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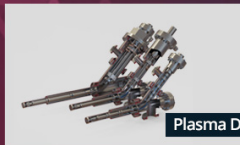
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PAPER

Investigations on argon and hydrogen plasmas produced by compact ECR plasma source

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Argon and hydrogen plasmas were produced by a Compact ECR Plasma Source (CEPS) attached coaxially to a large chamber. This paper presents characterization results of the two plasmas using a newly designed Langmuir Probe. Experiments in argon were conducted to benchmark the plasma parameters and to determine the efficacy of the CEPS for thruster applications, recommended by recent results (Ganguli *et al* 2019 *Plasma Sources Sci. Technol.* **28** 035014), while the hydrogen experiments were undertaken to determine the typical range of plasma parameters for assessing the usefulness of CEPS for different applications. In argon plasma, high densities ($\approx 10^{12} \text{ cm}^{-3}$), high electron temperatures and plasma potentials are obtained at fairly low pressures $\approx 0.3\text{--}0.5$ mTorr. The plasma potential drops substantially (≈ 65 V) within the CEPS itself, demonstrating its suitability as a plasma thruster. On the other hand, plasma densities are lower for hydrogen in front of the CEPS, and the electron temperatures and plasma potentials, higher. The hydrogen experiments have helped establish an important aspect of such plasmas. At low pressures (≈ 0.5 mTorr) plasma density is relatively low with a single, high temperature electron population; on the other hand, at higher pressures (≈ 6 mTorr), the plasma has *two* electron populations, a low temperature, high density population and another low density, high temperature warm population. For hydrogen this transition from the former (with single electron population) to the latter state (with two electron populations) occurs at a pressure, ≈ 3 mTorr while similar transition for argon occurs at ≈ 0.3 mTorr. Apart from the observed two states of plasma, each state with its own *distinctive* properties, another important feature of the hydrogen plasma is that the axial density profiles obey approximately $n/B = \text{constant}$ although no such scaling is observed for argon.

1. Introduction

Laboratory plasmas are produced by application of electrical energy, and the type of electrical energy employed is used to distinguish the different plasmas formed. This is so, since each form of electrical energy gives the plasma its own set of distinctive properties that may be exploited for specific applications, giving rise to the concept of dedicated plasma sources [1]. Thus one has DC plasma sources, AC and low frequency RF plasma sources, high frequency RF and helicon plasma sources, surface wave plasma sources, microwave and electron cyclotron resonance (ECR) plasma sources, etc [1–5]. Amongst the different plasma sources, there are those that rely on the *absorption of plasma waves* launched in the plasma, like the microwave and surface wave plasma sources. Another example is the helicon plasma source [6, 7], where plasma is sustained by absorption of RF, whistler waves (helicon waves) either through Landau damping or by collisions [8, 9]. The ECR plasma source is another notable source [10–12], where high frequency whistler waves (in microwave range) are absorbed very efficiently in the vicinity of ECR zone [13–15]. In particular, they yield very high-density, overdense plasmas that find various applications [16–21]. It is worth mentioning here that it is only in unbounded unmagnetized plasma that there exists a cut-off density [$\omega_{pe} < \omega$ (ω_{pe} : plasma frequency, ω : wave frequency in radians)] above which

wave propagation is not possible. In ECR produced plasmas, microwaves are launched as *whistler waves* inside a conducting waveguide in presence of an inhomogeneous axial magnetic field, decreasing along the waveguide axis. However, the condition for wave propagation is now reversed and reads, $\omega_{pe} > \omega$. The additional condition required for whistler wave propagation is $\omega_{ce} > \omega$ (ω_{ce} : electron cyclotron frequency in a magnetic field) [5, 22, 23]. As the wave propagates along the decreasing magnetic field it may encounter a resonance surface, where $\omega_{ce} = \omega$, following which the wave goes into cut-off for lower fields ($\omega_{ce} < \omega$). It may be noted that the plasma densities obtained in typical ECR discharges are high and considerably greater than the critical density corresponding to $\omega_{pe} = \omega$ [11, 24–26].

It turns out that in plasma loaded waveguides, the nature of the whistler modes can be altered considerably when the boundary conditions imposed by the waveguides are included, though the fundamental nature of the resonance described above remains unaffected. These modes have been studied in detail in several earlier papers [9, 11, 15, 24].

The authors' group at IIT Delhi has developed a permanent magnet based, highly portable, high density Compact ECR Plasma Source (CEPS) [27] that may be used in a number of ways. For instance, it has been used as a standalone source for filling any moderate volume system with high-density argon plasma with moderate power (~ 300 – 400 W) [17, 28, 29] or, using *multiple* CEPS to fill, industrial sized, large volume chambers (~ 1.2 cu. m) with plasma using moderate microwave power levels (~ 7 kW of power) [30, 31].

A configuration that allows for considerable flexibility in investigations and applications is one in which a *single CEPS is connected coaxially to a very large vessel*, an expansion chamber. In such a configuration the CEPS magnetic field produces a diverging field in the expansion chamber, decaying exponentially along the chamber axis. The authors have used this configuration extensively to characterize argon and hydrogen plasmas at different pressures and microwave powers. This paper presents some of these results.

Apart from calibration of the CEPS for plasma production in the above configuration, argon plasma was also investigated to determine the possibility of using the CEPS as a *thruster* for deep space vehicle propulsion. In general, plasma based thrusters are attractive on account of the very high specific thrusts attained by them. Additionally, they also have the advantage that the electric field required for accelerating ions are generated *internally* within the plasma itself, and not by external power supplies, as has to be done for ion thrusters [17, 32]. Helicon plasma systems, for instance, are known to produce '*double layers*' with fairly large potential drops that can accelerate ions [33, 34]. The ECR mechanism, on the other hand, can heat electrons to high temperatures, which result in very large plasma potentials that can also accelerate ions to high energies. It is worth mentioning here that helicon thrusters (thrusts $\sim$ few mN) and VASIMR (thrusts $\sim$ few N with additional ion heating) have been studied extensively [35–37] with input powers levels $\sim$ kW. In comparison, studies on ECR thrusters are relatively few, with the associated technology development still far from mature [38, 39]. Our investigations using the CEPS based plasma thrusters are an attempt to show that ECR plasma thrusters may indeed be strong contenders if nurtured suitably. This possibility is not unrealistic considering that the CEPS because of its high electron heating potential, compactness and efficiency, may in reality well prove to be a highly attractive alternative to other conventional plasma thrusters. Preliminary studies wherein the CEPS was connected to a small test chamber have already given such indications [17].

