Investigation of electron transport properties in Hall thrusters through measurements of magnetic field fluctuations

IEPC-2007-143

Presented at the 30th International Electric Propulsion Conference, Florence, Italy
September 17-20, 2007

G. Coduti, A. Lazurenko, S. Mazouffre and M.Dudeck
ICARE Laboratory CNRS, Orleans, Centre, 45071, France

T. Dudock De Wit, C. Cavoit and V. Krasnoselskikh
LPCE Laboratory CNRS, Orleans, Centre, 45071, France

and

A. Bouchoule
GREMI Laboratory, Orleans University, Centre, 45071, France

Measurements of the magnetic field fluctuations in a Hall thruster have been carried out between 1kHz and 30MHz with the aim of understanding electron transport through the magnetic barrier. A great part of scientific research effort is focused on the correct description of the electron current through the magnetic field in these thrusters, which is a crucial problem for development of fully predictive numerical simulation tools in this contribution. A novel technique of characterization of electron current by detection of non-stationary magnetic field is discussed. The diagnostic tools are small inductive coils installed around the accelerating channel. A model of localized electron currents in the form of rotating electron filaments, allows to reproduce the observed high-frequency (HF) magnetic field fluctuations with a good accuracy. On the basis of non-stationary magnetic field absolute magnitude the effective electron collision frequency can be estimated. Its value is sufficient to explain the electron transport.

I. Introduction

High-frequency (HF) instabilities (> 1 MHz) are basic phenomena observed in different Hall Effect Thrusters (HET).[1-4] Their existence is related to the physics of Hall thrusters – charged particle flow in crossed electric and magnetic fields. Some theoretical investigations were undertaken in order to discover the mechanism of their excitation.[1,5,6] These HF instabilities are extensively studied in connection with the anomalous transport in HET which is not well understood. A fully-kinetic PIC modeling of the Hall thruster discharge demonstrated that electron transport across the magnetic field could be provided by azimuthal electric field fluctuating at high-frequency.[6]

In this article we present recent results of HF instabilities investigation in the PPS100 and PPS®X000 HET. We present the implementation of a new method of assessing the anomalous electron transport properties in HETs by way of studying plasma instabilities in a 1.5 kW [7] and in a 5 kW class thruster. The basics instruments for these investigations are small inductive coils and coaxial Langmuir probes. Hereafter, we describe the principle of diagnostics and its implementation on the HET and we review and discuss the main outcomes of this work.

II. Principle of diagnostics

The principle of the utilized diagnostics is based on the detection of non-stationary magnetic field according to the Faraday's law:

$$\varepsilon = -\frac{d\Phi}{dt},\ \Phi = NSB \quad (1)$$

where ε is the electromotive force (voltage generated in the coil), Φ is the magnetic flux crossing the coil surface, N is the number of turns in the coil, S is the coil surface and B is the magnetic induction.

With a properly oriented coil axis it is possible to detect selectively the variations of any component of a non-stationary magnetic field. The coils were fabricated from ordinary 0.8 mm emailed transformer wire. Each coil has 20 turns of ~7 mm in diameter with overall longitudinal dimension of 8 mm. The coil signals are amplified before being transmitted through 50 Ω lines to an oscilloscope (Fig.1).

The system "coil + amplifier" was calibrated by observing an output voltage in function of frequency as a response to the magnetic field generated by variable-frequency (10 kHz – 50 MHz) current in a long conductor place near the coil (Fig.1). This system has a resonance at 20 MHz.

The gain of the system 'coil+amplifier' can be represented as

$$Gain = Gain(\omega) = \frac{U_{acq}}{U_{gen}} = \frac{U_{acq}}{I_{gen} R_{50\Omega}} \quad (2)$$

