STUDIES AND APPLICATIONS OF DOPPLER EFFECT FOR ELECTRON POLARIZATION AND DIAGNOSTICS OF ELECTRON BEAMS

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The Doppler effect at the electron cyclotron resonance (ECR) was studied experimentally. Both a non-relativistic and a relativistic Doppler effect at ECR was detected. Using Doppler effect at ECR, it was developed the method of measuring the electron energy distribution function for electron beams with energies from non-relativistic to relativistic ones. Measurements were made for non-relativistic electron beams in case of three experimental schemes: close RF cavities, open microwave resonator, and propagation of microwaves in free space. A new method of polarization of free electrons was considered that based on the special mode of microwave pumping using Doppler effect at the electron spin resonance in an external uniform magnetic field.

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1. INTRODUCTION

The work on disintegration of lithium by accelerated protons made at the UFTI, Kharkov in 1932 [1] predetermines further fast progress for charge particle accelerators and nuclear physics in the Soviet Union. At the same time new types of charge particle sources with special parameters and new methods of beam diagnostics had being developed. In this connection, the present work is devoted to applications of the Doppler effect *a)* in case of electron cyclotron resonance (**ECR**) for determining electron energy distribution in non-relativistic and relativistic electron beams, and *b)* in case of electron spin (magnetic) resonance (**ESR**) for polarization of free electrons. Let us note that usual Doppler effect had been called as normal Doppler effect after discovering of anomalous ("superlight") Doppler effect [2,3].

The normal Doppler effect (**NDE**) at ECR is investigated in Sec. 2. In the considered ECR observation scheme, the Doppler shift was observed very clearly, including the relativistic (transverse) correction.

In Sec. 3 a method of measuring the electron velocity (or energy) distribution function is developed. The method is grounded on NDE at ECR Measurements were made in case of three experimental schemes: close RF cavities, an open microwave resonator, and propagation of microwaves in free space or waveguides.

In Sec. 4 it is proposed a new method of polarization of free (i.e., not bounded in atoms) electrons by the special mode of microwave pumping in the external uniform magnetic field. The feature of the proposition consist in pumping (using NDE at ESR) by two microwaves with different frequencies.

2. DOPPLER EFFECT AT ECR

Experimental investigation of NDE at ECR was made in [4,5]. ECR was studied in case of interaction of a pulsed electron beam with a multimode resonator in the 10-cm range. Fig. 1 is a diagram of the experimental setup. The electron beam (energy W=1-12 keV, current I=0-3 A, diameter $2a$=10 mm, pulse length τ=25 μsec came from a gun consisting of an indirectly heated LaB_6 cathode and grid anode; the gun was immersed in a uniform magnetic field (H=0—1500 Oe, ±1% inhomogeneity). The beam was directed along the axis of a quartz tube of 30-mm diameter, evacuated to p~10^{-6} Torr. A 10-cm multimode resonator (i.d. $2b$=102 mm, height h=300 mm, diameter of end apertures 2d=33 mm, length of cutoff waveguides l=40 mm) was aligned axially with the tube. The resonator was excited by a coupled klystron oscillator (W~10 mW, τ=3… 10 μsec, f=1700…3800 MHz). The following modes were used: E_{01n} (n=0,2,...6), H_{11n} (n=1,3,5), H_{21n} (n=1,3,5).

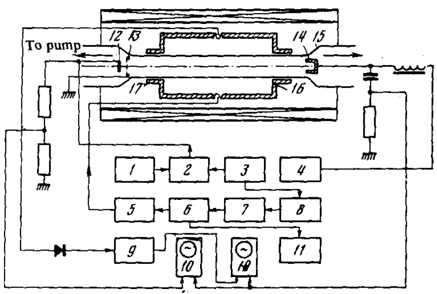


Fig. 1. *Experimental scheme. 1–15-kV rectifier; 2–pulse-shaping line; 3–trigger; 5–10-db attenuator; 6–power divider; 7–10-cm klystron oscillator; 8–delay line; 9–amplifier; 10–dual-beam oscillographs; 11–frequency meter; 12–cathode; 13–anode; 14–collector; 15–quartz tube; 16–resonator; 17–cutoff waveguides*

The ECR was registered, if the magnetic field was varied near the resonance frequency ω_c=17.7 H (MHz). The foregoing scheme for registering ECR is most sensitive to the microwave power absorption. For the observing the Doppler effect at ECR it is sufficient to excite in the resonator a mode having a sufficiently large number of half-waves spanning the height of the resonator. Since a standing wave can be resolved into two running waves, for an electron beam moving along the resonator axis, Doppler splitting of the ECR will be observed:

$$\omega^{(1,2)} = \omega\gamma\left(1 \pm v/v_{ph}\right) = \omega_c = eH/mc\,, \qquad (1)$$

where m, e, v are the electron rest mass, charge, and velocity, v_{ph} is the wave phase velocity, γ is Lorentz factor, ω is the wave frequency.

