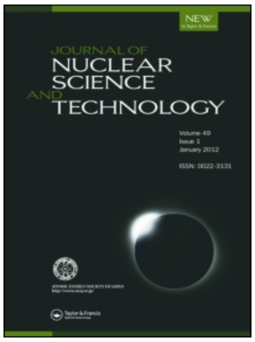

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ARTICLE

Analysis of X-ray spectra in 14.5-GHz ECR ion source for optimizing operation conditions

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ABSTRACT
An electron cyclotron resonance (ECR) ion source operating at 14.5 GHz was developed for the generation of charged ions at the Korea Atomic Energy Research Institute (KAERI). Experiments were carried out to study the plasma inside the ECR ion source by analyzing the X-ray spectra generated by it. The X-ray energy distribution and electron energy inside the plasma chamber are influenced by the status of the heated plasma. That status depends on various operation parameters such as microwave power, injected gas-pressure, and solenoid and trim coil currents. X-ray spectra were recorded to find the correlation between the plasma and the X-rays for variations in the operation parameters. A standard NaI(Tl) detector was used for that purpose. The X-ray energy distribution was studied in the range of 100–500 W for radiofrequency power. The influence of the injected gas pressure and the mirror ratio in the emission of X-rays were analyzed.

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KEYWORDS
X-ray; accelerator; analysis; ECR ion source; X-ray spectra; NaI(Tl) detector; plasma; electron temperature; electron confinement time

1. Introduction

An electron cyclotron resonance (ECR) ion source is used to produce intense, high-charge state ion beams of intermediate and heavy mass elements. It is widely used to produce ion beams for accelerator, atomic physics research, and industrial applications. The basic principle of the ECR ion source is the resonance absorption of energy by electrons in the form of microwaves at the same frequency as the electron frequency in the resonance zone [1]. Owing to its efficient heating of electrons, the ECR ion source produces soft and hard X-rays [2]. These X-rays are mainly generated by electron-ion collisions inside the plasma, or when free electrons collide with the wall of the plasma vacuum chamber. The energy distribution and number of X-rays are influenced by the state of the heated plasma. The plasma state depends on various operation conditions such as the radiofrequency (RF) power, the pressure of the injected gas, and the solenoid coil current. Also, ECR ion sources are usually built for a specific maximum resonance frequency, e.g. 10, 14.5, or 18 GHz. Even if two ion sources share the same frequency, the unique properties of their individual components such as chamber size, magnet material, magnetic field, cooling system, and the RF injector used for fabrication and experiments greatly influence the characteristics of each ion source. Because of this, experimental conditions may show similar trends, but the optimal experimental conditions cannot be predicted. Thus, various experiments for the optimization of the ion source must be performed. Additionally, the optimization of the ECR ion source is needed to produce a plasma and an ion beam stable for long periods of time and to maintain a high temperature for the electrons inside the plasma to increase the high charge state ion beam current. Because of all this, in this study X-ray spectra were recorded to determine correlations between plasma state and electron temperature and confinement time in the chamber for variations of the RF power, the gas pressure, and the coil currents. All experiments were conducted using a high-performance ECR ion source at 14.5 GHz. The data from the analysis of the X-ray spectra will help in the identification of the optimal operation conditions of the 14.5 GHz ECR ion source.

2. Experimental set-up

2.1. 14.5-GHz ECR ion source specifications

The 14.5-GHz ECR ion source was originally designed for the extraction of carbon ion beams for medical applications. However, due to an emphasis on heavy ion accelerator projects in Korea the design parameters of the ECR ion source were modified to allow for the extraction of various ion beams, thus allowing it to also be used as a heavy ion accelerator. In order to obtain various ion beams at high beam currents, the Korea Atomic Energy Research Institute (KAERI) designed and built the ECR ion source, as shown in Figure 1, incorporating the concept of the minimum-B (min-B) and the high-B modes [3,4]. The solenoid coils are composed of two axial coils to create mirror fields on both sides of

