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**Experimental Characterization of High-Brightness Electron
Photoinjector***

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ABSTRACT

Operational experience of the emittance compensated photoinjector at the Brookhaven Accelerator Test Facility (ATF) is presented in this paper. The photoinjector has demonstrated the stability and reliability required for UV and X-ray FEL applications. The RF gun has been routinely running at more than 100 MV/m peak acceleration field; the laser system of the photoinjector has achieved 2% peak to peak energy stability, 0.5 % point stability and better than 2 ps timing jitter. The highest measured quantum efficiency of the Cu cathode is 0.05%. The electron beam bunch length was measured to be 10 ps using a linac RF phase scan. The normalized rms emittance for a 0.5 nC charge was measured, to be from 1 to 2 mm-mrad, which agrees with PARMELA simulations.

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INTRODUCTION

After more than a decade of development ¹, tremendous progress has been made in photocathode RF gun technology. The reliability and brightness of electron beams produced by photocathode RF guns is now more than ever close to meeting the needs of X-ray Free Electron Lasers (FEL) and linear collider applications. To take advantage of these developments, a new photocathode RF gun injector and a new laser oscillator were installed at the Brookhaven Accelerator Test Facility (ATF).

The ATF, a facility dedicated for FEL and laser acceleration research ², consists of a laser driven RF gun injector, a 70 MeV linac and experimental beam lines. The new injector employs a one-and-half cell, S-band, copper RF gun³ with a pair of solenoid magnets optimally located for emittance compensation. The injector is arranged in-line with the linac. With the emittance compensation technique ⁴, the photoinjector is capable of producing bright electron beams for visible FEL and laser acceleration experiments. We present the operational results of the photoinjector in this paper. A brief description of the ATF in-line photoinjector and its laser system is presented in section two. In section three, the experimental measurements of the photocathode RF gun and its driving laser system for single pulse operation are discussed. A brief discussion of quantum efficiency measurements of the Cu cathode is also included in this section. In section four, the electron beam measurements for a 0.5 nC charge are presented, the experimental results are compared with simulations using the computer program PARMELA, the agreement is good within experimental error.

THE ATF IN-LINE INJECTOR

The design of the injector⁵ optimized the distance between the RF gun and the linac. The small emittance produced by the emittance compensation was frozen through acceleration in the linac. Fig.1 is a schematic of the ATF in-line injector and linac system. The S-band one-and-half cell photocathode RF gun is followed by a solenoid magnet. A second solenoid magnet is placed behind the RF gun to buck the first solenoid magnet. Magnetic measurements were performed to insure that the longitudinal magnetic field on the cathode surface was nearly zero. Following the solenoid magnet is a six-way cross for vacuum pumping. A 45 degree aluminum mirror mounted on an actuator for monitoring both the laser beam profile and Optical Transition Radiation (OTR) is also located in this cross. A copper block on an actuator is positioned next in line for charge measurements. The front surface of this copper block is coated with phosphor for beam profile and position monitoring. The beam is then injected into the linac. The distance between the cathode and the entrance of the linac is 81 cm, optimal for emittance compensation. The linac consists of two sections of SLAC type traveling wave linac. The RF gun and linac are powered by two separately XK-5 klystrons. At the exit of the linac is a beam profile monitor. The electron beam transport line that follows the linac consists of a group of quadrupole magnets which are used for emittance measurements or for beam matching in the experimental line. A phosphor coated momentum slit after the dipole magnet is used for energy spread measurement and energy selection. There are four pop-up beam profile monitors in the dispersive beam line after the dipole, three of them are used for emittance measurement.

In parallel with the installation of the new injector, the ATF photocathode laser system went through a major upgrade. The lamp pumped, actively mode-locked Nd:YAG oscillator and optical fiber pulse compression system were replaced by a diode pumped Nd:YAG oscillator. The Nd:YAG oscillator generated 81.6 MHz pulses with 21 ps FWHM pulse lengths and a 100 mW of average power. The seed pulse produced by the oscillator is imaged and amplified by two-stage Nd:YAG amplifiers. The IR is frequency quadrupled to UV (266 nm) on the laser table. This nonlinear process leads to a factor of two reduction in the laser pulse length. The UV beam is transported to the RF gun area via a 20 meter long evacuated pipe. The laser beam transport system near the injector includes an aperture, a set of telescoping lenses and a limiting aperture. This limiting aperture is imaged onto the cathode, by a pair of cylindrical lenses. The focal lengths and locations of these lenses were chosen to compensate for the ellipticity of the emitting area caused by oblique incidence. The relay imaging technique used throughout the optical transport improves the beam pointing stability. Since the laser beam overfills the limiting aperture, the transverse profile of the beam is nearly top hat. The spot size of the laser beam on the cathode can be changed by simultaneously changing the telescoping lenses and the limiting aperture.