This effect is illustrated in Fig. 2, where the relative amount of transmitted microwave power and the shift in the natural frequency of the resonator for the H_{115} mode are shown as functions of the magnetic field. In addition to $\omega^{(1,2)}$, the resonance is observed at $\omega=\omega_c$, which is determined by the electrons of the plasma that is produced when the beam ionizes the residual gas. Each of the three resonances corresponds to a sign reversal of the resonator frequency shift. The shift near a resonance can be used to determine the electron concentrations in the beam and in the plasma separately.

In Fig. 2 we observe unusual shapes of resonance that are characteristic of saturation. For the purpose of obviating saturation it is sufficient either to reduce the electron concentration or to select a mode that is only weakly coupled to the beam. Then a relative Doppler shift of the cyclotron-resonance magnetic field as a function of the ratio between electron velocity and the phase velocity was measured (see Fig 3). Here the dashed lines represent the non-relativistic expression

$$(H_c^{(1,2)} - H_0)/H_0 = \pm v/v_{ph}\ , \qquad (2)$$

where $H_0=mc\omega/e$, $H_c^{(1)}=mc\omega^{(1)}/e$, $H_c^{(2)}=mc\omega^{(2)}/e$.

The magnetic field strength was measured in the midplane of the resonator by means of a Hall probe and an RF oscillator pickup. The absolute magnetic field and its inhomogeneity were measured with ~2% accuracy. The accuracy of the measurements of relative changes $\Delta H/H$ in the magnetic field was $\sim 10^{-3}$. The accuracy of the relative Doppler shift measurements was determined from the ECR half-width: $Q_{eff}\cong 50$ and $\Delta H_c/H_c \sim 10^{-3}$.

Figure 3 shows that with the increase of v/v_{ph} the experimental values deviate from the calculated values in the direction of higher H_c. This effect can be accounted for by a relativistic correction of the Doppler shift whichcould be observed at relatively low electron velocities since the measurements were sufficiently accurate. Figure 4 shows the relativistic correction for $\omega_c^{(0)}$ (i.e., the relative magnitude of the transverse relativistic Doppler effect) as a function of v/v_{ph}. The dashed curve was calculated from

$$(\overline{H}_c - H_0)H_0^{-1} = \sqrt{1 - v^2/c^2} - 1 \approx v^2/2c^2, \qquad (3)$$

where $\overline{H}_c = \left(H_c^{(1)} - H_c^{(2)}\right)/2$.

Quite good agreement between theory and experiment is evident.

3. MICROWAVE METHOD FOR MEASURING ELECTRON DISTRIBUTION FUNCTION DUE TO NDE

3.1. Theoretical relations

As was shown in [5], it is possible to find the relationship between the electron velocity or energy distribution, $f(v)$ or $f(\gamma)$, and the shape of the cyclotron-absorption curve for an electromagnetic wave propagating along a magnetic field with a non-relativistic or relativistic electron beam; we assume: $E=E_{0\perp}\sin(\omega t\mp k_3 z)$, $H||0z$, $\omega=k_3 v_{ph}$.

If the ECR half-width for an electron with velocity v (or energy γ) becomes much smaller than the Doppler shift of the ECR then the cyclotron loss is governed

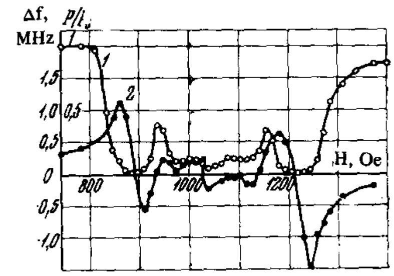
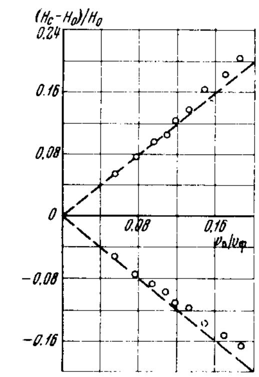


Fig. 2. *(1)- Transmitted microwave power, and (2)-frequency shift in the H_{115} mode versus magnetic field strength ($p=3\cdot 10^{-6}$ Torr, $U=10$ kV, $I=0.27$ A, $f=2898$ MHz, $Q_0=9000$, $v_{ph}=3.5\cdot 10^{10}$ cm/sec)*



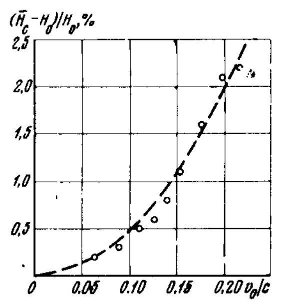


Fig. 3. *Doppler shift of the resonance magnetic field versus v_0/v_{ph} (H_{115} mode, $f=2898$ MHz, $Q_0=9000$, $U=10$ kV, $n_0=3.5\cdot 10^7$ cm^{-3}, $p=2\cdot 10^{-6}$ Torr)*

Fig. 4. *Transverse Doppler effect versus v_0/v_{ph} (with experimental conditions as for Fig. 3)*

primarily by resonance electrons in the velocity interval Δv_r, or the energy interval $\Delta\gamma_r$. If we impose additional condition of the "smoothness" of the distribution function, and if the Langmuir frequency of an electron beam is much less than electron cyclotron frequency:

$$\frac{1}{f}\frac{\partial f}{\partial v}\frac{1}{k_3\tau} \langle\langle 1, \quad \omega_0 << \omega_c\ , \qquad (4)$$

then the shape of the cyclotron-absorption curve is purely Doppler for all electrons. By changing the electron resonance frequency, we can systematically measure the entire electron or energy distribution.

