Radial characterization of an ion beam in a deflected magnetic nozzle

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Abstract

The radial characterization of an ion beam generated in a magnetically steered radio-frequency (RF) plasma source is presented. In the symmetrical magnetic nozzle (MN) configuration, radial profiles of the ion saturation current obtained with a planar Langmuir probe show a double-peaked profile. The same behaviour is confirmed by the radial measurements of the total ion current and the ion energy distribution functions (IEDFs) obtained with a retarding field energy analyzer. The IEDFs also show the presence of an ion beam centred at $r = -2$ cm. On the contrary, radial measurements taken with a magnetic nozzle deflected on the $r - z$ plane exhibit a single-peaked profile with both the local ion population and the ion beam centred at $r = -5$ cm, in the direction of the MN orientation. It is shown that the ion beam location is changed as a result of a deflected magnetic nozzle, and that it follows the direction of increasing radial magnetic field.

Keywords: Magnetic nozzle, Ion beam, Magnetic steering, RF plasma

Introduction

In the last decade, the aerospace industry has seen a boom in the manufacturing of small and nano-scale satellites for space communications, environmental and weather monitoring, and scientific research. The miniaturisation of spacecraft means that they are cheaper to build, cheaper to launch and provide greater flexibility when designing a space mission. However, their size poses restrictions in terms of mass, volume and power budget. Mechanical systems, such as reaction wheels, have been employed so far to control the thrust vector of the spacecraft and perform attitude and orbit control (AOC) manoeuvres. These devices are usually heavy and complex, and their movable components add potential failure modes to the mission. The concept of contactless thrust control could allow for more reliable AOC systems.

Electric propulsion (EP) systems have been extensively used in space missions given the high specific impulses that can be generated and the subsequent savings in propellant mass requirements. Contactless steering systems that employ electromagnetic fields to control the motion of charged particles have been studied in the past for Hall effect thrusters [1, 2]. Magnetic nozzle (MN) radio-frequency (RF) plasma thrusters
(sometimes referred to as Helicon thrusters) are a new electric propulsion technology which has become of interest in the last two decades as an alternative to other high power EP systems. A recent experimental campaign has shown thruster efficiencies of \( \approx 20\% \) and up to 70 mN of thrust for 6 kW of RF power input [3], and the generation of an accelerated ion beam caused by either a current-free double-layer or an ambipolar electric field has been demonstrated in such devices [4–7]. Due to the nature of their design, the idea of controlling the thrust vector by means of a steerable magnetic nozzle (a convergent-divergent magnetic field) has been proposed [8, 9]. Magnetic thrust vectoring would allow for a simpler and more reliable orbit and attitude control mechanism since it does not comprise of any moving/rotating components.

To assess the potential of magnetic thrust vectoring, it is important to characterize and understand the physical properties of a plasma generated and expanding in a deflected magnetic nozzle. The first experimental study of steering of an ion beam in a RF plasma thruster was done by Cox et al. [8] in the Chi-Kung reactor. Transverse magnetic fields (TMF) were applied with respect to the thruster axis, and their effect on the plasma accelerated in the electric field of a double-layer was investigated. It was noticed that the ion beam was effectively deflected as a result of the TMF. However, the magnetic field was not the dominant factor in controlling the ion beam deflection, as the latter was not following the orientation of the TMFs. Additionally, the system allowed only for magnetic steering in one plane. Merino and Ahedo [9] analysed the theoretical performance of a 3D magnetic steering system for a plasma jet. Assuming a fully magnetised ion population and a collisionless plasma, they modelled a steerable magnetic nozzle and its effect on the plasma plume. As they only presented an analytical model, no actual experimental data were discussed. Imai and Takahashi [7] measured the axial and horizontal thrust components of a MN RF plasma under an asymmetrical magnetic field. Thrust vector control by magnetic steering was experimentally demonstrated in two dimensions by mounting four additional solenoids after the plasma source exit by Takahashi & Imai [10]. Spatial mapping of the ion saturation current showed that the plasma plume was effectively being deflected, and that the plasma density profile was following the magnetic nozzle orientation, but the experiments lacked the characterization of an ion beam in the steered configuration. Due to the location of the thrust vector control system, the implementation of their design in an actual thruster would also not be trivial.