The studies with hydrogen, on the other hand, were conducted because of the general usefulness of hydrogen plasmas for a wide variety of applications that require reduction, passivation and cleaning in materials processing, thin film applications and nanoscale fabrications. The applications range from improving selectivity of graphene monolayers [40], fabrication of graphene ribbons using hydrogen plasma etching for nanoelectronics and spintronics applications [41–43], improving photo-catalytic performance of hydrogenated TiO₂ nanoparticles [44], removal of corrosion layers [45], rendering diamond-like-carbon films more corrosion resistant [46], selective heating of transition metals for fabrication of nickel-silicide electrodes for ultra-large-scale integrated devices, etc [47]. A somewhat different application pertains to the extraction of H⁺ beams from hydrogen plasmas for neutral beam heating of fusion plasmas [48, 49].

In what follows characterization results for argon plasma are presented first, following which results for hydrogen are presented. As will be seen there are considerable differences in the plasma properties of the two gases on account of the differences in their mass, as well as because hydrogen is a molecular gas, which gives it additional degrees of freedom. The latter aid the molecules in acquiring energy from electrons, which in turn alter the energy balance of electrons quite significantly. Apart from calibration of the CEPS, the argon experiments were performed mainly with the CEPS thruster in mind. The hydrogen experiments however, are expected to reveal specific plasma properties that could find use in a variety of applications both, new or known. It may be noted, however, that the argon and hydrogen experiments presented here are a first of their kind, on account of the fact that the CEPS is a relatively recent device and its working is yet to be fully understood, explored and exploited.

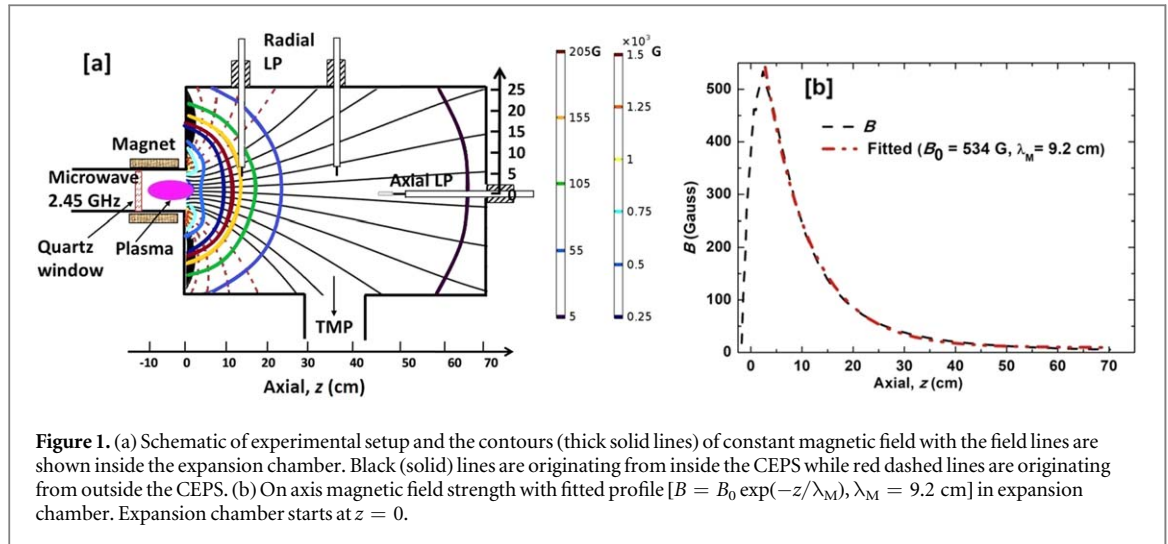


Figure 1. (a) Schematic of experimental setup and the contours (thick solid lines) of constant magnetic field with the field lines are shown inside the expansion chamber. Black (solid) lines are originating from inside the CEPS while red dashed lines are originating from outside the CEPS. (b) On axis magnetic field strength with fitted profile [$B = B_0 \exp(-z/\lambda_M)$, $\lambda_M = 9.2$ cm] in expansion chamber. Expansion chamber starts at $z = 0$.

2. Experimental setup and diagnostics

Figure 1 shows the experimental system comprising the CEPS (ID ≈ 9.1 cm, length ≈ 11.6 cm) [17, 28, 29] that is connected coaxially to a large expansion chamber (ID ≈ 48 cm, length ≈ 75 cm). The CEPS has a set of NdFeB ring magnets that creates a magnetic field whose ECR surface lies *within* the CEPS and produces a diverging field that decays exponentially along the expansion chamber with scale length, $\lambda_M \approx 9.2$ cm (figures 1(a) and (b)). All the experiments were performed at fixed microwave power. The net power delivered to plasma (=forward power — reflected power) was ≈ 600 W (forward power ≈ 630 W, reflected power ≈ 30 W).

Axial and radial, tungsten Langmuir probes (LP) were employed for obtaining plasma parameters (figure 1(a)). The tip of the axial probe was oriented along the magnetic field (i.e. the z axis). However, to protect it from head-on bombardment by energetic streaming ions, the tip itself was encapsulated in a ceramic cap. Such a construction restricts the probe collecting area to its midsection (0.25 mm dia. $\times$ 4 mm long) permitting particle collection normal to the magnetic field only. This design, arrived at after several trials, enabled the probe to survive the harsh plasma environment near the ECR zone inside the CEPS. Even then, it was necessary to keep sufficient distance from the ECR surface located at $z \approx -5.3$ cm inside the CEPS to avoid damage to the probe. (The junction between the CEPS and expansion chamber is taken as $z \approx 0$ (figure 1)). For argon for instance, LP data was recorded from $z \approx -3.5$ cm to the end of expansion chamber. For hydrogen, on the other hand, the high bulk electron temperatures saturated the LP amplifiers both in the ion saturation and electron transition regions, so that LP data was mostly recorded from $z \approx 3$ cm.

