UNDULATIVE INDUCTION FORMERS OF PICOSECOND ELECTRON BUNCHES

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The basic physical mechanism and the design idea of a new type of Undulative Induction Formers (UNIFs or EH-formers) of especially short intensive electron bunches are proposed and studied. The characteristic feature of the proposed EH-former is the employing of nonstationary crossed linearly polarized electrical and magnetic undulative fields (EH-fields). Namely, the EH-former turns out to be "opened" for an electron beam only during a very short (picosecond) time interval. A possibility to form rather intensive picosecond electron bunches is shown. Including, the picosecond bunches with a number of electrons in each bunch ~ $10^8 \div 10^{10}$.
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1 INTRODUCTION

The problem of forming especially short (including picosecond) intensive electron bunches with an arbitrary on-off time ratio is rather argent and topical for the modern accelerative technology. The manifested interest is determined by a necessity to observe experimentally a number of fast processes in various objects of a different physical nature [1-5]. Unfortunately, the available systems of such a type have some important drawbacks, which limit further extending their application area. Let us note two of these drawbacks especially. The first is existing limitations on the bunch density, because of the influence of the Coulomb electron repulsion mechanism. The second is requirement for the attaining large magnitudes of the on-off time ratio, including the case of single electron pulses. This drawback also is connected with the above-mentioned physical mechanism of Coulomb electron repulsion.

The new physical and design concepts are proposed in this paper for overcoming the above-noted difficulties of traditional systems. The key point of these concepts is the use of a non-stationary linearly polarized EH-accelerator section [5] as a main basic element of the picosecond former. We called the proposed system the *EH-formers*.

The proposed EH-former has a number of advantages comparing with the known analogous systems [1, 2]. Firstly, it is more compact and characterized by a simpler design. Secondly, it allows to change smoothly some key bunch parameters. Including, this gives an opportunity to adjust the bunch duration at the output. And, thirdly, this system can operate with a relatively large instant bunch current. This, in turn, opens a possibility to form bunches with a large charge density.

Two non-trivial physical mechanisms provide realization of the above-noted EH-former advantages. The first is the effect of "cutting out" of the picosecond bunch from a bunch with larger duration. A combination of two more particular effects put in the basis of the "cutting out" effect. They are the effect of electron reflection in the system input, and the capture effect in the work bulk of the EH-former [5], respectively. The second of the mentioned physical mechanisms is the effect of dynamic compression. The latter is used for compensation of the Coulomb electron repulsion in the formed bunch.

2 THE SYSTEM DESCRIPTION

The design block-scheme of the proposed picosecond EH-former is shown in Fig. 1. Here the electron gun 1 forms the nanosecond intensive electron bunches, which are directed in the input of the section of non-stationary linearly polarized EH-accelerators 2 [5]. The forming intensive picosecond punches occurs within this section. Then, the picosecond bunches enter in the acceleration section 3. Further compression (due to the compression effect) and the freezing (owing to increasing electron relativistic mass) take place there. Eventual acceleration of the formed picosecond bunches (in the case if it is necessary) is fulfilled within the accelerator 5. It is proposed to construct this accelerator accordingly with the design scheme of the honeycomb EH-accelerators [5].

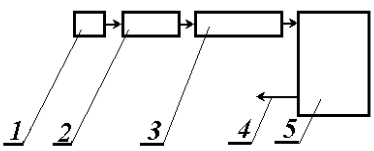

Fig. 1. Design block-scheme of the picosecond EH-former. Here: 1 is the electron gun, 2 is the section of non-stationary linearly-polarized EH-accelerators, 3 is the system for bunch compression and "freezing", 4 is the output for formed relativistic picosecond bunches, 5 is the output section of the stationary honeycomb EH-accelerator.

The design of the section of non-stationary linearly polarized EH-accelerators 2 (see Fig. 1) is shown in Fig. 2. Detail description its operation principles is given in [5]. In what follows, let us analyze the physical process in this section in more details.

The vector-potential

$$\vec{A}(y,z,t) = \vec{e}_x A(t) \sum_{j=1}^{m} \frac{a_j}{jk} ch(jky) \sin(jkz) . \quad (1)$$

is chosen for description of the forming EH-field [5]. Here k is the wave number, $A(t) a_j$ is the amplitude of j-th spatial field harmonic, e_x is the unite vector along x-axis, z is the longitudinal coordinate, t is laboratory time.