We turn now to a specific resonator version of the method of determining $f(\gamma)$. We assume that the microwave power of a wave transmitted through an electron-filled resonator is measured as a function of the magnetic field, i.e., that $P(H)$ is measured. In case of relativistic electrons and $f(\gamma)$=const(r) we have:

$$f(\gamma) = \frac{cmk_3\omega}{8\pi^2 e^2 Q_0 K}\left(\sqrt{\frac{P_0}{P(H)}} - 1\right), \quad K = \frac{\int_{V_P} E_{0\perp}^2\, dV}{\int_{V_R} E_0^2\, dV}\ , \qquad (5)$$

where Q_0 and P_0 are the Q of the resonator and the power transmitted through it far from ECR, $P(H)$ is the same, but near resonance, ω is the frequency of the diagnostic wave which coincides with the resonant frequency of the resonator, E_0 is the peak field in the resonator, and V_P and V_R are the plasma and resonator volumes. According to (1), Lorentz factor γ and magnetic field H are connected by the resonance condition

$$\frac{eH}{mc\omega} = \gamma \pm \frac{c}{v_{ph}}\sqrt{\gamma^2 - 1}\,. \qquad (6)$$

For the H_{11q} mode with $a<<b$ the microwave field can be assumed to be homogeneous over the plasma cross section. In this case and at $\gamma\approx 1$ f. (5) becomes

$$f(v) = \frac{0.24 m_0 \omega\, k_3 V_R}{\pi^2 e^2 Q_0}\left(\sqrt{\frac{P_0}{P(H)}} - 1\right), \qquad (7)$$

where v and H are connected by the resonance condition: $eH/mc\omega = 1 \pm v/v_{ph}$.

3.2. Experiments with close resonators [5]

The electron distribution function is studied in a beam-plasma discharge in a strong, homogeneous ($\Delta H/H<1\%$) magnetic field. The beam energy is W=10… 600 eV, the current is I=1…100 mA, the beam diameter is $2a$=1 cm, the residual gas pressure is $p = 10^{-5}…10^{-4}$ Torr, the magnetic field is H=500… 1500 Oe, and the plasma density is n~$10^8…10^{10}$ cm^{-3}. The discharge occurs at the axis of a multimode resonator operating in the 10 cm range (the inside diameter of the resonator is $2b$=10.2 cm, and its length is h=30 cm).

Experimental arrangement for measuring the distribution function is similar to Fig. 1. In measurements of the microwave power transmitted through the resonator as a function of the magnetic field we use the H_{115} mode (f=2898 MHz, Q_0=5000), while in measurements of the total number of electrons from the frequency shift we use the E_{013} mode (f=2568 MHz, Q_0=3000). These modes are excited alternately in the resonator by two 10 mW klystron oscillators operating in the "meander-modulation " regime. The power transmitted through the resonator is detected by an oscilloscope. The small shift of the resonant frequency is measured by a heterodyne frequency meter. The distribution functions are measured with n~10^8 cm^{-3} and $N<10^{10}$. The operating regime for the beam-plasma discharge is chosen near the point where the distribution function in the region with the beam and the plasma is not sharp. Fig. 5 shows the absorption lines (curve 1),a corresponds to $\omega_c \geq \omega_{c0}$ and curve 2),a corresponds to $\omega_c \leq \omega_{c0}$ and the corresponding electron distribution functions (curves 1),b and 2),b) obtained from Eq. (7). The parameter for curves 1 and 2 is the neutral gas pressure. Integrating curves 1b and 2b over the velocity, we find the following total numbers of electrons in the resonator: $N_1=1.7\cdot10^9\pm30\%$ and $N_2=3\cdot10^9\pm30\%$. From simultaneous measurements of N from the shift of the resonant frequency we find $N_1=1.8\cdot10^9\pm20\%$ and $N_2=3.5\cdot10^9\pm20\%$. Accordingly, the two methods for determining N give the same results within the experimental errors. The total number of beam electrons in the resonator, determined from the current and the average beam velocity, $N_b=Ih(ev)^{-1}$, is also equal to the value of N_b determined by an integration of the distribution function: N_b=(5–6$\cdot10^8$. This result demonstrates that it is possible to carry out absolute measurements of the distribution function by this microwave method.

