

# Beam Emittance and the Effects of the RF, Space Charge and Wake Fields - Application to the ATF Photoelectron Beam

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**Abstract:** Laser driven photoelectron guns are of interest for use in new methods of accelerations, future development of Linear Colliders and new experiments such as Free Electron Laser (FEL) and Inverse Free Electron Laser (IFEL). Such guns are potential source of low emittance - high current and short bunch length electron beams, where the emitted electrons are accelerated quickly to a relativistic energy by a strong RF, electric field in the cavity. We present a brief overview of the beam dynamic studies, e.g. emittance for the Brookhaven National Laboratory (BNL) ATF high brightness photocathode radio frequency gun (now in operation), and show the effects of the RF, Space Charge, and Wake fields on the photoelectrons.

## I. INTRODUCTION

This presentation includes beam dynamic analysis (e.g. calculations of emittance, energy, etc), with the effects of the RF, Self - field and Wake field on the particles in a cavity, e.g. photoelectrons, in the BNL photoelectron gun cavity. In that we show the effects of the interactions between the charged particles and the RF, Space Charge and the Wake fields on the beam dynamics. In section III, we give a sketch of the formulation used. (For more detailed analysis of the Gun e.g. see the Refs.)

## II. BNL PHOTOCATHODE GUN:

BNL Gun consists of a 1 1/2 cell, pi mode, resonant disk loaded structure (with the structure inner diameter of 83.03 mm, and length of 78.75 mm, operating at 2856 MHz), used as the injector to the 50 MeV electron LINAC at BNL Accelerator Test Facility (ATF). Designed to produce electron bunches which can be synchronized with the pico second (ps) pulse of 100 - Gwatt CO2 laser. The beam brightness is maximized by placing the photocathode at the end wall of the cavity that supports a strong standing wave field; the electric field gradients on the cathode is 100 MV/m.

Figure 1, shows a sketch of the BNL photocathode gun.

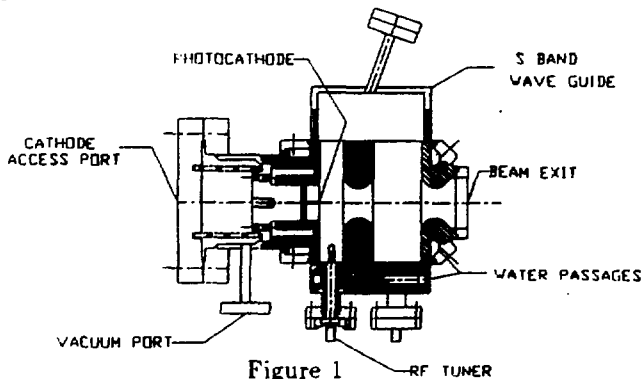


Figure 1

Figure 2 a,b,c, shows variations in the normalized transverse, longitudinal emittance, and kinetic energy (and momentum), with respect to the variations in the

initial phase angle. From these we note that the lowest emittance (and the highest momentum) occurs at the initial phase of  $\sim 55^\circ$ .

Thus in the following figures we illustrate the effects of the self - field, and wake field at various points along the cavity for the "standard" BNL gun, with 100 MV/m field gradient on the cathode, the laser spot size of 3 mm, and the laser pulse width of 2 ps, (i.e. .6mm). For clarity, we note the following definition used in this analysis: Normalized Transverse Emittance =  $\sqrt{x^2 p_x^2 - (x p_x)^2}$ . RMS Transverse Emittance =  $\sqrt{x^2 x'^2 - (x x')^2}$ , (for discussion of emittance including higher order moments see [3]).

