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Study of plasma parameters in a continuous ECR discharge sustained by 24 GHz/5 kW gyrotron radiation in a quasi-gasdynamic mode

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Introduction

Recent investigations of gasdynamic ECR plasma [1] resulted in development of pulsed high current ion sources capable to deliver ion beams with 100–500 mA current and normalized RMS emittance below 0.1 pi·mm·mrad [2] thanks to heating with mm-waveband gyrotron radiation. While the pulsed operation of gasdynamic ion sources was studied in details [1, 2], CW operation of such devices is not well investigated. SMIS 24 experimental facility was installed at the IAP RAS. At SMIS 24 the plasma is heated by 24 GHz radiation of CW gyrotron and confined in a simple mirror trap similar to SMIS 37 facility [1, 2], which was used for pulsed experiments. Detailed studies of CW gasdynamic ECR plasma parameters and ion beam extraction are presented in this work.

Experimental results

The scheme of SMIS 24 facility is shown in Fig. 1. The microwave radiation is generated by CW 24 GHz 5 kW gyrotron (manufactured by GYCOM). Radiation is delivered by means of over-sized cylindrical waveguide to high-voltage DC-break. Following the DC-break the microwaves pass through a specially developed coupling system which maximizes the electric field at ECR surface and minimizes reflection.

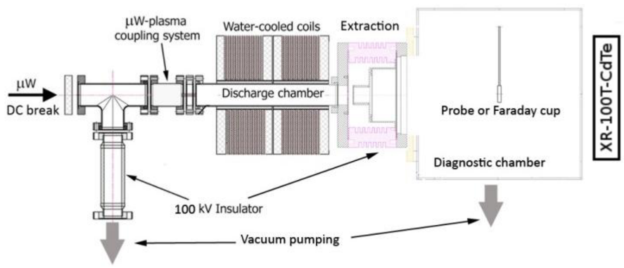

Fig. 1. SMIS 24 experimental facility

Plasma chamber size is 380 mm length and 32 mm in diameter. The magnetic field is produced by a pair of water-cooled coils of Bitter type forming a simple mirror trap. The maximum magnetic field on the axis reaches the value of 1 T. The mirror ratio (B_{max}/B_{min}) is equal to 3.5, the distance between magnetic mirrors (i.e. trap length) is 130 mm. The magnetic field distribution inside the plasma chamber is shown in figure 2.

A two-electrode extraction was used in the experiment for ion beam formation. Plasma and puller electrodes had 3 mm and 5 mm apertures, respectively. The available extraction voltage was up to 20 kV. The extraction system was placed far behind the magnetic mirror (see Fig. 2) to reduce the ion current density so that the total extracted current could meet the power supply maximum ratings.

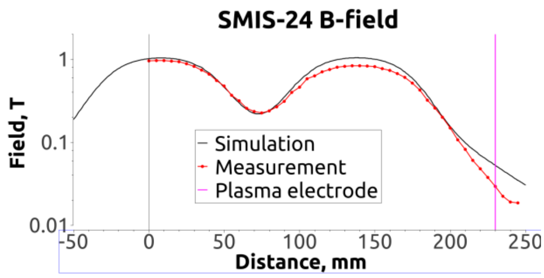

Fig. 2. Measured and simulated magnetic field strength on the axis of SMIS 24

A Langmuir probe was used for the measurement of plasma flux parameters (electron temperature and density). The probe was placed in the diagnostic chamber, where the magnetic field strength is low enough to consider the plasma unmagnetized. The Faraday cup was used to measure the total beam current. An x-ray spectrometer Amptek XR-100T-CdTe was used for plasma bremsstrahlung measurements. X-ray detector was placed on the axis of the magnetic system outside the vacuum enclosure facing towards the plasma. Helium was used in the experiments in the pressure range of 10^{-4}–$5{\cdot}10^{-4}$ Torr.

Electron temperature and density were estimated from Langmuir probe I-U curves. An example of typical I-U curve is shown in figure 4 in the case of 4 kW microwave power and $2.8{\cdot}10^{-4}$ Torr helium pressure. Curves shown: logarithm of electron current (thick solid line), derivative of electron current (dashed line), two linear fits (thin lines), estimated plasma potential is 4.1 V and indicated with vertical line. I-U curve in Fig. 3 is typical for bi-Maxwellian electron energy distribution function (EEDF). One can observe two characteristic energies of electrons, which are 17 eV and 49 eV.

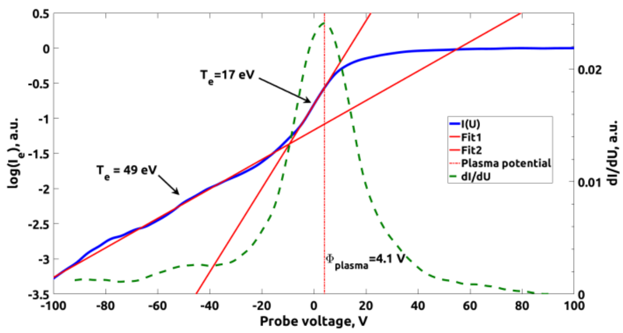

Fig. 3. A typical Langmuir probe I-U curve

The same shape of I-U curves is observed for all examined settings. It is believed that the EEDF of an ECR plasma in a magnetic trap consists of (at least) three populations [3]: (1) "cold" electrons with temperature close to the first ionization potential, (2) "warm" electrons with temperature dependent on the heating power and (3) a "hot" population creating high-energy bremsstrahlung.

