CONVERGENCE AND DEFLECTION OF A HALL THRUSTER PLUME

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Abstract

This paper presents a study about the convergence and deflection of a Hall thruster plume. This work considers the technological and economical spacecraft constrains/limitations. This means that our main objective is not only to be able to converge and deflect the plume, but also to do it in a way that it would not decrease substantially the Hall-thruster performance. Our approach makes a conceptual study about possible techniques on how to achieve the desired goal.

1. Introduction

Because electric propulsion has higher specific impulse than chemical propulsion, several electric thrusters have been developed. Indeed, fuel consumption saving may be performed with this technology. Hall thrusters, Ion engines, MPD (MagnetoPlasmaDynamic) thrusters and FEEP (Field Emission Electric Propulsion) are some of the devices developed. The Hall thruster has the advantage to be less sensitive to erosion comparing with ion engines. On the other hand, they have better power efficiency than the MPD thrusters. However, their high plume divergence has been an adverse effect to be taken into account in respect to the interaction with solar panels, instrumentation, etc.

Recently, thrust vector misalignment with respect to the center of gravity, or center of gravity shift due to propellant internal motion as well solar panels deployment has to be compensated with mechanical steering devices which are heavy, expensive and complex. Thus, deflecting an Hall thruster plume by other means (e.g. external electric or magnetic field) may provide considerable improvement on this technology.

This paper is divided in three parts. The first one discusses causes for the high divergence of Hall Thruster plume. In the second part, several techniques for plume deflection are analysed. The same is done in the third part, but regarding techniques for focusing the plume.

2. Plume divergence

Collisions with neutrals, charge exchange, electric and magnetic fields are presented hereafter as possible causes for the plume divergence.

In order to make a preliminary study, the simple model proposed by Baranov [3] has been used. It represents the neutral density, the plasma potential and the temperature of the electrons in the discharge chamber as a function of the distance from the anode. This model is one-dimensional, which is appropriate for a simple analytic study of the collision effects.

2.1 Collisions

If we assume that an ion is created at the anode and that it is accelerated by the potential, it is possible to calculate the mean free path as a function of the anode distance. This is shown in Figure 1.

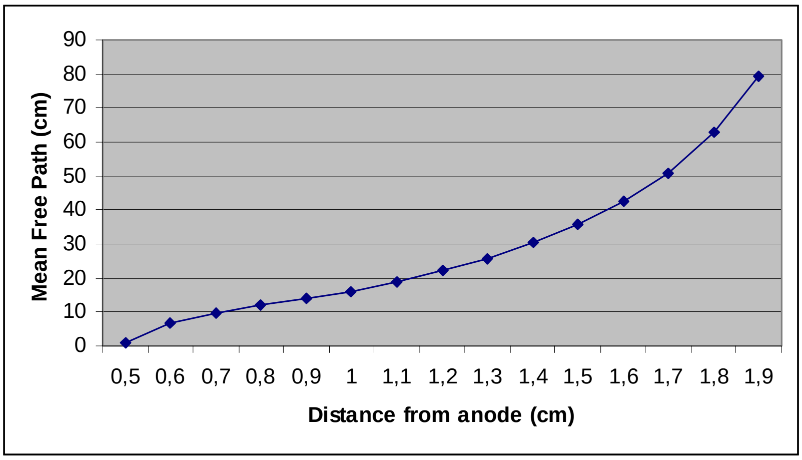

Fig. 1 – Mean free path versus anode distance for elastic collisions

Taking into account that all ions are created at the anode, our results state that less than 1% of the beam energy is contained outside the 37 degrees centreline angle. Considering that the real plume has about 5 % of the total energy at angles higher than 37 to 45 degrees (depending on the thruster), it is clear that elastic collisions are not the main process for the beam divergence. On the other hand, the assumption that all ions are created at the anode is not correct. Regarding collisions probability, this is a worst scenario because the mean free path is higher near the anode as shown in Figure 1.

2.2 Electric field

Hall thrusters are characterised by an ionisation zone and a high density electron zone [1]. This last one is the responsible for the ions acceleration. Different scenarios for these two zones are presented in Figure 2.