The aim of this study is to present the first measurements of a novel magnetic steering system based on the study by [9] incorporated into a radio-frequency plasma reactor at The University of Auckland. The aim of the research is to study how the characteristics of an expanding plasma are affected by different magnetic nozzle orientations, with particular focus on the generation of an accelerated ion beam. As such, it is out of the scope of the project to directly measure the thrust components and quantify the thrust vector capability of the system. Radial profiles of an argon plasma expanding in a magnetic nozzle deflected on the \( r-z \) plane are presented. Specifically, a retarding field energy analyzer was used to radially characterize the ion energy distribution function, and measurements of a deflected ion beam are presented. Radial profiles of the ion saturation current taken with a planar Langmuir probe are also discussed to qualitatively assess the plasma deflection expanding in an asymmetric magnetic field.
Experimental apparatus section briefly describes the experimental apparatus and the plasma diagnostics used. Magnetic nozzle deflections section presents the magnetic nozzle characteristics from magnetostatic simulations where the magnetic steering system was modelled. Finally, Results section discusses the experimental results.

Experimental apparatus

The experimental campaign to assess the performance of the magnetic steering system is performed in the apparatus Moa. The set-up is an expansion of Huia, a RF plasma reactor at The University of Auckland [11]. Figure 1a shows a sketch of the system with the key components. The plasma source region is defined by a 90 mm inner diameter borosilicate glass tube extended by a 500 mm diameter, 700 mm long stainless steel vacuum chamber to allow plasma expansion. Moa is pumped down to a base pressure \( \approx 2 \times 10^{-7} \) Torr via a turbo pump with a pumping speed capability of 625 L/s for argon. During the experiments, the flow rate of gas is kept at 12 sccm to maintain a chamber pressure of 0.5 mTorr. The plasma is created by a 1.3 turns loop antenna matched via an L-type matching network to maximise power transfer from a variable frequency 1 kW RF power supply with a frequency range between 27.12 and 40.68 MHz. The antenna is made of a 3 mm diameter copper wire that was wound around a cylinder with an external diameter of 10 cm to fit around the glass tube. The point on axis at the intersection between the end of the plasma source tube and the beginning of the vacuum chamber is set as the origin of the coordinate system used throughout this study, i.e. \((r, z) = (0, 0)\) cm.

The magnetic steering system, shown in Fig. 1b, is formed by three skewed, concentric coils of increasing diameter placed co-axially with respect to the plasma source, inclined at 15° with respect to the system axis \(z\) and precessed by an angle of 120° with respect to each other to create a rotational-symmetry arrangement. The three coils form the MTV system and the deflection of the magnetic nozzle is accomplished by independently...
varying the current input in each coil. The design of the magnetic system is based on the study presented by [9]. The steering system is mounted at the interface between the plasma source and the vacuum chamber to steer the MN at the beginning of plasma expansion. For the purpose of this study, only the most inner coil was employed to generate the non-symmetric magnetic field and allow the magnetic nozzle to deflect on the $r$-$z$ plane. The solenoid has an inner diameter of 70 mm, and a width of 40 mm to accommodate for 323 turns of AWG 12 copper wire.

**Plasma diagnostics**

Two main diagnostics probes were used to characterise the plasma expanding in the symmetric and deflected magnetic nozzle cases. A planar Langmuir probe (LP) was used to measure the ion saturation current, while a retarding field energy analyser (RFEA) was used to measure the plasma potential and the ion energy distribution functions. The probes were mounted on a movable (rotation and translation) 1/4” steel shaft introduced in the top ports of the expansion chamber. Both probes were moved radially in the region $-15 < r < 15$ cm.

The radial mapping of the ion saturation current $I_{\text{sat}}$ in Moa is used to detect steering of the plasma within the region of the deflected MN. The measurements are obtained with a Langmuir probe made out of a single sided 2 mm diameter nickel disk biased at -100 V to ensure total electron rejection. Radial profiles of $I_{\text{sat}}$ were taken with the probe placed at two different axial locations: $z_P = 9$ cm and $z_P = 19$ cm.

The design of the retarding field energy analyser used for this study is based on Ref. [12], whose similar design was also used in other studies [5, 8, 13]. The description of the RFEA and its electric circuit used herein are presented in details in Ref. [14]. It includes four mesh grids (earth, repeller, discriminator, and secondary grid) and one nickel collector plate where the ion current is measured. The aperture of the probe orifice has a diameter of 2 mm, and the grids are electrically insulated using a 0.1 mm thick polyimide sheet. The probe is operated in ion collection mode. The earth grid is grounded to ensure a uniform potential profile at the probe entrance, while the repeller grid is biased at $-90$ V to reject all incoming electrons. The voltage of the discriminator grid is swept from 0 V to 80 V to obtain the $I$-$V$ characteristics. The IEDFs presented in the paper were obtained from the raw $I$-$V$ characteristics by using a Gaussian deconvolution method [4, 7].

