IEPC-95-32

INVESTIGATION OF SMALL, CLOSED ELECTRON DRIFT, SPT.

G. GUERRINI*, A.N. VESSELOVZOROV*, ** and M. BACAL*

Abstract

The interest in low power electric thrusters stimulated our research on a small plasma thruster, SPT-20. The first results on the dependence of the thrust, the discharge current, the ion current and the axial electron current on the gas flow are reported. It was also shown that the drop of the discharge current with magnetic field is strongly affected by the emission current of the filament- neutralizer. It was also shown there that the facility pressure had a significant impact on the ion and the discharge currents.

I. Introduction

Recent work[1,2] indicates interest in ultra light controlled satellites, equipped with a low power electric thrusters. This work suggests that one of the most promising thrusters for these satellites can be the Hall-type thruster, which is widely used at present on satellites with 1 kW power on bord[3]. The main advantages of the Hall-type thruster are the high thrust and energetic characteristics, an acceptable lifetime, simplicity and reliability of its design. In the meantime the first experiments with Hall-type (or stationary plasma thruster, SPT) of small power and also small size have shown that with the reduction of size the thrust and energetic characteristics go down considerably. The purposes of our work are as follows :

1) Study the essential mecanisms in small size SPT, built according to the traditional scheme, in order to identify the main processes lowering the level of SPT characteristics when the thruster size is reduced.

2) Optimize small SPT design, in both traditional and new schemes, using all the existing knowledge.

II. The experimental thruster SPT-20

Fig. 1 shows schematically the experimental Hall-type thruster SPT-20. A coaxial discharge glass chamber is located in the magnetic field generated by the outer and inner poles. The magnetic system includes a coil and a soft iron magnetic circuit made of a back flange, three supporting rods, and the two poles: the inner pole (a rod) and the outer, ring-shaped, one. The gas, Xenon, was injected through one of the lateral tubes. The ring-shaped anode was fixed in the chamber using a rod, which also allows its electrical connexion. The main dimensions of the discharge chamber are as folows : the outer diameter of the accelerator channel is 20 mm, the inner diameter is 10 mm, the distance between the anode and the exit from the accelerator channel is 28 mm. The cathode-neutralizer was either a plasma cathode using LaB_6 (in the experiments at RRC Kurchatov Institute) or a tungsten filament, in the experiments at Ecole Polytechnique.

---

* Laboratoire de Physique des Milieux Ionisés, Ecole Polytechnique, 91128 Palaiseau, France.