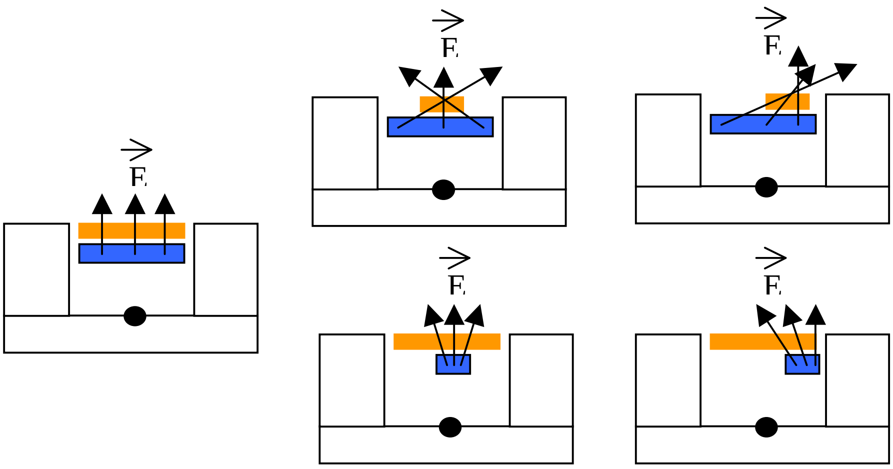

Fig. 2 – Possible scenarios for ionization and high electron density zones.

The left scenario is the ideal one. However, it is possible that some of the other four scenarios can also occur, and contribute for the high divergence of the plume.

The experimental data of the plume shape [1] states that ions can still be found at a 60 degree half cone angle with a velocity of 12 000 m/s. Discarding for now the magnetic field effect, two extreme possibilities may be true:

- These ions were accelerated from zero velocity to 12 000 m/s at a 60º angle from axial direction.
- These ions had an initial axial velocity v_a, and were then accelerated by a radial (90º from axial direction) electric field E_r.

For the first case, the needed accelerating potential is around 100 V. The Baranov model [3] states that the last 100 V of accelerating potential are applied near the thruster exit. This indicates that these ions are created in this zone.
For the second case, the initial axial velocity could not be higher than 6 km/s. Taking into account the mass of a Xenon ion, this means these ions were previously accelerated by a 24 V axial potential. On the other hand, the radial velocity is around 10 km/s. This corresponds to a radial accelerating potential of 68 V. From the discussion of these two possibilities, it is clear that the ions responsible for a high divergence of the plume are created near the thruster exit. It is then important to understand the shape of the electric field at this zone. However, trying to get the localization of the ionisation and electron zone is not an easy task. At least, a 2D approach is needed.

2.3 Charge Exchange

The charge exchange process results from collisions between a fast ion and a slow neutral. Insuch a type of collision, no momentum transfer occurs but only an exchange of charge. The result is then a fast neutral and a slow ion. Slow ions are more easily deflected by the electric or magnetic fields than fast ions.
Doing a similar treatment as for the elastic collision (see above), the mean free path versus the distance from anode is plotted in Figure 3.

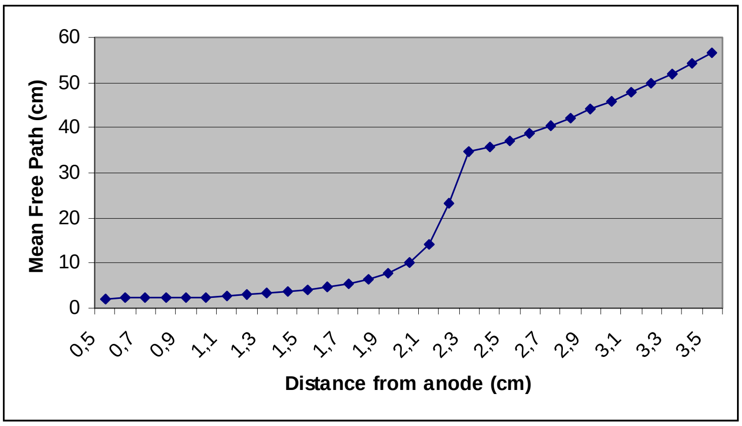

Fig. 3 – Mean free path for charge exchange collision

Comparing with the Figure 1, we can see tha the mean free path of charge exchange collisions is much lower than the elastic collisions one. So we expect much more charge exchange collisions than elastic collisions. Estimating the fraction of ions that are created by this process is useless, mainly because information of the electric field direction is necessary to quantify its contribution for the plume divergence. Simulation work should take this phenomenon in account.