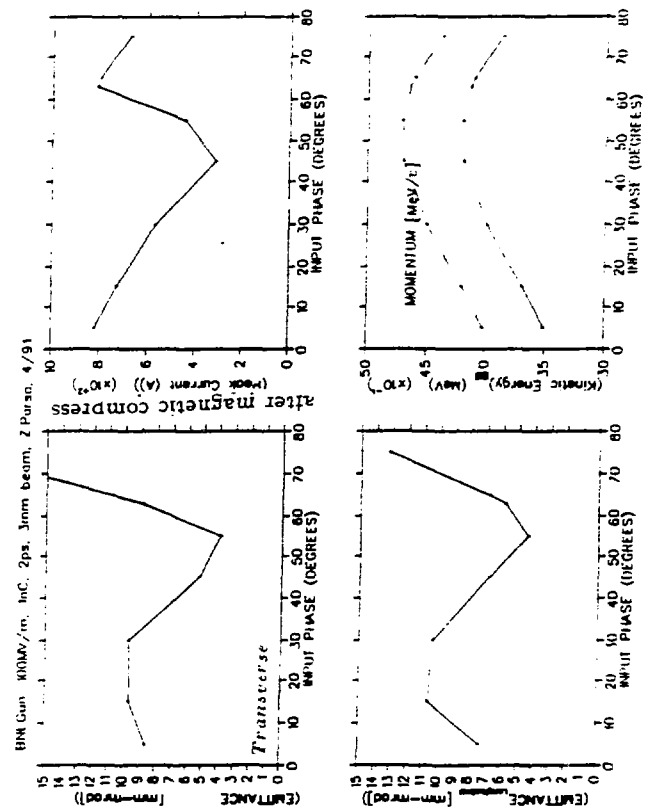


Figure 2

The kinetic energy of the particles on the cathode surface is 0.2 eV, the normalized transverse emittance is 1.28 mm-mrad. The particles are distributed uniformly in radial divergence and their charge follow a Maxwellian distribution in radius in order to get a gaussian distribution for the bunch charge density. The  $\sigma_R$  of the distribution used is 3mm thus the RMS radius =  $\sqrt{2} \times \sigma_R$  is  $\sim 4.2$  mm, with the Max Divergence = 1.561 rad, and the RMS Divergence of 0.904 rad.

**MASTER**

Figures 3 a-e show the constant field lines and the positions of the bunch at which points, the interaction between the bunch self field and the wake-field induced in the cavity (by the bunch as it passes through the cavity) are shown in Figure 4. Figure 3e, shows the position of the bunch at  $z \sim 98$  mm, where the normalized transverse emittance  $\epsilon_t^N = 7.2$  mm-mrad, the Average kinetic energy is 4.2 MeV. Additional information on the beam dynamics of the bunch at this position are shown in Figures 5-7. Figure 5, shows the deriving current density  $J_z$  (produced by the bunch shown in Fig. 3e), and the field as functions of  $z$ . Figure 6, shows the beam emittance, energy, and the rms bunch length as functions of  $z$ , and Fig. 7 shows the phase space plot of  $R$  vs  $P_R$ .