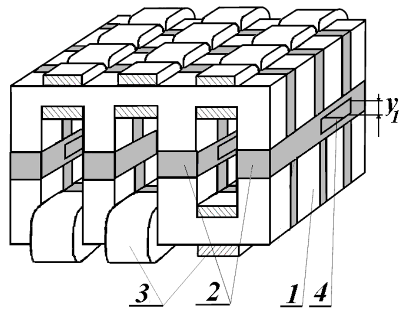

Fig. 2. Design of the picosecond electron EH-former. Here: 1 is the electromagnet poles made of some ferrite, 2 are gaps between the magnetic poles 1 filled by ceramic inserts, 3 are coils of the electromagnets, 4 are the windows in ceramic inserts made for the electron bunch passing.

Taking into account the well-known relationships $B = rot(A)$, $E = -\partial A/dt$, we can get definitions for the induction of magnetic field and the intensity of vortex electrical field, respectively:

$$\vec{B} = A(t) \cdot \left(\vec{e}_y \sum_{j=1}^{m} a_j ch\{jky\} \sin(jkz) - \right.$$

$$\left. - \vec{e}_z \sum_{j=1}^{m} a_j sh\{jky\} \cos(jkz) \right); \quad (2)$$

$$\vec{E} = \vec{e}_x E(t) \sum_{j=1}^{m} \frac{a_j}{jk} ch\{jky\} \sin(jkz) . \quad (3)$$

The generated Coulomb field within the electron bunch will be calculated using the method of large particles (the model of particle-particle interactions):

$$\vec{E}_i = \sum_{j=1}^{N} \vec{E}_{ij} = \sum_{j=1}^{N} \frac{q_j}{r_{ij}^3} \vec{r}_{ij} , \quad (4)$$

where E_{ij} is the intensity of Coulomb electrical field between some i and j particles, q_j is the j-th charge, $r_{ij} = r_i - r_j$, $r_{i,j}$ is the coordinates of i-th and j-th particles, $r_{ij} = |r_{ij}|$.

We will use the Hamilton equations for description of the particle motion in field (1):

$$\frac{dH}{dt} = \frac{\partial H}{\partial t} ; \; \frac{dP}{dt} = -\frac{\partial H}{\partial \vec{r}} ; \; \frac{dr}{dt} = \frac{\partial H}{\partial \vec{P}} , \quad (5)$$

here H is the is Hamiltonian, P is the canonical momentum.

The Bogolyubov-Zubarev method [6] is used for the finding asymptotic solution of the problem (5). The solution of equations (3) is looked for in the form $x = \bar{x} + \tilde{x}$, where $\bar{x}$ is averaged value, and $\tilde{x}$ is oscillative parts of the calculated values [6]. Calculations are done in the first approximation of the method, confining by the terms no higher the cubic (with respect to the amplitude of EH-field (1)) order.

3 ANALYTICAL ANALYSIS

Let us analyze shortly the physics of the system under consideration. The relevant calculation allows to clear up the detail scenario of the above-discussed effect of "cutting out" of the picosecond bunch from a bunch with larger duration. It is found that only those particles form the picosecond bunch, which enter in the system input at the time moment, when the magnetic field induction is approximately equal to zero. The rest of particles are reflected from the system input. Therein, part of the passed particles are further “captured” in the acceleration channel because the increasing of the magnetic field on time. As a result, the picosecond bunch is formed within the accelerative channel.

Inasmuch as the magnetic field changes during the bunch forming process the velocities of the "last" particles in the bunch are found to be somewhat higher than the particle velocities of the front part of the bunch. This phenomenon we called as the effect of inverse bunch modulation. As a result the particles of the back part of the bunch have trend to catch up the front bunch particles. As a sequence, the effect of dynamic bunch compression realizes in the system.

Let us introduce the "closing time" τ_{01} and the "opening time τ_{02} of the system input. After required calculation we obtain:

$$\tau_{01,02} = -\frac{p_0}{\sqrt{2} e E_0} \frac{1}{ch\{K_3\}} \left(1 \pm \frac{1}{\beta_0} sh\{K_3\} \right), \quad (6)$$

where $\beta_0 = v_0/c$, v_0 is the electron velocity in the system input, $.K_3 = eE_0 L / \sqrt{2} c p_0$, L is the system length, p_0 is the electron mechanical momentum in the input. The relationship (6) allows to calculate the duration of the “cut out” bunch

$$\Delta\tau_{input} = \frac{\tau_{tr}}{K_3} \frac{sh\{K_3\}}{ch\{K_3\}} , \quad (7)$$

