SPECTROSCOPIC ESTIMATION OF PLASMA PARAMETERS FOR ECR ION SOURCE IN THE INTENSE 14-MeV NEUTRON GENERATOR BEING DEVELOPED AT IPR

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Abstract

An accelerator based 14-MeV neutron generator, for fusion neutronics studies is being developed at IPR. ECR ion source is used to generate deuterium plasma. Electron density and temperature in the ECR plasma are measured using non-intrusive spectroscopic methods. Langmuir probes, though conventionally used for estimating local parameters in low-pressure microwave plasmas, are difficult to implement here owing to space constraint and heating of the probe from interaction with standing microwaves. Pure helium (He), He seeded hydrogen and deuterium plasmas are studied. Spectra for entire visible range are recorded for different fill pressures for a constant microwave power and different powers for a constant fill pressure. For optically thin plasmas of low density, line intensity ratio method can be used with appreciable reliability. CR model is used from ADAS (atomic data and analysis structure) to predict plasma parameters from suitable line ratios.

INTRODUCTION

Langmuir probes are used conventionally for the measurement of local electron temperatures. However, in cavity based microwave plasmas, like in the ECR ion source, radial probes are difficult to implement as the plasma is formed in the cusp of the hexapole magnet. Further, the interaction of the standing microwaves with the cavity material may lead to heating and in some cases even melting of the probe. Even axial Langmuir probes are not feasible, owing to the space constraint inside the helical antenna. Also, such probes may perturb the plasma and actual plasma parameters will not be measured. Additional complications arising due to the interaction of the plasma with the probe have also been encountered, resulting into sputtering of material from probe tip at high microwave power, contamination and erosion of the probe tip etc. Hence, to avoid these problems, non-invasive spectroscopic methods are highly sought for. Contrary to probes, spectroscopic measurements are not affected by the microwave, do not interact and hence do not contaminate or perturb the plasma and subsides the odds of catastrophic failures due to probe melting. In spectroscopic techniques, a spectrograph combined with an optical fiber and a sensor is used to collect emissions remotely so there is no interference with the plasma environment.

In this experiment, neutral helium (HeI) spectra are recorded and line emissions from various singlet and triplet states are measured. Specific intensity ratios are used to infer the electron temperature and electron density of the plasma and compared with earlier measurements with similar microwave ECR ion sources [1].

EXPERIMENTAL SETUP

The microwave is transported in the ECR ion source through a rectangular hollow wave guide to power circular wave guide. A three port circulator with the dummy load is used to protect the magnetron from the reflected power. Microwave system consists of a combination of a high voltage and high vacuum window and cross bar transition from rectangular wave guide to coaxial line with gas inlet at the dead end of the transition. At the end of the coaxial line a slow-wave structure is connected which will radiate circularly polarized microwave in axial direction. The microwave power applied was 288 watt.

The magnet system of the ECR source is made from high remanence (1.12T), high corcivity (1920 kA/m) NdFeB permanent magnet material. It consists of two radially magnetized rings producing an axial magnetic field of 2.14 kG at the maximum with a mirror ratio of 2.85. The Hexapole magnet for radial component is made from same block and induced a maximum magnetic field of 5kG inside the plasma chamber [2-3]. A schematic of the ECR ion source with the spectroscopic setup is shown in Figure 1.

At the other end of the vacuum chamber, the light emitted is relayed by an optical fiber through an optical port to a 0.5 m Czerny-Turner visible spectrometer (resolution 2.5 Å) fitted with a CCD camera, which had been calibrated for intensity measurements. Since the line of sight was axial hence local measurement of the plasma parameters were not possible, instead, an average estimation of the parameters were obtained. This should suffice for a general characterization of the ECR source.

Gas pressure during the experiment was varied from 2.7×10^{-5} to 6.2×10^{-5} mbar at the distant end of the vacuum chamber where the turbo molecular pump (TMP) is connected and 5.0×10^{-4} to 3×10^{-3} mbar at gas inlet of the ion source, keeping the microwave power constant throughout. Several combinations of input gases like, pure helium, helium seeded hydrogen and helium seeded deuterium are tested with the present setup. Results for the highest operating pressure (3×10^{-3} mbar) and for pure helium plasma are presented here.

