# Particle Simulation Code for Non-Relativistic Electron Bunch in LASERTRON

Hiroshi Nishimura

The Institute for Solid State Physics,
The University of Tokyo
Midori-cho, Tanashi-shi, Tokyo 188, JAPAN

## Summary

A particle simulation code was developed to investigate the motion of the non-relativistic bunched electron beam in LASERTRON.[1,2] This code treats the interaction between the non-relativistic charged particles and the electromagnetic fields in the cavity structure with cylindrical symmetry. The evolution of the bunch shape was traced under the external electrostatic field for acceleration. Discussion was made on the maximum value of the photoemitted current in terms of critical charge.

## Introduction

LASERTRON is the laser triggered RF power source for the accelerating cavity of electron-positron linear collider in the several TeV region. The merit of the LASERTRON is the high conversion efficiency in the high power region because the beam is bunched from its origin. Fig.1. shows the conceptional structure of the LASERTRON. Electrons were photoemitted by the irradiation of the mode-locked laser whose intensity is modulated at the RF frequency of the LASERTRON. Because of the high intensity of the photoemitted electron bunch, the force of space charge and of the wake field are not negligible. The bunch shape changed by the force also changes the space and wake field. The interaction between the electron distribution and the field makes the analitical investigation difficult. Therefore, the numerical simulation was required on the electron motion in the high intensity and non-relativistic region. In this short paper, the outline of numerical method of the particle simulation code was described. The concept of the critical charge that determines the maximum of the available photoemitted current was also discussed.

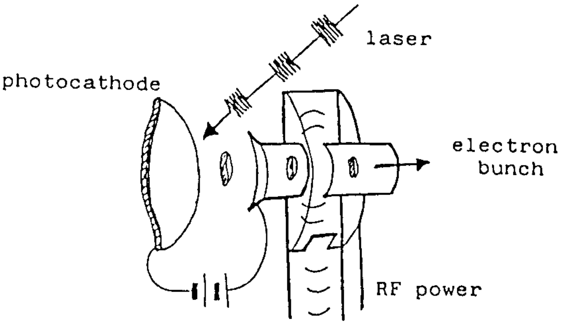

Fig.1. Conceptional Structure of LASERTRON

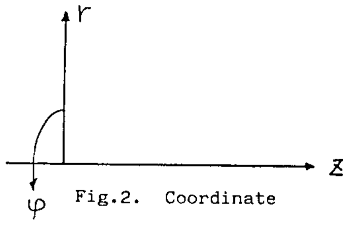

Fig.2. Coordinate

## Computational Method

The code was devided into two parts, the calculation of the fields and that of the particle motion. The field calculation was the extension of the numerical mesh method, which was first used by T.Weiland in his code BCI,[3] to the non-relativistic region in the sense that bunch shape changes and to the three dimentional bunch shape with cylindrical symmetry. And the particle-in-cell method of plasma physics[4] was used for particle motion. The coordinates were shown in the Fig.2.

The fundamental equations of the fields are the Maxwell eqations:

$$\mathrm{rot}\,\vec{E} = -\frac{\partial \vec{B}}{\partial t}\ , \qquad \mathrm{rot}\,\vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}\ , \qquad (1)$$

$$\mathrm{div}\,\vec{D} = \rho\ , \qquad \mathrm{div}\,\vec{B} = 0\ , \qquad (2)$$

$$\vec{D} = \varepsilon_0\vec{E}\ , \qquad \vec{B} = \mu_0\vec{H}\ .$$

The electric field is composed of the self-indused wake part and the external accelerating DC part. The latter is taken to be constant so the above equations are used for the wake part. From the symmetry, the field components are

$$\vec{E} = (\ E_z\ ,\ E_r\ ,\ 0\ )\ ,\quad \vec{H} = (\ 0\ ,\ 0\ ,\ H_\varphi\ )\ .$$

Eqs.(1) are treated as evoluation eqs. and (2) as initial conditions that are solved numerically for the given initial distribution of the particles.

The computational method for the eqs.(1) is the mesh method of the BCI with the extension of the following points:

(1) Solving the initial value problem for the electric field regarding it as static for the small initial velocity. This was done by solving the difference equation for the scalar potential. The solution was obtained by iteration for the given initial distribution of superparticles under the boundary conditions of the cavity.

