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ECR PLASMA SOURCE IN A FLARING MAGNETIC FIELD

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Abstract.

The propagation and absorption of an electromagnetic wave, near the electron cyclotron zone, of a cold plasma ($T_e \sim$ 1-5 eV) confined in a flaring magnetic field is studied. The case of both extraordinary and ordinary modes has been considered. Temperature effects and electron - neutral collisions have been taken into account in the dielectric tensor.

Introduction.

The ERIC plasma source, a device of stable isotopes separation by ion cyclotron resonance [1], consists of the microwave ECRH antenna pointed towards the flaring magnetic field of a supeconducting magnet (Fig.1).

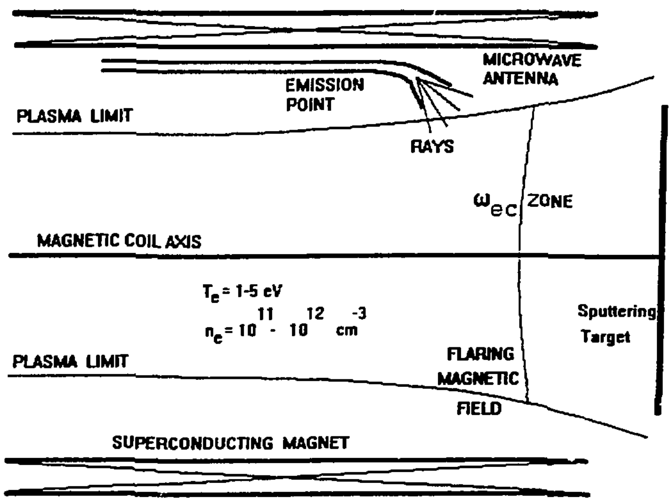

Fig. 1. Scheme of the ECR source in a flaring magnetic field.

The source region has a cylindrical shape of a 30 cm diameter and about 60 cm length, limited by a metallic pllate target. Plasma ignition takes place by ECRH in Argon (or Krypton) atmosphere at 10^{-4} Torr using cw 1.5 kW klystrons at 10, 18 or 29 GHz. The rare gas ions initialize sputtering on the metal plate biased to -2 kV and containing the isotopes to be separated. The plasma is thus composed of metal and gas atoms, electrons, metal and gas ions. Using experimental values of the electronic density and temperature spatial distributions, we study here the absorption of different rays penetrating the plasma at various angles with respect to the magnetic field direction.

Ray tracing calculation.

The dispersion relation for the extraordinary and ordinary modes of an electromagnetic wave with frequency $\omega/2\pi$ and wave vector $\vec{k}$ propagating in a plasma with electronic density n_e and refractive index $\vec{N}$, confined in a magnetic field $\vec{B}$, writes [2]:

$$D = N_\perp^2 + N_{/\!/}^2 - 1 + X \pm \frac{XY\left(\sqrt{(1-N_{/\!/}^2)^2Y^2 + 4N_{/\!/}^2(1-X)} \pm Y\left(1+N_{/\!/}^2\right)\right)}{2(1-X-Y^2)} = 0 \qquad (1)$$

where: $X=\left(\frac{\omega_p}{\omega}\right)^2$ with $\omega_p=\sqrt{\frac{e^2 n_e}{\epsilon_0 m_e}}$ the plasma frequency and $Y=\left(\frac{\omega_c}{\omega}\right)$ with $\omega_c=\frac{eB}{m_e}$ the electron cyclotron frequency. Also, $|\vec{N}|^2 = N_\perp^2 + N_{/\!/}^2 = \frac{|\vec{k}|c}{\omega}$ and $N_{/\!/} = \frac{\vec{B}}{|\vec{B}|}\cdot\vec{N}$

Using (1), the ray trajectories are determined by [3,4]:

$$\frac{d\vec{r}}{dt} = \vec{v}_g = -\frac{\partial D/\partial \vec{k}}{\partial D/\partial \omega} \quad \text{and} \quad \frac{d\vec{k}}{dt} = \frac{\partial D/\partial \vec{r}}{\partial D/\partial \omega} \qquad (2)$$

In our case, the components of the flaring magnetic field can be expressed analytically in cylindrical coordinates (r,θ,z) as follows:

$$B_r = \frac{2zrr_0^2}{\mathbb{Z}\left(r_0+(z^2/\mathbb{Z})\right)^3} B_0, \qquad B_\theta = 0, \qquad B_z = \frac{r_0^2}{\left(r_0+(z^2/\mathbb{Z})\right)^2} B_0 \qquad (3)$$

