ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
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THE METHOD OF AN INTENSE ELECTRON BEAM MODULATION

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НОВОСИБИРСК

Some techniques for modulation of intense relativistic electron beam (IREB) are described in the papers [1-5]. For the frequencies of about 1 GHz or higher these techniques are based on the usage of self-electric field of the beam. The beam passes through the drift tube with coaxial cavities and the induced electric field produces a coherent bunches of electrons. The limitation of such an approach is that the beam current can not exceed the space-charge limit.

In the present paper we suggest the method of IREB modulation which does not use the beam space charge effect and consequently has not this limitation. In the approach presented only self-magnetic field of the beam is used, whereas the beam space charge in the drift region is assumed to be neutralized.

The principle of this modulation technique is shown schematically at Fig.1. An annular electron beam with small angular spread is generated in a guiding magnetic field. The beam passes through the narrow coaxial slot in a thick anode into the drift region, where the toroid foil unit is installed. This foil unit consists of an inner and outer coaxial conducting tubes and connected by two thin conducting foils. The radius of the inner tube is just slightly less than the beam radius. The foil unit may be considered as a short-circuited secondary winding of a pulse transformer ~~in~~ which the beam is used as a primary winding. If the decay time of the current (dependent on the circuit inductance and conductivity) is much more than the beam duration, the current induced in the foils will be determined by the magnetic flux conservation law. This condition, in accordance to the estimates done, can be easily fulfilled. As a result, the induced current I_f is given by:

$$I_f = -I \frac{\ln(\frac{R_f}{R_b})}{\ln(\frac{R_f}{r_f})} \qquad (1)$$

where I - current of injected beam, R_b - beam radius, R_f and r_f - outer and inner tube

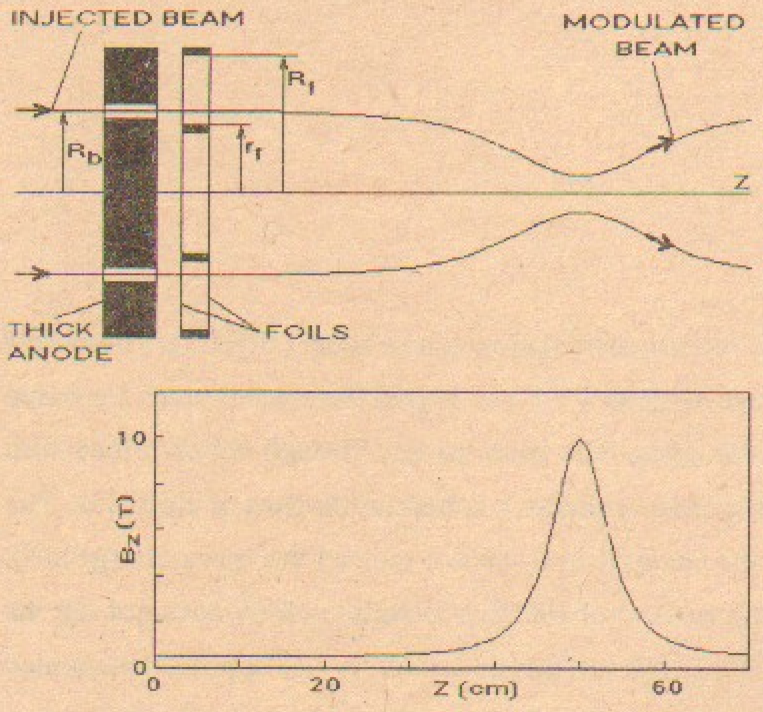

Fig.1 The scheme of the beam modulation technique. R_b - beam radius, R_f and r_f - outer and inner foil unit radii. At the bottom - magnetic field distribution.

radii, respectively. The minus sign means that the current in the inner tube is directed opposite to the beam current.

This current is directed radially along the foils. It causes the sharp change in the azimuthal component B_φ of the magnetic field. As a result, all the beam electrons get a pitch-angle $\varphi(r) = \frac{\delta B_\varphi(r)}{B_z}$ when they passe through the foil. If the beam thickness δr is much less than its radius R_b, this additional pitch-angle is practically the same for all the beam electrons $(\frac{\delta\varphi}{\varphi} \approx \frac{\delta r}{R_b} << 1)$. If the distance between foils is equal to the half of larmor helicoid step in the guiding magnetic field, then the pitch-angles obtained at the both foils add up to give the resultant pitch-angle [6]:

$$\varphi_S = \frac{4I_f}{cR_bB_z} \tag{2}$$

After the foil unit the beam propagates in the mirror magnetic field. If the mirror ratio $M = \frac{B_0}{B_m}$ is large enough $(M > \frac{1}{\sin^2(\varphi_S)})$, all the beam electrons should be reflected from the magnetic mirror. After the time delay $t \approx \frac{2L}{c}$ (L - distance between the foil unit and the point of reflection) the electrons pass through the foil unit in the opposite direction. It causes the total current of electrons through the foil unit became equal to zero. As a result the current induced in the foils falls down to zero too. After this moment, the injected beam electrons do not obtain additional pitch-angle and will freely pass through the mirror. It will last until all the reflected electrons passed through the foils. Then the induced current in the foils will be determined only by the injected beam and the electrons will obtain pitch-angles again. Then, in the same way, the process will recur and as a result the current behind the magnetic mirror

becomes modulated.

There are some effects which can disturb this ideal sequence outlined above. First of all it is the reentering of reflected electrons into the diode, that can affect beam generation and modulation. To decrease this effect the thick anode (with thickness more than step of larmor helix) with narrow coaxial slot can be used. Similar anode configuration has been used before in the virtual cathode microwave generator - reditron [7,8], where it effectively suppressed the electron reentering into the diode. In our case the transverse velocities of reflected electrons are large and in the analysis performed we assumed that all the reflected electrons are absorbed in the anode.

Another factor which determines the possibility of modulation is the angular spread of beam electrons. To study the influence of magnetic field configuration and beam angular spread on the possibility of beam modulation, we made computer simulation using a model of macro-particles. In the transport region the equations of motion in the mirror magnetic field have been solved. Longitudinal velocity have been determined using the energy conservation law and transverse adiabatic invariant $\frac{p^2}{B(z)}$. The space charge was assumed to be totally neutralized and the beam self magnetic field - to be small in respect with the guiding magnetic field.

When particles passe through the foil unit, the induced current is calculated according to (1). The change rate of the induced current is determined by some model coefficient of relaxation so that current rise time exceeds the electron pass time through the foil unit. Angular distribution of the injected beam is taken as Gaussian:

$$f(\theta) = const \exp\left(-\frac{\sin^2(\theta)}{\sin^2(\delta\theta)}\right) \tag{3}$$

For each particle passed through the foil with induced current I_f the 3-D equations were solved to find the resulting angular distribution.

The simulitions have been carried out for the magnetic field configuration shown in Fig.1. The electron energy is 2 MeV, injected beam current $I_0 = 20 - 50$ kA, beam radius 6 cm, inner and outer tube radius 5 cm and 10 cm respectively. Injected beam current increased in time as

$I = I_0 (1 - \exp(-\frac{t}{\tau}))$, where rise time τ was changed in a wide range.

The angular spread of the beam has an effect on the modulation due to the time of electron motion dependence on the pitch-angle. The longitudinal velocity of electrons and the point of reflection both depend on the pitch-angle. Pass time between the foil unit and reflection point is given by:

$$T(\theta) = \frac{1}{\beta c} \int_{z_0}^{z_m} \frac{dz}{(1 - \frac{B(z)}{B(z_0)} \sin^2\theta)^{0.5}} \quad (4)$$

Here z_0 - foil unit position, z_m - reflection point, $\theta = \theta(z_0)$, βc - module of electron velocity.

The magnetic field configuration have been chosen so that the pass time $T(\theta)$ depends slightly on the pitch-angle in the vicinity of operation angle φ_s. This dependence for magnetic field used in simulations is shown in Fig.2. The angular spread of 0.1 rad for the operating pitch-angle $\varphi_s = 0.35$ rad leads to 2% spread in the pass time.

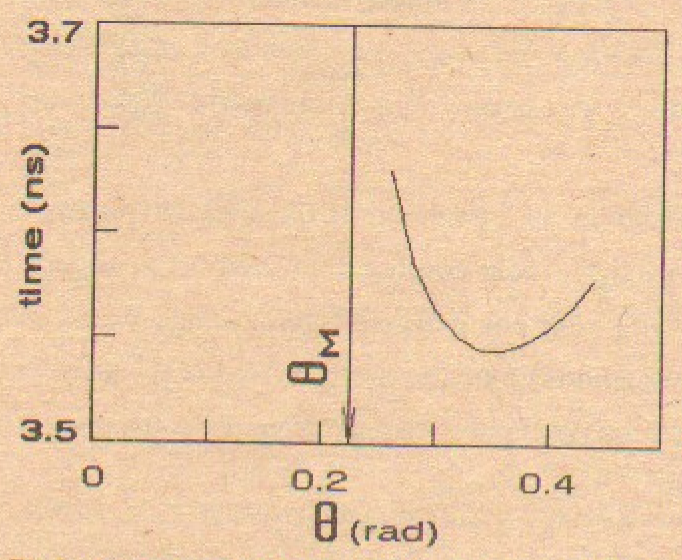

Fig.2 Motion time between the foil unit and reflection point versus the initial pitch-angle. θ_m is the loose cone angle.