**Permanent address: RRC Kurchatov Institute, Kurchatov Square, Moscow, Russia

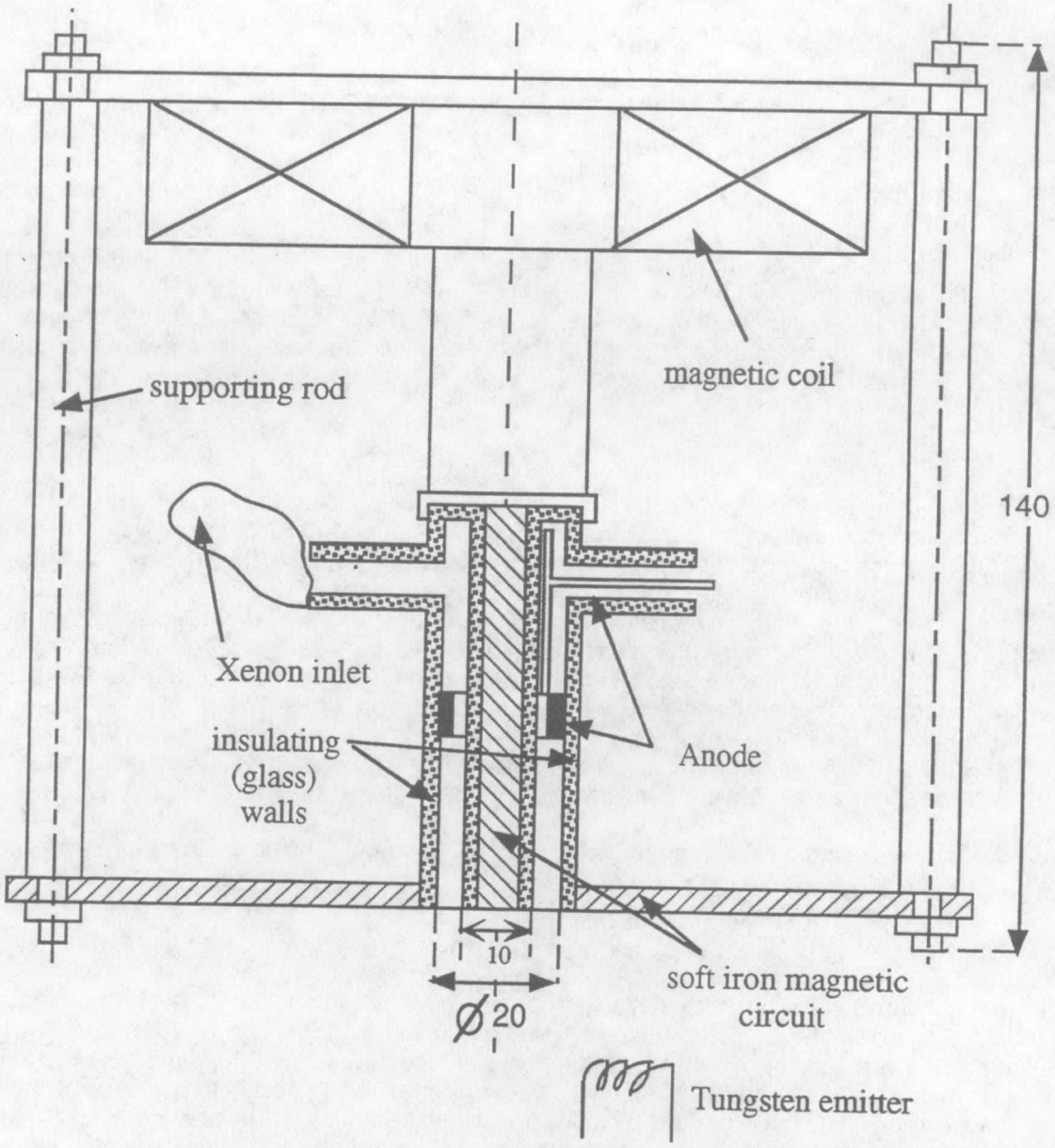

Fig.1 : Schematic representation of the Hall-type thruster SPT-20

The structure of the magnetic field can be inferred from Figs. 2 and 3. Fig. 2 presents the magnetic field lines obtained using iron powder. Note that in the region of acceleration the obtained magnetic field has not the typical for SPT lens-type structure. The magnetic field lines are note exactly perpendicular to the axis, therefore the magnetic field is not purely radial, but has an axial component B_Z. Fig. 3 shows the character of the change of the radial component H_r, measured with a Hall probe, inside the channel and at the channel exit, for various values of the current in the coil, I_M. Note that the maximum magnetic field H_r^{max} is located near the channel exit, in the region of the outer pole.

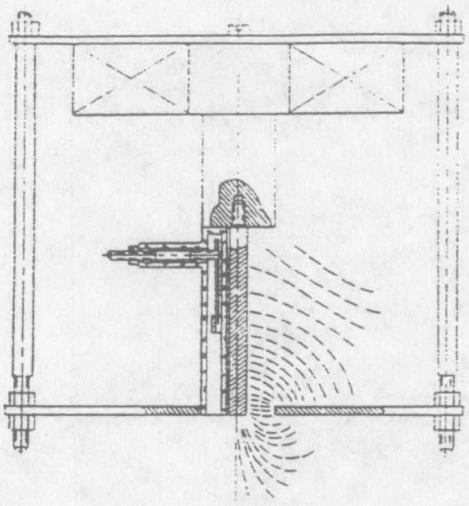

Fig 2 : Magnetic field lines obtained using iron powder.

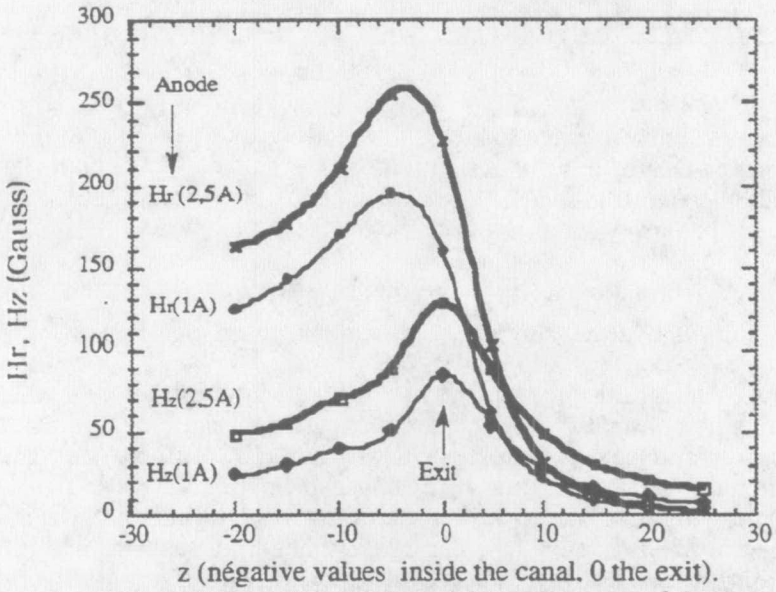

Fig. 3 : The axial variation of the radial and the axial components of the magnetic field H, for several values of the coil current in the prototype of Ecole Polytechnique.

