Numerical Study of Coulomb Scattering Effects on Electron Beam from a Nano-Tip*

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Abstract

Nano-tips with high acceleration gradient around the emission surface have been proposed to generate high brightness beams. However, due to the small size of the tip, the charge density near the tip is very high even for a small number of electrons. The stochastic Coulomb scattering near the tip can degrade the beam quality and cause extra emittance growth and energy spread. In the paper, we present a numerical study of these effects using a direct relativistic N-body model. We found that emittance growth and energy spread, due to Coulomb scattering, can be significantly enhanced with respect to mean-field space-charge calculations.

INTRODUCTION

High current, high brightness electron source plays a key role in next generation FEL projects. Using advanced rf cavities and magnetic focusing/compensation, the emittance out of photo-injector gets closer to the initial thermal emittance of the beam. Reducing the initial thermal emittance near the cathode becomes an active research in the accelerator light source community. Low emittance electron source using electrons emitted from small radius nano-tip has been proposed in a number of studies [1, 2, 3]. However, with low emittance and high current density, the stochastic scattering effects from Coulomb interactions become significant. In this paper, we present studies of these scattering effects through three-dimensional self-consistent computer simulations.

COMPUTATIONAL MODEL

A direct N-body model including relativistic effects is used in this study [4]. To calculate the fields generated by particle j at the position of particle i, the relative separation $\mathbf{r}_{ij}$ these two particles in the laboratory is transformed into the rest frame of particle j by:

$$\mathbf{r}'_{ij} \quad = \quad \mathbf{r}_{ij} + \frac{\gamma_j^2}{\gamma_j + 1}(\mathbf{r}_{ij} \cdot \boldsymbol{\beta}_j)\boldsymbol{\beta}_j \tag{1}$$

where $\mathbf{r}'_{ij}$ is the relative separation of two particles in the rest frame of particle j, $\gamma_j = 1/\sqrt{1-\beta_j^2}$, β_j is the speed of particle j normalized by the speed of light in vacuum. Within the rest frame of particle j, we assume that only electrostatic fields are present, which are given by:

$$\mathbf{E}'_{ij} = \frac{q_j}{4\pi\epsilon_0}\frac{\mathbf{r}'_{ij}}{|\mathbf{r}'_{ij}{}^3|} \tag{2}$$

where $\mathbf{E'_{ij}}$ is the electric fields seen by particle i from particle j in the rest frame of particle j, and q_j is the charge of particle j. Transforming this field into the laboratory frame and summing up the contributions from all particles, we obtain the electromagnetic fields on particle i as:

$$\begin{aligned}\mathbf{E}_i \quad &= \quad \sum_{j\neq i}\gamma_j(\mathbf{E}'_{ij} - \frac{\gamma_j}{\gamma_j+1}(\mathbf{E}'_{ij}\cdot\boldsymbol{\beta}_j)\boldsymbol{\beta}_j), &(3)\\ \mathbf{B}_i \quad &= \quad \frac{1}{c}\sum_{j\neq i}\gamma_j\boldsymbol{\beta}_j \times \mathbf{E}'_{ij}. &(4)\end{aligned}$$

SIMULATION RESULTS

In this study, we consider a nano-tip emitter in a high voltage pulse of 30 ps used at PSI for the low emittance gun (LEG) project. The tip has an emitting area of 30 nm radius and can carry a current up to 1 mA. The enhancement factor of the tip is about 10. The 500 kV long pulse field over 4 mm can be regarded as a DC field in the simulation. In Fig. 1 the on-axis field profile of the DC pulser is shown [5]. It can be seen that near the emitting surface, the field strength can be over 2 GV/m.

The large accelerating gradient near the cathode will mitigate the space-charge effects from the Coulomb interactions and improve the current limit set by the Fowler-Nordheim formulae. In this study, we have used 6400 real electrons emitted from a radius of 10 nm tip surface with a 30 ps pulse length. This is similar to the current density from the nano-tips in the LEG design. The initial distribution of electrons is uniform in longitudinal and transverse dimensions. The transverse momentum distribution is assumed to be Gaussian distribution with 30 meV temperature. The longitudinal distribution is assumed to be a half Gaussian distribution with the same temperature.

