RESEARCH OF EMITTANCE COMPENSATION OF CAEP CW DC-GUN PHOTOINJECTOR

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Abstract

Emittance growth induced by space charge effect is very important, especially for CW DC-gun photoinjector. In this work, the linear space charge force and its effect on electron transverse emittance is studied. Principle and properties of emittance compensation by solenoid are analyzed. We also simulate the 350 keV CAEP DC-gun photoinjector with a solenoid by the code Parmela. The simulation result indicates that the normalized transverse RMS emittance for electron beam of 80 pC is 1.27 mm*mrad after solenoid compensation.

INTRODUCTION

CW DC-gun photoinjector is the main electron source of high-average-current, low-emittance, high-brightness beams, which are required for many advanced accelerator applications, such as free electron lasers, and also is used in our CAEP CFEL[1]. It is well known that space charge effect is the most important mechanism for emittance growth in injectors. This effect can be compensated by a simple scheme using a single external solenoid for both focusing the beam and reducing the correlated emittance. In this paper, we will study principle and properties of emittance compensation by solenoid following B. E. Carlsten's works[2,3,4]. We will also simulate the magnetic field distributions of solenoid by SUPERFISH, and the beam bunch dynamics of CAEP DC-gun photoinjector by the code Parmela.

SPACE CHARGE ALGORITHM

Emittance Growth in a DC Laser Gun

Kim's theory [5] has been widely used for RF laser guns. By ignoring the RF effect which does not exist in a DC gun and the effect of transverse electric field which is small, emittance growth of a axial symmetry Gaussian bunch in a DC laser gun is as follow

$$\Delta\varepsilon_n^{sc} = \left(\frac{1}{2} - \frac{1}{\pi}\arcsin\frac{1}{\gamma}\right)\frac{m_0c^2}{eE_0}\frac{Q}{I_A}\frac{c}{3\sigma_r+5\sigma_z} \qquad (1)$$

where Q is the bunch charge, E_0 the average DC field gradient in MV/m, I_A constant current 17kA, σ_r and σ_z the transverse and longitudinal bunch RMS radius.

Emittance Growth During Drift

In drift space, there is no longitudinal accelerator force, and transverse emittance growth is caused mainly by defocus space charge force, resulting in a form as follow

$$\Delta\varepsilon_n^{sc} = \frac{L}{\pi\beta\gamma^2}\frac{Q}{I_A}\frac{c}{3\sigma_r+5\sigma_z} \qquad (2)$$

where L is drift length.

EMITTANCE COMPENSATION

Emittance Compensation Principle

A simple emittance compensation scheme is introduced by using a solenoid lens. It focus a charged particle beam to allow exact compensation of the nonlinear space-charge forces before the lens with the nonlinear space-charge forces after the lens, see Fig. 1. To study this

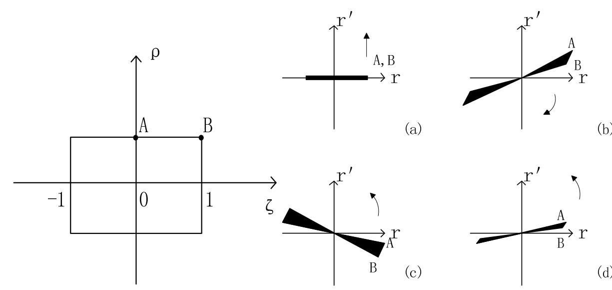

Figure 1: Structure of the beam and its evolution in phase space.

scheme, a slug beam is used. We define point A to represent center particles of the beam for $\rho = r_0$, point B for the axial edges particles. The phase space plots of beam corresponding to different axial locations are also examined. At the beginning in (a), points A and B are superposed, initial emittance is small. After drifting a distance in (b), because of different space charge force on points A and B, different expansion rates cause emittance growth. (c) is the phase space immediately after lens. It is seen that phase space is overturn, but the emittance is unchanged due to the assuming that lens is linear. Finally, (d) shows the emittance reduction after drifting a distance behind lens, which also because the different expansion rates of points A and B.

Solenoid Analysis

In this emittance compensation scheme, the external solenoid is used for both focusing the beam and reducing the correlated emittance. For our CAEP DC-gun injector, the magnetic lens consists of a solenoid and iron yokes, and its focal length can express as

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$$\frac{1}{f} = \frac{q}{8m\phi}\int_{-\infty}^{+\infty} B^2(z)dz \quad (3)$$

where ϕ is electric potential. Magnetic strength B could be calculated through SUPERFISH simulation, then focal length could be known by using Eq. 3.