(2) Off-axis mesh points can have the current component because the bunch has the 2 dimentional distribution. Currents are also devided onto the mesh points as charges. For example, the equation for the Ez becomes

$$E_{z\,ji}^{\,n+1} = E_{z\,ji}^{\,n} + \frac{\Delta t}{\varepsilon_0 \Delta x}\left(\left(1 + \frac{1}{2i}\right)H_{\varphi\,ji}^{\,n} - \left(1 - \frac{1}{2i}\right)H_{\varphi\,ji-1}^{\,n}\right) - \frac{\Delta t}{\varepsilon_0} J_{z\,ji}^{\,n}\ ,$$

where j,i,n represent the mesh at $z_j = j\Delta x$, $r_i = i\Delta x$ and $t_n = n\Delta t$.

(3) Including the external electric field for acceleration. The equation of the particle motion is

$$(\ \gamma v_z\ )_{n+1} = (\ \gamma v_z\ )_n + \frac{e}{m_0}\Delta t\ (\ E_z\ - v_r B_\varphi\ )_n\ ,$$

$$(\ \gamma v_r\ )_{n+1} = (\ \gamma v_r\ )_n + \frac{e}{m_0}\Delta t\ (\ E_r\ + v_z B_\varphi\ )_n\ ,$$

where $\gamma = (\ 1 - \vec{v}\cdot\vec{v}\ /\ c^2\ )^{-\frac{1}{2}}$, $\vec{v} = (\ v_z,\ v_r,\ 0\ )$ is the velocity, c = light velocity, $m_0$ = rest mass of the electron.

Simulation was carried out in the following way.
(1) Solve the initial value problem.
(2) Solve the field evolution.
(3) Solve the particle evolution.
(4) Repeat (2) and (3) for appropriate times.

(5) Make outputs.

Thus, the self-consistency between the particle distribution and the wake field is realized in this simulation.

Output examples of the code.

Fig.3. shows the simplified model of "LASERTRON Mark I-D" for the numerical analysis. The number of mesh is 60 x 30 and the size is 1 mm/mesh. This model is composed of three parts, acceleration gap (a), beam duct (b) and output cavity (c), where (a) and (b) are devided by the metal mesh of anode. The acceleration voltage is 100 KV for the gap of 20 mm. The bunch is composed of 40 superparticles in Z-R plane, 4 in Z and 10 in R direction. The charge takes the waterbag distribution in a disk-like bunch of 5 mm in radius and 0.6 mm in thickness at initial state. The initial velocity is 0.01 x light velocity. In Fig.3, the field induced by the bunch of .1 nC after the acceleration was shown, where the dash represents the electric field. The position of the bunch is the center of the anode and the wave front because the velocity of the bunch is about half of the light velocity. In Fig.4, three dimensional display is made with the third axis V, where V is the magnitude of scalar potential in the Coulomb gauge. This shows the deformation of acceleration field due to the space charge of bunch of 10 nC that is gradually debunching.

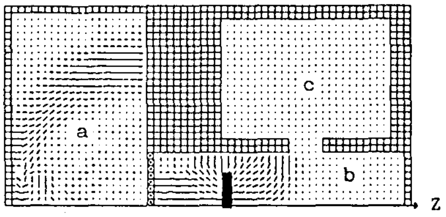

Fig.3. Output (1)

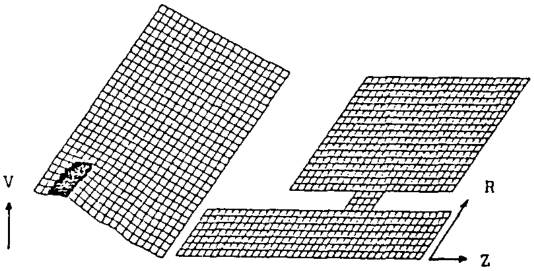

Fig.4. Output (2)

## Discussion

Simulation code was made and used for many parameter sets, and some scale to measure the charge is required to make physical interpretations on them. In this section, we introduce the concepts of surface charge limit, space charge limit and critical charge, the maximum charge that can be extracted from photocathode by the irradiation of the one laser pulse.

