Presented at PAC 2003 Conference, Portland, OR
12-16 May 2003

BNL - 69542

EMITTANCE MEASUREMENTS WITH A PULSED POWER PHOTO-INJECTOR*

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May 2003

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

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Abstract

This paper describes measurements of beam spot size and emittance of electron beams from a pulsed power photo-injector operating at 150keV output energy. In these measurements, electron bunches with charge up to 20 pC were created by a 300 fs pulse duration Ti: Sapphire laser system illuminating a polished copper cathode. Images of the electron beam were captured at two locations downstream from a solenoid focusing magnet. The focal spot size was studied as a function of bunch charge and accelerating gradient. Beam waists down to 85 microns were obtained. The focal spot size was found to be dominated by spherical aberration at low beam charges, however the beam trajectory is in good agreement with simulation.

INTRODUCTION

Photo-injector based electron sources represent the current state-of-the-art in the production of low emittance, high brightness electron beams. Pulsed power devices are capable of producing and maintaining a significantly higher accelerating gradient than other accelerating schemes, such as DC and RF guns. The benefit of larger accelerating gradient is investigated in section one, which presents simulations done with MAFIA and PARMELA of the electron trajectories, expected beam waist size and beam emittance. Section two describes the measurements of emittance made with the pulse power photo-injector.

SIMULATION

The electron emission from the pulsed gun as been modeled with numerous beam simulation packages [1]. The simulations presented here were performed in two stages. MAFIA was used to simulate the electron emission and initial acceleration. In the interest of computational efficiency, PARMELA was then used to transport the beam through the solenoid and calculate the expected waist size.

The geometry used for simulation in MAFIA is shown in fig. 1. It consists of two parallel electrodes, an anode and a cathode, with cylindrical symmetry. The spacing between the electrodes is adjustable (a 2mm gap is shown). The anode contains a 2mm diameter aperture to allow electron emission. The cathode is biased at −150 kV DC. A static voltage is assumed, as the real voltage pulse duration is 3000 times the duration of the photo-cathode laser. The electron bunch has a Gaussian temporal and spatial profile, with a FWHM of 300 fs and 0.43 mm, respectively. Thermal emittance has been neglected in these simulations, however previous simulations [1] for similar conditions have suggested that the typical thermal contributions to the emittance for this geometry is 0.17 mm-mrad.

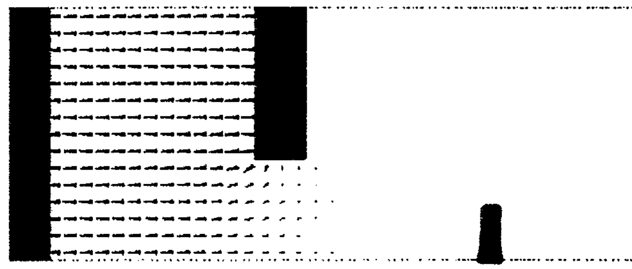

Figure 1 Geometry used in MAFIA (2mm electrode spacing). Field plot and electron bunch also shown.

After the beam has passed 2mm beyond the anode, the 4D phase space and charge of all of macro particles is recorded. The beam properties are calculated by MAFIA at this point. This information is used to generate an input file for PARMEL with a suitable charge distribution. PARMELA is used to transport the beam through the solenoid and predict the RMS spot size at the location of the 2nd BPM. The solenoid field was adjusted to produce a waist at this location.

This combination of MAFIA and PARMELA was used to simulate the beam for a variety bunch charges. The electrode spacing was varied in MAFIA as well. Shortening the electrode spacing has two effects: It increases the accelerating gradient, and it increases the lensing effect caused by the aperture in the anode. This lensing effect was found to play a critical role in determining the predicted focal spot size, due to spherical aberration in the solenoid lens. For low charge (under 1pC), this effect is the dominant factor in determining the beam spot size, and therefore limits the sensitivity of the emittance measurement. Figure 2 shows PARMELA calculated trajectories for the 0.5 pC beam emitted from electrode spacings (gaps) of 1 and 2 mm.

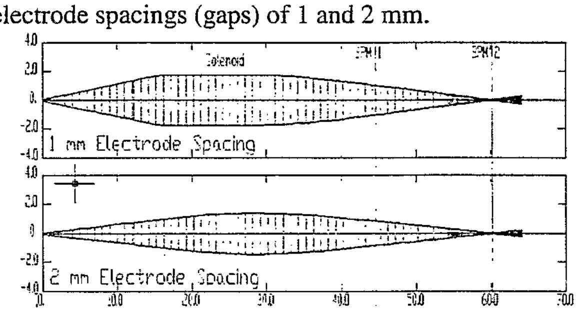

Figure 2 PARMELA simulations of beam trajectory.

The simulation results are shown in Table 1. Note that smaller emittance does not translate to smaller focal dimension, due to spherical aberration. The bias voltage on the cathode is 150 keV. Also shown is a case where the anode aperture replaced by a conductor that is beamtransparent (e.g. a foil or screen). In this case the beam divergence arises solely from space charge, and the focal spot size is not limited by spherical aberration.

