# EFFECT OF THE LONG SOLENOID TUNNEL ON THE GROWTH OF EMITTANCE IN THE PNC HIGH POWER ELECTRON LINAC

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*Abstract*

We developed a new, three-dimensional simulation code ETRA3D to calculate beam dynamics in the injector of PNC s high-power, high-duty electron linac. In ETRA3D, beam dynamics are calculated by Hamiltonian equations and the space-charge force is calculated by the potentials produced by other electrons. The Hamiltonian is calculated at each time step and the length of the time step is varied by a change in the Hamiltonian to reduce the error of transition and the calculation time.

The precision of ETRA3D was checked by comparing it with the envelop equation. The agreement between them was good. We demonstrated the capabilities of ETRA3D by an example in which the electron beam is not launched along the axis of the series of the solenoid coils. Under this condition, two-dimensional codes can not calculate the beam dynamics.

## 1 INTRODUCTION

The Power Reactor and Nuclear Fuel Development Corporation (PNC) is developing a high-power, high-duty electron linac for various applications including the transmutation of fission products, a Free Electron Laser, and as a positron source [1,4]. The injector for this linac consists of an electron gun, two magnetic lenses, an RF chopper, chopper slits, a pre-buncher and a buncher. Its main specifications are listed below;

| | |
|---|---|
| Electron Gun High Voltage | 200 kV(DC), |
| Beam Current | 300 mA, |
| Pulse Length | 4 m sec, |
| Pulse Repetition | 50 Hz, |
| Duty Factor | 20 %, |
| RF Frequency | 1249.135 MHz. |

Table 1. Main specifications of the injector

There is 2.3 m concrete radiation shield between the electron gun room and the accelerator room. The electron beam must pass through this region without significant growth in emittance, as far as possible. In the low-energy-region, a space-charge force is the predominant factor causing growth in emittance. To reduce such growth, there is a series of solenoid coils, covered from the exit of the electron gun to the first accelerator guide, except between the RF chopper and chopper slits. The shape and strength of the magnetic field produced by the solenoid coils is arranged by estimating the space-charge effect properly. We developed a new, three-dimensional simulation code ETRA3D for the PNC injector which is designed to account for the space-charge force accurately.

## 2. SIMULATION CODE ETRA3D

In ETRA3D, the positions and momentums of each electron are calculated at each time step according to Hamiltonian equations.[5]

$$\mathrm{H} = \sum_{i}^{N} \sqrt{\left(p_i - eA_i\right)^2 c^2 + \left(m_e c^2\right)^2} + e\sum_{i}^{N} \frac{\phi_i}{2}, \tag{1}$$

$$\dot{x}_i = \frac{\left(p_{x_i} - eA_{x_i}\right)c^2}{\sqrt{\left(p_i - eA_i\right)^2 c^2 + \left(mc^2\right)^2}}, \tag{2}$$

$$\dot{p}_{x_i} = \frac{qc^2 \sum_{j}^{x_i,y_i,z_i} \left(p_j - eA_j\right)\frac{\partial A_j}{\partial x_i}}{\sqrt{\left(p_i - eA_i\right)^2 c^2 + \left(mc^2\right)^2}} - e\frac{\partial \phi_i}{\partial x_i}. \tag{3}$$

Actually, the positions and momentums of each electron are calculated from eq.(2) and (3) by the Runge-kutta method.

When calculating the space charge force, ETRA3D does not use mesh which is used in PARMELA. When the beam dynamics are calculated by PARMELA, a suitable mesh size and number of the mesh intervals must be chosen because the results are depend on them. In ETRA3D , the space-charge force is calculated by the potentials produced by other electrons, so that the space charge effects are accurately included in ETRA3D. However, if there is an increase in the number of electrons, a longer calculation time is needed. To reduce calculation time, ETRA3D restricts the range where the particles produce the potentials.

In ETRA3D, beam dynamics are calculated at each time step according to the Hamiltonian equations; the transition matrixes are not used. If the time step is large, calculation time will be reduced, but then errors will be introduced. It is difficult to find a suitable length of the time step because it strongly depends on several conditions, namely, the beam current, electron energy, beam radius and the number of the electrons used for the calculations. In ETRA3D, the length of the time step is varied automatically to reduce a change in Hamiltonian if the external fields do not depend on the time. When they do not depend on the time, the Hamiltonian must be conserved. The main purpose of ETRA3D is to calculate the beam dynamics in the injector of PNC s high-power, high-duty electron linac, especially the electron gun to

0-7803-4376-X/98/$10.00  

RF chopper. These parts do not include the RF fields; therefor, we can use this method. It can reduce the errors arising from the time step and save calculation time.