**Magnetic nozzle deflections**

The magnetic steering system was modelled on ANSYS Electronics Desktop 2021-R1 and the magnetic field was computed using the software’s 3D magnetostatic solver. The symmetric magnetic nozzle configuration involved using all three coils to generate a maximum magnetic field on axis of $B_{z,\text{max}} = 320$ G. For the preliminary study of magnetic steering, only the most inner coil, MTV1, was used to deflect the magnetic nozzle on the $r$-$z$ plane and to also produce a $B_{z,\text{max}} = 320$ G. Figure 2a and b show the magnetic field lines and the field magnitude for the symmetric and deflected case, respectively. Along the $z$ axis, the magnetic field exhibits a single peak at the magnetic nozzle throat $(r, z) = (0, -8)$ cm and it then decreases rapidly to 67 G for the symmetric case, and to 26 G for the asymmetric field case. The deflection angle of the magnetic nozzle,
θ_{def}, was defined as the angle between the axis z and the central field line with vertex at 
the nozzle throat i.e., \( z = -8 \) cm. Magnetostatic simulations predicted deflections of the 
magnetic nozzle of up to θ_{def} = ±14°. The achievable MN orientations would be suffi-
cient to perform attitude and orbit control manoeuvres as the majority of thrust vector-
ing corrections do not exceed 8-10°[9].

A preliminary analysis of the ion gyroradius on axis, \( r_{g,i} \), was also carried out to esti-
mate the coupling between the ions and the magnetic field. Ions are assumed to be mag-
netized when the ratio of their Larmor radius \( r_{g,i} \) to the characteristics length of system 
\( R \) is \( r_{g,i}/R < 1 \). Considering ions with a thermal speed of approximately 400 m/s and 
at room temperature [15, 16], the ions are assumed to be well magnetized in the plasma 
source for both the symmetric and the deflected nozzle orientation \( (r_{g,i}/R < 1) \), where 
the characteristic length of the system is the glass tube radius i.e., \( R = 4.5 \) cm. In such a 
configuration (i.e. axial location of MN throat and antenna not coinciding), it has been 
shown that an increase in axial plasma density in the source is achieved when the ions 
are magnetized under the antenna [11, 15, 17]. In the expansion chamber, where the 
characteristic length of the system is the expansion chamber radius, where \( R = 25 \) cm, 
for the symmetric case, the ions are magnetized in the region of interest for the meas-
urements \( (r_{g,i}/R < 1) \). In the asymmetric magnetic field case, the ion gyroradius on axis 
becomes comparable to the chamber radius at a distance of 19 cm from the source exit 
\( (r_{g,i}/R \approx 1) \), leading to a partially-magnetized ion population in the \( z_{p} = 19 \) cm meas-
urements region.

Results
Radial measurements of the plasma were initially done in a symmetrical magnetic nozzle 
configuration to obtain a baseline profile of the plasma. For this study, the experiments 
were carried out at a frequency of 27.12 MHz, an RF power of 250 W, an argon pres-
sure of 0.5 mTorr, and a \( B_{z,max} \) of 320 G for both the symmetric and deflected magnetic
nozzle case. Given that the frequency used does not affect the overall plasma characteristics and behaviour [11], conducting the experiments at 27.12 MHz would have not resulted in any substantial difference than if they were run at the standard 13.56 MHz. During the data acquisition, the plasma remained stable with a reflected power always less than 0.5%.

**Ion saturation current profiles**

Figure 3a and b show the radial profiles of the ion saturation current measured with the Langmuir probe at $z_P = 9$ cm and $z_P = 19$ cm for the symmetric and deflected MN orientation, respectively.

For the symmetric case, $I_{\text{sat}}$ exhibits a peak at $r = -7$ cm and one at $r = 5$ cm when the LP is located at $z_P = 9$ cm. When the data is collected at $z_P = 19$ cm, the ion saturation current peaks are at $r = -10$ cm and at $r = 8$ cm. Measurements of $I_{\text{sat}}$ taken in the plasma source showed a single maximum on axis, implying that the double-peaked current profile occurs downstream in the diverging magnetic nozzle section. This feature has been reported in other RF devices when the plasma has been expanding in a magnetic nozzle [7, 18–20]. The formation of these high density conics has been attributed to hot electrons generated under the antenna that escape the plasma source along the last radial field lines leaving the glass tube [19–21]. Additionally, it has been shown that the generated thrust in a magnetic nozzle RF thruster is increased by this high electron pressure conical structure [22]. It is also worth noticing that the plasma presents an asymmetric radial profile even for the symmetric magnetic nozzle configuration. This asymmetry could be due to a non-uniform power deposition and subsequent plasma generation process in the source [7, 23]. The highest RF voltage drop occurring between the two antenna ends could lead to capacitive coupling happening under this region.

