

# SIMULATIONS OF FIELD-EMISSION ELECTRON BEAMS FROM CNT CATHODES IN RF PHOTOINJECTORS

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## Abstract

Average field emission currents of up to 700 mA were produced by Carbon Nano Tube (CNT) cathodes in a 1.3 GHz RF gun at Fermilab High Brightness Electron Source Lab. (HBESL). The CNT cathodes were manufactured at Xintek and tested under DC conditions at RadiaBeam. The electron beam intensity as well as the other beam properties are directly related to the time-dependent electric field at the cathode and the geometry of the RF gun. This report focuses on simulations of the electron beam generated through field-emission and the results are compared with experimental measurements. These simulations were performed with the time-dependent Particle In Cell (PIC) code WARP.

cal single-wall or multi-wall nanostructures which can be deposited on the surface of a metallic cathode. They have extremely low electrical resistivity and are very robust at high temperature. Due to small diameter (1-50 nm) and high aspect ratio ( $\sim 1000$ ) the enhancement factor is high (typically several hundreds).

To maintain the simplicity of the injector it is desirable that the external applied electric field produced by the standard RF system, needed anyway to further accelerate the beam, is enough to produce the desired beam intensity. In this contribution we show that cathodes deposited with multi-wall randomly oriented CNT's can produce ampere-level beam currents when they are simply exposed to the fields inside a standard RF gun.

## INTRODUCTION

To increase the power of the Free Electron Laser (FEL) to megawatt-level the injectors must be upgraded such that they could provide ampere level of average electron beam current [1]. Alternatively, low beam charge (picocoulomb-level) and extremely low emittance ( $10^{-10}$  m) are desirable to build compact ultra high brightness X-ray sources [2, 3].

Cathodes with deposited Field-Emitters (FE's) were extensively studied during the last decade and are proven to have some obvious advantages compared with the more standard photoemission or thermoionic cathodes. First of all there is no need for additional expensive components to extract the electrons from cathode: lasers (photoemission) and heating systems (thermoionic). In the case of FE's the electrons are extracted by an external electric field through quantum tunneling. The local electric field  $E$  at the surface of the FE is typically much larger than the applied electric field  $E_a$  by a factor  $\beta$  (enhancement factor) dependant on FE geometry. The current density of the electron beam is given by Fowler-Nordheim (FN) formula:  $j = aE^2 \exp(-\frac{b}{E})$  where constants  $a = \frac{1.42 \times 10^{-6}}{\Phi} \exp(\frac{10.4}{\sqrt{\Phi}})$  and  $b = -6.56 \times 10^{-9} \Phi^{3/2}$  depend on cathode material through the work function  $\Phi$  (in units of eV) [4] and  $E (= \beta E_a)$  is the external electric field at the surface of the FE.

Large effective emitting area combined with large enhancement factor are key elements to design efficient FE cathodes. In the recent years Carbon Nano Tubes (CNT's) proved to be promising FE candidates. CNT's are cylindrical

## EXPERIMENTAL SETUP

The testing of the CNT FE cathodes was carried out at Fermilab High Brightness Electron Source Lab (HBESL) and described in [5]. The schematic top-view of the injector relevant components is shown in Fig. 1. The main component of this injector (normally used as a photoinjector) consists of a 1.5-cell resonant RF gun operated at 1.3 GHz. The RF power is provided by a 2 MW klystron in macropulses with adjustable duration and 0.5 Hz repetition rate. The typical macropulse duration for these experiments was chosen at 40  $\mu$ s to compromise between achieving maximum charge in the bunch train and avoiding any significant energy depletion inside the gun due to beam loading. The peak field at the cathode can reach about 35 MV/m.

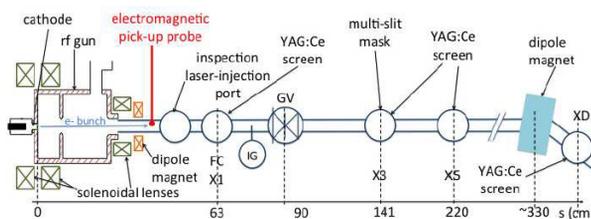


Figure 1: Simplified schematic top-view layout of HBESL injector.

