Magnetic fluctuations in a MPD thruster with passive systems for the control of MHD instabilities

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M. Zuin[1♠], M. Andrenucci[2,3Ж], V. Antoni[1◊], R. Cavazzana[1*], M. De Tata[≂], E. Martines[1♣], F. Paganucci[2,3♦], P. Rossetti[2Ͽ], G. Serianni[1ß], F. Tarallo[1‡],
[1] *Consorzio RFX, Associazione Euratom-Enea sulla Fusione, corso Stati Uniti 4, 35127 Padova, Italy*
[2] *Alta/Centrospazio, via A.Gherardesca 5, 56014 Pisa, Italy*
[3] *Department of Aerospace Engineering, University of Pisa, via Caruso, 56122 Pisa, Italy*

Abstract: An experimental analysis of magnetic fluctuations is performed in the plasma produced by an MPD thruster, equipped with passive systems for the control of magneto-hydrodynamic (MHD) instabilities, and in particular of the virulent kink instability. In previous experiments on other MPD thrusters, the development of the helical kink mode, due to a violation of the Kruskal-Shafranov criterion, was observed when a critical current level is exceeded and associated to the so called 'onset' phenomena observed in this kind of devices (increase of power losses and unstable operation).

The thruster was operated both in self-field and in applied-field configurations, with a maximum axial magnetic field of 100 mT induced by an external coil on the axis of the thruster. The effect of the passive control system on plasma instability is analysed in terms of the levels of the magnetic field fluctuations and of their axial, azimuthal and time periodicities, the diagnostic set up consisting of a system of magnetic coils located in the interelectrode and in the external plume regions. Different geometries of the control system have been tested and the effectiveness of each of them in reducing plasma instabilities at different plasma current levels is analysed.

I. Introduction

Magneto-plasma-dynamic (MPD) thrusters constitute a high power electric propulsion candidate for primary space missions. They act as electromagnetic plasma accelerators, with a possible range of operations spanning from orbit-raising to interplanetary manned and/or cargo missions of large spacecraft. The accelerating force is produced by the interaction between a current, driven by the application of a potential difference between an anode and a cathode, and a magnetic field which can be totally self-induced (i.e., produced by the plasma current itself) or a combination of a self-induced and an externally applied one. Presently, one of the major problems

♠ Researcher, Consorzio RFX, Corso Stati Uniti 4, 35127 Padova, Italy. matteo.zuin@igi.cnr.it
Ж Full Professor, Aerospace Engineering Dept., University of Pisa, AIAA Senior Member, E.P. Technical Committee. m.andrenucci@alta-space.com
◊ Senior Researcher, Consorzio RFX, Corso Stati Uniti 4, 35127 Padova, Italy. vanni.antoni@igi.cnr.it
* Researcher, Consorzio RFX, Corso Stati Uniti 4, 35127 Padova, Italy. roberto.cavazzana@igi.cnr.it
ƒ Project Manager, Alta SpA. p.rossetti@alta-space.com
≂ Graduate Student, Alta SpA. m.detata@alta-space.com
♣ Researcher, Consorzio RFX, Corso Stati Uniti 4, 35127 Padova, Italy. emilio.martines@igi.cnr.it
♦ Associate Professor, Aerospace Engineering Dept., University of Pisa, AIAA Senior Member. f.paganucci@alta-space.com
Ͽ Project Manager, Alta SpA. p.rossetti@alta-space.com
ß Researcher, Consorzio RFX, Corso Stati Uniti 4, 35127 Padova, Italy. gianluigi.serianni@igi.cnr.it
‡ Graduate Student, Consorzio RFX, Corso Stati Uniti 4, 35127 Padova, Italy. flavio.tarallo@igi.cnr.it