III. The test facilities

Fig. 4 shows a schematic view of the facility E-1 of the RRC Kurchatov Institute in which some tests of SPT- 20 were effected. The thruster is located in a rectangular vacuum chamber 100x100x250 cm^3, which was pumped with an oil diffusion pump with a pumping speed of ~ 200,000 l/s. Most of the investigation was made at a chamber pressure of $(2\text{-}4)10^{-5}$ Torr (as read on the ionization gauge, calibrated for N_2, without correcting it for Xenon; the corrected pressure value is 2.5 times lower).

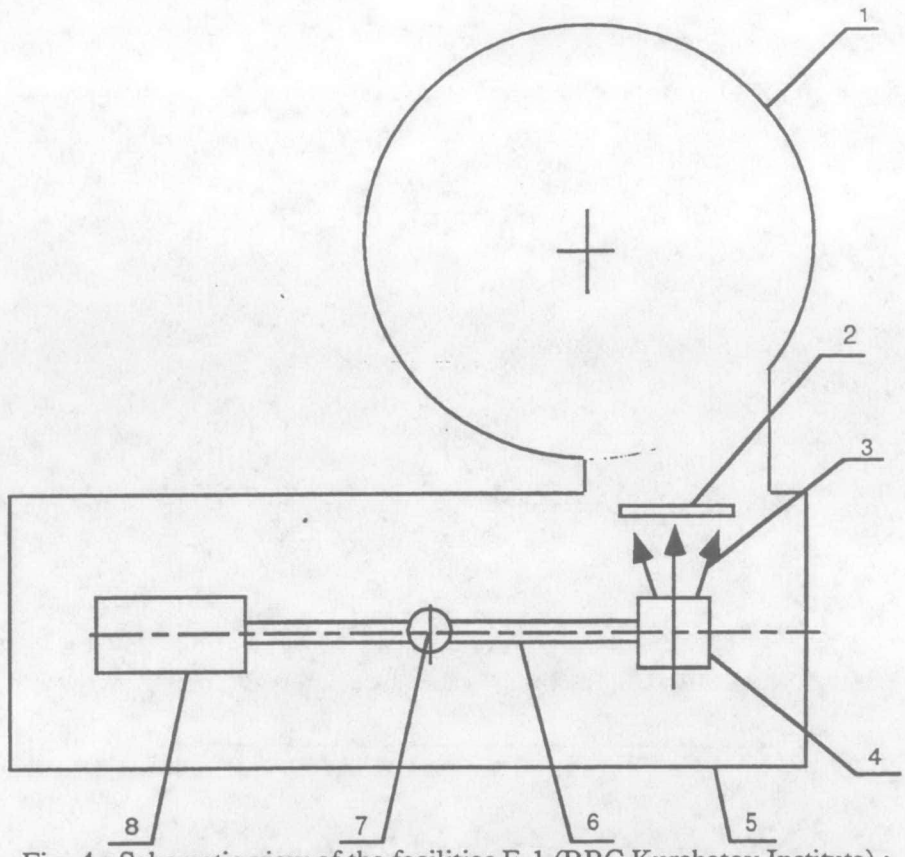

Fig. 4 : Schematic view of the facilities E-1 (RRC Kurchatov Institute) :
1 : Oil diffusion pump; 2 : ion collector ; 3 : plume; - 4 : thruster; 5: vacuum chamber - 6 : suspension rod for the thrustmeter; 7 : axis of suspension; 8 : damping system and the power components of the reaction system.

In the experiments at RRC Kurchatov Institute we measured the thrust F, the power consumed by the thruster (in the discharge) N_d, the gas (Xenon) flow $\dot{Q}_{Xe}$, the ion current in the plume I_i.

The thrust was measured using a thrust balance, designed on the principle of a torsion scale with reaction. This scheme ensures a fixed position of the thruster in space during the measurement of thrust, which eliminates the effect of the rigidity of current and gas leads on the accuracy of the thrust measurement. The scheme of the thruster and main components of the thrust balance are shown on Fig. 4. Here are shown the SPT, the thrustmeter suspension rod, the axis of suspension, the damping system and the power components of the reaction system. Since this thrustmeter is intended for the measurement of thrust up to 150g with an accuracy of 4%, we questioned the possibility of measuring thrust lower than 1 g. However, after some improvements of the mechanical and electronic components, a control calibration (Fig. 5) has shown the possibility of measuring thrust in the range of interest (0.1-1.0 g) with an accuracy ~ 0.05g, which is satisfactory for the first estimates of the thrust of SPT-20.