## 3 EXAMPLES AND DISCUSSIONS

*3.1 Envelop equation.*

The usual way to check the precision of a numerical procedure is to evaluate a variant for which a solution is known. We chose the case of beam dynamics in free space. The envelop of a round beam under the influence of the space charge can be calculated numerically by the envelop equation[6].

$$\frac{d^2R}{ds^2} + KR - \frac{\varepsilon^2}{R^3} = \frac{\xi}{2R}, \tag{4}$$

where R is the beam radius, and K, ε, and ξ are the focusing strengths, emittance, and space-charge parameter, respectively. The space charge parameter, ξ , is given by:

$$\xi = \frac{4Q^2 r_0 \lambda}{\beta^2 \gamma^2}, \tag{5}$$

where the beam particles have a charge Qe, λ is a uniform longitudinal particle-density, and $r_0$ is a classical radius of the electrons. We calculated the beam envelops using the envelop equation and ETRA3D under the following conditions:

| | |
|---|---|
| Beam current $I_e$ | 0.3A DC, |
| Electron energy $E_e$ | 200 keV, |
| Beam radius $r_b$ | 0.002 m, |
| Emittance ε | 0 π mm mrad. |

Table 2. The conditions for calculating the beam envelop

The results from the envelop equation and ETRA3D are shown in figs.1 and 2, respectively: the correspondence between them is close.

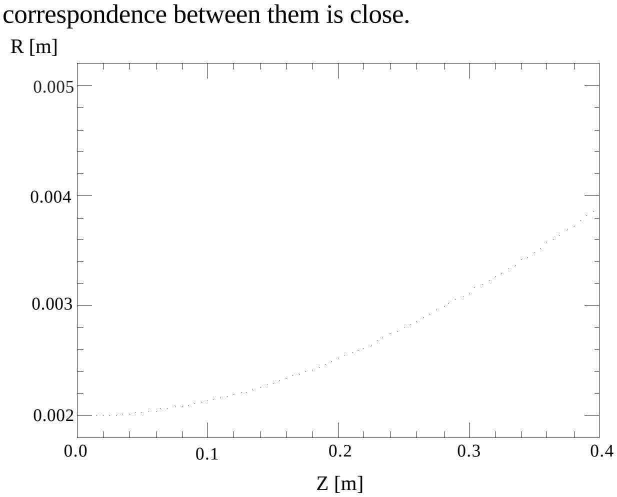


Figure 1 The result of envelop equation

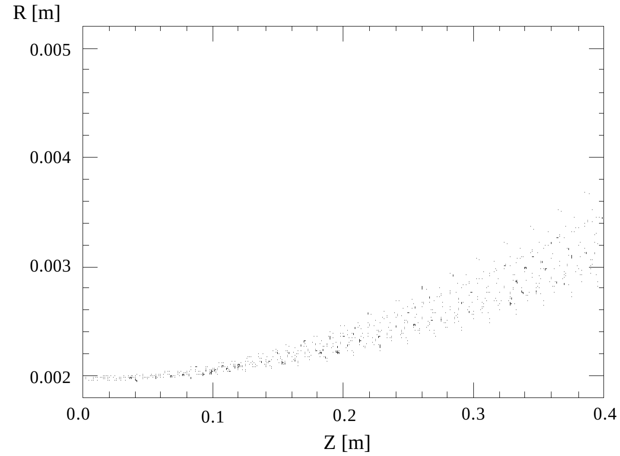


Figure 2 The result of ETRA3D

*3.2 beam dynamics in the series of the solenoid coils.*

To demonstrate the capabilities of our code, we choose the case in which the electron beam is not launched along the axis of the solenoid coils because of alignment errors between the electron gun and solenoid coils. We assumed that the cylindrically symmetric electron beams from the electron gun are at an angle to the axis of the solenoid coils.

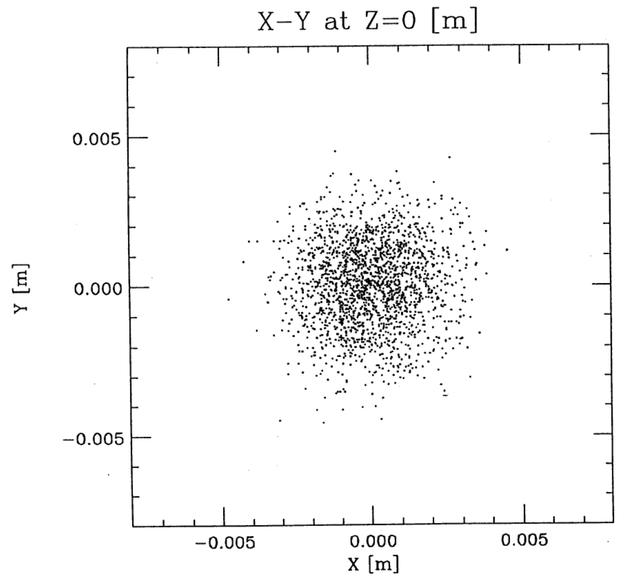


Figure 3. The beam distribution.

