Ion Acceleration in a Quad Confinement Thruster

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Abstract: We characterize the ion velocity flow field in the plasma ejected from a Quad Confinement Thruster using non-intrusive 2-D laser-induced fluorescence diagnostics. Measurements show a free-space ion acceleration layer located 8 cm downstream of the exit plane, with an observed ion velocity increase from 3 km/s to 10 km/s within a region of 1 cm thickness or less. The ion velocity field is investigated with different magnetic configurations, demonstrating how distorting the magnetic field produces changes in ion velocity magnitude and direction as well as in metastable (probed) ion density.

Nomenclature

DC = Direct Current
FSR = Free Spectral Range
HCN = Hollow Cathode Neutralizer
LIF = Laser-Induced Fluorescence
QCT = Quad Confinement Thruster
PMT = Photo-Multiplier Tube
SSC = Surrey Space Centre
PPU = Power Processing Unit
TRL = Technology Readiness Level

I. Introduction

THE Quad Confinement Thruster[1,2,3] (QCT) is a novel electric propulsion system invented in 2010 at the Surrey Space Centre (SSC), University of Surrey. The QCT contains a square discharge channel with the anode located at the closed, upstream end. An external hollow cathode neutralizer provides primary electrons for triggering the ionization process, which proceeds via electron-neutral collisions, and neutralizes the ejected ion beam. The magnetic field contains four cusps located at the channel wall and creates a barrier to electron migration, enhancing electron

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resident time and inducing ion acceleration by establishing a potential gradient. At the cusps, the magnetic field, in combination with the longitudinal electric field, produces an *E x B* open electron drift. The magnetic field topology is manipulated using four independent electromagnets on each edge of the channel, tuning the properties of the generated plasma. The magnetic field influences electron dynamics, determining the electrostatic potential distribution within the thruster channel and the shape of the ion acceleration front. As a consequence, a distortion of the magnetic field can indirectly produce a change in the direction of the ion acceleration, causing a shift of the center of thrust and a tilt of the thrust vector direction. Previous three-dimensional Langmuir probe measurements[4] have revealed an 11 degree asymmetry of the plasma density distribution when two of the magnets were switched off. The potential capability of thrust vectoring without movable gimbals represents one of the key features of the thruster.

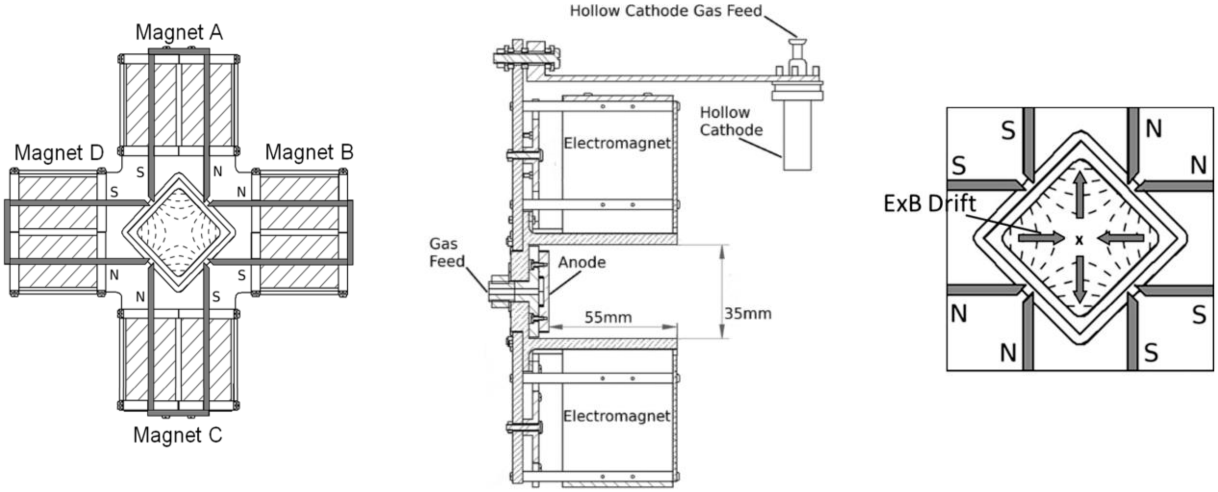

Figure 1. QCT schematic and magnetic field topology[3].