where ω is the pulsation. For a long wire, we can write the magnetic field as

$$B(\omega) = U_{acq} f_{tr}(\omega) \quad (3)$$

where $f_{tr}(\omega)$ is the 'effective' transfert function,

$$f_{tr}(\omega) = \frac{\mu\mu_0}{2\pi d R_{50\Omega} Gain} \quad (4)$$

III. HF magnetic field fluctuation in the PPS100 thruster

The measurements were carried out with the PPS100 Hall thruster at the French national facility PIVOINE. The thruster operated at its nominal operation mode, with a mass flow rate of 4.5 mg/s, a discharge voltage of U_d=300V and a discharge current of I_d=4.2A. Three coils were installed within the exit plane around the channel outer wall on a 70 mm radius. The axes of two coils (B7 and B3 on Fig.2) were oriented azimuthally, and the last coil B6 was oriented with its axis parallel to the thruster axis. Therefore, B7 and B3 detect the azimuthal component of the fluctuating magnetic field, whereas coil B6 detects the axial component. A shielded Langmuir probe was also installed at the same exit cross section of the thruster, and it will be referred to as A8.

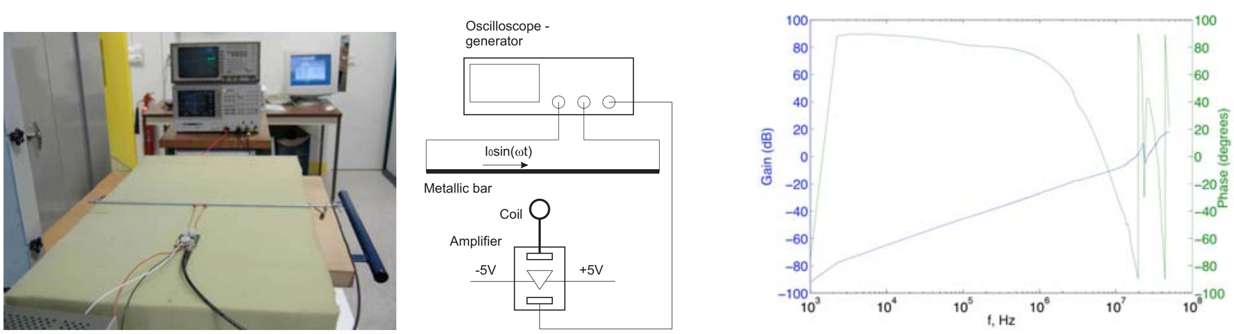

Figure 1. Scheme of amplifier and coil calibration setup. - Frequency characteristics of the system.

A typical coil recording is presented in Fig.3 along with the wave form of the discharge current. One can directly observe the modulation of the coil signal at the frequency of discharge current oscillations at 25 kHz. We calculated the power spectral density of the raw signals separately for two frequencies bands: f<1 MHz and f>1 MHz. Typical spectra are represented in Fig.4 for the coils B3, B6 and for the Langmuir probe A8. The spectrum of the B7 coil is close to that of the B3 one and is not shown. Three characteristic frequency bands can be distinguished in the spectra: 20-40 kHz, 100-500 kHz and 8-24 MHz.

The 20-40 kHz frequency range corresponds to the low-frequency oscillations in Hall thruster, often referred to as 'contour' or ' bulk oscillations.[8] These oscillations are conventionally considered as being the most important

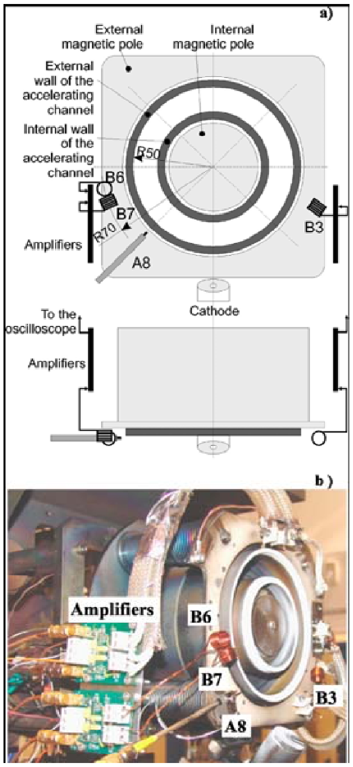

Figure 2. Location of magnetic field coils and the Langmuir probe on the PPS100 thruster.

