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ЕРЕВАНСКИЙ ФИЗИЧЕСКИЙ ИНСТИТУТ
YEREVAN PHYSICS INSTITUTE

V.M.TSAKANOV

CHARGED PARTICLE ACCELERATION IN FIELDS INDUCED BY HEAVY-CURRENT RELATIVISTIC BUNCH IN ELLIPTICAL CAVITY

ЦНИИатоминформ
ЕРЕВАН—1988

Նախնատիպ ԵՖԻ-1039/2/-88

Վ.Մ. ՑԱԿԱՆՈՎ

ԼԻՑՔԱՎՈՐՎԱԾ ՄԱՍՆԻԿՆԵՐԻ ԱՐԱԳԱՑՈՒՄԸ ԷԼԻՊՍԱՁԵՎ ՌԵԶՈՆԱՏՈՐՈՒՄ ՄԵԾ ՀՈՍԱՆՔԻ ՌԵԼՅԱՏԻՎԻՍՏԱԿԱՆ ԹԱՆՁՐՈՒԿՈՎ ԳՐԳՌՎԱԾ ԴԱՇՏԵՐՈՒՄ

Աշխատանքում ուսումնասիրվում է էլիպսաձև ռեզոնատորում ինտենսիվ ռելյատիվիստական թանձրուկով գրգռված դաշտերում լիցքավորված մասնիկների արագացման հնարավորությունը: Ցույց է տրված, որ էլիպսի կիզակետերից մեկի երկայնքով գլխավոր թանձրուկի անցնելու ժամանակ արագացված մասնիկների առավելագույն աճը իրականանում է էլիպսի երկրորդ կիզակետի երկայնքով: Հաշվված է էներգիայի կորստի կախվածությունը էլիպսի երկու կիզակետերի երկայնքով, որը հնարավորություն է տալիս որոշել արագացվելիք լիցքի ռեզոնատոր մտնելու ժամանակը: Հաշվարկում օգտագործվել է ռեզոնատորի սեփական մոդերի վերլուծման եղանակը: Գնահատված է մոդերի անհրաժեշտ քանակը, որի հաշվառումը տալիս է ստույգ արդյունք: Գլխավոր թանձրուկում մասնիկների 10^{13} թվի դեպքում արագացման տեմպը կազմել է մոտ 190 ՄէՎ/մ: Ցույց է տրված, որ արագացման քննարկված սխեմայի փոխակերպման գործակիցը չի գերազանցում 1,5-ից:

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V.M. TSAKANOV

CHARGED PARTICLE ACCELERATION IN FIELDS INDUCED BY HEAVY-CURRENT RELATIVISTIC BUNCH IN ELLIPTICAL CAVITY

A possibility of acceleration of charged particles in fields excited by intense relativistic bunch in an elliptical cavity is studied. It is shown that at arrival of the driving bunch along one focus of the ellipse the maximal energy gain of the accelerated particle takes place along the other focus of the ellipse. The energy loss function along both focuses is calibrated, which makes it possible to find the time of arrival of accelerated charge into the cavity. The method of expansion in cavity eigenmodes has been used in the calculation. A necessary number of modes was estimated, the account of which yields the most reliable result. At the number of particles 10^{13} in the driving bunch the acceleration rate made up about 190 MeV/m. It is shown that for the considered acceleration scheme the transformation ratio does not exceed 1.5.

Yerevan Physics Institute

Yerevan 1988

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В.М.ЦАКАНОВ

УСКОРЕНИЕ ЗАРЯЖЕННЫХ ЧАСТИЦ В ПОЛЯХ, ВОЗБУЖДАЕМЫХ СИЛЬНОТОЧНЫМ РЕЛЯТИВИСТСКИМ СГУСТКОМ В ЭЛЛИПТИЧЕСКОМ РЕЗОНАТОРЕ

В работе исследуется возможность ускорения заряженных частиц в полях, возбуждаемых интенсивным релятивистским сгустком в эллиптическом резонаторе. Показано, что при влете ведущего сгустка вдоль одного из фокусов эллипса, максимальный прирост энергии ускоряемой частицы осуществляется вдоль второго фокуса эллипса. Рассчитана функция потерь энергии вдоль обоих фокусов эллипса, что позволяет определить время влета ускоряемого заряда в резонатор. При расчете был использован метод разложения по собственным модам резонатора. Оценено необходимое количество мод, учет которых дает наиболее достоверный результат. При числе частиц в ведущем сгустке 10^{13} темп ускорения составил около 190 МэВ/м. Показано, что для рассматриваемой схемы ускорения коэффициент трансформации не превышает 1,5.

