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Reduction of transverse emittance in electron injectors caused by space charge effects

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ABSTRACT

We report that transverse emittance can be reduced by the space charge effects in electron injectors. The reduction of emittance in an ideal DC-accelerated continuous beam is numerically calculated and the mechanisms of the reduction are analytically discussed. Beam edge and image charge effects at a cathode produce a particular nonlinearity in r–r' phase space, which is discussed in the paper, and they contribute to reducing the emittance immediately after the cathode. We also show examples of reduced emittance for practical electron injectors such as that in the SCSS thermionic gun with a continuous beam, and those in the SPring-8 rf photoinjector and the BNL-type rf photoinjector with pulsed beams. For pulsed beams, the focusing effects caused by an rf cavity also contribute to reducing the emittance. These reductions only appear when the beam charge is low.

1. Introduction

Research on emittance evolution is important for designing low-emittance electron injectors. For these injectors, the emittance compensation technique [1] is widely used. Using this technique, the transverse projected emittance of an entire bunch can be reduced owing to the different rotation angle of each slice emittance in a phase space using beam-focusing devices. Details of the emittance variations in rf photoinjectors are described in Ref. [2]. This theory is valid even if each slice emittance in the bunch is constant.

For describing the beam dynamics in the electron injectors, the emittance is usually defined as an rms emittance. It can vary since the rms emittance is different from a constant volume of the Liouville's theorem. Therefore, investigation of evolution of the slice emittance is of the same importance as the emittance compensation technique described above.

There are many papers which describe the evolution of the slice emittance in electron injectors. In Refs. [3–5], they show simulation results calculated by MAFIA and Impact-T that the slice emittances of pulsed beams in rfgun cavities increase rapidly in the vicinity of the cathode, then they turn to decrease. In Ref. [6], the projected emittance of the bunch in the vicinity of a DC gun cathode is observed to decrease in the simulation by GPT. In Ref. [7], the emittances of DC continuous beam decrease immediately after a DC gun cathode in simulations calculated by KUAD2 and 3D FDTD.

In Refs. [3,4], the authors pointed out that these increasings are caused by nonlinearity of space charge forces and subsequent decreasings are self-linearization of transverse phase space distribution caused also by nonlinearity of space charge forces, that is, the nonlinearity is compensated by the space charge force itself. The emittance decreasings in Ref. [6] are also thought to be due to the self-linearizations. These are not phenomena of emittance compensations caused by an electrode or the other extra forces but relaxation process of the space charge force itself, although detail mechanisms on self-linearization and eventual emittance reductions are not enough discussed.

Phenomena of decreasing or oscillating emittance are also reported in a high current induction linac [8,9]. They are not caused by the self-linearization but by nonlinear fields of gun electrode or space charge fields produced by nonlinear charge distribution of the beam. These phenomena are also important for clearly understandings on emittance evolution.

The scope of this paper is to show analytical mechanisms for those self-linearizations and the emittance reductions. Making clear for these mechanisms could contribute to new approach for designing the low-emittance electron injectors.

In Section 2, we show the reduced emittance examples for an ideal DC-accelerated continuous beam which is caused by the same mechanism as described in Refs. [3–7]. In Section 3, we discuss the

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self-linearization mechanisms which cause emittance reductions analytically. In Section 4, we give further examples of reduced emittance for a practical DC gun with a continuous beam and practical rf photoinjectors with pulsed beams.

2. Emittance reduction in an ideal DC-accelerated continuous beam

We show an example of the calculated reduction of the transverse emittance for an ideal DC-accelerated continuous beam in Fig. 1. The initial conditions are given in Table 1.

A continuous beam with an initial thermal emittance of 0 mrad is extracted from a perfectly conducting planar cathode at $z=0$ m. The calculation takes into account the image charge effects at the cathode. After the beam is extracted, it is continuously accelerated by a uniform DC electric field, E_z.

The calculation is performed using the two-dimensional code KUAD2 [10], which solves the Maxwell equations by the finite element method using fine quadratic triangular elements in a calculation area. Electron trajectories are traced from one boundary ($z=0$ m) to the other ($z=100$ mm) in the calculation area. The traces are iterated until the trajectories converge. Therefore, this code is only suitable for a continuous beam, and the space charge effects including the image charge effects at the cathode are expected to be calculated accurately.

The normalized transverse emittance is defined as

$$\epsilon_r(z)=\sqrt{\langle r^2\rangle_z\langle(\gamma\beta r')^2\rangle_z-\langle\gamma\beta r r'\rangle_z^2} \tag{1}$$

where β is the particle velocity normalized by the light velocity in vacuum, γ is the Lorenz factor of the particles, and the brackets $\langle\rangle_z$ denote the average of each traced particle parameter when the particle passes point z. This definition of emittance is comparable to that of the slice emittance rather than to that of the projected emittance of a bunch. The emittance increases rapidly immediately after the cathode, then decreases and starts to increase again at $z=30$ mm.