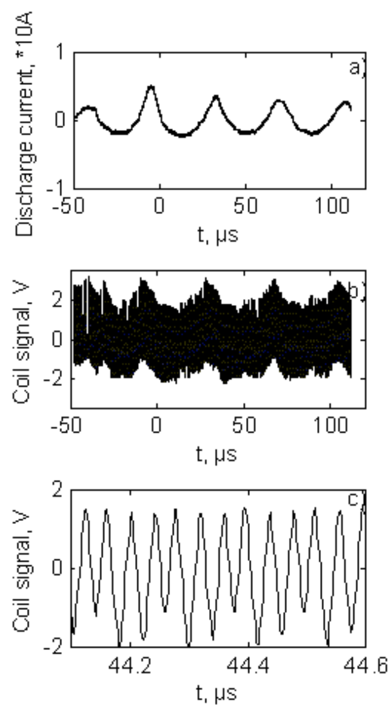

Figure 3. Time evolution of the discharge current (a), a typical coil B7 signal (b), and an zoom of the same coil signal (c).

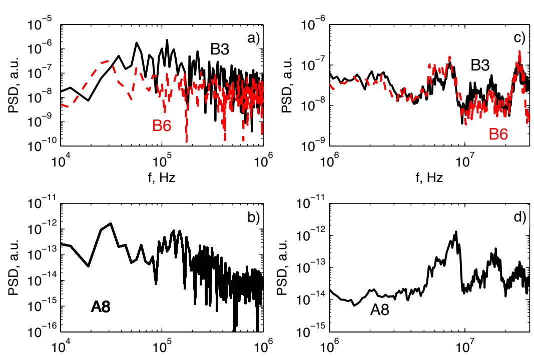

Figure 4. Power spectral densities of the coil signals and of the probe signal. Left panels for f<1 MHz and right panels for f>1 MHz.

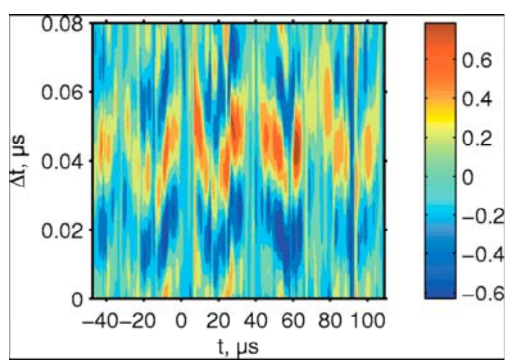

Figure 5. Cross-correlation function between B3- B7 coils.

ones and are associated with displacement of the ionization front.[10] Coil B3 and B7 detect the azimuthal magnetic field that is generated by currents of charged particles having axial and radial components. These currents are carried by ions leaving the thruster, wich have significant axial and radial components and negligible azimuthal component, and corresponding components of electron current. Coil B6 detects the axial magnetic field that is generated by azimuthal and radial currents. Such currents are made out of the radial components of ion and electron currents and the azimuthal component of electron current, which is referred to as Hall current.

The 100-500 kHz frequency range corresponds to the ‘transit-time’ (TT) oscillations in Hall thrusters, which are usually related to the ion flow through the channel.[8] The TT instabilities could be quite intense[11], but to our knowledge there have been no report on the significance of oscillations in this frequency range, in Hall thrusters that are currently under development. The B6 spectrum in this 100-500 kHz frequency range is flat, in contrast to the spectra of B3 and A8 (Fig.4). This observation corroborates the hypothesis of ion motion being responsible for TT oscillations. The ion current has a mostly axial direction, thus generating an almost azimuthal magnetic field that is detected by coils B3 and B7. We conclude that the TT oscillations are weaker than the low-frequency ones in this thruster operation mode.

Frequencies between 1 and 30 MHz correspond to the high-frequency (HF) oscillations. Such HF instabilities generate azimuthal waves that propagate with velocities close to the electron drift velocity ($\sim 10^6$ m/s) in the crossed electric and magnetic field.[12] By calculating the cross-correlation function, we show a strong correlation of the signals of similarly oriented coils (Fig.5). Red zones on Fig.5 correspond to the maximum of this function; the horizontal axis is recording time, the vertical axis is signal temporal shift Δt (dephasing). The cross-correlation function of B7 and B3 signals indicates that the source propagates in the azimuthal direction with a velocity of about $2\ 10^6$ m/s (Fig.5). The same velocity can be obtained from the autocorrelation function of each coil and the Langmuir probe. These observations are in perfect agreement with recent studies with the help of antennas and probes.[12]