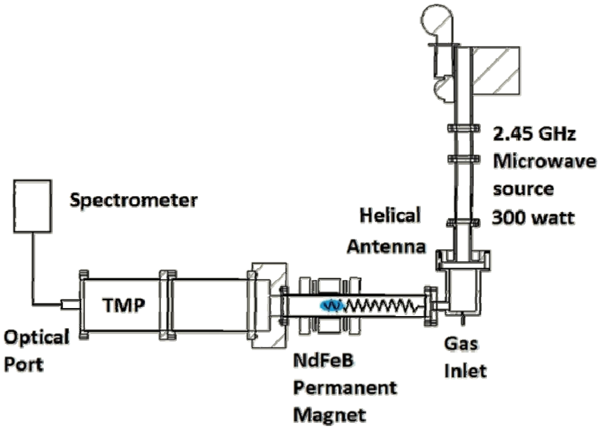


Figure 1: Schematic of the experimental setup.

LINE RATIO DIAGNOSTIC

In principle, intensity of a spectral line is a function of both electron temperature and density. However, it is possible to identify certain spectral lines which are highly sensitive to electron temperature but do not vary strongly with electron density and vice versa. Such spectral lines have proved to be quite useful in determining the plasma electron density and temperature. Dominant processes responsible for formation of the excited level population for the chosen transitions need to be accounted for while calculating the photon emissivity coefficients.

The emissivity (photons cm^{-3} s^{-1}) of a spectral line of wavelength λ_{ul} due to a transition from the upper level u to the lower level l is given by:

$$\varepsilon(\lambda_{ul}) = n_u A_{ul} \tag{1}$$

Here A_{ul} is the spontaneous transition probability from upper to lower level, n_u is the number density population of the upper level u of the emitting ion. In the framework of the CR model the emissivity can be derived as the sum of photon emission arising from the recombination of ions (of density n_i) with electrons, from the excitation of ground state atoms (n_g) by electrons. It can be expressed as:

$$n_u A_{ul} = PEC_{reco} n_e n_i + PEC_{excit} n_e n_g \tag{2}$$

Here the two PECs are the 'effective' photon emission coefficients for the two dominant processes (i.e. recombination and excitation of ground state atoms by the electrons). The metastable states are considered as unresolved in this case. With an assumption of average electron density and temperature along the emission length L, the intensity (photons cm^{-2} s^{-1} Sr^{-1}) of a spectral line can be given as:

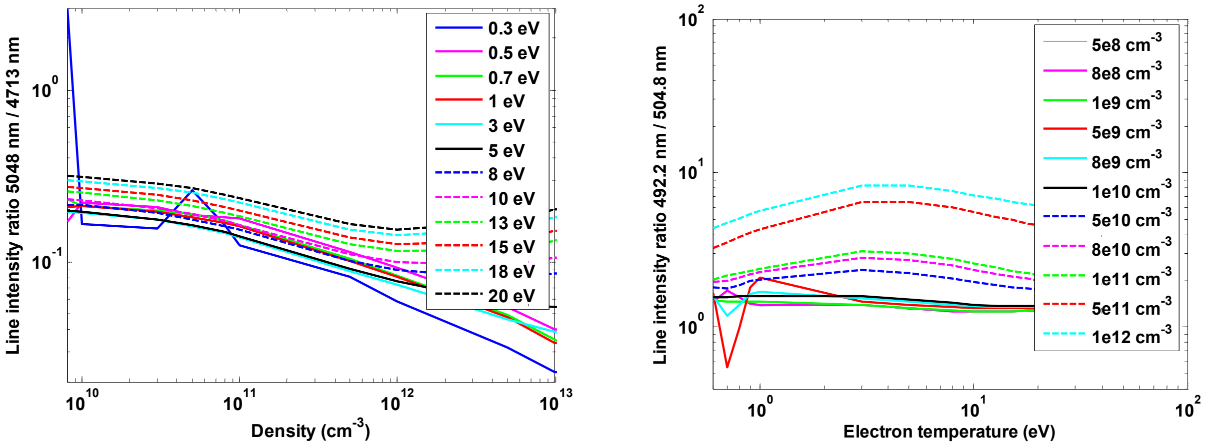
$$I(\lambda_{ul}) = \frac{L}{4\pi}\left(PEC_{reco} n_e n_i + PEC_{excit} n_e n_g\right) \tag{3}$$

The population density N_u is usually calculated by solving a set of coupled rate equations for a number of levels of the atom. In each equation, one includes all the processes of populating and depopulating the level by excitation, de-excitation, spontaneous emission, ionization and recombination from adjacent ionization stages. The ADAS [4] code derives the PEC values for the particular line λ_{ul} after calculating the population distribution of the levels. If only ionizing or recombining plasma is considered, the ratio of two intensities simply reduces to the ratio of either the excitation or recombination PECs.

