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Estimation of electron temperature in 14.45 GHz ECR ion source plasma by analysis of Bremsstrahlung spectra

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Electron Cyclotron Resonance Ion Sources (ECRIS) are known to produce intense X-rays of the order of 100's of keV. Energy of electrons in the resonantly heated microwave plasma has been estimated by analyzing the Bremsstrahlung spectra obtained using a standard alkali halide (NaI [Ti]) crystal detector. Experiments were carried out on argon plasma discharge from high performance ECR ion source operating at 14.45 GHz. The dependency of X-ray emission with microwave power has been studied in the range 50-400 W. It is verified that maximum energy gained by electrons in ECR plasma follows a power law $E_{max} \alpha P^{3/8}$. X-rays of more than 800 keV energy can be generated at very low microwave power as 400 W. The influence of magnetic field and gas pressure in the production of X-rays has also been analyzed.

Keywords: ECR ion source, Plasma, Bremsstrahlung spectra, Electron Cyclotron Resonance Ion Sources, Microwave power

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1 Introduction

The basic principle of ECR is the resonance absorption of energy by electrons from microwave that has the same frequency as the electron's gyro frequency in the resonance zone. This gain in energy is considered to be a stochastic process and depends on the phase difference at which the particle faces the electric field and the amplitude of the electric field. By multiple passages through the resonance zone, the electron may get heated to very high energies with an upper limit in energy due to the invariants at relativistic energies [1]. Bremsstrahlung from this electron occurs when a sudden change in the direction of motion occurs or when it hits the walls. Thus, free bremsstrahlung gives an account of the energy gained by the electrons inside the plasma[2]. The nature of hot electrons in plasma can be studied by Langmuir probes also. But this invasive method cannot be used at very high plasma temperatures and high plasma densities due to destruction of probe itself after exposing it to the plasma. Langmuir probe measures the local parameters of the plasma. In case of ECR ion sources, the plasma is highly anisotropic due to complex axial and radial magnetic fields. Langmuir probe theory is not well suited for the highly magnetized plasmas[3] due to anisotropy in electron diffusion coefficients in different directions. Analysis of Bremsstrahlung spectra of the ECR plasma is a non invasive plasma diagnostic method and had been used for finding out various plasma parameters like electron temperature, electron energy distribution function, electron density, ion temperature etc[4-6]. This paper presents a systematic study that has been carried out to see how the electron temperature in ECR plasma varies with microwave power, magnetic field and pressure.

2 Experimental Details

The X-ray measurement is done on M/S Pantechnik make 14.45 GHz Hypernanogan ECR ion source which is installed in VECC, Kolkata, for the heavy ion acceleration program[7]. ECRIS has both axial and radial magnetic field for producing stable plasma. Maximum axial and radial magnetic fields are 1.21 Tesla. Radial magnetic field is produced by sextupole magnet made of NdBFe arranged in Halbach configuration. axial magnetic field is produced by two solenoid coils carrying a current of maximum of 1200A.

The view port available on the analyzing magnet which is situated in the horizontal magnetic axis of ECRIS is covered by a mylar window and is used for X-ray measurements. A standard 3"×3" NaI (Ti) scintillation detector was placed along this direction.

The detector was calibrated using a standard cobalt source. The background noise spectrum was acquired without the plasma and is subtracted from all the spectra to obtain the noise free data. Extraction voltage in ECRIS is kept constant to 10 kV for all the measurements. 2 kW, Ku band microwave generator of CPI make was used for producing plasma. X-ray spectra were obtained at various ECR ion source parameters. Spectrum acquisition time was set to 100 sec. A schematic of the experimental set up is given in Fig. 1.