2.4 Magnetic Field

The Hall thruster needs a magnetic field in order to operate properly. We have also studied the possible effects of this magnetic field on the ion trajectories. In Figure 4, we show the deviation angle (in respect to the axial direction) for ions created at different distances from anode.

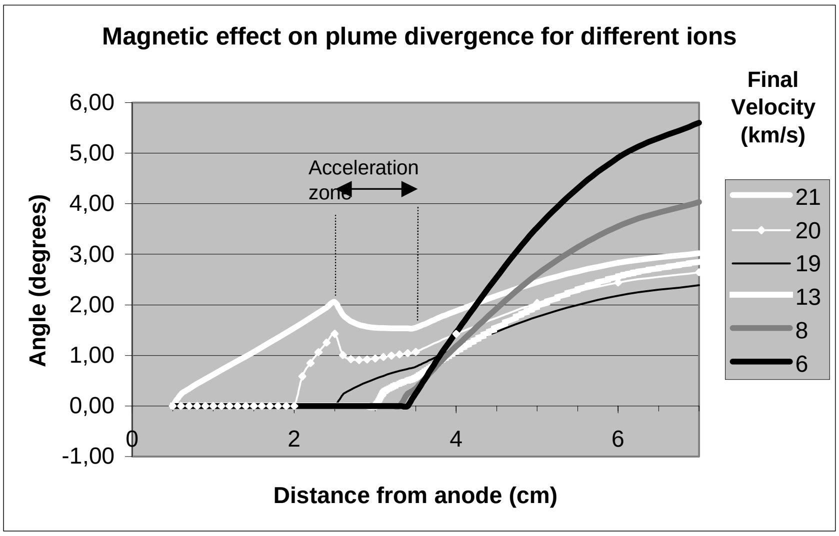

Fig. 4 – Magnetic effect on plume divergence for ions created at different distances from anode.

It is clear that, even if the magnetic field created a significant deflection, it is not the main responsible for high plume divergence.

3. Plume Deflection

In his work [9], David Fearn concluded that the main deflection concern is the compensation of the Centre of Mass shift, mainly due to solar panels deployment and shift of propellant centre of mass. He has shown that the ability to perform a thrust vector deflection around 8º is enough to compensate these effects. We have thus used this value for our calculations..

3.1 Electric Deflection

To deflect the plume direction, one of the issues is to use an external electric field. The SPT-100 Hall thruster has a discharge chamber of about 10 cm radius, so a distance between plates of 20 cm is adequate. Our estimates have led that a plate's length of 2,34 cm and a difference potential of 5 V should be enough for the wished deflection. In terms of engineering, this scenario seems realistic. However some considerations should be covered here. The electric field can be considered uniform when d<<L1. That is not our case, as shown in Figure 5. This means that a more refined study is required.

On the other hand, the design should avoid the interaction between the deflecting plates and the hollow cathode. It is important to guarantee that the electrons are accelerated toward the anode discharge chamber and not toward the plates as shown in Figure 6. This can be solved if the plates are at a lower potential than the hollow cathode. However, this solution increases the divergence of the ion beam as presented in Figure 7.