Parameters		Mafia Results			PARMELA
		Norm.	RMS	RMS	Size
Gap	Charge	Emit.	Div.	Duration	@ waist
(mm)	(pC)	(mm-mrad)	(mrad)	(ps)	(μm)
1	0.5	0.12	48	0.13	100
1	3	0.48	53	0.18	180
1	10	0.98	66	0.32	510
2	0.5	0.15	26	0.14	60
2	3	0.51	34	0.25	170
2	10	0.90	51	0.53	490
1	0.5	0.12	2	0.12	30

Table 1 Simulation results.

MEASUREMENT

Pulse generator

The device used to generate the voltage pulse used for acceleration has been described in detail elsewhere [1]. The generator can deliver pulses from 150kV to 1 MV at the cathode, with a pulse duration of 1 ns and a rise and fall of 100 ps. The pulse-to-pulse amplitude stability of the generator is about 5%. The cathode consists of a flat, polished copper surface, with the edges beveled to reduce field enhancement. The anode is a stainless steel plate with a 2 mm diameter hole in the center. Micrometers external to the vacuum system control the position of this plate, allowing the inter-electrode spacing to be adjusted in-situ.

The laser used to extract electrons from the cathode was a frequency tripled, regeneratively amplified Ti: Sapphire system. The parameters of this system are: up to 80 μJ of 266 nm light, with a pulse duration of 300fs. The laser spot on the cathode had a FWHM of 0.43mm. The quantum efficiency (QE) of the cathode was measured to be 7×10^{-6} for an applied field of ~100 MV/m. The QE and it's dependence on the applied field has been studied previously [1]. Synchronization between the voltage and the photo-cathode laser is accomplished by using a 250mJ KrF Excimer laser to trigger a high pressure SF_6 spark gap in the pulser transmission line.

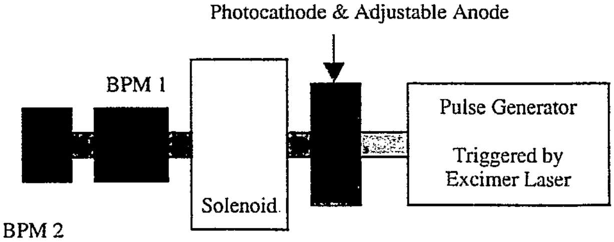

Figure 3 System Schematic

Emittance Measurement

To measure the emittance, a solenoid-focusing magnet has been placed at the output of the HV diode (fig. 3). The current to the solenoid is changed to vary its focusing strength. Two beam profile monitors (BPM) with a drift distance of 15.4 cm between them, are located down stream from the solenoid. Each BPM consists of a ~30μm thick layer of phosphor (Gd_2O_2S:Tb) deposited on a 37μm thick Al foil mounted perpendicular to the beam axis. A metal mirror behind the foil allows the phosphor to be imaged onto a camera outside the vacuum system. This mirror is electrically isolated and connected to a charge sensitive preamplifier, allowing it to act as a Faraday Cup.

For these measurements, the pulse generator was configured for a maximum voltage of 150 kV. Electrode spacings of 1, 1.5 and 2 mm were investigated, resulting in accelerating gradients of 75-150 MV/m. No field emission current was observed at these gradients; previous measurements[1] have observed the onset of significant dark current only at fields greater than 600 MV/m for a well-conditioned cathode.

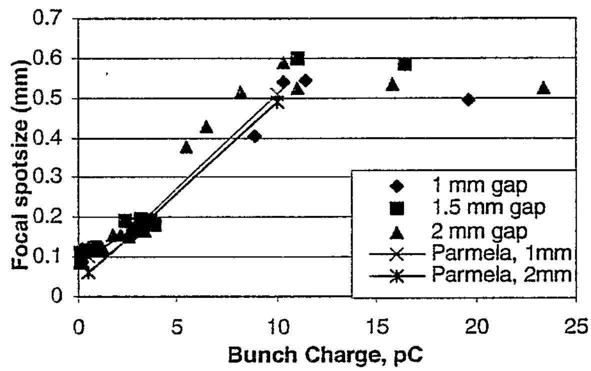

Figure 4 Waist size vs bunch charge

Figure 4 shows the measured rms beam radius at BPM 2 as a function of bunch charge. The minimum beam radius measured was 85 μm. Figure 5 shows several images from BPM 2, including cross sectional profiles. Both the experiment and the PARMELA simulations indicate, as the beam charge is increased from 0.3 pC to 11 pC, the spot size progresses from a spherical aberration dominated regime to a space charge dominated regime. The cross sectional profiles in the space charge dominated regime deviate significantly from the Gaussian distribution in both the simulations and experiments. The images at BPM 1 could only be obtained for high charge values (greater than 5 pC), as sufficient charge was required to cause observable illumination from the phosphor. For these shots, the measured spot varied from 2.3mm to 3.5mm RMS. Images in BPM 1 and BPM 2 with similar experimental parameters were paired for the emittance calculation. Similar charge values could not always be obtained, as a minimum of 5 pC was required to obtain an observable image on the 1st BPM.