facing MPD thruster operation is the onset of a critical regime, which is found when the power is increased beyond a threshold value[1]. In this regime, large fluctuations in the electrode voltage signals and damage to the anode are observed along with efficiency degradation. Recently, an experimental campaign aimed at the investigation of electrostatic and magnetic properties of plasma fluctuations has evidenced a strong relation between this so-called 'onset' phenomenon and the growth of a large-scale magnetohydrodynamic (MHD) instability, with the features of a helical kink mode, due to a violation of a MHD stability criterion [2,3,4,5]. It is the well-known Kruskal-Shafranov (KS) criterion of a widely general validity for almost all current-carrying plasma devices. The KS criterion indicates, for a finite-length cylinder, or, equivalently, in a periodic toroidal geometry, a minimum ratio between the externally applied (axial) magnetic field, B_z, and the azimuthal magnetic field, B_θ, induced by the current flowing in the plasma, in order to insure the stability of the m/n=1/1 (m and n azimuthal and toroidal periodicity, respectively) kink mode. It is worth to mention that a pure Z-pinch, i.e. with no applied magnetic field, is always unstable to m=1 perturbations and is likely to be unstable to m=0 as well[6]. The minimum ratio B_z/B_θ depends on the geometry of the system: the KS criterion is usually cast in the form $q(r)=rB_z/RB_\theta>1$ in toroidal geometry (r and R minor and major radii of the torus, respectively) or for the case of a cylinder of finite-length, L, $q(r)=rB_z/(L/(2\pi))B_\theta>1$, where q(r), function of the minor radius r, is the so-called safety factor. In thermonuclear fusion devices, such as the tokamaks, the stability of the kink mode is essential in order to reach the ignition condition, as it is well known that its growth drives the system to large energy and particles losses and consequent disruptions[6]. In ITER (the International Thermonuclear Experimental Reactor), for instance, the condition q>1 will be obtained by means of extremely large toroidal magnetic field (up to 5.3 T) induced by superconducting coils immersed in a huge cryostat[7].

In MPD thrusters the situation is, somehow, even more complicated than in fusion devices, because of their open geometry. It has actually been observed that the application of an external magnetic field does not necessarily drive the system to a q(r)>1 condition, because the axial length L of the system is not a constant, but a function of the applied magnetic field itself, $L=L(B_\theta)$[8].

On the basis of these experimental observations, a recent attempt of controlling plasma instability in this kind of devices was focused on intercepting the undesired helical current components, associated to the deformation of the plasma column, due to the developed kink mode. The method was based on the insertion in the inter-electrode region of the thruster of an insulating plate in the (r,z) plane, which divided the plasma channel in two halves, thus impeding the formation of azimuthal plasma current components and preventing the free development of the kink mode[9]. The method, despite its simplicity, proved to be successful not only in significantly reducing plasma and electrode voltage fluctuations, but also in improving thrust efficiency, by reducing the power needed to sustain the discharge for a given plasma current[10].

In the present work we present the results of a further experimental campaign aimed at confirming and extending the results obtained.

In particular, different geometries of the passive control system have been tested, in different experimental conditions, spanning from low to high plasma current discharges, in self and applied-field configurations.

II. The experimental equipment

The MPD thruster under investigation has been operated both in self-field and in applied-field configurations, as an axial magnetic field up to 100 mT on the thruster axis can be induced by means of an external solenoid. The anode consists of a copper ring, 62 mm internal and 108 external diameters, placed at the thruster outlet, while a copper hollow cathode, 16 mm in diameter, is located in the inner region of an insulating cylindrical support, made of MACOR®. A schematic of the thruster is shown in Fig. 1, where the z = 0 of our cylindrical system of coordinates is indicated to be at the thruster outlet, with the z-axis pointing towards the open side of the device (r = 0 is set to coincide with the thruster axis). The electric power is supplied by a Pulse Forming Network (PFN), which can supply quasi-steady current pulses (I_p) lasting 5 ms.

The propellant feeding system provides gas pulses with a long plateau after few milliseconds from fast acting solenoid valve activation, which precedes of 20 ms the electric discharge. The discharge takes place at t = 0, when a steady state mass flow rate is reached. The propellant used for the experiments described in this paper is argon at a mass flow rate of 100 mg/s, with an uncertainty within 5%.

The thruster is mounted on a thrust stand inside a cylindrical vacuum chamber (*length* = 3.5 m, *radius* = 0.6 m), which allows maintaining a backpressure of the order of 10^{-2} Pa during the pulse. The size of the vacuum chamber is large enough to avoid plasma-wall interactions for the plume of the thruster; this is an important condition, which validates the hypothesis that the plasma is freely expanding and that boundary effects are not crucial in determining the discharge behaviour.

