Cyclotron-Undulator Cooling of a Free-Electron-Laser Beam

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Abstract— **We propose methods of fast cooling of an electron beam, which are based on wiggling of particles in an undulator 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 the use of 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, $\Omega_u = V_{\parallel} h_u$ is comparable with the electron cyclotron frequency, $\Omega_c = eB_0/\gamma mc$ (here $V_{\parallel}$ is the electron axial velocity, h_u is the undulator wavenumber, and γ is the relativistic mass factor). In this situation, the velocity of undulator oscillations V_u depends strongly on the initial axial velocity.

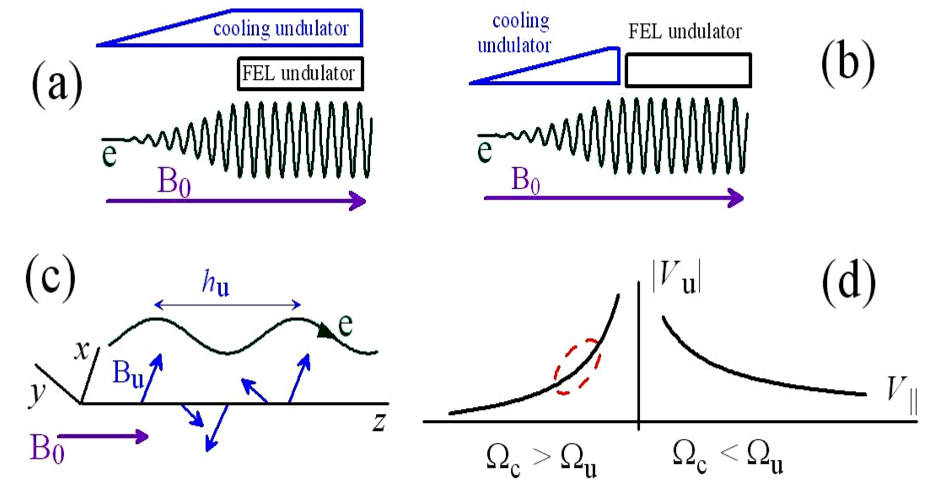

Figure 1 a and b: Schematics of non-radiative cyclotron-undulator cooling systems with the operating FEL undulator placed inside and outside of the cooling system. c: Electron motion in the circular polarized undulator with the uniform axial field. d: Characteristic dependence of the undulator velocity 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 adiabatically growing field in the input section, where each electron gets its own rotatory velocity (Fig. 1a). If at the input of the system every particle possesses only the axial velocity $V_0 = \bar{V} + \delta V$, then the axial velocity in the regular region of the undulator is determined by the energy conservation law: $V_{\parallel}^2 \approx V_0^2 - V_u^2$. Thus,

$$V_{\parallel}^2 \approx \bar{V}^2 + 2\bar{V}\delta V - V_u^2(\bar{V}) - \alpha\delta V \ , \quad \alpha = \partial V_u^2 / \partial V_{\parallel} \ .$$

If $\alpha = 2\bar{V}$, then the spread in $V_{\parallel}$ disappears. This condition is independent of the initial spread, δV. Evidently, we should use the range of parameters, where $\partial |V_u| / \partial V_{\parallel} > 0$ (Fig. 1 d), so that the initial axial velocity excess, δV, is compensated by the greater rotatory velocity, V_u. If such a cooling system is used in a FEL, then the operating FEL undulator designed to produce optical radiation can be placed inside the regular section of the cooling undulator (Fig. 1 a). Another way is to "switch off" the field of the cooling "undulator" sharply (Fig. 1 b). Then, forced undulator oscillations of the particles are just transformed into free cyclotron oscillations possessing the same rotatory velocities, $V_{\perp} = V_u$ (and, therefore, the same axial velocities).

Let us consider a 5 MeV electron bunch with the parameters typical for modern photo-injectors: axial velocity spread $\delta\gamma_{\parallel}/\gamma_{\parallel} = 10^{-2}$, normalized emittance $\varepsilon \approx \pi$ mm mrad, and the bunch radius $r_e \sim 1$ mm. In the case of a cooling undulator with $\lambda_u = 5$ cm, $K = 0.2$ and with the adiabatically tapered entrance, in the regular section of the cooling undulator the spread in axial electron velocity can be decreased down to $\delta\gamma_{\parallel}/\gamma_{\parallel} = 10^{-3}$ or even less. According to simulations, the undulator length should amount tens cm. In this case, the non-relativistic cyclotron wavelength $\lambda_c = 2\pi c/(\gamma\Omega_c) \approx \lambda_u/\gamma = 5$ mm corresponds to the axial magnetic field $B_0 \approx 2$ T