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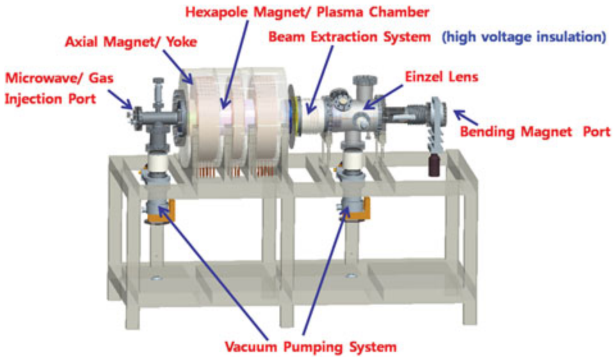

Figure 1. Schematic view of the 14.5-GHz ECR ion source installed at KAERI.

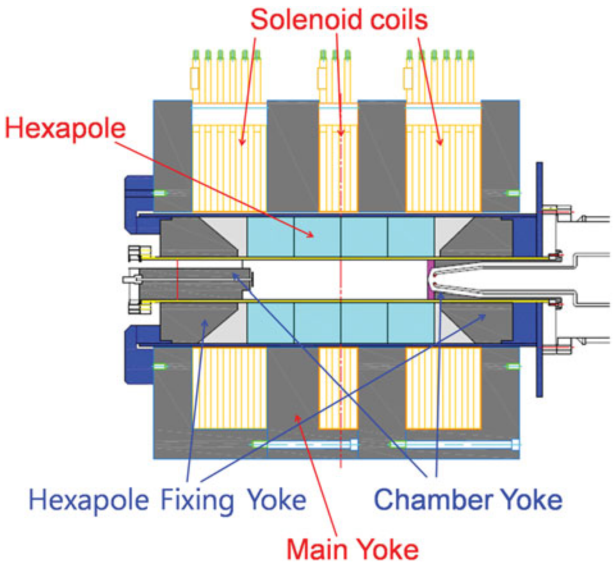

Figure 2. Inner structure of the 14.5-GHz ECR ion source.

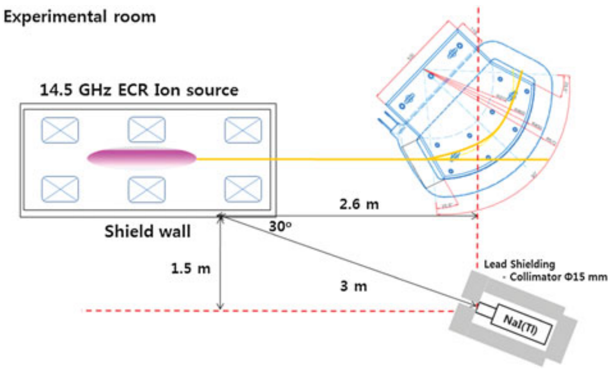

Figure 3. Experimental set-up using NaI(Tl) detector for recording X-ray spectra with respect to various experimental conditions.

the chamber with one trim coil at the center to control the minimum magnetic field strength ($B_{\min}$). There are three different kinds of iron cores to obtain as strong an axial field at both ends of the ECR plasma region as possible, the main yoke, cone yokes, and inside-chamber plugs, as shown in Figure 2. The inner space of the plasma chamber at the RF input side is fully occupied by the iron plug, except for three rectangular openings for microwave injection, vacuum pumping, and gas injection. The positions of these openings and their shapes are designed to minimize the magnetic reluctance in the magnetic circuit. The hexapole is composed of NdFeB permanent magnets. The number of sectors and the outer diameter are optimized to create a strong hexapole field at a fixed inner diameter. An aluminum tube (5-mm wall thickness) welded with stainless steel (SUS304) nipples and flanges are used to improve the production of secondary electrons. A 2-kW klystron (14.5 GHz) supplies the microwave energy to the plasma. Microwaves are injected in an axial direction at an off-axis position to protect the RF window from the dense plasma. A movable beam extractor with an 8-mm aperture covers various ion species and different charge numbers of the beam. The beam divergence can be controlled by using an Einzel lens and a beam extraction grid. The plasma chamber, the hexapole magnet, and the cone yokes are electrically insulated from other grounded components with a G10 cylinder (5.5-mm thickness) and nylon end covers. Two pumping systems composed of 230 l/sec turbo molecular pumps at the RF input side and the beam extraction side maintain the base pressure of the vacuum system at around 10^{-8} mbar. A lead shielding box of 10 mm thickness around the solenoid coils and 20 mm around the beam extraction chamber is installed to shield the ECR plasma from the high-intensity and high-energy bremsstrahlung X-rays.