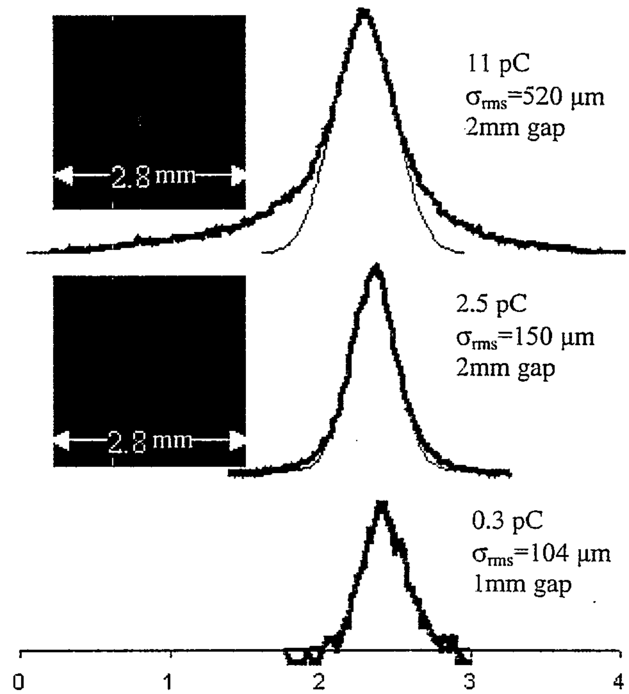

Figure 5 Images obtained with 2nd BPM. Gaussian fit to cross section above half max is displayed. The image for the 0.3 pC case is too faint to show in print. PARMELA simulation (not shown) agrees with the measured profiles.

Emittance Estimate

Due to the limitations imposed by the presence of spherical aberration, this measurement is not very sensitve to the beam emittance. To make a measurement of emittance using a two position technique, it is necessary that the beam spot approaching the focus be dominated by the beam emittance [2]. In this case, for charges above 1-2pC the beam waists shown in figure 3 are space charge dominated. Below this value in our experimental arrangement, the spherical aberration, rather than the emittance or charge, is the dominant factor. However, for cases where the space charge is not dominant, we can assume that the measured waist size is a sum in quadrature of aberration and emittance terms. The emittance can then be estimated by:

$$\varepsilon_n \approx \beta\gamma\left(\frac{\sigma_1\sigma_{2,\varepsilon}}{L}\right)$$

Here $\sigma_{2,\varepsilon}$ represents the beam radius at the beam waist (BPM 2) with the aberration removed, σ_1 represents the beam radius at the BPM 1 and L is the drift distance between the two BPMs. Using the smallest spot obtained (85 µm), the normalized emittance for a low charge (~ .1 pC) is 0.6±0.4 mm-mrad. The 0.3 pC spot shown in figure 5 (104 µm) yields an emittance of 0.5±0.5 mm-mrad. For a charge of 1 pC, the emittance is 1.2±0.7 mm-mrad. Here the assumption that space charge can be ignored is probably not valid, so this case is likely an upper bound. The current density at the cathode in this case is 2.3 kA/cm^2, comparable to that in RF guns. For these parameters, the simulations predict the beam at emission to be limited by thermal emittance to ~0.2 mm-mrad.

In addition to spherical aberration, other factors tend to increase the spot size at BPM 2. The shot-to-shot fluctuation of the beam energy shifts the focus around the location of BPM 2, introducing uncertainty in the location of the waist. In addition, the larger spot measured on BPM 1 must contain a charge of at least 5 pC for the image to be visible. The measured σ_1 is thus larger than that expected for low charges. Both of these effects will tend to cause overestimation of the beam emittance.

CONCLUSION & FUTURE PLANS

Photoemission from a copper cathode has been observed with a 300 fs laser. The resulting electron bunch has been accelerated using a pulsed high voltage to an energy of 150 keV. This beam has been focused by a solenoid, and beam profiles have been acquired at two BPMs. The waist size is dominated by spherical aberration in these cases, reducing the resolution of the emittance measurement. An emittance value of 0.5 mm-mrad for a current density at emission of 0.7 kA/cm^2 was obtained.

Simulations have demonstrated that the spherical aberration is caused by the anode aperture and resulting large beam divergence. Increasing the electrode gap will reduce this effect, while covering the anode aperture with a foil or conducting screen will remove it.

We plan to increase the voltage to ~900kV and measure emittance for higher gradients. We will also improve the diagnostic system to reduce or remove the spherical aberration; this will improve the resolution of our emittance measurement.

ACKNOWLEDGMENTS

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

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