GENERATION AND MEASUREMENT OF SUB-PICOSECOND ELECTRON BUNCH IN PHOTOCATHODE RF GUN*

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Abstract

We consider a scheme to generate sub-picosecond electron bunch in the photocathode rf gun by improving the acceleration gradient in the gun, suitably tuning the bunch charge, the laser spot size and the acceleration phase, and reducing the growth of transverse emittance by laser shaping. A nondestructive technique is also reported to measure the electron bunch length, by measuring the high-frequency spectrum of wakefield radiation which is caused by the passage of a relativistic electron bunch through a channel surrounded by a dielectric.

GENERATION OF SUB-PICOSECOND ELECTRON BUNCH

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[1]:

$$\Delta\sigma_z = 2qcL^2/I_a R\sigma_z\gamma^4 \qquad (1)$$

where q is the charge of bunch, 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 bunch charge should be chosen appropriately. Furthermore, the bunch length can be compressed in the gun by tuning the acceleration phase[2]. For our laser pulse (the measured rms length is about 2.0 ps), we use the code ASTRA[3] to simulate the bunch length evolution as a function of acceleration phase at different charges and acceleration gradients, and the results are shown in Fig. 1. The acceleration gradient of our photocathode rf gun, which is a second generation gun machined by the Department of Engineering Physics of Tsinghua University, is achieved at about 80 MV/m. The acceleration gradient of the third generation gun is achieved at 120 MV/m at present[4], whose cathode seal technique is improved by replacing the HELICOFLEX seal with a MATSUMOTO gasket to eliminate the cathode gap as much as possible[5].

The bunch length can be compressed further in the drift space by a suitable energy spread of the beam, if the length

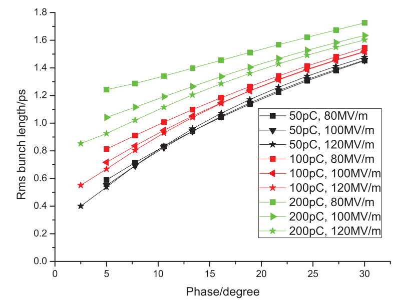

Figure 1: The rms bunch length vs. acceleration phase at different charges and acceleration gradients.

of drive laser pulse is appropriate[6]. For our relatively short laser pulse, the bunch length changing caused by energy spread is small because of the relatively short drift space and the small energy spread at the exit of the gun.

The coupling between the transverse and longitudinal emittances is another factor in lengthening the electron bunch. The laser shaping technique is an effective way to restrain the growth of transverse emittance, which consists of spatial and temporal shaping[7]. In this paper, we only consider the spatial shaping. 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 the laser spot by an aperture, as shown in Fig. 2. For the 2 mm diameter gaussian spot and clipped spot (a

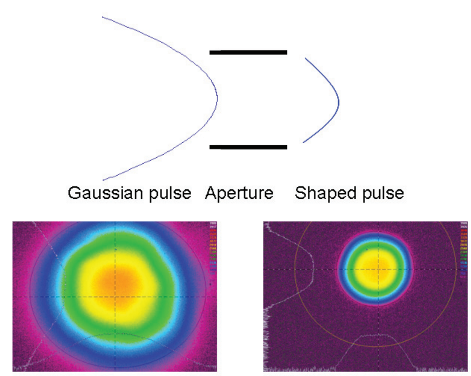

Figure 2: Clipping shaping: sketch and shaping result (UV light).

gaussian spot with 0.8 mm rms size clipped by a 2 mm diameter aperture), the evolution of transverse emittance and rms bunch length are shown as Fig. 3, where the acceleration gradient is 120 MV/m, the bunch charge is 200 pC, the acceleration phase is 5 degrees, and the magnetic field of the solenoid is 2500 Gauss. The rms bunch length

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at the focal point of the solenoid (around 0.9 m) is about 0.97 ps for the clipped laser spot, while it is 1.26 ps for the gaussian laser spot. Equation (1) shows that the bunch

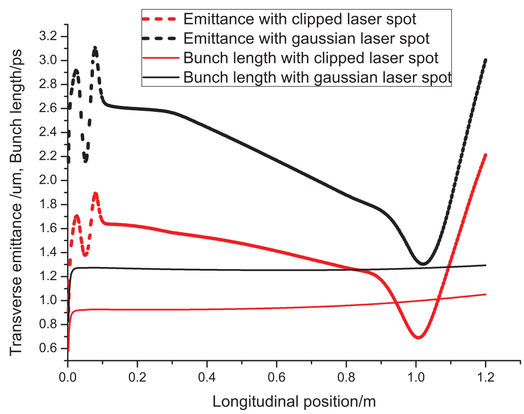

Figure 3: Transverse emittance and rms bunch length vs longitudinal position for different laser spots.

lengthening due to the space charge effect is proportional to the diameter of laser spot. So the bunch length can be modulated by tuning the diameter of laser spot, the current distributions of bunches at the focal point of the solenoid are shown in Fig. 4. However the transverse emittance will grow seriously when the diameter of laser spot is too large. The optimal transverse emittances are $0.7\ mm \cdot mrad$, $1.2\ mm \cdot mrad$ and $1.75\ mm \cdot mrad$ respectively. Nevertheless, the transverse emittance is not critical in all the applications.

