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# DEVELOPMENT OF NEW METHODS FOR CHARGED PARTICLE ACCELERATION AT YEREVAN PHYSICS INSTITUTE

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Abstract Theoretical and experimental works done at YPI are reviewed: the acceleration of charged particles by surface waves arising at total internal reflection, by inversion of the Vavilov-Cherenkov effect, by inversion of the free electron laser and by wake fields generated in passive and active (plasma) structures by intense relativistic electron beams. For the plasma case special attention was made on nonlinear effects, when the acceleration rate and the transformation ratio are high. The possible self-acceleration of electrons in a relativistic bunch passing through a plasma column is also considered.

## ACCELERATION BY SURFACE WAVES,ARISING AT TOTAL INTERNAL REFLECTION

The main property of the surface waves(their propagation in vacuum with a smaller than light velocity) makes them appropriate for acceleration of charged particles. This idea was first stated probably by Lohman in 1962. Later on, this phenomenon was independently discussed at YPI in 1972. A more complete analysis providing a sufficiently high acceleration rate and at the same time the fullfilment of vertical and phase equillibrium conditions was carried out in reference[1]. High acceleration rate and phase equillibrium conditions are achieved by an additional vertical magnetic field. Vertical equillibrium is provided by a sign-changing magnetic field parallel to the surface and perpendicular to the particle trajectory. In this case, as it follows from the equations of motion, jumps in radiation phase are needed. The full system of equations was studied and optimal conditions for the type of the focusing system, angle of reflection and polarisation of the laser beam were derived. Finally, the breakdown properties of the dielectrics, which could be used in future experimental equipment were analysed. Acceleration gradients of the order of 100MeV/m are expected.

## INVERSE VAVILOV-CHERENKOV EFFECT

In 1962 K.Shimoda suggested in his pioneering work to use the inverse Vavilov-Cherenkov effect for particle acceleration. Starting from 1972 the detailed theory of this effect was developed in the works of the Yerevan group.Special attention was made on the problem of the stability of motion. In particular, the role of the laser wave magnetic field, whose strength in the medium is higher than that of the electric field, was considered. It was shown that at relativistic velocities, the effect of the magnetic field disturbes the phase equillibrium. To ensure the stability it was suggested to introduce a constant magnetic field directed along the wave magnetic field. A system of three Cherenkov waves was proposed and analysed, where stable mode of particle acceleration with a large phase volume of the beam is also feasible[2]. For both of these versions a method has been developed to take into account the multiple scattering effect on acceleration stability and it was shown, that the latter is possible only for sufficiently high strengths (flux ~ $10^{14}$W/cm$^2$) of the wave electric field and short (picosecond) pulses[2].

In a series of works(see review[2]) an interesting feasibility to create high accelerating gradients using the double inversion of the Vavilov-Cherenkov effect was proposed. First a particle beam, accelerated in an ordinary machine, is modulated by the inverse Cherenkov effect. Then it passes into another specially chosen medium and produces Cherenkov radiation with higher field strength which is used again for acceleration of another particle beam by an inverse Cherenkov effect. Acceleration gradients of the order of 10 GeV/m may be expected.

## ACCELERATION BY WAKE FIELDS

The first proposal on wake field acceleration in passive structures belongs to G.A.Voss and Th.Weiland. The experimental studies of the effect were carried out at DESY with a device called by authors the wake field transformer. Later on, the method was also studied experimentally at ANL.

From 1985 theoretical studies were carried out at YPI in search of ways to enhance the acceleration rate and the transformation ratio in various deaccelerating passive structures. In particular, calculations were made for cylindrical waveguides with elliptical cross section, when the driving beam passes through one of the focuses and generates the wake fields along the axis going through the other focus; the problem of increasing the transformation ratio and the acceleration rate by using specially shaped sequences of the driving beam bunches, with various distributions of charge in each bunch, was also studied in detail[3,4,5]. Acceleration rate ≃ 100MeV/m and transformation ratio ≃ 10 may be obtained.

