Pres. 17th Int'l. Conf. on the Application of Accelerators in Research & Industry – CAARI 2002, 12-16 November 2002, Denton, TX

BNL-69311

PERFORMANCE DATA OF A PULSED POWER PHOTO-INJECTOR*

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October 2002

* Work supported by U.S. Department of Energy: Contract No. DE-AC02-98CH10886.

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Abstract. There has been a lot of interest in compact sources of high brightness, relativistic electron beams. One approach for developing such a source is to apply a high gradient that remains constant during the generation and acceleration of the electron beam. In this paper, we describe high voltage pulse generators that deliver up to 5 MV with 1 ns pulse duration. These devices are synchronizable to an external trigger with jitter of ~ 0.5 ns and can establish gradients in excess of 1 GV/m between two electrodes without breakdown. In the presence of field gradients up to 0.5 GV/m, electron beams of bunch lengths ranging from 1 ns to 0.3 ps and diameter < 300 μm have been generated by irradiating the cathode with UV lasers. Characteristics of these electron beams as well as those produced via field emission at gradients up to 1 GV/m will be discussed.

INTRODUCTION

Today, applications requiring high brightness electron sources are typically met by RF photo injectors, which have been shown to be capable of producing bunches of a 1-5 nC with a pulse duration of a 1-20 ps [1]. These devices typically provide an emittance of 1-5 mm-mrad and brightness of $2x10^{13}$ A/m^2rad^2. These values are achieved by extracting electrons from the cathode via illumination by a laser in the presence of a strong RF field. The maximum accelerating gradient in such devices is typically on the order of 100 MV/m, limited by the voltage holdoff capabilities of the cavity.

A gun based on pulse-power technology [2,3] has been proposed as an alternative source for some of these applications. In such a device, a pulsed high voltage would be applied between the cathode and the anode establishing a high field gradient. If the cathode is illuminated simultaneously with a laser pulse, releasing photoelectrons, these electrons can be accelerated to relativistic energies within a short distance from the cathode, reducing the deleterious effects due to space charge and varying accelerating field. Such pulsed injectors are capable of maintaining much higher, constant (relative to the electron bunch length and interelectrode transit time) field gradients – on the order of a GV/m. Two such devices are operational at BNL one delivering up to 1 MV and another up to 5 MV. The performance of these devices has been characterized, and extensive simulations of the beam parameters have been performed[4]. Measurements of the beam emittance are currently underway. We present here, a brief review of the 1 MV pulse generator and photoinjector as well as the preliminary results of the emittance measurement.

PERFORMANCE OF THE PULSE GENERATOR

This section provides a brief overview of the capabilities of the pulse generator, as well as dark current results from the pulsed diode.

Voltage Output, Jitter and Pulse Stability

Both the pulse generators consist of a low voltage, high current power supply charging a capacitor bank, self triggered spark gap, a resonant transformer followed by a laser triggered spark gap, and a transmission line terminating at the cathode of the photoinjector with a matched termination. One of the pulse generator can deliver 1 MV at the cathode while the second one can deliver up to 5 MV. Details of the pulse generators and the experimental arrangement of the photoinjector can be found elsewhere [2,5]. Figure 1 shows a typical output voltage pulse measured at a capacitive probe on the transmission line 15 cm prior to the cathode. The pulse-to-pulse stability of the generator is about 5%.

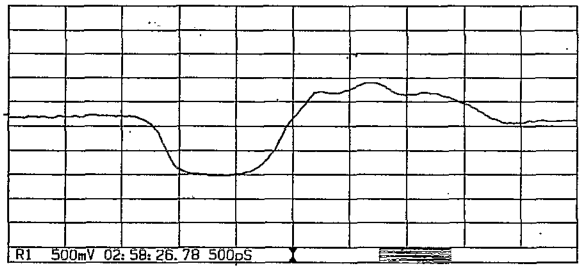

FIGURE 1. Output pulse for 1 MV pulser. Amplitude corresponds to 900 kV on the cathode.

Synchronization between the voltage and the photo-cathode laser poses a major challenge for the efficient operation of the pulsed gun as an electron source. The 1-σ jitter between the laser and the voltage pulse has been minimized to 0.5 ns by transverse laser triggering of the high pressure SF_6 spark gap of the pulser transmission line. .

Dark Current

The experimental arrangement for the measurement of dark current and photocurrent is described in detail elsewhere[2]. In brief, the cathode is attached to the end of the transmission line and is enclosed in a vacuum chamber with windows for the photocathode laser. The anode is parallel to the cathode and can be moved to adjust the interelectrode spacing in vacuum, allowing the field gradient to be varied without affecting either the vacuum or the voltage amplitude.

The dark current and maximum field before breakdown were measured for copper cathodes subjected to several surface preparation techniques [6]. The largest voltage hold-off and lowest dark current were achieved with OFC copper cathodes mechanically polished with a diamond polishing compound. After conditioning to 800 MV/m (800 kV across a 1 mm gap), these cathodes exhibited a Folwer-Nordheim field enhancement factor of 27. This value was calculated using the a work function (4.37 eV) derived from photoemission results for a similarly prepared cathode[7]. Field gradients up to 1.66 GV/m have been applied to such cathodes without encountering breakdown The field enhancement factor under these conditions is ~ 18 [8]. Typical charge values at 600 MV/m were 10 pC corresponding to 10 mA for a 1 ns pulse .

