Performance Improvement due to Kink Instability Suppression in MPD Thrusters

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Abstract: Previous experimental investigations, carried out at Alta/Centrospazio in collaboration with Consorzio RFX, on magnetic and electrostatic fluctuations in gas-fed MPD thrusters (both self and applied field), have shown that gross magnetohydrodynamic instabilities develop whenever the current rises beyond a threshold value. These instabilities have m/n = 1/1 azimuthal and axial periodicity and are interpreted in terms of helical kink modes. The paper deals with experimental observations relating the kink mode amplitude, measured by a set of magnetic coils, to the main discharge parameters. In particular, it is shown that a significant decrease in the applied voltage driving the discharge with no significant variation of thrust is observed when these instabilities are suppressed. The suppression has been obtained by means of a passive system (patent pending), consisting in an insulating plate, axially inserted into the discharge chamber of the thruster. The plate divides the discharge chamber in two halves and interrupts the helical currents produced by the kink, effectively stabilizing the kink itself.

I. Introduction

MPD thrust efficiency is normally observed to decrease above a current threshold condition, whose value depends on thruster geometry, propellant, mass flow rate, and applied magnetic field. When this threshold value is reached, a variety of disturbing phenomena, including severe fluctuations of the arc voltage and increased erosion, has usually been observed. The condition at which this unstable discharge behaviour occurs is usually referred to as "the onset". A number of theories (especially on self-field MPDs) have been put forward to explain the onset phenomena and to understand the origin of the performance degradation, in particular to clarify the role played by plasma instabilities. Theoretical and experimental efforts have been dedicated by some Authors to the investigation of plasma microinstabilities[1,2] as responsible for the enhanced collisionality and anomalous

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resistivity and of plasma macroinstabilities[3,4,5], which could be related to the drastic transition associated with the onset. Despite the long series of efforts, the origin of the plasma phenomena regulating the thruster performance is still a matter of debate. In particular, no theory has proved conclusive in explaining the behaviour in detail or in prompting ways to control or postpone the detrimental effects associated with the onset.

Since 2000, Alta/Centrospazio (Pisa) and Consorzio RFX (Padova) have collaborated in an extensive experimental activity aimed at assessing onset phenomena in MPDs, by means of both intrusive (electrostatic and magnetic probes) and non-intrusive (imaging techniques) diagnostics. On the basis of measurements coming from electrostatic and magnetic probe arrays, the existence of critical regimes has been related to the onset of a basic magneto-hydrodynamic (MHD) instability, well known in the community of nuclear fusion research as the (m = 1; n = 1) kink[6]. This explanation has been suggested by the observation that the application of an axial external magnetic field makes the symmetry of the thruster similar to that of fusion devices, in particular to the straight Tokamak (by posing the axial coordinate $z \rightarrow \Phi$ and the length of ejected plasma $L \rightarrow 2\pi R_0$[7]). The only difference, which anyway can influence the onset mechanism, is that the MPD thruster, contrary to Tokamaks, is an open system. The limitation of the thrust efficiency has been therefore linked to the Kruskal-Shafranov limit[6,7], as it is well known by the experience on fusion devices that the presence of a large MHD instability affects the current profile, and locally modifies the density and temperature of the plasma. Recently, further evidence that the onset of critical regimes in MPDs is related to the generation of large scale kink modes has been obtained in the framework of an experimental investigation of the thruster plasma plume by means of an integrated system of both electromagnetic and optical probes, and ultraviolet tomography[8,9]. The plasma emissivity maps obtained with tomographic algorithm techniques, applied on the optical probe signals, have allowed to obtain a detailed characterization of the kink topological features at various thruster operating conditions, with and without an externally applied magnetic field. In both cases, a localized out-of axis region, more emissive than the background nearby, has been observed, displaced at different azimuthal angles, as soon as the critical conditions are reached. If an external magnetic field is applied, the emissive structure rotates azimuthally.

On the basis of the experimental evidence above mentioned, it is possible to conceive different methods of suppressing and/or postponing the onset of the kink instability, in some cases taking inspiration from methods adopted in plasma fusion research. A first successful attempt of controlling and suppressing kink instabilities in MPDs by adopting a passive method is illustrated in the following paragraphs.

II. The Experimental Equipment

A. The MPD system

The MPD thruster under investigation can operate both in self-field and in applied-field configurations, as an axial magnetic field on the thruster axis can be induced by means of an external solenoid. The anode consists of a copper ring, 200 mm in diameter, placed at the thruster outlet, while a copper hollow cathode, 20 mm in diameter, is located in the inner region of an insulating conically shaped support. A schematic of the thruster is shown in Fig. 1.

