PRODUCTION OF HIGH BRIGHTNESS ELECTRON BEAMS WITH A 17 GHZ RF GUN

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Abstract

We report on beam measurement results from the MIT 17 GHz RF gun experiment. Tests of a 1.5 cell RF gun have been completed, with bunch charges up to 0.1 nC and beam energies up to 1 MeV produced. The normalized rms emittance of the beam after 35 cm of transport from the gun has been measured to be about 3 πmm mrad for a 50 pC bunch. This agrees with PARMELA simulations at these beam energies, and can be shown to correspond to a beam brightness of about 80 A/(πmm mrad)^2 at the gun exit. Results of a 2.4 cell 17 GHz RF gun are also reported. This gun has been built and cold tested and high power RF conditioning has begun. The gun is designed to produce a 2 MeV beam with peak accelerating gradients of 200 MV/m. After emittance compensation, simulations predict a 0.1 nC bunch with a normalized emittance of 0.5 πmm mrad can be produced, corresponding to a beam brightness of 800 A/(πmm mrad)^2.

1 INTRODUCTION

The need for higher brightness electron beams has fueled an increasing interest in recent years in the use of high frequency RF guns[1][2][3]. Previous studies[4] showed that the emittance of a beam produced from an RF gun will scale inversely with RF frequency under ideal circumstances. The MIT 17 GHz photocathode RF gun (the first to operate above 3 GHz) is a multi-cell electron accelerating structure consisting of coupled TM_{010} mode cavities excited by side wall coupled microwaves from a WR-62 waveguide. Initial experiments demonstrating beam production from a previous version of the 17 GHz RF gun have been completed at MIT and have been previously reported [5]. The results presented in this paper are for a new RF gun experiment that includes a number of improvements over the previous experiment, including an improved beamline that features the addition of an emittance compensating solenoid and emittance diagnostics. In this paper, we report on the successful high power operation of a 17 GHz RF gun consisting of 1.5 cells, as well as the initial operation of a 2.4 cell RF gun.

2 BEAMLINE DESIGN

A schematic of the beamline for the RF gun experiment is shown in Fig. 1. The UV drive laser is injected at near normal incidence by an aluminum mirror inside the laser injection chamber. The mirror is slightly offset from the beam axis to allow the electron beam to be transported to downstream diagnostics. The laser beam for the RF gun photocathode is generated by a Ti:Sapphire laser system, which produces 2 ps, 1.5 mJ pulses at 800 nm after chirped pulse amplification. The pulse duration of 2 ps was verified using a single-shot autocorrelator. These pulses are frequency tripled to 10-20 μJ of UV, and then focused on the back wall of the copper cavity. Emittance compensation is performed with a 6.5 cm long, 5 kG peak field solenoid. The emittance is measured by breaking the beam into individual beamlets using an array of 50 μm slits drilled in a thin (0.125 mm) tantalum foil placed about 35 cm from the gun cathode. The location of the slits in the beamline was chosen to allow for measurement of the emittance during the minimum of the emittance compensation process. In order to reconstruct the phase space, the beamlets are imaged downstream of the slits using a scintillating YAG crystal and CCD camera. By measuring the emittance at this location, it is desired to demonstrate the best quality electron beam that could be delivered to a booster linac for additional acceleration. The beam energy in this experiment is determined with a 90 degree bend, Browne-Buechner style magnetic spectrometer. The spectrometer is imaging in the bend plane, resulting in a better than one percent energy resolution.

2.1 Beam Simulations

The emittance compensation was designed to be effective for a 0.1 nC beam with energy of at least 2 MeV. The high energy is necessary to limit beam degradation due to space charge forces and velocity spread during transport. In this case, PARMELA simulations indicate a normalized rms emittance of 0.5 πmm mrad can be produced after emittance compensation. For lower energy beams ($\sim$ 1

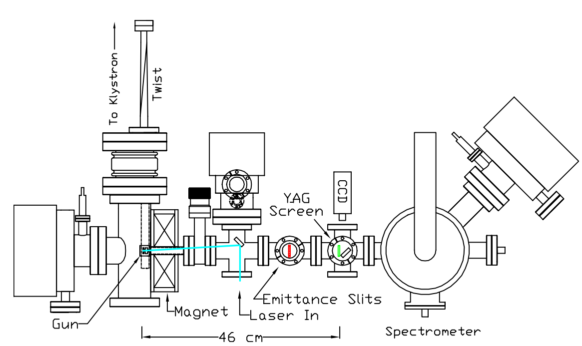

Figure 1: Schematic of RF gun beamline.