PHOTOEMISSION STUDIES

Photoemission studies were conducted using two different lasers, 248 nm, 23 ns KrF laser and 266 nm 300 fs laser. In both the cases, the charge and the beam profile were measured so that the emittance and electron beam brightness can be calculated.

To measure the emittance, a solenoid-focusing magnet has been placed at the output of the HV diode. The current to the solenoid is changed to vary its focusing strength. Two beam profile monitors (BPM) with a drift distance of 15 cm between them, are located down stream from the solenoid. Each BPM consists of a phosphor deposited on Al foil mounted perpendicular to the beam axis. A mirror behind the foil allows the phosphor to be imaged onto a camera outside the vacuum system. The mirror also acts as a Faraday Cup. The charge collected by the Faraday cup and hence the current from the cathode can be measured using an electrometer connected to the Faraday cup. A small permanent magnet has been used to eliminate any low energy electrons away from the BPM and the Faraday cup.

Charge & Quantum Efficiency Measurements Using 248 nm, 23 ns Laser

Initial photoemission measurements have been made by illuminating the cathode with the KrF excimer laser. The laser spot illuminated the center 1 mm diameter of the cathode at normal incidence. The laser energy during the negative cycle of the voltage pulse was ~1.5 μJ. The laser pulse duration was 23 ns FWHM, much longer than the voltage pulse duration of 1 ns. Inter-electrode spacing was set to 2.11 mm and 1.19 mm. Voltage amplitudes ranging from 200kV to 800 kV were applied to the cathode coincident with the laser pulses. The quantum efficiency (QE) for the diamond polished copper cathode was $1x10^{-4}$ at a field gradient of 450 MV/m. Measurement at fields exceeding 500 MV/m was limited by dark current. Figure 2 illustrates the increase in the electron yield with the applied field as anticipated from a cathode under the Schottky effect. All charge values shown in figure 2 are normalized to this laser energy.

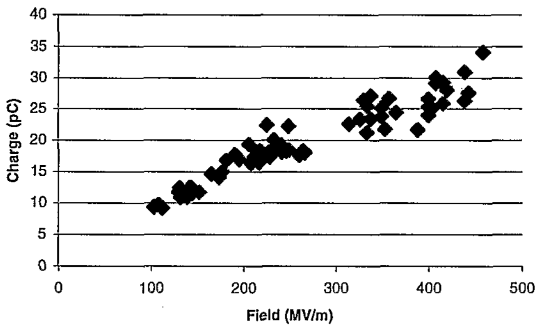

FIGURE 2. Charge vs. Applied field for an excimer laser energy during the voltage pulse of 1.5 μJ.

Figure 3 shows the transverse profile of the electron beam generated by the excimer laser. Since the pulse duration of the excimer is much larger than the duration of the voltage pulse, the electrons are emitted at all amplitudes of the voltage pulse resulting in a significant energy spread in the beam. As the focusing strength of the solenoid is a function of the beam energy, the spot size on the BPM is much larger than that for a focused, single energy beam and hence is not a valid measurement for the emittance.

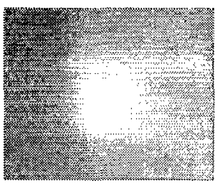

FIGURE 3. Image of the smallest electron beam created by KrF excimer. The 1-σ radius of the image is 0.9 mm. The center 0.350 mm diameter of the spot is saturated, so the actual 1-σ radius could be slightly smaller.

Emittance Measurement Using 266nm, 300 fs Laser

An ultra short laser pulse (laser pulse duration << voltage pulse duration) from a Ti:Sapphire laser system has been used as a photocathode laser for emittance measurements. The Ti: sapphire system consists of an oscillator and a regenerative amplifier. The amplifier output is a pulse of 800 μJ at 800 nm, with a pulse duration of ~300fs. The wavelength is converted to 266nm (4.66 eV photon) by two nonlinear crystals. The pulse energy @ 266nm is ~40 μJ at the laser. For the initial measurements, the system parameters were: maximum voltage of ~400 kV, electrode spacing of 2.16 mm. With ~11μJ of 266 nm on the cathode and a QE of ~2x10^{-5} (lower than that mentioned above due to reduced Schottky effect and photon energy), charge values of ~80 pC is expected from the cathode. Beam images have been taken on both BPMs. Figures 4a & 4b show the smallest spots yet obtained on the 1st & 2nd BPM, respectively. For the purposes of estimating the emittance in the next section, the spot in figure 4b is assumed to be the focal spot. Figure 5 shows a spot measured at BPM 1 for similar beam parameters.