The electron current density from this source is about 110 kA/mm^2, which is much higher than that from the conventional plane surface photocathode, which is about 100 A/mm^2. In this case, the stochastic scattering effects are no-longer negligible and can dominate the mean-field space-charge effects to drive the growth of transverse emittance and energy spread. Fig. 2 shows the slice emittance

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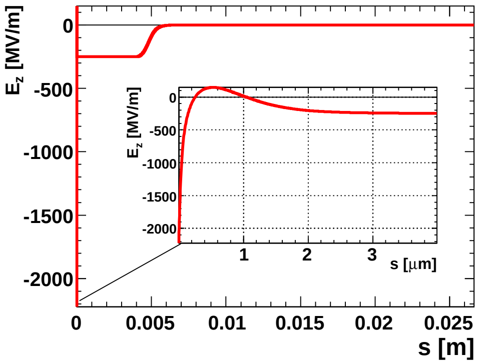

Figure 1: Longitudinal electric on axis field profiles, field near tip shown in the inset.

distribution at the end of the simulation from the direct N-body simulation, described in the last section, and from a mean-field space-charge Poisson solver calculation. The mean-field space-charge solver uses $640,000$ macroparticles and $32 \times 32 \times 32$ three-dimensional grid to smooth out the density fluctuation of discrete particle and was discussed in [6]. The stochastic scattering effects drives more than a factor of two larger final emittance than that from the space-charge mean field. Fig. 3 shows the uncorrelated energy spread at the end of the simulation from the N-body calculation and from the mean-field space-charge calculation. The final energy spread due to stochastic scattering is more than one order of magnitude larger than that due to the mean-field space-charge effects.

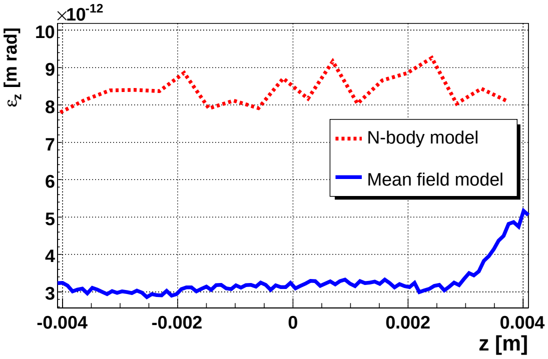

Figure 2: Slice emittance distribution at the end of the simulation from the N-body calculation and the mean-field calculation.

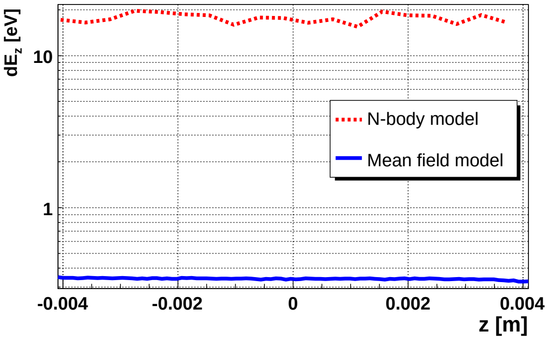

Figure 3: Uncorrelated energy spread from the N-body calculation and the mean-field calculation.

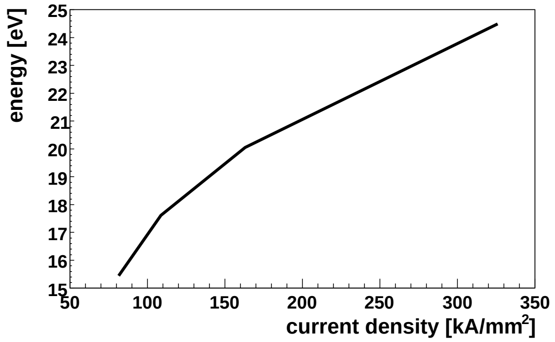

Figure 4: Uncorrelated energy spread as a function of current density from the N-body simulations.

The effects of stochastic Coulomb scattering depend on the current density and the energy of beam. Fig. 4 shows the final root mean square (rms) energy spread as a function of current density from the N-body simulations. A larger current density has stronger Coulomb interactions among electrons and results in a larger final energy spread. Fig. 5 shows the energy spread as a function of final accelerated energy. As the energy increases with higher accelerating gradient, the final energy spread also increases. This is due to the fact that rms energy spread depends not only on the absolute energy deviation but also on the energy of beam. As the energy increases, the stochastic scattering effects become weaker. However, the decreasing of energy spread from stochastic scattering does not compensate the increase from the beam energy. This results in a net increase of final rms beam energy spread. Fig. 6 shows the averaged slice emittance as a function of current density from the N-body simulations with two accelerated energy. The averaged slice emittance increases nearly linearly with the increasing current density at 1.2 MeV. With half of the accelerated energy, the averaged slice emittance has increased by more than 100%. The dependence of current density also becomes stronger at lower energy. This suggests that a high accelerating gradient would be preferable in order to maintain small slice emittance.