$\vec{z}$ being the axis of the magnetic coil and B_0 the homogeneous zone magnetic field whose maximum intensity is 3 Tesla. $\mathbb{Z}$ = 340 cm, r_0= 15 cm, r and z in centimeters. The radial profile of the electronic density and temperature has been determined experimentally using Langmuir probes:

$$\mathbb{G}(r) \simeq \left(1-\left(\frac{r}{a}\right)^2\right)^{3/2}\mathbb{G}(0) \quad \text{where } \mathbb{G} = T_e \text{ or } n_e,\ a = 7.8 \text{ cm and r in cm.} \qquad (4)$$

An exemple of ray trajectories at different emission angles with respect to the magnetic field direction, for $\omega/2\pi$= 29 GHz, $T_e(0)$= 5 eV, $n_e(0) = 10^{12}$ and B_0= 2 T is shown in Fig. 2. The ordinary mode absorption is extremely low. The relationship between the wave polarization and the extraordinary mode has been discussed elsewhere [5]. At a given point s of the trajectory, the power absorption is given by:

$$P(s) = P_0 \exp\left(-2\int_0^s \mathrm{Imag}(k_\perp)ds'\right) \qquad (5)$$

The quantity $\mathrm{Imag}(k_\perp)$ is determined by resolving the dispersion relation expressed in terms of the dielectric tensor components ϵ_{ij} assuming a maxwellien electron distribution function [2,6]:

$$N_\perp^4\left(\epsilon_{11}(1-\chi_{33}) + \chi_{13}(2N_{/\!/}+\chi_{13}) + N_{/\!/}^2\chi_{33}\right) - N_\perp^2 \times$$
$$\left(\epsilon_{12}^2(1-\chi_{33}) + (\epsilon_{11}-N_{/\!/}^2)X\left((\epsilon_{11}-N_{/\!/}^2)(1-\chi_{33}) + \epsilon_{33}^0 + \chi_{13}^2 + (N_{/\!/}+\chi_{13})^2\right) - 2i\epsilon_{12}\chi_{13}(N_{/\!/}+\chi_{13})\right)$$
$$+ \epsilon_{33}^0\left((\epsilon_{11}-N_{/\!/}^2)^2 + \epsilon_{12}^2\right) = 0 \qquad (6)$$

with $\epsilon_{13} = N_\perp\chi_{13}$ and $\epsilon_{33} = \epsilon_{33}^0 + N_\perp^2\chi_{33}$. In the cold plasma limit and in the case of an oblic propagation, one has [6]:

$$\epsilon_{33}^0 = 1-X, \quad \epsilon_{11} = 1 + \frac{1}{2}X\zeta_0\left(Z(\zeta_1) + Z(\zeta_{-1})\right), \quad \epsilon_{12} = -i\,\frac{X\zeta_0}{2}\left(Z(\zeta_1) - Z(\zeta_{-1})\right) \text{ and}$$

$$\chi_{13} = \frac{X}{2Y}\left(\frac{v_e}{c}\right)\zeta_0\left(1+\zeta_1 Z(\zeta_1)\right), \qquad \chi_{33} = \frac{X}{2Y^2}\left(\frac{v_e}{c}\right)^2\zeta_0\zeta_1\left(1+\zeta_1 Z(\zeta_1)\right) \qquad (7)$$

where and $Z(\zeta_p)$ is the Fried and Conte function:

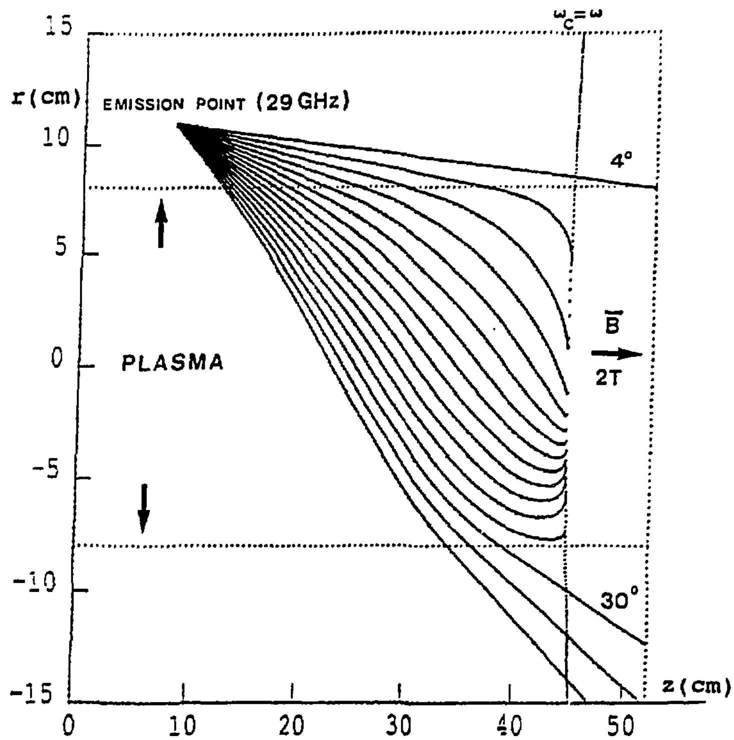

Fig. 2. Ray tracing at 29 GHz for the emission angles between 4° and 34°. Here, B = 2T, $n_e = 10^{12}\,cm^{-3}$ and $T_e = 5$ eV.

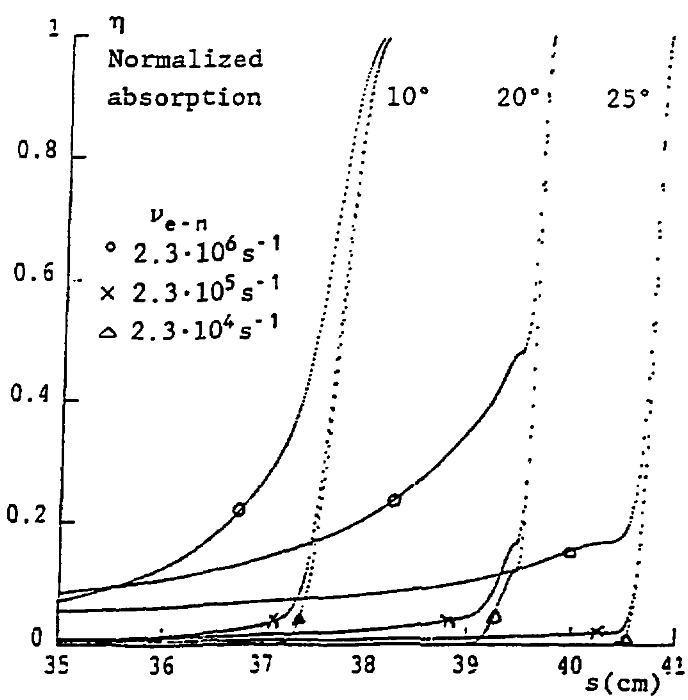

Fig. 3. Influence of the electron- neutral elastic collisions on the ray absorption.

$$Z(\zeta_p) = \exp\left(-\zeta_p^2\right)\left(-2\int_0^{\zeta_p} e^{t^2}dt + i\sqrt{\pi}\right) \quad \text{with } p = 0,\pm 1 \tag{8}$$

In fact, the electrons move within a neutral gas of density $n_n = 10^{12}$ to 10^{13} cm^{-3}. In order to study the influence of electron - neutral elastic collisions we have used in (8) ζ functions with imaginary arguments [7]:

$$\zeta_p = \frac{c}{N_{/\!/} v_e}\left(1 - pY + \frac{i\nu_{e-n}}{\omega}\right) \tag{9}$$

where $v_e = \sqrt{\frac{2\,T_e(r)}{m_e}}$ is the electron mean velocity and $\nu_{e-n} = \sigma_{e-n}^{el}\, n_n\, v_e$ is the electron - neutral elastic collision frequency and $\sigma_{e-n}^{el} \approx 10^{-15}$ cm^2 [8] the corresponding cross section. In our experimental conditions ν_{e-n} is typically of the order 10^5 s^{-1}. The neutral gas influence upon the power absorption of the extraordinary mode along the ray trajectory curvilinear abscissa until the electron cyclotron zone (ω_{ce}) is presented in Fig.3 for three emission angles, 10°, 20° and 25°. An increase of the thickness of the absorption region is observed.

As a conclusion we can calculate the microwave power absorption distribution near the electron cyclotron zone in a flaring magnetic field at low electronic temperatures. The presence of the neutral gas has no significant influence.

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