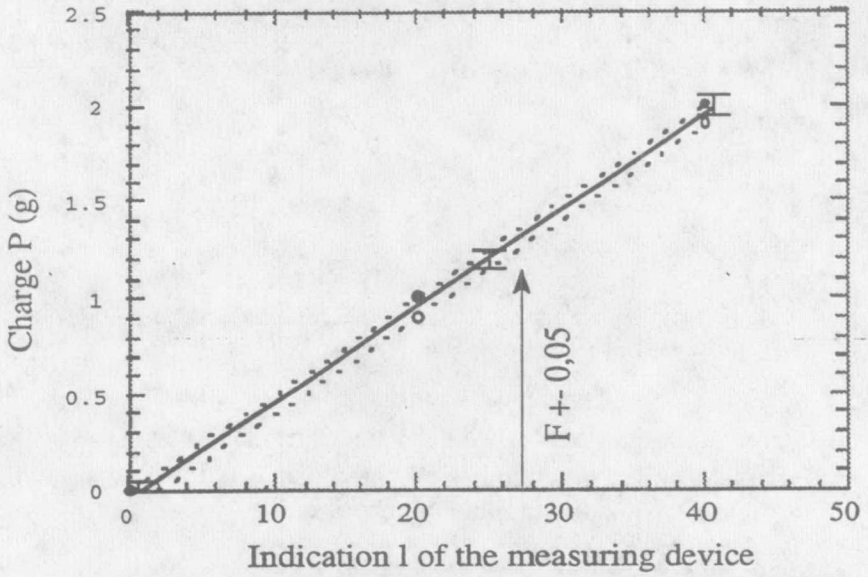

Fig.5 : Dependence of the indication l of the measuring device on the charge P on the thruster.

At Ecole Polytechnique experiments were effected in a smaller facility, denoted X-1, pumped by an oil vapour diffusion pump, with a pumping speed for Xenon of 600 l/s. Here the volt-ampere characteristic, as well as the dependence of the discharge current, the ion current and the axial electron current on the magnetic field and on gas flow were measured.

In both facilities the ion current was measured on a metal target: 20 x 20 cm^2 (at RRC Kurchatov Institute) or 20cm in diameter at Ecole Polytechnique, biased to -30 V. The gas flow was measured with a calibrated capacity, with an accuracy of 5%.

IV. Energetic efficiency and thrust

Figures 6 and 7 present the variation with the gas flow of the discharge current, ion current in the beam, the discharge power and the thrust. Note that at constant discharge voltage and magnetic field, these dependences are linear. For values $V_d = 160$ V and $B_r^{max} = 350$ Gauss the observed dependences can be written as follows :

$$I_d = 10.5\ (\dot{Q}_{Xe} - 0.024) \quad (1)$$

$$I_i = 2.75\ (\dot{Q}_{Xe} - 0.02) \quad (2)$$

$$F = 5\ (\dot{Q}_{Xe} - 0.024) \quad (3)$$

where the flow $\dot{Q}_{Xe}$ is in cm^3/s, while the values I_d, I_i and F are in A and g, respectively.

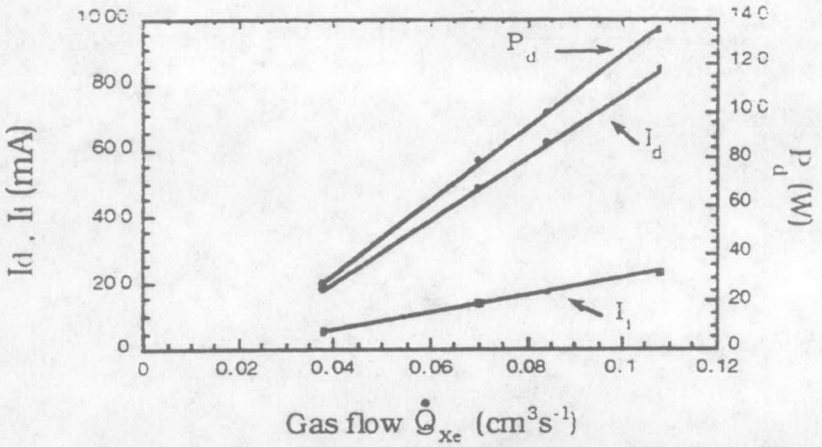

Fig. 6 : Dependence on the gas flow of the discharge current I_d, ion current I_i and discharge power P_d. The chamber pressure is $4.5x10^{-5}$ mbar (N_2), the discharge voltage is 160 V and the maximum radial magnetic field 350 Gauss.