The ideas of using longitudinal wake fields excited by electrons or electron bunches in a plasma to accelerate charged particles were initiated by B.M.Bolotovsky and Ya.B.Fainberg in early fifties. At nearly the same time A.I.Akhiezer and R.V.Polovin formulated and exactly solved the equations for free nonlinear longitudinal waves in an infinite relativistic plasma. Since the end of seventies and up to now in works of the Yerevan group both of these ideas were used in consideration of the generation of longitudinal nonlinear waves in plasma by extended bunches of relativistic electrons. Some of the results of these investigations (see ref.[6,7,9] and review[8] ) are as follows. The essential parameters in question for the case of a fixed bunch are the ratio $n_b/n_0$ , where $n_b$ - is the density(fixed) of the electron bunch, $n_0$ - is the electron density of a neutral cold plasma in equillibrium, $\gamma_b$- the Lorentz factor of the bunch, d - longitudinal length of the bunch and $\omega_p$ - the plasma frequency. It was shown that when

$$\frac{n_b^2}{n_0^2}\left(1-2\,\frac{n_b}{n_0}\right)^{-1} \gg \gamma_b^2 \gg 1,\ \frac{n_b}{n_0} \le \frac{1}{2}\ ,\ d = \frac{v_b}{\omega_p}\,\gamma_b \qquad (1)$$

the maximum of the electric field behind the bunch in the nonlinear longitudinal wake field is

$$E_{max} = \sqrt{2}\,\frac{mc\omega_p}{e}\,\gamma^{1/2}$$

For the case when

$$\gamma_b \gg \frac{n_b^2}{n_0^2}\left(1-2\,\frac{n_b}{n_0}\right)^{-1} \gg 1,\ \frac{n_b}{n_0} \le \frac{1}{2}\ ,\ d = 2\,\frac{v_b}{\omega_p}\frac{n_b}{n_0}\left(1-2\,\frac{n_b}{n_0}\right)^{-1/2} \qquad (2)$$

the maximum of the field is

$$E_{max} = \sqrt{2}\,\frac{mc\omega_p}{e}\left(\frac{n_b}{n_0}\right)^{1/2}\left(1-2\frac{n_b}{n_0}\right)^{-1/4}$$

In both cases (1,2) the deaccelerating electric field inside the bunch is of the order of $mc\omega_p/e$, and therefore the transformation ratio could be sufficiently high along with a high value of the acceleration rate.

The above mentioned results follow from the exact solution of the equations of magnetic hydrodynamics for bunches which are infinite in transverse directions. The results for cylindrical bunches with a finite radius a show, that the conditions for the fullfilment of the above mentioned results are the following:

$$\frac{n_b}{n_0}\frac{d^2}{\lambda_p^2} \ll 1,\ \lambda = \frac{2\pi v_b}{\omega_p},\ \frac{\lambda_p^2\gamma_b^2}{a^2}\frac{n_b}{n_0} \ll 1,$$

$$\frac{n_b}{n_0}\frac{r^2}{a^2} \ll 1,\ 0 \le r \le a\ ;$$

For $n_b/n_0 \ll 1$ the influence of ion motion is not essential, but for $n_b/n_0 \le 1/2$ a restriction, namely – $\gamma_b < 1/2(M_i/Zm_e)^{1/4}$ exists where $M_i$ is the ion mass.

The Yerevan group has taken into account in a selfconsistent way the inverse action of the beam and plasma electron fields on the longitudinal density and momentum distributions in the electron bunch. It is assumed that some quasistationary state of the plasma-beam system arises for a while after the injection of the electron bunch into the plasma, when the energy exchange between the bunch and plasma electrons is practically negligible[10]. In this situation the velocity of the bunch front (at z = d) is assumed to be fixed and exceeds the phase velocity of the excited quasistationary longitudinal wave. Then in the extreme relativistic case the longitudinal distribution of the bunch electrons is practically not changed, but in the momentum distribution at the end of the bunch (at z = 0) one finds accelerated electrons. For case (1) we have for the dimensionless momentum

$$\rho_b(0) \equiv P_z(0)/mc = \rho_b(d) + 4\gamma_b^3,\quad \rho_b(d) \equiv P_z(d)/mc$$

and for case (2)

$$\rho_b(0) \approx \rho_b(d) + 2\gamma_b^2\left(1-2\frac{n_b}{n_0}\right)^{-1}; \quad \gamma_b \ge \gamma_{ph} \gg 1 ;$$