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through the cavity, we'll proceed from equations for the vector $\vec{A}$ and scalar Φ potentials:

$$\Delta\vec{A} - \frac{1}{c^2}\frac{\partial^2\vec{A}}{\partial t^2} + \frac{1}{c^2}\frac{\partial\nabla\Phi}{\partial t} = -\frac{4\pi}{c^2}\vec{j}\,, \qquad (3)$$

$$\Delta\Phi = 4\pi\rho\,.$$

obtained from the Maxwell equations in the Coulomb-like gauge $\nabla\cdot\vec{A} = 0$. Potentials $\vec{A}$ and Φ we'll find as usual in the form of series

$$\vec{A}(\vec{z},z,t) = \sum_n q_n(t)\vec{A}_n(\vec{z},z), \qquad (4)$$

$$\Phi(\vec{z},z,t) = \sum_n z_n(t)\Phi_n(\vec{z},z),$$

where $\vec{A}_n(\vec{z},z)$, $\Phi_n(\vec{z},z)$ are the sets of orthogonal functions dependent on coordinates only and satisfying the equations

$$\Delta\vec{A}_n + \frac{\omega_n^2}{c^2}\vec{A}_n = 0,$$

$$\Delta\Phi_n + \frac{\omega_n^2}{c^2}\Phi_n = 0, \qquad (5)$$

$$\Delta\cdot\vec{A}_n = 0.$$

with boundary conditions on cavity walls $\vec{A}_n \times \vec{n}\,\big|_S = 0$ and $\Phi_n\big|_S = 0$ (equality to zero for electric field tangential component). Having divided variables in (5) for functions $\vec{A}_n$ and Φ_n, we come to the following expressions in the general form in Cartesian coordinates:

$$A_{nkx} = \frac{\partial\psi_n}{\partial x}\sin\beta_k z\,, \qquad A_{nkz} = -\frac{\lambda_n^2}{\beta_k}\psi_n\cos\beta_k z\,, \qquad (6)$$

$$A_{nky} = \frac{\partial\psi_n}{\partial y}\sin\beta_k z\,, \qquad \Phi_{nk} = \psi_n\sin\beta_k z\,.$$

Here $\beta_\kappa = \frac{\pi\kappa}{\mathcal{D}}$ is longitudinal wave number; $\lambda_n, \Psi_n(x,y)$ are transverse eigennumbers and eigenmodes of cavity, satisfying a two-dimensional wave equation

$$\Delta\Psi_n + \lambda_n^2 \Psi_n = 0, \tag{7}$$

with a boundary condition $\Psi_n/S = 0$.

Using orthogonality of $\vec{A}_n$ and Φ_n functions for the expansion unknown coefficients, from (3) we obtain

$$\ddot{q}_n + \omega_n^2 q_n = \frac{1}{2U_n}\int\limits_V \vec{j}\cdot\vec{A}_\ell \, dV,$$

$$\tau_n(t) = \frac{1}{2T_n}\int\limits_V \rho\,\Phi_n \, dV, \tag{8}$$

where $U_n = \frac{1}{8\pi}\int\limits_V \vec{A}_n^2\, dV$, $T_n = \frac{\omega_n^2}{8\pi c^2}\int\limits_V \Phi_n^2\, dV$ are norms of functions $\vec{A}_n$ and Φ_n . Equation (8) for a point-like driving bunch $j_z = QV_z\,\delta(\vec{r}-\vec{r}')\,\delta(z - V_z t)$ has a solution

$$q_n(t) = \frac{QV_n}{2U_n\omega_n}\cdot\begin{cases} 0, & t < 0 \\ \int_0^t A_{nz}(V_z t', \vec{r}')\sin\omega_n(t-t')dt', & 0 < t < \frac{\mathcal{D}}{V_z} \\ \int_0^{\mathcal{D}/V_z} A_{nz}(V_z t', \vec{r}')\sin\omega_n(t-t')dt' & t > \mathcal{D}/V_z \end{cases} \tag{9}$$