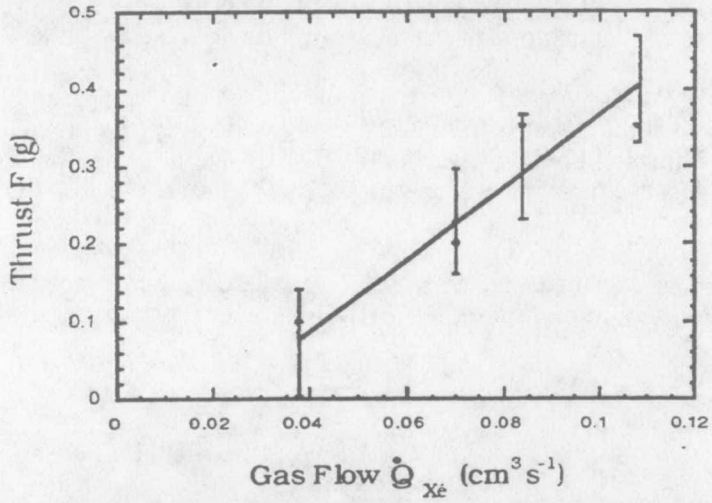

Fig. 7 : Dependence of the thrust on the gaz flow. The measured thrust values are presented together with vertical bars, indicating the error +/- 0.05g. The chamber pressure is $4.5x10^{-5}$ mbar (N_2), the discharge voltage is 160 V and the maximum radial magnetic field is 350 Gauss.

Fig. 8 shows the variation of the ratios I_i / I_d and $I_i / I_{\dot{m}}$ with the flow of Xenon. The ratio I_i / I_d characterizes the energetic efficiency of the thruster, while the ration $I_i / I_{\dot{m}}$ the degree of gas ionization ($I_{\dot{m}}$ is the current equivalent of the gas flow, assuming single ionization). When the Xenon flow is enhanced from 0.04 to 0.1cm^3/s the degree of ionization goes up from $I_i / I_{\dot{m}} = 0.34$ to 0.54, while the ratio I_i / I_d varies in the range 0.325 to 0.275.

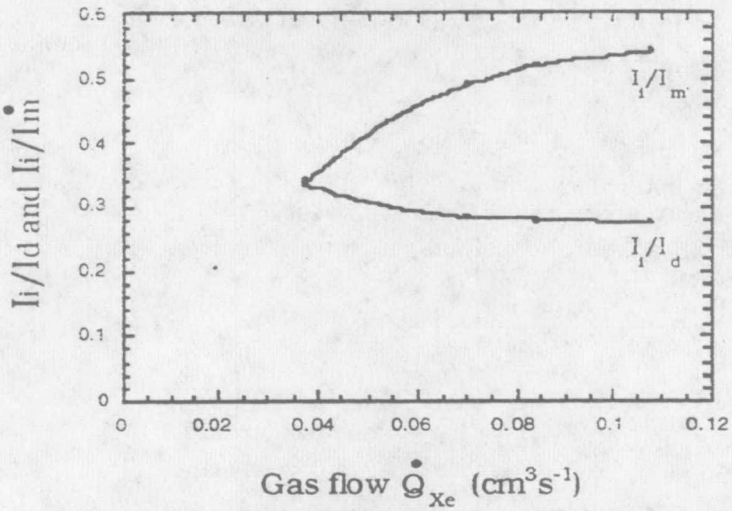

Fig. 8 : The variation of the energetic efficiency, I_i/I_d and the degree of gas ionisation I_i/I_m', on gas flow. The chamber pressure is $4.5x10^{-5}$ mbar (N_2), the discharge voltage is 160 V and maximum radial magnetic field is 350 Gauss.

An important parameter of SPT is the energetic cost of thrust, which characterizes the power spent per unit thrust : $\gamma = P_d / F$. From the analytic expressions for I_d and F, it follows that, at V_d = const, the cost of thrust does not depend on the gas flow, and for V_d = 160 V is 336 W/g. On Fig. 9 this value of γ is plotted as a horizontal line. The experimental points with the error bars are also shown.