The RF gun is embedded in the external magnetic field created by three solenoids to control the transverse size of the electron beam and to partially compensate the emittance growth. The beam current is measured with a Fara-

day cup "FC" and the transverse beam profile can be monitored at positions designated by: "X1", "X3" and "X5" (Fig. 1). In addition to the normal YAG screen at "X3" there is an insertable multi-slit mask used to measure the transverse emittance. The dipole magnet is used to determine beam momentum, and the electromagnetic pick-up probe which can measure the transient fields due to passing electron bunches was used to estimate the single bunch duration.

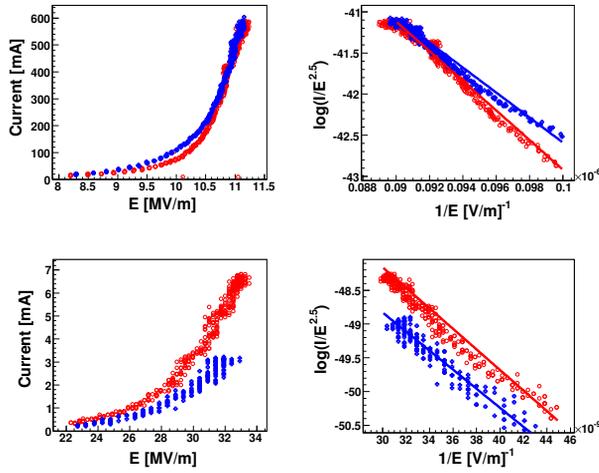


Figure 2: I-E curves (left) and Fowler-Nordheim plots (right) for the "large cathode" (top) and "small cathode" (bottom). For the "large cathode" the measurements were performed with solenoids off (red) and solenoids on (blue). In the case of the "small cathode" the results for the early measurements are shown in red and measurements performed two months later in blue.

In our experiments we tested a "large cathode" with CNT's deposited inside a 15 mm diameter circle. Another cathode ("small") with deposition area 100 times smaller was also tested. The measured I-E curves (current vs. field intensity) are shown on the left side in Fig. 2 for both cathodes. Based on FN formula the dependence  $\log(I/E^2)$  vs.  $1/E$  should be linear. However, since we only measure the average current over an RF period, the linearity applies to  $\log(I/E^{2.5})$  vs  $1/E$  [6] and it is shown for the experimental data in Fig. 2 (right side).

### BEAM SIMULATIONS

Beam dynamics simulations were performed with the PIC time-dependent WARP code [7] which includes a particle generation module based on field-emission model [8]. In these simulations the macroparticles are emitted on the cathode surface and the charge distribution is uniform in the transverse plane. The longitudinal charge distribution mimics the FN formula with the values of beam current and field enhancement factor  $\beta$  same as derived from the experimental measurements (Fig. 2).

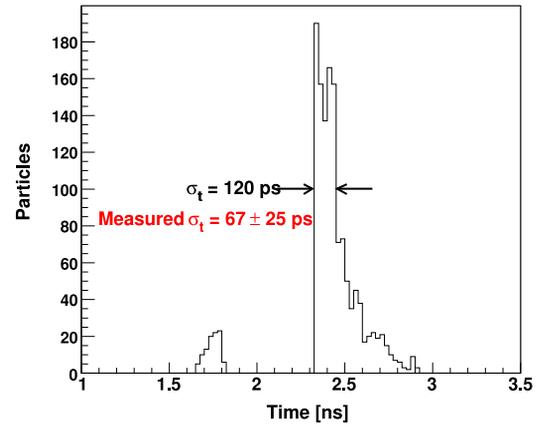


Figure 3: Histogram of particle arrival time at the plane  $z = 0.32$  m. This simulation was performed with the "large cathode" and the peak field was set at 11.2 MV/m..

The most critical feature of the electron bunches obtained through FE process in this RF gun is the large longitudinal length when compared with beams generated in photoinjectors. These CNT's have a large enhancement factor ( $\beta \approx 500$ ) and therefore the amplitude of the field at cathode surface is above the emission threshold for a large portion of the RF period (several hundreds of picoseconds). In the case of the "large cathode" when the peak field at cathode is 11.2 MV/m (Fig. 3) simulations indicate  $\sigma_t = 120$  ps just downstream of the gun. The secondary peak in Figure 3 is determined by electrons emitted during the descending E-field at cathode that can be trapped inside the gun for more than an RF period. The measured value of the bunch length [5]  $\sigma_t = 67 \pm 25$  ps is somewhat smaller but still consistent with simulations.