Fig. 2 shows the emittance reductions calculated by KUAD2 and GPT [11], which is a more widely used code than KUAD2. In GPT, the spacecharge2Dcircle element is used in the space charge calculation. Using this element, each particle is represented as a symmetrical circle about the beam axis, whose radius is equal to that of the particle itself. The space charge fields are calculated as sum of fields produced by each circle, and tracking of each particle is performed with these space charge fields. The other elements in GPT could not reproduce the reduction phenomena. The space-charge2Dcircle element cannot model the image charge effects at the cathode, therefore they are not taken into account in the calculation by KUAD2 for comparison in Fig. 2. Minimum emittance values are not in agreement between the two codes, although significant features in the emittance reduction are observed in both cases.

Fig. 3(a) shows the minimum emittance as a function of the number of particles used in GPT. The number of particles used in the calculation in Fig. 2 is 2×10^4, which corresponds to the leftmost plot in Fig. 3(a). The emittance still does not converge. Increasing the number of particles in GPT may result in more significant emittance reduction, although we cannot show the calculation results because of the calculation time. Meanwhile, the number of trajectories used in the calculation by KUAD2 in Fig. 1 is 4096, which corresponds to the leftmost plot in Fig. 3(b). In this case, the emittance converges satisfactorily. The number of trajectories used in the calculation by KUAD2 in Fig. 2 is also 4096. Therefore, the calculation by KUAD2, which shows good convergence, is expected to be more accurate than that by GPT with a limited number of particles. This is entirely because GPT is a time domain code and accordingly requires a longer calculation time than KUAD2, which is specially designed only for the simulations of continuous beams.

These evolution patterns of emittance are similar to the phenomena described in Ref. [3–7].

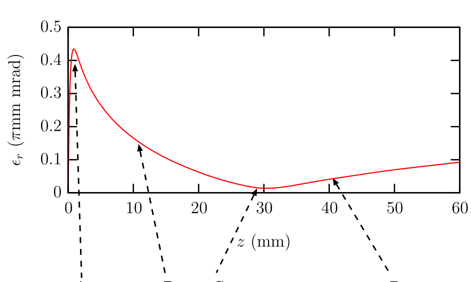

Fig. 1. Emittance behavior along a beam axis for an ideal DC-accelerated continuous beam. Points A, B, C and D are used for discussions in Section 3.

Table 1
Parameters for an ideal DC-accelerated continuous beam.

Extracted current from cathode	40 A/cm^2
Initial beam spot size	ϕ 2.0 mm uniform
Applied electric field, E_z	5.0 MV/m
Accelerated region	In all of a calculation area

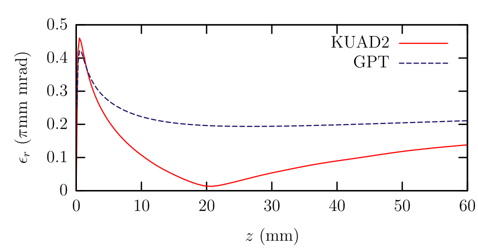

Fig. 2. Emittance reductions calculated by KUAD2 and GPT. The image charge effects at the cathode are not taken into account.

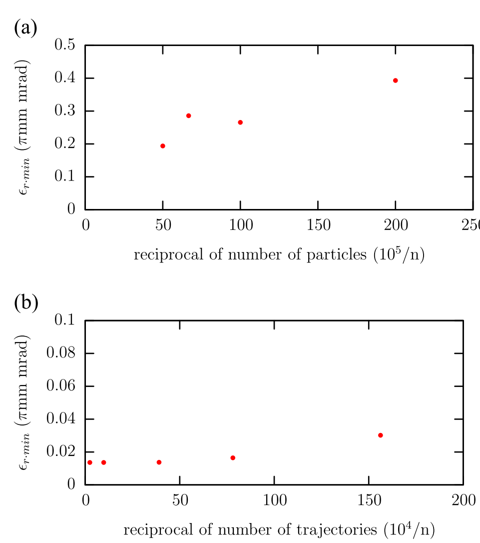

Fig. 3. Minimum emittances calculated by GPT and KUAD2. (a) Dependence of minimum emittance on number of particles used in GPT for the calculation shown in Fig. 2. (b) Dependence of minimum emittance on number of trajectories used in KUAD2 for the calculation shown in Fig. 1. Image charge effects at the cathode are taken into account.