Ultraviolet imaging of a magneto–plasmadynamic thruster

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We present a project of an imaging system of a plasma produced by a magneto–plasmadynamic (MPD) thruster for space applications, in the ultraviolet range. This system consists of four detectors placed outside the thruster (5 cm from the anode surface), plus nine arrays of ultraviolet (UV)-enhanced photodiodes, viewing the plasma at three different axial positions (z = 3.5, 8.0, and 12.5 cm from the cathode tip) obtained carving directly their lodgings in the cylindrical structure of the anode, in between anode and cathode. We used single UDT455 UV/LN detectors with low noise, built-in amplifiers. The system allows the imaging of m=1 helical instabilities which limit the MPD thrust efficiency.

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I. INTRODUCTION

Magneto–plasmadynamic (MPD) thrusters are high power electric space propulsion devices that utilize the $j \times B$ force to accelerate a plasma to high velocities ($>10$ km/s). They constitute a feasible option for space missions, in particular for manned missions to Mars.1 Currently, the major limit on the use of MPD thrusters is their low efficiency, and in particular a limitation of the thrust at high current and applied axial magnetic field $B_z$ (the axial field is required to stabilize the plasma column).2 Recent results2 show that this limitation is connected to the onset of an $m=1, n=1$ magnetohydrodynamic instability (being $m$ and $n$ the azimuthal and axial wave numbers, respectively), in all respect similar to that occurring in tokamaks, and well known in the fusion plasma community as the kink instability connected to the Kruskal–Shafranov limit. Up to now, the detection and characterization of this $m=1$ kink in MPD thrusters is granted by electrostatic and magnetic probe arrays;3 unfortunately, magnetic fluctuations are not a direct proof of the existence of a kink. On the other hand, imaging systems in the visible spectral range are performed for similar kinks in plasma gun devices,4 but require rather expensive charge coupled device cameras. Therefore, we exploited our knowledge in low-cost, high temporal and spatial resolution arrays for plasma imaging,5,6 to build a system for a MPD thruster in the ultraviolet (UV) range (namely, from 50 to 200 nm). Direct imaging of the $m=1$ kink can be in principle provided, describing in a detailed way the connection between performance limitations and onset of the kink.

II. THE EXISTING DIAGNOSTIC

The feasibility of a project of UV imaging in a MPD thruster is based on a previous, preliminary version, tested in Centrospazio, Pisa. Four, single UDT 455 UV/LN photodiodes7 with built-in, low noise amplifiers are installed in a square, metal case [see Fig. 1(a)]. The pinhole has been designed in order to obtain a cone of sight =90° wide: in this way, the entire plasma plume is detected [see Fig. 1(b)]. This choice reduces the spatial resolution, but it maximizes the signal. The metal case is fixed on a metal support: all the instrumental apparatus is finally installed inside the vacuum chamber, at 5 cm from the anode surface (the anode is a copper belt fixed onto the edge of a metal or plastic cylinder, for details see Ref. 2). The apparatus allows one to view the entire plasma plume from above (two detectors at 45° and 135°), and from the right and left side (two detectors at 0° and 180°). The cables have been extracted through a vacuum feedthrough, and the signals have been sent to a digital scope. Regarding amplifiers, we tested gains in the range 1000–10 000: the resulting, measured bandwidth is in the range 250–300 kHz. Due to the high level of the radiation in the ultraviolet range, lower gains ($\times 4700$) of the amplifiers have been used; thus increasing the time resolution (290 kHz). A typical UV signal for a 4.5 kA discharge is shown in Fig. 2(a): apart from the ionization peak, the average signal closely follows the current wave form [see Fig. 2(b)]. Superimposed to this slow behavior, it is evident there is an oscillation at a frequency =40 kHz [expanded inset in Fig. 2(a)]. This oscillation, measured by detectors placed on opposite sides of the plasma plume, displays a definite out-of-phase relation, as shown in Fig. 3(a). Since the cone of sight