LP data was analyzed carefully for determining the bulk electron density (n), bulk electron temperature (T_e), plasma potential (V_p) and warm electron density and temperature (n_w , T_w), if present. The details of the LP procedure, data acquisition, its validity, and analysis of the plasma parameters from the I - V data can be found elsewhere [9, 50, 51]. As will be explained in section 3.2, for purposes of LP analysis and other reasons, it is reasonable to assume that the positive ions in the hydrogen plasma are all H^+ ions. Figures 2(a) and (b) show typical I - V characteristics for the axial LP recorded at $z \approx 10$ cm for argon and hydrogen plasma respectively, at 1 mTorr pressure and microwave power ≈ 600 W (cw). The plot of $\ln(I_e)$ versus probe voltage V in figure 2(a) for argon shows two distinct slopes indicating the presence of two electron populations. One population, detected at deeply negative probe biases, corresponds to a low density, high temperature ($T_w \approx 68$ eV) warm population, while the other, found at low probe biases corresponds to bulk electrons with low temperature ($T_e \approx 3.6$ eV). In contrast, $\ln(I_e)$ versus V plot for hydrogen in figure 2(b) indicates that only one electron population—the bulk population, is present. It may be noted however that the bulk population has a much higher temperature ($T_e \approx 27$ eV).

3. Plasma characterization results

3.1. Characterization of argon plasma

Axial profiles of the different plasma parameters are presented in figure 3 at argon gas pressures, $p_{Ar} \approx 0.3$ and ≈ 0.5 mTorr and for ≈ 600 W (cw) microwave power. The profiles commence from $z \approx -3.5$ cm, the closest one could approach the ECR zone inside the CEPS without damaging the probe. It is seen that the trends for the two profiles at $p_{Ar} \approx 0.3$ and ≈ 0.5 mTorr are approximately similar. For instance, closest to the ECR zone

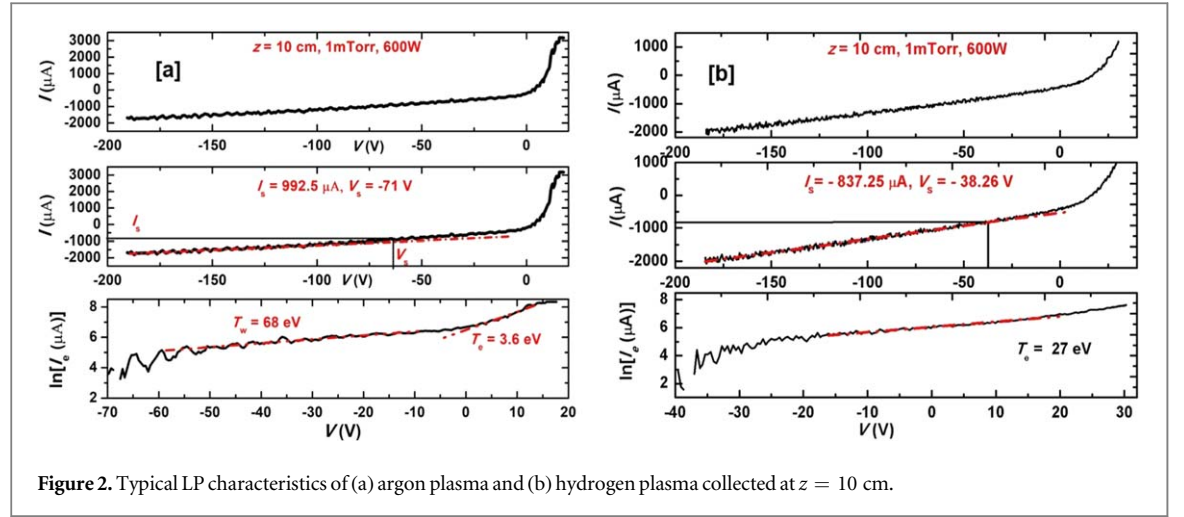


Figure 2. Typical LP characteristics of (a) argon plasma and (b) hydrogen plasma collected at $z = 10$ cm.