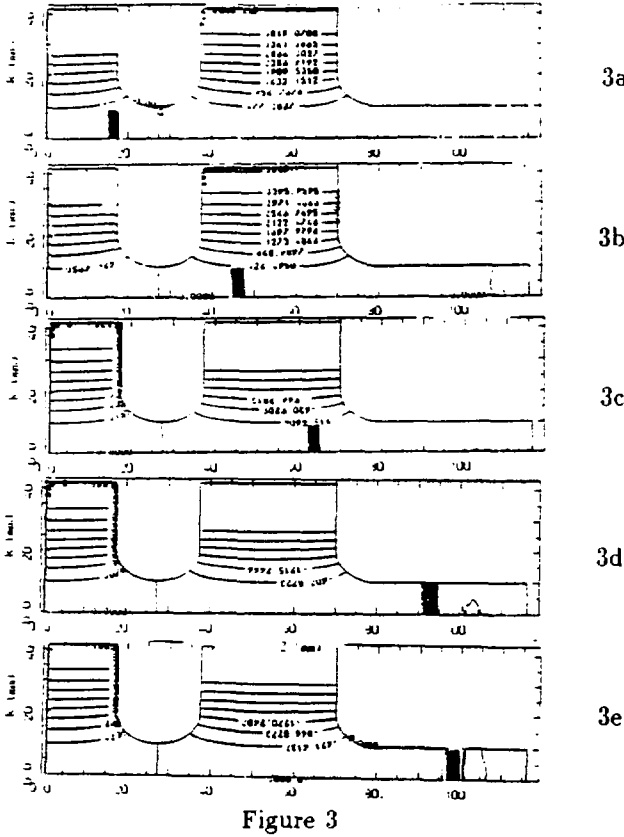


Figure 3

### III. FORMALISM

This section provides a brief (due to space limitations) sketch of the formalism used to study the interaction of charged particle bunches with the fields inside the accelerating structures, (e.g. the BNL photocathode gun discussed in section II).

We assumed that the fields  $\vec{E} = E(r, z, t)$  and  $\vec{H} = H(r, z, t)$ ; and the source  $J = J(r, z, t)$ , and  $\rho = \rho(r, z, t)$  are axisymmetrical, hence the wave equations can be expressed as two uncoupled sets of  $TM$ -like mode ( $H_\phi$ ,  $E_r$ ,  $E_z$ ) and  $TE$ -like mode equations.

Since a general  $TM$  field can be expanded as a sum of infinite  $TM_{0np}$  modes of a resonant cavity; and a general  $TE$  field can be expanded as a sum of infinite  $TE_{0np}$  modes of a resonance cavity (with  $J_r$  and  $J_z$  as the driving currents for the  $TM$  field and  $J_\phi$  as the driving current for the  $TE$  field), a charged particle  $q$  moving with a velocity  $\vec{v} = v_r \vec{e}_r + v_z \vec{k}$  inside a  $TM$  field is

subject to a force  $\vec{F} = F_r \vec{e}_r + F_z \vec{k}$  and gives rise to a current  $J = J_r \vec{e}_r + J_z \vec{k}$ . When the particle is inside a  $TE$  field, it is subject to a force  $\vec{F} = F_\phi \vec{e}_\phi$  that gives rise to a current  $\vec{J} = J_r \vec{e}_r + J_\phi \vec{e}_\phi + J_z \vec{k}$ . Then for an initial driving current of the type;  $\vec{J} = (J_r(r, z, t), J_z(r, z, t))$  in presence of a  $TM$  field,

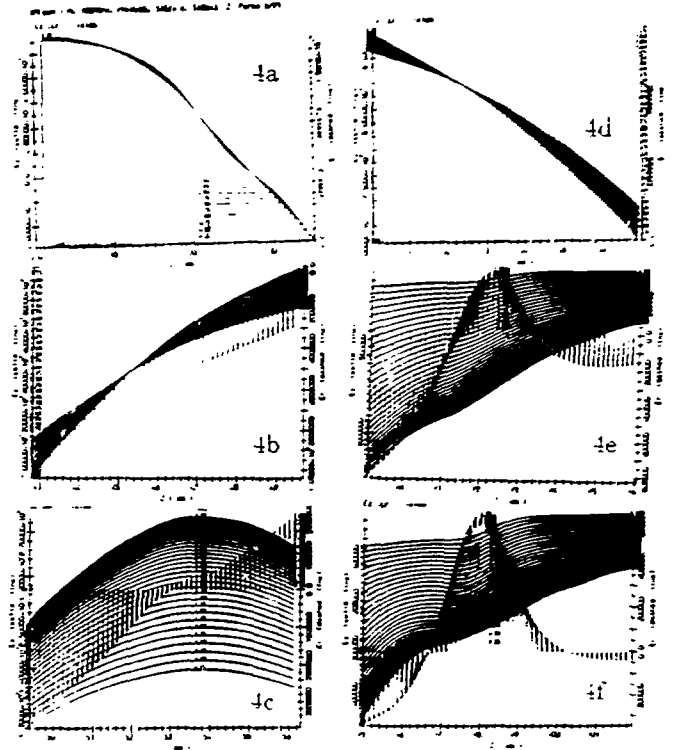


Figure 4

$$\nabla^2 \vec{H} - \frac{1}{c^2} \frac{\partial^2 \vec{H}}{\partial t^2} = -\nabla \times \vec{J} \quad (1)$$

