UDC 533.9

SOME ASPECTS OF POLARIZED PARTICLE BEAMS PRODUCTION AND USING FOR FUSION REACTIONS

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1. Polarization of the free electrons by the special mode of resonance wave pumping

In the works [1, 2] some advantages of fusion reactor with polarized nuclei are considered where fusion rates can be enhanced or suppressed by nuclei polarization that can be used in the CTR. For this trend, the methods of polarized plasmas and intense polarized charge particle beams producing are strongly needed. In this work it is proposed the new method of particle beam polarization (of electrons or nuclei with spin 1/2) by the special mode of microwave pumping in the external uniform magnetic field. For explanation the principle, let us consider polarization of the beam of free electrons. However, firstly we must comment the historical problem concerning the possibility of polarization of free electrons (or another charge particles).

In the well known book "Polarized Electrons" [3] 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 going through, free electrons in external uniform magnetic field. For this case it is proposed the special mode of microwave pumping at the Doppler-shifted electron spin resonance.

It is known that some physicists consider (mainly, under the influence of the book [4] with references to N.Bohr and W.Pauli [5]) 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 [6-10]. The authors of these works were obliged to prove contrary statements [8, 9]. In Ref. [8] 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)". In Ref. [9] it is told: «...Pauli on the other hand overshot the mark when he attempted to prove that spin and magnetism of the free electron could not be measured by a suitable variant [*] of the Stern-Gerlach experiment. In fact invention of the continuous Stern-Gerlach effect [**] for a trapped electron or positron by Dehmelt and Ekstrom has enabled the present researches to measure the ***g*** factors for electron and positron with error limits 2 and 4 orders of magnitude smaller, respectively, than the best previous work. (Ref.[*]. L. Brillouin, C.R. Acad. Sci. Paris, V.184, 82 (1927); Proc. Natl. Acad. Sci. USA V.14, 756 (1928). Ref.[**]. H. Dehmelt, P. Ekstrom, Bull. Amer. Phys. Soc., V.18, 727 (1973); H. Dehmelt, Proc. Natl. Acad. Sci. USA V.83, 2291 (1986))».

Finally, these authors proved their rightness, and their works turned out as very successful [7-10].

Besides, in sixties the effect of spontaneous "self-polarization" of the ultrarelativistic electrons in storage rings was discovered [11]. The time duration of this process is about 10^4 sec [3, 11]. 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. It seems expedient to use a resonance pumping to decrease the polarization time sufficiently (of course, with account of the two-level system pumping peculiarities).

Let us consider the beam of monoenergetic, weak relativistic electrons that passes along the axes through number of long superconducting solenoids created the uniform, stable magnetic field of 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 running along the solenoid axis circularly polarized electromagnetic wave 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 electron beam propagate in the same direction; in the even sections they 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 $a=0$. Frequency resolution of the ECR and ESR was reached in the experimental works [7-10].
4. At the resonance pumping, it is occurs an absorption *or* induced radiation of wave quanta and, accordingly, the electron transitions to high *or* to low energetic spin level (that correspond to electron spin parallel *or* antiparallel to the magnetic field). At the quantum absorption, the electron receives the additional impetus $\Delta p = h\omega / 2\pi v_{ph}$ in the direction of the wave propagation, and due to the induced radiation it receives 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 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 $(\omega_{sd} >> \omega_s, \omega' = \omega_s)$ and becomes much more than for the opposite direction (*op*) wave $(\omega_{op} \approx 0.5\omega_s, \omega' = \omega_s)$. Then $\Delta p_{sd} >> \Delta p_{op}$. (Note that in Ref.[12] it was considered in details the interaction of an oscillator with the resonance photons at the normal and anomalous Doppler effect; in [13, 14] it was studied experimentally the normal and anomalous Doppler effect at the ECR. The considered polarization method can be realized as well by the analogous alternation of sections with pumping at the normal and anomalous Doppler effect).

6. 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 about 1 in every section (see item 7). Suppose that at the moment $t=0$ an electron beam enters to 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 2nd section exit they will have $m_s = -1/2$ again and the momentum $p_2 \cong p_1$; further this cycle is repeated, and at the 2n-1 section exit the electrons will have $m_s = +1/2$ and the momentum $p_{2n-1} = p_0 + nh\omega_{sd} / 2\pi v_{ph}$. Electrons with the initial spin $m_s = +1/2$ go out of 2n-1 section with $m_s = -1/2$ and the momentum $p_{2n-1} = p_0 - nh\omega_{sd} / 2\pi v_{ph}$. So, populations of the spin levels practically not change 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[15]):

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

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 [15] (with account of $\tau = L / v$, where L is the pumping section length, *v* is the velocity of the resonance electron):

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

or by its quantum analog [15]. 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.