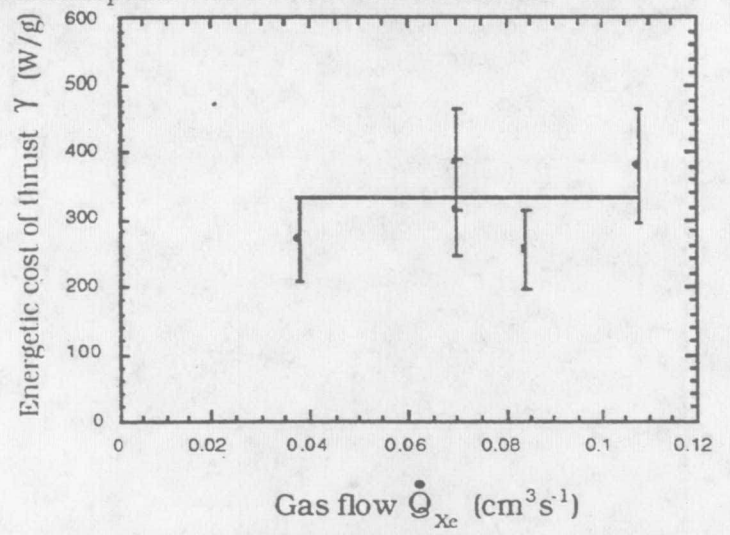

Fig. 9: Dependence of the energetic cost of thrust, γ, on gaz flow. The chamber pressure is $4.5x10^{-5}$ mbar (N_2), the discharge voltage is 160 V and the maximum radial magnetic field is 350 Gauss.

A second important parameter, which indicates the efficiency of using the working fluid for producing thrust. is the specific impulse.The value of the specific impulse corresponds to the thrust, produced by the unit of the working fluid weight. It is usually calculated by the equation:

$$P_{sp} = F / \dot{m}g \qquad (4)$$

Here g is the acceleration of gravity, $\dot{m}$ is the mass flow of the working fluid. In SPT thrusters the the specific impulse is determined by the degree of gaz ionization and the potential difference through which the ions

go through, before going out from the thruster. Figure 9 shows the variation of the specific impulse with the gaz flow at V_d = 160 V. It can be noted that the specific impulse goes up up with the gas flow, and attains 700 s at the maximum flow 0.1 cm^3/s.

The thrust efficiency is defined as the ratio between the kinetic power and the electrical power: Fig. 11 shows the dependence of thethrust efficiency on the gaz flow at Vd = 160 V.Note that the thrust efficiency goes up with the gaz flow and is 0.1 at at the maximum gas flow, 0.1 cm^3/s.

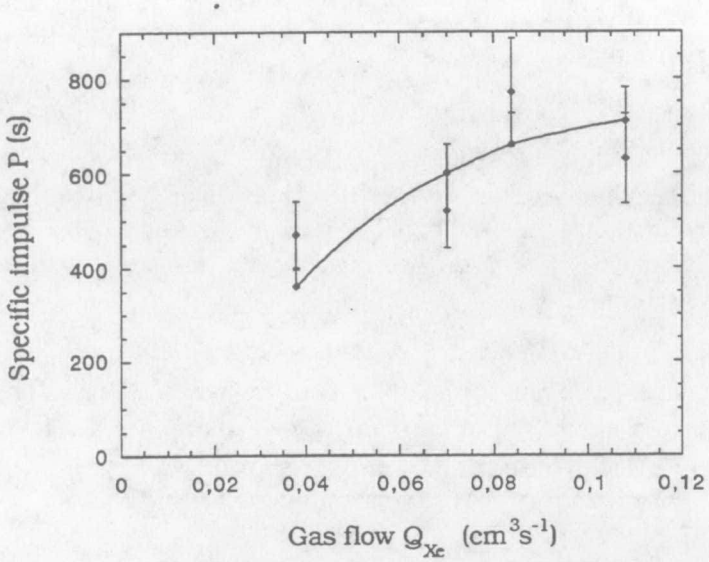

Fig 10 : Specific impulse vs Gas flow

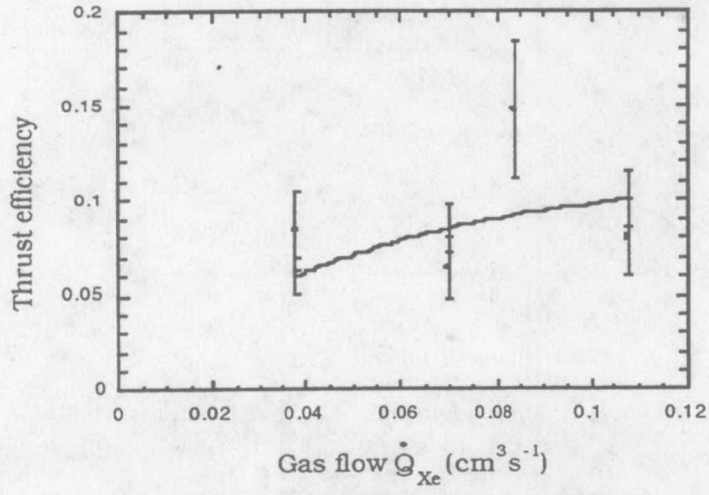

Fig 11 : Thrust efficiency vs gas flow.

V. Facility effect

Due to the low gas flow of SPT-20, the pressure in the large facility E-1 could be as low as 2 x 10^{-5} Torr, and could be enhanced by partially closing a valve. The effect of the facility pressure, at constant gas flow, on the ion current is shown on Fig. 12.