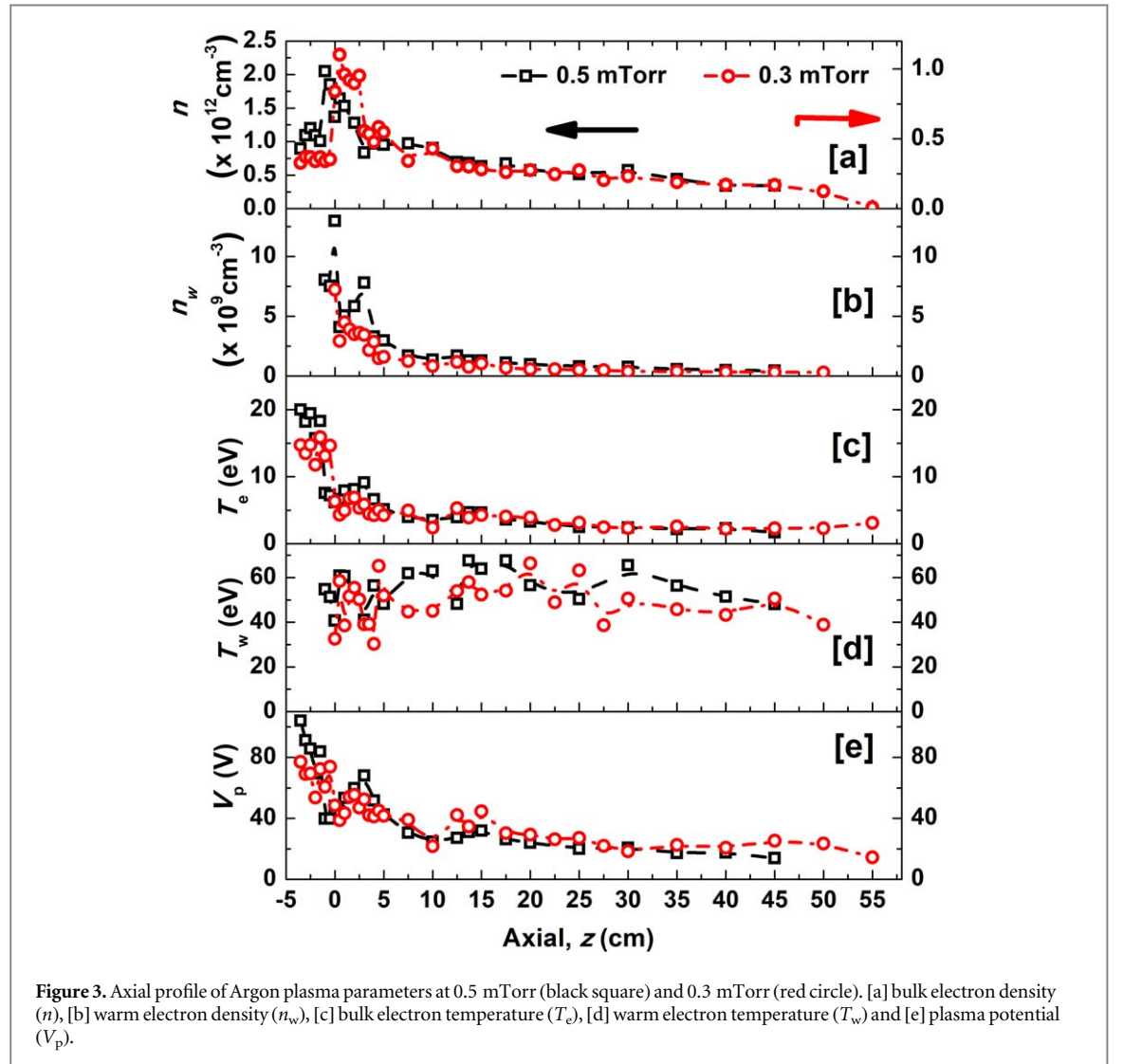


Figure 3. Axial profile of Argon plasma parameters at 0.5 mTorr (black square) and 0.3 mTorr (red circle). [a] bulk electron density (n), [b] warm electron density (n_w), [c] bulk electron temperature (T_e), [d] warm electron temperature (T_w) and [e] plasma potential (V_p).

($z \approx -3.5$ cm), the bulk densities and bulk electron temperatures lie in the range $n \approx (0.25\text{--}1.0) \times 10^{12} \text{ cm}^{-3}$ and $T_e \approx 15\text{--}20$ eV, respectively. However, by $z \approx 0$, these densities rise to, $n \approx (1.1\text{--}2.25) \times 10^{12} \text{ cm}^{-3}$ with a concomitant decrease in the bulk temperatures to about $T_e \approx 5$ eV. Accompanying this change in the bulk electron population, is the sudden onset of a separate warm electron population at $z \approx 0$, with density, $n_w \approx (0.7\text{--}1.3) \times 10^{10} \text{ cm}^{-3}$ and temperature, $T_w \approx 50\text{--}60$ eV. Following these initial variations in n and n_w within the CEPS (up to its edge), there is a rapid decrease in these quantities from $z \approx 0$ to $z \approx 7.5$ cm, after

which they decrease more slowly to $\approx(1-3) \times 10^{11} \text{ cm}^{-3}$ and $\approx(3-3.7) \times 10^8 \text{ cm}^{-3}$ respectively, by $z \approx 55 \text{ cm}$. Also, after the initial sharp fall in temperature within the CEPS from $\approx 20 \text{ eV}$ to $\approx 5 \text{ eV}$, T_e decreases slowly with z (to $\approx 2.4 \text{ eV}$ upto $z \approx 20 \text{ cm}$), settling finally at $\approx 2 \text{ eV}$ at $z \approx 55 \text{ cm}$. Although the fall in T_e is not severe, it will be seen later (figure 5) that the rapid fall in density from $z \approx 0$ to $z \approx 7.5 \text{ cm}$ is a consequence of magnetic and geometric expansion. T_w fluctuates marginally along the system length lying mostly within, ≈ 50 to 60 eV . It is observed from figure 3 that the plasma potential, V_p drops by about $\approx 65 \text{ V}$ (from $\approx 104 \text{ V}$ to $\approx 39 \text{ V}$) for $\approx 0.5 \text{ mTorr}$ and about $\approx 39 \text{ V}$ (from $\approx 77 \text{ V}$ to $\approx 38 \text{ V}$) for $\approx 0.3 \text{ mTorr}$ within the CEPS itself (from $z \approx -3.5$ to $z \approx 0$). Beyond $z \approx 0$, V_p drops gradually, decreasing to about $\approx 20-25 \text{ V}$ by about $z \approx 45$ to 50 cm .