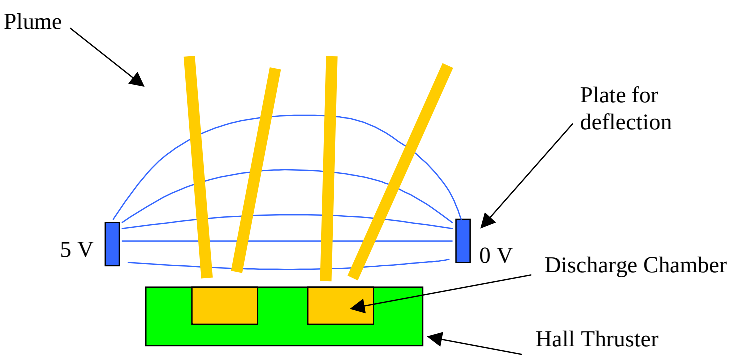

Fig. 5 – Electric field non-uniformity

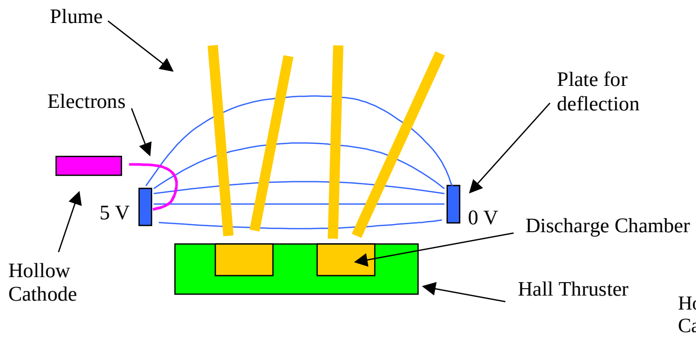

Fig. 6 – Electrons going toward the deflecting plates

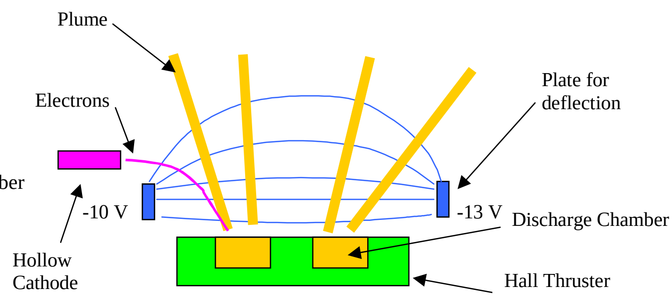

Fig. 7 - Divergence of the plume created by the deflecting plates

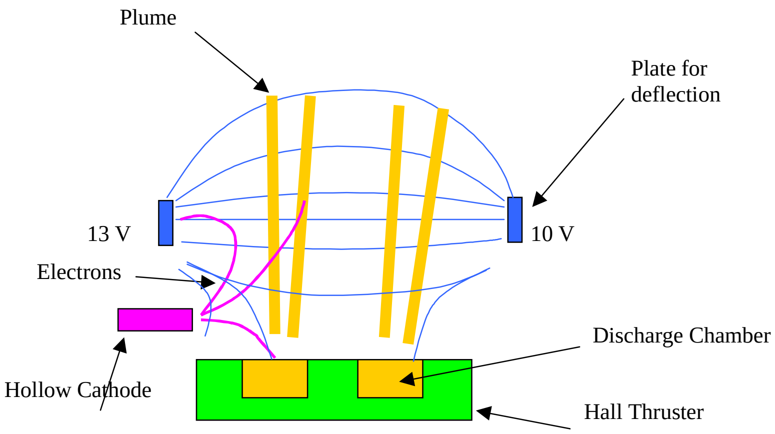

Fig. 8 – Beam deflection and convergence

Another solution is to place the hollow cathode below the deflecting plates, as presented in Figure 8. However, this may cause some problems for the beam neutralization. This solution has the advantage to decrease the beam divergence. On the other hand, it creates a retarding potential witch causes the ions to slow down. But a more important subject of research has to be focused in the interaction between the deflecting plates, the hollow cathode and the anode. Because the potential between plates is small, the electric field can be highly perturbed, both by the accelerating potential and by the beam flow. Instabilities may arise. To assess these possible effects, a full Hall thruster simulation is required, both inside and outside the discharge chamber, the results of which will be presented in a future work.

3.2 Magnetic Deflection

Using a magnetic field for plume deflection is probably the first method that comes to mind. However, it is necessary to assess all the physical and technical issues. We have assumed a magnet as shown in figure 9. All the plates have a thickness of 2 cm, witch seems reasonable for avoiding magnetic flux linkages.