MeV), the simulations showed that the emittance compensation is much less effective, with the normalized emittance for a 50 pC bunch increasing from about 1 πmm mrad at the gun exit to about 3 πmm-mrad after transport to the slits. It is evident that the successful production of ultra high brightness beams in high frequency electron sources will depend on the attainability of the high field gradients necessary to produce a beam of sufficient energy. For a 1.5 cell gun, peak accelerating fields in excess of 300 MV/m will be required to obtain these parameters. Simulations have also shown that a similar beam energy and emittance can be achieved in a 2.4 cell gun with peak accelerating fields of only 200 MV/m. Assuming a 2 MeV beam can be produced, the normalized rms brightness of the beam defined by

$$B_n = \frac{2I}{\varepsilon_n^2}, \quad (1)$$

where ε_n is the normalized rms emittance and I is the peak current in the electron bunch, could reach values of about 800 A/(πmm mrad)^2. This would represent a significant advance in electron beam sources, allowing for breakthroughs in accelerators designed for various applications, including TeV colliders and free electron lasers.

3 HIGH POWER OPERATION OF THE 1.5 CELL RF GUN

The high power experiment utilizes a 17 GHz relativistic klystron amplifier constructed by Haimson Research Corporation[6] to provide a 50 ns to 1 μs pulse of up to 26 MW of microwave power. The klystron is driven by a 560 kV, 1 μs flattop modulator pulse. A 0.27 μperv Thomson CSF gun produces a space-charge limited electron beam at 560 kV with 95 A transmitted through the klystron. The amplifier chain includes a TWT amplifier to provide up to 5 W to the klystron. The klystron gain is approximately 67 dB. To date, up to 4 MW of incident power have been coupled into the 1.5 cell RF gun cavity yielding accelerating gradients approaching 200 MV/m.

3.1 *Bunch Charge Measurements*

With 15 μJ of 266 nm light incident on the gun cathode, and about 200 MV/m accelerating gradients in the half cell, bunch charges up to 0.11 nC have been observed. This corresponds to a quantum efficiency for the copper cathode of about 3 x 10^{-5}. Field enhancement of the laser induced electron emission was observed by varying the laser injection phase. The measured dependence of charge on injection phase is seen in Fig. 2, and is in good agreement with that predicted from photoemission theory [7], which states that the electron yield will be proportional to the square of the difference between the effective work function of the cathode material and the photon energy. The beam energy was measured to be 0.9 MeV with the magnetic spectrometer. This agrees with the energy calculated based on a peak accelerating gradient of 170 MeV/m at the cathode. This field gradient is verified from calculations of the stored energy based on forward and reflected RF power measurements.

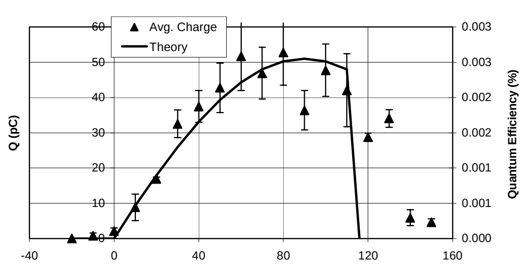

Figure 2: Average charge vs. laser injection phase.

3.2 *Emittance Measurements*

Transverse beam profile images were obtained by using a YAG crystal as a scintillator and storing the image using a CCD camera and frame grabber. Emittance measurements were performed by passing the beam through an array of 50 μm slits placed 13 cm before the scintillator. By measuring the width of each beamlet at the YAG screen position as well as the relative intensity of each beamlet over the entire transverse dimension of the beam, the Twiss parameters can be determined and the geometric rms emittance can be calculated.