2.2. NaI(Tl) detector installation

A standard NaI(Tl) detector with a multi-channel analyzer system was used to record the X-ray spectra with respect to various operation parameters of the ECR ion source outside of the shield wall. Figure 3 shows the geometry of the experimental set-up for the measurement of the X-ray spectra. The 50 mm (D) × 50 mm (L) NaI(Tl) detector with a collimator of 15 mm in diameter was used to detect the X-rays created in the ECR plasma. The detector was located at a 3 m distance and a 30° angle from the shield wall. It is important to maintain a stable temperature inside the laboratory because the NaI(Tl) detector's temperature dependence with respect to relative light output and decay time. Because of this, two air conditioners were installed in order to keep the laboratory temperature at 25 °C during the experiment. The detector covered an energy range from 10 to 3000 keV and had an energy resolution of 6.5% at 662 keV. It was calibrated by using three standard sources; Cs-137, Co-60, and Eu-152 with 1 μCi activity and 662 keV, 1173.2 and 1332.5 keV, and 122 and 344 keV peaks, respectively. Figures 4 and 5 show the recorded spectra using the sources and the detector's linearity graph. The linear fitting was performed to convert each energy value to its corresponding channel. The R^2 of the linear equation for the energy is 1.0000

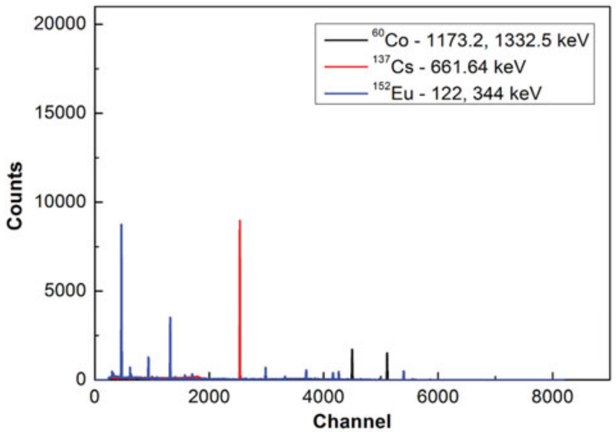

Figure 4. Combined energy spectrum of the standard gamma-ray sources for calibration of the NaI(Tl) detector.

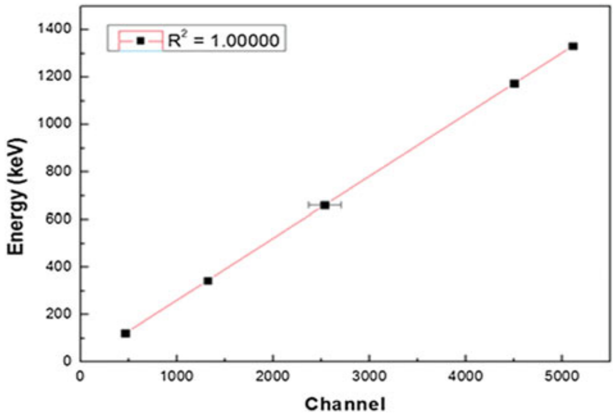

Figure 5. Linearity of the NaI(Tl) detector was obtained by using the Origin program.

according to the Origin software [5]. The background noise spectrum was measured without the plasma and was subtracted from all the spectra to obtain the noise-free data. The background was minimized but not completely eliminated. The X-ray spectra were measured with respect to various ECR ion source parameters such as gas pressure, RF power, and solenoid coil currents. The extraction voltage of the ECR ion source was kept constant at 10 kV for all the measurements. Spectrum acquisition time was set to 600 seconds.