Line ratios using S→P transitions are better suited to measure electron temperature. The contributions from the metastable 2^1S and 2^3S states due to excitation transfer are small since these S-S transitions are forbidden and the resulting cross-sections are small. The $4^1S \rightarrow 2^1P$ (504.8 nm) / $4^3S \rightarrow 2^3P$ (471.3 nm) ratio is attractive for electron temperature estimation [5]. These transitions are in the same spectral region and have similar branching ratios. Being energetically further apart from the metastables than the n = 3 transitions, they are less affected by excitation transfer from these levels. CR model calculations of the optically thin line ratio ($I_{504.8}$ / $I_{471.3}$) are shown in Figure 2a as a function of electron density for fixed temperatures, for the case of ionizing plasma where majority of the population comes from ground term.

The third transition is the $4^1D \rightarrow 2^1P$ (492.2 nm). It is also in the same spectral region and more sensitive to electron density than electron temperature. The ratio 492.2 nm / 504.8 nm is used for density estimation. CR model calculations of the optically thin line ratio ($I_{492.2}$ / $I_{504.8}$) are shown in Figure 2b as a function of electron temperature for fixed densities, for the case of ionizing plasma.

The effect of opacity is pronounced in the presence of appreciable amount of neutrals and optical escape factors are preferably calculated as a function of neutral densities. Such a case is not envisaged in our experiment owing to the low neutral densities observed even at the highest operating pressure of 3×10^{-3} mbar.



(a) (b)

Figure 2: (a) CR model calculations of the optically thin line ratio ($I_{504.8}$ / $I_{471.3}$) as a function of electron density for fixed temperatures, for the case of ionizing plasma where majority of the population comes from ground term. (b) CR model calculations of the optically thin line ratio ($I_{492.2}$ / $I_{504.8}$) as a function of electron temperature for fixed densities, for the case of ionizing plasma.

RESULTS

A distinct variation in the observed spectra has been observed at the different operational conditions. A typical spectrum recorded at an inlet pressure of 3 × 10^{-3} mbar with pure helium is shown in Figure 3 with all the transitions marked. It can be noted that the singlet transition lines 504.8 nm ($4^1S \rightarrow 2^1P$) and 728.1 nm ($3^1S \rightarrow 2^1P$) are more intense than the triplet transition lines 471.3 nm ($4^3S \rightarrow 2^3P$) and 706.5 nm ($3^3S \rightarrow 2^3P$), respectively. Stronger singlet emissions may be attributed to the presence of other impurity line emissions in the vicinity of these lines, especially 728.1 nm, or may be due to recombination.

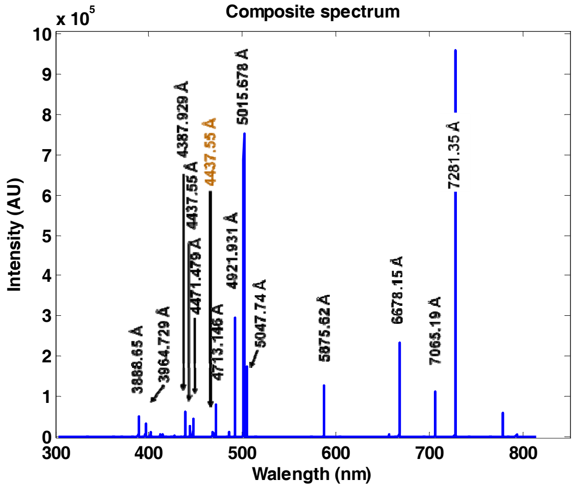


Figure 3: Most prominent helium line emissions recorded at 3 × 10^{-3} mbar inlet pressure.

The intensities of singlet and triplet lines are obtained by fitting a Gaussian profile to the experimental data and integrating the area under the Gaussian. Electron density is estimated as 1 × 10^{10} cm^{-3} and electron temperature as 0.8 eV at 3 × 10^{-3} mbar inlet pressure for the pure helium plasma. Electron temperature and density obtained at the present microwave power and fill pressure of gas is in conformation with that obtained at similar source but at higher microwave power by Podder et al. [1].

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