By visual observation, the plasma discharge within the square channel presents a higher intensity emission from two of the four quadrants, corresponding with the regions of inward *E x B* electron drift (Figure 1 and Figure 2). Moreover, other studies have shown the plasma discharge properties are strongly influenced by the background residual pressure in the vacuum chamber, suggesting a coupling between the physics of the plasma within the channel and that of the outer plume. The latter features a semispherical structure which extends about 6-8 cm from the thruster exit plane. We will show later in this paper how this structure is correlated to the accelerating potential front.

Understanding the fundamental physics of the plasma discharge, particularly the ion acceleration mechanism, is a key step in evaluating and exploiting the thruster's propulsive capability and performance. In assessing the feasibility of thrust vectoring, manipulation of the ejected ion trajectories by distorting the magnetic field topology must be demonstrated and quantified. Pursuant to these goals, we characterize the ion velocity field in the plasma ejected from a 200 W laboratory model QCT using a non-intrusive laser-induced fluorescence (LIF) diagnostic. Time-averaged local measurements of most probable velocity vectors (2-D, axial and radial velocity components) and the corresponding velocity distribution functions are carried out in several locations for different magnetic configurations and anode voltages. Ion velocimetry using LIF[5,6] relies on the Doppler shift of the xenon ion fluorescence excitation lineshape. Here, using LIF, we measure this shift relative to that of a stationary optogalvanic reference. A tunable external cavity diode laser is used as the source of exciting photons. The precise wavelength detuning in time is reconstructed using the known reference xenon transition and the interference peaks from a Fabry-Perot interferometer. Homodyne detection and optical bandpass filtering are applied to reject noise from background plasma light and scattered laser photons.

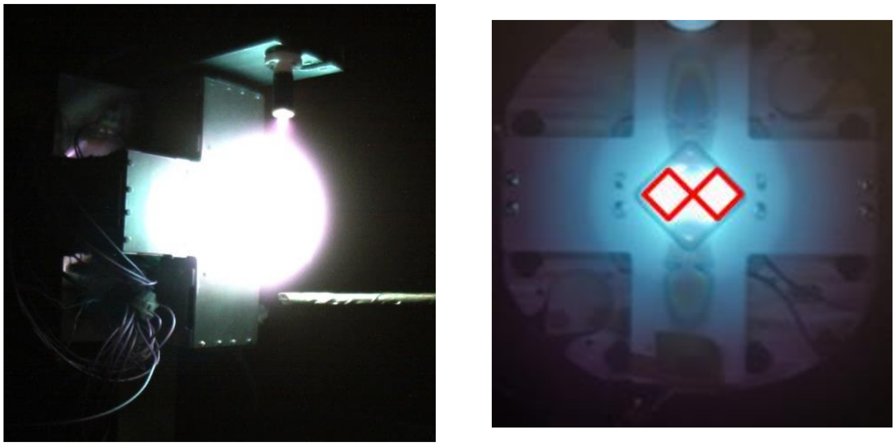

Figure 2. Visual features of the QCT plasma discharge. On the left: the QCT plume presents a semi-spherical plume structure. On the right: the discharge channel features higher intensity emission regions.

II. Experimental setup

Figure 1 shows a schematic of the QCT laboratory model used in this work. The square boron nitride discharge channel presents a side-area projection that is 35 mm high and 55 mm deep (see center schematic). The square–shaped tantalum anode has a side dimension of 25 mm. The magnetic field intensity is about 250 G. In nominal conditions, the thruster operates at an anode power of 200 W (130 V anode voltage, 1.6 A anode current) with a xenon anode mass flow of 0.8 mg/s. An external hollow cathode electron source is located 37 mm downstream of the exit plane and 94 mm outward from the channel centerline, pointing at about 60 degrees. The hollow cathode is operated on argon (0.12 mg/s flow rate) in order to exclusively probe through LIF ions coming from the main discharge channel and to avoid the detection of ion populations originating from the hollow cathode flow. The tests are carried out in the Stanford Plasma Physics vacuum facility. The 4 m long, 1.5 m diameter vacuum chamber is equipped with cryo-panels and cold shrouds. The system provides a base pressure of 5e-7 Torr and maintains 3e-5 Torr during thruster operation.

