Measurements of Bremsstrahlung Spectra on SECRAL*

ZHAO Huan-Yu[1,2;1)] ZHAO Hong-Wei[1] MA Xin-Wen[1] SUN Liang-Ting[1] ZHANG Xue-Zhen[1] LI Xi-Xia[1] WANG Hui[1] MA Bao-Hua[1] CAO Yun[1,2] FENG Yu-Cheng[1] ZHU Yu-Hua[1] SHANG Yong[1,2]

1 (Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China)
2 (Graduate University of Chinese Academy of Sciences, Beijing 100049, China)

Abstract The axial emitted bremsstrahlung spectra were measured on SECRAL (Superconducting ECR ion source with Advanced design in Lanzhou) using an HPGe detector. The spectral temperature $T_{\rm spe}$ was obtained from the linear fit of the spectra in the semi-log present. The evolution of $T_{\rm spe}$ with microwave power and magnetic field configuration is investigated in this paper.

Key words ECR plasma, bremsstrahlung spectrum, hot electron, spectral temperature $T_{\rm spe}$

1 Introduction

Electron cyclotron resonance (ECR) ion sources have been developed at the Institute of Modern Physics (IMP) since 1987 and great progress in the production of multiply charged ion beams with ECR ion sources have been made[1]. However, study on the mechanism of ECR ion sources was deficient here. In order to deepen understanding of the mechanisms of ECR ion sources, some efforts have been made at IMP in the last two years[2].

Our study was mainly focused on the hot electrons in ECR ion sources, for they are of great interest in the process of the highly charged ions production. In an ECR ion source the plasma is confined by a minimum-B magnetic configuration which is formed by a superposition of an axial mirror field and a radial multi-pole field. Electrons are 'heated' by the resonance interaction with the microwave where the electron Larmor frequency equals to the frequency of the incident microwave. Then neutral atoms are step-by-step stripped by energetic electrons to high charge states. It is well known that in plasma the electron interaction with ions leads to radiation emission, which is called bremsstrahlung. In the general sense of the term, the bremsstrahlung spectrum is characteristic of the electron distribution function (EDF). As for a Maxwellian distributed electron population of temperature $T_{\rm e}$, the bremsstrahlung spectrum fulfills the following expression[3]:

$$j(E): \exp(-E/kT_{\rm e}),$$

where E is the photon energy, and $j(E)$ the emitted photon number per energy unit. That means the spectral distribution shows a linear decrease with photon energy in a semi log coordinates (ln (j)-E). Therefore, a linear fit of the logarithm of the spectrum will lead to a spectral temperature ($T_{\rm spe}$) in keV which can represent electron mean energy. However both theory and experiment have shown that ECR plasma is far from thermodynamic equilibrium, and the electron distribution function is non-Maxwellian[4], which means the so-called $T_{\rm spe}$ cannot represent the real

Received 20 April 2007
* Supported by Knowledge Innovation Project of CAS (KJCX1-09) and National Natural Science Funds for Distinguished Young Scholar (10225523)
1) E-mail: zhaohy@impcas.ac.cn

electron energy. Nonetheless, this spectral temperature provides us an indicator to show the relative energy of the hot electrons in ECR plasma.

In order to investigate how the microwave power and the magnetic field configuration influence hot electrons in ECR plasma, some measurements of bremsstrahlung spectra were performed on SECRAL (Superconducting ECR ion source with Advanced design in Lanzhou).

2 Experimental setup

2.1 SECRAL

SECRAL (as shown in Fig. 1) is a fully superconducting ECR ion source with a compact and unique structure and high performance in the production of intense highly charged ion beams[5]. It was designed to work at 18—28GHz, and in our measurements it was running at 18GHz. The magnetic fields of SECRAL are produced by a superconducting magnet assembly comprising three axial solenoid coils and six sextupole coils with a cold iron structure. At full excitation, the magnetic field can reach its maximum value as follows: the peak mirror field on the axis is 3.6T at injection, 2.2T at extraction, and a radial sextupole field of 2.0T at the plasma chamber wall.

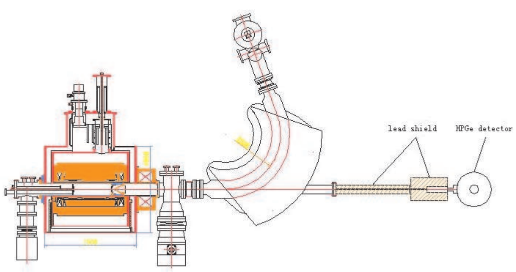

Fig. 1. The overview of the experiment setup for the measurement of bremsstrahlung spectra on SECRAL.

2.2 Measurement system

The experimental setup is shown in Fig. 1. In order to measure the emitted energy spectra, a high purity germanium (HPGe) detector was applied. Because there was no access to the plasma in the radial direction, only the axial bremsstrahlung spectra were measured. The HPGe detector was installed at the axis of the ion source behind the straight-through port of the analyzing magnet. In order to prevent the X-ray photons scattered by the walls and surroundings disturbing the measured spectra, the detector was enclosed by a lead shield; in addition a lead collimator with a diameter of 10cm and a length of 80cm was set up between the straight-through port and the detector. Acquirement of the spectra was realized by a 919 multi-channel analyzer.