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is wide, this is compatible with a localized structure (a kink), rotating at a frequency of 40 kHz, in the counterclockwise direction (looking towards positive \( z \); this is the ion diamagnetic drift direction). In our interpretation, the out-of-phase \((m=1)\) oscillation arises as the structure approaches and gets away from the detector, as sketched in Fig. 3(b), following approximately the formula
\[
\left( \frac{1}{a + r_s \cos ft} \right)^2,
\]
\(a\) being the radius of the plume, \(r_s\) the radius of the kink, \(f\) the rotation frequency (mainly determined by the axial plasma velocity), and \(t\) the time. The plasma conditions when the structure arises are in good agreement with those characterizing the onset of an \(m=1\) kink, as deduced from the magnetic and electrostatic measurements of Ref. 3.

III. THE UPGRADE OF THE DIAGNOSTIC

The promising physics results summarized in the preceding section have inspired a drastic upgrade of the diagnostic, along the following main directions:

(a) The UDT, single detectors, with the built-in amplification, proved to be rather robust, and not sensitive to magnetic noise;
(b) The concept of the built-in amplification has been ex-
tended: no amplifiers are placed outside the vacuum vessel, as in previous versions of the diagnostic. This choice minimizes possible sources of magnetic noise;

(c) The spatial resolution has been improved: to obtain this, the dimension of the metal case of Fig. 1(a) has been reduced, and the built-in amplifier has been miniaturized;

(d) The improvement of the mechanical structure of the anode, i.e., the replacement of the metal cylinder with a plastic one, has allowed us to place the UDT detectors in a metal case, inserted in a hole carved into the plastic.

Details of the new configuration are shown in Fig. 4. The metal case [Fig. 4(a)] houses the UDT detector [Fig. 4(b)]. It is an aluminum cylinder, with an external diameter of 20.5 mm, and 26.5 mm long, with a tip (10 mm diameter) which is in direct contact with the plasma. The cylinder is inserted in a housing, carved in the plastic structure of the anode. The amplifier circuit [Fig. 4(c)] is obtained on a disk of 18 mm diameter, which can be inserted into the aluminum cylinder. An aluminum cover, with a bolt, closes the metal case [Fig. 4(d)]. The amplification gain is determined by a resistor, and can be chosen in the range 1000–4700–10 000 (depending on the UV emission in the region between the cathode and anode, which is not yet known). To change the gain it is necessary to disassemble the anode structure, to extract the cylinder, open the cover, and replace the resistor. From the preliminary measurements we summarized in Sec. II, it is evident that the UV emission changes by a factor \( \approx 4 \) in the current range 2–8 kA, and with \( B \), ranging from 0 to 80 mT: therefore, it is likely that this operation will be necessary only in a very preliminary stage, using a few plasma shots as calibration tests.

The reduced dimension of the metal case allows for placing quite a large number of the detectors inside the plastic structure of the anode. In the final version of the diagnostic design, we placed 45 detectors around the anode, arranged in nine arrays, viewing the plasma at three different axial positions \( (z=3.5, 8.0, \text{ and } 12.5 \text{ cm from the cathode tip}) \). This choice allows for measuring both the azimuthal mode number \( m \) (three arrays at 120° one to the other, for each section), and the axial mode number \( n \) (three axial positions). Moreover, to increase the resolution in the \( z \) direction, we maintained the four, single UDT detectors outside the anode (monitors), in the “big” metal cases (Fig. 1). In this way, the measurement of \( n \) relies on four axial positions. We are also studying how to increase the number of UDT detectors outside the anode, in the same section of the four monitors. Up to now, the system is complete with the 45 internal UDT sensors, plus the four external, old ones. This experimental apparatus will soon be tested in Centrospazio, Pisa.

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6 P. Franz et al., these proceedings.
7 UDT Sensors Inc., 12525 Chadron Ave., Hawthorne, CA 90250 (http://www.udt.com)