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DOPPLER EFFECT AT THE ELECTRON CYCLOTRON AND SPIN RESONANCES AND ITS APPLICATIONS FOR PLASMA DIAGNOSTICS AND ELECTRON POLARIZATION IN A WARM BEAM

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In the Ref.[1] it is considered the method of electron polarization using the Doppler effect at the electron spin resonance (ESR), in the case of the monoenergetic electron beam. In this work the development of the method is discussed for the warm beam, i.e., for the kinetic case instead of the hydrodynamic one.

In the analogous case, the electron cyclotron resonance (ECR) was applied for measuring the electron longitudinal velocity distribution [2-4]. To see the analogy in details, let us consider a connection between the electron longitudinal velocity distribution function $f(v_z)$ and the curve of the cyclotron absorption of an electromagnetic wave in a plasma, $P(\omega-\omega_c)$, which represents the dependence of the wave power (after passing through the plasma) versus the frequency shift near the ECR. The calculations were based on the expression that describes the power transference from the electromagnetic wave to the electron at the resonance electron cyclotron frequency:

$$p_a = \frac{e^2 E_a^2}{2m\tau}\frac{1}{(\omega'-\omega_{c0})^2+\tau^{-2}}, \qquad (1)$$

where E_a is the electric field intensity amplitude of the right hand circularly polarized wave, ω_{c0} is the electron cyclotron frequency ($\omega_{c0} = eH/mc$), $\omega' = \omega \pm k_3 v_z = \omega_{c0} \pm k_3 v_z$ is the Doppler–shifted frequency of the wave, *e* and *m* are the electron charge and mass, τ is the electron time of flight through the pumping area. It is supposed here that except of τ another factors of the ECR broadening are negligible.

For a given frequency difference $\Delta\omega = \omega - \omega_{c0}$ the resonance electrons are those with longitudinal velocities in the interval between v_r and $v_r \pm \Delta v_r$, where

$$v_r = \pm\frac{\omega-\omega_{c0}}{k_3}, \Delta v_r = 1/k_3\tau \qquad (2)$$

The ESR has the analogous contour (e.g., see[5]):

$$P/P_0 = (\gamma H_1)^2/[(\omega'-\omega_s)^2+(\gamma H_1)^2+\tau^{-2}], \qquad (3)$$

where *P* is the mean power going from the wave to the electron spin and back, ω' is the Doppler-shifted wave frequency, γ is the gyromagnetic ratio, H_1 is the magnetic field intensity amplitude of the right hand circularly polarized wave, τ is the electron time of flight through the pumping area, ω_s is the frequency of the electron spin resonance (ESR): $\omega_s = eH(1+a)/mc\gamma_l$, were *e* and *m* are the charge and mass of electron, *c* is the light velocity, γ_l is the Lorentz factor, *a* is the anomalous part of the electron magnetic moment ($a \cong$ 0.001).. (The parameters $\gamma H_1/\omega_s, (\tau\omega_s)^{-1}$ can be of order 10^{-4} – 10^{-5}). It is supposed that another factors of the ESR broadening are negligible. The probabilities of the electron spin flip due to the quantum absorption or induced radiation are equal one to another and are determined by the following expression [5] (with account of $\tau = L/v$, where L is the pumping section length, *v* is the velocity of the resonance electron):

$$|c(t)|^2 = \frac{(\gamma H_1)^2}{(\omega'-\omega_s)^2+(\gamma H_1)^2+\tau^{-2}} \times \sin^2\left(\frac{t}{2}\sqrt{(\omega'-\omega_s)^2+(\gamma H_1)^2}\right) \qquad (4)$$

or by its quantum analog [5]. At the conditions $\omega' = \omega_s$ and $\gamma H_1 = \pi/\tau$ (because $\sin^2(...)=1$, and $(\gamma H_1)^2 >> \tau^{-2}$) we have $|c(t)|^2 \approx 1$, that is, the probability of an electron spin flip is about 1 to the moment of its exit out of a section.

The half-width of the both resonances can be much smaller than the frequency Doppler shift:

$$1/\tau \text{ or } \nu_{eff} \text{ are } << k_3 v_z, \qquad (5)$$

where ν_{eff} is the frequency half-width of the cyclotron resonance for a single electron with velocity v_z. In the general case, ν_{eff} denotes the frequency with which the

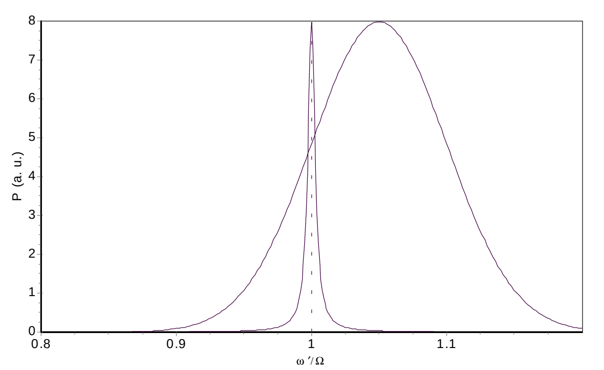

Fig.1.

wave phase shifts in relation to the electron rotation (by collisions, non-homogeneous, etc.). This situation is shown in the Fig.1, where the wide curve represents a warm plasma or dispersed beam (the Gauss contour), and the narrow curve does the Lorentz contour of the ECR (or ESR) resonance.