### Surface Charge Limit

The time interval of the laser pulse is 350 psec for the S band, but the pulse width is several ten psec that is shorter than the filling time of the charge onto the cathode. Therefore the photoemitted charge by the single laser pulse is less or equal to the surface charge on cathode of the area of the laser cross section. Thus the surface charge limit, Qsf, is defined as

$$Qsf = E_{\perp} S_L , \qquad (4)$$

where $E_{\perp}$ is the electric field strength on the surface that is determined by the external accelerating voltage and $S_L$ is the cross section of the laser beam.

### Space Charge Limit

The space charge also limits the maximum emitted current. The effect of the space charge force at the surface of cathode can be treated localy, so the one dimensional disk model is intuitive to estimate this. In this model, space charge limit is defined as the charge with which the tail of the bunch is unable to be emitted from the surface because of the coulomb force due to the rest of the bunch. Longitudinal space charge field, Es, is given by $Es = Q/2\varepsilon_0 S_B$, with Q = total charge in bunch, $S_B$= cross section of bunch = $S_L$.Space charge limit, Qsp, is defined as

$$Es = E_{\perp} \text{ for } Q = Qsp ,$$

therefore

$$Qsp = 2\,Qsf . \qquad (5)$$

In the disk model, electron beam is fully debunched in the space charge limit, but the two dimensional numerical simulation by the code shows that the same situation occurs for the bunch with charge several times larger than above Qsp because self-field has the transverse component that makes a decrease in the longitudinal debunching force. The debunching of a bunch with Q = Qsp is not so large because the velocity of debunching is much slower than that of the center of mass of the bunch. It is possible to generate RF power by a bunch with Q = Qsp if it is emitted. This means that there must be a form factor that depends on the struncture of LASERTRON in the definission of the space charge limit. Therefore the definission, Eq.(5), is to be regarded as the minimum of the space charge limit.

From eqs.(4) and (5), it is concluded that the maximum emitted current is determined not by the space charge, but by the critical charge. Results of the simulations show that the emitted bunch with charge Q = Qsp will be accelerated by the external field with small debunching. In case of LASERTRON Mark-I, it was found by the simulation that there is no severe problem with beam dynamics. Problems with Mark-I were mainly concerning with the emission process, including vacuum or degas, quantum efficiency and maximum available accelerating voltage.

### Critical Charge

Critical charge, Qc, is defined as the maximum charge that can be emitted by the single laser pulse. From the above discussion, it is the surface charge limit,

$$Qc = Qsf.$$

The maximum photo current, Ic, is given by

$$Ic = Qc \cdot f_{RF} ,$$

where $f_{RF}$ is the RF frequency.

### Saturation

The saturation of the emission occures from two limitaions, one is from the critical charge and the other is from the laser power. Of course, there are many other factors that limits the emission, we take above two factor into consideration. When the laser is weak, it limits the emission current strength, but when laser power is strong, the current is limited by the critical charge. Therefore, when the laser power is strong enough to emit critical charge, the emission current strength shows linear dependence on the accelerating voltage as shown in Fig.5. This linear dependence of current on voltage is one of the most significiant characterS of the LASERTRON.

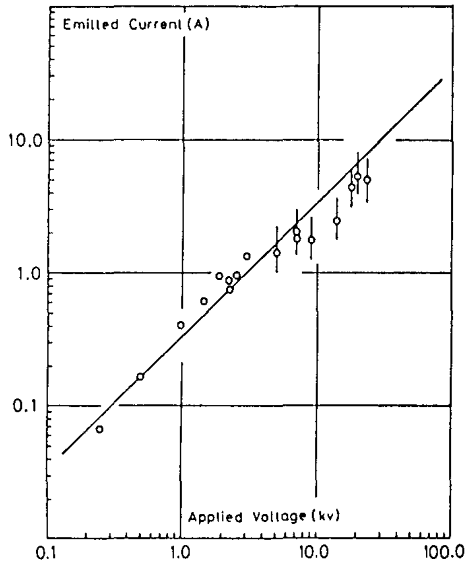

Fig.5. Voltage dependence of Emission Current From Ref.(1)

## Conclusion

The simulation code was made and used for LASERTRON, and it was found that the most important problem to be solved is concerned with the emission process of electrons. There may be no severe difficulties with beam dynamics in the acceleration after the emission. Investigations should be done on the structure of the gun in order to increase the critical charge.

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