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PHOTOCATHODE INJECTOR CHARACTERIZATION

RF gun and laser system characterization

The ATF in-line photoinjector has been in operation more than six months and has met the design requirements for single pulse operation. It took about two weeks of RF conditioning for the RF gun to reach the design acceleration field of 100 MV/m. The angular distribution and the beam profile of the OTR generated by the electron beam of the RF gun were measured using a photomultiplier tube (PMT) and a CCD camera respectively. Fig.2 shows the OTR experimental data and theoretical fit for two different RF power levels. The data showed that the highest electron beam energy is about 6 MeV, which corresponds to a peak acceleration field of 130 MV/m. Since the peak surface field in the RF gun cavity is expected to be 20 % greater than the on axis accelerating field. The peak field is estimated to be 160 MV/m. At the present time, the highest acceleration field achievable in the RF gun is RF power limited (10 MW).

The diode pumped Nd:YAG laser oscillator achieved its design specifications after several reworks by the manufacture. In order to reach the stability and reliability requirements of the photoinjector, a major effort was devoted to reducing the sources of thermal vibrational and atmospheric instability in the laser room and gun hutch. All sensitive optical elements (such as the frequency quadrupled crystals) were moved into the laser room for better environment control. We experimentally studied the energy and point stability of the laser system. A wedge was installed just upstream of the cathode so that a small fraction of the laser energy is split off for laser energy and profile monitoring. The peak to peak energy stability of the laser system was measured to be 2% (The measurement error

is dominated by thyatron trigger noise of the klystron modulators). The pointing stability was measured using a Spiricon frame grabber to measure the laser beam centroid. For a 1.5 mm diameter laser beam, better than $7 \mu\text{m}$ pointing stability was measured, corresponding to 0.5 %. The time jitter of the laser system was investigated by observing the electron energy spread. Since the resolution of the energy spread measurement is about 2 ps, there is no observable change in beam energy spread due to laser time jitter. We therefore concluded that the time jitter of the laser system is better than 2 ps.

Quantum efficiency measurement:

Photoelectron emission from a cathode in an RF gun is influenced by a number of factors such as the relative energy difference between the photon energy and the work function of the cathode, modification of this work function by the strong electric fields present in the cavity and the absorption coefficient of the cathode for the irradiating photon beam. It also is influenced by other material properties such as the density of states, and surface dependent properties like the enhancement due to surface irregularities. The current density for a field assisted single photon process can be written in a general form⁶ as,

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

A is a material dependent constant, I_L is the intensity of the photon beam, R_i is the polarization dependent reflectivity, $h\nu$ is the photon energy, ϕ is the work function of the cathode, α is $(e/4\pi\epsilon_0)^{1/2}$ in MKS units, β 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. For an elliptically polarized photon beam, Eq. (1) can be modified

by expressing $(1 - R_i)$ as,

$$(1 - R_i) = [(1 - R_p) \cos^2 \theta + (1 - R_s) \sin^2 \theta] \quad (2)$$

where θ is the polarization angle.

The highest quantum efficiency of Cu was measured to be 5×10^{-4} (Fig.3). Our experience shows that you must start with a clean system and reasonable vacuum (better than 10^{-7} torr). We have observed that:

1. Initial RF conditioning in the RF gun will improve the quantum efficiency (QE) by factor of 2 to 3.
2. For a oblique incident photoinjector, polarization optimization gives a factor of two increase in quantum efficiency compared to the normal incident situation (Fig.4).
3. For a Cu cathode, a factor of two improvement in QE is due to Schottky effect for a field of 70MV/m to 120 MV/m on the cathode (Fig.3).
4. Strong field conditioning (more than 120 MV/m) can increase QE significantly.

We have observed as large as a factor of four improvement in QE from strong field conditioning.

We have also observed significant improvement in QE when a train of laser pulses was used, but this technique is not always dependable.