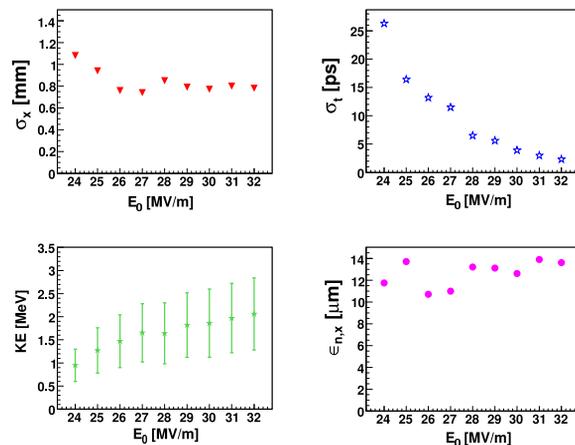


Figure 4: Projections of the beam phase-space at the plane  $z = 0.32$  m as a function of the peak electric field at the "small cathode".

In the case of the "small cathode" the threshold for the external electric field to produce a detectable beam current is closer to the peak value and therefore the time window for emission is significantly narrower. Depending on the peak field at the cathode the bunch length is in the range 3 to 25 ps (rms) Fig. 4.

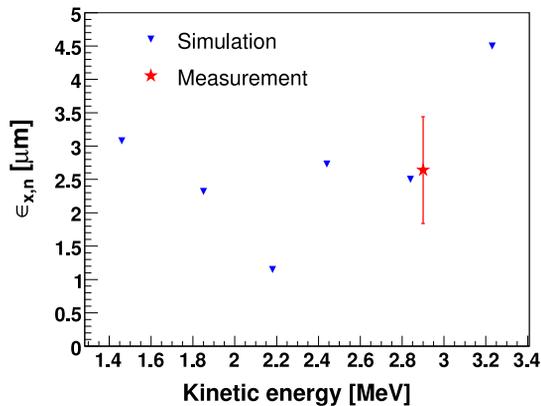


Figure 5: Normalized transverse emittance evaluated for different kinetic energy slices.

The relatively large electron bunch length combined with the large energy spread ( $\delta \equiv \frac{\Delta W}{W} \approx 30\%$  Fig. 4) makes the measurement of the transverse beam emittance difficult because of the quads' chromatic effect. During the experimental measurement of the transverse emittance we actually select only a portion of the beam with about 5% energy spread around the central value of 2.9 MeV. Figure 5 shows the simulations for the normalized transverse emittance when only particles within narrow energy slices are considered. In this case ("small cathode" and 5 mA current) the measured value of  $2.6 \pm 0.8 \mu\text{m}$  is consistent with "slice" simulations of the normalized transverse emittance.

Projections of the phase space at the exit from the gun ( $z=0.32$  m) for the case of "large cathode", high current (500 mA) and peak field at cathode 11.2 MV/m are shown in Fig. 6. As mentioned before the main features are large energy spread ( $\approx 35\%$ ) large bunch duration ( $\sigma_t \approx 120$  ps) and secondary peak formation due to beam trapped inside the gun.

## CONCLUSIONS

Field emitted current from the CNT's deposited on a circular area with diameter of 1.5 cm is close to 1 A when exposed to RF fields with relatively low peak field (12 MV/m). Beam dynamics simulations performed with the time-dependent PIC code WARP show good agreement with measurements.

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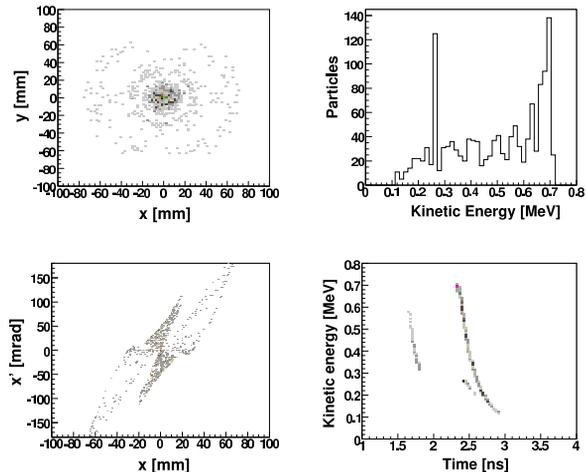


Figure 6: Projections of the beam phase-space at the plane  $z = 0.32$  m. The beam was produced with the "large cathode".

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