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

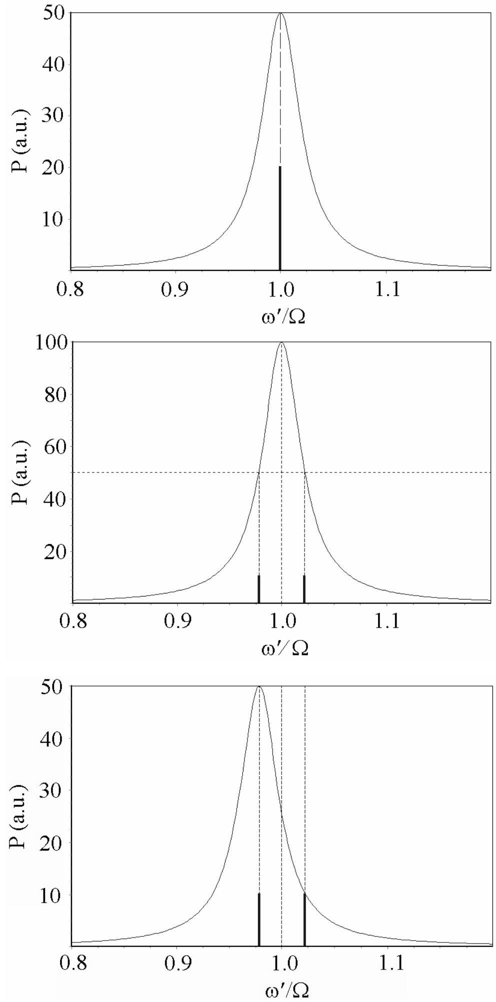

Fig. Stages of polarization by resonance pumping

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. above): $\omega_{s,new} = \omega_s - \Delta\omega_{1/2}, \omega' = \omega_{s,new}$. 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 normal Doppler effect can be realized on the one straight part of the racetrack, and the opposite-direction wave at normal Doppler effect (or the same-direction wave at anomalous Doppler effect) can be used on the another part.

The calculations show that considered polarization method (of particles and nuclei with spin ½, e.g., *p, T, He*^{3},...) can have not only cognitive but practical significance also. This method allows to increase the polarized beams intensity and will be useful in fusion researches [1, 2], particle and nuclear physics, etc.

2. Fusion reactions with polarized nuclei

The problem of fusion reactions with polarized nuclei is tightly connected with the problem of neutron-free (or neutron-lean) fusion reactors [1,2]. In the work [2] the data concerning neutron-lean fusion reactor are presented, as follows. In the ITER the heat load on the divertor is estimated as 20 MW/m^2, which is one order higher that conventional technology allows. The high neutron flux of 10 MW/m^2 on the first wall requires the development of new materials which are to be sound during 100 MW·year/m^2 of neutron flux for commercial reactor. All of these problems come from the 14 MeV neutrons from D-T reactions. The production of neutrons from D-D fusion is half that from D-T fusion, while yielded energy is much smaller, thus the D-D reaction do not resolves the neutron problem. To avoid these engineering problems, a conceptual design of a fusion commercial reactor “ARTEMIS” [2] has been carried out on the basis of a field-reversed configuration (FRC) with D-^{3}He fuel. The “ARTEMIS” has several attractive characteristics: (1) The high beta value of an FRC and direct energy converters should enable to construct a cheap 1 GWe power plant of about 1 billion dollars. (2) Because of its low neutron flux (about 0.2 MW/m^2) conventional materials allow to keep the reactor sound during 30 years. (3) Because of its low neutron yields the reactor is intrinsically safe and environmentally acceptable. By use of polarized fuels in the reactor the energy gain can be increased on 1.5 times. By opinion of the authors of Ref.[2], up to now there is no clear conclusion whether D-D reactions are suppressed by polarization or not. So in this project it is assumed that D-D reactions are not suppressed. In the “ARTEMIS” with non-polarized fuel and the net output power 1 GWe, the neutron yield and the plasma volume are 56 MW and 196 m^3, respectively. In the case of polarization fuels, the net output power is also 1 GWe and the heat load on the first wall is limited to applicable level of 2 MW/m^2. In the small volume mode, plasma volume decreases to 33 m^3 and required energy confinement time is decreased from 6.9 sec to 1.5 sec. The neutrons wall loading increases 2.4 times to 0.43 MW/m^2 (however, without account of suppression of the D-D reactions by polarization). By opinion of the authors of Ref.[2], this operation mode gives a possibility of developing economic fusion reactor.

