32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, P-4.130 (2005)

Efficiency enhancement due to kink instability suppression in MPD plasma thrusters

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Magneto-Plasma-Dynamic (MPD) thrusters constitute a high power electric propulsion option for primary space mission, ranging from orbit raising to interplanetary missions of large spacecrafts [1]. The acceleration of the plasma particles is produced by the interaction (Lorentz force) between a current, driven by the application of a potential difference between an anode and a cathode, and a magnetic field, which can be only self-induced (i.e. produced by the plasma current itself) or have an externally applied component as well. Presently, one of the major problems facing MPD thruster operation is the onset of a critical state, which is found as the power is increased beyond the full ionisation condition. In this regime, large fluctuations in the arc voltage signals and damages to the anode are observed along with performance degradation. Recently, an experimental investigation of electrostatic and magnetic properties of plasma fluctuations has evidenced a strong relation between this so-called "onset" phenomenon and the growth of large-scale magneto-hydrodynamic (MHD) instabilities, with the features of helical kink modes, due to a violation of the Kruskal-Shafranov stability criterion [2].

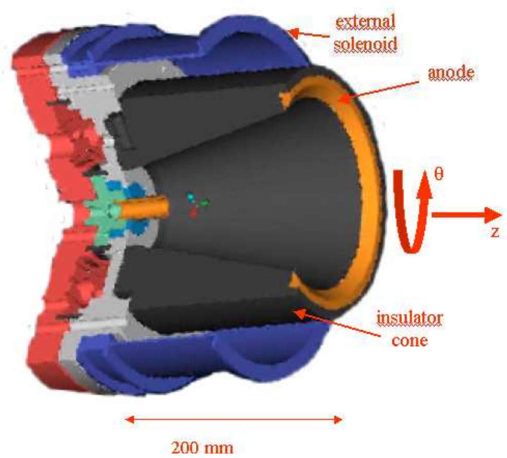

Fig. 1

In this paper we present the first attempt of controlling and suppressing these instabilities, and the effects of the reduction of plasma fluctuations on the power balance of the system. The anode of the MPD thruster under investigation 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 (see Fig. 1). The electric power is supplied to the thruster by a Pulse Forming Network (PFN), configured to give quasi-steady current pulses (I_{dis}) lasting

2.5 ms, ranging from 2 to 10 kA. The propellant feeding system is based on fast acting solenoid valves; the discharge takes place when a steady state mass flow rate is reached. The main propellant used for these experiments is argon at mass flow rates ranging from 100 to 600 mg/s. The thruster can operate in both self-field and applied-field MPD configuration as an external coil can produce an axial quasi-steady magnetic (B_{ext}) up to 100 mT on the thruster axis. The diagnostic setting up consists of two azimuthal arrays of probes located in the inter-electrode region. The first consists of 4 equally spaced bi-axial magnetic coils, measuring B_θ and B_z fluctuations; the second is made of 8 equally spaced electrostatic probes, measuring the floating potential. A linear array of 21 magnetic coils, alternatively measuring B_θ and B_z, is placed at the thruster outlet, covering the full anode radius. Different geometrical modifications of the insulator support system have been studied and tested in order to obtain effects on plasma instabilities, without sensibly changing the magnetic topology of the discharge.