III. Cycloyron Radiation Cooling

A disadvantage of the non-radiative "axial" cooling is that the operating undulator of the FEL should be placed inside the cooling system. Moreover, the uncompensated axial velocity spread is limited by the transverse velocity spread. Since the cooling system does not remove the transverse spread, it is impossible to improve axial cooling by the use of the additional second stage of the cooling system. An alternative method of cooling, namely, cyclotron radiation cooling, might be more attractive. In this case, the cooling system consists of two sections (Fig. 2), namely, the undulator section with the adiabatically tapered entrance, and the cyclotron radiation section (the region of the uniform magnetic field). The non-adiabatic exit of electrons from the undulator section is accompanied with transformation of the forced oscillations into the free cyclotron oscillations with the same oscillatory velocity. Then, in the radiation section, electrons lose their transverse momentums due to the cyclotron radiation. Optimally, at the output of the cooling system, electrons possess only the 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 waveguide, and the cyclotron resonance condition, $\omega = \Omega_c + k_{\parallel} V_{\parallel}$, is fulfilled for the lowest transverse mode in the so-called grazing regime, when the wave group velocity, $V_{gr} = c^2 k_{\parallel}/\omega$, coincides approximately with the axial electron velocity (Fig. 2).

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 as compared to the non-radiative scheme. However, the important advantage of the radiation scheme is that the rotatory 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).

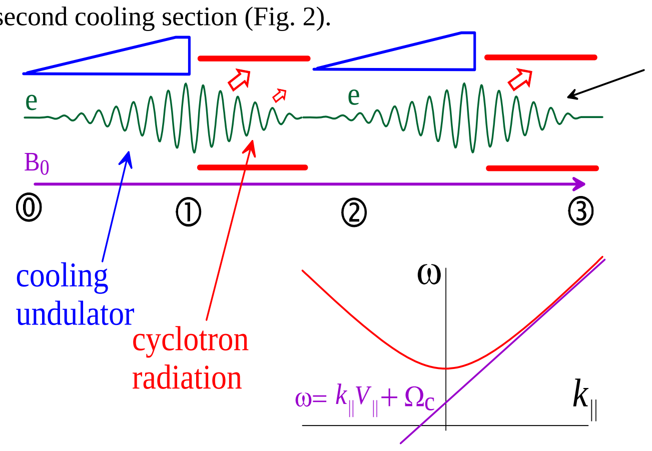

Figure 2: Schematic of the two-stage cooling system with cyclotron radiation sections, and electron-wave dispersion characteristics in the radiation sections.

IV. Ubitron Radiation Cooling

The abnormal dispersion of the undulator velocity of electrons, $\partial |V_u| / \partial V_{\parallel} > 0$, 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.

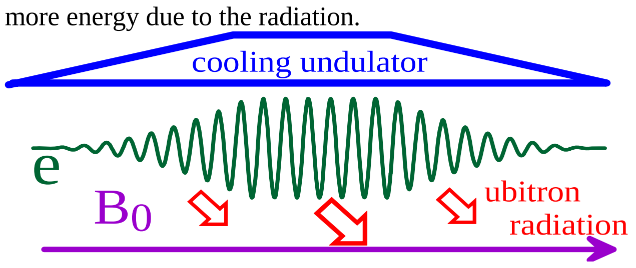

Figure 3: Ubitron radiation cooling system.

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 $\lambda_c \sim \lambda_u/\gamma$, 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

$$\Omega_c \sim \omega_u - k_{\parallel u} V_{\parallel} \approx \omega_u (1 - \beta_{gr,u}\beta_e) \ ,$$

leads to the following estimation: $\lambda_c \sim \lambda_u / \gamma(1 - \beta_{gr,u}\beta_e)$. If the group velocity of the undulator wave is close to the speed of light, $\beta_{gr,u} \to 1$, the optimal conditions 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 $\lambda_u = 3$ 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 $TE_{1,1}$ transverse mode of a waveguide with the radius $R \approx \lambda_u$, then $\beta_{gr} \approx 0.95$, and the non-relativistic cyclotron wavelength $\lambda_c \approx \lambda_u / 5 = 0.6$ cm corresponds to the axial magnetic field $B_0 \approx 1.8$ T. In this case, the rf pulse power $P_u = 0.5$ GW corresponds to the undulator parameter $K = 0.25$, whereas the rf pulse duration of 0.5 ns corresponds to the cooling system length of about 3 m only.

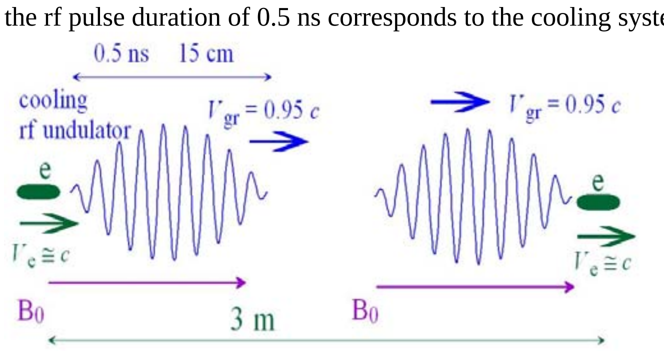

Figure 4: Schematic of the cooling system based on a short powerful rf pulse co-propagating with the e-bunch.