Energy distribution of electrons lost from the plasma sustained by the 28 GHz/10 kW gyrotron in a simple mirror magnetic trap

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Introduction

In the ECR plasma, electron energy distribution function (EEDF) takes significantly non-Maxwellian shape that determines plasma confinement regime and ionization efficiency, which, in turn, affects the performance of the ion sources based on such plasmas. Understanding the formation of the EEDF will make it possible to predict ion composition in the plasma and the beams acquired from the ion source and tune it to the optimal performance. In this work, the EEDF of the hot electrons escaping from the simple mirror magnetic trap were directly measured with a recently developed method [2] in a wide range of neutral gas pressures and gyrotron powers along. Additionally, the spectra of bremsstrahlung caused by energetic electrons leaving the plasma were obtained. A series of experiments was performed on the newly constructed Gasdynamic Ion Source for Multipurpose Operation facility (GISMO) [1] allowing record-breaking specific energy input into the plasma. For certain values of neutral gas pressures, obtained distributions showed a threshold-like evolution in shape with the increase in input power, which was accompanied with the appearance of bremsstrahlung. This effect is presumably associated with the development of kinetic instabilities in the plasma.

Experimental setup

The experiments described in this work were carried out on the Gasdynamic Ion Source for Multipurpose Operation facility, a gasdynamic ECR source with a high specific energy input created at the IAP RAS [1].

The setup diagram is shown in fig.1. By using a modern gyrotron generating radiation at a frequency of 28 GHz with power up to 10 kW, GISMO makes it possible to achieve record-breaking values of the specific energy input into the plasma of a continuous ECR discharge at a level of up to $50-100\,W/cm^3$, whereas for traditional ion sources this value does not exceed $1-5\,W/cm^3$.

Another important advantage of GISMO is the ability to operate in a wide range of gas pressures in the discharge from 10^{-2} Torr to 10^{-6} Torr, which makes it possible to conduct research both in classical (collisionless) and quasi-gasdynamic (collisional) confinement modes.

In GISMO, the plasma is confined in a simple trap made of permanent magnets. The parameters of the trap are $B_{max} = 1.5$ T, $B_{min} = 0.25$ T, and the mirror ratio, respectively, is 6. Due to the peculiarities of the configuration of the magnets, there is a cusp, an area with $B = 0$, downstream the mirror trap. It is important to note that the presence of a cusp makes it possible to observe only electrons located close to the symmetry axis of the system. A significant fraction of the electrons is lost on the chamber walls, thus generating bremsstrahlung.

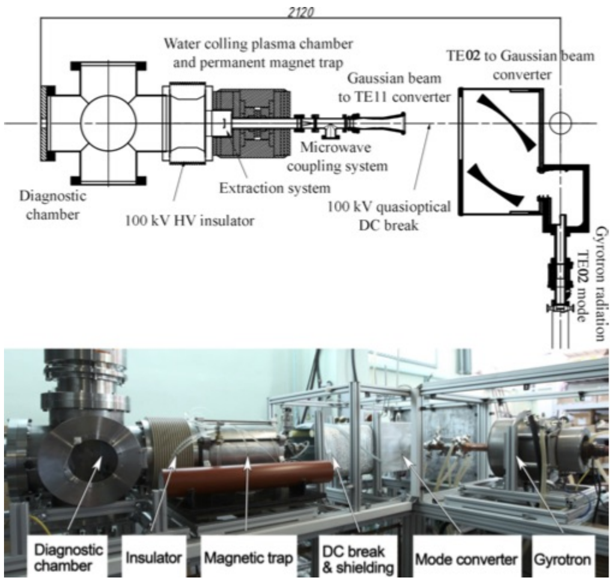

Figure 1: The experimental scheme

The energy distribution of electrons escaping the magnetic trap was obtained as follows. The method is similar to ion mass spectrometry with an inverted polarity of an electromagnet that deflects charged particles, as described in [3]. A secondary electron multiplier and a Stanford SR570 current preamplifier were used to register electron currents as small as 1 pkA. A voltage of -3.5 kV was applied to the cathode of the electron multiplier with respect to the chamber potential, which prevented the registration of electrons with energies below 3.5 keV. The geometry of the system made it possible to allow scanning with the resolution of about 1 keV.