and

$$\frac{d\vec{p}}{dt} = q \left( \vec{E} + \vec{v} \times \vec{B} \right) \quad (2)$$

form a set of "self-consistent" system of equations, where  $\vec{v} = (v_r, v_z)$ . thus the beam-cavity interaction can be completely described, from the point of view of the field propagations, by means of one scalar equation:

$$L\phi = \frac{1}{c^2} \frac{\partial^2 \phi}{\partial t^2} - r \frac{\partial J_z}{\partial r} - r \frac{\partial J_r}{\partial z} \quad (3)$$

This hyperbolic equation gives the time evolution of the fields from some initial time  $t = 0$  (knowing the driving current) where  $L \equiv \frac{\partial^2}{\partial z^2} + \frac{\partial^2}{\partial r^2} - \frac{1}{r} \frac{\partial}{\partial r}$ , and the pseudo scalar potential  $\phi = rH_\phi$ ;  $\vec{H}_\phi = H_\phi(r, z, t)$ ,  $J_r = J_r(r, z, t)$  and  $J_z = J_z(r, z, t)$ . The driving current is due to the motion of the bunch of particles around the axis of cavity, and since the deriving current must be axisymmetrical the particles (of the bunch) can only move in the  $r-z$  plane; (so their charge density and current are the same as those produced by "rings of charge" centered on  $z$ -axis); can move axially or expand radially.

Using the standard Finite Difference Method (FDM) that allows the transform of the differential problems into

the algebraic ones, via the discretization of the operators ( $L$ ) and functions ( $\phi$ ,  $J_r$ ,  $J_z$ ), over a mesh, one solves simultaneously the equations, for the field propagation and the equation of motion for the particles. Thus the effects of the e.m. interactions on the beam dynamics properties, such as emittances, energy spreads, ... can be obtained (e.g. with the code ITACA), knowing the field  $H_\phi$  at each mesh point at present and at next integration time the equation is integrated with respect to the standard R. K. methods

$$\begin{aligned} \frac{\partial E_r}{\partial \tau} &= -\frac{\partial H_\phi}{\partial z} - J_r \\ \frac{\partial E_z}{\partial \tau} &= \frac{1}{r} \frac{\partial (r H_\phi)}{\partial r} - J_z \end{aligned} \quad (4)$$

where the charge distribution obtained becomes:

$$\begin{aligned} \rho_i(r, r_i, z, z_i) &= e^{-\frac{(z-z_i)^2}{2\sigma_z^2} - \frac{(r-r_i)^2}{2\sigma_r^2}} e^{-\left(\frac{r-r_i}{\sigma_r}\right)} \alpha_{0i} \\ \alpha_{0i} &= \frac{q_i}{(2\pi)^{3/2} \sigma_r^2 \sigma_z} \cdot I_0\left(\frac{r r_i}{\sigma_r^2}\right) \end{aligned} \quad (5)$$

and the corresponding current densities become:

$$J_z = \beta_{\parallel}^i \alpha_{0i} e^{-\frac{(z-z_i)^2}{2\sigma_z^2}} e^{-\frac{(r-r_i)^2}{2\sigma_r^2}} \quad (6)$$

$$J_r = \beta_{\perp}^i \alpha_{1i} e^{-\frac{(z-z_i)^2}{2\sigma_z^2}} e^{-\frac{(r-r_i)^2}{2\sigma_r^2}} \quad (7)$$

which satisfy the continuity equation, guarantees gauge invariance ( $\nabla \cdot \vec{E} - \rho/\epsilon = 0$ ) and minimizes the unphysical fluctuation in the driving current.