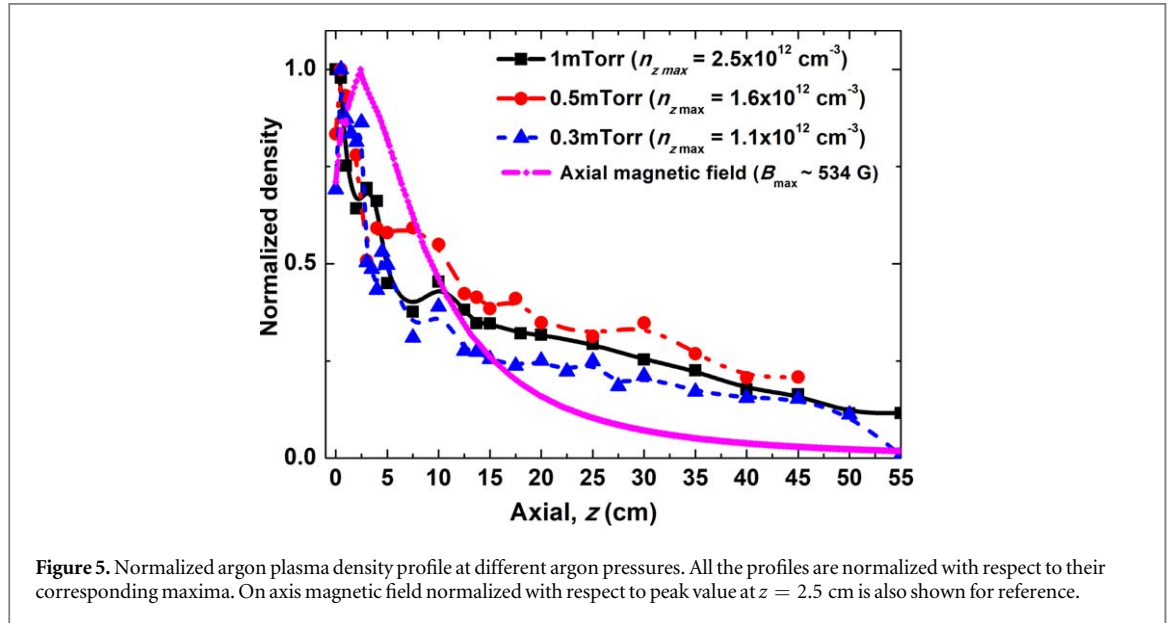
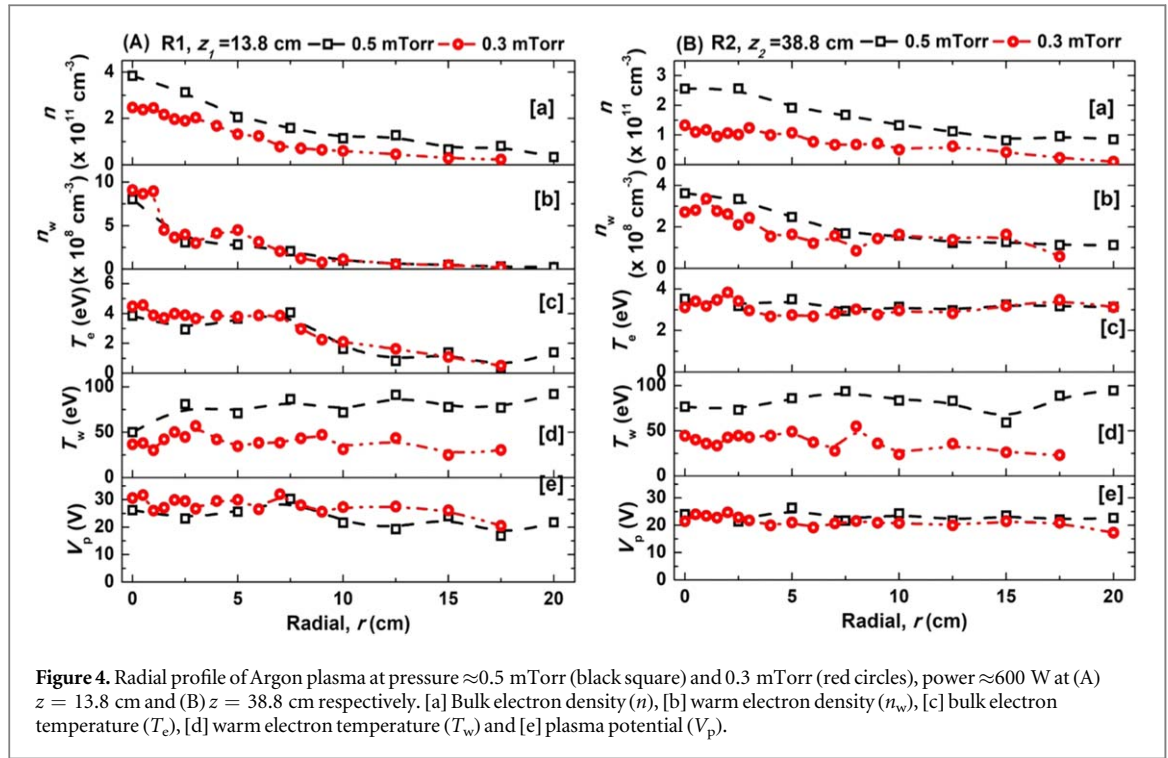
A few remarks regarding the nature of the CEPS produced plasma are in order. (i) It may be noted firstly that the plasma densities and electron temperatures are high ($\sim 10^{12} \text{ cm}^{-3}$) within the CEPS, even for $\approx 0.3 \text{ mTorr}$. This is due to the ECR heating mechanism that can yield high plasma densities even at fairly low pressures. The additional advantage gained from the CEPS is that its magnetic field offers better confinement resulting not only in high plasma densities ($\sim 10^{12} \text{ cm}^{-3}$) but high electron temperatures as well ($15-20 \text{ eV}$); both features are of importance for thruster applications. (ii) A fairly ubiquitous feature of ECR plasmas is that the electrons either have a *relatively low bulk density along with a high bulk temperature* or a *relatively high density, low temperature bulk population, accompanied by a low density, high temperature warm population*. It is usual for ECR plasmas to show a transition from the former situation to the latter one, under a change of conditions that perturb the plasma somehow (viz. geometric or magnetic field expansion, etc). It turns out however, that *at sufficiently low pressures this transition may be inhibited*. For instance with argon, this transition is blocked for pressures below $\approx 0.05 \text{ mTorr}$, and for hydrogen this blocking occurs up to a much higher pressure, $\approx 2 \text{ mTorr}$. (iii) It is possible to interpret the profiles in figure 3 in another way. It was observed above that T_w varies between $50-60 \text{ eV}$. It turns out that the rate constant for ionization by electron impact on argon passes through a broad maximum precisely in this range of temperatures [5]. *This implies that the warm electrons can be regarded as a source of ionization for plasma production*. It follows therefore, that the *bulk plasma density profile should follow the warm electron profile*, since T_w is already in the correct range and will not exercise any control over the bulk density profiles. The strong correlation between the bulk and warm electron densities is seen clearly in figures 3(a) and (b). The latter feature is not new and has been reported in earlier studies on ECR plasmas [24, 52, 53]. (iv) From the thruster application point of view, the most important plasma parameter is the plasma potential. It is seen that the potential drops are very steep and can accelerate ions very efficiently as they exit the short section of the CEPS, giving strong indication that the CEPS may actually turn out to be an efficient thruster. Even inside the expansion chamber, the small gradient in V_p can give rise to a weak electric field that can help in overcoming friction due to collisions of ions with neutral atoms.