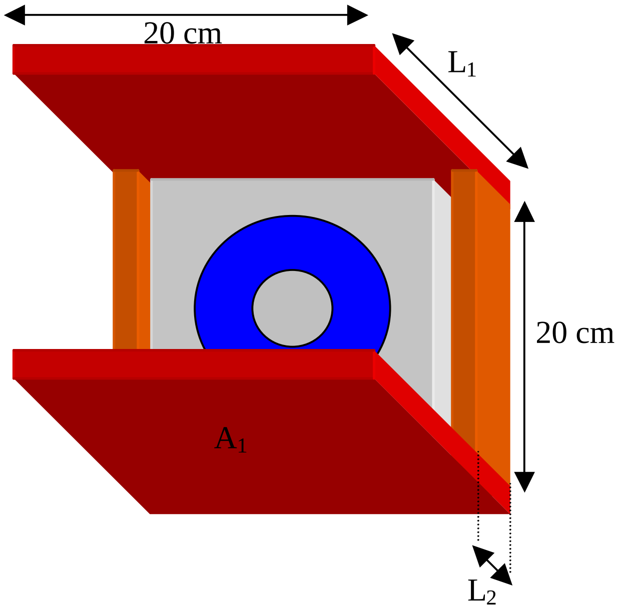

Fig. 9 – Magnetic system for plume deflection

The power consumption and the needed mass for this magnetic deflection system versus the length L_1 are presented in Figure 10.

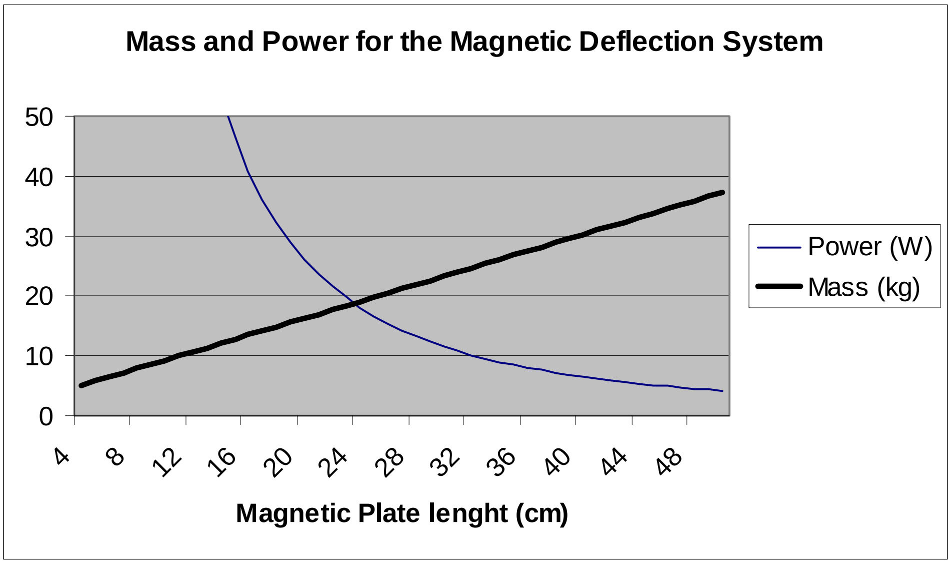

Fig. 10 – Needed mass and power for the magnetic deflection of the Hall thruster plume

It is clear that this system is not acceptable. Even with a plate of 4 cm length, the needed mass is around 5 kg and the power consumption is more than 200 W.

3.3 Electron and Ionisation zone positioning

In Figure 3, different scenarios explaining the beam divergence where presented. Non-uniformity of the electron distribution and of the ionisation zone can also be used for deflecting the direction of the beam. This could be achieved by the following ways:

- Internal magnetic field asymmetry
- Applied and internal electric field asymmetry

The possibility of controlling the magnetic field inside the discharge chamber may lead to a shift of the zone of higher electron density. This would change the direction of the electric field responsible for accelerating the ions. On the other hand, applying additional electric fields inside the thruster could also change the localisation of the electrons. The same applies for the localisation of the ionisation zone. If azimuthal control of these parameters is possible, a deflection of the plume can be achieved. However, a simulation code is necessary to assess these possible solutions.

4. Plume Convergence

Plume focusing is of great importance in Hall thrusters. Indeed, this device has a high plume divergence, which is unwished mainly because of its interaction with the spacecraft. If one wants to have a Hall thruster plume comparable with the Ion thruster plume, our goal should be to contain 95% of the plume energy within 20º of thruster centerline angle.

4.1 Electric focusing

The analysis performed for the plume deflection is valid for the required focusing effect. But for this case, the deflecting requirement for the ions trajectory is around 20º and not 8º. On the other hand, as stated above, the solution of figure 8 seems to be the best one for plume focusing.