When processing the data and reconstructing the EEDF, the following corrections for the electron current were taken into account (Fig. 2): the coefficients of secondary emission and backscattering of the electron multiplier cathode, as well as the transport function that determines the fraction of electrons with a particular energy lost on the way from the plasma electrode to the detector due to the geometric peculiarities of the system.

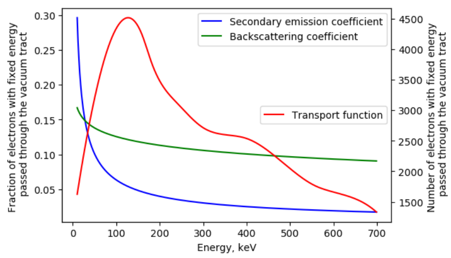

Figure 2: Factors that affected the electron signal

Experimental results

The EEDFs were measured in a wide range of hydrogen pressures and powers of microwave radiation that sustains the ECR discharge. Simultaneously with these measurements, bremsstrahlung spectra were obtained. Amptek's XR-100T-CdTe X-ray detector was installed in a way to observe the end of the plasma chamber, where the energetic particles precipitated and emitted bremsstrahlung.

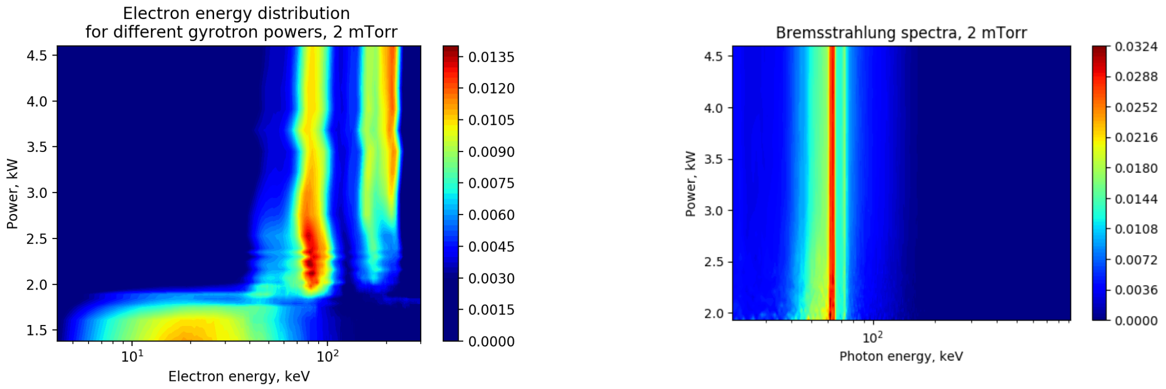

Figure 3: EEDF (a) and bremsstrahlung spectrum (b) evolution with gyrotron power for 2 mTorr

Energy distributions and bremsstrahlung spectra showed unconventional behavior as the function of external parameters. An example of obtained distributions is presented in Fig. 3a. A threshold-like effect is seen at the power of about 2 kW, where the EEDF shape dramatically changes along with the number of electrons reaching the detector and the intensity of bremsstrahlung (Fig. 5a, b). A fraction of 'hot' electrons is presumably formed from the instabilities. The latter increase of the gyrotron power barely changes the shape of the distributions (Fig. 4), while electron current and bremsstrahlung count rate nearly reach saturation. However, the evolution of the EEDF shape came along with bursts of electrons that formed the energetic peaks on the distribution. Such bursts can be associated with kinetic instabilities occurring in the ECR plasma when the gyrotron power exceeds some threshold value ($\propto$ 1.7 kW). The bremsstrahlung that is seen by detector through steel walls of the vacuum chamber ($> 10 - 20$ keV) appears with the development of the unstable hot fraction of electrons. The spectrum shape does not change with the increase of the gyrotron power (Fig. 3b), but the growth of the count rate is strongly corre-

