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Monocolor Radiation Source Based on Low-Energy Electron Beam and Dc Fields With High Gradient of Electromagnetic Energy Density

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A new route of monocolor radiation generation, which is based on the interaction of a low-energy electron with targeted designed driving DC fields, is proposed. It does not require the driving fields to be of high electromagnetic energy density. Instead, it relies on a high gradient of the electromagnetic energy density which can be achieved through reasonablly arranging components generating DC fields.

An ideal radiation source is required to be of desirable frequency spectrum (for example, the most desirable is monocolor) and high total output power. Pursuing a high total power often drive people to consider a technique route based on electron beam [1-12]. Many routes of radiation generation [1-12] hire the electron beam in different ways. For example, in free electron laser (FEL) [1,2], an electron beam interacts with a combined field of magnetic components and incident electromagnetic (EM) wave to generate radiations at new frequency components differing from the incident wave. Bremsstrahlung refers to the interaction of such a beam with 3-D ionic Coulomb potential and usually has a broad frequency spectrum [13].

The frequency spectrum has a closed relation with the properties of the field that the beam interact with. The properties include strength and space-time shape. Moreover, people are familiar with the radiation generation from transition among quantum states. In this quantum route, the energy of an electron should be high enough to afford that of photons generated. This viewpoint often drives people to pursue high energy electron beam whose kinetic energy can afford that of photons generated. Therefore, many beam-based routes emphasize the usage of accelerator. Emphasis on high strength of driving field and accelerator will affect economy of these routes. It is worthy to study how to ensure a radiation source, when technique targets are satisfied, to be as low cost as possible. Here, we present a new route of radiation generation based on low-energy electron beam.

The essence of this route is to use "defected" driving field to interact with the beam. The phrase "defected" means that the EM energy density has a large gradient. The driving field is static or DC. For example, we can put a solenoid, as shown in Figure 1, on the boundary region of two materials whose magnetic permeability are μ_1 and $-\mu_2$. The difference $|\mu_1-\mu_2|$ will lead to contours of DC magnetic field B_s to be bent. It is well-known that if $|\mu_1-\mu_2|=0$, B_s contours will be planes normal to the axis of the solenoid, denoted as z-axis in Figure 1 $|\mu_1-\mu_2|\neq0$, will mean a gradient $\partial_x|B_s|^2$. The larger $|\mu_1-\mu_2|$ is, the larger $\partial_x|B_s|^2$. If a DC electric field E_s is applied along the x-direction and a low-energy electron beam is injected into such a configuration along y-direction, it is feasible to achieve the generation of a quasi-monocolor radiation if the initial position of the beam on the x-z plane is appropriate. Detailed analysis is presented as below.

The DC fields that interact with the beam are: $E_s = E_0\vec{e_x}$ and $B_s = B(x)\vec{e_z} = B_0\dfrac{x}{w}\vec{e_z}$ if $|x|w$ and $B_s = B_0 sign(x)\vec{e_z}$ elsewhere. Namely, B_S drops from B_0 at $x=w$ to $-B_0$ at $X=-w$. Single-body dynamics of electron in such a field figuration can be strictly analyzed from 3D relativistic Newton equation set [14].

$$d_s[\Gamma d_s X] = -W_B\left[\eta + d_s Y * \frac{X}{H}\right] \tag{1}$$

$$d_s[\Gamma d_s Z] = 0, \tag{2}$$

$$d_s[\Gamma d_s Z] = 0, \tag{3}$$

where $\frac{1}{\Gamma} = \sqrt{1-(d_s X)^2-(d_s Y)^2-(d_s Z)^2}$, $\eta=E_0/cB_0$, $s=\omega t$, $Z = \frac{z}{\lambda}$, $Y = \frac{y}{\lambda}$, $X = \frac{x}{\lambda}, H = \frac{w}{\lambda}, W_B = \frac{\omega_B}{\omega}$ and $\lambda=c/\omega$ and ω are reference wavelength, (which is set as 1 mm), and frequency, (which is thus $0.3TH_Z$). The initial conditions read $(X,Y,Z,d_s X,d_s Y,d_s Z)|_{s=0}=\left(X_0,0,0,0,\frac{C_y}{\sqrt{1+C_y^2}},0\right)$, where constants C_y is initial momentum component. Eqs. (1-3) will yield

$$\Gamma^2 = \frac{1+\left[C-\dfrac{W_B X^2}{2H}\right]^2}{\left[1-(d_s X)^2\right]} = \left(D + W_B\eta X\right)^2, \tag{4}$$

where $D = \dfrac{1}{\sqrt{1+C_y^2}}$ is the initial value of and $C = \dfrac{C_y}{\sqrt{1+C_y^2}} - \dfrac{W_B X_0^2}{2H}$.

