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Spatially varying optical emissivity in a dipole plasma: experiments and modeling

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Plasmas confined in a dipole magnetic field are a subject of continuing interest in the laboratory [1], due to its unique confinement scheme depending on the plasma β (ratio of plasma pressure to magnetic pressure), and its prevalence in planetary magnetospheres [2]. A microwave (2.45 GHz) generated compact dipole plasma is sustained by electron cyclotron resonance (ECR) heating [3]. The dipole field is generated using a single water-cooled permanent magnet (NdFeB). Visual observations of this plasma indicate alternate bright and less bright regions analogous to the radiation belts in the Earth's magnetosphere (cf. Fig 1a). Preliminary investigations reveal that the observed bright zones of energetically trapped particles in the plasma correspond to regions of excitation by ECR frequency and its harmonics [3].

We perform optical measurements in two experimental systems of different geometries: (a) a cylindrical system (E1), and (b) a spherical system (E2). To quantify the variations in the optical emission intensity, the measured line integrated intensities I are inverted using two techniques namely the (a) Linear inversion and a more standard (b) Abel inversion [4], to obtain the local emissivity ϵ of the plasma in the visible region. The equations for the inversion of the two techniques (a) and (b) are presented below:

(a) $\epsilon(r_j) = \frac{2}{\Delta r}\left(I(r_j) - I(r_{j-1})\right)$,

(b) $\epsilon(r) = -\frac{1}{\pi}\int_r^R \frac{I'(x)dx}{(x^2-r^2)^{1/2}}$.

We develop the linear inversion technique based on a discrete approximation of the continuous local emissivity in the plasma, and thus, Δr is the radial resolution of the measurements. The linear inversion technique is used in E1 to obtain preliminary results. It necessitates the use of an invasive probe, which constitutes of an innovative telescopic arm, whose use enables to keep the optical fiber at the edge of the system and protect it from radiative heat from the plasma. The popular Abel inversion technique is implemented in E2, where owing to the geometry of the system, an innovative mechanical optical measurement probe is designed to obtain cord integrated light intensities in the midplane of the plasma (cf. Fig 1b). The novel design of the optical probe ensures that the probe head is always at the edge of the plasma boundary and moves along the circular arc via a gear mechanism. The integrated light intensity is obtained via two measurement methodologies: (a) optical spectrometer and (b) Silicon photodiode. The use of the spectrometer enables us to perform wavelength (and hence, transition) specific local emissivity analysis. Abel inversion is performed to the data using multiple algorithms described in previous literature, such as the Matrix method, Fourier method, etc. [5,6] (cf. Fig 2a). We thus map the local emissivity for different wave power and neutral pressure combinations.

Modeling of the optical measurements is also performed in this study. We calculate the photon emission rate for different high intensity transitions, using the following formula [7],

$$\Phi_{ab}(r) = n_e(r)\sum_c n_c k_{ab}^c(r)$$

where $n_e(r)$ is the electron number density, n_c is the number density of atoms in level–c, which is the level from which the electrons are excited, and $k_{ab}^c(r)$ is the photon emission rate coefficient of the transition from level–a to level–b. The emission rate coefficient is calculated by the convolution of the optical cross section of the transition and the spatially varying EEDF of the dipole plasma. A reasonably good agreement is found between the undulations in optical emissivity seen from the experimental data and the results from theoretical modeling (cf. Fig. 2).

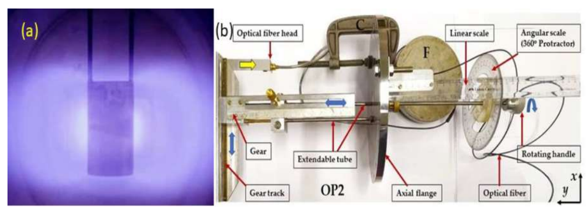

Fig 1: Digital pictures of (a) dipole plasma, (b) optical probe to obtain intensities to perform Abel inversion.

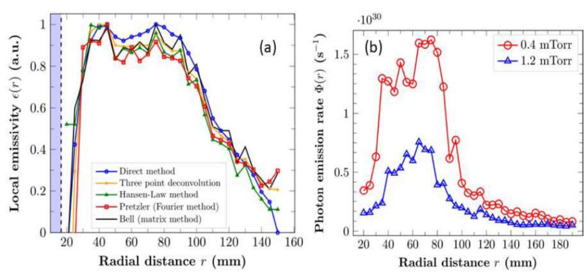

Fig 2: (a) Local emissivities in E2 obtained via Abel inversion at 0.4 mTorr and 300 W power (b) Photon emission rate in E2 at pressures of 0.4 and 1.2 mTorr.

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