3. X-ray spectra analysis

3.1. *Varying RF power*

The RF power serves to transfer heat directly into the plasma formed within the ECR chamber. As the power increases, the heat transferred to the plasma increases as well, and the electrons present in the plasma are able to be even more active. However, if the heat transfer medium, which continues to be exposed to the heat, leads to an increase in the overall temperature of the device cooling it becomes necessary. When the power is set too high, the cooling unit reaches its limit. Thus, the heat can no longer be efficiently transmitted to the plasma. Therefore, it is important to find the optimal power setting for passing heat to the plasma while also ensuring a stable long-term operation. The bremsstrahlung spectrum from the ECR plasma provides direct information on the energy of electrons heated by the ECR ion source. The nature of the electrons in the ECR plasma is similar to a Maxwellian distribution and this property can be utilized to determine the electron temperature. With this approximation, the electron temperature equals the spectral temperature which is the inverse slope of the semi log plot of the emission coefficient versus energy

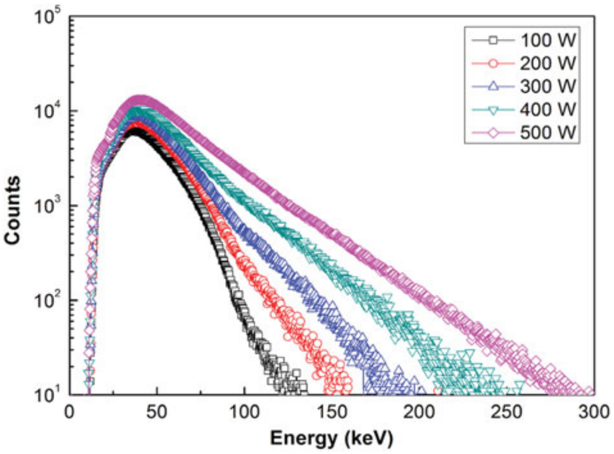

Figure 6. X-ray spectra for various radiofrequency powers from 100 to 500 W.

$$I\ (\upsilon) = A_0 \exp\left(-\frac{h\upsilon}{kT_e}\right), \quad T_e = -\frac{d\,(h\upsilon)}{d(\ln j\,(h\upsilon)} \qquad (1)$$

where $I(v)$ is the electron emission coefficient, hv the photon energy, k the Boltzmann constant, and T_e the electron temperature [1,6]. It is necessary to specify the appropriate energy range in order to analyze the X-ray spectrum by using the above equations. Because the number of X-rays measured in the tail region of the spectrum is low, it is difficult to obtain an accurate maximum energy. Asymptotic analysis is used to analyze the spectrum. Using the Origin software, the maximum energy can be estimated via asymptotic analysis and a significant energy range can be set [1]. Figure 6 shows the X-ray spectra at RF powers from 100 to 500 W. The gas injected into the ECR plasma chamber was He at 5.0×10^{-7} mbar and the solenoid coil current was 700 A. Various gases such as CO_2, He, and CH_4 can be used for optimization experiments of the ECR ion source. However, compared to other gases it is advantageous to use He to produce the plasma and to find operation conditions for increasing the plasma density since the He ions in the ECR chamber is only generated. The operation conditions obtained by using the He gas can be used as initial conditions for experiments using different gases. When the trim coil current is 300 A, the minimum magnetic field of the ECR ion source is 0.45 T. The power radiated by the plasma per unit time in volume

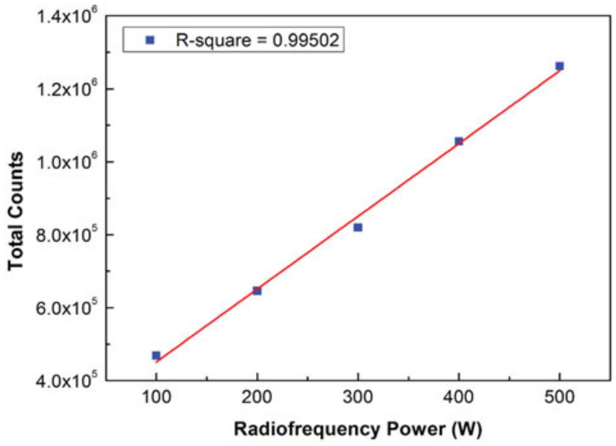

Figure 7. Total counts for 600 seconds corresponding to the X-ray spectra in Figure 6. The total counts increases linearly the RF power.