3 Experimental results and discussions

The bremsstrahlung spectra were measured on a room-temperature ECR ion source (LECR3) before[2]. It was found that the counting rate of the spectra measured on SECRL was much higher than that on LECR3 with the same measurement system, in spite of that the distance between the plasma and the detector was longer on SECRAL. That is to say that the electron density is higher in SECRAL than LECR3. Considering that SECRAL was running at 18GHz while LECR3 at 14.5GHz, it is easy to explain this difference. According to Girard's theory[6], there exists a relation between the product $n_\mathrm{e}E_\mathrm{e}$ and the microwave frequency, which can be concluded by the following formula:

$$n_\mathrm{e}E_\mathrm{e} \approx \sqrt{\frac{\varepsilon_0 m_\mathrm{e}\omega_\mathrm{rf}^2}{e^2}} m_\mathrm{e}c^2 \ ,$$

According to this expression, the higher rf frequency the higher the product of the electron density n_e and the electron energy E_e. This explains why the counting rate of bremsstrahlung spectra on SECRAL is much higher compared with that on LECR3.

In order to investigate the influence of the external parameter of the ion source on hot electrons in the plasma, the bremsstahlung spectra were measured under different ion source conditions with argon as the main gas, and sometimes mixing gas oxygen was added to enhance highly charged ion currents. At the same time extracted ions were analyzed in mass and charge by the analyzing magnet and the currents were measured by a polarized Faraday cup.

The spectral temperature T_spe was obtained through a linear fit of the logarithm of the spectrum within some energy range. The fit became less and less accurate with the range increasing, which confirmed the non-Maxwellian distribution of hot electrons in ECR plasma. Still, the spectral temperature $T_{\rm spe}$ provides us a comparative index of the hot electron energy.

3.1 Effect of rf power

The bremsstrahlung spectra were recorded for the plasma with different rf power injected. In this experiment the rf power was the only variable, and the other parameters of the ion source were kept as constant as possible. The measured spectra in the semi log coordinates with the linear fit are presented in Fig. 2(a). The curve shows a strong dependency of the counting rate on rf power. At first the counting rate increases rapidly with the increasing power, then the increase of the counting rate becomes less and less pronounced. Qualitatively speaking, this means the electron density first increases with rf power, then saturates. This effect is in accordance with A. Girard's calculation result[7]. Another phenomenon worth noticing is that the nonlinearity of the semilog plot is more and more pronounced with the increasing rf power, which means the EDF is close to a Maxwellian distribution only at low rf power, as collision interactions are dominant when microwave power is low.

The spectral temperatures $T_{\rm spe}$ derived from the linear fit of the logarithm of the spectra in the range from 120keV to 530keV are presented versus rf power in Fig. 2(b) with the corresponding current intensities of $\rm Ar^{9+}$. The spectral temperature $T_{\rm spe}$ increases dramatically with rf power when the power is below 600W (from 77keV at 200W to 103keV at 400W); and if rf power keeps increasing, $T_{\rm spe}$ trends to be saturated (from 109keV at 600W to 124keV at 1800W). The intensity of $\rm Ar^{9+}$ shows the same trend with rf power increasing. The familiar phenomena have been observed by other authors[3, 4], the difference is the rf power value of the turning point. Some authors ascribe the saturation of the temperature to the rf-induced end loss of high-energy electrons[7]. Another possible explanation[4] is that an electron receives a perpendicular energy kick when it crosses the resonance zone; after several back-and-forth travels, the electron becomes trapped between the two resonance zones, which means it does not cross the resonance zone anymore. As a result, the rf heating become inefficient and the energy of the electron comes to saturation.

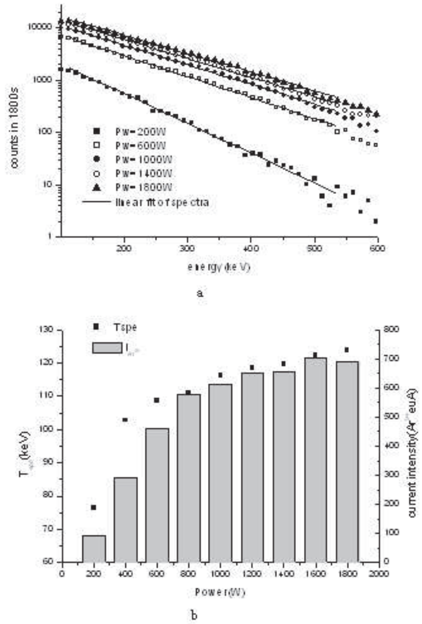

Fig. 2. (a) The measured and the fitted bremsstrahlung spectra for microwave power from 200W to 1800W; (b) the evolution of $T_{\rm spe}$ and the intensity of $\rm Ar^{9+}$ with microwave power.