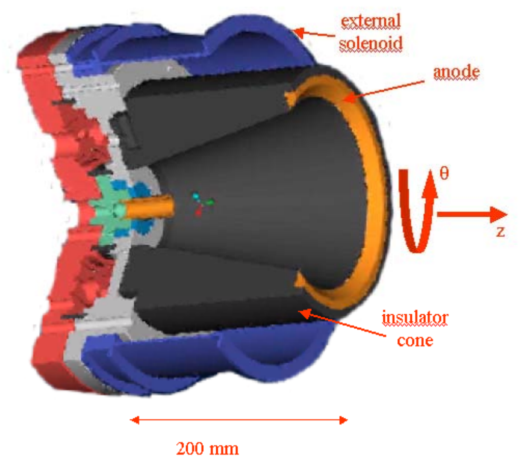

Fig. 1: Schematic of the MPD thruster under investigation, showing anode and cathode shape, and the cylindrical system of coordinates used.

The electric power is supplied by a Pulse Forming Network (PFN), which can be configured to supply quasi-steady current pulses (I_{dis}) lasting 2.5 ms or 5 ms. The propellant feeding system is based on a fast acting solenoid valve, which provides gas pulses with a long plateau after few milliseconds from valve activation, which precedes 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 ranging from 100 to 660 mg/s, with an uncertainty within 5%. A quasi-steady magnetic field (B_{ext}) up to 100 mT on the thruster axis can be induced.

The thruster has been mounted on a thrust stand inside a cylindrical vacuum chamber (*length* = 3.5 m, *radius* = 0.6 m), which allows to maintain a back pressure of the order of 10^{-2} Pa during the pulse. The thrust stand and thrust measurement procedure is described in Ref. 10. 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.
To avoid anomalous discharges involving the vacuum chamber, 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 is then obtained by subtracting the cathode voltage signal from the anode voltage signal. The electrical characteristics (I vs. ΔV curves) obtained by previous experiments[14] for three different B_{ext} values can be found in Fig. 3. In particular, at low B_{ext} values, a clear knee in the electrical characteristic is observed at a current level I_{cr} decreasing with B_{ext}. This abrupt change in the electrical characteristic is associated to the onset, i.e. the transition from *standard* to the so-called *critical* operating regimes, characterized by unstable behaviour and largely increased power losses[10,11].
In the experiments described herein the discharge current I_{dis} has been varied in the range 1.5 - 8 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 45 kW to 1.6 MW. The voltage difference between the anode and the cathode ranges from 30 to 200 V after breakdown, corresponding to a charge of the PFN ranging from about 400 to 1400 V.

B. The diagnostic system

The diagnostic setting up consists of two azimuthal arrays and one linear array of magnetic probes. The probes are made of magnetic coils wound on a support structure. The two azimuthal arrays are located in the inter-electrode region, on the internal surface of the insulating cone, so that they do not perturb the plasma. Each of them consists of 4 equally spaced bi-axial magnetic coils, measuring B_θ and B_z fluctuations. They are placed at two different axial positions, namely z = -150 mm and z = -109, where z = 0 corresponds to the thruster outlet. The linear array is made of 21 magnetic coils, alternatively measuring B_θ and B_z. It is placed at the thruster outlet, covering the full anode radius. The estimated bandwidth for the signals extends up to 6 MHz. The sampling frequency was 20 MHz. The azimuthal arrays have been used to discriminate the contribution of different azimuthal periodicities. Any fluctuating quantity f(θ) can be Fourier-decomposed in the azimuthal direction as $f(\theta)=\sum_m a_m e^{im\theta}$. 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 [6,7,9], it was sufficient to use only 4 probes for each array. The use of two different arrays, axially spaced, allows to obtain information about the axial periodicity. The radial array has been used to gather information on the radial magnetic fields profiles.