IV. HF magnetic field fluctuation in the PPS®X000 thruster

The PPS®X000 thruster is a laboratory model of the SNECMA’s high power PPS®-5000 technological demonstrator with a nominal power of 5 kW and with an external diameter of the accelerating channel of 150 mm.[9,14] This thruster is under development for high-power space telecom platform. The whole campaign was carried out at the PIVOINE-2G facility.[14] Four coils were installed around the accelerating channel, at its cut-off plane and outside of the ionic plume. The coils were placed on the same radius at ~20 mm from the channel (Fig.6); three of them (B2, B3, B4) were oriented in radial, azimuthal and axial directions, the fourth (B1) was in azimuthal direction and shifted relatively to B3 by an azimuthal angle $\Delta\varphi$. Two probes A5 and A6 are installed on the thruster and are separated azimuthally by 10 mm. Additional probe diagnostics was also installed, as seen in the right-down part of Fig.6.

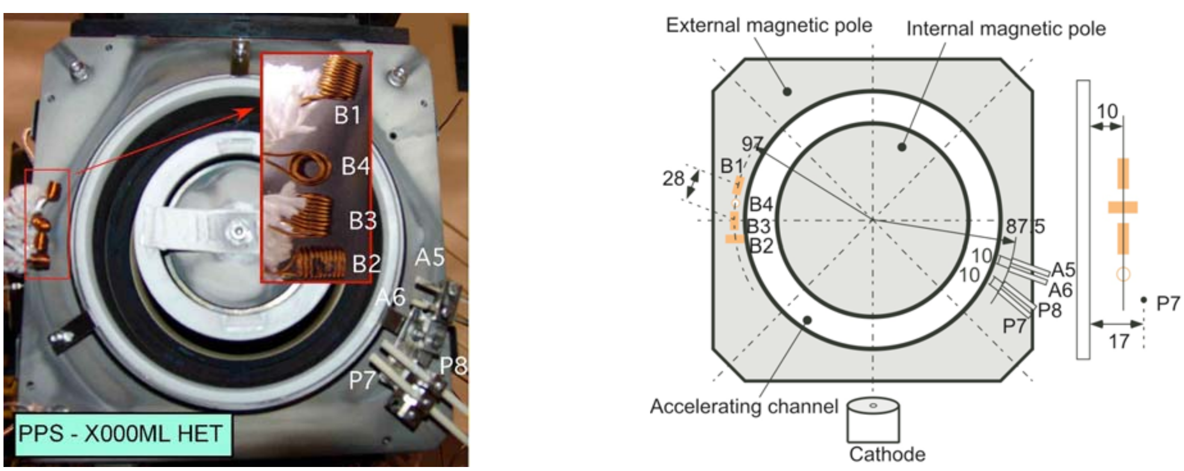

Figure 6. Picture and drawing of the PPS®X000 HET equipped with coil (B1, B2, B3, B4) and Langmuir probes (A5, A6, P7, P8).

The coils B1 and B3 detect the azimuthal component of the fluctuating magnetic field, whereas coil B4 detects the axial component. The signal from the coil was directly observed on the oscilloscope with 50 Ω ac operation mode. The signals are recorded using two oscilloscopes Tektronix (TDS 5104 and DPO 4034). The typical signal obtained by B3 coil, and its Fourier spectrum are presented in Fig.7. A closer look at this signal along with B1 signal (Fig.7) shows their forms are not very different, and one can distinguish their temporal shift Δt. These direct observations are confirmed by calculating their cross-correlation function.