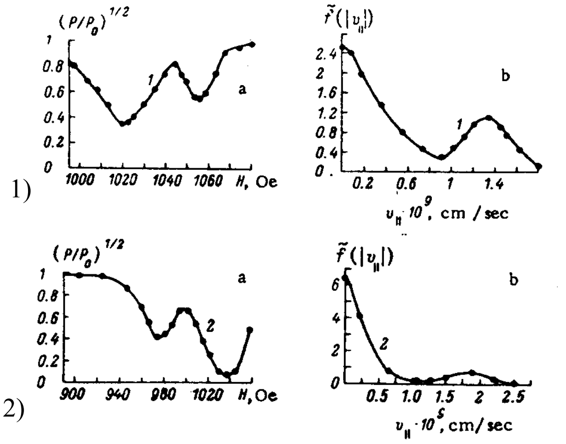


Fig. 5. Absorption lines, $[P(H)]^{1/2}$ and the corresponding distribution functions. 1) $\omega_c \geq \omega_{c0}$, Q_0=1600, I=10 mA, W_e=500 eV, $N=1.7\cdot10^9$; 2) $\omega_c \leq \omega_{c0}$, Q_0=5000, I=7 mA, W_e=1000 eV, $N=3\cdot10^9$ (see text)

A helical resonator was used in subsequent measurements. As the helical guide supports slow waves ($v_{ph}<c$), the resolving power of the method can be increased, and the electron velocity distribution measured in the energy range between 10 and 1000 eV.

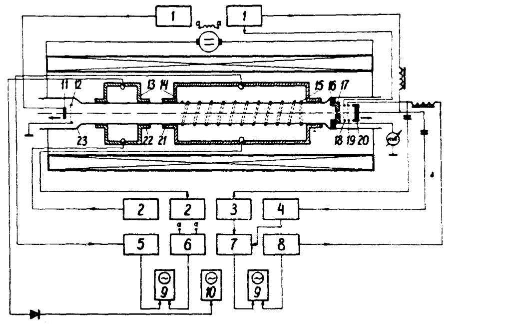


***Fig. 6.** Experimental setup (1–600 V rectifier, 2–10 cm klystron generator, 3–audio generator, 4–selective amplifier, 5–microwave receiver, 6–saw-tooth current generator, 7–phase sensitive detector, 8–saw-tooth voltage generator, 9–double-beam oscilloscopes, 10–single-beam oscilloscope, 11–cathode, 12–anode, 13–E_{010} cavity, 14–metalic screen, 15–helix, 16–vacuum seal, 17–collector, 18–ion reflector, 19–analyzing electrode, 20–analyzer collector, 21, 22–cutoff waveguides, 23–quartz tube*

Fig. 6 is a diagram of the measuring setup. The electron beam was created by a gun consisting of a heated LaB_6 cathode and a mesh anode, with the following parameters: beam voltage U~10…1000 V, current I~1… 100 mA, beam diameter $2a$=10 mm, magnetic field H variable between 0 and 1 kOe, magnetic field inhomogeneity 1%. The beam was shot down the axis of a quartz tube 30 mm in diameter, which was evacuated down to pressures of the order of

10^{-6} Torr. A cavity operated in the E_{010} mode (*13*) was mounted coaxially with the tube and served to measure electron density, together with an overmode helical resonator (*14*) which was used for the measurement of the distribution of electrons over axial velocity. The last resonator was excited via a coupling loop from a generator (2) delivering 10 mW at the resonant frequency f=1750 MHz. The microwave power transmitted through the resonator was registered with a receiver (*5*) and oscillograph (*9*). The mode excited at f=1750 MHz was identified with the result p=1, q=l, r=8 where p, q, r are the numbers of half wave variations along the azimuthal, radial and axial directions. We have v_{ph}/c=0,4 and k_3=0,8 cm^{-1} in accordance with the dispersion relation of the screened helix.

The magnetic field was varied linearly in time, by means of a saw-tooth generator (*6*) whose output was connected to the excited winding of a DC generator used to energize the solenoid. The microwave power transmitted through the resonator was displayed on the scope screen vs. magnetic field, provided square law detection was secured. In the case of linear detection the registered quantity was $\sim\sqrt{P}$. Peaks of cyclotron absorption on the plasma ($\omega_c=\omega$) and beam $\omega_c=\omega\pm k_3v_0$ can be discerned on the oscillograms. The peaks corresponding to the beam clearly exhibits dependence of both Doppler shift and absorption profile half-width on electron velocity. The measurements shown that ω_c-$\omega/\omega=\pm v_0/v_{ph}$ and $|\omega_c^{(1,2)}-\ \omega|\sim\tau^{-1}$) in accordance with theory. The electron velocity distribution was derived from $\sqrt{P(H)}$) curves using formula (6) at $\gamma\approx 1$. To check the electron velocity distribution measurements obtained with the new microwave method we have simultaneously measured the distribution function by means of the well established multi-electrode retarding analyzer.