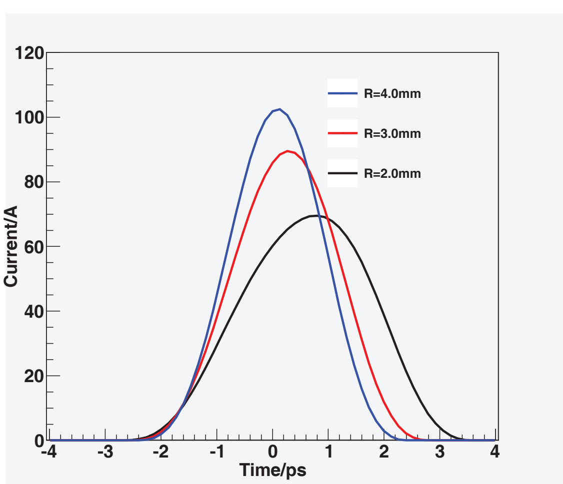

Figure 4: Transverse emittance and rms bunch length vs longitudinal position for different laser spots.

In summary, to generate sub-picosecond electron bunch directly in the photocathode rf gun, we need to improve the acceleration gradient of the gun as high as possible, restrain the growth of transverse emittance through laser shaping technique, and carefully tune the energy (bunch charge) and diameter of laser spot according to the requirements of applications.

BUNCH LENGTH MEASUREMENT

As a relativistic electron bunch travels along the vacuum channel in the tube, it drives coherent Cherenkov radiation wakefields[8] that are confined to a discrete set of modes due to the waveguide boundaries. The power (energy) at certain modes is correlative to the length of electron bunch. So the bunch length can be measured by observing the frequency spectrum of the wakefield radiation. Fig. 5 is a sectional drawing of hollow cylindrical dielectric tube coated on the outer surface with metal to form a dielectric-lined waveguide. We now present a brief summary of analysis for the fields set up within this structure.

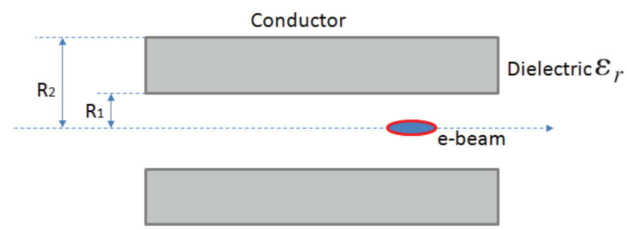

Figure 5: The sectional drawing of a beam-driven cylindrical dielectric-lined waveguide.

Fourier expansion of the longitudinal fields in a circular cylindrical waveguide takes the form:

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

Then $e_z(r)$ and $h_z(r)$ satisfy the Bessel's equation

$$\left[\frac{d^2}{dr^2} + \frac{1}{r}\frac{d}{dr} + \left(k_\perp^2 - \frac{l^2}{r^2}\right)\right]\begin{pmatrix} e_z(r) \\ h_z(r) \end{pmatrix} = 0 \quad (3)$$

In our case, only $TM_{0,n}$ waveguide modes are excited, $l = 0$. According to the boundary conditions, we can get that

$$\frac{I_0'(x_1)}{x_1 I_0(x_1)} + \varepsilon \frac{E_0'(y_1)}{y_1 E_0(y_1)} = 0 \quad (4)$$

where $I_0(x)$ is the modified Bessel function with $x_1 \equiv \left|k_\perp^{(1)}\right| R_1$, $E_0(y) \equiv J_0(y)N_0(y_2) - N_0(y)J_0(y_2)$ with $y \equiv \left|k_\perp^{(2)}\right| r$, $y_1 \equiv \left|k_\perp^{(2)}\right| R_1$, $y_2 \equiv \left|k_\perp^{(2)}\right| R_2$ and $\left(k_\perp^{(2)}\right)^2 \equiv \varepsilon\mu(\omega/c)^2 - k^2 > 0$, the J_0 and N_0 are ordinary Bessel functions of the first and second kinds.The n_{th} root of this equation is the k_n , and the $f_n = c \cdot k_n/2\pi$ is the frequency of the n_{th} mode radiation excited in the structure.

