

# EXPERIMENTAL OPERATION OF A 17 GHz PHOTOCATHODE RF GUN

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## Abstract

Initial operation of a 17 GHz RF photocathode electron gun has been achieved at MIT. This is the first photocathode electron gun to operate at a frequency above 2.856 GHz. Such electron guns have the potential for achieving record high values of electron beam quality. The 1.5 cell,  $\pi$ -mode, copper cavity was tested with 5-10 MW, 100 ns, 17.145 GHz pulses from a klystron amplifier built by Haimson Research Corp. Conditioning resulted in a maximum surface field of 250 MV/m. Dark current of 0.5 mA was observed at 175 MV/m, consistent with Fowler-Nordheim field emission theory if a field enhancement factor of about 100 is assumed. Electron bunches were generated by a regenerative laser amplifier that produces 20-40  $\mu$ J UV pulses. Faraday cup measurements indicated 0.12 nC bunches were produced with a kinetic energy of about 1 MeV. This corresponds to a peak current of about 120 A, and a density at the cathode of 8.8 kA/cm<sup>2</sup>. Phase scans of laser induced emission reveal an overall phase stability of better than  $\pm 20^\circ$ , corresponding to  $\pm 3$  ps synchronization of the laser pulses to the microwave field.

## 1 INTRODUCTION

The goal of the 17 GHz photocathode experiment is to construct an ultra high-brightness source of electrons which can be used for free electron lasers or future linear colliders. The photocathode RF gun is a novel electron beam source intended to meet the requirements set by future high-energy linear colliders and next generation free electron lasers. A coupled pair of pillbox  $TM_{010}$ -like resonators is excited by sidewall coupled microwaves at 17 GHz. The axisymmetric copper cavity

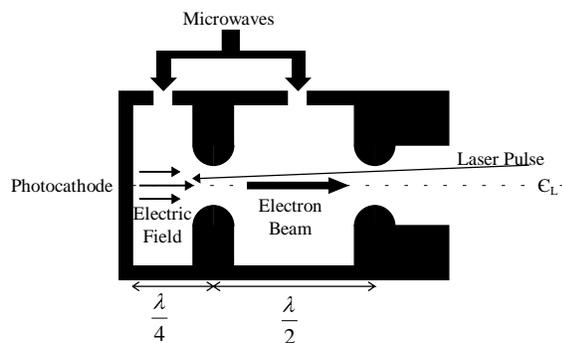


Figure 1: Schematic of the RF gun cavity

is shown in Figure 1. Note that the axial length of the structure is determined by the microwave wavelength. A picosecond ultraviolet laser pulse illuminates the back wall of the structure at the axis of symmetry. Electrons are released by the photoelectric effect and are accelerated by the axial electric field.

The M.I.T. experiment operates at a frequency of 17 GHz. Previous photocathode RF gun experiments have operated at 3 GHz or below. From an analysis of the Vlasov-Maxwell equations governing the dynamics of the electron beam production in the photocathode RF gun, scalings of the quality of the beam which can be produced in an RF gun with frequency have been derived [1]. According to these scaling laws, the brightness of the beam, a figure of merit for the beam quality, varies as the square of the RF gun frequency.

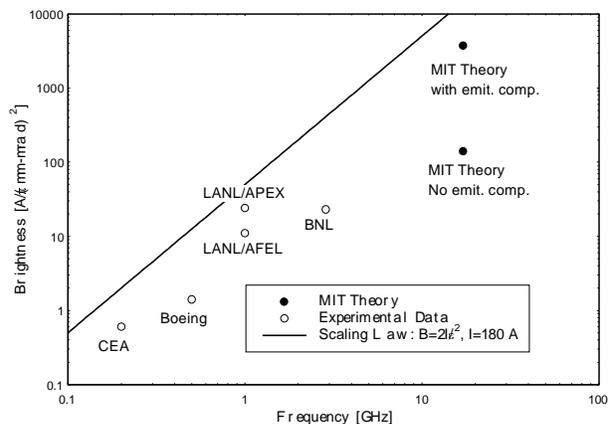


Figure 2: Scaling of brightness with frequency

Figure 2 illustrates experimental values of beam brightness for several frequencies. Theoretical values are given for the M.I.T. experiment for two cases. The lower value, corresponding to the present experimental setup, assumes no emittance compensation. The higher value assumes the use of a solenoidal field to achieve the maximum brightness possible. For our experiment, an axial field of 10 kG would be required.

## 2 DESIGN OF EXPERIMENT

The major system components of the MIT experiment are shown in Figure 3. The RF gun cavity is located in a large vacuum vessel shown at the bottom of the diagram. The RF gun cavity is a traditional B.N.L.-style sidewall coupled 1.5 cell structure. The RF gun is composed of

three pieces of OFHC copper which are clamped together and attached as a single piece to the WR-62 coupling waveguide. The RF gun has been studied theoretically by analyzing the eigenmodes of the accelerating structure in the absence of coupling holes and the excitation of the modes through the coupling to the waveguide. The coupling holes were modeled by choosing the magnetic polarizabilities of the holes empirically to match cold test data with theory. The polarizabilities were substantially smaller than the values predicted using Bethe's expressions for the polarizability of an elliptical aperture in an infinitely thin wall. However, the observed values were consistent with the finite thickness of the walls in which the RF gun coupling holes are located.

