EH-UNDULATIVE SYSTEM FOR “EFFECTIVE COOLING” OF ELECTRON BEAMS

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The system for forming charged particles beams with small energy spread is proposed and studied. It is constructed on the basis of the Undulative Induction Accelerator (EH-accelerator). The obtained results of numerical modeling show that the proposed system allows to reduce the beam energy spread more than ~40 times. The mechanism of energy “equalization” of electrons during the accelerating beam is investigated. This mechanism is called the "effective cooling".
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1 INTRODUCTION

The problem of forming beams with small particle energy spread is rather "popular" and topical in various areas of vacuum electronics and acceleration technologies. The main goal of this paper is to substantiate a possibility of constructing the quasi-stationary EH-coolers on the basis of "effective cooling" effect. The linearly polarized stationary Undulative Induction Accelerators (EH-accelerators) is proposed as a technological basis for such system.

Unlike to the earlier studied analogues EH-coolers [1-3] the proposed system has a number of advantages. Firstly, it is quasi-stationary. This means that amplitudes and phases of the EH-fields are constant during the time of beam passing. Hence, the particle energy turns out to be the same as well for the first and the last bunch particles. Secondly, the proposed system is more compact and more acceptable technologically.

The project analysis shown that practical realization of the proposed system should not meet any essential difficulties because all its basic elements are well known in technologies of Linear Induction Accelerators (LINAC).

2 OPERATION PRINCIPLES

The proposed scheme of system for “effective cooling” is shown on Fig. 1 (where only one period of undulation is shown only, for simplicity). As it is mentioned above, design of this system is based on the section of a stationary linearly polarized EH-accelerator [1] (see Fig.1).

The system works in the following manner. The magnetic component of joint EH-undulative field (see item 1 in Fig.1) is generated by permanent magnetic undulator 2 in the work bulk of the EH-cooler. The vortex electrical component 6 is generated by special induction coils 4, which are situated between the magnetic poles of the magnetic undulator 2. Each these coils consist of the ferrite core and the winding. The magnetic screens are used in the system input and output for reducing influence of border magnetic fields on dynamics of the beam motion.

The basic work principles of the acceleration process had been described earlier in papers [1-3]. Therefore, let us pay our attention to the “effective cooling” mechanism only.

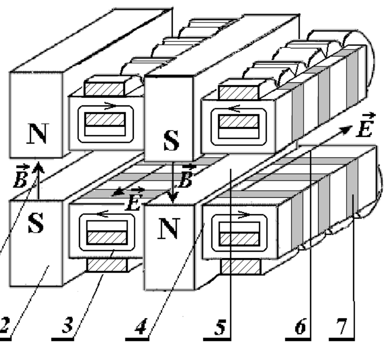

Fig. 1. Design of the stationary linearly polarized EH-cooler (only one period). There: 1 is the vector of induction of the undulative magnetic field $\vec{B}$, 2 are the poles of permanent undulator, 3 are directions of magnetic fluxes in the ferrite cores, 4 are the inductors, which consist of the ferrite cores and winding, correspondingly, 5 is the accelerating channel, 6 are vectors of intensity of the vortex electrical field $\vec{E}$.

The electron bunch moves under influence of the undulation magnetic field 1 on undulation-like trajectory. Acceleration of the electrons occurs under influence of the undulation vortex electrical field 6. Therein, it is important that different electrons with different initial energy are characterized by the different amplitudes of oscillations. Namely, the higher is electron energy the smaller is its oscillation amplitudes. This means that the electrons with higher energy move on shorter trajectories than the electrons with lower energy. Hence, the particles with lower initial energy obtain some more energy during the acceleration process than the particles with higher energy. As a result, the *energy equalization process* realizes during the electron bunch acceleration. As it is mentioned above, we referred this physical mechanism of energy equalization to as the “*effective cooling*” of electron beam in the EH-system. The system constructed on this basis is called the *EH-coolers*.

We choose for the project analysis the model, which

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is close considerably to the real EH-accelerator. The asymptotic hierarchical method (see [3]) is used as a basic mathematical tool.

The method of secondary sources and the method of magnetic streams are used for calculation of undulative magnetic and electric fields for the given geometry of the magnetic poles and the ferrite cores. The calculated parameters are shown in Table 1. The parameters of the initial (i.e., non-cooled) electron bunch are also given in this table.

As the analysis shows the two following typical peculiarities of the considered real EH-accelerative structure could be noted. The first is presence of remarkable expressed high harmonics of the EH-field. The second is generation of the longitudinal component of the EH-field. Both these features are not taken into account in the earlier studying simplified models [1-3]. As it will be shown below that the accounting these features could essentially change the project characteristics the proposed EH-cooler.