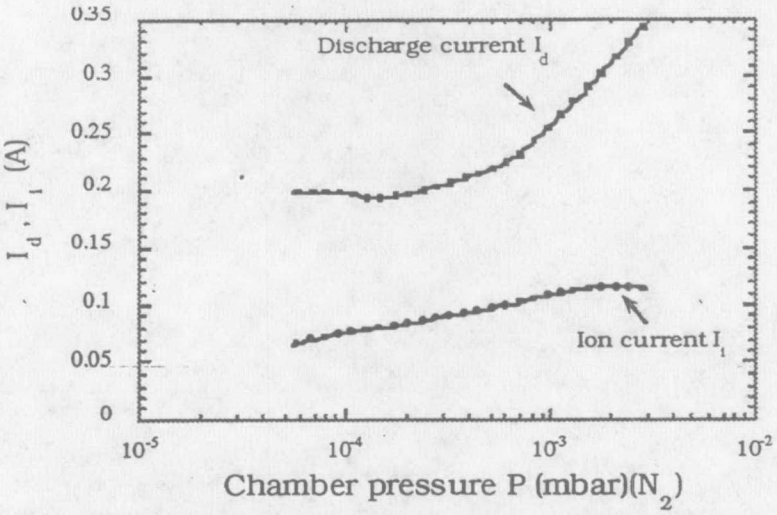

Fig 12 : Effect of facility pressure on the ion current and the discharge current. The discharge voltage is 160 V, the xenon gas flow 0.06 cm^3s^{-1} and the maximum radial magnetic field is 350 Gauss.

It can be noted that the ion current goes up when the background pressure is enhanced and attains a saturation level. The degree of ionization $I_i / I_{\dot{m}}$ also goes up, from 0.24 at the lowest pressure ($6x10^{-5}$ Torr), to 0.44 at the highest one studied here (saturation level) (see Fig. 13).

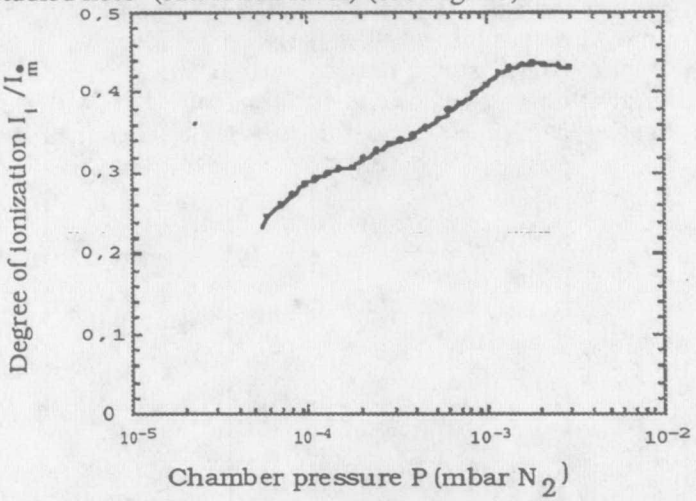

Fig. 13 : Effect of facility pressure on the degree of ionization.The discharge voltage is 160 V, the xenon gas flow is 0.06 cm^3s^{-1} and the maximum radial magnetic field is 350 Gauss.

The results obtained in the smaller facility X-1 at Ecole Polytechnique show that at similar discharge voltage and facility pressure, but lower gas flow, full gas ionization (degree of ionization 0.95) is attained (Fig. 14) . Thus, the interference of the facility pressure upon the ion current is rather complex. Earlier work[4] has only discussed this point theoretically.

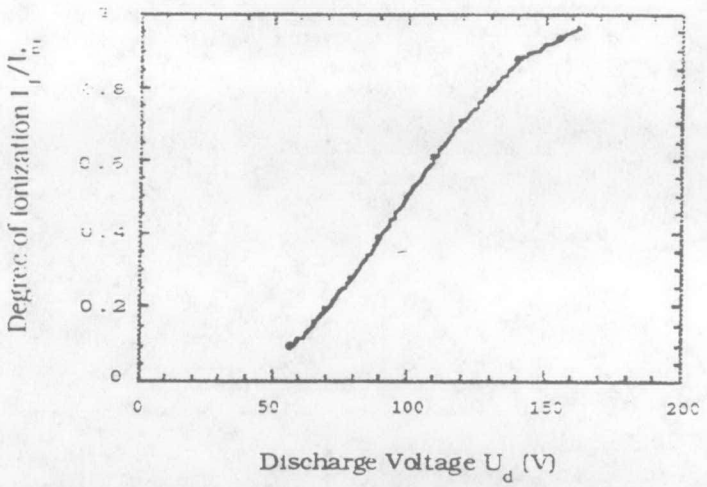

Fig. 14 : Degree of ionization vs discharge voltage measured in the facility X-1 at Ecole Polytechnique. The filament heating current is 16.5 A, the xenon gas flow is 0.04 cm^3s^{-1} and the maximum radial magnetic field is 190 Gauss. The chamber pressure is $2x10^{-4}$ mbar (N_2).