Finally, we obtain a conservation law

$$1 = (d_s X)^2 + \frac{1+\left[C-\dfrac{W_B X^2}{2H}\right]^2}{(D+W_B\eta X)^2}5 \tag{5}$$

which suggests a time-periodic behavior of X. It is easy to find, from this conservation law, that when $\frac{X_0}{H}$ is at a given value <1 and other parameters are same, smaller H will lead to smaller time cycle of X. In principle arbitrary value of the time cycle of X can be achieved by choosing appropriate and feasible parameter-values. For example, B_0 is around 1T, E_0 is around $1V/cm$, and H is around 1 μm. In such a case, EM energy density of the driving field $|E_0|^2+|B_0|^2$ is not too high, but it has a great gradient nearby $x=0$. Namely, around $x=0$, there is a narrow but steep valley of the EM energy density profile. In ref. [14], we have pointed out that an extreme case in which $w=0$ and $B_s=B_0$ if $x<0$ and $Bs=0$ elsewhere, can effectively generate quasi-monocolor radiations whose wavelength is determined by incident position and values of E_0 and B_0 and in principle can be at any desirable value by choosing appropriate parameter-values. Such a step-like B_s-profile is too ideal, in contrast, slope-like B_s - profile is more realistic.

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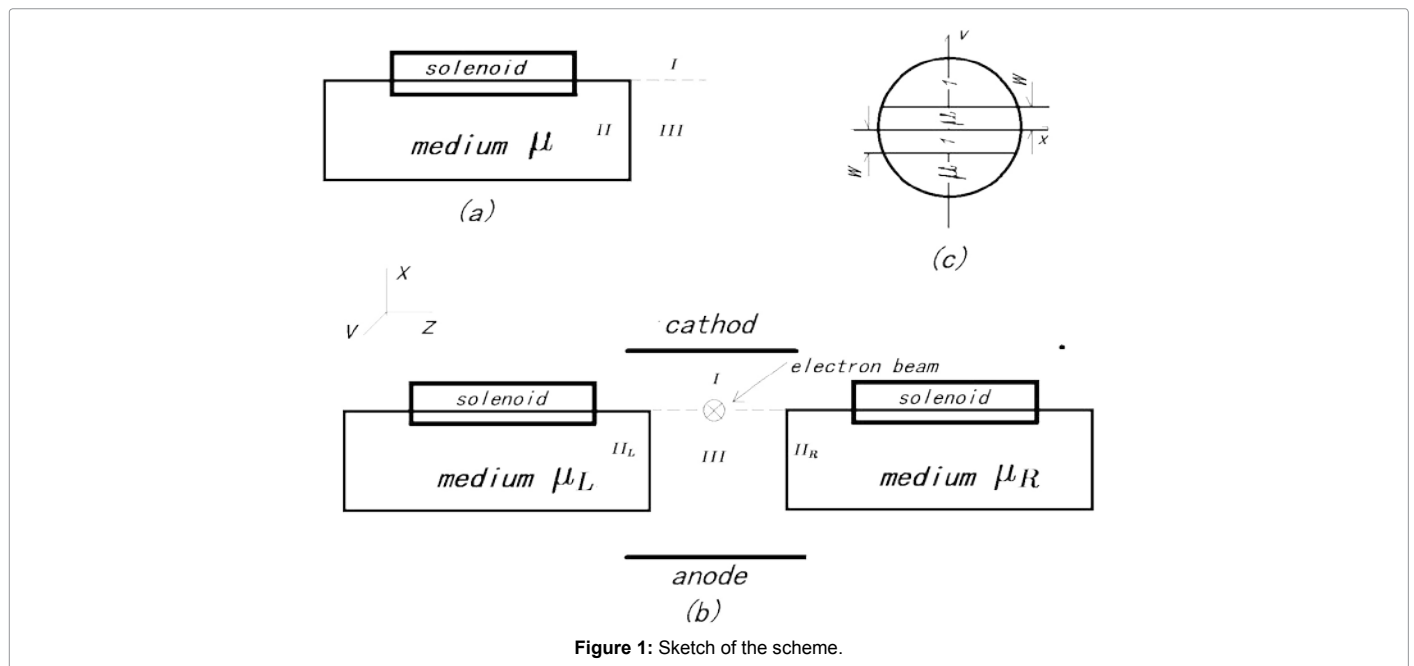
Figure 1: Sketch of the scheme.

DC driving fields, by target designing, can have a not-too-high maximum of EM energy density but a high gradient of the EM energy density. The interaction of a low-energy electron beam with such driving fields is feasible to generate monocolor radiations if the beam is of appropriate initial position and incident direction. This represents an efficient and economic route of achieving monocolor radiation source in principle at arbitrary wavelength.

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