With respect to $E_z = \sum_n (\dot{q}_n A_{nz} + \tau_n \nabla_z \Phi_n)$, the expression for the loss function of the point-like ultrarelativistic driving bunch ($V_z = c$) after integration (1) takes a rather simple form:

$$V_o(S) = -\eta(S)\sum_\ell 2P_\ell(\vec{r},\vec{r}')\cos\frac{\omega_\ell S}{c} \tag{10}$$

where $\eta(S) = 0.1/2.1$ at $S<0$ *(in front of the bunch);*
$S=0$, $S>0$ (behind the bunch), respectively, and

$$P_\ell(\vec{z},\vec{z}') = \frac{\omega_n^2\left[1-(-1)^\kappa \cos\frac{\omega_{n\kappa}\mathcal{D}}{c}\right]}{2U_n\beta_\kappa^2}\Psi_n(\vec{z})\Psi_n(\vec{z}') . \qquad (11)$$

Note that electromagnetic fields are absent in front of the bunch due to the causality principle. At finite Lorentz factor γ the excited wave passes ahead of the bunch by a quantity $\Delta S \approx \mathcal{D}/2\gamma^2$; therefore, at $\gamma \sim 100$ the ultrarelativistic approximation is quite justified.

Thus, the problem reduces to finding of transverse eigenfunctions $\Psi_n(\vec{z})$ of the elliptical cavity. The wave equation (7) *for* elliptical boundaries is studied in [9] . Its solutions represent Mathieu's functions

$$\Psi_{mn}(\xi,\eta) = \begin{cases} Ce_n(q_m,\xi)\,ce_n(q_m,\eta) & \text{even solutions} \\ Se_n(q_m,\xi)\,se_n(q_m,\eta) & \text{odd solutions}, \end{cases} \qquad (12)$$

where (ξ, η) are elliptical coordinates; $Ce_n(Se_n)$, $ce_n(se_n)$ are modified and angular Mathieu's functions; $q_{mn} = \frac{\lambda_{mn}^2}{4} C\varphi^2$ are parametric zeros $Ce_n(Se_n)$ at $\xi=\xi_o$ (boundary ellipse with eccentricity $e_o = ch^{-1}\xi_o$); $C\varphi$ is focal distance. If the driving bunch trajectory lies in the plane of the ellipse semi-major axis, then the odd modes are not excited, since they are antisymmetric relative to it.

An elliptical cavity is characterised by the presence of two chosen directions along the ellipse focuses $F_1(0,0)$, $F_2(0,\pi)$. In this case electromagnetic waves excited in one focus of the ellipse and reflected from the lateral surface are concentrated in the other focus along which the accelerated bunch may be injected. Calculations show that such division of trajectories of the driving and accelerated bunches yields a most optimal energy transfer between them.

At such division of trajectories (Fig. 1) the loss function (10) takes the form:

$$V_{F_1}(S) = -\eta(S) \sum_{\ell} 2P_\ell\, Ce_\ell^2(0)\, ce_\ell^2(0) \cos\frac{\omega_\ell S}{c} ,$$
$$V_{F_2}(S) = -\eta(S) \sum_{\ell} 2P_\ell\, Ce_\ell^2(0)\, ce_\ell(0)\, ce(\pi) \cos\frac{\omega_\ell S}{c} . \qquad (13)$$

For the distances behind the driving bunch $S < (4h^2 + \mathcal{D}^2)^{1/2} - \mathcal{D}$, where h is the nearest distance from the bunch trajectory to the lateral wall, fields do not manage to reflect from the walls and reach the driving bunch trajectory. Therefore, for such distances the field pattern on the driving bunch trajectory is to coincide with the pattern when the point-like relativistic bunch crosses two parallel planes. For this case we know an exact analytical expression for the loss function [10]. Fig. 2 shows the ratio of the loss function in the elliptic cavity to that at the bunch travelling normally to two planes with account of 500 and 1000 first excited modes. In the second case the relative error does not exceed 10 % and the spreading appears only near the bunch where the series (13) has logarithmic divergence (at $S = 0$), which also agrees with the results of [10]. Such divergence vanishes when considering extended bunches.