The LIF scheme used in this study is shown in Figure 3. The $5d[4]_{7/2} - 6p[3]_{5/2}$ XeII transition (834.953 nm vacuum wavelength) is optically pumped by a laser beam generated by a New-Focus TA-7600 semiconductor tapered amplifier seeded by a New Focus TLB-6817-P tunable external cavity diode laser. After amplification the laser power is 33 mW. The fluorescence resulting from the subsequent radiative decay of excited ions to the $6s[2]_{3/2}$ state is collected through an optical system of lenses and mirrors and detected through an Hamamatsu 1P21 photomultiplier tube. The optogalvanic signal from the $6p'[3/2]_1 - 8s'[3/2]_1$ XeI transition (834.973 vacuum wavelength) obtained from a hollow cathode xenon cell provides the stationary reference to which the Doppler-shifted line is compared. The interference fringes of a Fabry-Perot interferometer constitute fixed frequency markers (FSR = 1.5 GHz) throughout the laser wavelength scan. The combined use of the optogalvanic cell and Fabry-Perot interferometer allows to accurately reconstruct the instantaneous lasing wavelength as a function of time. An additional Burleigh WA-1500 wavemeter provides a visual wavelength reading while setting up the laser parameters.

Before PMT detection, the collected light, comprising laser-induced fluorescence and spurious background emission is passed through optical shortpass and bandpass filters in order to reject laser scattered light and photons originating from plasma transitions other than the considered one. Finally, homodyne detection is used to extract the target laser-induced fluorescence signal from the overall fluorescence emitted by the plasma in the allowed wavelength bands of the filters. An extended description of the LIF system can be found in previous works[5,6].

Two perpendicular laser beams are focused in the same point in the thruster plume (Figure 3) in order to instantaneously probe two velocity components during the same wavelength scan. The beams are mechanically modulated at different frequencies for enabling the use of homodyne detection to identify the fluorescence originating from one or the other.

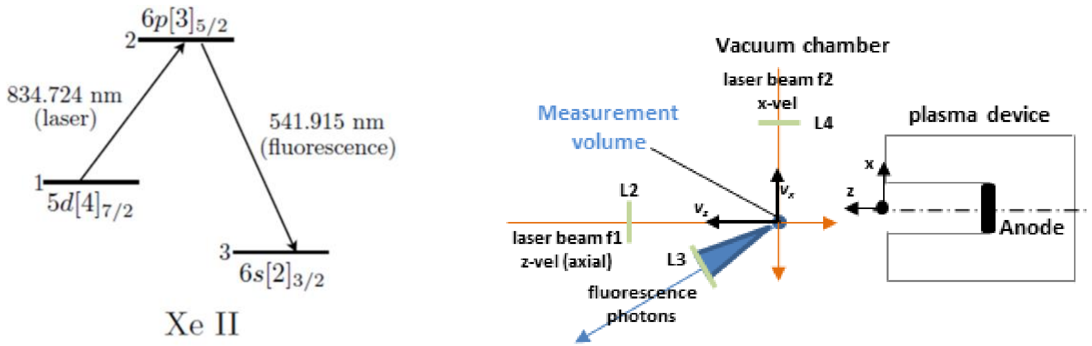

Figure 3. On the left: LIF scheme used to probe xenon ions during this study. On the right: optical arrangement inside the vacuum chamber. Two perpendicular laser beams are used to probe two velocity components during the same wavelength scan.

III. Ion flow field

The ion velocity measurements are performed on a symmetry plane located in the region of brightest plasma visible emission as depicted in Figure 4. The coordinate system and the magnets labelling used in the following velocity maps and plots are illustrated in Figure 4 as well. Measurements are performed operating the thruster under a broad range of conditions; in particular, the electromagnets currents have been widely varied to study the effect of the magnetic field distortion on the ion flow field. In this paper we report a restricted set of results to show evidence of ion acceleration and the influence of the magnetic field on the ion velocity vector.