3 SINGLE-PARTICLES THEORY

Let us to expand the magnetic and electric components of the EH-field in a Fourier series. Representing the field harmonics in form $B(x)c_i$ and $B(x)b_i$ $E(x)a_i$ we get the looked for series:

$$\vec{E} = \vec{e}_x E_0(x,z)\sum_{i=1}^{\infty} a_i ch\{iky\}\sin(ikz), \quad (1)$$

$$\vec{B} = B_0(x,z)\left(\vec{e}_y \sum_{i=1}^{\infty} c_i ch\{iky\}\sin(ikz) - \right.$$

$$\left. - \vec{e}_z \sum_{i=1}^{\infty} b_i sh\{iky\}\cos(ikz)\right), \quad (2)$$

where $B_0(x,z) = Q(z)B(x)$; $E_0(x,z) = Q(z)E(x)$ are amplitudes of corresponding harmonics. The multipliers $B(x)$ and $E(x)$ take into account the possibility of changing the magnetic and electrical fields along *x*-axis. The multiplier

$$Q(z) = \frac{1}{2}\left(th\{\chi z\} - th\{\chi(z-L)\}\right), \quad (3)$$

takes into account that the fields in the input and in the output of the system decrease smoothly. Here χ is the parameter of screening.

The Lorentz equation is chosen for single- particle description of the electron dynamics in fields (1), (2). Application of the hierarchic asymptotic method allows to get the averaged system of equations and corresponding set of total solutions. The latter are expressed via these averaged values. Let's accomplish the analysis of the "effective cooling" process dynamics, using the method of large particles and the obtained solutions.

We divide the cooled beam into ten large particles. In what follows, their energy dynamics (on the normalized longitudinal coordinate $T = z/L$, where L the system length) is studied. The results of relevant calculations are shown on Fig. 2. It should be noted that because the parameters of the system don not change in time the effect of "capture" in the system is absent. In contrast, this effect essentially determines the dynamics of non-stationary versions of the EH-coolers [1-3]. Some of their specific features are mentioned above in this paper. Dynamics of the considered effect of equalization of electron energies in such stationary EH-cooler is obviously illustrated Fig. 2.

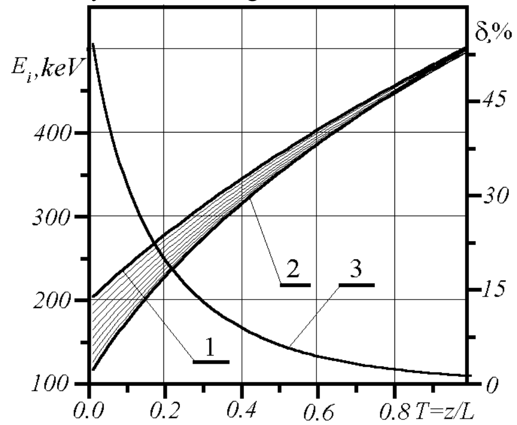

Fig. 2. Dependencies of averaged kinetic electron energy $\overline{E}_i$, and the corresponding energy spread $\delta = (\overline{E}_{max} - \overline{E}_{min})/\langle\overline{E}\rangle$ of ten large particles ($i = 1,2,...,10$) on the normalized longitudinal coordinate $T = z/L$. All particles differ from each other by initial energies only. Curves 1, 2 show maximal and minimal electron energies, accordingly, curve 3 shows the dependence of corresponding energy spread $\delta = (\overline{E}_{max} - \overline{E}_{min})/\langle\overline{E}\rangle$ on the undimensional longitudinal coordinate. All parameters are given in Table 1.

Due to the system is stationarity the electron beam velocity don not depend on the time of electron entering in the system. Therein, the maximum of "effective cooling" efficiency can be determined as

$$\left.\sqrt{\sum_{i=1}^{N}(\overline{\boldsymbol{H}}_i - <\boldsymbol{H}>)^2 /(<\boldsymbol{H}> - mc^2)}\right|_{z=L} \to \min, \quad (4)$$

i.e., the maximum of cooling we determine as the system state, when the relative energy spread is minimal. Therein, we assume that the spatial distribution of the initial bunch in the system input has a Π-type form. Analysis of the definition (4) gives an opportunity to get the expression for the optimal amplitude of intensity of the undulative electrical field:

$$E_0 = \frac{\langle \mathbf{H}_0 \rangle kcp_0 + 2kc^2 p_0^2}{4e^2 B_0 L}. \quad (5)$$

It should be pointed out that expression (5) has been obtained in the zeroth Bogolyubov approximation. This means that fast spatial electron oscillations here are not accounted. More exact analogous results can be obtained in the case, when the motion equations are integrated in following higher approximations. However, the main features, which are described by expression (5), conserve in these cases, too. For instance, the analogous calculations accomplished for the first Bogolyubov approximation give the result for E_0 which differ at 5-7 % from the (5).