As for the coils B1 and B3 the azimuthal coordinate varies only, it can be concluded that they detect a rotating in azimuth perturbation that generates a non-stationary magnetic field. A closer look at this signal along with B1 signal (red curve) shows that their forms are not very different, and one can distinguish their temporal shift Δt. With Δt=0.1 µs, the azimuthal propagation velocity is $2.8\ 10^5$ m/s. The same velocity can be obtained from the correlation functions of Langmuir probes. These observations are in agreement with the earlier studies by antennas and electrostatic probes which reported detection of azimuthal wave.[3,13] This result is confirmed by measurement by the Laser Induced Fluorescence (LIF) (Fig.9).[15] We find a azimuthal velocity smaller of a factor 10 compared to that of PPS100 thurster. A parametric study of the non-stationary magnetic field was performed as a function of mass flow rate varied between 6 and 20 mg/s, and as a function of radial magnetic field Br varied between 0.01 and 0.016 T (Fig.8 (a)-(b)).

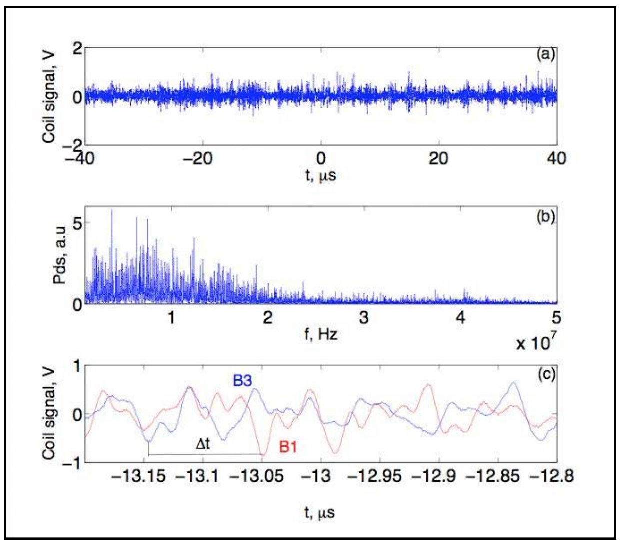

Figure 7. B3 signal (a), its spectrum (b) and zoom of the B1 and B3 signals (c).

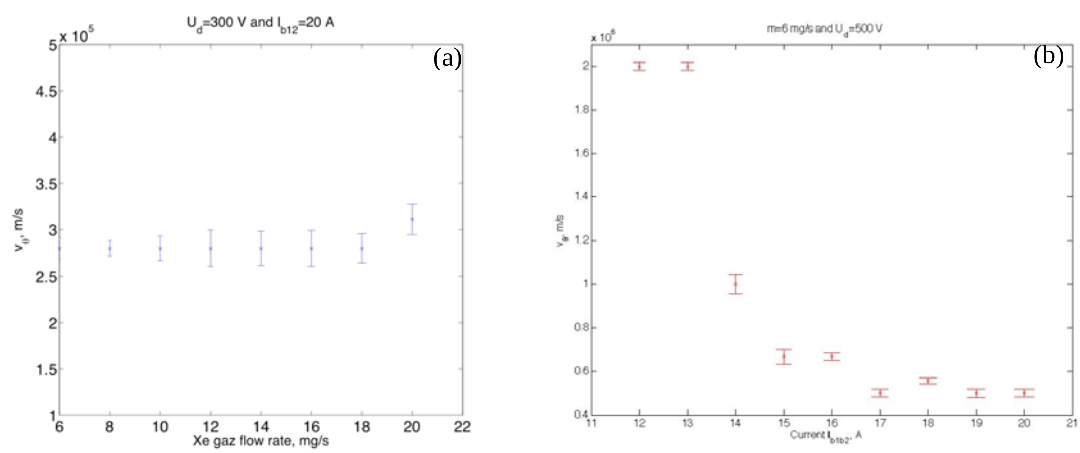

Figure 8. Azimuthal velocity of the instability as a function of Xe gas mass flow rate (a) and as a function of radial magnetic field Br (b)

When the discharge voltage and magnetic field are kept constant (U_d=300V, I_{b1b2}=20A), the inferred azimuthal velocity v_θ is constant as a function of Xe gas mass flow rate in this range of thruster operation parameters (Fig.8 (a)) and stays ~ 2.8 10^5 m/s. We see also, for nominal operation mode (U_d=500V, m=6mg/s), that v_θ decreases when we increase the magnetic field of the thruster; it seems to decrease as 1/B (Fig.8 (b)).