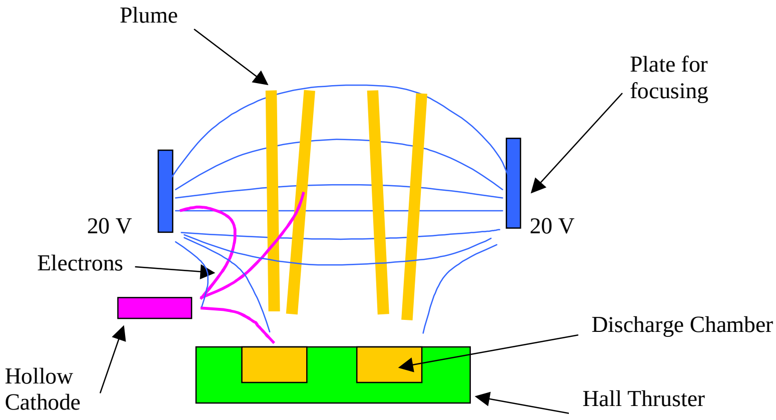

Fig. 11 – Beam convergence

A higher potential on a longer plate can be envisaged as described in Figure 11. This may lead to lengths of 8 to 15 cm instead of 2,5 cm, which is still technically feasible and reasonable. But as stated before, some problems with neutralization may arise. An additional hollow cathode for neutralization above the deflecting plates may be necessary.

4.2 Magnetic focusing

Here again, the problem is similar to that of the plume deflection. However, the focusing requirement is harder to meet because the required ion deflection is 20º instead of 8º. We concluded that this solution should be disregarded for 8º deflection and the same applies for focusing the plume.

4.3 Electron and Ionisation zone positioning

As for deflection, it may be possible to change the position of the ionisation and/or the position of the zone of high electron density, in order to control the direction of acceleration of the ions. However, for focusing this may be done symmetrically which simplifies the design.

5. Preliminary numerical analysis

A fully kinetic two dimensional PIC code has been build at GoLP. The first objective is to assess the best algorithms for this kind of simulation. In Figure 12, it is shown the ion and electron density and the potential on a two-dimensional view of the Hall thruster. We have assumed a cylindrical symmetry with the hollow cathode placed on the external topside of the simulation area.

