

# Experimental Results of the ATF In-line Injection System

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The initial experimental results of the Brookhaven accelerator test facility (ATF) in-line injector is presented. The ATF in-line injector employed a full copper RF gun with a pair of solenoid magnets for emittance compensation. The maximum acceleration field of the RF gun was measured to be 130 MV/m. The electron yield from the copper cathode was maximized using p-polarized laser and the Schottky effect. The quantum efficiency under optimum conditions was measured to be 0.04%. The measured electron bunch length was less than 11 ps, which agreed with the laser pulse length measurement using a streak camera. The normalized rms. emittance for 0.25 nC charge is  $0.9 \pm 0.1$  mm-mrad, which is almost four times smaller than the emittance predicted by the space-charge effect for a non-emittance compensation photocathode RF gun. The normalized rms emittance for 0.6 nC charge was measured range from 1 to 3 mm-mrad. This measurement was first experimental demonstration of emittance compensation in a high-gradient, S-band photocathode RF gun.

## I. INTRODUCTION

A new photocathode RF gun injector based on the emittance compensation technique [1] was installed at the Brookhaven accelerator test facility (ATF).

The ATF is a facility dedicated for FEL and laser acceleration research [2], consisting of a laser driven RF gun injector [3], 70 MeV linac and experimental beam lines.

We will present experimental results of photoemission and electron beam emittance measurement for the emittance compensation RF gun. Comparison of experimental results with simple analytical predictions show that the measured emittance smaller than the uncompensated emittance. This indicates that the emittance compensation actually works.

## II. THE ATF IN-LINE INJECTOR

The design of the injector [4] optimized the distance between the RF gun and the linac. The small emittance produced by the emittance compensation was frozen through the acceleration in the linac. The cell photocathode RF gun was followed by a solenoid magnet. A second solenoid magnet was placed behind the RF gun to buck the first solenoid magnet. Following the solenoid magnet is a six-way cross for vacuum pumping port, and a 45 degree aluminum mirror mounted on an actuator for monitoring the laser beam profile and optical transition radiation (OTR). There were beam profile and charge measurement devices located before and after the ATF two sections linac. A group of quadrupole magnets positioned subsequently can be used for emittance

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measurement or beam matching for the experimental lines. There are two beam profile monitors with five meter separation after the linac. A pop-up beam profile monitor and momentum slit were installed after the dipole magnet for energy spread measurement and energy selection.

The ATF diode-pumped Nd:YAG oscillator can generate 81.6 MHz pulses with 14 ps FWHM pulse length and 100 mW power. The IR was frequency quadrupled to UV (266 nm) on the laser table. The UV laser pulse was transported to the RF gun hutch via 20 meter long evacuated pipe. The optics in the gun hutch was designed to compensate for the ellipticity of the emitting area caused by the oblique incidence.

## III. RF GUN CHARACTERIZATION AND ELECTRON EMISSION MEASUREMENTS

It took about a week of conditioning for the RF gun to reach the designed acceleration field 100 MV/m. A four inch mirror was mounted on a precision optical rotation stage outside the window of the six-way cross for angular distribution measurement of optical transition radiation (OTR). A PMT was used to detect angular distribution of OTR while a CCD camera was used to measure the beam profile from OTR. Fig.2 plotted OTR experimental data and theoretical fittings for two different RF power levels. The data showed that the highest electron beam energy is about 6 MeV, which corresponds to the peak acceleration field 130 MV/m. The peak surface field in the RF gun cavity is about 20 % higher than the acceleration field.

The effect of the coupling slot between the waveguide and RF

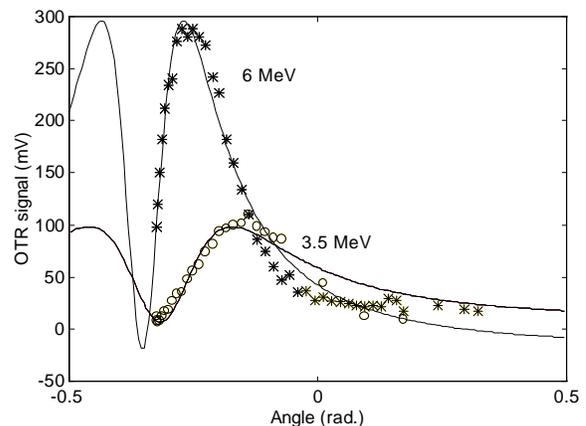
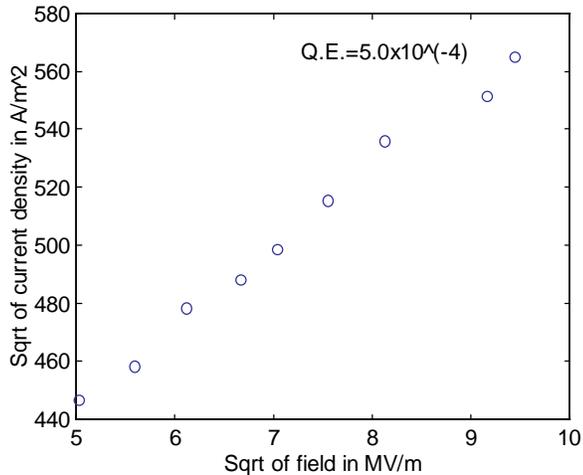


