THE DESIGN OF A COMPACT THz SOURCE BASED ON PHOTOCATHODE RF GUN*

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Abstract

Narrow-band THz coherent Cherenkov radiation can be driven by a subpicosecond electron bunch traveling along the axis of a hollow cylindrical dielectric-lined waveguide. We present a scheme of compact THz radiation source based on the photocathode rf gun. On the basis of our analytic result, the subpicosecond electron bunch with high charge (800pC) can be generated directly in the photocathode rf gun. A narrow emission spectrum peaked at 0.24 THz with 2 megawatt (MW) peak power is expected to gain in the proposed scheme (the length of the facility is about 1.2 m), according to the analytical and simulated results.

THEORY OF WAKEFIELDS IN A CYLINDRICAL DIELECTRIC-LINED WAVEGUIDE

The structure of DLW is shown as Fig. 1. Fourier expansion of the longitudinal fields in a circular cylindrical waveguide takes the form:

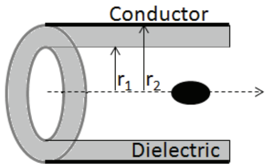

Figure 1: The structure of DLW

$$\begin{pmatrix} E_z(r,t) \\ H_z(r,t) \end{pmatrix} = \frac{1}{(2\pi)^3}\int_{-\infty}^{\infty} d\omega dk \times \sum_{l=-\infty}^{\infty} \exp\left[-i(\omega t - kz - l\theta)\right] \times \begin{pmatrix} e_z(r) \\ -ih_z(r) \end{pmatrix} \quad (1)$$

For a given l in Eq. (1), the eigenmodes can be obtained with the boundary conditions[1][2]. The eigenfunctions will be designated by subscripts such as $e_{z,n}(r)$, $h_{z,n}(r)$ and the eigenvalues by ω_n , k_n , etc. For the transverse distribution of electron bunch is azimuthally symmetric, the electromagnetic field excited by the bunch is independent of θ , only TM_{0n} modes are excited. In our case, the influence of the transverse distribution of electron bunch on the electromagnetic field is weak (the proof will be presented in the next section), so only the temporal distribution of electron bunch is considered. The orthonormality relation between any two eigenmodes and radiative power flow can be written as[2]

$$\sum_{i=1}^{N=2} \int_{R_{i-1}}^{R_i} dr \cdot r \left[\varepsilon_i e_{z,m}(r)\, e_{z,n}(r) + \mu_i h_{z,m}(r)\, h_{z,n}(r)\right] = C_n \delta_{mn} \quad (2)$$

$$\overline{P_{0n}} = -\beta c q_0^2 \frac{e_{z,n}^2(0)}{C_n} \Theta(-s) \cdot {\alpha_n}^2 \quad (3)$$

where q_0 is the charge, $\Theta(-s)$ means the radiation is excited behind the electron. The α_n is the form factor and defined by

$$\alpha_n = \left| \int_{-\infty}^{\infty} ds f(s)\, e^{-ik_n s} \right| \quad (4)$$

Where $f(s)$ is the longitudinal distribution function of the electron bunch and $\int dsf(s) = 1$ .For a gaussian distribution,the form factor is

$$\alpha_n = \exp\left(-\frac{\sigma_z^2 k_n^2}{2}\right) \quad (5)$$

The pulse length and energy of the THz radiation are given by

$$t_{pulse} = \frac{L}{v_g} - \frac{L}{\beta c} \quad (6)$$

$$U = \frac{L}{\beta c} \cdot \overline{P_{0n}} \quad (7)$$

where the v_g is the group velocity of the radiation, L is the length of DLW structure. The magnitude of the electric field on the longitudinal axis is given approximately by[2]

$$\left[E_z(r=0)\right]_{0n,\max} \cong -2q_0 \frac{{e_{z,n}}^2(0)}{C_n} \alpha_n \quad (8)$$

SCHEME OF COMPACT NARROW-BAND TERAHERTZ RADIATION SOURCE

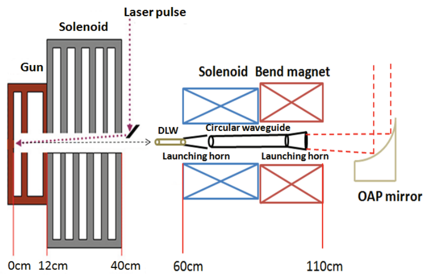

Figure 2: layout of the proposed THz radiation facility

Fig. 2 is the layout of the proposed THz radiation facility. The subpicosecond electron bunch is generated in

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the photocathode rf gun and focused by the solenoid. The narrow-band THz radiation is driven by the electron bunch when it travelling through the DLW tube. The launching horn and circular waveguide is used to transport the radiation. The electron bunch is restricted by another solenoid during the transportation. Finally, a bend magnet is used to bend the electron bunch to the Faraday cup.