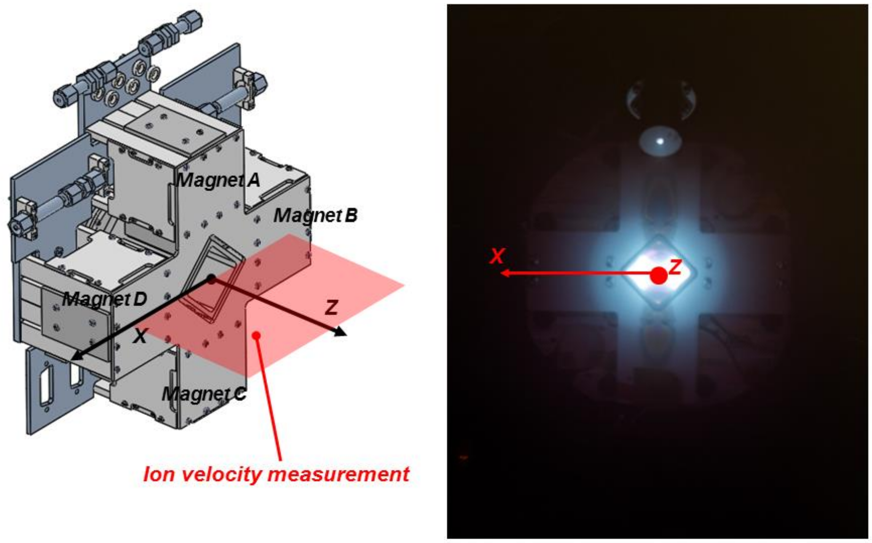

Figure 4. Ion velocity measurements are performed throughout a plane located in the brightest plasma visible emission region. The coordinate system and magnets labeling are shown in the figures above.

Figure 5 shows the ion velocity field using the nominal magnetic field topology, obtained by passing the same current level (in this case 1 A) through all the electromagnets. Under these conditions and applying an anode voltage of 130 V, the anode current settles at 1.6 A. The maps illustrate the axial velocity component, the radial velocity component, the angle of the velocity direction relative to z-axis and the velocity vectors.