The ion saturation current profile for the deflected MN case (Fig. 3b) presents a very different trend. $I_{\text{sat}}$ shows a single peak centred at $r = -4$ cm for $z_P = 9$ cm, and at $r = -5$ cm for $z_P = 19$ cm. A possible cause of the double-peak to single-peak profile

![Fig. 3](image-url)
transition in the deflected magnetic nozzle case could be the non-uniformity of the magnetic field in the plasma source (which is clear in Fig. 2b). Some of the high energy electrons created under the antenna will be lost to the source walls following the bent streamlines thereby inhibiting their escape from the plasma source into the chamber and reducing local ionization downstream of the MN. The drop in the collected $I_{sat}$ when compared to the symmetric case could be caused by an increased plasma loss to the source wall before expanding in the chamber, following the deflected field lines. When analysing the radial profiles, it is interesting to consider the direction of the central magnetic field line. At $z = 9$ cm, the central magnetic field line deflected by $\theta_{\text{def}} = 14^\circ$ has a radial coordinate of $r = -4.2$ cm, which coincides with the peak in current measured at $(r - z) = (-4, 9)$ cm. On the other hand, the radial position of the deflected central field line at $z = 19$ cm would be $-6.7$ cm, while the $I_{sat}$ peak is measured at $(r - z) = (-5, 19)$ cm. This discrepancy could be explained by ion demagnetization, and the subsequent ion detachment from the field lines, at $z = 19$ cm where the calculated gyroradius of the thermal ions is comparable to the chamber radius.

**Ion beam detection**

For thruster applications, the existence of an accelerated ion population is a key contribution to the axial momentum flux exhausted from the source i.e., the axial force [22]. In the current experimental set up, ion-neutral collisions affect the accelerated ion population expanding in the magnetic nozzle, where charge-exchange collisions create slow ions and fast neutrals. Thus, the ion beam component decreases and the measured thermal ion population increases. The formation of the high-density conics in the symmetric MN case have also been linked to downstream ionization that would add to the local ion population [18]. At the operating conditions of this study, the presence of an ion beam can be detected by an RFEA and it is characterised by a second peak in the IEDF at a higher voltage than the plasma potential, where the beam potential, $V_B$, is defined as the location of this second maximum. To ensure that the RFEA was actually measuring an accelerated ion population, the ion energy distribution functions measured at the same experimental

![Image](image.png)

**Fig. 4** I-V characteristics measured with the RFEA at $(r, z) = (0, 19)$ cm at $P_{RF} = 250$ W, $B_{z,\text{max}} = 320$ G in a symmetric MN configuration, and 0.5 mTorr: (a) Radial-facing RFEA, $V_P = 21.98$ V; (b) Source-facing RFEA, $V_P = 21.28$ V and $V_B = 40.25$ V
condition but with the probe orifice first facing the chamber walls (radial-facing) and then facing the plasma source exit (source-facing) were compared. Figure 4 shows the \( I-V \) characteristics and the derived IEDFs for both the radial-facing and source-facing RFEA orientation. The radial-facing profile shows one peak located at a plasma potential of \( V_P = 21.98 \) V. On the other hand, the IEDF obtained from the source-facing RFEA presents two peaks: one at the local plasma potential \( V_P = 21.28 \) V, and the second one at a higher potential, \( V_B = 40.25 \) V. Because of the extreme similarity between the measured plasma potentials, one can infer that the IEDF does not present a distribution broadening effect, nor that the probe orientation is significantly perturbing the plasma, but that the RFEA is actually measuring a higher energetic, directional ion beam [4, 12, 13].