High current density electron beam emitted from a nanotip has a larger emittance growth due to stochastic scattering effects. However, given initial small size of the beam, it can have a very small initial emittance compared with

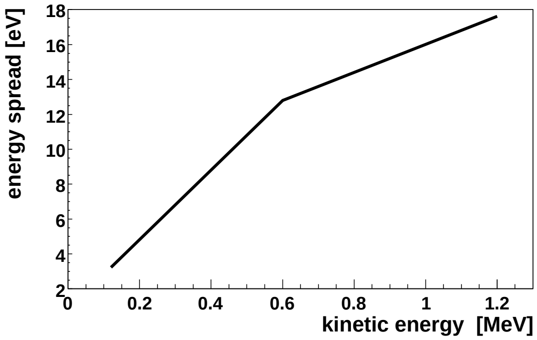

Figure 5: Uncorrelated energy spread as a function of accelerated energy from the N-body simulations.

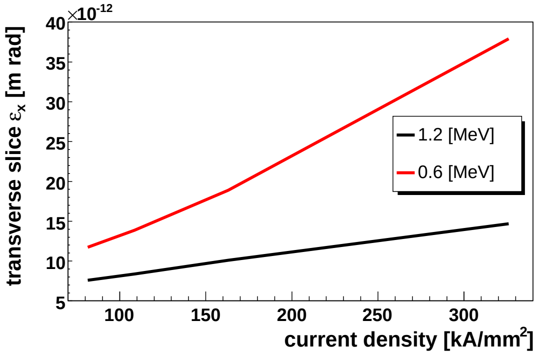

Figure 6: Averaged slice emittance as a function of current density from the N-body simulations with two acceleration energy.

conventional plane surface cathode. To make a comparison with conventional plane surface cathode, we simulated the same amount of electrons (6400) emitted from a radius of about 1 um with the same initial temperature as the nano-tip simulation. This corresponds to the same current density for 1 nC charge out of 1 mm radius used in conventional plane cathode. The external field is the same as before except without the field enhancement from the nano-tip. Fig. 7 shows the final slice emittance from the 10 nm nano-tip and from the 1 um plane surface. It is seen that given the increase of slice emittance from stochastic scattering, the final emittance from the nano-tip is still about order of magnitude smaller than that from the plane surface.

SUMMARY

In this paper, we studied the stochastic scattering effects on high brightness electron beam emitted from a nano-tip. We found that the stochastic Coulomb scattering effects will dominate the emittance growth and energy spread compared with the mean-field space-charge effects. The energy spread increases with the increase of current density and the accelerated energy. The slice emittance growth increases almost linearly with the current density for the nominal 1.2 MeV accelerated energy. This dependency becomes stronger with lower accelerated energy. For 6400 real electron emitted from 10 nm nano-tip emitter used in this study, even though the stochastic scattering causes significantly slice emittance growth, it is still about a factor of 10 smaller than the same amount of electron emitted from a 1 um conventional plane surface. The stochastic scattering effects on electrons from a nano-tip cause large energy spread of the beam. However, this large energy spread may help to reduce effects of microbunching instability inside the beam delivery system [7].

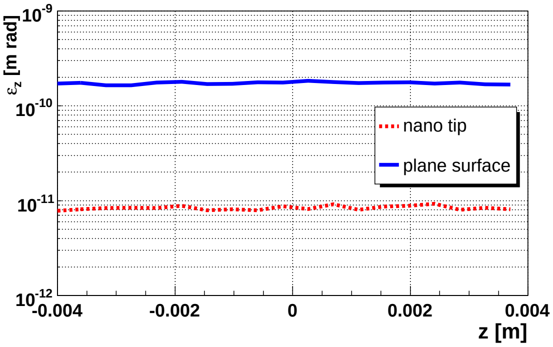

Figure 7: Final slice emittance distribution from the 10 nm nano-tip and from the 1 μm plane surface.

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