POLARIZATION OF FREE ELECTRONS BY MEANS OF RESONANCE MICROWAVE PUMPING USING NORMAL AND ANOMALOUS DOPPLER EFFECT

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The method of electron polarization by pumping the electron spin resonance (ESR), using a running wave with a phase velocity close to the electron beam velocity, is proposed. Repeatedly alternating pumping by the following wave and by the counter wave, it is possible to realize nearly full electron polarization. Similar, and even more effective, this method can make electron polarization using alternation of a normal Doppler effect on the following wave (thus the wave phase velocity exceeds the velocity of the beam) and an anomalous Doppler effect on the following wave too (when, on the contrary, the velocity of the beam exceeds the phase velocity of the wave).
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1 POLARIZATION OF FREE MONOENERGETIC ELECTRONS

The effect of spontaneous "self-polarization" of the free (i.e., non-bounded in atoms) ultrarelativistic electrons in storage rings is described in many papers (e.g., [1, 2]). The time duration of this process is about 10^4 - 10^5 sec. On the other hand, for the non-relativistic electron the characteristic time of the spontaneous spin flip is very long: in an external magnetic field of 100 kOe it is about 10^7 sec [3]. So, it seems expedient to use a resonance pumping for sufficient decreasing the time of electron polarization (of course, with taking into account the two-level system pumping peculiarities).

In this paper proposed is a new method of particle beam polarization (of electrons or nuclei with a spin 1/2) by the special mode of microwave pumping in the external uniform magnetic field. To explain the principle, let us consider polarization of the beam of free electrons. Some comments about historical problems concerning the possibility of free electrons (or another particles) for polarization were considered in Ref.[4].

Let us consider the beam of monoenergetic weak relativistic electrons that passes along the axes through a number of long superconducting solenoids creating the uniform stable magnetic field of a high intensity H (about 100 kOe). The resonance pumping is realized at 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 main peculiarities of the resonance pumping are as follows.

1. The pumping is realized by the circularly polarized electromagnetic wave, running along the solenoid axis, of the determined frequency and amplitude.
2. In the 1st, 3rd, ..., 2n-1 sections (the section includes the solenoid and pumping system) the wave and even sections are counterstreaming.
3. Precision parameters of the experiment allow to exclude excitation of the electron cyclotron resonance (ECR) that is very nearly to the ESR: its frequency is equal to ω_s at $a=0$. The frequency resolution of the ECR and ESR was reached in the experimental works [5-8].
4. At the resonance pumping, an absorption *or* induced radiation of wave quanta and, accordingly, the electron transitions to high *or* to low- energetic spin level (that correspond to the electron spin parallel *or* antiparallel to the magnetic field) ocur. At the quantum absorption, the electron obtains the additional impetus $\Delta p = h\omega/2\pi v_{ph}$ in the direction of wave propagation, and due to the induced radiation it obtains the same impetus in the opposite direction.
5. The phase velocity of the wave is chosen from the condition: $\Delta v << v_{ph} - v_0 << v_{ph}$, where v_0 is the velocity of the electron beam, Δv is the small velocity spread of electrons. In this case, to take into account the Doppler effect, the resonance frequency of the wave, being in the same direction (*sd*) as the electron beam, is increased sufficiently $(\omega_{sd} >> \omega_s, \omega' = \omega_s)$ and becomes much more than for the wave $(\omega_{op} \approx 0.5\omega_s, \omega' = \omega_s)$ being in the opposite direction (*op*). Then $\Delta p_{sd} >> \Delta p_{op}$. (Note that in Ref.[9] one considered in details the interaction of an oscillator with resonance photons at the normal and anomalous Doppler effect; in [10, 11] the normal and anomalous Doppler effect at the ECR was studied experimentally. The polarization method under consideration can be realized as well by the analogous alternation of sections with pumping at the normal and anomalous Doppler effect).
6. Suppose that the length of pumping distance (L) and the pumping wave amplitude (H_l) are chosen so as the probability of the electron spin flip is about 1 in every section (see item 7). Suppose that at the moment $t=0$ an electron beam enters to the 1st section. If some electrons have at the entrance the spin projection m_s= *-1/2* and momentum p_0, then at the exit of the 1st section they will have m_s= *+1/2* and the momentum $p_1 = p_0 + h\omega_{sd}/2\pi v_{ph}$; at the exit of the 2nd section they will have m_s= *-1/2* again and the momentum $p_2 \cong p_1$; further this cycle is repeated, and at the exit of the 2n-1 section the electrons will have m_s= *+1/2* and