The beam current $I_c$ and the electron energy $E_e$ are same as in the example of the envelop calculations. The beam distribution at z=0 is shown in fig.3. The distributions of the beams are cylindrically symmetries and their centers coincides with the axis of the solenoid coils at z=0. But they are set at an angle to the axis of solenoid coils by adding 3 mm mrad to all $\theta_x$ and $\theta_y$. Figs.4 and 5, respectively, shown the magnetic field produced by the solenoid coils and the beam trajectories.

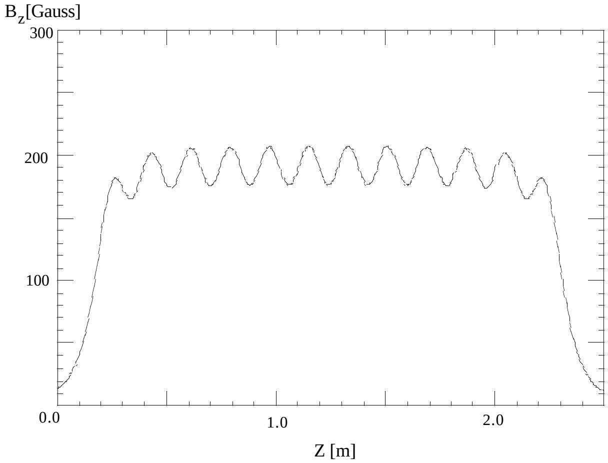


Figure 4. The magnetic field.

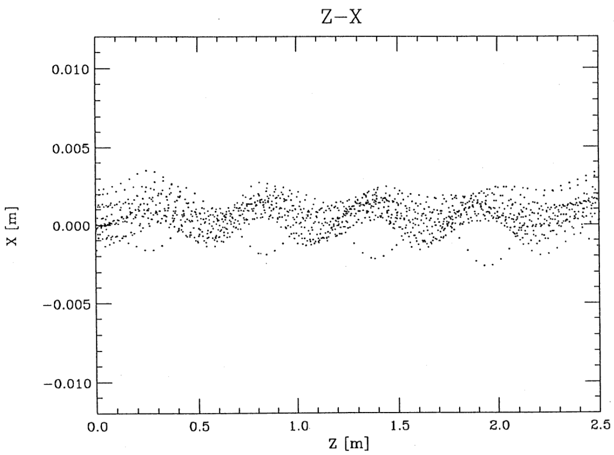


Figure 5. The beam trajectories.

In fig.5, the whole beams spiral along the axis of the solenoid coils.

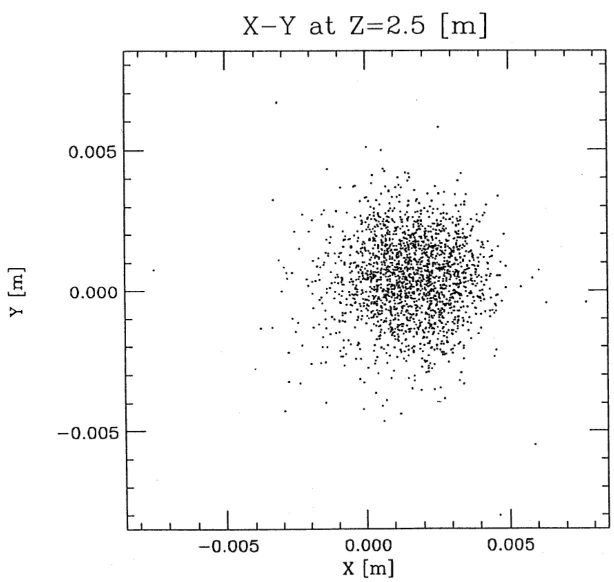


Figure 6. The beam distribution

The beam distribution at z = 2.5 m is shown in fig.6. It is clear from fig.6 that the centers of the beams do not coincide with the center of the solenoid coils, and the distributions of the beams has lost their cylindrical symmetry. If the centers of the beams do not coincide but the distributions still keep their shape, it is not difficult to launch the beam along the beam transport system. But if the shape of the distributions change, they can not be restored to the original shape. This simple example demonstrates that two-dimensional codes can not calculate beam dynamics when the electron beam is not launched along the axis of a perfectly aligned beam transport system.

## 4 ACKNOWLEDGeMENT


The authors are grateful Dr. An Yu for valuable discussions and Dr. Woodhead for editorial work. This work was performed under the auspices of the U.S. Department of Energy under Contract No. DE-AC02-76CH00016, and the Power Reactor and Nuclear Fuel Development Corporation.


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