Figure 1 Angular distribution of OTR.

gun cavity was investigated experimentally. The main effect of the coupling slot is introduction of  $TM_{110}$  mode besides the acceleration mode  $TM_{010}$  mode in the RF gun cavity. The combining effect of those two modes is that the electric center of the cavity shifted toward the coupling slot. The field

emission current (dark current) profile was used to determine the electric center of the cavity because its strong dependence on the field strength. We aligned the laser spot on the RF gun cathode to the RF gun cavity mechanical center within 50  $\mu\text{m}$ . It was found that the laser spot has to be shifted toward the coupling slot by about 1 mm in order to overlap the photoelectron beam and dark current.



**Figure 2** The Schottky effect measurement.

Photoemission from a cathode in an RF gun is influenced by the relative energy difference between the photon energy and the work function of the cathode, modification of this work function by the strong electrical fields present in the cavity, absorption coefficient of the cathode for the irradiating photon beam, and other material dependent properties such as the density of states, and surface dependent properties such as the enhancement due to surface irregularities. The current density for a field assisted single photon process can be written in a general form as,

$$j = AI(1 - R_i)(h\nu - \phi + \alpha\sqrt{\beta E})^2 \quad (1)$$

$A$  is a material dependent constant,  $I$  is the intensity of the photon beam,  $R_i$  is polarization dependent reflectivity,  $h\nu$  is the photon energy,  $\phi$  is the work function of the cathode,  $\alpha$  is  $(e/4\pi\epsilon_0)^{1/2}$  in MKS units,  $\beta$  is the field enhancement on the surface and  $E$  is the applied electric field. The term  $\alpha\sqrt{\beta E}$  expresses the lowering of the work function due to the Schottky effect. The Schottky effect measurement for optimized polarization was shown in Fig.2.

#### IV. ELECTRON BEAM MEASUREMENT

There are many factors that affect the performance of an emittance compensation RF gun injector. Extensive studies were carried out to simulate emittance compensation injector and to produce a procedure to achieve the emittance compensation experimentally. We compared the electron beam profile from RF gun to the exit linac in two cases. The first

case considered is that, optimized conditions for emittance compensation are assumed, good transmission through six meter linac was achieved, and a small good beam profile can be observed on the collimator right after the linac. Using computer program TRANSPORT, if no emittance compensation assumed, either poor transmission or large beam profile at the exit linac would be observed for any setting of the solenoid current. The reason for that is when emittance compensation realized, electron beam follows laminar flow trajectory while in the other case that electron beam will follow a cross over trajectory in the linac.

Generally speaking, to measure the beam emittance is to determine the three parameters in the beam matrix. We have used two profile monitors emittance measurement method for its simplicity and short time for data acquisition. In this method, the electron beam was focused to produce a beam waist at one of the beam profile monitors. The first measurement was with 50 MeV electron beam, table 1 lists the normalized 100% emittance and quadrupole currents for focusing the beam at two beam profile monitor separately.

**Table 1:** Initial emittance and corresponding quadrupole current.

	Focus at near BPM	Focus at far BPM
Emittance(mm-mrad)	22	15
Focusing quadrupole current (I)	6.65	4.5