The thruster electrodes are floating with respect to the ground and the arc voltage (ΔV) is obtained by measuring the potential of each electrode with respect to the ground by means of two high voltage probes. The arc voltage

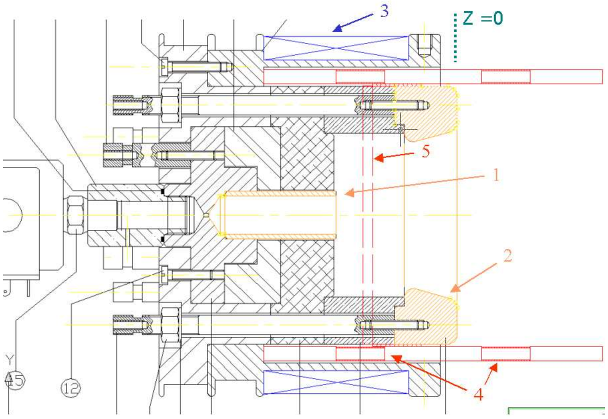

Fig. 1: Schematic of the MPD thruster and of the diagnostic system. 1) Cathode; 2) Anode; 3) External solenoid; 4) Magnetic pick-up probes; 5) Flux-probe

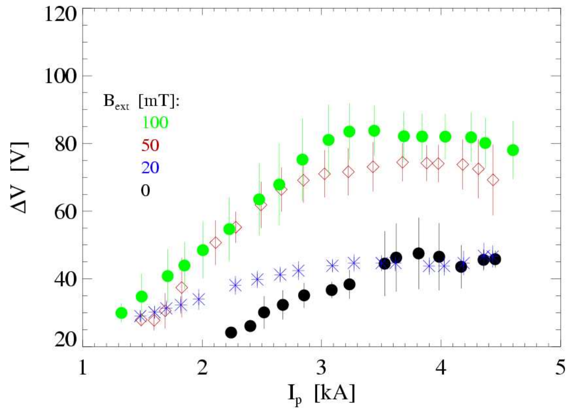

Fig. 2: Electrical characteristics of plasma discharges at different B_{ext} values.

is then obtained by subtracting the cathode voltage signal from the anode voltage signal.
In the experiments described herein the discharge current I_p has been varied in the range 1.5 - 5 kA, and an external field B_{ext} from 0 to 100 mT has been applied. The thruster has been operated in power regimes spanning from 30 to 400 kW. The voltage difference between the anode and the cathode ranges from 20 to 90 V after breakdown, corresponding to an initial charge of the PFN ranging from 600 to 1200 V.
The electrical characteristics (I_p vs. ΔV curves) obtained for four different B_{ext} values can be found in Fig. 2.

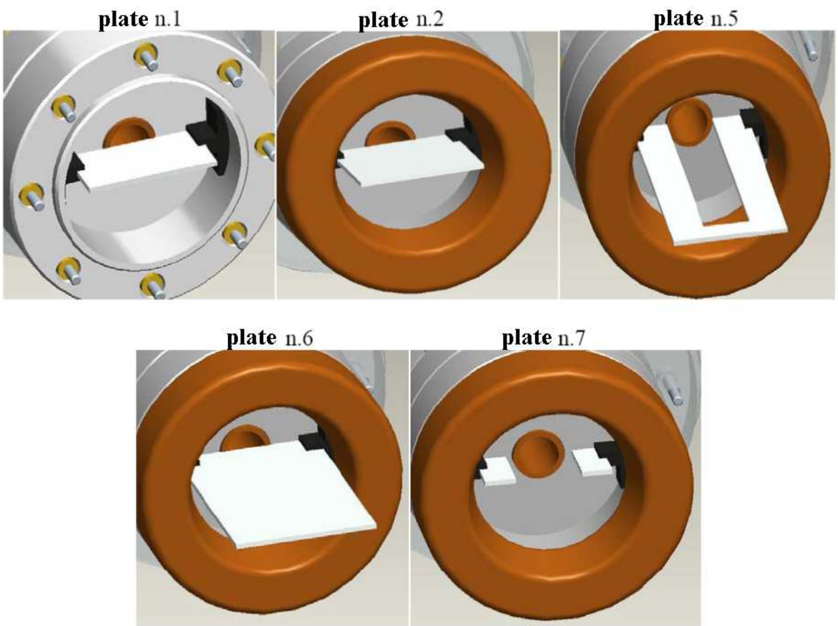

Fig.3: Schematic of the passive control systems (white plates) used.