Radial LP profiles were taken at two axial locations: (i) Location R1 at $z \approx 13.8 \text{ cm}$; (ii) Location R2 at $z \approx 38.8 \text{ cm}$. Figures 4(A) and (B) give respectively, the radial variations of the plasma parameters at locations R1 and R2 for argon gas pressures, $p_{Ar} \approx 0.3$ and $\approx 0.5 \text{ mTorr}$ and 600 W (cw) microwave power. It is seen once again that the nature of the variations for the two pressures are approximately similar with the warm electron population being present in both cases. It can also be seen that the bulk density profiles mimic the warm population profiles, implying that the latter acts as a source for the bulk plasma since T_w is high enough for efficient ionization. The bulk densities for $\approx 0.3 \text{ mTorr}$ are uniformly lower than that for $\approx 0.5 \text{ mTorr}$. Also, as expected, the densities for R2 are lower than that for R1. Another notable feature is that the radial spread of the plasma is higher for R2 as compared to that for R1. V_p is about $\approx 30 \text{ V}$ for R1 and about $\approx 20 \text{ V}$ for R2. It is also seen that V_p is nearly uniform along the radius indicating a very low radial electric field component.

To see the effect of the geometric and magnetic field expansion, profiles of the on-axis plasma density n , normalized with respect to their values at $z \approx 0$, have been plotted for pressures, ≈ 0.3 , ≈ 0.5 and $\approx 1 \text{ mTorr}$ in figure 5 for $z \geq 0$. For reference, the on-axis magnetic field B normalized with respect to its maximum at $z \approx 2.5 \text{ cm}$ is also shown. It is seen that for *all* pressures there is an initial region from $z \approx 0$ up to $z \approx 5-7.5 \text{ cm}$ in which *all densities fall faster than B*. The latter is followed by a short transition region (up to about, $z \approx 10-15 \text{ cm}$) beyond which is another region (up to about, $z \approx 55 \text{ cm}$) where the *densities fall slower than B*. A possible reason for the initial rapid fall could be that closer to the source, the plasma that emerges from within the CEPS can through cross field transport, *easily reach field lines that enter the expansion chamber from outside the CEPS* (shown as red dashed lines in figure 1(a)) *and are not loaded with plasma*. As a result the plasma density drops more rapidly than B along the axis. As the plasma flows out along the axis to larger values of z , field lines that are still unloaded at these axial locations occur only at large values of the radius, thereby reducing the depletion of plasma from the central region and allowing the plasma density to drop less rapidly than B .

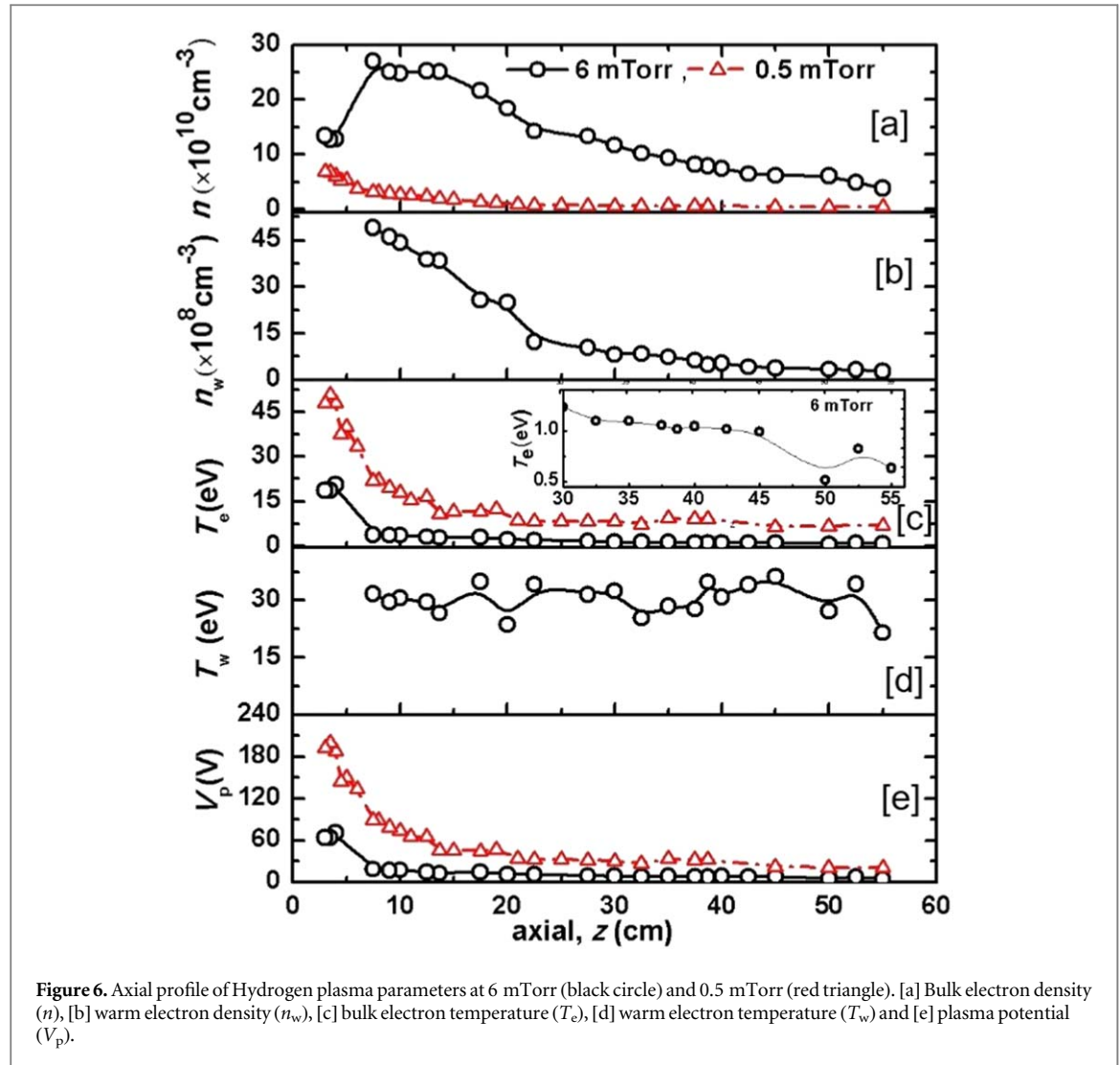
3.2. Characterization of hydrogen plasma and comparison with argon results