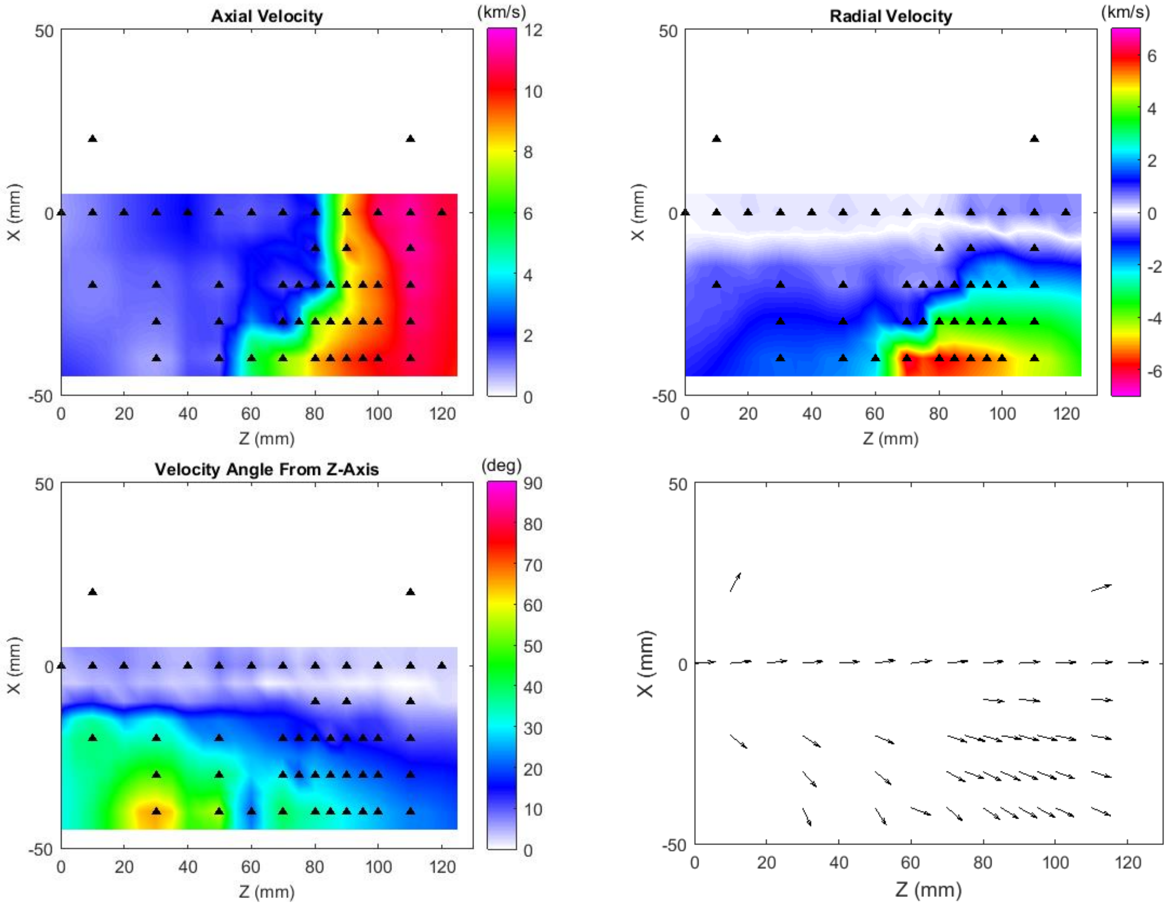

Figure 5. Ion velocity measurements in case of nominal magnetic field. At the top: maps of axial velocity and radial velocity components. At the bottom: resulting velocity angles and vectors.

The axial velocity map highlights that a steep increase of ion velocity is taking place at about 8 cm downstream of the exit with an observed increase from 3 km/s to 10 km/s within a region of 1 cm thickness or less. This layer is located "in free space", i.e. in a region detached from the exit plane, characterized by weak magnetic field intensity and lower neutral density in comparison with the discharge channel. The location of the acceleration front is atypical and differs from that one observed in other types of open-channel thrusters, such as Hall Effect Thusters and Cusped Field Thrusters. Indeed, in these latter devices, ion acceleration takes place around the exit plane: in some cases the front extends just few centimeters beyond the exit[6], in other cases it is even located inside the channel[10]. The peculiar location of the acceleration front in the QCT is due to factors determining the underlying plasma physics in the plume and in the discharge channel. A full description of the physical processes would require a comprehensive investigation comprising multiple probes, however the known physical features of the device allow the formulation of some hypothesis. The nature of the acceleration is electrostatic and ion acceleration is triggered by a potential drop, the position of which matches that of the observed acceleration front. Figure 6 gives a visual impression of the location and extension of the latter throughout the plume relative to the thruster geometrical dimensions. Potential drops in narrow spatial regions detached from plasma boundaries have been observed in other laboratory plasmas and are usually defined as single or double layers[8] depending on their characteristics. As an example, single and double layers have been reported in multiple plasma devices with electron drift current[7] or in expanding plasmas[9]. The location of the acceleration layer observed in the QCT plume suggests a similar structure. Electrons flowing from the hollow cathode remain attached to the magnetic field lines leaking from the iron rails of the thruster (the exit plane is made of aluminum) and move throughout a semi-spherical shell with a certain thickness and certain radius depending on the relative position of the hollow cathode orifice and magnetic field topology. This electron rich shell creates a local breakdown of quasi-neutrality, creating a potential jump bounded between an ion-rich region (upstream towards the thruster) and an electron-rich region (downstream). Particle kinetic phase-spaces are characterized by trapped lowenergy electrons on the high potential side, a population of drifting electrons accelerating from the low-potential side to the high potential side of the structure migrating from the electron-rich shell towards the discharge channel and an accelerated beam of ions gaining energy from the potential jump. The shape of the potential front influences the direction of ion acceleration occurring in the direction of the potential gradient. As a result of the spatial distribution in the potential, the velocity vectors are aligned to the z-direction at the centre of the plume and their angle progressively increases moving outward and reaches a value of about 65-70° at the periphery. Visual observation of the QCT plume reveals plasma emission is preferentially originating from a semi-spherical region in front of the thruster with a radius comparable to that one of the identified acceleration front, suggesting a correlation between electrostatic topology and visual shape of the plume.