A variety of geometries of the passive control system has been tested, in order to explore the relevance of different plasma regions in the various experimental conditions. In particular, we decided to test plates occupying the total section of the inner plasma channel, or just a fraction of it, or even protruding outside of the thruster outlet, extending in the outer plasma plume. In Fig. 3, the schematic drawings of those actually used are shown. Hereafter the different geometries will be recalled with the numbering indicated in Fig. 3, while, with the number 0, we will refer to the standard MPD configuration, without any system for the control of plasma instabilities. The plates are made of plexiglass, a rather poor material, which, anyway, has proved robust enough to support the heat fluxes produced in the plasma channel without any detectable damage after few shots of testing.

III. The diagnostic system

The diagnostic setting up consists of two azimuthal arrays of magnetic (pick-up) probes made of coils wound on a support structure, constituted by 4 cylinders, as shown in Fig. 1. In order to obtain a less perturbative diagnostic system as possible, the two azimuthal arrays have been located on the external surface of the insulating supporting cylinder (at r = 58 mm), one at z = - 40 mm (in-between the electrodes, axially), the other at z = 20 mm, thus outside of the thruster outlet, in a marginal position with respect to the plasma plume. Each array consists of 4 equally spaced magnetic coils, measuring B_z fluctuations. An additional magnetic coil, of radius r_c = 54.5 mm, has been placed coaxially to the thruster, wound around the supporting insulating structure at z = -37 mm, in order to measure the fluctuations of the magnetic flux on the total thruster section (r,θ); this probe will be named, hereafter, flux-probe. The estimated bandwidth for the signals extends up to 1 MHz. The sampling frequency was 5 MHz. The azimuthal arrays have been used to discriminate the contribution of different azimuthal periodicities. It was sufficient to use only 4 probes for each array, since it was already experimentally known that in MPD thrusters the dominant modes present after the onset had mode number m = 0 and m = 1 (where the mode number m comes from the Fourier-decomposition of signals in the azimuthal direction as: $f(\theta) = \sum_m a_m e^{im\theta}$)[3]. The use of two different arrays, axially spaced, allows obtaining information about the axial periodicity.

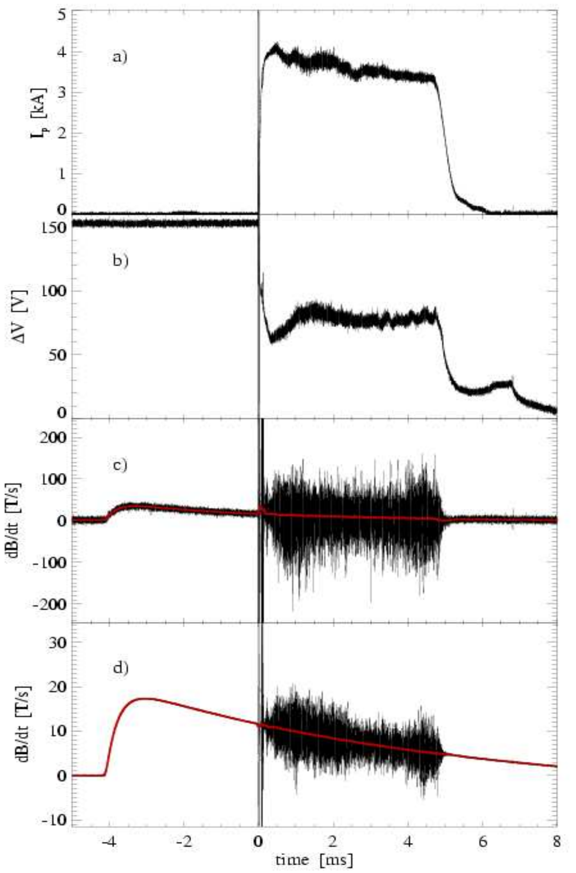

Fig. 4: Time history of a typical plasma discharge. a) Plasma current I_p; b) Applied voltage ΔV; c) Pick-up coil signal (at z=??); d) Flux-probe signal. Red lines are the low frequency component of the time-derivative of the B_z magnetic field. B_{ext}=100 mT in this case.