To measure the energy distribution of particles by means of the retarding potential method we have to differentiate collector current with respect to analyzing grid voltage: $f(W_{||})=\partial I_c/\partial U_g$. We have used a setup permitting to carry out such differentiation and to display the distribution function on the scope screen (see Fig. 6). A small amplitude sine wave signal ($f\cong$ 500 Hz), derived from generator (*3*), was superposed to the saw-tooth retarding voltage from generator (*8*) and applied to the analyzing grid (*19*). This causes an alternating component of the same frequency in collector current, which is proportional to $\partial I_c/\partial U_g$. The alternating component was monitored with a phase sensitive detector (*7*), whose output was connected to the oscilloscope (*9*).

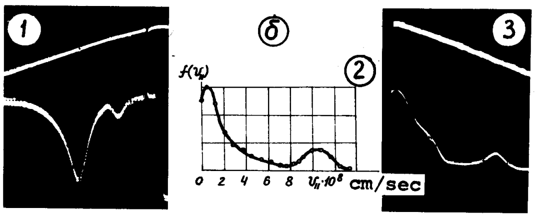


Fig. 7. *The function $[P(H)]^{1/2}$ (l) and the electron distribution function, measured with the microwave method (2) and the retarding potential method (3), in the initial stage of the beam plasma discharge (U=300 V, I=10 mA, H=400-700 Oe, $n=3.7\cdot 10^8$)*

Fig. 7 is a comparison of electron distribution measurements in the initial stage of the beam-plasma discharge, by the microwave method and the retarding potential method. The oscillogram (1) is $[P(H)]^{1/2}$ curve used to calculate $f(v_{||})$ curve (2), and the oscillogram (3) is distribution functions $f(W_{||})$ obtained by the retarding potential method. In the initial stage of the discharge both methods give like results. When the pressure is further increased, in the region in which a plateau in the distribution function is formed, the results of the two methods diverge. This can be explained by the increase in diameter of the beam-plasma discharge which occurs at this stage and which makes the distribution function radius dependent. By means of the probe analyzer we investigate only a small part of the discharge near the axis, 2 mm in diameter, whereas the resonator data pertain to the whole cross-section of the discharge, 30 mm in diameter, and it appears that the difference between the two methods is quite possible.

This method can also be used to measure the velocity (or energy) modulation of the electron beam, or to determine the strength of an alternating electric field from the electron oscillation velocity: $\tilde{v}_{||} = e\tilde{E}/m_0\Omega$ [6].

3.3. Experiments with an open resonator [7]

In the open cylindrical resonators developed in [8] one can excite oscillations with different space distributions. That property can give possibility to measure the velocity distribution function with resolution along the radius, i.e., $f(v,r)$ instead $f(v)$.

In our experiments the velocity distribution function was measured for two oscillation modes with different caustics. In this case an electron gun, open 8-mm resonator, and collector were placed in pulsed uniform magnetic field. Measurements were carried out at beam current 0.1…1 A, energy 10…30 keV. The resonator parameters: 29.4 cm length, 7 cm inner radius, 10 cm outer radius, 30…40 GHz frequency working range, *TE* mode of oscillation. For the demonstration of the resolution along the radius, it was selected two different modes: one with the caustic radius R_1=10 mm (that was smaller than the beam radius b=15 mm), and another with the caustic radius R_2=20 mm (that was smaller than the beam radius). In the first case (a, R_1=10 mm) the microwave power has two maxima of absorption, according to cyclotron resonance for the beam and the plasma created by the beam-plasma discharge. In the first case (b, R_2=20 mm) the microwave power has only one maximum of absorption, according to cyclotron resonance for the plasma because $b<R_2<R_{plasma}$.

Accordingly, the two averaged electron distribution functions determined with formula (5) are shown in Fig. 8. These experimental data prove the possibility of measuring the electron distribution function with resolution along the radius.

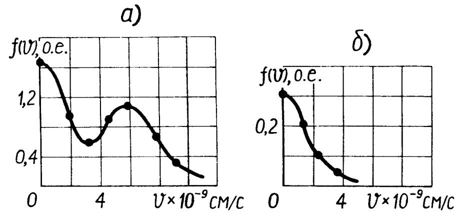


Fig. 8. *Parameters: a) U=10 kV, I=0.4 A, H_{max}=14.7 Oe, R_1=10 mm, f_1=36.6 GHz, λ_{g1}=3 cm; b) U=10 kV, I=0.2 A, H_{max}=14.7 Oe, R_2=20 mm, f_2=36.7 GHz, λ_{g2}=1.5 cm*