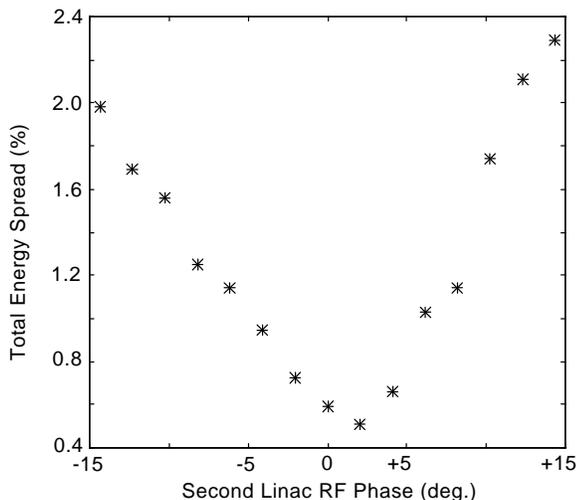
The large emittance was determined to be the result of some emittance growth mechanisms. There are many mechanism could cause emittance growth, such space-charge effect, wake field effect, nonlinear magnetic field and chromatic effect. Since measurement was done at high energy (higher than 10 MeV), space charge effect is negligible. Also wake field effect can be ignored since the measurement was using relative low charge (0.25 nC). The ratio of the emittance being equal to the ratio of the quadrupole magnet currents suggested chromatic effect. Emittance growth for a single quadrupole magnet from chromatic effect can be estimated by[5],

$$\Delta\epsilon = \frac{\sigma^2 \Delta p}{f p} \quad (2)$$

where  $\sigma$  is the beam size at the quadrupole,  $f$  is the focal length of the quadrupole, and  $\Delta p/p$  is the relative energy spread of the electron beam. Since the focal length of the quadrupole magnet is inverse proportional to its current. We concluded from Eq.(2) that the large emittance measured was caused by the emittance growth due to the chromatic effect.

To reduce chromatic effect, we first steered the laser so the photoelectron beam and dark current overlap on each other, this will reduce the energy spread and beam steering from dipole mode. Since the chromatic effect causes geometric emittance growth, we lowered the linac power to reduce the electron

beam energy to 37 MeV. The injector design called for 2.0 mm laser diameter with 1 nC charge. Due to a defect in the double crystal, the largest laser spot that we could produce at the time with good mode quality was about 1 mm. We scaled the charge down to about 0.25 nC by reducing the laser energy. The peak acceleration field at the gun was set to about 80 MV/m.



**Figure 3** Energy spread vs. linac RF phase.

We then transported the electron to the momentum slit. The horizontal beam size observed on the momentum slit is given by,

$$x = \sqrt{\beta\epsilon} + D \frac{\Delta p}{p} \quad (3)$$

where  $\beta$  is the beta function at momentum slit,  $\epsilon$  is the horizontal emittance,  $D = 5.4$  mm/% is the dispersion at the slit. We adjusted beam optics so that the beam size due to the energy spread was dominant over the emittance term. The RF gun phase and linac phase were optimized to minimize the energy spread. The energy spread of the electron beam bunch was measured by changing the RF phase of the second linac section. The electron beam energy was about 17 MeV at the entrance of the second linac section, space charge effect was negligible. The energy spread as the function of the second linac RF phase was plotted in Fig.3. The minimum full width energy spread (100 % of the beam) is 0.5%, which corresponds to the full width electron beam bunch length less than 11 ps. The laser pulse was measure to 9 ps FWHM using a single shot streak camera.

We then observed electron beam on the collimator right after the linac, we adjusted solenoid magnet until we had 100 % electron beam transmission and the smallest beam profile. We also modified beam optics so the electron beam will be smaller at the quadrupole magnets. The normalized 100 % emittance measured is 4.7 mm-mrad, which corresponding 0.9 mm-mrad

normalized rms emittance. Upton repeated the measurements the spread of the measured emittance is about  $\pm 10$  %.

When increased the charge of electron to 0.6 nC, a beam halo was observed. Therefore instead of measuring total emittance, we measured the emittance of the core beam (FWHM). The measured normalize rms emittance range from 0.5 mm-mrad to 1.5 mm-mrad. Realizing that we may under estimated the emittance [6], we believed that the real emittance is between 1 to 3 mm-mrad.

The emittance due to space-charge contribution in a non-compensation photocathode RF gun can be estimated using following simple analytical formulas[7],

$$\epsilon_c = \frac{c^2}{8\sqrt{2\pi}\alpha f} \frac{Q}{I_A} \frac{1}{(3\sigma_x + 5c\sigma_z)} \quad (4)$$

where  $\alpha = eE_0 / 2mc^2k$ ,  $I_A$  is Alfven current equal to 17000 A. For  $Q = 0.25$  nC, the space charge emittance would be 3.4 without emittance compensation. Similarly, the space charge emittance for 0.6 nC would be 8.2 mm-mrad. Comparing our experimental results with the predictions from Eq.(4), we concluded that we have experimentally demonstrated emittance compensation in a S-band, high-gradient photocathode RF gun.

## V. ACKNOWLEDGMENT

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