the momentum $p_{2n-1} = p_0 + nh\omega_{sd} / 2\pi v_{ph}$. The electrons with the initial spin $m_s = +1/2$ go out of the 2n-1 section with $m_s = -1/2$ and the momentum $p_{2n-1} = p_0 - nh\omega_{sd} / 2\pi v_{ph}$. So, the populations of the spin levels practically are not changed but the different spins are separated in the velocity space. The resonance frequencies for these groups will be shifted due to the Doppler effect. (Fig.1, top and middle).

7. The ESR have the contour (e.g., see[12]):

$$P / P_0 = (\gamma H_1)^2 / [(\omega' - \omega_s)^2 + (\gamma H_1)^2 + \tau^{-2}], \quad (1)$$

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 wave amplitude, τ is the electron time of flight through the pumping area. (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 [12] (with taking into account $\tau = L / v$, where L is the pumping section length, v is the velocity of the resonance electron):

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

or by its quantum analog [12]. 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 the section.

8. To maintain the required $|c(t)|^2 \approx 1$, the velocity change of these two electron groups (with different spins) can be compensated by suitable increasing of the pumping power. Particularly, if the Doppler frequency shifts for these groups reach the half-width of the ESR: $\omega_{1/2} = n\Delta v \gamma_l \omega / v_{ph}$, then the pumping power must be doubled (see Fig.1, middle; here $\Omega \equiv \omega_s$).

9. If the shifts reach the half-width of the ESR, one can retune the ESR frequency on its resonance half-width in the last section (see Fig. 1, bottom): $\omega_{s,new} = \omega_s - \Delta\omega_{1/2}, \omega' = \omega_{s,new}$. Then, at the suitable L and H_1 as determined above, 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 (with $m_s = -1/2$ in this case).

In practice, it is worth while to use a racetrack instead of the line of solenoids. In this case, the pumping by the same-direction wave at a normal Doppler effect (NDE SD) can be realized on the one straight part of the racetrack, and the opposite-direction wave at normal Doppler effect (NDE OD) - or the same-direction wave at anomalous Doppler effect (ADE) - can be used on the another part (see Fig 2a, b).

The calculations show that the polarization method under consideration (for polarization of particles and nuclei with a spin ½, e.g., p, T, He^3,...) can have not only a cognitive but a practical significance too. This method allows to increase the polarized beams intensity and will be useful in fusion researches, particle and nuclear physics, etc.

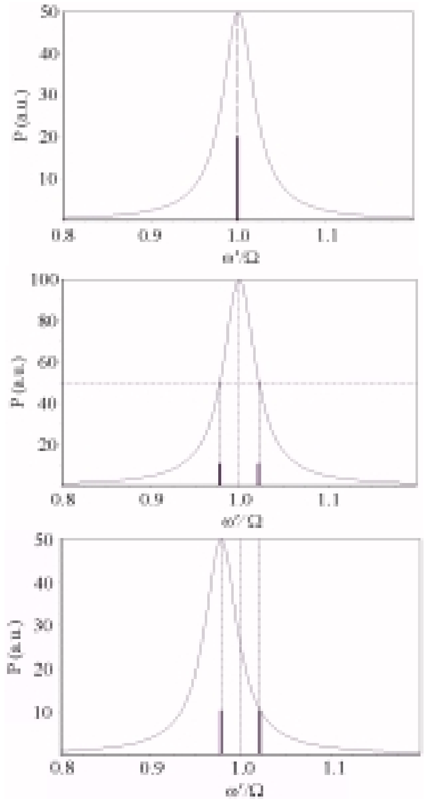

Fig. 1. Stages of polarization by resonance pumping (bold vertical segments correspond to the electron groups with different spins).