3 Bremsstrahlung Analysis

Bremsstrahlung spectra from ECR plasma directly gives the information on energy of electrons that is heated by electron cyclotron resonance. The nature of electrons in ECR plasma is similar to Maxwellian distribution and this property can be utilized to get the electron temperature[8]. With this approximation, the electron temperature equals the spectral temperature which is the inverse slope of the semi log plot of emission coefficient versus energy[9] :

$$T_e = -\frac{d(h\nu)}{d(\ln j(h\nu))} \quad \ldots (1)$$

where the electron emission coefficient $J(h\nu) = N(h\nu)\times h\nu$ in which $h\nu$ is the energy of photon and $N(h\nu)$ is the number of photon emitted per second and per unit of photon energy. Figure 2 shows a plot of J ($h\nu$) versus $h\nu$ for 400 W of microwave power indicating T_e = 70keV at an argon pressure of 1×10^{-5} mbar and solenoid coil currents 800A each.

Keeping Argon gas pressure at 1×10^{-5} mbar and solenoid coil currents at 800 A, the microwave power was varied from 50 to 400 W to see the dependency of X-ray production on power. Fig. 3 shows T_e with microwave power that was calculated using the method described in section 3. It is seen that T_e is as high as 70 keV and maximum electron energy of 856 keV were observed at 400W of microwave power. There is significant increase in the hot electron population with increase in microwave power which helps in high charge state production (Fig. 3).

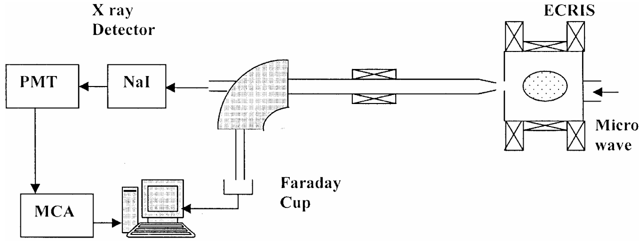

Fig. 1—Schematic of the experimental set up

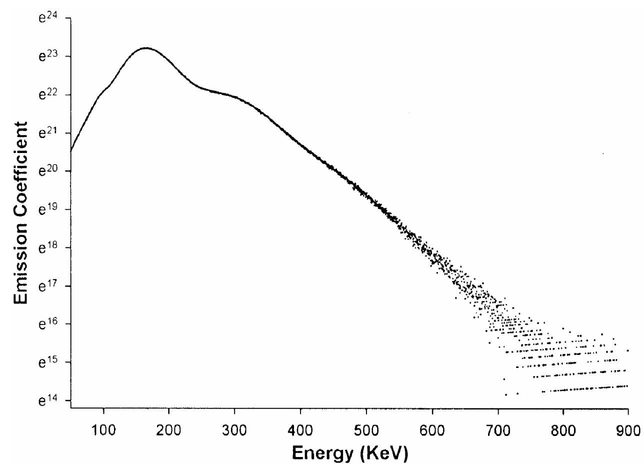

Fig. 2—Emission coefficient versus energy

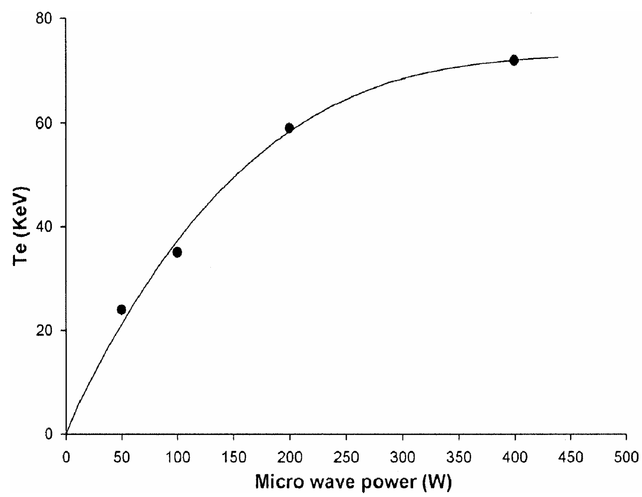

Fig. 3—T_e for various power level

Verification of power law—The maximum energy gained by electrons due to ECR heating is related to microwave power[10] by $E_{max}\ \alpha\ P^{3/8}$. Spectrum of photon counts with energy is plotted for 50, 100, 200 and 400W of microwave power (Fig. 4). Maximum electron energies are estimated from these plots where they reach asymptotic value of zero. These asymptotic zeros have ± 25 keV uncertainties. Maximum electron energies of 409, 524, 674, 856 keV were obtained at 50, 100, 200 and 400W of microwave powers, respectively. It is interesting to see that (856/674) = $(400/200)^{3/8}$ = 1.29.

