A NEW POSSIBILITY OF COHERENT MICROWAVE RADIATION BY RELATIVISTIC PARTICLES

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Many scientists are interested nowadays in the problem of high power sharp-directed microwave radiation production. It is generally admitted that submillimeter and shorter wave (up to light) range radiation may be produced by means of relativistic and ultrarelativistic electron beams provided that Doppler shift permits radiation wavelengths essentially smaller than generating system characteristic size.

Undulator-based free electron lasers (FEL) are the most promising among facilities of this type [1].

The first impressive results produced by superconducting linac in the USA [2] and electron storage rings in the USSR [3] raised hopes of a rapid and large scale implementation of such facilities. However, the further detailed theoretical consideration revealed [4] that radiation generation needed a special accelerating facility construction since low current densities and wide energy spread of now existing accelerators could not provide proper conditions for FEL generation based on such facilities. Complex is also the problem of small period (less than 1 cm) magnetic field production.

This paper shows that normally crossing constant or pulsed magnetic and electrical fields can provide the condition to start generation using the beams of already operating accelerators.

Nonrelativistic particle moving in crossing electrical E and magnetic H fields, its trajectory is known [5] to depend on the particle initial velocity to drift velocity $v_{dr} = cE/H$ relation. The same picture will also be valid in relativistic case.

In view of the possible practical application the case of small drift velocity particle movement, that is, trochoidal movement, will be of the most interest. That is exactly why such device may be called a relativistic trochotron or creditron (Crossfield Relativistic Electron Drift Interaction). Similar to undulator based FEL relativistic case radiation in the direction of drift velocity will be increased by that from the corresponding parts of circumferences shifted relatively each other; differing, however, from undulator case, the number of such trajectories, hence the efficiency, may reach a high value, the length of the device being rather small.

Let us consider the angular and spectral characteristics of such device radiation in detail.

If $\beta_{\parallel} = v_{dr}/c \ll 1$, radiation characteristics of a trochoidally moving particle will be approximately the same as those of a circumferentially moving electron [6], that is, the radiation angle $\theta = 1/\gamma$, radiation power $W = 2e^2c\gamma^4/3R^2 = 2e^2c(eH/m_o c)^2\gamma^2/3$, radiation approaching its maximum value at a frequency $\omega \cong 3\omega_o\gamma^3/2 \simeq 3eH\gamma^2/2m_o c$.

To define creditron generated oscillation spectrum it is necessary to find increments of instability development for each harmonic. The main instability for relativistic particle beams has bean shown to be [7] the radiation one, its increment at n-th harmonic being

$$\alpha_n = I_m\left[-(iN|K|n\omega_o W_n/2\mathcal{E}+n^2\omega_o K^2(\Delta\mathcal{E}/\mathcal{E})^2\right]^{1/2} =$$

$$= \omega_o\left\{\left[\left(N^2K^2n^2W_n^2/4\omega_o^2\mathcal{E}^2\right)+K^4n^4\left(\Delta\mathcal{E}/\mathcal{E}\right)^4\right]^{1/2}/2-\right.$$

$$\left.-K^2n^2\left(\Delta\mathcal{E}/\mathcal{E}\right)^2/2\right\}^{1/2} \qquad (1)$$

Energy spread of particles is taken into account. Here N is number of particles inhabiting one circumference, ω_o- revolution frequency of a particle, W_n- radiation power at n-th harmonic, $K=\frac{1}{\beta^2}\left(\frac{1}{\gamma^2}-\frac{1}{\nu_r^2}\right)$, where ν_r-

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betatron oscillation number (in case presented $\nu_r \simeq 1$), while $\gamma = \mathcal{E}/m_o c^2$-relativistic factor.