Figure 6 shows axial profiles of n , T_e , V_p and n_w , T_w , (when the warm population is present) obtained at $\approx 600 \text{ W}$ of microwave power and hydrogen gas pressures $p_{H_2} \approx 0.5$ and $\approx 6 \text{ mTorr}$. The axial profiles start at $z \approx 3 \text{ cm}$, which is the closest the LP could be taken towards the CEPS mouth. Although hydrogen is a molecular gas, for



temperatures above ≈ 0.2 eV, it can go into a *highly dissociated state* [54]. This would be easily possible in ECR plasma since ions typically acquire temperatures of $\approx$ few tenths of eV, which they can transfer very efficiently to the neutrals through collisions. Thus in steady state the gas molecules would have sufficient energy to become dissociated into H atoms that ionize to produce H^+ ions. Thus it would be reasonable (and convenient) to assume that the hydrogen plasma has only H^+ ions, and *not* H_2^+ , H_3^+ , etc.

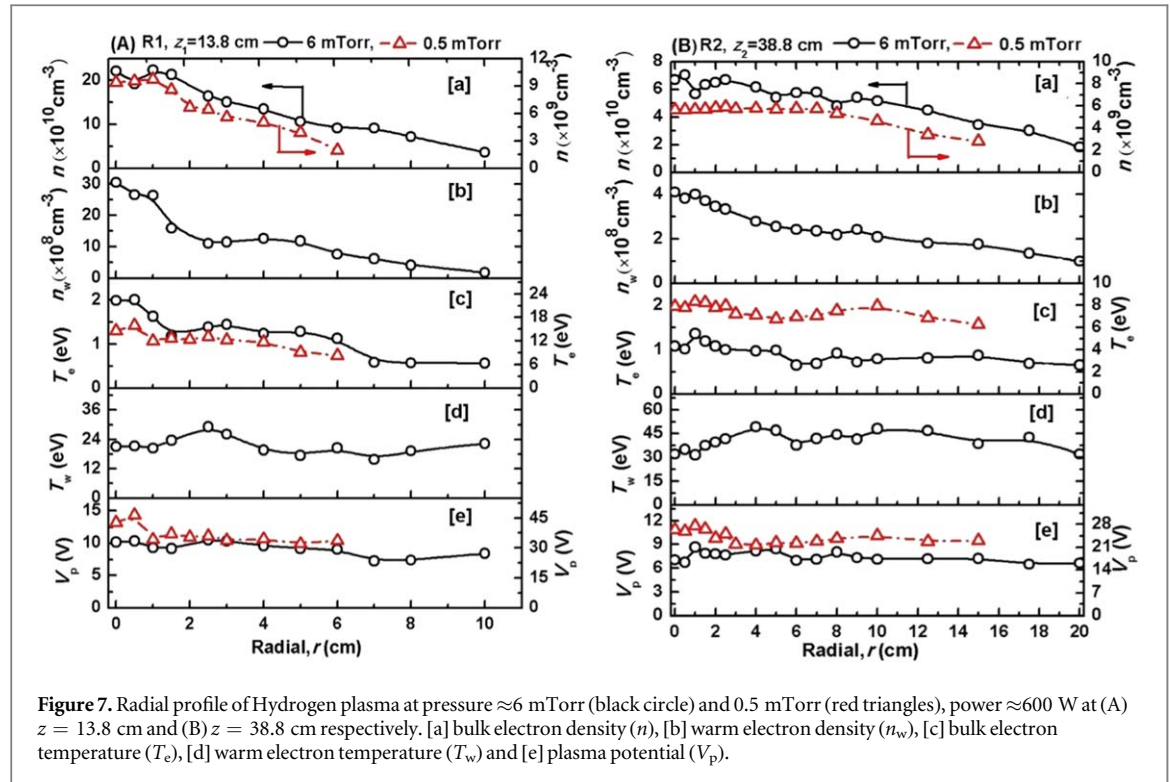
Examining the profiles for ≈ 0.5 mTorr first, it is seen that *there is no warm population* for this case. Instead one finds a relatively low, bulk density with $n \approx 7 \times 10^{10} \text{ cm}^{-3}$ decreasing smoothly with z to $n \approx 0.46 \times 10^{10} \text{ cm}^{-3}$ at $z \approx 55$ cm. The corresponding bulk electron temperature starts at $T_e \approx 45$ eV and decreases monotonically to $T_e \approx 7$ eV at $z \approx 55$ cm. Both, the fall in n and T_e are on account of the diverging magnetic field that helps the plasma expand. (It may be recalled that a similar high temperature, low density population was observed for argon at 0.5 mTorr, though the densities there were *higher* and the T_e values lower; the results for argon were obtained *inside* the CEPS, while those for hydrogen are about 3 cm *in front of the source mouth*.) It is interesting to note that the profile for n follows closely the T_e profile, indicating that *ionization within the expansion chamber is due to bulk electrons, with T_e controlling the profiles this time*. It was noted above



that T_e decreases from ≈ 45 eV to ≈ 7 eV along the expansion chamber. It turns out that the rate constants for ionization by electron impact on H atoms are moderately high and vary marginally in this temperature range. Thus one may conclude that electrons in the bulk population have sufficient energy to maintain the plasma to offset plasma losses. Going on to the plasma potential, one sees that $V_p \approx 200$ V at $z \approx 3$ cm, which is much higher than what was obtained for argon. Since V_p is related to T_e linearly, its profile tracks T_e fairly closely. V_p decreases monotonically along the axis, falling to ≈ 20 V at $z \approx 55$ cm.