The time history of the currents passed through the mirror and induced in the foils are shown in Fig 3. The current rise time τ was changed from 5 ns to 50 ns, angular spread from 0.05 to 0.3 rad. The value of injected current $I_0 = 35$ kA gives the operating pitch-angle φ_s corresponding to the minimum of the $T(\theta)$ dependence curve (Fig.2).

For the large angular spread the current modulation doesn't occur, but some equilibrium solution can be obtained (Fig.3a) for arbitrary rise time τ. The reason is that the large part of the beam electrons is reflected from the mirror even if the induced current in the foils is equal to zero. For the small angular spread ($\delta\theta << \theta_m = arcsin(\sqrt{M})$) such an equilibrium solution with constant current through the mirror also can exist. But in this case the solution is unstable and after a short time a 100% current modulation occurs (Fig.3b). The beam modulation appears even for the slow rise time of injected beam.

The influence of operating pitch-angle position on the $T(\theta)$ dependence has been tested by changing the injected beam current for fixed angular spread (0.1 rad) and rise time τ (5ns).

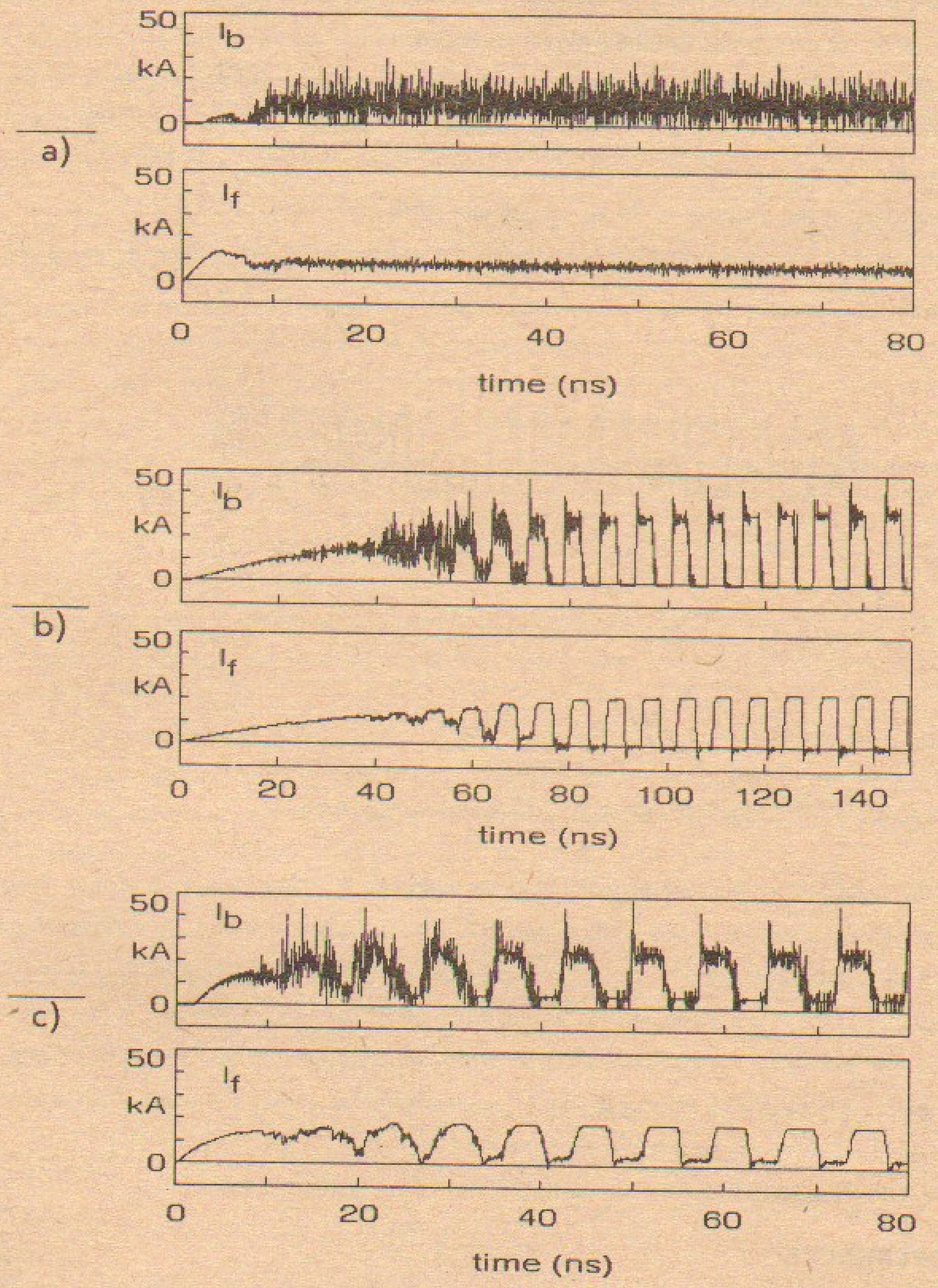

Fig.3 The time history of the currents passed through the mirror (I_b) and induced in the foils (I_f).
a) $I_0 = 35kA$, $\delta\theta = 0.3rad$, $\tau = 5ns.$,
b) $I_0 = 35kA$, $\delta\theta = 0.1rad$, $\tau = 50ns.$,
c) $I_0 = 25kA$, $\delta\theta = 0.1rad$, $\tau = 5ns.$