Consider a uniform driving bunch of duration T. For the loss function of such bunch, according to (2), we obtain

$$V_{F_1}^{-}(S) = -\sum_{\ell} \frac{2P_\ell(\vec{\tau}_{F_1}, \vec{\tau}_{F_1})}{T\omega_\ell} \sin\frac{\omega_\ell S}{c} \quad \text{inside the bunch}$$

$$V_{F_1}^{+}(S) = -\sum_{\ell} \frac{4P_\ell(\vec{\tau}_{F_1}, \vec{\tau}_{F_1})}{T\omega_\ell} \sin\frac{\omega_\ell T}{2} \cdot \cos\omega_\ell\left(\frac{S}{c} - \frac{T}{2}\right) \quad \text{behind the bunch.} \tag{14}$$

Fig. 3 shows the loss function $V(\tau)$ along both focuses with account of 1000 first excited modes. Wake-fields are excited along the first focus by a uniform bunch of electrons, 0.5 cm at length, the number of particles being 10^{13}. The cavity size is given in Fig. 1. One can see that the splashes of electromagnetic fields with alternating polarity appear in both focuses of the ellipse. The peaks are shifted along the movement direction by ~ 8 cm. For the given sizes of the cavity this approximately corresponds to the time interval required for excited in the first focus fields to reflect from the lateral surface and reach the axis of the other focus. The difference of ~ 1 cm occurs due to the longitudinal size of the cavity. Thus, the basic contribution to the loss function at such acceleration scheme comes from fields reflected from the lateral wall.

The fields reach the second focus at a distance ~ 6.4 cm. Accelerated bunch of electrons may be injected at a maximum point of $V(\tau)$ function along the second focus. Here the maximal rate of acceleration attains ~ 190 MeV/m. The peak width is 0.5-0.8 cm. At points with a negative value of loss function the opposite-sign particles (positrons) can be accelerated.

However in such acceleration scheme the transformation ratio turns out to be very low. Indeed, one can readily see from (14) that the principal excited mode yields a maximal transformation ratio equal to 2. Insofar as the trajectories of bunches are equivalent from the viewpoint of cavity excitation, then from the energy conservation law we can show that with account of all excited modes the transformation ratio for symmetric driving bunches cannot exceed 2 [11] . Fig. 4 presents the dependence of the transformation ratio of the considered acceleration scheme on the number of excited modes. Obviously, for such schemes the transformation ratio does not exceed 1.5 . High transformation ratio may be obtained when using nonstandard driving bunches [7,8] - linear, piece-linear - the obtaining of which is connected with certain difficulties. Another possibility to increase the transformation ratio may be the utilization of sequence of heavy-current bunches.

In conclusion, the author would like to express his sincere gratitude to E.M. Laziev for the posing of the problem and permanent interest in the work.

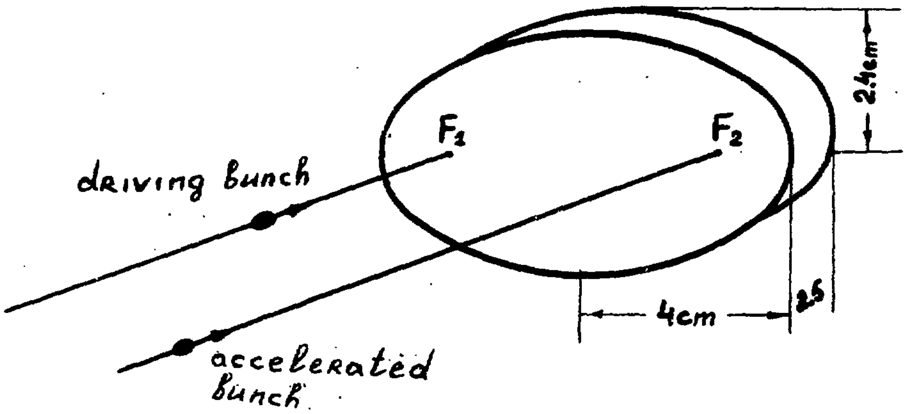
driving bunch
accelerated bunch
F1
F2
2.4cm
4cm
2.5