Emittance Compensation Analysis

In this work, we only consider space charge force in transverse, so the transverse equation of motion obeys

$$\beta c\frac{d}{dz}(\gamma\beta c\frac{dr}{dz}) = \lambda_l \quad (4)$$

For a uniform density slug, this force can be empirically represented by [3]

$$\lambda_l = \rho\frac{\lambda_0}{\gamma^2}[1+2.25\rho^2 e^{-A_r/0.85} - \frac{\varsigma^2}{2}(1-e^{-A_r/0.36})] \quad (5)$$

Where the normalized force λ_0 is

$$\lambda_0 = \frac{eQ}{2m_0\varepsilon_0\pi r_0\sqrt{(\beta c\tau_b)^2+4r_0^2}} \quad (6)$$

τ_b is the bunch length in time, Q is the bunch charge, and A_r is the beam's aspect ratio in its own frame of reference.

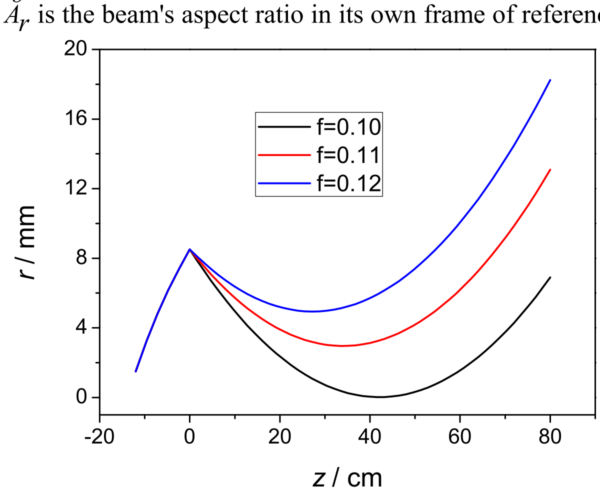

Figure 2: Beam radius with different solenoid focuslength.

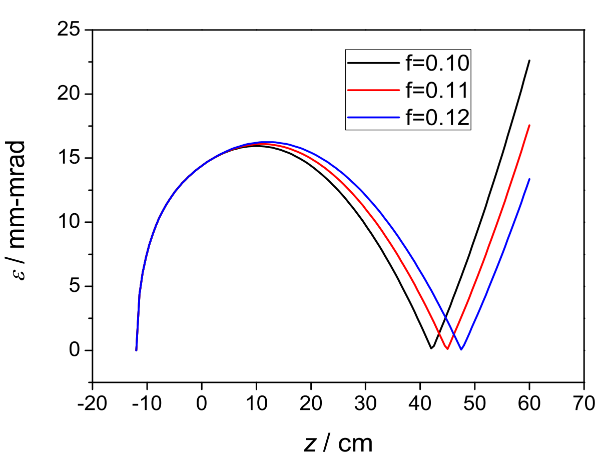

Figure 3: Transverse emittances with different solenoid focus length.

In DC-gun photoinjector, electrons escape form cathode and be accelerated at positon z_1. The solenoid locates in position $z = 0$, and its focal length is f. After focused by a solenoid lens, electron beam drifts to position z. Following the equations above, the particle positions and divergences at a given position z upstream and downstream from the lens could be get. It is assumed in this work that beam density is uniform and there is no appreciable relative longitudinal motion. With $r_1' = 0$, beam radius r as a function of move distance z is plotted in Fig. 2. It could be found that beam radius decrease at first and then increase. And with long lens focal length, the beam has small radius.

In a uniform beam bunch, we have $\langle\varsigma^2\rangle=1/3$, $\langle\varsigma^4\rangle=1/5$. According to equations above and transverse emittance definition $\varepsilon = \beta\gamma(\langle r^2\rangle\langle r'^2\rangle - \langle rr'\rangle^2)^{1/2}$, the normalized emittance can be rewritten as a function of the axial position and lens focal length as

$$\varepsilon_{al} = \frac{2}{\sqrt{45}}\beta\gamma\,|\,ad-bc\,| \quad (7)$$

where parameters a, b, c, d are some integral expression. Before the lens, they are

$$a = \frac{1}{\gamma(z)\beta(z)c}\int_{z_1}^{z}\frac{1}{\beta(z')c}C(z')dz' \quad (8a)$$

$$b = \frac{1}{\gamma(z)\beta(z)c}\int_{z_1}^{z}\frac{1}{\beta(z')c}D(z')dz' \quad (8b)$$

$$c = r_1 + \int_{z_1}^{z}\frac{dz'}{\gamma(z')\beta(z')c}\int_{z_1}^{z'}\frac{C(z'')}{\beta(z'')c}dz'' \quad (8c)$$

$$d = \int_{z_1}^{z}\frac{dz'}{\gamma(z')\beta(z')c}\int_{z_1}^{z'}\frac{D(z'')}{\beta(z'')c}dz'' \quad (8d)$$