The beam modulation occurs in a wide range of the currents, but if the pitch-angle becomes close to the loose cone angle θ_m, the modulation becomes only partial (Fig.3c).

For the tested system configuration the modulation frequency (140 MHz) is rather small. To increase the frequency it is possible to change the distance between the foil unit and magnetic mirror and to make some changes in magnetic field configuration. In Fig.4 the results of simulations for the distance about 10 cm and modulation frequency 0.5 GHz are shown.

In conclusion, the performed analysis shows the existence of wide range of conditions where the suggested scheme can provide the beam modulation. This gives one the opportunity to carry out an experimental test of this approach. The main problem that have to be solved for such an experiment, is the beam space charge neutralization. Notice meanwhile, that beam transport with total space charge neutralization and without induced plasma current have been realized, for example, in [9]. Requirements to the beam angular spread seems to be quite reasonable. As for the foils heating by the beam electrons and induced current, it should not have a dramatic effect on such a test experiment.

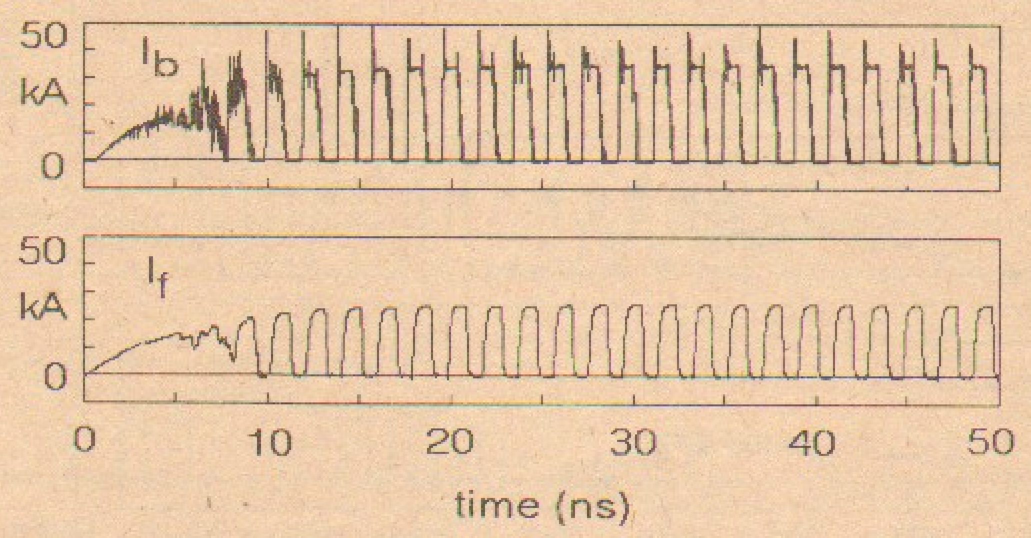

Fig.4 Beam modulation at the short system. $I_0 = 35kA$, $\delta\theta = 0.1 rad.$, $\tau = 5ns$.

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для модуляции тока сильноточного РЭП

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