VI. Effect of magnetic field value

The effect of the magnetic field value was studied in the X-1 facility, both with Xenon and Argon, with the thruster operating with a tungsten filament-neutralizer (diameter 0.5 mm). We found that the level of filament electron emission was determining the discharge current drop when the magnetic field is enhanced (see Figs. 15 and 16). Note that at low filament heating current (16 A) there is almost no drop of the discharge current when the maximum radial magnetic field goes up from 0 to 260 Gauss. It was found that this feature was related to the fact that the beam potential goes up to +150 V when the filament heating (and thus, emission) is low.

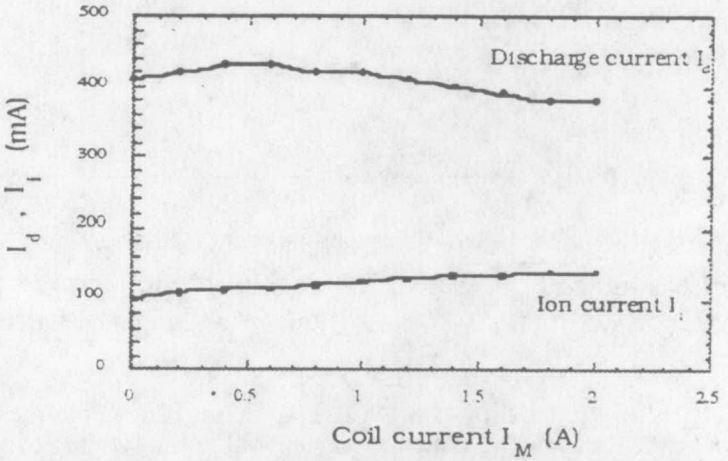

Fig. 15 : Variation of I_d and I_i versus the coil current I_M. Filament heating current : 16 A. Argon. X-1 facility. The chamber pressure is $2x10^{-4}$ mbar (N_2).

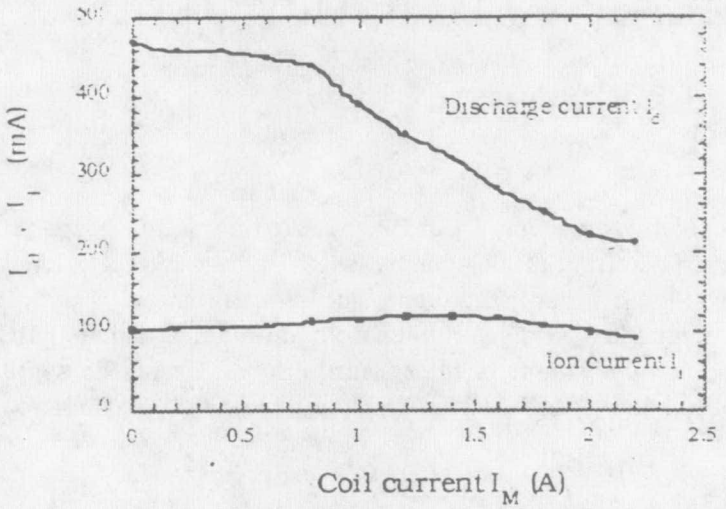

Fig. 16 : Variation of Id and Ii versus the coil current I_M. Filament heating current : 16,8 A. The pressure in the facility is 2×10^{-4} mbar (N_2). Argon. X-1 facility.

ACKNOWLEDGEMENTS. We acknowledge the support of CNES (France).

REFERENCES.

1. T.S. Colbert, V.M. Gravyshin, S.A. Khartov, V. Kim, G.A. Popov, R.K. Tchuyan, Colloque International "Propulsion des véhicules spatiaux", 8-10 Nov. 1994, Toulouse, France.

2. L. Bussolino, G.B. Amata *et al*, Paper IAA-94-IAA.L.1.2.766

3. A.I. Morozov, Yu.V. Esinchuk, G.N. Tilinin, A.V. Trofimov, Yu.A. Sharov, G. Ya. Schepkin, Soviet Physics-Technical Physics, 17, 38 (1972)

4. T. Randolph, M. Day, V. Kim, H. Kaufman, V. Zhurin, K. Kozubsky, 23rd International Electric Propulsion Conference, Seattle, Wa, Sept., 13-16, 1993. Paper IEPC-93-093.