IV. Experimental results

In Fig. 3 an example of the time evolution of typical discharge signals, plasma current, I_p, and applied voltage, ΔV, between the cathode and the anode, is shown, along with the signal of a single pick-up coil of the array at z = -40 mm, and the signal of the flux-probe.

The example refers to a discharge with B_{ext}=100 mT, whose generation, occurring at t=-4 ms, can be clearly observed in the low frequency component (the superposed red line) in the pick-up probes signals. After its generation B_{ext} is observed to follow a slow time evolution and to remain almost constant (i.e. the time derivative of the axial magnetic flux is close to zero) during the flat top phase of the discharge. The generation of the plasma current is accompanied by large fluctuations on the magnetic signals, sign of developed MHD instabilities. A detailed analysis, in an expanded time window of the signals (numerically integrated) from the inner array of probes (Fig. 5a) actually shows that such fluctuations have a quasi-regular behaviour with an m=1 azimuthal periodicity. An azimuthal propagation can be deduced by the phase shift between probes in different azimuthal positions, evidenced by the black dashed line in the figure at a frequency close to 100 kHz. The same feature is observed on the external array of probes (Fig. 5b) located at z = 20 mm. A time shift, $\Delta t \approx 3\ \mu s$, between two probes in the same azimuthal, but different axial positions, can be measured (dashed blue line).

This corresponds, at 100 kHz, to an estimated axial wavelength λ_z (= $f^{-1}\Delta z/\Delta t$) of the mode of ~20 cm, comparable to the axial dimension of the total plasma plume, thus confirming previous observations on different MPD thrusters of the formation of helical rotating structures with *m/n*=1/1 periodicities, due to the development of the kink mode instability[2].

The effect of the various configurations of the control system is investigated in Fig. 6, where the RMS value of the signal of a single coil from the arrays at *z* = -40 mm and *z* = 20 mm and of the flux-probe, evaluated over time intervals of 0.5 ms during the flat-top phase of the discharge, is shown as a function of the plasma current for all the B_{ext} conditions explored. An increase of the RMS value with the plasma current is observed without any control system.

In the discharges with B_{ext}=0, a reduction of the fluctuation levels is observed to be induced by all the inserted plates on the signals of the two arrays of probes (taken at *r* = 58 mm, *z* = -40 mm and at *z* = 20

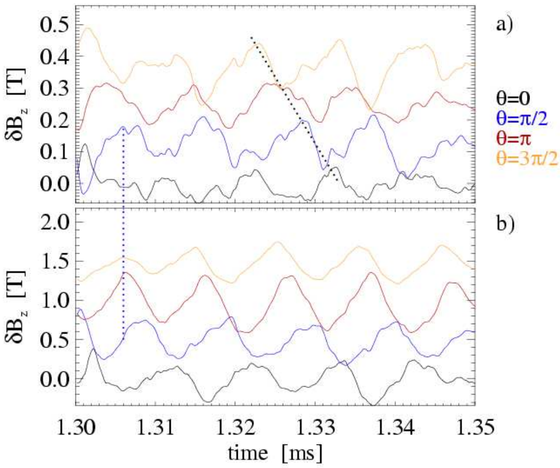

Fig. 5: Expanded time window of magnetic field fluctuations form the arrays located at z=-40 mm a) and at z= 20 mm b). (Signals at θ>0 have been vertically shifted.)