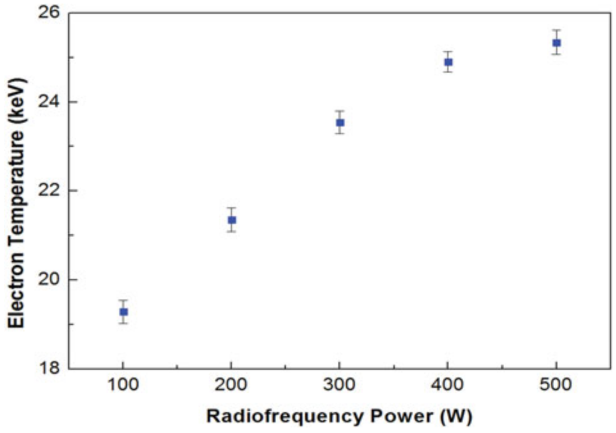

Figure 8. Electron temperature for various RF powers.

is described by the following equation:

$$J\ (h\upsilon) = \left(3.0\ \times 10^{-21}\right)\ N_{\mathrm{i}}N_{\mathrm{e}}Z^{2}\frac{1}{\sqrt{kT}}\exp\left(-\frac{h\upsilon}{kT}\right)\Delta V \tag{2}$$

where N_{i} is the ion density, N_{e} the electron density, Z the atomic number, k the Boltzmann constant, T the electron temperature, and $h\upsilon$ the energy of the radiated photon [7]. The equation shows that the power radiated is linearly related to the electron density. Figure 7 shows that the total X-ray count increases roughly linearly with increasing RF power. The linear increase with the RF power is seen because the X-ray count depends on the electron density. Thus, it can be assumed that the plasma density improves with increasing RF power. It is expected that in order to achieve the highest possible X-ray counts, the RF power should match the plasma as closely as possible. Also, the highest X-ray counts were recorded as 1.26×10^{6} counts (2103 cps) at 500-W RF power. The dead time of the NaI(Tl) detector was estimated at 2.378 ± 0.02 μs by analyzing the X-ray spectrum because real and live time of the X-ray spectrum were 603.00 and 600.00 seconds, respectively [8].

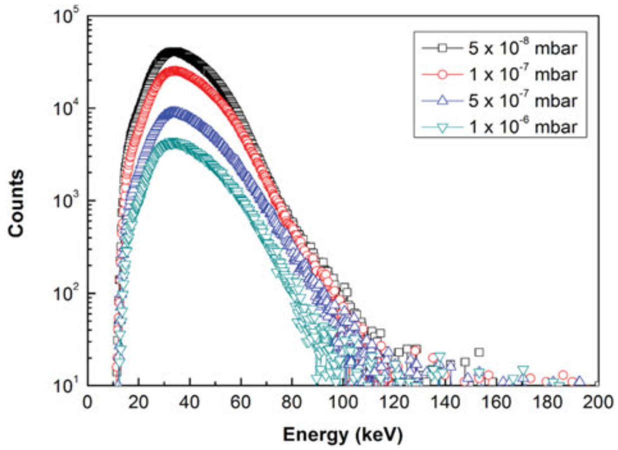

Figure 9. X-ray spectra for various He gas pressure values at 500-W RF power and 300-A trim coil current.