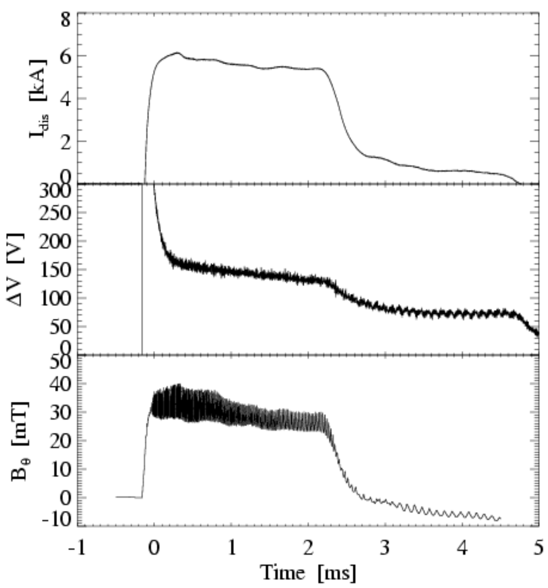

Fig. 2: Time history of a typical discharge: total plasma current I_{dis}, applied voltage ΔV, and B_θ measured by one probe of the internal diagnostic system (mfr= 400 mg/s and B_{ext} =100 mT in this case).

In some discharges a circular array of 8 equally spaced electrostatic probes has been placed at the thruster outlet. Each probe is a tungsten wire, 1 mm in radius, 2 mm long, housed in a quartz tube. These probes have been used for measuring the floating potential V_f, which is related to the plasma potential V_p and to the electron temperature T_e by $V_f = V_p - \alpha T_e$, where α is a positive constant which depends on the gas used[12].

III. Experimental Results

Typical waveforms of plasma current I_{dis}, applied voltage between anode and cathode ΔV, and a signal (numerically integrated) from one of the probes of the azimuthal array placed at z = -109 mm, measuring B_θ fluctuations, are shown in Fig. 2, for a condition beyond the onset threshold (B_{ext} = 100 mT in this case). It can be clearly observed that the magnetic measurements exhibit a high level of fluctuations during the discharge, superposed to the average level of the magnetic field induced by the plasma current itself.
This is found to be mostly related to a regular oscillation at a frequency of about 100 kHz, corresponding to m = 1 modes, and in some conditions also m = 0 modes. Previous studies have shown that such oscillation develops only when the threshold current is exceeded. This is shown in Fig. 3, where the I_{dis}-ΔV characteristic of

the discharge is plotted for 3 different B_{ext} values, together with the dependence of the total amplitude of m = 0 and m = 1 modes on the current. It is clearly seen that the change in slope of the electrical characteristic, which marks the onset condition, is correlated to a rise of the plasma mode amplitude. This shows that the onset is actually due to the development of a plasma instability, which takes the form of an m = 1 kink mode. This mode is responsible for the enhanced power losses, which lead to an efficiency degradation.

This behaviour is analogous to what is observed in some types of fusion devices, such as spheromaks and reversed field pinches, where an anomalously large loop voltage is required to sustain the plasma current when large scale MHD modes develop. Indeed, both in fusion devices and in MPDs the condition for the development of m=1/n=1 modes (n being the mode number in the axial direction) is well described by the so-called Kruskal-Shafranov criterion, which gives a threshold on the ratio between the axially applied magnetic field and the plasma current[6,13].

The new result that we present in this paper is the proof that suppressing the kink mode results in a reduction of the input power for a given current and thus an increase of the thrust efficiency. This is not only important from the physics point of view, being a further proof that the efficiency loss at the onset is due to the kink mode, but also from a technological perspective, because it opens up the concrete possibility of operating MPDs at high efficiency also beyond the onset threshold. The kink mode suppression has been obtained by inserting in the inter-electrode region an insulating plate, extending in the r-z plane (Fig. 4). The plate divides the discharge in two halves and interrupts the helical currents produced by the kink, effectively stabilizing the kink itself.