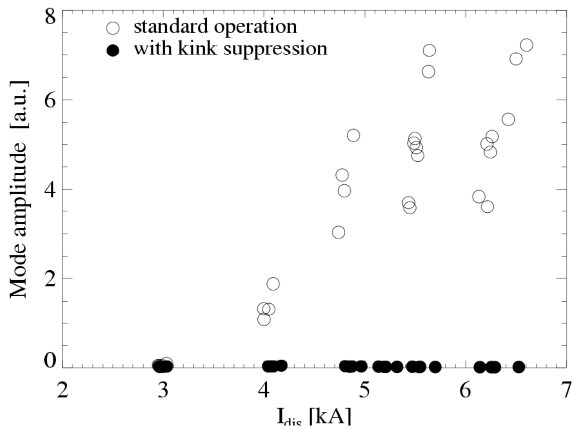

Fig. 2

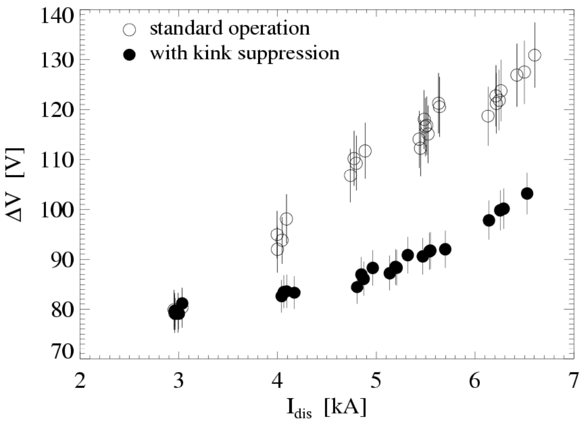

Fig. 3

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 (kink modes), which are known to dominate in this kind of plasmas [2]. In Fig. 2 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 by the electrical characteristics of the discharge in the two conditions, as reported in Fig. 3. 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). It is important to say that kink suppression does not affect thrust measurements, confirming that at high power levels the acceleration produced by MPD thrusters depends mainly on the total plasma current [1]. 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 thruster efficiency η_T ($\eta_T = P_{th}/P_{tot}$, where $P_{th} = \frac{T^2}{2\dot{m}}$ is the thrust power and $P_{tot} = \Delta V \cdot I_{dis}$ is the total electric power).

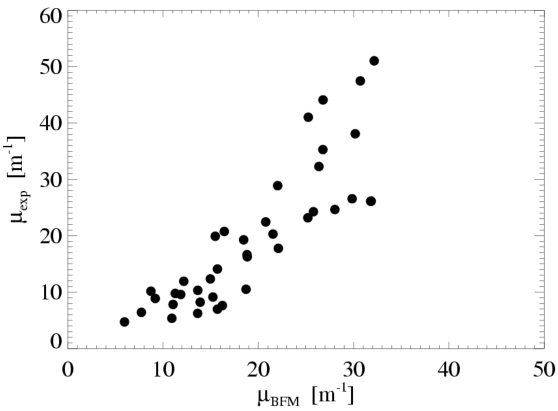

Fig. 4

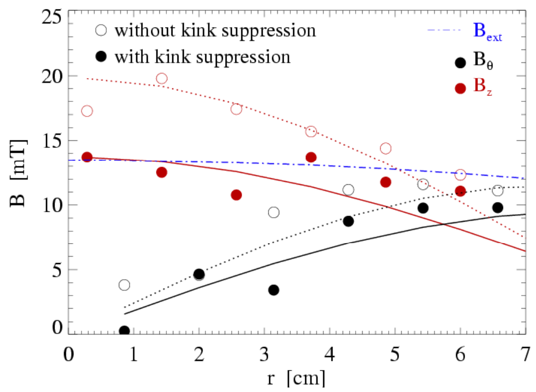

Fig. 5

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 [3] the plasma produced by the applied field MPD thrusters is expected to relax to minimum energy states (Taylor states). These are called 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 $B_\theta(r) = B_0 J_1(\mu r)$, $B_z = B_0 J_0(\mu r)$ 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 dependence [4]. Good qualitative agreement is generally found in all experimental conditions, as can be seen in Fig. 4, where different μ coefficients deduced by the BFM fit (μ_{BFM}) are compared with those estimated as $\mu_{exp} = \mu_0 I_{dis}/(\pi a^2 B_{ext})$ 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 imputed to 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. 5 an example of fit of the experimental profiles, measured at the thruster outlet, with those predicted by the BFM is shown. B_z is evaluated as the sum of the one 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 profiles; 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.

In conclusion, we reported experimental observations relating the kink mode amplitude to the main discharge parameters. In particular, it has been shown that a decrease in the applied voltage sustaining the discharge is observed when these instabilities are suppressed, resulting in a significant increase of the thrusters efficiency.

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