For the case which is nearest to existing laboratory conditions

$$\frac{n_b}{n_0} \ll 1,\ \gamma_b \gg 1,\ d = \frac{\pi v_b}{2\omega_p},\ \rho_b(0) \approx \rho_b(d) + 2\frac{n_b}{n_0}\gamma_b^2 ;$$

The relations, which define the phase velocity and wave vector of the wake through $\gamma_b$, $n_b/n_0$, d and $\omega_p$ are derived (dispersion relation).

The increase of the momentum of bunch electron inside the plasma follows from conservation of the Hamiltonian and the decrease of the potential energy of electrons at the rear part of the bunch. This decrease is due to the motionless ion excess at the end of the bunch. Consideration of ion motion , gives the same restrictions as for the previous. Results obtained show the possible longitudinal contraction of the beam.

For example if $n_b/n_0 = 10^{-3}$, $n_0 = 10^{13}cm^{-3}$, $\gamma_b = 10^4$, d = 3mm the maximal energy at the end of the bunch approaches the value ~ 100GeV, and the number of accelerated particles is ~3 $10^8$ when the cross section of the bunch is $1cm^2$. When $\gamma_b = 10$ in this example the distance needed for noticeable contraction of the bunch is a few meters long.

For the experimental investigation of various schemes of wake field generation in passive and active structures and demonstration of the effects of self-acceleration of the electron beams in plasma a linac is under construction at YPI with the following parameters: energy - 30MeV(50MeV at half the current), pulse current - 1.0 - 1.5A, pulse duration - 8 $10^{-6}$sec, bunch duration - 3.6 $10^{-11}$ sec, repetition rate - 50 - 100Hz, particle density in a bunch - (2.2 - 3.3)$10^9cm^3$, bunch length - 0.5 - 1.0cm, bunch diameter - 0.5 - 0.7cm, average power - 30 - 45KW. The new linac will have also a beam monochromatization system.

## INVERSE FREE ELECTRON LASER(IFEL)

The accelerators based on IFEL may become in the future a promising source of intense electron beams with energies up to hundreds of GeV.

Having in mind this final goal, experiments were carried out at YPI to observe laser acceleration in undulators and for elaboration of experience for future developments. The first experimental results were delivered at the previous conference[11]. A 8MeV microtron 10MW $CO_2$ laser, undulator with period 5.25mm, 20cm length and magnetic field up to 1KOe were used. Later on the energy of the microtron was increased up to 12MeV and the laser power was doubled. The results[12] with the new arrangement are presented in Fig. 1, where the maximum change of electron energy is given as a function of the undulator magnetic field H. The curve shows the standard interaction function F(H) of electrons and the laser wave.

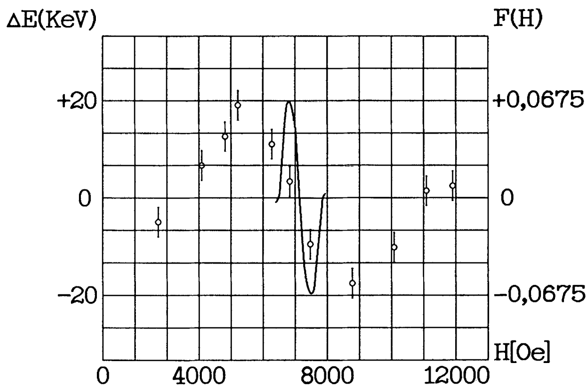


Fig. 1

At present the collaboration YPI - Troitsk branch of Kurchatov Institute has assembled a new experimental setup at Yerevan where a 5GW $CO_2$ laser, developed at the Kurchatov Institute is used. Now the measurements are underway, and an acceleration rate up to ~ 30 MeV/m is expected.

At the next stage it is planned to construct the prototype of the IFEL-accelerator with electron energy up to 1GeV, and current up to 1KA. To this end,as the estimates show, ~ $10^{13}$W laser power will be needed.

A more detailed description of the ideas and results presented in this talk are given in a recent review[8].

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