ELECTRON BEAM BRIGHTNESS MEASUREMENT

The brightness, B , of the electron beam is a quantity which represents the quality of the electron beam,

$$B = \frac{I}{\varepsilon_{nx}\varepsilon_{ny}} = \frac{Q}{\sqrt{2\pi}\sigma_z\varepsilon_{nx}\varepsilon_{ny}} \quad (3)$$

where I is the peak current of the electron beam, ε_{nx} and ε_{ny} are transverse normalized rms emittance, Q is the total charge in the electron bunch and σ_z is the rms electron bunch length. To determine the brightness of the electron beam, the transverse emittance of the beam, the bunch length and the total charge in the bunch have to be measured.

If no coupling in the 6-d phase space is assumed, the transverse emittance basically can be determined by a 2x2 symmetric beam matrix,

$$\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix} \quad (4)$$

and the emittance is,

$$\varepsilon = (\sigma_{11}\sigma_{22} - \sigma_{12}^2)^{1/2} \quad (5)$$

where $\sigma_{12} = \sigma_{21}$. Generally speaking, in order to measure the beam emittance we need determine the three parameters in the beam matrix.

There are many factors that affect the performance of the emittance compensated photocathode RF gun injector. Extensive simulation studies were carried out to model such an injector and to develop a procedure to achieve the highest emittance compensation experimentally. We compared the electron beam profile from the RF gun to the exit of the linac in two cases. For the first case, optimized conditions for emittance compensation were assumed. Good transmission through the six meter linac was achieved, and a small

good beam profile was observed on the beam profile monitor right after the linac. Then we consider the case of no emittance compensation. Using the computer program TRANSPORT, with no emittance compensation, it predicts that either poor beam transmission or large beam profile at the exit linac would be observed for any setting of the solenoid current. The reason is that when emittance compensation is realized, the electron beam follows laminar flow trajectory otherwise the electron beam will follow a cross over trajectory in the linac. We have been able to optimize the electron beam by observing the electron beam profile on the beam profile monitor right after the linac.

A 0.5 nC charge electron beam was produced for a laser spot size of 1.5 mm diameter. The electron beam bunch length was measured to be 10 ps using the linac RF phase scan technique. The measured minimum energy spread is 0.5 % for the full beam, which agrees with the linac phase scan result for the bunch length measurement.

The three beam profile monitor method was used to measure the electron beam emittance⁷. The beam profile monitors after the first dipole magnet were used. They were chosen for several reasons: the most important one is that there is a large separation between them. For emittance measurement all dipole and quadrupole magnets between them were turned off (degaussed carefully). Another advantage of this location is that the dipole magnet can reduce the dark current and any low energy tail. The disadvantage of measuring the emittance in the dispersive region is that only the vertical emittance can be measured, the horizontal emittance we assume that is equal to the vertical, which was confirmed by the circular beam profile after the linac. The frame grabber used in the experiment has only 8-bit dynamic range, the camera apertures were reduced to avoid saturation. Both the full width half maximum (FWHM) and full width(FW) of the electron

beam profiles were measured. The normalized FWHM emittance measured range from 3.8 to 4.3 mm-mrad. The normalized FW emittance ranged from 10 to 14 mm-mrad. We analyzed the systematic error in the emittance measurement⁷, Fig.5 shows the measurement error for three different beam profile monitor resolutions. If an 0.05 mm beam profile monitor resolution is assumed, our measurement error is on the order of 30 %. We therefore concluded that the normalized rms emittance is in the range 1 to 2 mm-mrad.

The measurement results were compared with PARMELA simulations for a field of 90 MV/m at the cathode and a 7 MV/m linac gradient. Fig.6 and Fig.7 plot the normalized rms emittance and beam profile along the beam line calculated by PARMELA. The 1.5 mm-mrad normalized rms emittance and 2.0 mm diameter spot size at the linac exit agree with our experimental observations.

CONCLUSION AND ACKNOWLEDGMENT

Our measurements show that the ATF photoinjector, both laser system and RF gun, is very close to satisfying the requirements for future X-ray FEL applications.⁸

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Figure 1. The schematic of the ATF injector and linac system.

HQ - quadrupole magnet; HT, LT - steering magnet; PM, HPOP-UP - beam profile monitor; HD1/FD1 - dipole magnet.

Figure 2. Experimental measurements (dots) and theoretical fit (solid curve) of the angular distribution of the optical transition radiation produced by the electron beam from the RF gun.

Figure 3. The experimental results and theoretical fit of the Schottky effect in the photocathode RF gun.

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Figure 7. The rms beam profile along the photoinjector calculated by PARMELA

Fig.1

Fig.2

Fig.3

Laser polarization

Fig.4

Fig.5

Fig.6

Fig.7