**Ion beam characterization**

The retarding field energy analyzer is used to radially characterize the ion energy distribution function, the total ion current, and the plasma and ion beam potentials. The probe is placed at \( z_P = 19 \) cm and with the orifice facing the plasma source exit to collect the ion beam signal. The standard deviation of the measured current is calculated to be \( 0.2 \mu A \). For the symmetric case, the total ion current plot in Fig. 5 shows a double-peaked, slightly asymmetric profile confirming the ion saturation current profile measured by the Langmuir probe. Indeed, the \( I_0 \) plot presents a maximum at \( r = -11 \) cm and at \( r = 8 \) cm. Contrarily, the deflected MN case shows a single peak centred at \( r = -5 \) cm, again similar to the \( I_{sat} \) profile of Fig. 3a.
Figure 6 shows the contour plots of the normalised ion energy distribution functions as a function of radial position and potential for the symmetric magnetic nozzle case. The IEDFs show a local thermal population of ions at $V_p \approx 20$ V with a double-peaked profile at $r = -11$ cm and $r = 8$ cm, consistent with the measured total ion current. The energy distributions show the presence of a second, higher energetic ion population at a potential of $V_B \approx 40$ V. This accelerated population is defined as the ion beam, and it appears centred at $r = -2$ cm. An estimate of the ion beam energy at the location of its centre i.e., $(r,z) = (-2, 19)$ cm can be found as $\epsilon_B = e(V_B - V_p) \sim 19$ eV. The ion beam potential is constant between $-5 < r < 5$ cm, and then decreases by 10 V at the edges.

Fig. 6 Ion energy distribution functions as a function of radial position and discriminator voltage taken with the RFEA at $z = 19$ cm for the symmetric magnetic nozzle case

Fig. 7 Ion energy distribution functions as a function of radial position and discriminator voltage taken with the RFEA at $z = 19$ cm for the deflected magnetic nozzle case
The measurements taken with the asymmetric magnetic nozzle orientation clearly show the deflection of the ion beam in the direction of increasing radial magnetic field. As seen in Fig. 7, the local ion population presents a single peak at \( r = -5 \text{ cm} \) at a slightly higher potential than the symmetric case i.e., \( V_p \approx 24 \text{ V} \). The energy distribution of the ion beam is not centred anymore, but it shows a shifted profile that also peaks at \( r = -5 \text{ cm} \), and it is characterised by a narrower beam width. Additionally, the potential of the accelerated ions peaks at \( r = 0 \text{ cm} \) where \( V_B \approx 43 \text{ V} \) to then decrease radially e.g., \( V_B \approx 38 \text{ V} \) at \( r = -5 \text{ cm} \). The energy of the ion beam in the deflected case at \((r,z) = (-5,19) \text{ cm}\) is then estimated to be \( \epsilon_B \sim 14 \text{ eV} \). It is noticed that the ion-neutral mean free path for the operating pressure is shorter than the distance between the source exit and the probe position i.e., \( \lambda_{mfp} \sim 10 \text{ cm} \) and \( z_p = 19 \text{ cm} \). Thus, the accelerated ion beam component is decreased at the measurement location due to charge-exchange collisions, and elastic collisions could affect its direction, further reducing the collected beam current. Additionally, the plasma profile structure for both the symmetric and deflected magnetic nozzle scenario peaks in the centre and decreases radially, indicating the presence of an electric field that would accelerate the ions outwards increasing the plasma cross-field diffusion.

**Conclusion**

The first measurements of a magnetic steering system mounted co-axially in a magnetic nozzle radio-frequency plasma thruster at The University of Auckland are presented. A Langmuir probe and a retarding field energy analyzer were used to radially characterize the plasma expansion in a symmetric and deflected magnetic nozzle. In the symmetric configuration, both the ion saturation current and the ion energy distribution radial profiles showed a double-peaked behaviour. The latter could be a sign of high density conics formation and local ionization downstream of the plasma source caused by transport of hot electrons from the antenna region. The measurements taken in the deflected magnetic nozzle case proved that the plasma was affected by the asymmetric magnetic field. Radial profiles of the ion saturation current, the total ion current and of the IEDFs changed from a double-peaked to a single peak profile centred around \( r = -5 \text{ cm} \) in the direction of the magnetic nozzle. However, further experiments are required to fully understand the generation of the high-density conics, and how to optimize the magnetic steering system to allow for the conics to be created even when the magnetic nozzle is deflected.

The ion energy distribution functions clearly showed the radial location of the ion beam changing with the deflected magnetic field. The direction of the accelerated ion beam was found to be following the magnetic nozzle orientation, even though the ion beam intensity and its direction were affected by ion-neutral collisions and ion demagnetization; thus, further measurements of the ion energy distribution functions closer to the plasma source exit are necessary to quantify and better characterize the steering of an ion beam.

**Authors’ contributions**

A.C. run the experiments, acquired the data and redacted the manuscript. F.F. helped in the data acquisition and the construction of the apparatus. C.C. and R.B. provided guidance in experimental RF plasmas and diagnostics. J.C. and N.R. are doctoral supervisors of A.C. and F.F. All authors reviewed the manuscript. The author(s) read and approved the final manuscript.
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Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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