction. The experimental setup has captured the general trends and behavior of the DC respectively to magnetic topology and geometries. A configuration was found to be able to reach requirements performances expected. Several parameters are still available to optimize the RCDC and should be characterized in a near future. In a second time, a 2D axisymmetric model of a RCDC is developed in MSL. The model allows to capture more physics than the 0D model and shows already some qualitative promising results.

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