3.4. Measuring by the microwave-probe method [9]

Let us consider a case which is commonly encountered under experimental conditions: a wave is generated and received by linear-polarization antennae. In the case of a linearly polarized wave, absorption will be accompanied by rotation of the plane of polarization of the wave (Faraday effect). If E_{xa} denotes the projection of E_a on the plane of polarization of the input (i. e. the plane parallel to the narrow part of the rectangular wave guide), then

$$E_{xa}=E_{0a}e^{-\alpha l}\cos\beta l, \quad \alpha l = \ln(E_{0a}/E_a), \tag{8}$$

where α is the damping constant, and β is the Faraday-effect constant; the power received by the detector is $P(H)\propto E_{xa}^2$. In principle, both α and β are expressed in terms of the distribution function. It can be shown, however, that if the inequalities (4) are fulfilled, we have $\beta l<<1$, i.e. the Faraday effect can be neglected (in this case, $\alpha l\leq 1$). The distribution function in the case of a linearly polarized wave has the form

$$\text{at } \gamma\approx 1 - f(v_r) = -\frac{m_0\omega}{2\pi^2 e^2 l}\ln\left(2\sqrt{\frac{P(H)}{P_0}}-1\right), \tag{9}$$

where $v_r=\pm(\omega_c-\omega)/k_3$;

$$\text{at } \gamma>>1 - f(\gamma_r) = -\frac{m_0\omega}{2\pi^2 e^2 l}\ln\left(2\sqrt{\frac{P(H)}{P_0}}-1\right), \tag{10}$$

where $\gamma_r=\omega_c(\omega\pm k_3c)$.

The distribution function measurements were performed in a beam plasma discharge in a strong longitudinal magnetic field (H=10–15 kOe) with only a small degree of inhomogeneity along the system axis ($\Delta H/H$<1%). The measuring circuit is shown in Fig. 9.

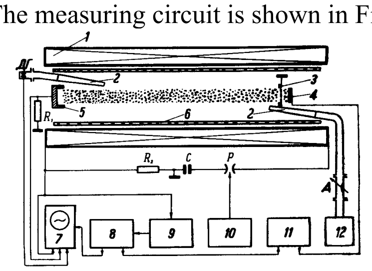


Fig. 9. *Measuring device: 1–pulse solenoid; 2–dielectric antennae; 3–anode; 4–cathode; 5–collector; 6–chamber; 7–oscilloscope; 8–10–starting device; 11–shaper; 12–8-mm generator*

The magnetic field was produced by the discharge of a bank of capacitors C(7x140 μF) through a pulse solenoid (L=150 μH); the field period T=2.4 msec, the circuit damping Γ=300 sec^{-1}. The electron gun consists of a flat LaB_6 cathode and a grid-like anode. Both the gun and the beam collector were positioned in the homogeneous part of the magnetic field. The beam was injected along the magnetic lines of force into a glass chamber 10 cm in diameter and 50 cm long. The beam-plasma discharge had the following parameters: electron beam energy W_e=1…10 keV, current I=0.5…1 A. Pulse length τ=200 μs, beam diameter $2a$=2.5 cm, residual gas pressure p=10^{-5}…10^{-4} Torr, plasma density $n\cong 10^{10}$ cm^{-3}. The discharge was probed at a slight angle ($\alpha=\angle k, H\approx 8°$) to the external magnetic field (the condition for quasi-longitudinal propagation of the wave was fulfilled: $\omega_0^2<<\omega^2\sin^2\alpha$). A signal from an 8 mm generator (12) (f=36 GHz, P~100 mW) was passed through a decoupling attenuator and a rectangular cross-section waveguide and thence to the dielectric transmitting antenna (2), forming a directed linearly-polarized probe-wave. After passing through the plasma, the signal was received by the receiving antenna, positioned in the same way as the transmitting antenna, and after detection the signal was fed to an oscilloscope (7); both the antennas were outside the plasma. The condition for an unbounded plasma was fulfilled, ka ”l. The measurements were made in the following manner. The discharge-gap P was broken down by operating the starter (10) and capacity C was discharged through the solenoid. At the instant the current through the solenoid reached the required value (corresponding approximately to the resonance value of the magnetic field) the comparator (9) triggered a device (8), which in turn triggered the oscilloscope (7) and the pulse-forming line (11). The latter applied a negative pulse to the gun cathode (4). The generator (12) operated in a continuous regime. Because of the arrangement of the trigger circuit, the time for which the beam-plasma discharge existed was the same as the time required to traverse the ECR. Signals, proportional to $H(t)$, $I(t)$, $P(t)$ were recorded simultaneously by the oscilloscope (7) (see Fig. 10). The relationships $P(t)$ and $H(t)$ obtained in this way (with the beam current remaining constant during the injection pulse) determine the dependence of the UHF power passing through the plasma on the intensity of the external magnetic field $P(H)=P(\Delta\omega)$, ($\omega=const$). On the $P(H)$ curve there are two resonance peaks, corresponding to the resonance absorption of the UHF power by the plasma electrons ($\omega=\omega_{co}$), and the beam electrons ($\omega-k_3v_{\parallel}=\omega_c$); in the experiment the directions of propagation of wave and beam were the same). The shift of ω_c in the case of the beam electrons is due to the Doppler effect, as is confirmed by a set of $P(H)$ curves with beam energy as parameter: $\omega_{c0}-\omega_c/\omega_{c0}=v_{\parallel}/c$.