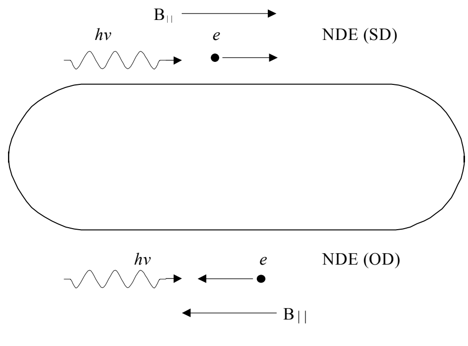

Fig. 2a.

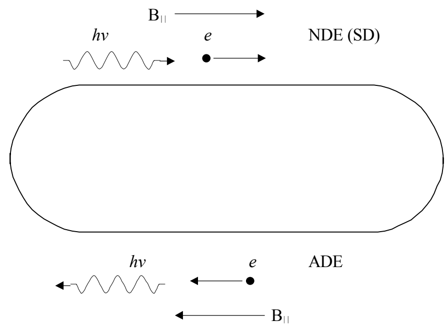

Fig. 2b.

2 ELECTRON POLARIZATION IN A "WARM" BEAM

In this part 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 [13, 14]. The half-width of the both resonances can be much smaller than the frequency Doppler shift:

$$1/\tau \text{ or } \nu_{eff} \text{ are } << k_3 v_z , \qquad (3)$$

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 wave phase shifts in relation to the electron rotation phase (by collisions, non-homogeneous, etc.). This situation is shown in the Fig. 3, 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.

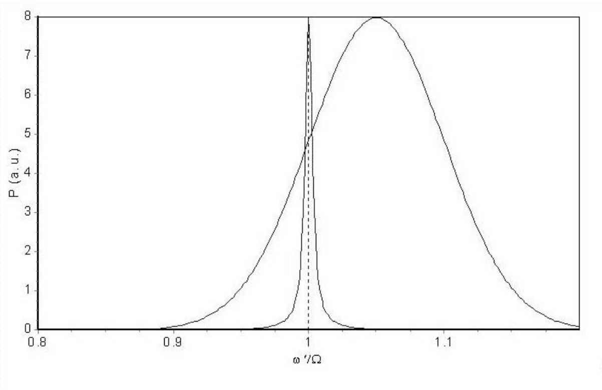

Fig. 3.

Changing the electron cyclotron frequency as a parameter, we can systematically measure the entire electron longitudinal velocity distribution [13, 14].

By the same way, scanning step by step the electron spin precession frequency (e.g., changing the longitudinal magnetic field) and using for every step the microwave pumping procedure described in Part 1, one can polarize the electron beam in the case of the velocity ("warm") electron beam dispersed (see Fig. 4).

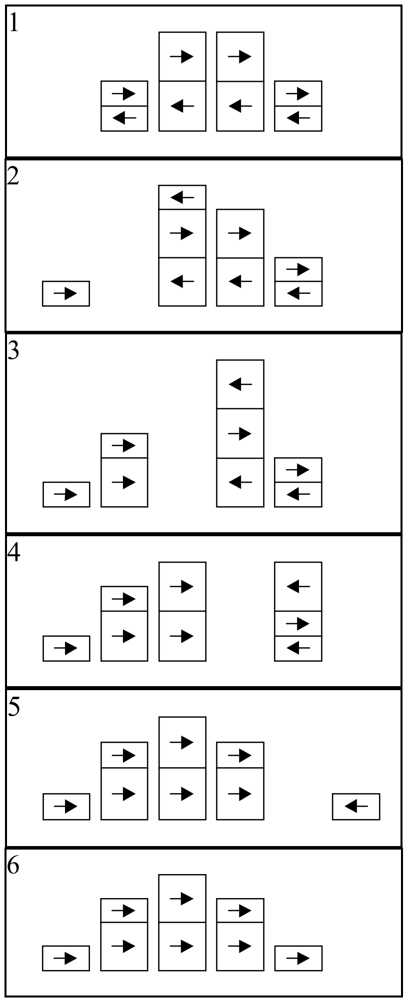

Fig. 4.

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