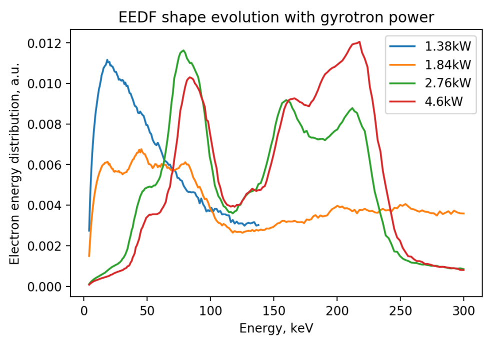

Figure 4: EEDF shape evolution with power for 2 mTorr of neutral gas

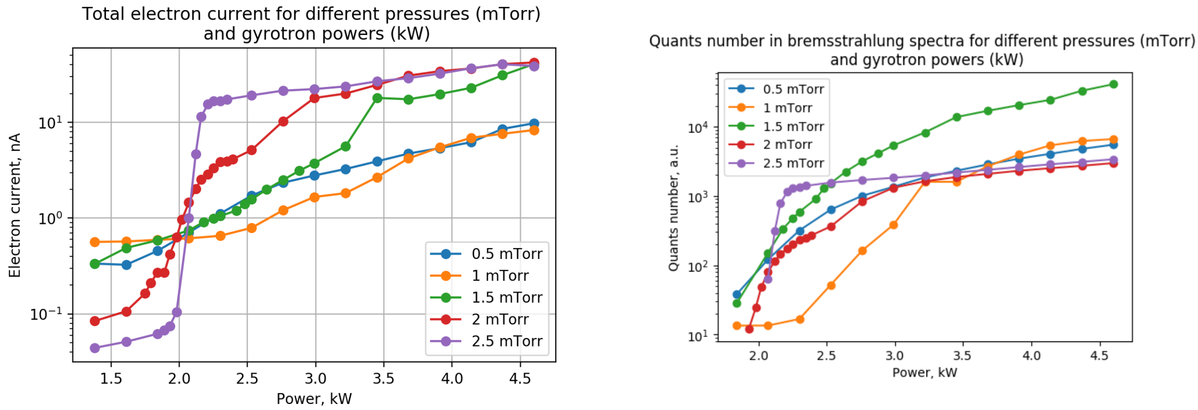

Figure 5: Total electron current (a) and quants number (b) dependence on power and pressure.

lated with the number of electrons escaping from the plasma. This fact leads to the conclusion that the main source of bremsstrahlung in the ECR sources might be hot electrons leaving the plasma and hitting the walls of the chamber.

Conclusion

The energy distributions of the electrons lost from gyrotron-heated ECR plasma with specific energy input of up to 100 W/cm^3 were obtained for the first time. The observations showed that the shape of the EEDF dramatically changes when the power exceeds certain threshold, presumably as a result of the development of the kinetic instabilities. Bremsstrahlung is also strongly correlated with the above-mentioned threshold, which gives the potential of the bremsstrahlung suppression by the EEDF modification.

Acknowledgements:

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References

[1] V.A. Skalyga, A.F. Bokhanov, S.V. Golubev et al., Status of the gasdynamic ion source for multipurpose operation (GISMO) development at IAP RAS, Review of Scientific Instruments **90**, 12 (2019)

[2] S.V. Golubev, I. V. Izotov, D.A. Mansfeld and V.E. Semenov, Experimental electron energy distribution function investigation at initial stage of electron cyclotron resonance discharge, Review of Scientific Instruments **83**, 2 (2012)

[3] I. Izotov, O. Tarvainen, V. Skalyga et al., Measurement of the energy distribution of electrons escaping minimum-B ECR plasmas, Plasma Sources Science and Technology **27** (2018)