When a charge bunch traverses the structure, The orthonormality relation between any two eigenmodes and the radiative power flow at certain $TM_{0,n}$ mode can be written as[9]

$$\sum_{i=1}^{N=2} \int_{R_i}^{R_i} dr \cdot r\left[\varepsilon_i e_{z,m}(r) e_{z,n}(r) + \mu_i h_{z,m}(r) h_{z,n}(r)\right] = C_n \delta_{mn} \quad (5)$$

$$\overline{P_{0n}} = -cq_0^2\beta\frac{e_{z,n}^2(0)}{C_n}\Theta(-s)\cdot g(\sigma_z) \qquad (6)$$

where q_0 is the charge, $c\beta$ is the velocity of the electron, $\Theta(-s)$ means the radiation is excited behind the electron, $g(\sigma_z)$ is the form factor. For gaussian shape, $g(\sigma_z) = \exp(-4\pi^2\sigma_z^2/\lambda_n^2)$, where σ_z is the rms length of the bunch, $\lambda_n = 2\pi/k_n$ is the wavelength of TM_{0n} . For uniform shape, $g(\sigma_z) = \sin^2(k_n \cdot \sqrt{3}\sigma_z)/(k_n \cdot \sqrt{3}\sigma_z)^2$. Fig. 6 shows the power of wakefield radiation as a function of frequency for electron bunches with different rms lengthes, where the charge is 200 pC, the beam energy is 5.55 MeV, the inner and outer radii of the structure are $R_1 = 1.2\ mm$, $R_2 = 6.5\ mm$ respectively. The material of the dielectric is fused silica $\varepsilon_r = 3.8$.

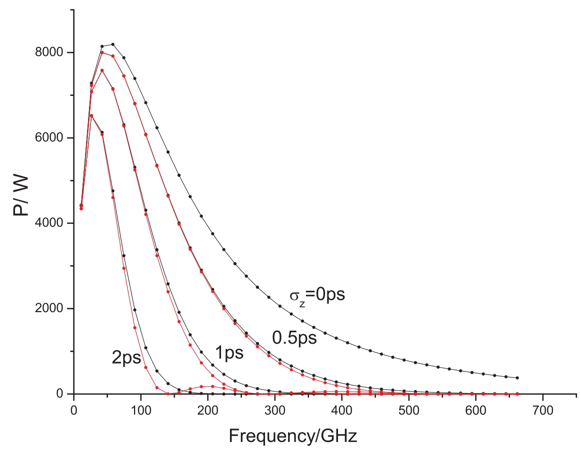

Figure 6: The power of wakefield radiation as a function of frquency, for bunches with different rms length. The black line is for gaussian shape, and the red line is for uniform shape.

The sketch of the measurement setup is shown in Fig. 7. The dielectric length should be several centimeters to make sure that the Cerenkov wakefield radiation dominates the transition radiation which is emitted as the bunch enters or leaves the structure[10]. The radiation emits from the

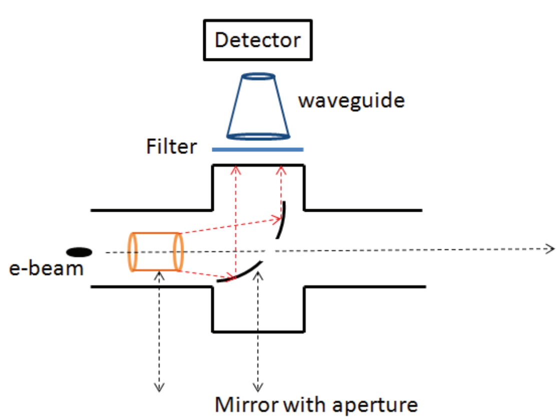

Figure 7: The sketch of measurement setup.

structure, and then is reflected parallel by a parabolic mirror. The aperture in the mirror is used to ensure the passage of electron beam, and the transition radiation generated by the passage of electron beam through the aperture is weak and easy to calibrate. The filters filtrate out the other radiation except for the radiation at specified frequency. The detector can be a Schottky barrier diode, a golay cell, or a bolometer. The precision of the diode is relatively low compared with the golay cell and bolometer, and it works in certain bandwidth. The bolometer is expensive and needs a cryogenically cooled environment. The golay cell is a good choice with high precision and portability. Three or four filters will be used to reconstruct the spectrum of the radiation, and the bunch length can be measured. After calibration, just one filter is needed, and single shot measurement can be achieved. Besides, the charge of the bunch can also be concluded.

SUMMARY

In this paper, we analyse the impact factors of the electron bunch length, and draw the conclusion that to generate sub-picosecond electron bunch directly in the photocathode rf gun, we need to improve the acceleration gradient of gun as high as possible, restrain the growth of transverse emittance through laser shaping technique, and carefully tune the energy (bunch charge) and diameter of the laser spot according to the requirements of applications. In order to measure the electron bunch length, the coherent Cherenkov radiation wakefield is also analysed, which is excited by the relativistic electron bunch traveling through a hollow cylindrical dielectric element. Based on the analysis, a nondestructive technique for the measurement of bunch length is reported. The advantage of this technique is routine to calibrate, and can be single shot measurement.

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