3.2 Influence of magnetic configuration

In order to investigate the influences of the confinement magnetic fields on hot electrons, the bremsstrahlung spectra from the plasma with different excitation current of the superconducting coils were measured. To simplify the situation, only one current was varied at each time.

3.2.1 Minimum axial field $B_{\rm min}$

The axial bremsstrahlung spectra at 1.6kW rf power with the different excitation current of the middle coil were measured (as shown in Fig. 3). The direct reaction of the change of the excitation of the middle coil is the minimum axial field $B_{\rm min}$: when the excitation current varied from 14.5A to 22.5A, the $B_{\rm min}$ changed from 0.47T to 0.528T. It is found that the spectral temperature $T_{\rm spe}$ increases from 128keV to 172keV as the $B_{\rm min}$ increases from 0.47T to 0.528T. Similar phenomena were observed on VENUS[8]. The dependence of the electron energy on $B_{\min}$ is possibly due to the effect of the magnetic gradient at the ECR heating region. According to H. Koivisto's model[9], the electron heating inclines to be more efficient with the decreasing gradient of the magnetic field.

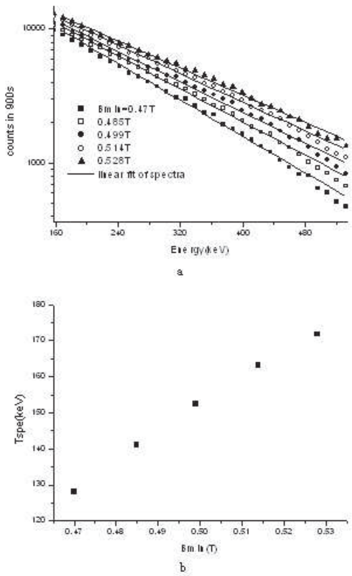

Fig. 3. (a) The measured and the fitted bremsstrahlung spectra for $B_{\min}$ from 0.47T to 0.528T; (b) the spectral temperature as a function of $B_{\min}$.

3.2.2 Excitation current at injection

When we tuned the excitation current of the coil at the injection, not only the peak field at the injection was changed, but also the $B_{\min}$ was, which made the analysis complicated. When the excitation current at injection was tuned from 110A to 140A, the spectral temperature varied from 133keV to 159keV. The spectral temperatures $T_{\rm spe}$ versus $B_{\rm inj}$ and versus $B_{\min}$ are both presented in Fig. 4. It seems that the spectral temperature shows the same evolution with $B_{\min}$ as that in the previous case. However, what differs from the previous case is that the counting rate has hardly dependence on the excitation current at injection coil. That means the electron density keeps unchanged in this case. The more careful experiments are necessary for the further investigation.

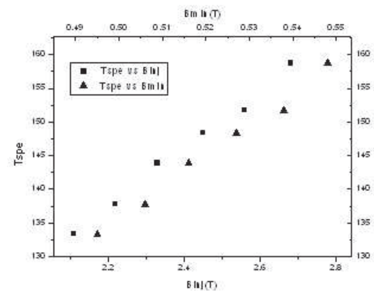

Fig. 4. The spectral temperature as functions of $B_{\min}$ and $B_{\rm inj}$.

4 Conclusion

As the characteristic of the electron distribution function, bemsstrahlung spectra provide us useful diagnostics for the hot electrons in ECR plasma. The deviation of the measured spectra from the linear fit in the semilog present confirms that the EDF in ECR plasma is non-Maxiwellian. However the spectral temperature derived from the linear fit represents the mean energy of the hot electrons to some extent. In our experiments, a saturation of the spectral temperature and the counting rate with the increasing rf power was observed, which was in agreement with the corresponding current intensities of Ar^{9+}. In addition, the spectral temperature exhibited a growth with the increasing $B_{\min}$, which is possibly due to the influence of the gradient of the magnetic field on ECR heating. To verify these, more investigations are necessary.

References

1 ZHAO H W, WEI B W, LIU Z W et al. Rev. Sci. Instrum., 2000, **71**: 646

2 ZHAO H Y, ZHAO H W, MA X W et al. Rev. Sci. Instrum., 2006, **77**: 03A312

3 Girard A, Briand P, Gaudart G et al. Rev. Sci. Instrum., 1994, **65**: 1714

4 Barué C, Lamoureux M, Briand P et al. J. Appl. Phys., 1994, **76**: 2662

5 ZHAO H W, SUN L T, ZHANG X Z et al. Rev. Sci. Instrum., 2006, **77**: 03A333

6 Girard A, Hitz D, Melin G. Rev. Sci. Instrum., 2004, **75**: 1381

7 Girard A, Pernot C, Melin G et al. Phys. Rev., 2000, **E62**: 1182

8 Lyneis C, Leitner D, Todd D et al. Rev. Sci. Instrum., 2006, **77**: 03A342

9 Koivisto H. Rev. Sci. Instrum., 1999, **70**: 2979