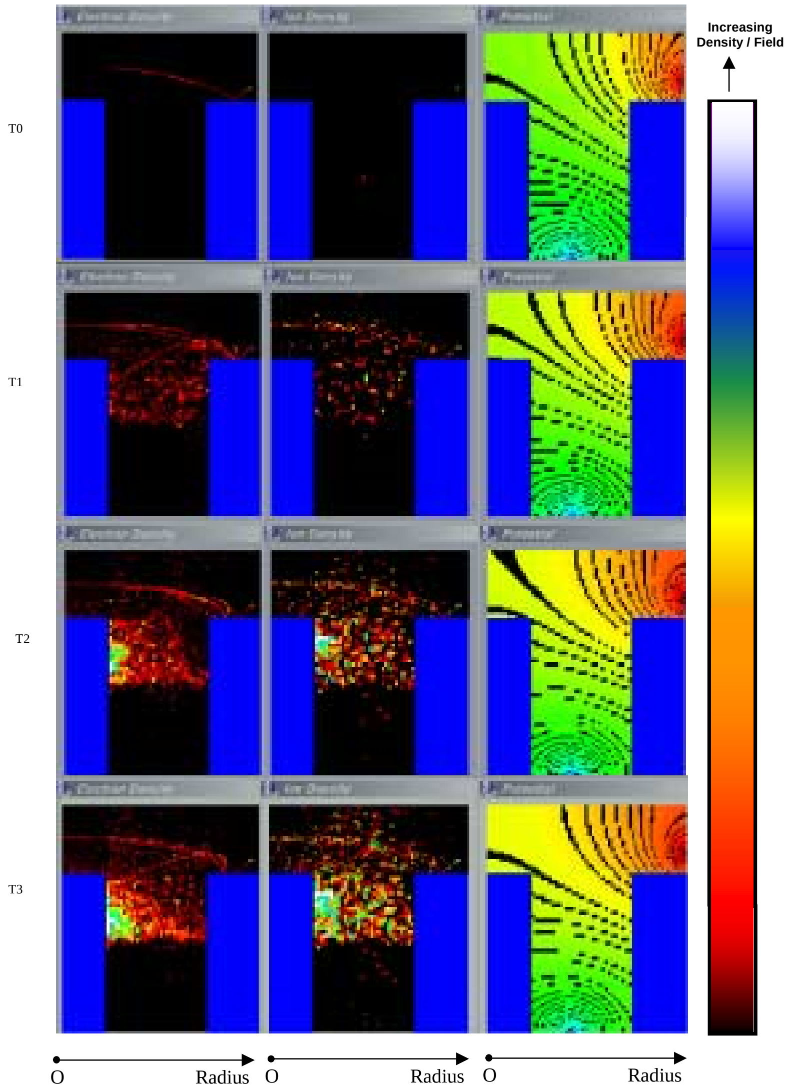

Fig. 12 – PIC Hall thruster simulation during start-up.

It can be seen clearly that the cathode has the tendency produce divergence in the ions trajectory. However, this simulation has been done during start-up. As time goes on, an electron layer will tend to deform the electric field in order to make it more axial and less radial.
As a preliminary exercise, we have computed the plume shape after a stable situation was reached. The Figure 13 shows the fraction of total beam energy as a function of angle from thruster centreline. The estimated value for the plume divergence is thus 31 º, much less than the experimental result. However this PIC code was run with very few particles (around 1000). As explained before the purpose of this code was to assess the algorithms for the development of a parallel code, which will allow simulation runs with more than 100 millions particles.

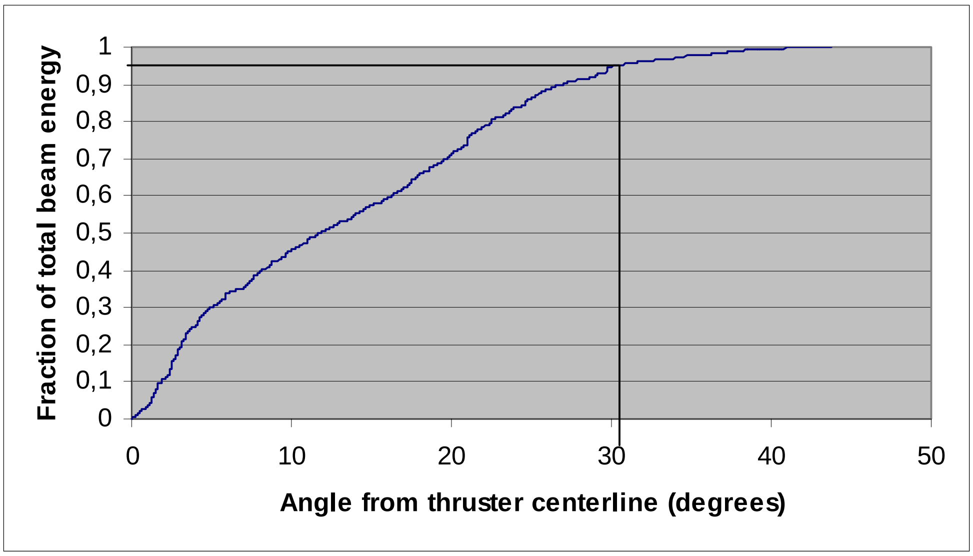

Fig. 13– Fraction of total beam energy vs angle for a PIC code with few particles.

6. Conclusions

The possible processes leading to the divergence of a Hall Thruster plume have been identified. We have sorted out that ions created near the thruster exit are the main responsible for the plume divergence. The charge exchange processes can play an important role on the creation of these ions. On the other hand, it was shown that the divergence is due to a radial electric field present in this zone. The magnetic field may have some effect on the divergence but it is not at all the main responsible.

The conceptual study about possible techniques for deflecting and focusing the Hall Thruster plume have lead to the same conclusions for both goals. Applying an external magnetic field should be discarded. This is not the case for the possibility of applying an external electric field around the plume. Indeed, it seems technologically feasible and interesting. However, instabilities may arise and great care should be taken with the hollow cathode operation. Both neutralisation and start-up process can be affected.

Another promising technique that needs further analysis by mean of detailed numerical simulations is controlling the position of both the ionisation zone and the high electron density zone. This may be achieved by applying internal electric or/and magnetic fields.

A parallel PIC code for Hall thruster simulation is being developed at GoLP. It will be used to study the feasibility of several techniques presented here.

7. Reference

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