The nature of the plasma profiles for ≈ 6 mTorr are very different from the profiles considered above for ≈ 0.5 mTorr. To begin with, one observes the presence of a warm population that commences not from $z \approx 3$ cm, but from $z \approx 7.5$ cm. Thus, as for argon, one finds a relatively low density ($n \approx 1.8 \times 10^{11} \text{ cm}^{-3}$), high electron temperature ($T_e \approx 23$ eV) population at $z \approx 3$ cm. Due to the onset of expansion induced by the expanding magnetic field in the region, both the density and electron temperature begin to fall. Thus, at $z \approx 4$ cm, $n \approx 1.28 \times 10^{11} \text{ cm}^{-3}$ and $T_e \approx 20$ eV. As noted above however, the onset of the warm population at $z \approx 7.5$ cm triggers a rise in the bulk density to $n \approx 2.7 \times 10^{11} \text{ cm}^{-3}$ along with a fall in $T_e \approx 3.7$ eV, at that location. The corresponding warm electron density and temperature are respectively, $n_w \approx 5 \times 10^9 \text{ cm}^{-3}$ and $T_w \approx 32$ eV. Beyond $z \approx 7.5$ cm, all three quantities, n , n_w and T_e decrease monotonically in the expanding magnetic field, while T_w fluctuates between ≈ 30 eV and ≈ 40 eV. One observes once again the startling similarity between the bulk and warm density profiles, n and n_w indicating clearly that the warm population is the source for the hydrogen plasma. Note that T_w does not exercise any control over the bulk density profile as it is large enough to ionize the H atoms all along the chamber. The plasma potential, $V_p \approx 65$ V at $z \approx 3$ cm, decreasing to a $\approx$ few Volts near the chamber end.

The difference between the densities and temperatures of the plasma at the two pressures is notable. Also noticeable is the relatively low density and high temperature of hydrogen with respect to argon. This can be attributed to the lower ionization rate constant and higher collisional energy losses for hydrogen [5, 55, 56].



As for argon, radial profiles of the different parameters for hydrogen plasma are presented in figures 7(A) and (B) at axial locations R1 and R2, corresponding to $z \approx 13.8$ cm and ≈ 38.8 cm respectively, for pressures ≈ 0.5 mTorr and ≈ 6 mTorr. It is seen again that there is the warm population present only for ≈ 6 mTorr and not for ≈ 0.5 mTorr. The profiles are as expected. The most noticeable feature of the radial plots is the spread of the plasma density at R1 and R2. It is seen that at R1, the radial extent of the plasma for ≈ 0.5 mTorr is only ≈ 6 cm, while R2 it is about ≈ 15 cm. It may be recalled that for argon the radial profiles at R1 extend up to $r \approx 18$ cm. The spread is a little higher for pressure ≈ 6 mTorr due to enhanced collisions (that aid cross-field transport) and is about ≈ 10 cm at R1, while at R2 it is about ≈ 20 cm. That the cross-field transport coefficient for hydrogen is smaller than that for argon is particularly noticeable at R1. Because the magnetic field is strong at R1 this reduction may be attributed to the difference in their masses, since the transverse transport coefficients are proportional to $\sqrt{(\text{ion mass})}$.

Like in figure 5 for argon, figure 8 gives the axial profiles of the hydrogen plasma densities at pressures of $p_{\text{H}_2} \approx 0.3, 0.5$ and 1 mTorr, normalized to their maximum values in the range. As before, the normalized profile for the magnetic field is also shown. What is most noticeable about this set of profiles is that irrespective of the pressure, the density profiles follow for the most part (except for minor deviations) the B profile (i.e., $n/B = \text{const.}$ scaling). It is a little unusual for such scaling to be observed in such a large chamber due to *unloaded* field lines penetrating the chamber from *outside* the CEPS since such field lines tend to get populated by plasma through cross-field transport.

However, it was seen in the radial profiles at R1 that cross-field transport is not very efficient for hydrogen. A similar result was observed in another set of experiments using argon reported recently by the authors, wherein the CEPS was connected to a *small* test chamber [13], and the n/B ($=\text{constant}$) scaling was found to hold very accurately along the entire chamber length, over a wide range of pressures. The latter results with argon are very different from the results presented above in figure 5, where considerable deviations from n/B scaling could be seen. Overall, one can state that n/B scaling is observed when cross-field transport is absent or inhibited and plasma flow occurs predominantly along the field lines, only to be lost at the chamber wall where the field lines intersect the latter. It is necessary however, for electrons to be fairly strongly magnetized, even though the ions need not be. The latter however, would have to be bound to the electrons (and hence the field lines) by quasineutrality.

4. Conclusions

In conclusion, argon and hydrogen plasma characterization results produced using the Compact ECR Plasma Source (CEPS) attached to a large chamber are presented. Apart from benchmarking the system (determining

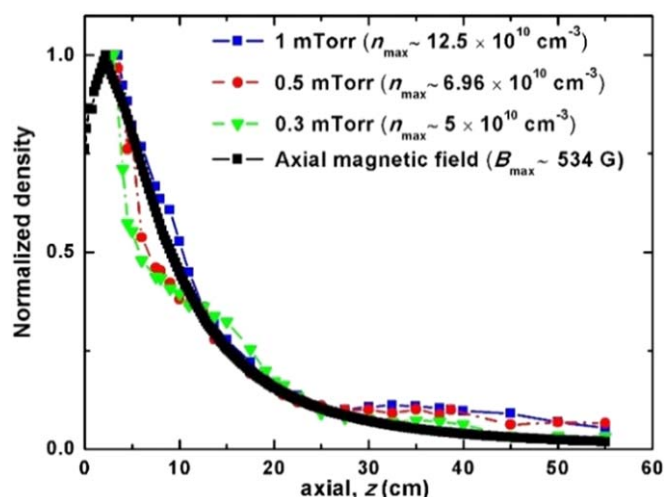


Figure 8. Normalized hydrogen plasma density profile at different hydrogen pressures. All the profiles are normalized with respect to their corresponding maxima. On axis magnetic field normalized with respect to peak value at $z = 2.5$ cm is also shown for reference.

density, temperature, potential profiles, etc., at different pressures), the argon results give strong indication that it may be possible to develop the CEPS further for thruster applications. The hydrogen results are substantially different from those of argon, having lower plasma densities and higher electron temperatures and obeying the scaling, $n/B = \text{constant}$. It was seen that at low pressures the plasma density is relatively low with a single, high temperature electron population, while at higher pressures, the plasma passes to a state with *higher* bulk plasma density and *two* electron populations, a low temperature, high density population and another low density, high temperature warm population. One may exploit the situation by choosing to opt for either of the two distinct states by adjusting the pressure. The latter scenario holds for argon as well.

Although the current studies focused on argon and hydrogen, future studies have been planned that would explore the efficacy of CEPS for other gases and molecular gases in particular.

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