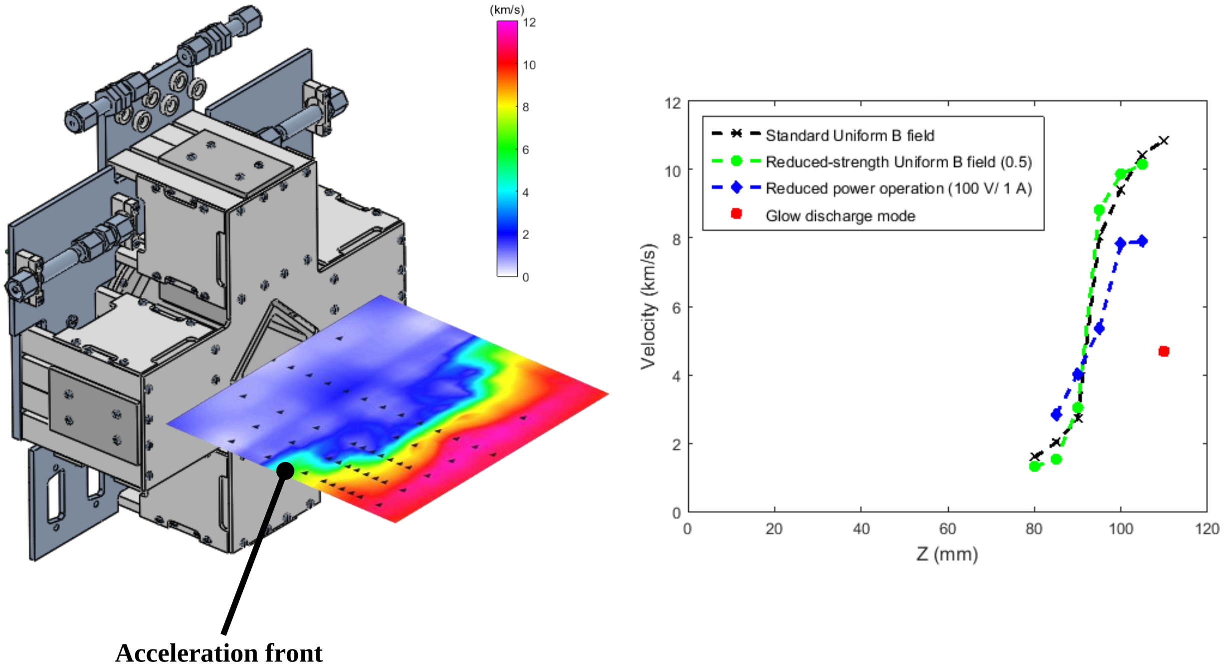

Figure 6. On the left: ion (axial) velocity flow field downstream of the thruster exit plane. On the right: ion acceleration profile under different testing conditions.

Figure 6 (on the right) shows the ion acceleration profile for different testing conditions. The comparison between measurements obtained applying the nominal magnetic field and those acquired for the glow discharge mode demonstrates that strong ion acceleration takes place only in the magnetized case highlighting the impact of the magnetic field on the discharge physics, in particular on the electrostatic potential distribution determining ion acceleration. A decrease of the anode power (case with 100 V anode voltage and 1A anode current) causes a weakening of the acceleration, due to the reduction of the potential drop strength resulting from the decrease of the anode voltage level. Finally, the ion velocity increase is independent on the magnetic field strength, at least in the interval between the nominal value and half of it. The location of the acceleration layer remains fixed, at about 8 cm downstream of the exit plane, for all the tested conditions. This latter observation reveals that the acceleration front is connected to the system physical geometry and magnetic topology.

The magnetic field was altered by switching off two electromagnets. For the measurements reported in Figure 7, only Magnets C and D are powered (see Figure 4 for the thruster geometrical configuration). The distortion of the magnetic topology generates changes in both ion flow field and metastable (probed) ion density. A non-uniform distribution of metastable ions in the plume is produced, with higher LIF signal observed on the side with weaker magnetic field. The acceleration front is still located at about 8 cm from the exit plane with an axial velocity increase from 3 km/s to 10 km/s taking place in a 1 cm region as in the case of the nominal magnetic configuration. However, a higher radial velocity component is observed on the side with stronger magnetic field with a consequent change of the velocity angle. In this specific case we can observe a radial velocity delta of about 2 km/s between the two sides of the mid-plane (x = 0) and a velocity angle delta of about 15 degrees. This is a first direct demonstration that the manipulation of the magnetic field modifies the ion velocity vector direction. The magnetic field topology influences the distribution of the plasma properties resulting in a different electrostatic potential structure responsible for ion acceleration.