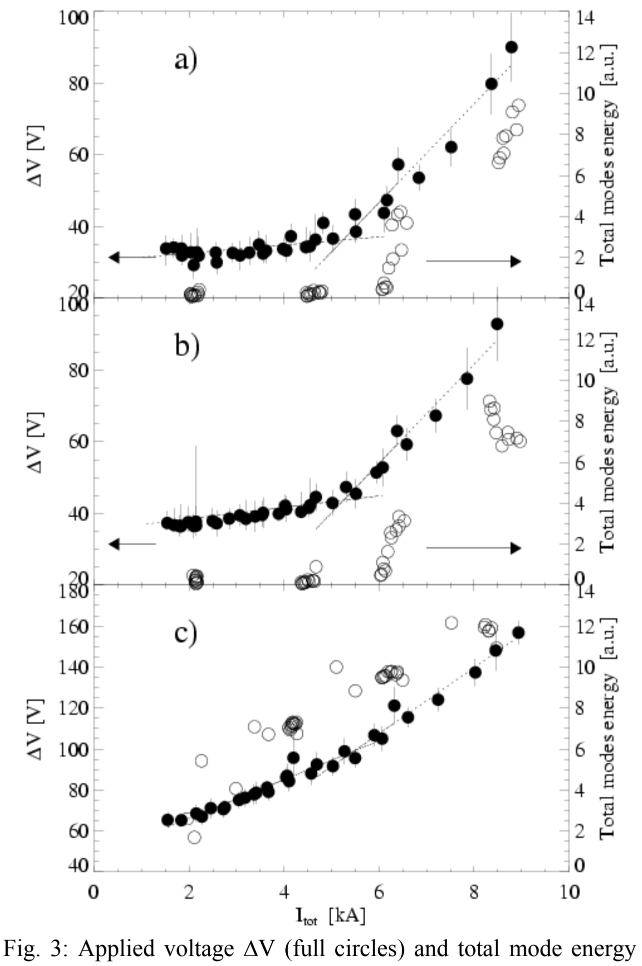

Fig. 3: Applied voltage ΔV (full circles) and total mode energy plotted as a function of the plasma current, for three different B_{ext} values (from ref. 14).

By computing the spatial Fourier transform of the signals from the azimuthal arrays, and averaging the resulting mode amplitudes over 1 ms during the discharge, we study the dependence on the discharge parameters of modes with azimuthal periodicity m=1. In Fig. 5 the mode amplitude is plotted as a function of I_{dis}, both with developed kink mode and in case of successful instability suppression. In standard operating condition the mode amplitude strongly increases with I_{dis}, but when the large-scale kink mode is successfully suppressed negligible magnetic fluctuation energy is observed. Similar results are obtained by analysing the electrostatic component of plasma fluctuations. This implies that an almost quiescent plasma has been produced. The effect of plasma instability damping on the discharge properties can be clearly deduced from the electrical characteristics of the discharge in the two conditions, as reported in Fig. 6. At low current levels (below 3 kA), when the amplitude of the mode is small also in standard condition, the two ΔV-I_{dis} curves almost coincide. At higher current levels, well above the onset critical condition (which appears between 3 and 4 kA), a large reduction of the applied voltage, about 30% of the maximum value, can be seen when good control of the kink mode is obtained (lower curve).

The effect of kink suppression on thrust is illustrated in Figs. 7 and 8. Fig. 7 shows two measurements of typical oscillations of the mobile mass of the thrust stand soon after two shots at the same operation condition (mfr= 400 mg/s; B_{ext}=40 mT; ΔV_{PFN}=1400 V) with and without plate insertion. In Fig. 8 a comparison between the operation with and without plate insertion is made in terms of maximum amplitude of oscillation of the mobile mass as a function of discharge current (mfr= 400 mg/s; B_{ext}=40 mT). As shown in Ref. 10, the amplitude of the oscillation can be correlated to thrust impulse bit. Figs. 6 and 7 indicate that kink suppression by means of plate

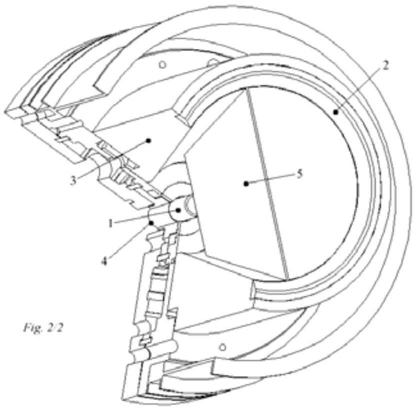

Fig. 4: Schematic of the thruster with the kink suppression plate inserted.

insertion does not significantly affect the thrust. This means that when kink mode damping is effective the same thrust is obtained at given plasma current, but with lower applied voltage, i.e. lower total electric power. This result, while confirming that plasma instabilities are indeed responsible for power losses in this kind of devices, implies that the change in the discharge power balance, related to reduction of plasma fluctuations, actually results in a significant improvement of the thrust efficiency η_T ($\eta_T = P_{th}/P_{tot}$, where $P_{th}=\dfrac{T^2}{2\dot{m}}$ is the thrust power and $P_{tot} = \Delta V \cdot I_{dis}$ is the total electric power).