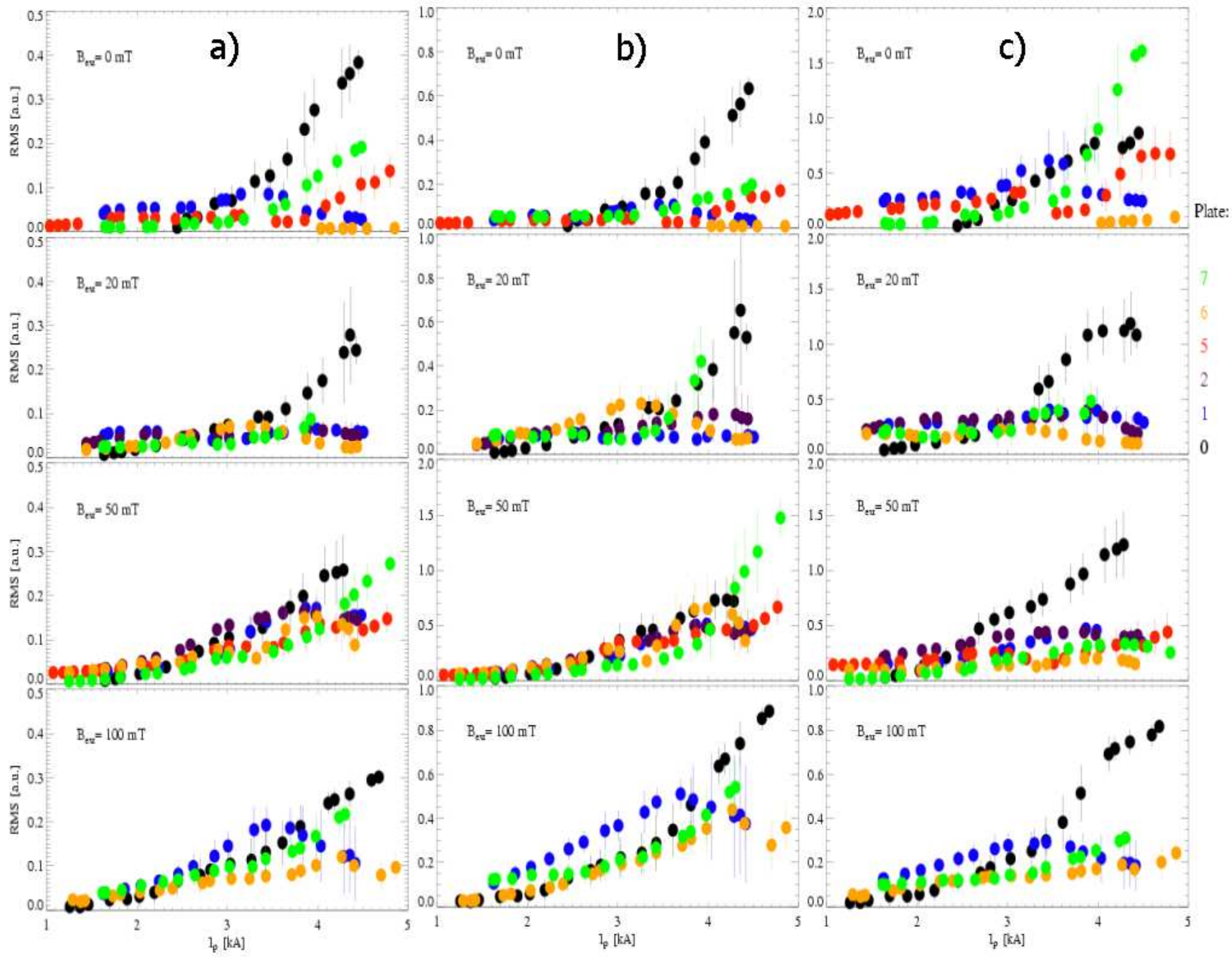

Fig. 6: RMS of magnetic signals: a) taken at z = -40 mm, b) at z = 20 mm, c) of the flux-probe, as a function of the plasma current, in different B_{ext} conditions and with the various plates for MHD control.

mm, Fig. 5a,b), with the largest effect produced by the large plates (n° 1 and 6). The less intrusive plate, n° 7, which is actually rather effective in reducing plasma fluctuations at r= 58 mm, is observed to have almost no-effect on the signal from the flux-probe (Fig. 5c). It is worth to note that the flux-probe gives a measure of the magnetic fluctuations averaged over the entire plasma section, while the coils at the edge of the plasma column give a local measure of the same quantity. The plate n° 7 seems, instead, to be more effective in reducing plasma fluctuations in the whole plasma channel in discharges with non-zero external magnetic fields (B_{ext}= 20,50 and 100 mT), which show a fluctuation level reduced at high current even of a factor up to 6. At B_{ext}>20, also the plates n° 1 and 6 give a larger effect, in terms of reduction of the RMS value, on the flux-probe signal, than on the two probes measuring the magnetic fluctuations at the edge of the plasma channel, which means that the plasma regions affected by fluctuations strongly depend on the magnetic topology of each discharge, and in particular on the radial profile of the magnetic fields, determining the position of the rational surface and then the radial eigenfunction of the resonant plasma deformation.