In this condition, the cyclotron loss is governed primarily by resonance electrons in case of the ECR, and the electron spin flip is realized primarily for resonance electrons in case of the ESR.

By changing the electron cyclotron frequency as a parameter, we can systematically measure the entire electron longitudinal velocity distribution. In the case of $\nu_{eff} << 1/\tau$ the microwave power absorbed per unit volume has the form:

$$P_a = \frac{e^2 E_a^2}{2m} \int_{-\infty}^{+\infty} f(v_z) \frac{1 - \cos L(k_3 \mp (\omega_{c0} - \omega))}{v_z L(k_3 \mp (\omega_{c0} - \omega))^2} dv_z \quad (6)$$

Here L is the longitudinal dimension of the interaction region, the "$\mp$" signs correspond to the cases in which the electron and wave are moving in same and opposite directions, respectively.

In the case of $\nu_{eff} >> 1/\tau$ the microwave power absorbed per unit volume has the form:

$$P_a = \frac{e^2 E_a^2}{2m} \int_{-\infty}^{+\infty} f(v_z) \frac{\nu_{eff}}{[\omega - (\omega_{c0} \mp k_3 v_z)]^2 + \nu_{eff}^2} dv_z \quad (7)$$

With account of (5), the integrals in the formulae (6) and (7) take the form:

$$\int_{-\infty}^{+\infty} \frac{\pi}{k_3} f(v_z) \delta(v_z - v_r) dv_r = \frac{\pi}{k_3} f(v_r) \quad (8)$$

The wave damping in the plasma is obtained the form

$$P_a = -\frac{d}{dt}\left(\frac{E_a^2}{8\pi}\right) \quad (9)$$

As a result, with account of (5)-(9), the distribution function is determined as follows:

$$f(v_r) = \frac{m\omega}{4\pi^2 e^2 L} \ln \frac{P_0}{P(\Delta\omega)}, \quad (10)$$

where P_0 and $P(\Delta\omega)$ represent the wave power at input and output of the plasma.

Let us turn now to the specific RF cavity version of the method of determining $f(v_z)$. It is assumed that the microwave power of a wave transmitted through a plasma (or beam) filled the cavity is measured as a function of the magnetic field, i.e., that $P(H)$ is measured. For the H_{11q} mode of the cavity it was received [3] the expression:

$$f(v_r) = \frac{0.24 m\omega k_3 V_R}{\pi^2 e^2 Q_0}\left(\sqrt{\frac{P_0}{P}} - 1\right), \quad (11)$$

where V_r is the cavity volume, Q_0 is the cavity quality factor, P_0 is the transmitted RF power far from gyroresonance, $P=P(H)$ is the same but near the resonance.

As an example, in the Fig.2 it is presented the comparison of electron velocity distribution measurements in the initial stage of the beam-plasma discharge, by this microwave method and the retarding potential method [5]. The oscillograms (left) present the experimental $P(H)$ curve used to calculate with the equation (10) the curve $f(v_z)$ (middle), and the oscillograms (right) do the distribution function $f(mv_z^2/2)$ obtained by the retarding potential method. As one can see, both methods give like results.

By the same way, scanning step by step the electron spin precession frequency (e.g., by changing the longitudinal magnetic field) and using for every step the microwave pumping procedure described in Ref.[1], one can polarize the electron beam in the case of the dispersed (warm) electron beam.

References

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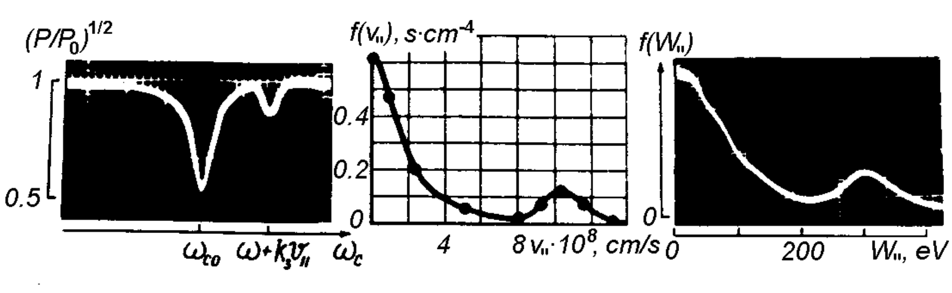

Fig. 2. Comparison of electron velocity distribution measurements