Abstract—We propose methods of fast cooling of an electron beam, which are based on wiggling of particles in the presence of an axial magnetic field. We use a strong dependence of the axial electron velocity on the oscillatory velocity, when the electron cyclotron frequency is close to the frequency of electron wiggling in the undulator field. The abnormal character of this dependence (when the oscillatory velocity increases with the increase of the input axial velocity) can be a basis of various methods for fast cooling of moderately-relativistic (several MeV) electron beams. Such cooling may open a way for creating a compact X-ray free-electron laser based on the stimulated scattering of a powerful laser pulse on a moderately-relativistic (several MeV) electron beam.

I. INTRODUCTION

We propose to provide cooling by using the electron wiggling in a circular polarized “cooling” undulator in the presence of an axial magnetostatic field (Fig. 1). If the bounce-frequency of electron oscillations in the undulator, \( \omega_u = \gamma \delta \gamma \), is comparable with, is compensated by the greater rotatory velocity, \( \gamma \delta \gamma \), and the non-relativistic cyclotron wavelength \( \lambda_{\text{cc}} \approx \frac{c}{\gamma \delta \gamma} \), corresponds to the axial magnetic field \( T \approx 8.10^{-3} \), \( c \) is the electron axial velocity, \( \omega_u \) is the undulator wavenumber, and \( \gamma \) is the relativistic mass factor. In this situation, the velocity of undulator oscillations \( V_u \) depends strongly on the initial axial velocity.

Let us consider radiation of a particle, which performs free cyclotron rotations in the radiation section. We suppose that this section represents a wave guide, and the cyclotron radiation does not perturb the axial electron velocity. Thus, from the viewpoint of the uncompensated spread, the single-stage radiation scheme has no advantages compared to the non-radiative scheme. However, the important advantage of the radiation scheme is that the rotational velocity is absent at the output. Therefore, a further decrease in the spread can be provided by organizing the downstream second cooling section (Fig. 2).

Figure 1 a and b: Schematics of non-radiative cyclotron-undulator cooling systems with the operating FEL undulator placed inside and outside of the cooling system. c: Electron motion in the circular polarized undulator with the uniform axial field. d: Characteristic dependence of the undulator velocity on the axial electron velocity (the optimal range is shown schematically).

II. NON-RADIATIVE “AXIAL” COOLING

Non-radiative “axial” cooling is based on the fact that the axial velocity spread is the only factor important for the FEL operation. This spread can be decreased due to its “transformation” into the spread in the velocity of electron rotation in the cooling system. Electrons move along axial magnetic field and enter the cooling undulator with the “transformation” into the spread in the velocity of electron rotation in the cooling system. The spread in axial velocity can be decreased down to \( \lambda_{\text{cc}} \approx 10^{-3} \gamma c \). In this situation, the cyclotron radiation does not perturb the axial electron velocity. Thus, from the viewpoint of the uncompensated spread, the single-stage radiation scheme has no advantages compared to the non-radiative scheme. However, the important advantage of the radiation scheme is that the rotational velocity is absent at the output. Therefore, a further decrease in the spread can be provided by organizing the downstream second cooling section (Fig. 2).

Figure 2: Schematic of the two-stage cooling system with cyclotron radiation sections and electron wave dispersion characteristics in the radiation sections.

IV. UBITRON RADIATION COOLING

The abnormal dispersion of the undulator velocity of electrons, \( \varepsilon V_u \sim |\varepsilon V_u| > 0 \), can be used to provide also a cooling method based on the ubitron radiation of electrons inside the regular part of the undulator with guiding axial magnetic field (Fig. 3). In this situation, electrons with higher initial energies have bigger undulator velocities and, therefore, lose more energy due to the radiation.

Figure 3: Ubitron radiation cooling system.

V. RF UNDULATOR COOLING

Finally, we discuss the possibilities to use cyclotron-undulator cooling schemes for electron bunches with higher energies. Since in the case of a magnetostatic cooling undulator the non-relativistic cyclotron wavelength is estimated as \( \lambda_{\text{cc}} \approx \frac{c}{\gamma \delta \gamma} \), an increase in the electron gamma-factor results in an increase of the axial magnetic field required. However, for high-energy electrons, instead of the magnetostatic cooling undulator, one can use an rf undulator (a powerful rf pulse), which co-propagates together with the bunch (Fig. 4). In this case, the condition of closeness of the cyclotron and undulator frequencies \( \Omega_a \approx \gamma c/\lambda_{\text{cc}} \), which is an optimal condition for the cooling, can be provided at a moderate magnetic field.

Let us consider cooling of electrons with \( \gamma > 100 \) in a rf pulse with \( \lambda_{\text{cc}} = 3 \) cm (Fig. 4). A super-radiant GW-power-level Cherenkov backward-wave oscillator can be used as the source. If this pulse is formed by the TE11 transverse mode of a waveguide, with the radius \( \rho = \lambda_{\text{cc}} \), then the group velocity of the electron wave front is close to the speed of light, \( \beta_g \approx 1 \), the optimal conditions for the cooling can be provided at a moderate magnetic field.

Figure 4: Schematic of the cooling system based on a short powerful rf pulse co-propagating with the e-bunch.

Figure 5: Schematic of the two-stage cooling system with cyclotron radiation sections and electron wave dispersion characteristics in the radiation sections.