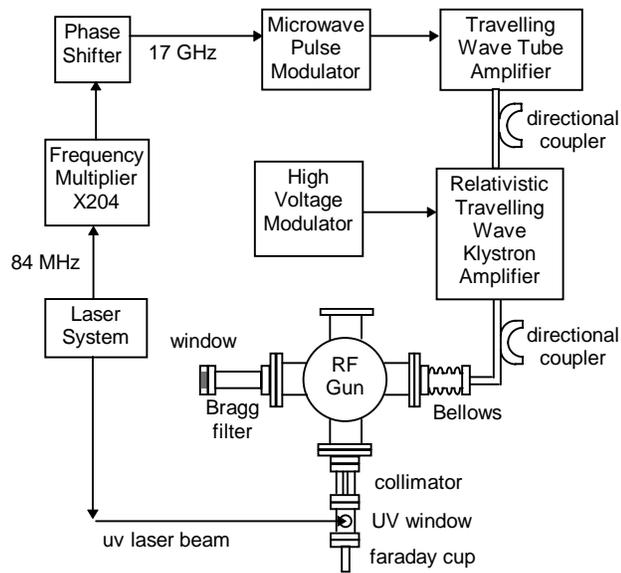


Figure 3: Major experimental components

The RF gun requires a 50 ns, 7.2 MW pulse of 17 GHz microwaves to achieve the design gradient of 250 MV/m fields at the cathode. The experiment utilizes a 17 GHz relativistic klystron amplifier constructed by Haimson Research Corporation. The klystron is driven by a 580 kV, 1  $\mu$ s flat-top modulator pulse. A Thomson CSF gun produces a 100 A pulse. The beam is space-charge limited and the gun perveance is 0.27  $\mu$ perv. The amplifier chain includes a TWTA to provide about 10 W to the klystron. The klystron gain is approximately 60 dB. Dark current of 0.5 mA was observed when 3.5 MW of microwave power was coupled into the cavity. This corresponds to a peak electric field of 175 MV/m, and is consistent with Fowler-Nordheim field emission theory if a field enhancement factor of about 100 is assumed.

The klystron amplifier has been found to generate power in other spurious modes when connected to a mismatched load. Microwaves associated with these modes are slightly

higher in frequency than the operating frequency of the klystron. To eliminate these modes, which reduce the stability and gain of the amplifier, a Bragg filter was designed and installed on the RF gun coupling waveguide. The Bragg filter structure is shown in Figure 4. This filter is reflective for frequencies between 16.7 and 17.2 GHz, and transmits for higher frequencies. The use of the Bragg filter allowed cavity coupling at 17.15 GHz, while minimizing impedance mismatches at higher frequencies that would cause the spurious oscillations to occur. Up to 8 MW of klystron power was coupled into the cavity, with amplitude stability of  $\pm 5\%$ . Phase stability was also measured using a phase discriminator. This stability was found to be  $8^\circ$  from shot-to-shot, and less than  $4^\circ$  during a single shot.

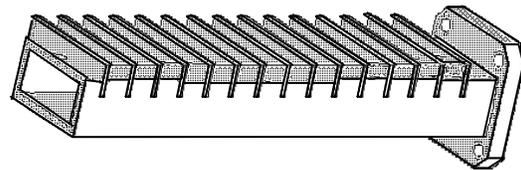


Figure 4: Bragg filter

The laser beam for the RF gun photocathode is generated by a Ti:Sapphire laser system, which produces 1.9 ps, 1.9 mJ, 2 mm diameter pulses at 800 nm. The pulse duration of 2 ps at 800 nm was verified using a single-shot autocorrelator. Pulse-to-pulse laser energy fluctuations are approximately  $\pm 10\%$  at 800 nm. These pulses are frequency tripled to 20-40  $\mu$ J of UV, and then focused on the back wall of the copper cavity. The ultraviolet spot size is approximately 0.7 mm in diameter and 1 ps in duration estimated from the infrared pulse measurements using nonlinear optical theory. Measurement of the frequency sidebands using a spectrum analyzer [2] indicated a laser phase jitter of less than 5 ps, or 30 degrees.

The timing scheme used in the M.I.T. RF gun experiment is slightly different from that of other photocathode experiments. A photo-diode samples the light pulses bouncing back and forth in the optical cavity of the Ti:Sapphire laser oscillator. The IR pulses of this oscillator are used as input to a regenerative amplifier. The frequency of these pulses is 84 MHz and is dictated only by the length of the cavity. No external oscillator is used. The signal from this photodiode is used as input to a frequency multiplier box, which filters and amplifies the signal. The output signal is about 17 GHz and is phase-locked to the laser system. This milliwatt level signal is used as input to the microwave amplifier chain which drives the RF gun experiment (see Figure 3).