Figure 8 shows the change in the electron temperature with the RF power change, obtained through spectrum analysis. Equation (3) describes the relation between the RF power and the electron temperature.

$$\frac{dW}{dVdt}\ \approx 1.4\ \times 10^{-27}T^{0.5}n_{i}Z \tag{3}$$

where T is the electron temperature, n_{i} the ion density, and Z the average atomic number [9]. The more power is introduced into the chamber, the higher the temperature of the electrons with saturation occurring at 500 W. Beyond that point the electron temperature does not rise any further because the heat is not transmitted efficiently to the plasma. In this experiment, an optimal RF power value of 500 W was confirmed through X-ray spectroscopy analysis of the power change.

3.2. *Gas pressure changes*

Because no plasma is generated below 5.0×10^{-8} pressure, the pressure range of the injected gas was set from 5.0×10^{-8} to 1.0×10^{-6} mbar at a power level of 500 W, a solenoid coil current of 700 A, and a trim coil current of 300 A. Maintaining each gas pressure value for 10 minutes, X-ray spectra were recorded. Figure 9 shows the X-ray spectra at different gas pressures. The energy range was set using asymptotic analysis and the electron temperature was subsequently calculated. Figure 10 shows the electron temperature with respect to the gas pressure changes. The electron temperature, fitted to an energy range between 50 and 110 keV, decreased with increasing neutral pressure. This is in agreement with computer models [9] that predict that the mean energy of electrons decreases as the neutral pressure increases. The mean energy discussed in these models refers to a mean overall electrons in the simulation, so it is related to the electron temperature, but not identical. From a physical standpoint, the fact that the electron temperature decreases as the neutral density

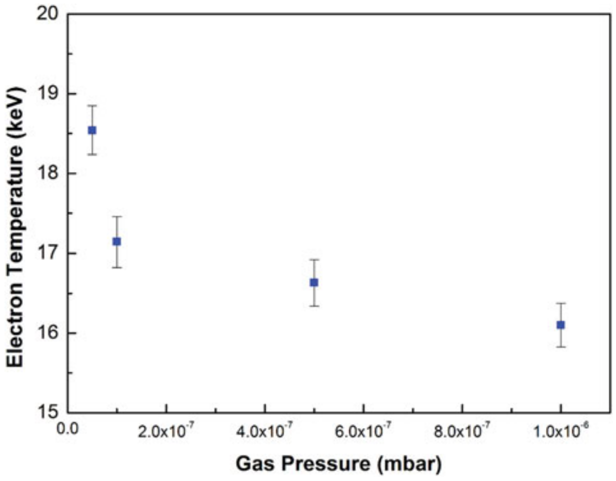

Figure 10. Electron temperature with respect to He gas pressure. The energy range is 50–110 keV.

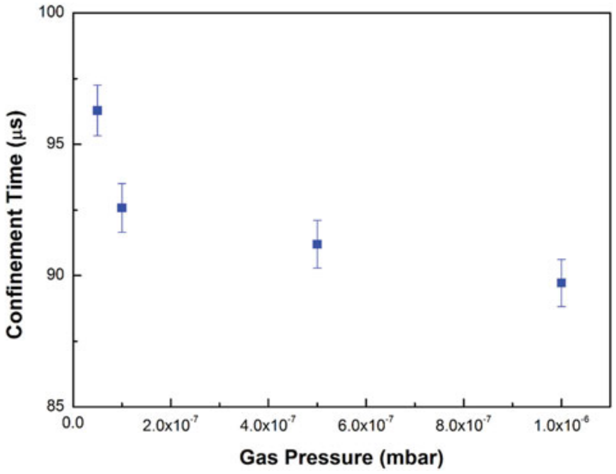

Figure 11. Electron confinement time for different He gas pressure values.

increases makes sense, as electrons will suffer more frequent collisions with neutrals. More frequent collisions, in turn, will scatter electrons into the loss cone more rapidly. The higher the neutral pressure, the lower the mean energy. This is a supplementary explanation of the role of neutral pressure in the creation or destruction of high charge states: In order to produce high charge states it is necessary to reach high electron energies to overcome the ionization potentials, but highly energetic electrons can only be produced at low pressures. Therefore, high charge states are not compatible with high neutral pressures. To summarize, low pressure operation is required to fulfill two major criteria for the production of high charge states: (i) a high confinement time; (ii) high energy electrons.