Energies of “cold” and “warm” popula-tions were calculated by means of I-U curves analysis, whereas characteristic energy of the “hot” population was estimated as a spectral temperature of bremsstrahlung spectrum [4]. An example of bremsstrahlung spectrum with spectral temperature fit is demonstrated in Fig. 4 for 4 kW microwave power and $2.8 \cdot 10^{-4}$ Torr helium pressure.

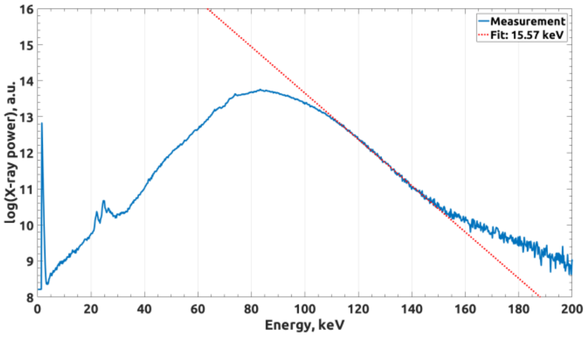

Fig. 4. Bremsstrahlung spectrum and spectral temperature fit

Measurements of characteristic electron energies are summarized in Fig. 5, where all electron “components” are plotted together.

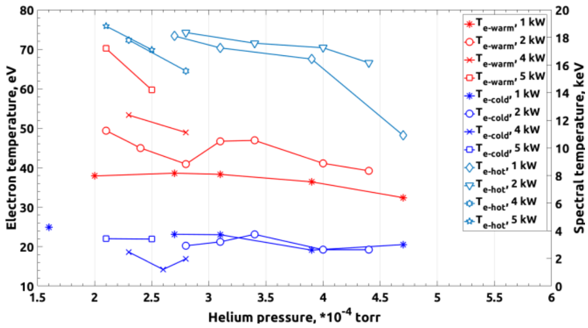

Fig. 5. Characteristic electron energies

It is of note that regardless the helium pressure and heating power characteristic energy of “cold” electrons remains in the range of 15–25 eV, which is consistent with helium ionization potential (24.47 eV). Energy of “warm” component is growing with the heating power, though dependence on pressure is unclear. “Hot” component energy seems to depend on helium pressure rather than on heating power.

All of acquired I-U curves had shown a distinct maximum of dI/dU (see Fig. 3), which enables the rough estimation of electron density (assuming Maxwellian EEDF with temperature in-between “cold” and “warm” components), as [5]:

$$I_e\left(U = \phi_{plasma}\right) = e n_e S_{probe} \cdot \sqrt{e T_e / 2\pi m_e}, \quad (1)$$

where n_e is the electron density, e and m_e is the electron charge and mass, S_{probe} is the current collecting surface, T_e is the electron temperature in eV.

Estimated electron density for different heating power and helium pressure is shown in Fig. 6. Assuming that the plasma flux follows magnetic field lines, the density value was corrected by the factor of 28.5, which is the ratio between magnetic field strength in the mirror point and the probe position. Given the scatter of data, no explicit dependence was found. However, it is of note that estimated plasma density is on the order of a cut-off density, which is equal to $7 \cdot 10^{12}$ cm^{-3} at 24 GHz.

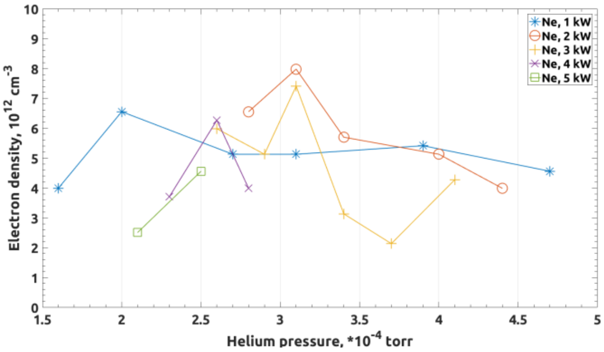

Fig. 6. Plasma density estimated for mirror point

Experiments on ion beam formation didn’t show strong dependence on gas pressure and heating power. The facility demonstrated a stable long-term (>1 hour) extraction of CW ion beam with mean value on the level of 2.8 mA at 1 kW power, $4 \cdot 10^{-4}$ Torr helium pressure and 20 kV extraction voltage. Ion beam current density at extraction region was 40 mA/cm^2, which corresponds to plasma flux density of 1.13 A/cm^2 at the mirror point. The region with flux density of ~600 mA/cm^2, which is the value of plasma flux at extraction region in SMIS 37 facility [2], may be found in-between, thus suggesting the possibility of forming continuous ion beams with parameters similar to those at SMIS 37, if the extraction system is shifted towards higher flux, i.e. closer to the mirror point (see Fig. 2).

Conclusion

The experiments in gasdynamic CW ECR discharge confinement by 24 GHz gyrotron radiation demonstrated plasma parameters similar to those obtained in pulsed mode at SMIS 37 facility. Three electron components were observed – “cold” fraction with energies on the order of helium ionization potential, “warm” fraction with energies in the range of 30–70 eV, which is optimal for low charge states production, and “hot” fraction with spectral temperature in the range of 10–20 keV. Plasma density found to be on the cut-off level. A long-term reliable operation with ion current density >1 A/cm^2 (estimated) was demonstrated.

Acknowledgements

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