Table 1. Parameters of the EH-cooler

Parameters	Magni-tudes
The general parameters of the system	
Induction of the magnetic field, *B*	180 *Gs*
Intensity of the electrical field E	1 *MV/m*
Length of the system *L*	1 *m*
Period of undulation Λ	20 c*m*
Width of the system H	40 *cm*
Distance between the magnets (Y_1)	3,5 *cm*
Sizes of the magnet poles (L_1)	3,5 *cm*
Height of the induction block H_1	5 *cm*
Parameters of electron beam in the system input	
Average energy of the beam $\langle \boldsymbol{E}_0 \rangle$	150 *keV*
Energy spread $\Delta\boldsymbol{E}$	45 *%*
Diameter of the beam d	2 *mm*
Angle of the beam divergence $\pm\alpha$	$1{,}5^{0}$
Duration of electron bunch $\Delta\tau$	$\sim 3\cdot 10^{-8}$ *c*
Parameters of electron beam in the system output	
Average energy of the beam $\langle \boldsymbol{E}_0 \rangle$	500 *keV*
Energy spread $\Delta\boldsymbol{E}$	1.07 %
Diameter of the beam d	6 *mm*
Angle of the beam divergence $\pm\alpha$	$0{,}017^{0}$

4 INHOMOGENEOUS MODEL OF THE EH-COOLER

As it is known [2] the inhomogeneous (with respect to the field amplitudes) nonstationary EH-cooling systems could be rather affective for practice. At the same time, these systems have one essential defect. Namely, the capture effect here limits the rate of electron beam acceleration and, consequently, the level of its cooling. As a result, this version of the effective cooling effect can be used practically for the cooling short bunches only. In contrast, the capture effect does not realize in the stationary EH-coolers. Hence, we might expect that the stationary system could be suitable for the cooling longer bunches. So, let us discuss the inhomogeneous stationary EH-coolers in more details.

We choose the longitudinal inhomogeneity in the following form:

$$B_y(z) = B_0 ch\left\{\frac{eE_0}{\sqrt{2}c\langle p_0\rangle} z\right\} + \frac{\sqrt{2}c^2\langle p_0\rangle}{eE_0\beta_0} sh\left\{\frac{eE_0}{\sqrt{2}c\langle p_0\rangle} z\right\},$$

where B_0 is the induction of the magnetic field for the equivalent homogeneous system, E_0 is the intensity of the vortex electrical field of the EH-system (that we, as before, consider as homogeneous one).

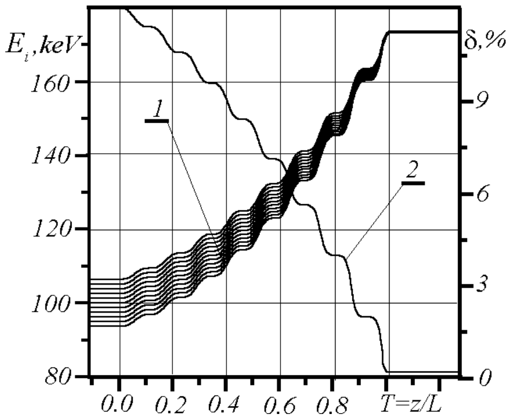

Fig. 3. Dependencies of kinetic energy for ten electrons (which differ by initial energies only - curve 1), and relative energy spread (curve 2) on the non-dimensional longitudinal coordinate $T = z / L$ for the longitudinally inhomogeneous model. Here: the intensity of the electrical field is E =190 kV/m, the period of undulation is 20 cm, the system length is 1 m.

The dynamics of the "effective cooling" process in such model is illustrated on Fig. 3. Curve 1 demonstrates the dependence of non-averaged energy E_i (first Bogolyubov approximation) for ten electrons on the longitudinal coordinate *T*. Curve 2 illustrates analogous dynamics for the relative energy spread $\delta(T)$. As it is readily seen the decreasing the initial energy spread at 75 times (from ~12% to ~0.16%) can be attained in the discussed inhomogeneous EH-cooler.

5 CONCLUSION

Thus, the performed analysis gives a hope that the proposed linearly polarized stationary EH-cooler will to solve a number of problems of forming electron beams with low energy spread. The authors consider that proposed EH-coolers could be useful for wide experimental practice.

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