$$\tau_e \cong 3.5 \times 10^5 T_e \frac{1}{B_z Z}\left(1+\frac{2\theta}{\pi}\right) \qquad (4)$$

where T_e is the electron temperature, B_z the minimum magnetic field, and θ the loss cone angle. Figure 11 shows the confinement time for various gas pressures. For very large gas pressure values the confinement time of the electrons becomes shorter and shorter. It would require a huge amount of power to sustain a linear increase of the electron density with the gas pressure. It is also interesting to see that the higher the gas pressure, the lower the confinement time, which explains why it is necessary to work at low neutral pressures to obtain charged ions.

3.3. Influence of minimum magnetic field

The ECR ion source produces both radial and axial magnetic fields, which depend on the position and the current of the solenoid and the hexapole magnet for plasma confinement. The effect of the magnetic field configuration on X-ray spectra has been shown recently [7]. One study that was carried out previously showed that increasing the magnitude of the minimum magnetic field caused the electron energy to increase [7]. It is essential to examine X-ray spectra to understand the influence of the minimum magnetic field related to the trim coil current on a uniform maximum magnetic field related to both injection and extraction solenoid currents. Another parameter related to the magnetic field is the mirror ratio, as described in the equation below:

$$\alpha = \arcsin\sqrt{\frac{B_{\min}}{B_{\max}}} = \arcsin\sqrt{\frac{1}{R}} \qquad (5)$$

where $R = B_{\max}/B_{\min}$ is the mirror ratio [10]. In theory, lowering the mirror ratio causes a larger loss cone angle (α) and consequently, a larger number of ions escape confinement in the mirror field. The collision rate between electrons and ions decreases for escaping ions, and X-rays with higher energies are emitted due to lower energy loss.

In this study, keeping both injection and extraction coil currents at 700 A, the X-ray spectra were recorded at 500 W and 5.0×10^{-7} mbar He gas pressure. Tables 1 shows the mirror ratio for minimum magnetic field parameters required for measuring X-ray spectra. The X-ray spectra for the minimum magnetic field are displayed in Figure 12. To change the mirror ratio of the ECR ion source, the magnitude of the solenoid currents was varied. Because the ECR hexapoles were permanent magnets, the radial field was fixed. The data shown in Table 1 consist of calculated values based on a magnetic field model of the ECR ion source. The mirror ratio, as shown in Table 1, is defined as the ratio $B_{\max}/B_{\min}$. By far, the most dramatic changes that occur

Table 1. Summary of minimum magnetic field parameters.

Trim coil current (A)	300	400	500
$B_{\min}$ (Tesla)	0.45	0.48	0.51
Mirror ratio (R)	3.62	3.39	3.20
$1/R$	0.276	0.295	0.313

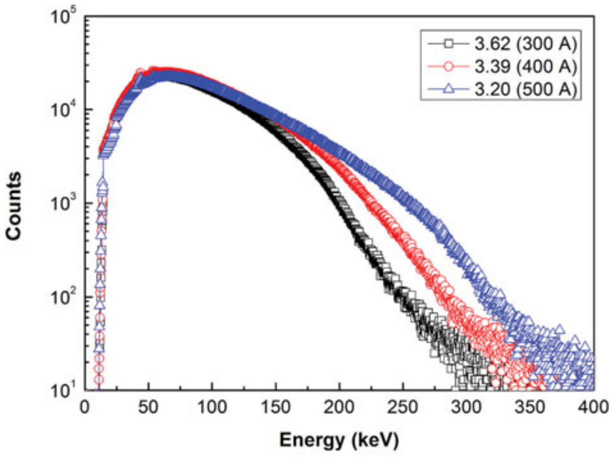

Figure 12. X-ray spectra for various mirror ratios. The mirror ratio is calculated using the minimum magnetic field based on the trim coil current.