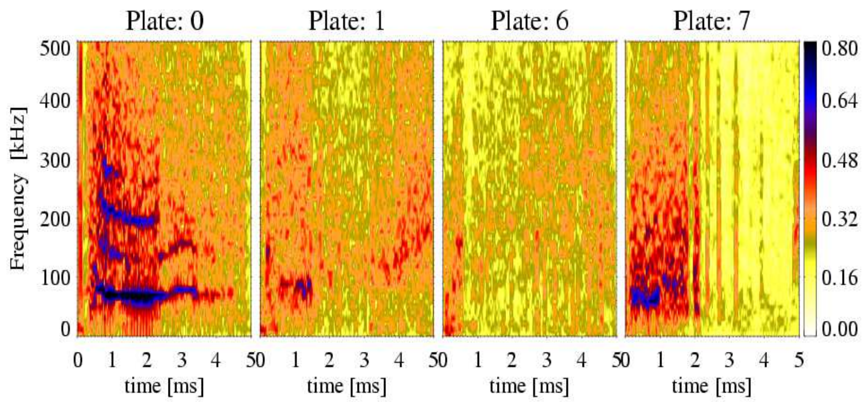

Fig. 7: Spectrograms of the flux-probe signal with various control systems. The color-scale is the same for all windows. I_p = 4 kA, B_{ext} = 20 mT in these cases.

In Fig. 7 the spectrogram of the flux-probe signal taken in a discharge at I_p=4 kA, with B_{ext}=50 mT is shown as an example of the time behaviour of the main frequency component of the fluctuations without and with some of the control systems. In the standard MPD thruster configuration the spectrum is dominated by a single frequency (≈100 kHz and higher harmonics), consequence of the regular (non-sinusoidal) oscillations shown in Fig. 4, which is largely depressed, when the control plates are inserted.

The observation of the reduction of the RMS values of the magnetic signals in Fig. 6 can therefore be attributed to the successful suppression of the rotating kink mode. It is important to note that the small wings, constituting the plate n° 7, which do not actually divide the entire plasma chamber, but are confined in the region at a radius larger than the cathode radius, are effective in strongly reducing the amplitude of the kink mode only after 2 ms of its development. Although we do not have any direct information on that, it is reasonable to infer that this could be due to an evolution of the radial eigenfunction of the mode, which is not constant in time, but evolves towards larger radii during plasma channel formation.

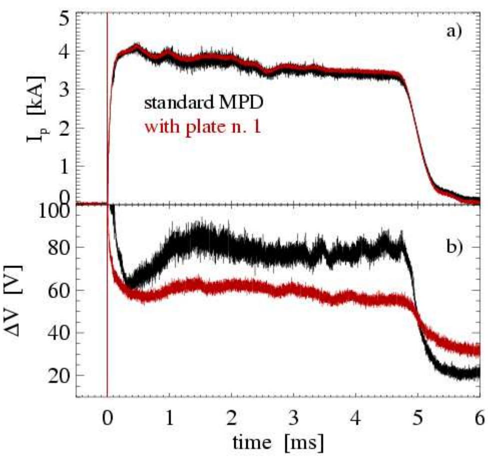

Fig. 9: a) Plasma current, Ip, and b) applied voltage, ΔV, time evolution during discharges in standard MPD configuration (black curves) and with the insertion of one of the control systems used (red curves). B_{ext} =100 mT in these cases.

The effect of the control systems on the power balance of the discharges is studied in terms of the variation of the discharge signals (I_p and ΔV), whose time evolution in a single shot is shown in Fig. 8, and of the electrical characteristics in Fig. 9.

In Fig. 8, showing an example at B_{ext}=100 mT with and without the insertion of the plate n° 1, it can be clearly seen that along with a reduction of the amplitude of the fluctuations of both I_p and ΔV, a significant reduction of the mean value of the latter is present during the flat top phase of the discharge, which is an indication of the reduction of power losses.