### 3 RESULTS

Initial operation of the RF-gun was achieved in December, 1996. Current associated with photo-emission was observed with a Faraday cup located about 20 cm from the cavity. A typical set of experimental traces is shown in Figure 5. Extremely narrow, 2 ns FWHM negative Faraday cup signals are observed following the positive photo-diode signal by about 6 ns. This delay is consistent with the physical locations of the two diagnostics and cable signal delay. The integrated Faraday cup signal indicates 0.12 nC of charge for an electric field strength of 130 MV/m at the cathode at the time of injection. This value is inferred from the forward and reflected power at the rf cavity. Assuming a 1 ps pulse, this corresponds to a peak current of about 120 A, and a density at the cathode of 8.8 kA/cm<sup>2</sup>.

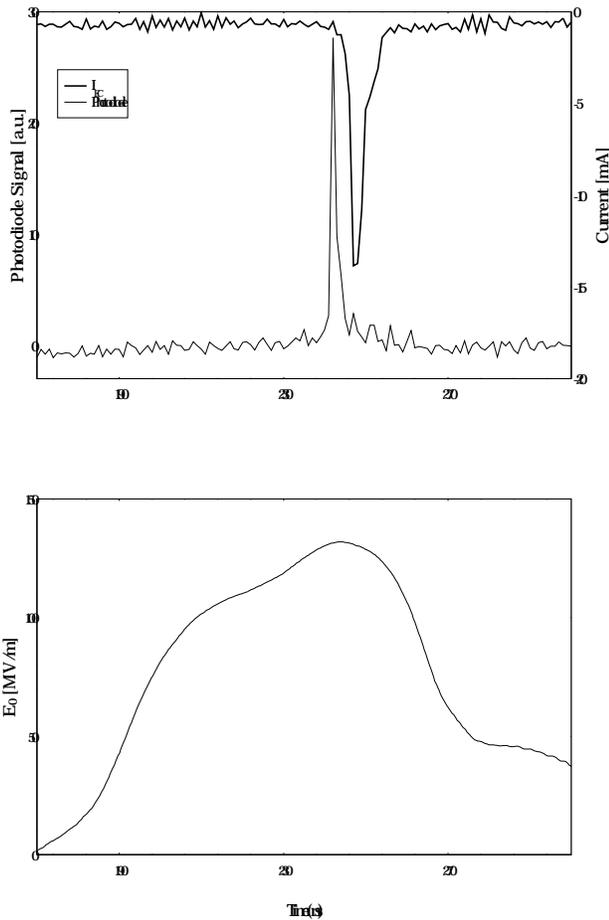


Figure 5: Experimental observation of emission

In order to verify that the laser pulses are injected at a nearly fixed phase relative to the 17 GHz microwaves, scans were performed using a variable phase shifter at the input to the relativistic klystron. Twenty shots were observed at each phase shifter setting and the percentage of shots exhibiting a Faraday cup signal was recorded. The percentages are graphed as a function of phase in Figure 6. The rising edge of the curve at about 180° is

consistent with Schottky field enhancement causing an increase in photoemission. The falling edge at 300° is consistent with cathode back-bombardment due to electrons being reflected by the cavity electric field. The width of the 100% emission indicates a phase stability of better than  $\pm 20^\circ$ . This corresponds to synchronization of the laser pulses to the microwave field with an error of approximately  $\pm 3$  ps.

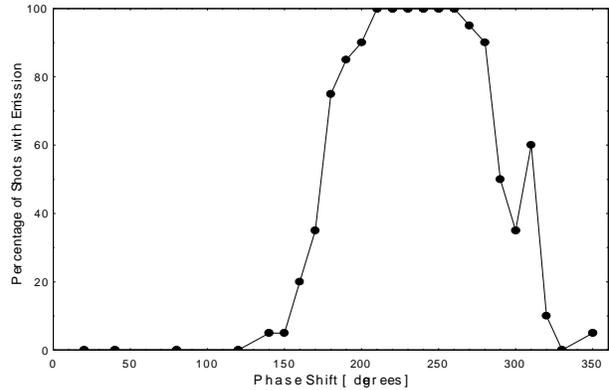


Figure 6: Dependence of emission on phase

Although the beam energy has not yet been directly measured, two factors suggest it is at least 1 MeV at the highest cavity RF fields. In earlier measurements of dark current, the transmission of electrons through metal sheets was measured. These experiments indicated energies between 1.7 and 2.5 MeV. Secondly, assuming an initial beam size at the gun exit of 0.7 mm, then the space-charge divergence of the beam would be too large, and the beam would not reach the Faraday cup, unless its kinetic energy was  $>1$  MeV.

### 4 FUTURE PLANS

The next step in the 17 GHz RF gun experiment is the characterization of the electron beam quality. A Browne-Buechner magnetic energy spectrometer is being installed at this time. This will provide information about the average energy and energy spread of the electron beam. The emittance of the electron bunch will be measured initially using magnetic steering coils and narrow collimators. Emittance compensation will be added later to increase the beam's brightness.

### REFERENCES

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- [2] D. von de Linde, "Characterization of the noise in continuously operating mode-locked lasers," Appl. Phys. B, pg. 201 (1986).