Plasma confined in a dipole magnetic field

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Dipole field is one of the most fundamental magnetic field configurations in the universe [1, 2]. There has been a long quest to understand charged particle generation, confinement, and underlying complex processes in a plasma confined by a dipole magnetic field. Planetary magnetospheres such as those of Earth and Jupiter are burning examples of such naturally occurring systems. The rather simple magnetic field structure holds together colossal plasmas in space, and high β (ratio of plasma to magnetic pressure) plasmas can be sustained. It is of interest to investigate such a magnetic confinement scheme and the resulting plasma behaviour, in the laboratory. Unlike other confinement schemes that rely on magnetic curvature and shear, dipole plasma confinement derives stability from plasma compressibility that utilizes the large flux tube expansion of a dipole field.

Experiments at MIT, Columbia University [1], and the University of Tokyo [2], have relied on large devices that employ superconducting electromagnetic coils. We report results of a table-top dipole plasma device, fabricated with a single permanent magnet that employs water cooling [3], and uses electron cyclotron resonance (ECR) heating for plasma generation. The system employs a single water-cooled cylindrical permanent magnet having surface magnetic field ~ 0.5 T to create the dipole magnetic field. There have been motivational differences and/or engineering challenges when compared with the earlier experiments. While primitive terrella experiments [1, 2, 4] often lack adequate diagnostic technologies, the dimensions of large dipole experiments hinder obtaining finely resolved spatial measurements, necessary for complete characterizations. Further, most of the large experiments have been operated in the pulsed mode, wherein time-dependent variations in the plasma parameters including optical emissions have to be accounted for, leading to added technological challenges. Our experimental system thus emerges advantageous in this regard for its length scale as well as steady-state operation allows the possibility for detailed space resolved measurements. Moreover, it provides a low cost experiment with simpler technology.

Voluminous plasmas can be sustained in our developed experiment, e.g., a single permanent magnet of volume ~ 17 cm3 and maximum surface field of ~ 0.5 T, can confine a plasma of volume ≥ 3.4×104 cm3. Visual observations of the plasma indicate alternate bright and relatively less bright regions with structural resemblance to the earth's radiation belts that trap charged particles. Measurement of plasma parameters such as electron density, electron temperature, and space potentials have been carried out using Langmuir and emissive probes. The plasma was characterized in the polar directions employing special "y-shaped" probes. Optical diagnostics comprising of a photodiode, optical fiber, and a high-resolution spectrometer were utilized for the measurement of optical emissions from the plasma. Line integrated intensities were obtained along chords from near the center to the plasma edge, from which the local plasma emissivity has been determined using Abel inversion [5].

Particle balance which results from an inter-relationship between generation and loss was investigated, and dependence of production, loss, and plasma retention rates as a function of wave power and discharge pressure was determined. The developed mathematical model solves the particle balance equation, considering generation through ionization and losses through diffusion and recombination, and incorporates the measured values of plasma parameters and dipole fields in space [6]. The plasma β determined from experimentally measured data, increases steadily from a small value near the magnet to ~ 7% in the midplane (~ 8 cm from the magnet center), and thereafter the increase is more gradual and almost levels off to ~ 10% at the chamber edge (~ 20 cm). In general, the electron temperature and the plasma potential are higher at the polar cusp regions and decreases toward the equatorial plane, with the profiles become more spherically symmetric away from the magnet. The location of the mid-plane density peak seems to match closely with the region where β starts to level off, and the space potential starts to decrease exponentially. The plasma retention rate is highest a little downstream from the magnet (~ 3 – 7 cm), can explain the density depletion close to the surface of the magnet. An investigation of diffusion induced transport reveals that peaked density profiles, are realized as a natural outcome of the solution of diffusion equation, thereby confirming the phenomenon of inward diffusion as observed in earlier experiments. Two independent diffusion models are developed, and the plasma density profiles are determined and compared with those obtained experimentally. Diffusion is predominantly governed by the classical (~1/B2) scaling law [7]. The compact device bears promise for basic studies on dipole plasmas, studying dusty plasmas, or even for plasma processing, because of the possibility of confining energetic electrons.

References

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