After the lens, they are

$$a = \frac{1}{\gamma_0\beta_0 c}\int_{z_1}^{0}\frac{C(z')}{\beta(z')c}dz' + \frac{C(0)}{\gamma_0\beta_0^2c^2}z - \frac{r_1}{f} - \frac{1}{f}\int_{z_1}^{0}\frac{dz'}{\gamma(z')\beta(z')c}\int_{z_1}^{z'}\frac{C(z'')}{\beta(z'')c}dz'' \quad (9a)$$

$$b = \frac{1}{\gamma_0\beta_0 c}\int_{z_1}^{0}\frac{D(z')}{\beta(z')c}dz' + \frac{D(0)}{\gamma_0\beta_0^2c^2}z - \frac{1}{f}\int_{z_1}^{0}\frac{dz'}{\gamma(z')\beta(z')c}\int_{z_1}^{z'}\frac{D(z'')}{\beta(z'')c}dz'' \quad (9b)$$

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$$
\begin{aligned}
c = r_1 &+ \int_{z_1}^{0} \frac{dz'}{\gamma(z')\beta(z')c} \int_{z_1}^{z'} \frac{C(z'')}{\beta(z'')c} dz'' + \\
&\frac{z}{\gamma_0\beta_0 c} \int_{z_1}^{0} \frac{C(z')}{\beta(z')c} dz' + \frac{C(0)}{2\gamma_0\beta_0^2 c^2} z^2 - \frac{r_1}{f} z - \qquad (9c) \\
&\frac{z}{f} \int_{z_1}^{0} \frac{dz'}{\gamma(z')\beta(z')c} \int_{z_1}^{z'} \frac{C(z'')}{\beta(z'')c} dz''
\end{aligned}
$$

$$
\begin{aligned}
d = &\int_{z_1}^{0} \frac{dz'}{\gamma(z')\beta(z')c} \int_{z_1}^{z'} \frac{D(z'')}{\beta(z'')c} dz'' + \\
&\frac{z}{\gamma_0\beta_0 c} \int_{z_1}^{0} \frac{D(z')}{\beta(z')c} dz' + \frac{D(0)}{2\gamma_0\beta_0^2 c^2} z^2 - \qquad (9d) \\
&\frac{z}{f} \int_{z_1}^{0} \frac{dz'}{\gamma(z')\beta(z')c} \int_{z_1}^{z'} \frac{D(z'')}{\beta(z'')c} dz''
\end{aligned}
$$

Where z_1 is cathode position and $z_1 = -L$, r_1 is initial radius. C and D are space charge force coefficient

$$C = \lambda_0 (1 + 2.25 \exp(-Ar/0.85)) / \gamma^2$$

$$D = \lambda_0 (1 - \exp(-Ar/0.36)) / (2\gamma^2)$$

According to the equations above, we plot the relations between emittance and distance z in Fig. 3. From the figure, it is found that minimal emittance is zero. That is because we only consider the correlated emittance in this work.

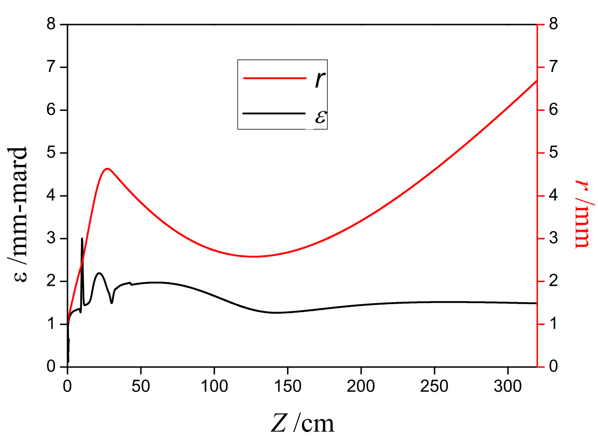

Figure 4: Results of solenoid compensation.

SIMULATION RESULT

In this section, we present some results of the emittance compensation simulation. For CAEP DC-gun photo-injector, DC gun electric potential is 350 kV, DC-gun length is 12 cm, FWHM of the laser pulse is 10 ps, cathode diameter is 3 mm. With 80 pC bunch charge, normalized emittance at the gun exit is 5.14 mm*mrad simulated by Parmela, comparing to result of 6.78 mm*mrad calculated by Eq. 1.