We wanted to know the effect that could have the discharge voltage on HF instabilities. For this study, we preferred to with draw the coils and amplifiers installed on the thruster by simple precaution. Indeed, this study is based on the variation of discharge voltage U_d, we didn't know if the components that constituted the circuits were going to hold excessive temperature of the thruster. These values are given by the calculation of cross-correlation function of signal between the probes A5 and A6. The figure (Fig.9) presents v_θ variation for three nominal operations modes (I_{b1b2}=17A, m=6mg/s; I_{b1b2}=20A, m=6mg/s; I_{b1b2}=20A, m=4mg/s). v_θ increases with the discharge voltage U_d. With $E_z=B_r*v_\theta$ and if B_r is fix then E_z increases with U_d, this result is confirmed by measurement by the Laser Induced Fluorescence (LIF) (Fig.9).[15]

If we fix the flow at 6 mg/s, we see that, for a given discharge voltage, v_θ decreases with coil current I_{b1b2}. We find the results in the figure (Fig. 8 (b)). Now, if we fix I_{b1b2} at 20A and we look at v_θ as a function of Xe gas mass flow rate, we see that, for a given discharge voltage, v_θ stays almost the same: we find the results in the figure (Fig.8 (a)).

We deduced the magnitude of induced magnetic field outside the channel (at the location of the coils) by applying the transfert function obtained from the calibration (Eq. 3 and 4) (Fig.10 (a)). The magnetic field has amplitude of ~10^{-6} T being significantly smaller than the stationary magnetic field, thus affecting only a little electron motion.

The HF component of magnetic field was extracted by applying a digital 'ellip' high-pass filter (Fig.10 (b)-(c)). All three components of the non-stationary magnetic field have close magnitude.

The source of such non-stationary magnetic field can be modeled by a system of electron current localized in the plasma volume. The currents can be directed various way, but the whole current system is supposed to turn around the center of the channel as a rigid body with frequency of 8 MHz corresponding to the first HF spectral peak (Fig. 11). The contribution to the magnetic field were calculated separately for each current and then added to obtain the resulting field. The calculation was done with the help of the vector potential $\vec{A}$:

$$\vec{A} = \frac{\mu_0}{4\pi}\int \frac{\vec{I}}{R} dl \quad (5)$$

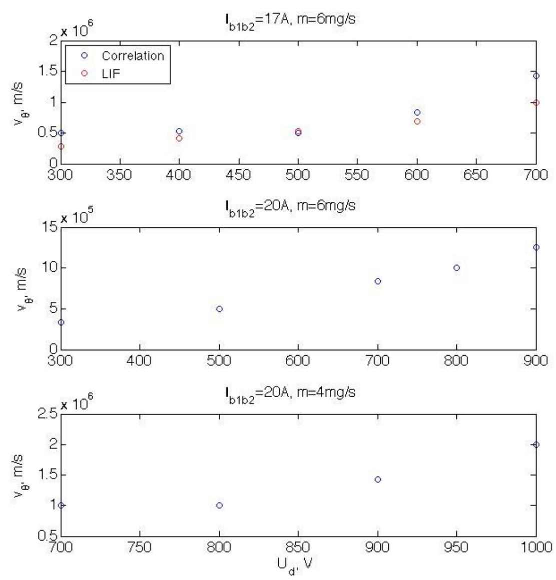

Figure 9. Azimuthal velocity of the instability as a function of discharge voltage U_d.

where $\vec{I}$ is the current of charged particles, and dl is the infinitely small linear element of the current. The magnetic field is calculated for a coil located in (x_0=97mm, y_0=0, z_0=10 mm).

For simplicity, the current of the charged particles I is considered as three types of elementary currents: an axially oriented current I_z, an azimuthal current I_θ and a radial current I_r. The absolute value of the all the current was chosen to be equal to the estimated electron current through the magnetic barrier I_d. The values of elementary currents were taken to be 0.2* I_d.

The total magnetic field from each elementary current are presented in figure (Fig.12). It can be seen that the axial current I_z cannot reproduce the experimentally observed HF magnetic field (see Fig 10 (c)). But, these elementary currents give a correct order of magnitude for the magnetic field.