A robust decrease (up to 50%) of the power needed to sustain the discharge at high current levels is actually observed to be induced by the plate n° 1 in all discharges with B_{ext}>20 mT (Fig. 9). It is interesting to note that at B_{ext}=50 mT the insertion of all the plates produces a reduction of the applied voltage, while at B_{ext}=100 mT only the plates n° 1 and 7 seem to be effective in this respect (with the plate n° 6 largely perturbing the discharge and increasing the request of power). At low B_{ext} (≤ 20 mT) no clear effect on the electrical characteristics is seen, despite the decrease of the magnetic fluctuations measured outside of the plasma channel.
It is important to note that at low current levels the insertion of the plates actually gives rise to a detrimental effect on the electrical characteristics, which anyway appear as functions only slightly depending on the plasma current.
The decrease of the power losses seems to be mostly related to the reduction of fluctuations in the core plasma as evaluated by means of the flux-probe, as the strong suppression of the RMS of the signals taken at the edge of the device in low B_{ext} (≤ 20 mT) discharges does not correspond to any evident variation of the I_p vs. ΔV curves. This suggests (and confirms) the importance of taking measurements (direct or indirect, i.e. by means of the emitted radiation analysis) of plasma fluctuating parameters inside of the current channel in order to correctly understand the physics of this kind of devices.

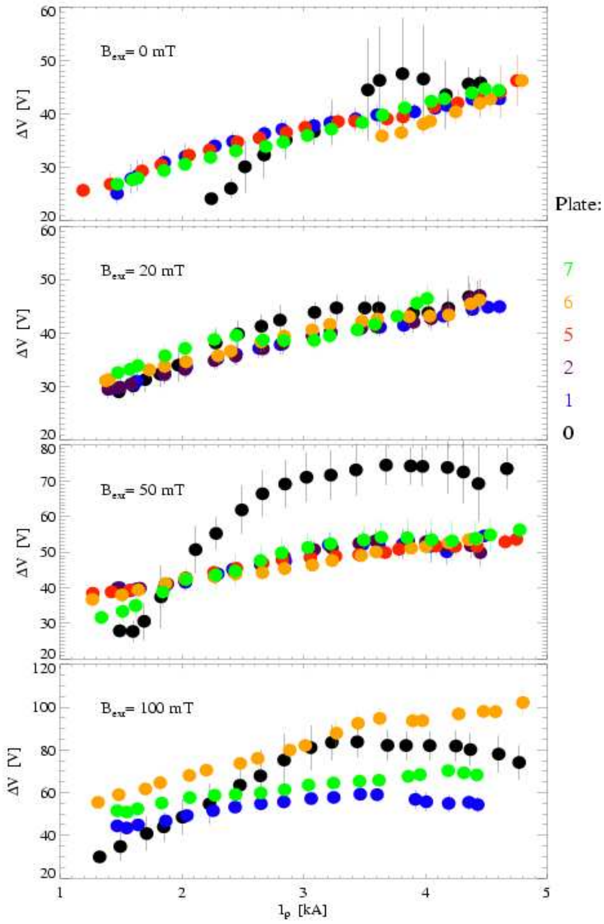

Fig. 9: Electrical characteristics of plasma discharges with various geometries of the inserted plate.

V. Conclusions

A set of experiments has been performed in order to confirm and extend previous results on the control of large-scale MHD instabilities developing in the plasma channel of a MPD thruster when operating at high current levels in self-field and applied-field configurations.
The technique is based on a reconfiguration of the thruster geometry obtained by means of the insertion in the interelectrode region of an insulating plate, which divides the plasma channel, intercepting the helical current components produced by the instability.
A variety of geometries of the insulating plate has been tested, and the efficacy of each of them in different experimental conditions has been investigated. We observed that an insulating plate placed in front of the cathode region and even small plates located in the outer radial positions are effective in decreasing plasma fluctuations and power losses at high B_{ext} conditions. The effect at low B_{ext} is not that clear.
It has been proved that large plates, extending outside of the interelectrode region, while exhibiting an intense capability of reducing magnetic fluctuations, have a detrimental effect on the power balance of the discharge.
The importance of measuring plasma fluctuations in the core of the plasma channel in order to correctly relate fluctuations reduction and power balance improvement has been highlighted.
The effect of control systems on thruster performance is the object of one parallel study presented at this Conference[11].

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