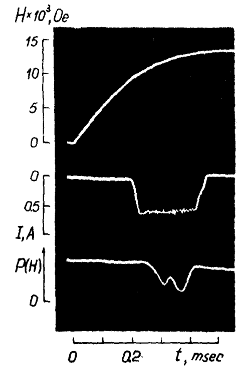


***Fig. 10**. Oscillograms: magnetic field (top); electron beam current (middle); microwave energy passing through the plasma (bottom)*

The measured *p(H)* relationships were transformed into $f(v_{||})$ using formula (9). Fig. 11 shows the distribution function obtained from the data in Fig. 10. The shape of the $f(v_{||})$ curve is typical of a beam-plasma discharge in a regime with a developed instability, when the distribution function has a diffuse form. Under the conditions of our measurements (n~10^{10} cm^{-3}, l~10 cm, ν_{ef}~$10^{-2}\omega$) inequalities (1) are fulfilled for electron energies $W_{||} \cong 10\ldots100$ eV. For lower values of $W_{||}$ the measured distribution function is averaged for different velocities.

Integrating the velocity distribution function shown in Fig. 11, we obtain an average electron concentration in the discharge $n \approx 2 \cdot 10^{10}$ cm^{-3} which, within the limits of measuring accuracy, is in agreement with the electron concentration obtained using the resonator method.

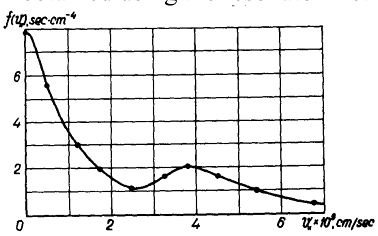


***Fig. 11.** Longitudinal-velocity electron distribution in the beam-plasma discharge*

4. POLARIZATION OF FREE ELECTRONS BY RESONANCE MICROWAVE PUMPING WITH ACCOUNT OF NDE

In this chapter it is described a new method of electron polarization by the special mode of microwave pumping in the external uniform magnetic field [10].

In the well known book "Polarized Electrons" [11] Dr. J. Kessler said that the inapplicability of the common polarization methods (like the Stern-Gerlach experiment) for free electrons does not mean that it is absolutely impossible to find effective electron polarization filters; so, it is necessary to search "unusual" electron polarization filters of high efficiency. Following to this terminology, in the given work it is considered an "active filter" for polarization of the free electrons (i.e., not bounded in atoms) in external uniform magnetic field.

It is known, that some physicists consider (mainly, under the influence of the book [12] with references to N. Bohr and W. Pauli [13]) that it is impossible to measure the magnetic moments of the free electrons or polarize them (these problems are connected). However, namely free electrons were used for very precise measurements of the electron anomalous magnetic moment [14-17]. The authors of these works were obliged to prove statements [14-16] contrary to [12,13]. In Ref. [14] one can read: "*Experiments with free electrons.* It has be emphasized by Bohr that, being a quantum phenomenon, the magnetic moment of the electron due to its spin cannot determined by experiments which require a classical interpretation of the orbital motion. The validity of this statement evidently does not preclude the possibility of measuring g_e of free electrons... It is, however, characteristic of the two proposed arrangements, which we shall discuss below and which under way, that they are both essentially based upon the observation of quantum phenomena". In Ref. [15] it is told: "Bohr has pointed out (see Pauli, 1933) that an attempt to measure the magnetic moment of a free particle by means of a change in the classical trajectory of the particle (i.e., by a Stern-Gerlach type experiment) would violate the uncertainty principle, since it would require a simultaneous measurement of the particle's position and momentum. Other writers interpreted this argument as implying that the magnetic moment of a free particle could not be measured in any way and was therefore a meaningless concept (see Mott and Massey, 1965)". Finally, authors of [15-17] proved their rightness, and their works turned out as very successful [17]. Besides, in sixties the effect of spontaneous "self-polarization" of the ultrarelativistic free electrons in storage rings was discovered [18]. The time duration of this process is about 10^4 sec [11,18]. On the other hand, for the non-relativistic electron the characteristic time of the spontaneous spin flip in external magnetic field of 100 kOe is about 10^7 sec. To improve the situation, it seems expedient a special microwave pumping for sufficient decreasing the time of electron polarization. As it is known, the one frequency pumping cannot polarize. The features of our proposition consist in pumping in the external uniform magnetic field by two microwaves with different frequencies, using NDE at electron spin (magnetic) resonance (ESR). In practice, it is worth while to use a racetrack (see Fig. 12).