The present measurements and modeling suggest the electron current through the magnetic field to be localized rather than uniformly distributed in the plasma volume. From the friction force between the instability and the electrons[4], the electron effective collision frequency can be estimated as 10^5-10^6 s^{-1} in the core plasma, whereas the 'classical' collision frequency ~ 10^5 s^{-1}.[7] We calculate the electronic mobility μ_e by the formula I_e=0.2*I_d. We estimate the electron density at 1.82 10^{11} cm^{-3} and the electric field with 7.52 10^3 V/m, we have the electronic mobility equalizes to 0.58 $m^2V^{-1}s^{-1}$, whereas the 'classical' diffusion by collisions with particles $\mu_e = \frac{m_e \nu_e}{e B_r^2}$ gives the mobility of 0.038 $m^2V^{-1}s^{-1}$ for a collision frequency ~10^6 s^{-1} measured with T_e=20eV. The given electronic mobility by the 'classical' diffusion is much smaller than fluctuation electronic mobility. These calculation are made for PPS®X000 thruster and for working conditions U_d=500V, m=6mg/s and I_{b1b2}=17A.

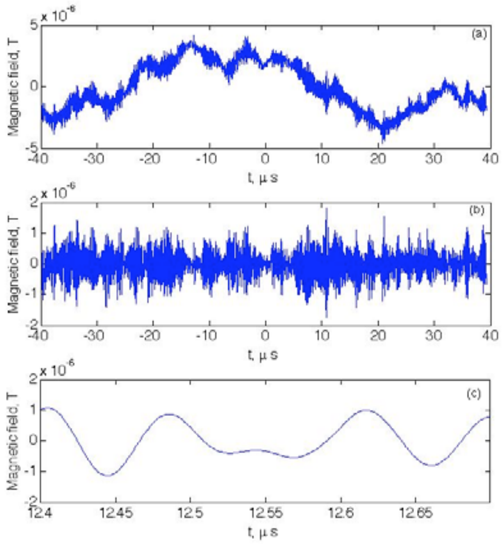

Figure 10. Magnetic field detected by coil B3; (m=6mg/s, U_d=300V and I_{b1b2}=13A)
(a) total field, (b) HF field>1MHz, (c) zoom on HF field.

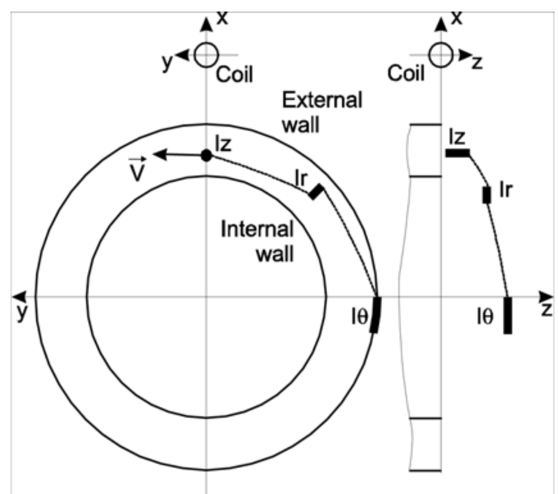

Figure 11. Configuration of elementary currents

V. Conclusion

The HF magnetic field fluctuations measurements in a Hall thruster reveal the nature of the physical processes that govern electron transport. Magnetic field measurements give complementary information about ion acceleration processes and Hall current evolution. We have shown that source of HF instabilities can be represented by localized currents with different orientations. This approach permits to reconstruct the anomalous electron current in a HET. We have demonstrated that the localized (in axial, radial and azimuthal directions) detection of the non-stationary magnetic fields represents a valuable and very important type of diagnostic for probing non-stationary processes in Hall thrusters. Such a diagnostic can be both nonintrusive and intrusive.