Fig.1

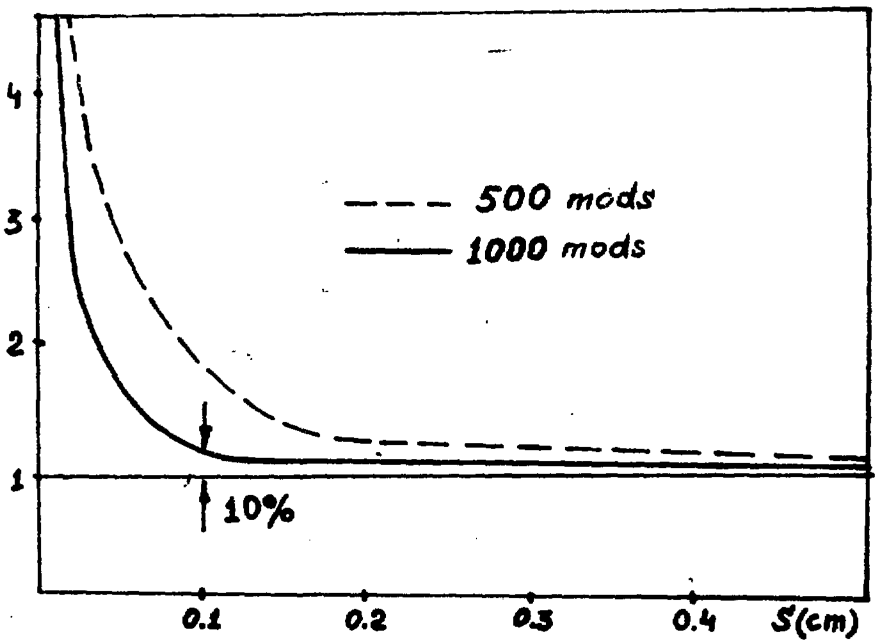
4
3
2
1
500 mods
1000 mods
10%
0.1
0.2
0.3
0.4
S(cm)

Fig.2

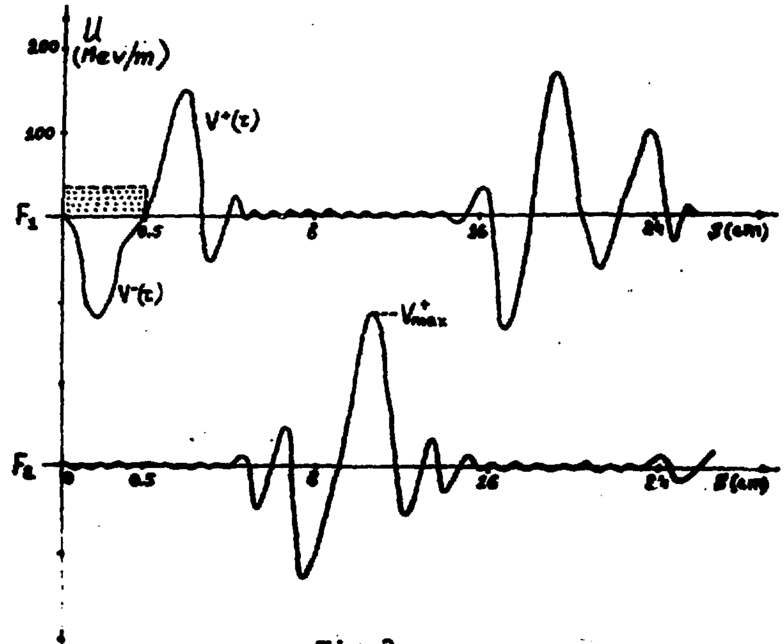

Fig.3

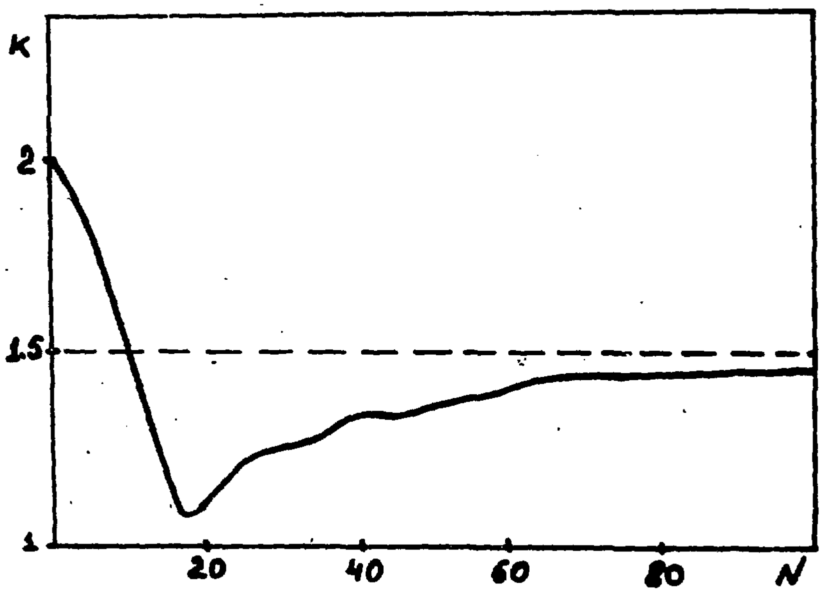

Fig.4

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