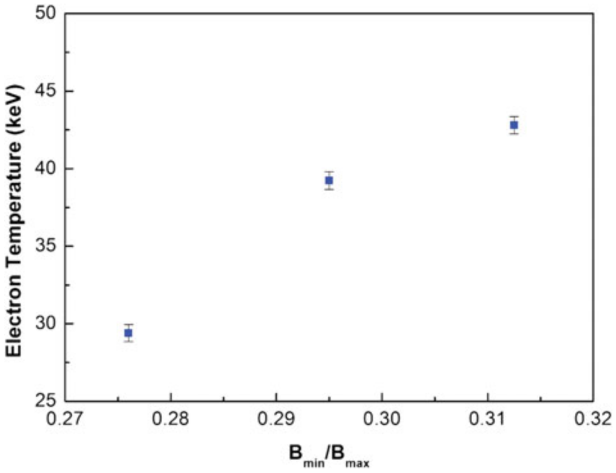

Figure 13. Electron temperature for various mirror ratios.

as $B_{\mathrm{min}}/B_{\mathrm{max}}$ increases are the drop in the gradient of the magnetic field near the resonance point, and the decrease in axial distance between the extraction and injection resonance zones. Simple ECR heating models show that the energy gain of electrons is inversely proportional to this slope [9]. Previous experimental studies have confirmed this theoretically predicted behavior with the observation of increased spectral temperatures as the slope was decreased [9]. Figure 13 shows the electron temperature for $B_{\mathrm{min}}/B_{\mathrm{max}}$. The electron temperature is seen to either increase slowly or to remain nearly constant with $B_{\mathrm{min}}/B_{\mathrm{max}}$, depending on the fit range. Electrons with an electron temperature, or mean energy, of approximately 42.5 keV appear to be less sensitive to changes in the magnetic field configuration. In general, to reach higher energies electrons will need to make multiple passes through the resonance zone. In a magnetic field configuration with a lower slope in the resonance zone an electron will require, on average, fewer traverses to reach a given energy. Competing with the heating process is the scattering of electrons into the loss cone of the mirror field, with less energetic electrons scattered more rapidly. Increasing the minimum magnetic field has two effects. A decreased mirror ratio causes a smaller resonance zone that increases the heating efficiency of the electrons. This increases the number of higher energy electrons, and thus the number of detected X-rays at higher energies increases. The second effect of increasing the minimum magnetic field is an increase in the total X-ray count at lower mirror ratios. It means that the plasma density inside the ECR ion source increases with the minimum magnetic field.

4. Conclusion

The bremsstrahlung spectra presented in this study were emitted through the extraction end of the ECR ion source at KAERI. The integrated count numbers, average electron temperatures, and electron confinement times were obtained from the X-ray spectra while varying several parameters such as RF power, gas pressure, and minimum magnetic field in order to obtain some insight into the behavior of the electrons inside the plasma. The ultimate goal was to find the optimal operation conditions for the plasma because it is important that the recorded bremsstrahlung spectra reflect the spectra emitted by the electrons as accurately as possible. Experimental results have displayed various trends. Increasing power leads to a linear increase in the amount of counts but saturates the electron temperatures of the spectra since the higher power causes plasma heating. On the other hand, increasing the gas pressure decreases the temperature and confinement of electrons which is observed in the spectra. Decreasing the mirror ratio appears to increase the temperature and counts of the observed spectra. Lastly, increasing the injection solenoid current causes a temperature increase since the higher current leads to a stronger magnetic field, which traps the electrons in the plasma. It should be noted that in this study these trends were only observed in the motion of the electrons and the status of the ECR plasma. The optimal operation conditions, as obtained through the various experiments are: (i) RF power: 500 W, (ii) Solenoid coil currents : 700 A/500 A/700 A, (iii) Pressure : as low as feasible, 5.0×10^{-7} mbar in this experiment (taking into account the requirements for plasma generation mentioned above). In the future, extraction experiments for various ion beams will be conducted using the optimal operation conditions that were determined in this study.

Disclosure statement

No potential conflict of interest was reported by the authors.

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