Variation with magnetic field—Magnetic mirror field is the basis of axial electron confinement in

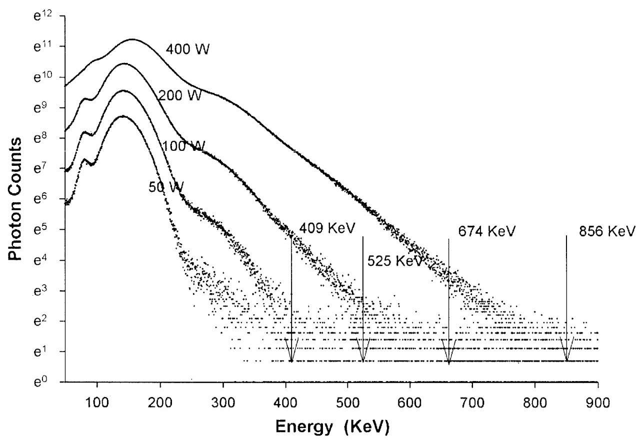

Fig. 4—Photon count versus energy for various power levels

ECRIS although several experiments show that electron heating is not sensitive to the mirror ratio. Mirror field has a minimum on axis which can be represented as *B* (0, 0). And a maximum on the wall of the plasma chamber which can be expressed as B_{max}. Mirror ratio, β is defined as the ratio of maximum magnetic field to minimum magnetic field. Electron heating shows a strong dependence to the location (Z_μ) and the magnetic field at fundamental resonance zone ($B(Z_\mu)$) in the plasma chamber, *B* (0, 0), and the axial distance of the electron's turning position[11] from midplane (Z). Assuming an axial mirror field of the form $B(Z) = B(0,0)(1+\beta Z^2)$ where $\beta = B_{max} / B(0,0)$ is the mirror ratio. The rate of heating of electron at $Z=Z_\mu$ is given by :

$$\left(\frac{dW}{dt}\right)_{Z=Z_\mu} \propto \frac{E^2}{\gamma(\gamma^2-1)^{1/6}} \frac{r^{5/6}}{(r-1)^{2/3}\beta^{1/6}} \qquad \ldots (2)$$

where *E* is the electric field, γ is relativistic mass factor of electron and *r* is the ratio of *B* (*Z*) to *B* (0, 0). Eq. (2) shows that as the midplane magnetic field approaches the fundamental resonance field the rate of heating increases strongly[12]. Practically, it is achieved by increasing the axial magnetic field by increasing the solenoid coil currents. Fig. 5 shows X-ray spectrum showing the increase in the temperature of electrons by increasing the solenoid currents. Electron temperatures from the X-ray spectrum were obtained by the method explained in section 3.

Variation with pressure—Fig. 6 shows the variation of electron temperature found from the X-ray spectra with variation in pressure at a power level of 400 W and solenoid currents of 800A. It is very complex to explain why and by what ratio the electron energies change as the pressure change results in variations in loss processes and microwave power absorption. But the trend in the graph in Fig. 6 indicates that the energy of electron decreases with the increase in pressure. This proves the theory that the increase in pressure increases the collision rate which has adverse effect in energy gain. Data from Fig. 6 is fit to obtain Eq. (3) and it is seen that for this ECRIS with above mentioned parameters, the electron