where $\tau_{tr} = L/v_0$. It is readily seen that the vortex electric field plays an important role in the cutting out process. Let us analyze relationship (7) in the following two limited case. The first is the case $K_3 >> 1$ (case of strong electric field). After simple calculation it is easily to obtain (non-relativistic case $\beta_0 << 1$):

$$\Delta\tau_{input} \cong \tau_{tr} / K_3 \cong \sqrt{2} mc / eE_0 , \quad (8)$$

i.e., the stronger is electric field the less is duration of the “cut out” bunch in the input. The second is the case of weak electric field $K_3 << 1$:

$$\Delta\tau_{input} \cong \tau_{tr} , \quad (9)$$

in the case only if $\tau_{tr} \le \tau_{cup}$, where τ_{cup} is the capture time [5].

The compression effect could be illustrated by the dependency of the non-dimension output electron velocity β_{out} on its fly-in time in the system input τ (the Coulomb electron interactions is neglected):

$$\beta_{out}(\tau) = \sqrt{1 - \frac{1-\beta_0^2}{\left(ch\{K_3\} + K_4\sqrt{1-\beta_0^2}\cdot\tau\cdot sh\{K_3\}\right)^2}} \quad (10)$$

where $K_4 = eE_0 / \sqrt{2}mc^2$. It is readily seen that indeed, the less is the fly-in time τ the higher is the output electron velocity $c\beta_{out}$.

4 NUMERICAL ANALYSIS

In what follows, let us discuss the forming process in the dense picosecond bunches. The Coulomb interactions play important role in this case. We take they into account further. Let us use the numerical modeling of the process considered in combination with the method of large particles. Calculation of the Coulomb electric field is accomplished in accordance with the above-described scheme (see definition (4) and corresponding commentaries). The results of numerical modeling are shown in Fig. 3 and in Tab. 1.

Table 1. Results of project analysis of the EH-former

Parameters	Values
Induction of the magnetic field, *kGs*	2.65
Intensity of the vortex electrical field, *MV/m*	1.7
Period of undulation, *cm*	11
Length of the system, *m*	65
Bunch energy in the output, *keV*	240
A number of electrons in the bunch	$\sim 10^9$

The spatial distribution of the formed bunch is illustrated in Fig. 3. As it is easily seen, the proposed forming system allows to form quasi-stable bunches with a peak density ~ $2.3\cdot 10^{-8}$ mm^{-3}. The latter corresponds to number of electrons in the bunch $\sim 10^9$.

It should be mentioned that the result obtained is the best from the analogous ones, which can provide traditional picosecond formers with a large on-off time ratio. Let us illustrate this affirmation by the following example. The Department of Energy of the United States has announced at beginning of 2000 the competition (Program Solicitations, DOE/SC-0008, Section 36 "Advanced Concepts and Technology for High Energy Physics Accelerators") on developing a "relatively inexpensive" (no more expensive than $1million) system for forming picosecond bunches with a high density of charge. The required parameters of the announced system are close to the above obtained. So, the proposed EH-former could be used for successful solving the announced problem.

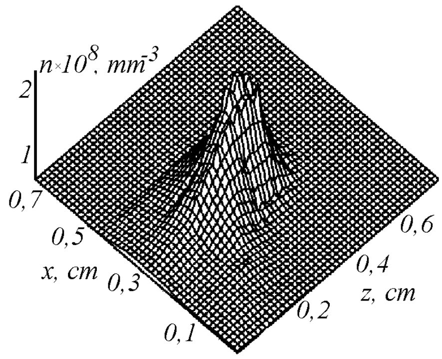

Fig. 3. Spatial distribution of the formed high-density electron bunch. Here: induction of the magnetic field is 2.65 kGs, intensity of the vortex electrical field is 1750 kV/m, period of undulation is 11 cm, length of the system is 65 cm, beam energy in the input is 100 keV, current strength of the input beam is 50 A, a number of electrons in the output bunch is ~10^9.

6 CONCLUSION

Thus, a new concept for construction of the system for forming intensive picosecond bunches with a large on-off time ratio (EH-former) is proposed and substantiated. The accomplished analysis showed that the combination of the two specific physical mechanisms forms the basis of the proposed formers. The first is the effect of "cutting out" the picosecond bunch from a bunch with larger duration. The second is the effect of dynamic compression of the formed electron bunch. The physics of both these effects is studied in this paper.

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