Generation of the Subpicosecond Electron Bunch in the Photocathode RF Gun

The length of electron bunch is affected by such factors as space charge effect, beam energy and energy spread, and the coupling effect between the transverse and longitudinal emittances. The bunch lengthening due to the space charge effect can be estimated in a drift space by[3]:

$$\Delta\sigma_z = 2qcL^2/I_a r \sigma_z \gamma^4 \tag{9}$$

where q is the bunch charge, c is the speed of light, L is the drift distance, $I_a = 1.7\ kA$, r is the bunch radius, σ_z is the bunch length and γ is the beam energy. In the photocathode rf gun, the energy of electron beam is low, so the space charge effect plays the dominant role. In order to decrease the bunch lengthening caused by the space charge effect, the acceleration gradient should be as high as possible and the radius of the drive laser spot should be chosen appropriately. To decrease the bunch lengthening caused by the coupling effect between the transverse and longitudinal emittances, laser shaping[4] should be considered to restrain the growth of the transverse emittance. Furthermore, the bunch length can be compressed in the gun by tuning the acceleration phase[5].

We consider to improve the cathode seal technique[6] of our gun machined by the Department of Engineering Physics of Tsinghua University, and look forward to improve the acceleration gradient to 120 MV/m.Although the uniform laser spot can be achieved by using a spatial shaper, it is difficult to transport the shaped spot to the cathode. So we plan to clip an expanded gaussian laser spot by an aperture to restrain the impact of nonlinear space charge force on the transverse emittance.To obtain a short electron bunch with relative high charge (800 pC), the radius of aperture is chosen at 4 mm. For our laser pulse (the measured rms length is about 2.0 ps), the simulated evolutions of the rms beam size and bunch length along the longitudinal position are shown in Fig. 3, when the acceleration phase is set at 4 degrees. Fig. 4 shows the transverse distribution and current distribution of electrons at the focal point of the first solenoid, the rms length of electron bunch is about 0.65 ps. The result is simulated by the code ASTRA[7].

The Dimensions of DLW Structure

The material of the dielectric is fused silica, and the dielectric constant is $\varepsilon_r = 3.8$. According to the transverse distribution of electrons shown in Fig. 4 (a), the inner radius of the DLW is chosen at $400\ \mu m$. Based on the Eq.

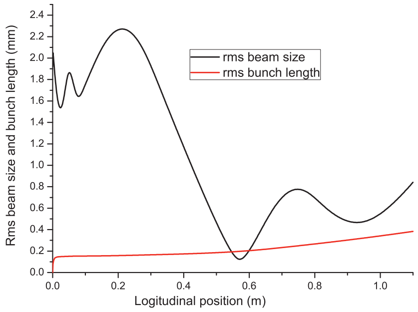

Figure 3: The rms beam size and bunch length evolutions along the longitudinal position

(2) and the electron bunch length $\sigma_z = 0.65\ ps$ shown in Fig. 4 (b), the r_2 is chosen at $550\ \mu m$. Then, only the TM_{01} mode is coherently excited, and the frequency is about $0.241\ THz$. The $1\ cm$ length of the structure is a preliminarily choice.

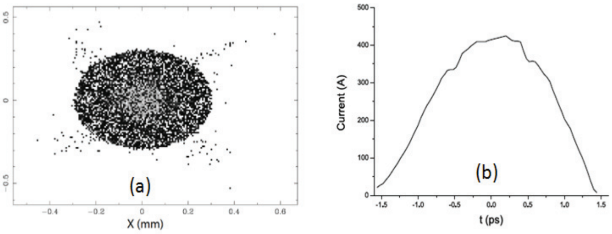

Figure 4: The transverse distribution and current distribution of electrons

Impact of the Form Factors of Electron Bunch on the THz Radiation

In the respect of the impact of transverse form factor on the THz radiation, we start with the solution equation of the longitudinal electromagnetic field. The longitudinal components of the fields satisfy Bessels equation

$$\left[\frac{d^2}{dr^2} + \frac{1}{r}\frac{d}{dr} + \varepsilon\mu\omega^2/c^2 - \frac{l^2}{r^2}\right]\begin{pmatrix} e_z(r) \\ h_z(r) \end{pmatrix} = \begin{pmatrix} \tilde{J}_z(r) \\ 0 \end{pmatrix} \tag{10}$$

where

$$\tilde{J}_z(r) = 4\pi \int_{-\infty}^{+\infty} dt \int_{-\infty}^{+\infty} dz \int_0^{2\pi} dz e^{i(\omega t - kz - l\theta)} \left[\frac{1}{\varepsilon}\frac{\partial \rho}{\partial z} + \frac{\mu}{c^2}\frac{\partial J_z}{\partial t}\right] \tag{11}$$