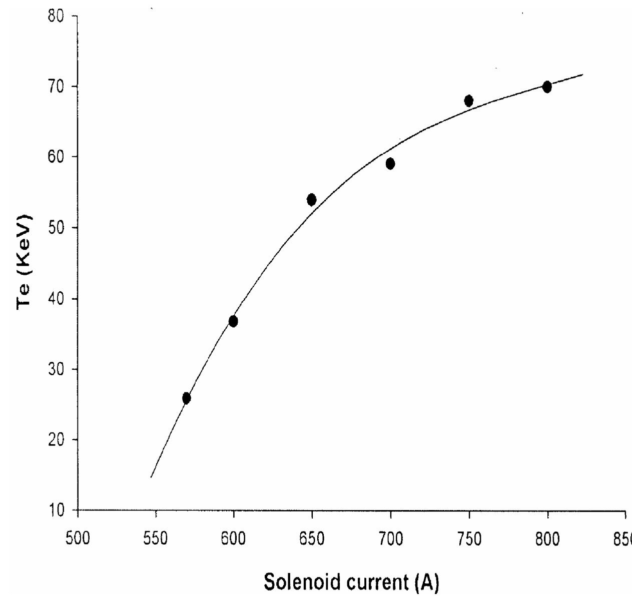

Fig. 5—T_e with solenoid current

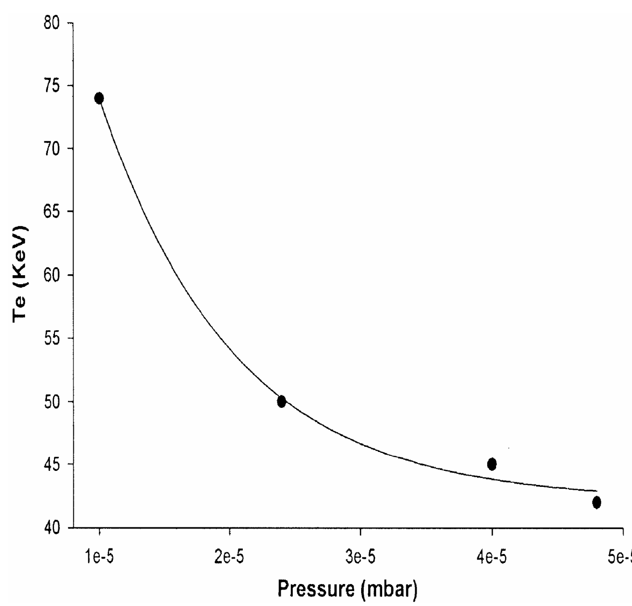

Fig.6—T_e with pressure

temperatures are found to exponentially decay with P_r as:

$$T_e = 42.11 + 84.17e^{-10^5 P_r} \quad \ldots (3)$$

where T_e is electron temperature in keV, P_r is pressure in mbar. This decrease of temperature is due to the increase of collisions with the increase in pressure.

4 Conclusion

Experimental study is carried out to see the effect of ion source parameters such as microwave power, magnetic field and gas pressure on electron temperature. It was observed that change in microwave power follows the power law $E_{max} \alpha P^{3/8}$ producing 856 keV electrons with mere 400 W of microwave power. With increase in the magnetic field, magnetic field at mirror mid plane approaches towards the B_μ making the magnetic field gradient at resonance gentler causing more effective heating of electrons by microwaves. It is also seen that in a given pressure range, the electron temperature exponentially decays with increase in pressure due to the increase in collision rate.

References

1 Jaeger F *et al*, *Plasma Physics,* 14 (1972) 1073.
2 Bernhardi K & Wiesemann K, *Plasma Physics,* 24 (1982) 867.
3 W Lochte-Holtgreven (Editor) *" Plasma diagnostics" North Holland Publishing Co".* (1968) Chapter 11, p 668.
4 Grubling P *et al.*, *Rev Sci Instrum,* 69 (1998) 1367.
5 Friedlein R *et al*, *Nucl Instrum Methods Phys Res B,* 98 (1995) 585.
6 Chew K H, *J Vac Sci Technol A,* 11 (1993) 1186.
7 Mallik C *et al*, *Proc III Asian Particle Accelerator Conf,* (2004) 64-66.
8 R Geller, *Electron Cyclotron Resonance Ion sources and ECR plasmas*, IOP Publishing Ltd (1996) 22.
9 Lamourex M, *Radiat Phys Chem,* 59 (2000) 171.
10 Bardet R *et al, Nuclear Fusion,* 15 (1975) 865.
11 Bernhardi K *et al., Plasma Physics,* 18 (1976) 77.
12 Grawe H, *Plasma Physics*, 11 (1969) 151.