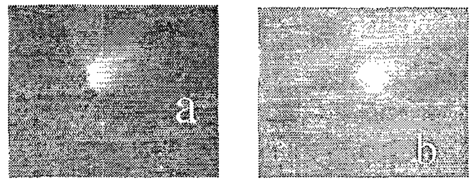

FIGURE 4a & b. Images of electron beams created by Ti: sapphire. 4a is the smallest spot yet obtained on BPM 1. The horizontal dimension of this spot is 190 μm (1-σ). The saturated center area in 100 μm in diameter. 4 b is the smallest spot on BPM 2, with a 1-σ radius of 110 μm.

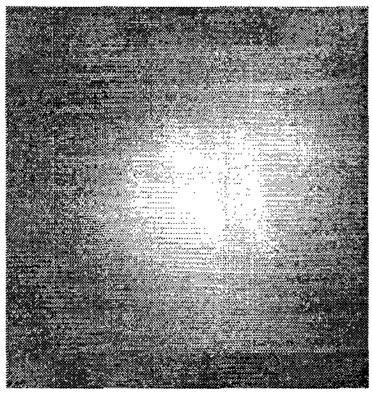

FIGURE 5. Spot on BPM 1 for beam parameters similar to those of the spot shown in figure 4b. The 1-σ beam radius is 2.9 mm.

Emittance Estimate

It is possible to estimate the emittance of the electron beam based on the images in figure 4b and figure 5. The geometric emittance of an electron beam based on the beam dimension at the focus and a known distance form the focus is given by:

$$\varepsilon = \frac{\sigma_w}{L}\sqrt{\sigma_L^2 - \sigma_w^2} \qquad (1)$$

Here σ_w represents the beam radius at the beam waist (BPM 2), σ_L represents the beam radius at the BPM 1 and L is the drift distance between the two BPMs. This expression yields a geometric emittance of 2 mm-mrad (corresponding to a normalized emittance of about 3 mm-mrad).

Several factors may act to cause the measured emittance to be higher than the emittance of the beam exiting the pulsed diode. A number of assumptions are inherent in the above calculation. The most significant is the assumption that the spot shown in figure 4b represents a focus. If a smaller spot is found, the emittance will decrease. The expression used to calculate the emittance assumes that the beam profile is Gaussian. The spot in figure 5 has been shown to have a Gaussian profile, however the focal spots in figure 4 contain too few pixels to obtain a reliable fit. Although the charge was not measured for the images shown in figures 4 & 5, the expected charge from the cathode for the laser energy used would imply a significant current density. This may cause some degradation of the emittance due to space charge in the 50 cm of beam transport between the cathode and BPM 2. No emittance compensation is included in the system.

FUTURE PLANS

The emittance measurement is still in progress. This system can be used to measure the emittance as a function of bunch charge, bunch energy and accelerating gradient.

ACKNOWLEDGMENTS

The authors would like to thank Marc Montemagno and John Walsh for their expert technical assistance and V. Radeka for his support. This work was supported by DOE contracts DE-AC02-98CH10886, DE-AC03-76SF00515 and DE-FG02-97ER82336.

REFERENCES

1. Travier, C., Nucl. Instr. and Meth in Phys. Res. **A 340**, 26 (1994)

2. Srinivasan-Rao, T. and Smedley, J., "Table Top, Pulsed, Relativistic Electron Gun with GV/m Gradient," in Adv. Accel. Con. Workshop, AIP Conference Proceedings 398, Ed. S. Chattopadhyay, J. McCullough and P. Dahl, AIP Press, NY 1997, P. 730.

3. Villa, F. and Luccio, A., Laser and Part. Beams **15**, 427 (1997)

4. Srinivasan-Rao, T., Smedley, J., Batchelor, K., Farrell, J.P., and Dudnikova, G., "Optimization of Gun Parameters for a Pulsed Power Electron Gun"; BNL 65748 ; pres. 8th Workshop on Advanced Accelerator Concepts, Baltimore, MD, 6-11 July (1998);

5. Farrell, J. P., Batchelor, K., Meshkovsky, I., Pavlishin, I., Lekomtsev, V Dyublov, A., Inochkin, M., Srinivasan-Rao, T. and Smedley, J., "A sub-picosecond pulsed 5 MeV electron beam system," in CP576, Application of Accelerators in Research and Industry, Sixteenth Int'l. Conf. American Institute of Physics, Edited by J.L. Duggan and I.L. Morgan pp 787-790 (2001).

6. Srinivasan-Rao, T., Schill, J., Ben-Zvi, I., Batchelor, K., Farrell, J.P., Smedley, J., Lin, X.E., and Odian, A., "Simulation, Generation, and Characterization of High Brightness Electron Source at 1 GV/m Gradient"; BNL 66464; pres. PAC'99 Conf., New York, NY, 3/29-4/2/99; Proc. 1999 Particle Accelerator Conf., Eds. A. Luccio & W. Mackay, p. 75 (1999).

7. Smedley, J., The Physics of the Pulsed Power Electron Gun, Ph.D. Thesis (2001)

8. Srinivasan-Rao, T., Schill, J., Batchelor, K., Smedley, J., and Farrell, J.P., "Dark Current Measurements at Field Gradients Above 1 GM/m"; BNL 65746; pres. 8th Workshop on Advanced Accelerator Concepts, Baltimore, MD, 6-11 July (1998).