Making use of [6]

$$W_n = dW/dn \quad \text{and} \quad nW_n = ndW/dn = ydW/dy =$$

$$= \left(3^{3/2} e^2 c \gamma^4 y^2 / 4\pi R^2\right) \left[2K_{2/3}(y) - \int_y^{\infty} K_{1/3}(x) dx\right] \quad (2)$$

where $y = 2n/3\gamma^3$, $K_{1/3}$ and $K_{2/3}$-McDonald functions, the expression for α may be transformed to

$$\alpha(y) = \left(3Nr_o \gamma^3/8R\right)^{1/2} \left[\left(f^4 + \delta^4 y^4\right)^{1/2} - \delta^2 y^2\right]^{1/2} (3)$$

where $r_o = e^2/m_o c^2$ is the classical radius of electron, $\delta = \left(3\gamma^3\right)^{1/2} \left(\Delta\mathcal{E}/\mathcal{E}\right) / \left(Nr_o/R\right)^{1/2}$ and

$$f(y) = \left\{3^{1/2} y^2 \left[2K_{2/3}(y) - \int_y^{\infty} K_{1/3}(x) dx\right] / 2\pi\right\}^{1/2}$$

It is evident that the function $f(y)$ defining the increments of various harmonics at $\delta = 0$ reaches its maximum value at $y = 4/3$. This means that the maximum increment corresponds to the frequency

$$\omega = 2\gamma^3 \omega_o = 2\gamma^2 eH/m_o c$$

its wavelength being

$$\lambda = 2\pi m_o c^2 / 2\gamma^2 eH = \lambda_o / 2\gamma^2,$$

where λ_o-dipole radiation wavelength of a rotating nonrelativistic particle. This result means that with the particles moving along circumference oscillations are most probably excited with the frequency, like in the case of a relativistic particle moving along sine curve in FEL, increased, as compared to a certain characteristic frequency, by the factor of $2\gamma^2$. This fact underlines the deep community of the two movements.

The energy spread of particles differing from zero, that is $\delta \neq 0$, $\alpha(y)$ reaches its maximum value at y, defined from equation

$$f^3 \frac{\partial f}{\partial y} + \delta^4 y^3 - \delta^2 y \left(f^4 + \delta^4 y^4\right)^{1/2} = 0 \qquad (4)$$

From this expression follows that increase of δ results in $y(\alpha = \alpha_{max})$ decreasing, the latter approaching $y = 1/3$ at $\delta \Rightarrow \infty$.

Function $F(y,\delta) = \left[\left(f^4 + \delta^4 y^4\right)^{1/2} - \delta^2 y^2\right]^{1/2}$ characterizes oscillation increment dependence on y. It shows that growth of δ results in, first, increment decrease and, second, that it will be maximal at lower y value.

Besides that, if more than one bunch rotates along each of the shifted circumferences, radiation angular distribution of such a system will differ from that of a single electron, becoming sharply elongated along and against drift velocity, it will result in the growth of the part of radiated energy that will be transformed into coherent radiation energy.

The above said shows that radiation characteristics of creditron are similar to these of undulator, both devices having similar dependence of angle, power and frequency of radiation on energy. However, expressions for W and ω including magnetic field dependent factors,creditron admits sufficiently higher field strength values. This might result in rather essential differences: on one hand, radiation power of creditron increases at the same energy, and, on the other hand, that very same radiation frequency may be obtained, the energy of electrons being sufficiently less, since at the values of external magnetic field $H \geqslant$ 10 kOe the value of $\lambda_o < 1$ cm, while in undulators, due to the specificity of alternating field structure this value can never be less than some centimeters. And here is the promise of creditron.

At the same time the equation obtained implies that the energy spread requirements increase with gamma. Physically it follows from the fact that the higher the energy the higher the number of the harmonic at which radiation instability develops.

Energy spread resulting in additional particle movement in azimuthal direction and hence to partial mixing of particles originating from different bunches, that in its turn causes steep decrease of oscillation increments and coherent oscillation power generated, this spread should be diminished. Nevertheless, creditron's efficiency

$$G = \left(1/v_{dr}\right)\int_{0}^{L}\alpha dl=\alpha L/\beta_{\parallel}c=2\pi\alpha RN_{eff}/c =$$

$$= 2\pi\alpha N_{eff}/\omega_{o} \gg 1 \qquad (5)$$

even at high enough δ values (about 10 and more), where N_{eff} is the effective number of interaction periods.

This signifies that in such devices up to light range the requirements to energy spread and density of particles used might be less strict than those in undulator based FEL.

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