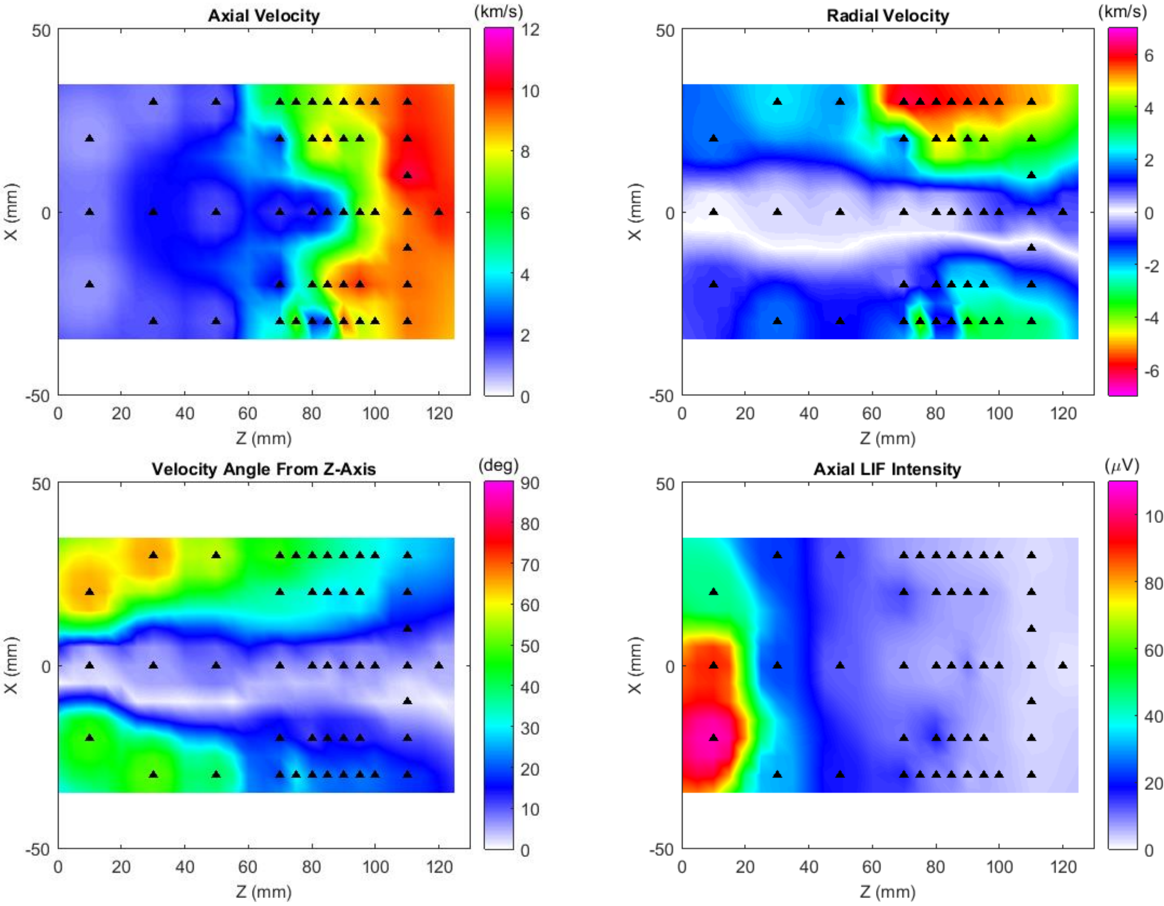

Figure 7. Ion velocity measurements in case of distorted magnetic field. Only two electromagnets are powered (Magnet C and D). At the top: maps of axial velocity and radial velocity components. At the bottom: resulting velocity angle and axial LIF signal intensity.

IV. Conclusions

We have characterized the plasma ejected from a 200 W Quad Confinement Thruster applying a non-intrusive laser-based technique. In particular, Laser-Induced Fluorescence measurements map the 2-D ion velocity field throughout the plume for multiple plasma discharge conditions. Measurements show a free-space ion acceleration layer located 8 cm downstream of the exit plane with an observed ion velocity increase from 3 km/s to 10 km/s within a region of 1 cm thickness or less. Hypothesis on the origin of this acceleration layer are formulated; in particular, the electrostatic potential structure associated to a double-layer can explain the origin of ion acceleration in a plasma region detached from physical boundaries.

The ion velocity field is investigated with different magnetic configurations, demonstrating how the manipulation of the magnetic field produces a change of the plasma properties distribution with a consequent impact on the ion velocity direction. Asymmetries in ion velocity angle, up to 15 degrees, have been measured in the case of a non-uniform magnetic field configuration.

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