A typical emittance measurement can be seen on the right side of Fig. 3. The bunch charge for each measurement is estimated by integrating over the intensity profile of the beamlets. On the left side of Fig. 3 a roughly linear dependence between emittance and charge can be seen, which is in good agreement with theory [8] as well as with PARMELA simulations. For these beam energies (0.8-1.0 MeV), PARMELA simulations suggest a roughly 3 fold space charge induced emittance growth occurs between the exit of the gun and the location of the slits. For the measured normalized emittance of $\varepsilon_n \approx 3\,\pi$mm mrad for a 50 pC beam at the location of the slits, an emittance

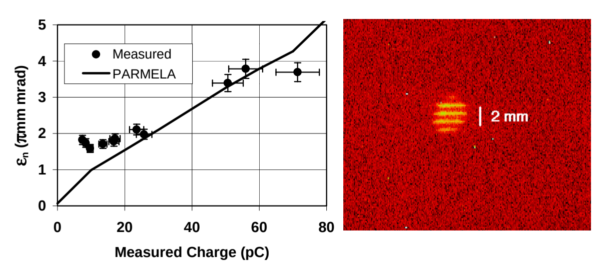

Figure 3: Image of individual beamlets produced by the slits after a 13 cm drift length (right), and (left) depedence of normalized emittance on charge for a 0.8 MeV beam as determined from measurement (dots) and from PARMELA simulations (line).

of about 1 πmm mrad at the exit of the RF gun can be inferred, corresponding to a normalized rms brightness of about 80 A/(πmm mrad)^2 . While this result is comparable to the best results produced from lower frequency RF guns [9][10], it does fall short of the design goals set for the 17 GHz gun due to the lower than expected beam energy and the resulting inability to perform emittance compensation.

4 A 2.4 CELL RF GUN

A 2.4 cell RF gun was built to overcome the difficulties experienced with the 1.5 cell gun in obtaining high beam energies. It is designed to produce a 2 MeV beam with an accelerating gradient of only 200 MV/m. The shortened "half cell" is designed to improve synchronization of the electron beam with the accelerating fields in the gun, resulting in reduced energy spread and improved longitudinal bunching. The gun is equipped with symmetrizing coupling holes to eliminate the dipole field asymmetry caused by the single waveguide coupling scheme. PARMELA simulations of the acceleration and subsequent emittance compensation have demonstrated that a brightness of 800 A/(πmm mrad)^2, corresponding to $\varepsilon_n \approx 0.5\,\pi$mm mrad for a 100 A peak current beam, should be obtainable.

Cold tests performed on the gun resulted in a measured ohmic quality factor of 2350, and a coupling coefficient of about 1.67. The longitudinal field profile was measured using a "bead hang" technique [11], which showed the field strength in each cell to be equal to within 20%.

High power conditioning of the 2.4 cell gun has resulted in up to 2.5 MW of RF power successfully coupled into the RF gun, corresponding to peak accelerating gradients of about 140 MV/m after approximately 10^5 processing shots. A beam energy of 1.25 MeV has been measured with the magnetic spectrometer. This represents a modest improvement over the 1.5 cell RF gun, but the energy is still too low to allow for the realization of the design beam brightness. To date, efforts to operate at higher power have resulted in RF breakdown in the cavity. Efforts are ongoing to try to increase the sustainable field gradient to 200 MV/m in order to obtain the optimum beam brightness.

5 CONCLUSIONS

High power tests of a 1.5 cell 17 GHz RF gun have been completed. High power conditioning of the gun has yielded accelerating gradients of 200 MV/m, and electron beam emissions of over 0.1 nC have been measured corresponding to a quantum efficiency of 3 x 10^{-5} for the copper cathode. Schottky enhancement of photo-emission has been verified, and laser to RF phase stability of 2 ps has been measured. An rms normalized emittance of 3 πmm mrad has been measured after 35 cm of beam transport from the gun for a 1 MeV, 50 pC beam, in good agreement with simulations. The maximum beam energy produced by the $1\frac{1}{2}$ cell gun has been limited to about 1 MeV by RF breakdown when the field gradient exceeds 200 MV/m. A 2.4 cell gun has been built to achieve a higher beam energy. In this gun, peak accelerating fields of 200 MV/m are sufficient to produce a 2 MeV beam. If successful, a 100 pC, 1 ps electron bunch with a normalized emittance of 0.5 πmm mrad should be obtainable after emittance compensation. To date, peak accelerating fields of about 140 MV/m have been obtained in this gun, and beam energies of up to 1.25 MeV have been measured.

6 ACKNOWLEDGMENTS

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