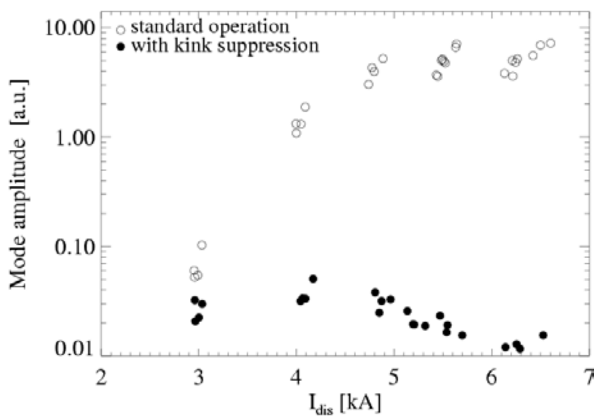

Fig. 5: Mode amplitude plotted as a function of the total plasma current without and with (full circles) effective kink suppression (mfr= 400 mg/s; B_{ext} = 40 mT).

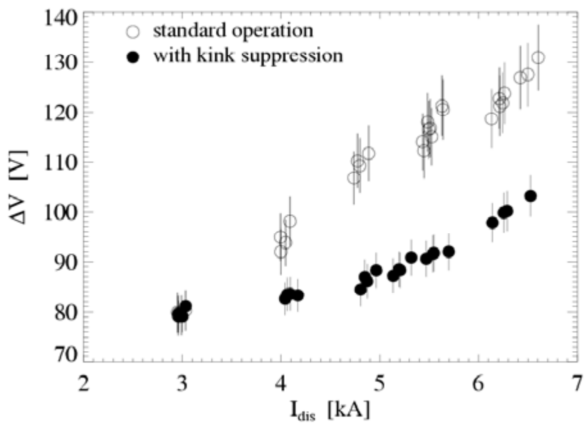

Fig. 6: Applied voltage ΔV plotted as a function of the total plasma current without and with (full circles) effective kink suppression (mfr= 400 mg/s; B_{ext} = 40 mT).

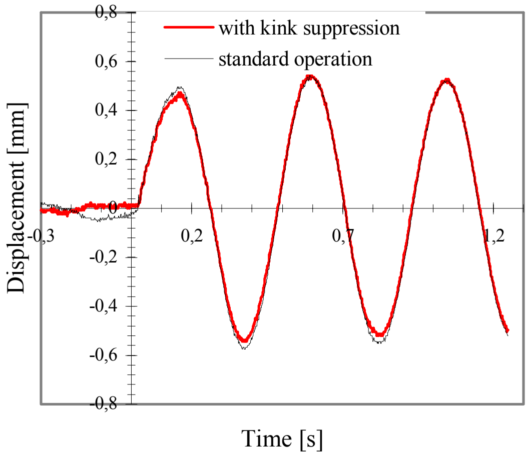

Fig. 7: Mobile mass oscillations with and without plate insertion (mfr=400 mg/s; B_{ext} =40 mT; ΔV_{PFN}=1400 V).

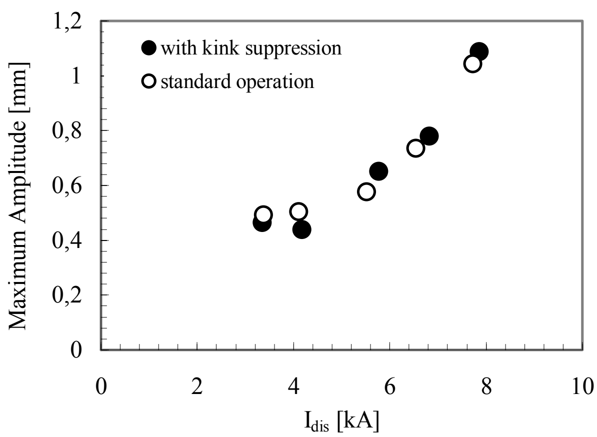

Fig. 8: Maximum amplitude of oscillation of the mobile mass, as a function of the discharge current, with and without plate insertion (mfr= 400 mg/s; B_{ext} = 40 mT).