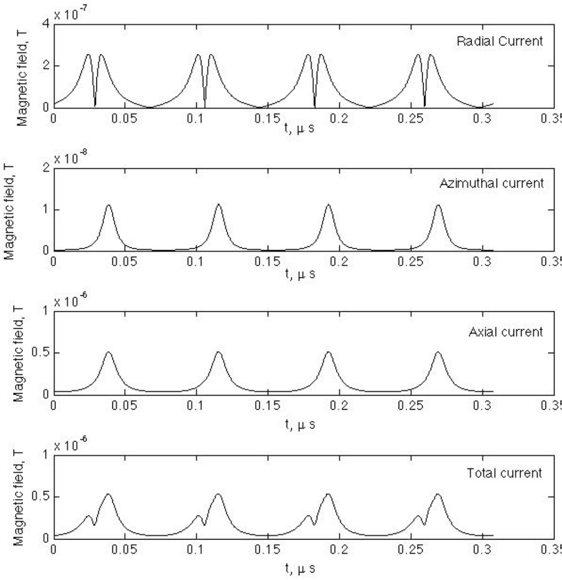

Figure 12. Simulated magnetic field

Acknowledgments

The authors acknowledge the technical support of P. Lasgorceix, C. Legentil and S. Sayamath. This work was performed in the frame of research program GDR n°2759 CNRS/CNES/SNECMA/Universities "Propulsion Spatiale à Plasma".

References

[1]Esipchuck, Y. V., and Tilinin, G. N., "Drinft instability in a Hall-current plasma accelerator," *Sov. Phys. Tech. Phys.*, Vol. 21, No. 4, 1976, pp. 477.

[2]Litvak, A. A., Raitses, Y., and Fisch, N. J., "Experimental studies of high-frequency azimuthal waves in Hall thrusters," *Phys. Plasmas*, Vol. 11, No. 4, 2004, pp. 1701.

[3]Prioul, M., "Experimental Study of Hall Thruster," PhD thesis University of Orleans, 2002.

[4]Lazurenko, A., Vial, V., Prioul, M., and Bouchoule, A., "Experimental investigation of high-frequency drifting perturbations in Hall thrusters," *Phys. Plasmas*, Vol. 12, No. 1, 2005 (013501).

[5]Litvak, A. A., and Fisch, N. J., "Rayleigh instability in Hall thrusters," *Phys. Plasma*, Vol. 11, No. 4, 2004, pp. 1379.

[6]Adam, J. C., Héron, A., and Laval, G., "Study of stationary plasma thrusters using two-dimensional fully kinetic simulations," *Phys. Plasma*, Vol. 11, 2004, pp. 295.

[7]Lazurenko, A., Dudock De Wit, T., Cavoit, C., Krasnoselskikh, V., Bouchoule, A., and Dudeck, M., "Determination of the electron anomalous mobility through measurements of turbulent magnetic field in Hall thrusters," *Physics of Plasmas*, Vol. 14, 2007, pp. 1-11 (033504).

[8]Morozov, A. I., and Savelyev, V. V., *Rev. Phys. Plasmas*, Vol. 21, 2000, pp. 203.

[9]Duchemin, O., Dumazert, P., Cornu, N., Estublier, D., and Darnon, F., "Stretching the operational envelope of the PPS-X000 plasma thruster," *paper AIAA-04-3605 at the 40th Joint Propulsion Conference*, USA, 2004.

[10]Boeuf, J-P., and Garrigues, L., *J. Appl. Phys.*, Vol. 84, 1998, (3541).

[11]Zhurin, V. V., Kaufman, H. R., and Robinson, R. S., *Plasma Sources Sci. Technol*, Vol. 8, R1, 1999.

[12]Lazurenko, A., Albarède, L., and Bouchoule, A., *Phys. Plasmas,* Vol. 13, 2006 (083503).

[13]Choueiri, E. Y., *Phys. Plasmas*, Vol. 8, 2001, pp.1411.

[14]Mazouffre, S., Lazurenko, A., Lasgorceix, P., Dudeck, M., D'Escrivan, S., and Duchemin, O., "Expanding frontiers: Towards high power Hall effect thrusters for interplanetary journeys," *Proceeedings of the 7th International Symposium on Launcher Technologies*, Barcelona, Spain, paper 0-25, 2007.

[15]Gawron, D., Kulaev, V., Mazouffre, S., and Sadeghi, N., "A LIF study on the acceleration layer features in a 5 kW-class Hall effect thruster" *Proceeedings of the 30th International Electric Propulsion Conference*, Florence, Italy, paper 160, 2007.