Also, electron beam dynamics in CAEP DC-gun photo-injector is simulated by Parmela, including emittance compensation by a 18 cm solenoid. The results show in Fig. 4.

By simulation, compensation results are showed in Fig. 5 and 6. It is clear that bunch minimal radius increases monotonously with the increment of ampere-turns of solenoid, whereas minimal emittance decreases at first and then increases. The position of minimal radius increases at first and then decreases, but position of minimal emittance always decreases. And we could also find that the least emittance is $\varepsilon_{\min} = 1.27$ mm*mrad at $z = 140.90$ cm. At this position, the solenoid ampere-turns is $NI = 3680 A\square N$, and its corresponding bunch minimal radius is $r = 2.58$ mm.

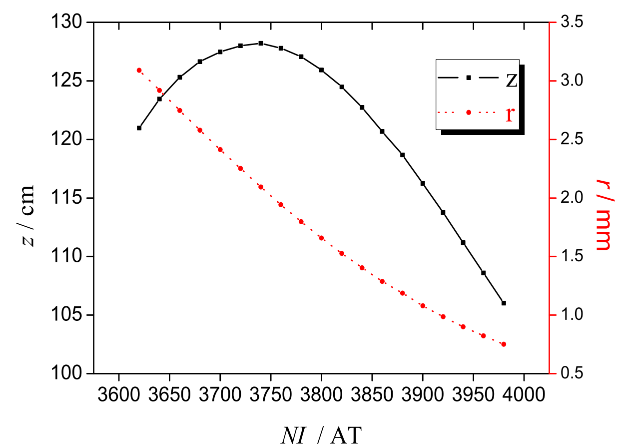

Figure 5: Minimal radius and positions with different solenoid current.

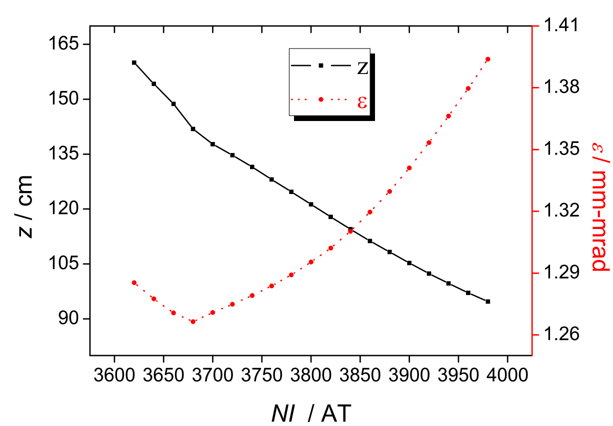

Figure 6: Minimal transverse emittances and positions with different solenoid current.

From these figures, it is also found that the position of minimal beam radius is smaller than that of minimal emittance with the same solenoid ampere-turns. For application, the buncher cavity must be put little upstream

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from the position of minimal beam radius, in order to induce some focusing force in accelerating section.

Finally, the minimal transverse emittances with different bunch charge are plotted in Fig. 7. We know that bunch charge could affect the space charge force. This figure indicates that minimal transverse emittance increases almost linearly with increasing bunch charge.

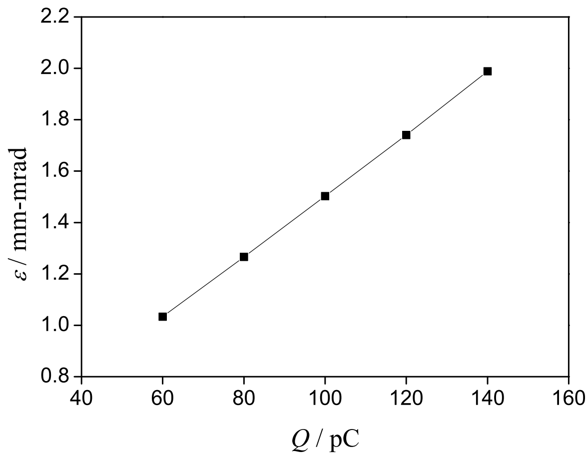

Figure 7: Minimal transverse emittances with different bunch charge.

CONCLUSION

The CAEP DC-gun has constructed and is in the middle of commissioning. In his paper, we have studied a simple emittance compensation scheme which uses an external solenoid both in theory and simulation. Simulated by Pamela, the normalized transverse emittance of 80 pC bunch at the 350 keV DC-gun exist is 5.14 mm*mrad. And after compensated by a solenoid, it becomes 1.27 mm*mrad. It indicates that this compensation method is sufficient to minimize the emittance growth in DC-gun photo-injector.

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