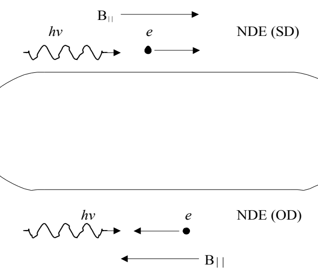


Fig. 12

The pumping can be realized by the running along the straight parts of the racetrack circularly polarized electromagnetic waves. The pumping by the same-direction wave at normal Doppler effect (NDE-SD) can be realized on the one straight part of the racetrack, and by the opposite-direction wave at normal Doppler effect (NDE-OD) can be used on another. Precision parameters of the experiment allow to exclude excitation of the electron cyclotron resonance (ECR) that is very nearly to the ESR with frequency equal to $\omega_s=\omega_c(1+a)$, where a is the anomalous part of the electron magnetic moment: a$\cong 0.001$. Frequency resolution of the ECR and ESR was reached in the works [15-17]. At the resonance pumping, it is occurs absorption or induced radiation of wave quanta and, accordingly, the electron transitions to high or to low energetic spin level. At the absorption the electron receives the additional impetus Δp in the direction of the wave propagation, and due to the induced radiation it receives the impetus in the opposite direction. The phase velocity v_{ph} of the wave can be chosen from the condition: $\Delta v << v_{ph}-v << v_{ph}$ where v is the velocity of the electron beam, Δv is the small velocity spread of the electrons. In this case, for account of the Doppler effect, the resonance frequency of the wave, that is in the same direction (SD) as the electron beam, is increased sufficiently ($\omega'=\omega_s$; $\omega_{SD}>>\omega_s$) and becomes much more than for the opposite direction (OD) wave ($\omega_{OD}\approx 0.5\omega_s$), then $\Delta p_{SD}>>\Delta p_{OD}$.

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 expression [19]:

$$|c(t)|^2 = \frac{(gH_1)^2 \sin^2\left(0.5t\sqrt{(\omega' - \omega_s)^2 + (gH_1)^2}\right)}{(\omega' - \omega_s)^2 + (gH_1)^2} \qquad (11)$$

where ω' is the Doppler-shifted wave frequency, g is the gyromagnetic ratio, H_1 is the wave amplitude, $\omega_s=gH$. The parameters gH_1/ω_s and $(t\omega_s)^{-1}$ can be of order $10^{-4}\ldots10^{-5}$. It is supposed another factors of the ESR broadening, and probability of spontaneous spin flip is negligible. At the conditions $t=\tau$, $\omega'=\omega_s$ and $gH_1=\pi/\tau$ (τ is the electron time-of-flight through the pumping area) we have $|c(t)|^2=1$ for the probability of an electron spin flip to the moment of its exit out of a section.

Suppose the length of pumping distance L and the pumping wave amplitude H_1 are chosen so as the probability of the electron spin flip is very close to 1 in every section. If some electrons have at the SD section entrance the spin projection $m_s=-1/2$ and momentum p_0, then at the exit of this section they will have $m_s=+1/2$ and the momentum $p_1=p_0+\hbar\omega/v_{ph}$; at the OD section exit they will have $m_s=-1/2$ again and the momentum $p_2 \cong p_1$; further this cycle is repeated. After n cycles electrons with initial $m_s=-1/2$ will have $\Delta p=n\hbar\omega/v_{ph}$, and electrons with initial $m=+1/2$ will have $\Delta p=-n\hbar\omega/v_{ph}$. So, electrons with different spins are separated in the velocity space. The resonance frequencies for these groups will be shifted due to the Doppler effect. To maintain the required $|c(t)|^2=1$, the velocity change of these two electron groups can be compensated by suitable increasing of the pumping power (or frequency changing). When the shifts exceeds the half-width of the ESR, one can retune the ESR as follows: $\omega'=\omega_{s,new}=\omega_s-\Delta\omega_{1/2}$. Then, it is possible to make spin flip of the near electron group (with $m_s=+1/2$) and do not change spin of another electron group (with $m_s=-1/2$). After all, nearly full polarization of the electrons can be realized.

An example of parameters for polarization. The phase velocity v_{ph}=1,000·10^{10} cm/s can be supported by a diffraction grating. The beam velocity, v=0.992·10^{10} cm/s (γ=1.060), and current I~10 mA are ensured by a suitable source. The resonance magnetic field is H=90.00 kOe. The resonance frequency of the same direction wave, f_{SD}=2.972·10^{13} Hz, is ensured by a CO_2 laser. The resonance opposite direction frequency, f_{OD}=1.193·10^{11} Hz, is ensured by a gyrotron. The length of pumping areas is L=6.32·10^2 cm, in this case $\omega\tau=10^5$. In accordance with the criterion $H_1=\pi/g\tau$, the amplitude of SD and OD waves is H_1=2.825 Oe, it is corresponds to power of the both oscillators P=19.1 W (at the microwave beam cross-section 0.1 cm^2 and group velocity $v_g=c$). The oscillators' frequency and power can be adjusted for optimization of the result. Changing of the electron velocity per one turn is $|\Delta v|$=1.9·10^4 cm/s. The one turn length in a racetrack is about 2·10^3 cm. So, the polarization process, being automated, can take about 50 turns and time ~10 µs.

The calculations show that considered polarization method can have not only cognitive but practical significance also. This method allows increasing the polarized beams intensity and will be useful in particle and nuclear physics, fusion researches, and other fields.

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