Where, in Eqs. (5-7)  $q_i$ ,  $\sigma_r$ ,  $\sigma_z$  are the charge and coordinates of the  $i$ -th particle;  $\beta_{\perp i}$  and  $\beta_{\parallel i}$  are the radial and axial components of the  $i$ -th particle beta respectively;  $I_0$  and  $I_1$  are the 0-th and 1st-order modified Bessel function of the first kind; and  $\alpha_{1i} = \frac{q_i c}{(2\pi)^{3/2} \sigma_r^2 \sigma_z} I_1\left(\frac{r r_i}{\sigma_r^2}\right)$  (For detailed formulation see references.)

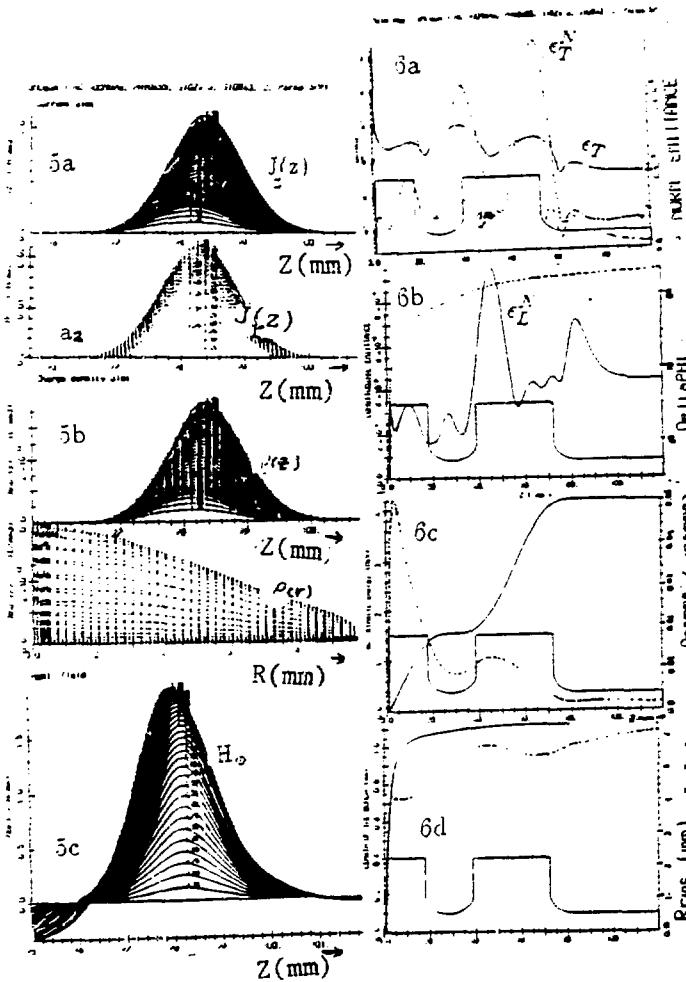


Figure 5

Figure 6

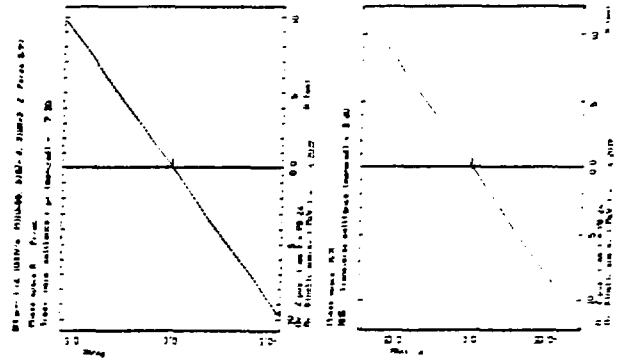


Figure 7

SUMMARY: We presented some of the results of our studies for the BNL RF Gun, laser induced photoelectrons and showed the interaction between the self field and the wake induced in the cavity. we also presented the beam parameters obtained at the gun exit ( $z \sim 98$  mm), and provided an overview of the formalism used. With this method our preliminary analysis indicate (Fig 2), that at 100 MV/m field on the cathode and 1nC charge the initial phase of  $55^\circ$  will provide smallest emittance and largest Kinetic energy at the gun exit. Due to space limitation, additional information is given in References.

#### REFERENCES

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