As to suppression of the D-D reactions by polarization, there is experimental evidence of such suppression shown by the partial wave analysis in the reaction D(D,p)T [16]. The suppression is understood to occur when deuterons are polarized in parallel so that at low energies the Pauli principle suppresses the two deuterons from approaching each other to initiate the reaction [17]. Accordingly to theoretical analysis of Ref.[17], the combined central and spin-dependence forces yield polarized cross sections which are about 8 % of the unpolarized ones in the low energy region. This is certainly consisted with [16] which predicted the polarized cross sections to be about 5 % of the unpolarized one at the energy 290 keV.

As stated in the Ref.1, a fusion reactor could be fueled with polarized atomic gas, using the optical pumping method. Injection of polarized frozen would be attractive, but appears problematical. There would be little practical value if the depolarization rates were rapid compared with the fusion reaction rate. However, the mechanisms for depolarization of nuclei in a magnetic fusion reactor are surprisingly weak [1], as follows.

(1) Inhomogeneous static magnetic fields on a scale that is large compared with the ion gyroradius cannot change the polarization. (2) Simple electrostatic Coulumb scattering does not affect the nuclear spins. The rates of spin-orbit and spin-spin depolarization estimated in [1] are small compared with the typical 1 s^{-1} rate for fusion energy multiplication or the 10^{-2} s^{-1} rate for complete fuel burn up. (3) Magnetic fluctuations. A polarized moving nucleus will tend to be depolarized by those harmonics of the fluctuating fields which are left-circularly polarized with respect to the magnetic field, if the Doppler-shifted frequency in the frame of the nucleus is equal to its precession frequency. (This mechanism is close to one that considered above in the part 2 of the present work for charged particle polarization). In a roughly Maxwellian plasma amplitudes and phase stability of such waves should be rather small to cause the depolarization. (4) Atomic effects, as recombination, charge exchange, spin exchange, cannot make the sufficient depolarization as well. That analysis made in the work [1] allows to consider the problem of fusion reactions with polarized nuclei as attractive one.

References

1. R.M. Kurlsrud e.a., *Phys. Rev. Lett.,* 1982, V.49, p.1248.
2. Y. Tomita, T. Takahashi, H. Momota, *Nucl. Instr. and Methods*, 1998, V.A 402, p.421.
3. J. Kessler, *Polarized Electrons*, Introduction, 2-nd Edition, Springer-Verlag, 1985.
4. N.F. Mott and H.S.W. Massey, *The Theory of Atomic Collisions*, Ch.IV, Oxford, 1965.
5. W. Pauli, *Handbuch der Physik, Quantentheorie*, p.242, Springer-Verlag, Berlin, 1933.
6. F. Bloch, *Physica*, **19**, 821 (1953).
7. G. Gräff e.a., *Phys. Rev. Lett.,* **21**, 340 (1968).
8. A. Rich, J.C. Wesley, *Rev. Mod. Phys.,* **44**, 250 (1972).
9. R.C. Van Dyck, P.B. Schwinberg, H.G. Dehmelt, *Phys. Rev. D*, **34**. No.3, 722 (1986).
10. H.G. Dehmelt, *The Nobel Lecture*, Stockholm, 1989.
11. A.A. Sokolov, I.M. Ternov, *Relativistic Electron*, Moscow, “Nauka”, 1974.
12. I.M. Frank, *Uspekhi Fiz. Nauk*, 1979, V.129, p.685.
13. B.I. Ivanov, *Soviet Physics JETP*, **28**, No.1, 23 (1969).
14. 10.D.V. Gorozhanin, B.I. Ivanov, M.I. Kapchinsky, *Radiophys. & Quant. Electronics*, **27**, 621 (1984).
15. W. Louisell, *Radiation and Noise in Quantum Electronics*, Ch.5, McGrow-Hill Book Co., 1964.
16. B.P. Ad’yasevich e.a., *Yad. Fiz*., 1969, V.9, p. 283.
17. J.S. Zhang, K.F. Liu, G.W. Shuy, *Phys. Rev. Lett.*, 1986, V.57, p.1410.