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Initial investigations in the development of the Electron Cyclotron Resonance (ECR)-based Large Negative Ion Beam Source (ELNIBS)

Plasma based large area negative hydrogen ion source is an essential part of Neutral Beam Injector (NBI) modules of thermonuclear fusion reactors like ITER, since H-/D- ion beams can be efficiently converted into high energy neutral H0/D0 beams (˜ 1 MeV/u) for heating of fusion plasma [1]. The target H- current that has to be delivered to the NBI of ITER is around 40 A which requires production of ˜ 33 mA/cm2 H- current density over a grid area of approximately 2 m2 [2]. This in turn demands production of high-density uniform hydrogen plasma of the order of 1012 cm-3 at operating pressures of 2-3 mTorr (0.27 –0.4 Pa) [3] and electron temperature (Te) ˜ 1-2 eV, to avoid electron stripping of H-. Further, plasma uniformity of 10% over the plasma grid is desired, which ensures a good quality beam extraction. Present negative ion sources use around 0.8-1 MW RF (1 MHz) inductive power to achieve the target plasma density [4]. Such high-power investments face several technical and economic challenges that have triggered the search for alternate technologies offering more efficient power coupling / absorption [5]. Microwave based Electron Cyclotron Resonance (ECR) absorption can be one such scheme [6], since this scheme, due to the microwave power being coupled to a set of resonating electrons, enables a very efficient production of high plasma densities at low pressures and relatively lower powers, encouraging utilization of ECR schemes for negative hydrogen ion sources.
Tarey et. al. [7] have shown that multiple Compact ECR Plasma Sources (CEPS, patentee: Plasma Lab, IIT Delhi) [8] can be configured in appropriate arrays to produce uniform, large area, high density plasma in argon at very modest power. On this basis, the Plasma Physics Laboratory at IIT Delhi (PPL-IITD), in collaboration with Neutral Beam Division at Institute for Plasma Research, has been associated with the development of an ECR-based large area negative hydrogen plasma source (ELNIBS) for the past few years in a 1 m diameter and 0.5-1.5 m long (scalable) stainless steel chamber. The uniqueness of this source is that it is based on plasma generation through electron cyclotron resonance (ECR) mechanism in contrast to the rf-based sources being used in fusion devices currently.
However, one must note that the ECR based sources have an inherent magnetic field, which also provides one the challenge in identifying the right set of source and magnetic field configurations along with the optimal operating conditions that would deliver the required plasma parameters suitable for large area production of H− ions suitable for extraction for fusion applications. Further, unlike argon, hydrogen is a molecular gas, wherein plasma particles can exist in various neutral / ionic state: H2, H, H+, H2+, H3+, H-, etc. and as suggested by some recent experiments using both gases [9], the behaviour of hydrogen plasma differs significantly from that of argon, emphasizing the need for a detailed scientific investigation of hydrogen plasma production using different CEPS-based [10] source array configurations optimizing it for the conditions suitable for fusion plasmas. These above challenges also make the efforts in the development of ELNIBS unique.
This paper presents the journey of the development of ELNIBS viz., optimization of source configuration through plasma characterization with the ultimate detection of negative hydrogen ions in ELNIBS. The characterization process used electrostatic probes [11,12], viz., Langmuir probes (LP) and retarding field analyzers / retarding particle analyzers (RFEA / RPA), along with a quadrupole molecular beam mass spectrometer (MBMS). Experiments were performed with the geometrical configuration of 1 m diameter, 1m high cylindrical expansion chamber. Hydrogen plasma was produced using the optimal configuration of a CEPS mounted onto the top dome of the chamber. The magnetic field configuration of the source section (cylindrical, diameter Φ = 91mm and length, ⊠ = 110 mm) has the field strength decaying exponentially into the 1m diameter plasma expansion chamber. The plasma was characterized under different operating conditions of microwave power (400–600 W) and gas pressure (1–3 mTorr) using a Langmuir probe that was fabricated in-house. The low-pressure plasma was observed to have a moderately uniform high density (˜ 1011 cm-3) plasma across a cross-section of 70 cm with low electron temperature (˜ 1 - 3 eV) in the downstream section (≈ 30-40 cm downstream of plasma generation). The RFEA measurements showed energetic ion beams emanating from within the source mouth, with upstream ion beam energies being as high a few 10s of eV. A molecular beam mass spectrometer (MBMS, Model: Hiden HPR-60) was used to investigate the relative intensity of the plasma produced positive ions (H+, H2+, H3+) as well as negative ions (H-) along with its respective energy spectra and that of gas neutrals. Detailed results with varying microwave power and gas pressure will be presented.

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