The fields $e_z(r)$ and $h_z(r)$ can be expanded in terms of their eigenmodes, as

$$\begin{pmatrix} e_z(r) \\ h_z(r) \end{pmatrix} = \sum_{n=1}^{\infty} A_n \begin{pmatrix} e_{z,n}(r) \\ h_{z,n}(r) \end{pmatrix} \tag{12}$$

Table 1: Parameters used in the simulation

Bunch charge	Q	800pC
Bunch energy	E	5.53 MeV
rms energy spread		5%
rms bunch length (Gaussian)	σ_z	0.65 ps
rms bunch size (Gaussian)	σ_x	110 μm
rms normalized emittance	ε_n	7.5 $mm \cdot mrad$
Dielectric inner radius	r_1	400 μm
Dielectric outer radius	r_2	550 μm
Length of the dielectric	L	1 cm
Dielectric constant	ε_r	3.8

Table 2: Analytical and simulated results of the radiation

	frequency	$E_{z,max}(0)$	power
Analytical	0.241THz	49 MV/m	2.05 MW
Simulated	0.240THz	50 MV/m	2.13 MW
	pulse length	energy	
Analytical	56.49 ps	0.115 mJ	
Simulated	57.04 ps	0.12 mJ	

Because the electron bunch is azimuthally symmetric ($l = 0$) and only exist in the vacuum area ($r < r_1$), the orthonormality relation Eq. (2) can be used to find the amplitudes A_n

$$A_n = \frac{1}{C_n(k^2-{k_n}^2)(\beta^2-1)} \int_0^{r_1} drre_{z,n}(r)\tilde{J}_z(r) \qquad (13)$$

For the TM_{01} mode, the $e_{z1}(r)$ is a monotone increasing function of r , so if $\Delta = \frac{e_{z,1}(r_1)-e_{z,1}(0)}{e_{z,1}(0)} \ll 1$, we get the approximation $e_{z,1}(r < r_1) \approx e_{z,1}(r = 0)$. In our case, the $\Delta = 0.0021$ and the value of $\int_0^{r_1} drr\tilde{J}_z(r)$ is only relevant to the charge, therefore we can conclude that the electromagnetic fields and radiation power can be regarded as approximately independent of the transverse distribution of the electron bunch.

In our case, the temporal form factor of electron bunch ($\sigma_z = 0.65\ ps$) shown in Fig. 4 (b) calculated by Eq. (4) is 0.604. For a gaussian distribution with $\sigma_z = 0.65\ ps$, the form factor calculated by Eq. (5) is 0.614. The difference between this two values is 1.67%

Simulation of the THz Radiation

We simulate the radiation by using the code xoopic[8], and the gaussian electron bunch is used on account of the demonstration in the above section. The parameters used in the simulation are shown in Table 1. The longitudinal electric field is shown in Fig. 5, and the power spectrum is shown as Fig. 6, which is calculated numerically from the longitudinal on-axis electric field.

The low frequency hump in the Fig. 6 represents the coherent transition radiation excited by the electron bunch entering and leaving the structure. The analytical and simulated results are shown in Table 2.

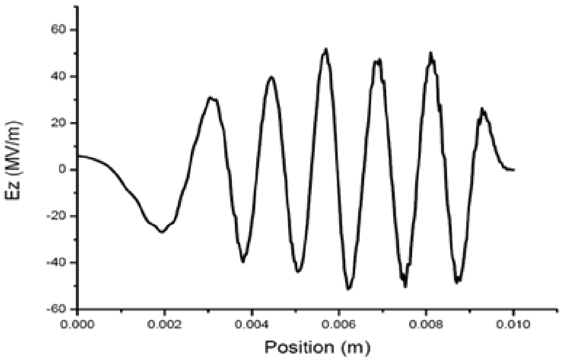

Figure 5: The longitudinal electric field on the axis

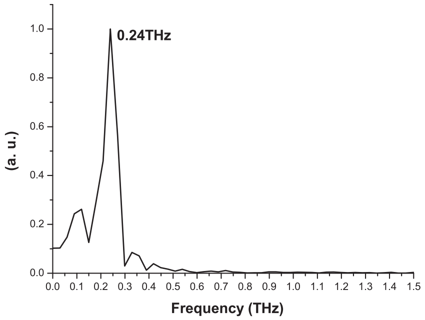

Figure 6: The power spectrum of the coherent Cerenkov radiation

SUMMARY

A scheme of compact THz radiation source based on the photocathode rf gun is proposed.We estimate that 2 MW peak power CCR at 0.24 THz wavelength can be produced using the electron beam capably obtained by the worldwide BNL type photocathode rf gun. When the gun is operated at 120 Hz repetition, above 10 mW average power can be gained, which can be potentially improved by times by extending the length of the DLW.

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