IV. Data Interpretation

To better understand the effect of the kink suppression on the discharge equilibrium, the modification of the radial profiles of B_z and B_θ components of the magnetic field has been studied. As we previously proposed[6,14], the plasma produced by the applied field MPD thrusters is expected to relax to minimum energy states (Taylor states). These are *force free states* with magnetic field profiles corresponding to the solution of the equation $\nabla\times\mathbf{B} = \mu\mathbf{B}$, where μ is a constant given by $\mu = \mu_0\mathbf{J}\cdot\mathbf{B}/B^2$. A cylindrically symmetric solution of this equation is $B_\theta(r) = B_0J_1(\mu r)$, $B_z = B_0J_0(\mu r)$ and $B_r(r) = 0$, where B_0 is the magnetic field on the axis (r=0) and J_0, J_1 are the Bessel functions of zero and first order, respectively (Bessel Function Model, BFM), and μ describes the radial dependance[13]. Good qualitative agreement is generally found in all experimental conditions, as can be seen in Fig. 9, where different μ coefficients deduced by the BFM fit (μ_{BFM}) are compared with those estimated as $\mu_{exp} = \mu_0I_{dis}/(\pi a^2B_{ext})$ where a is the average plasma column radius in the inter-electrode region**.** It must be noticed that the spontaneous plasma paramagnetic action is taken into account for the estimation of μ_{BFM}, while this is neglected for μ_{exp}. The non-perfect quantitative agreement found between the two sets of values could also be explained by the different z positions at which they are estimated, as all physical quantities in MPD thrusters, due to the conical geometry, are intrinsically not z-independent. In Fig. 10 an example of fit of the experimental profiles, measured at the thruster outlet, with the curves predicted by the BFM is shown. B_z is evaluated as the sum of the field experimentally measured by the magnetic coils, which is paramagnetically produced by the plasma, and the stationary one, induced by the external solenoid. The effect of kink suppression is mostly visible on the z component of the magnetic field; in particular, lower B_z values are measured by our magnetic coils, and the resultant B_z profile closely resembles the unperturbed externally induced B_{ext}. This means that the paramagnetic effect, normally related to the distortion of the plasma column induced by the kink mode, is largely reduced. No strong modification of B_θ profile can be observed, which means that the J_z distribution seems mostly unaffected, in agreement with what previously deduced by thrust measurements.

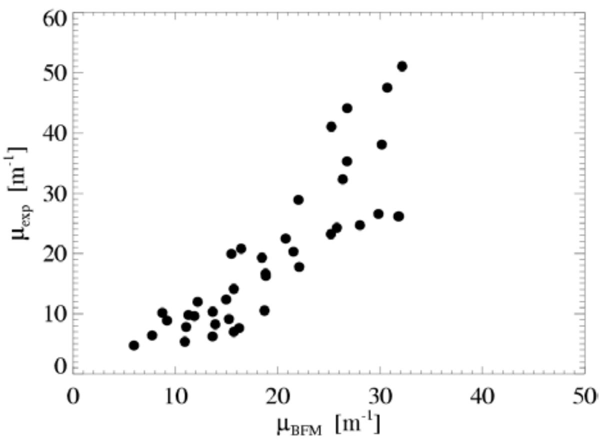

Fig. 9 Experimental μ_{exp} value, plotted as a function of that predicted by the Bessel Function Model μ_{BFM}.

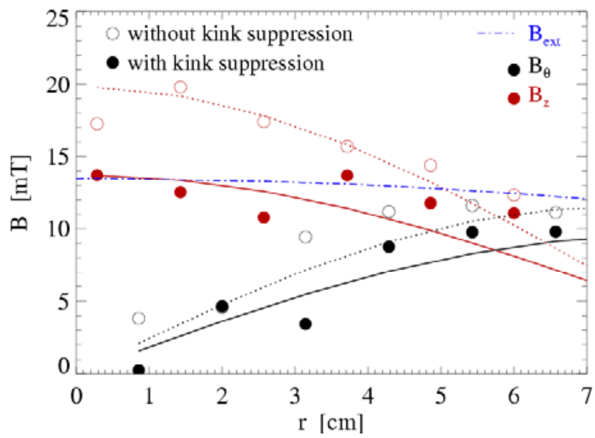

Fig. 10: Experimental radial B_θ and B_z profiles, without and with (full circles) effective kink suppression. Dashed blue line is the radial profile for B_{ext} at the thruster outlet.

V. Conclusions

In conclusion, we have presented a method for increasing the MPD thruster efficiency in conditions where the "onset" phenomenon usually degrades the performance. The efficiency increase is related to a suppression of the m = 1 kink mode which in the past had been associated to it, thus confirming the relationship between the two phenomena. The efficiency increase is due to a reduction of the voltage required to sustain the discharge, without a significant modification of the thrust level. While our technique, which uses a dielectric plate immersed into the plasma, is only a proof of principle, it clearly shows that MPDs can work with high efficiency in high current regimes, and opens up new perspectives for the development and future use of this kind of thrusters.

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