

High Power Operation of a 17 GHz Photocathode RF Gun

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ABSTRACT

We report the first operation of a 17 GHz RF photocathode electron gun. 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 $1\frac{1}{2}$ cell, ρ -mode, copper cavity was tested with 5-10 MW, 100 ns, 17.145 GHz pulses from a 24 MW Haimson Research Corp. klystron amplifier. Klystron power is stable to within $\pm 5\%$ up to 15 MW. Conditioning resulted in a maximum surface field of 250 MV/m, corresponding to an on-axis gradient of 150 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 2 ps, 1.9 mJ pulses at 800 nm with $\pm 10\%$ energy stability. These pulses were frequency tripled to 46 mJ of UV, and then focused on the wall of the cavity. Preliminary beam measurements indicate 0.12 nC bunches were produced with a kinetic energy of about 1 MeV. This corresponds to a peak current of about 100 A, and a density at the cathode of 2 kA/cm^2 . Both single and multiple pulse laser induced beam emission were observed.

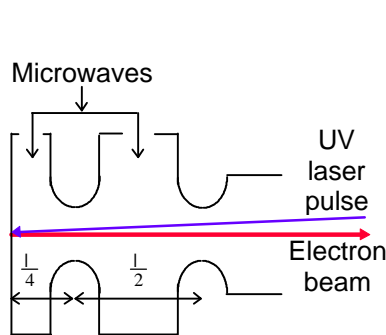


Figure 1. side view of rf gun structure

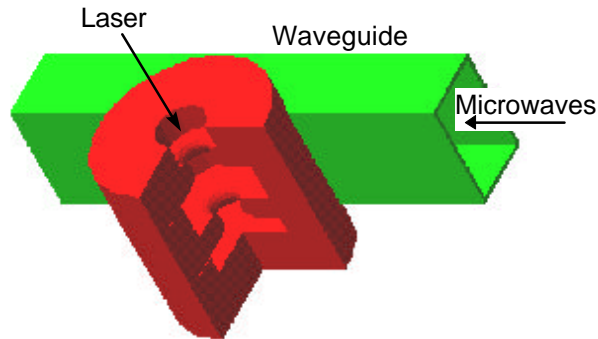


Figure 2. rendered view of rf gun

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 lasers¹. A coupled pair of pillbox TM_{010} -like resonators is excited by sidewall coupled microwaves at 17 GHz. The axisymmetric structure is shown in cross section in Figure 1. Note that the axial length of the structure is determined by the microwave wavelength. A three dimensional view of the RF gun structure and coupling waveguide is shown in Figure 2. A picosecond ultraviolet laser pulse illuminates one wall of the structure at the axis of symmetry. Electrons are released by the photoelectric effect and are accelerated by the electric field of the microwaves in the cavity.

According to photoinjector scaling laws^{2,3}, operating at high frequency will allow production of extremely high brightness beams. The high frequency of operation raises the RF breakdown limit allowing strong electric fields to be used. In turn, the intense fields result in rapid acceleration of the electrons to relativistic speeds and reduced space charge induced emittance growth. The variation of rms normalized emittance with frequency is shown in Figure 3 according to scaling laws including the assumption of emittance compensation (solid curve). Data points indicate experimental results. Note that it is possible to achieve lower emittance than the scaling law suggests at the cost of lower charge in an electron bunch. Figure 4 shows the theoretical variation in beam brightness with frequency⁴.

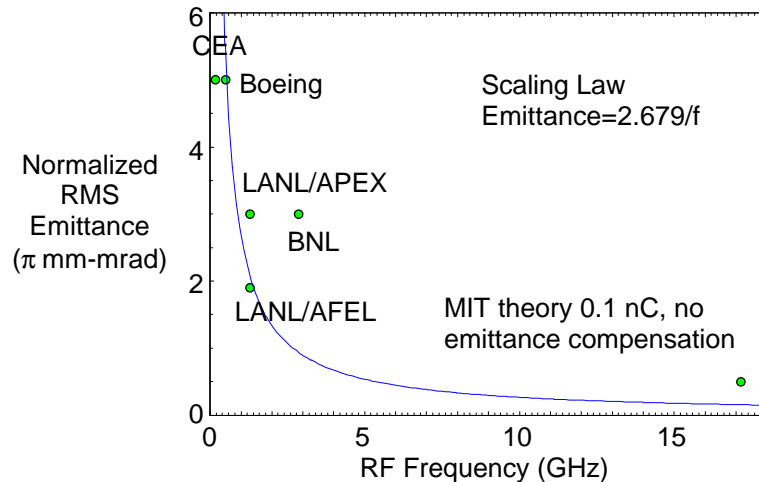


Figure 3. emittance frequency scaling

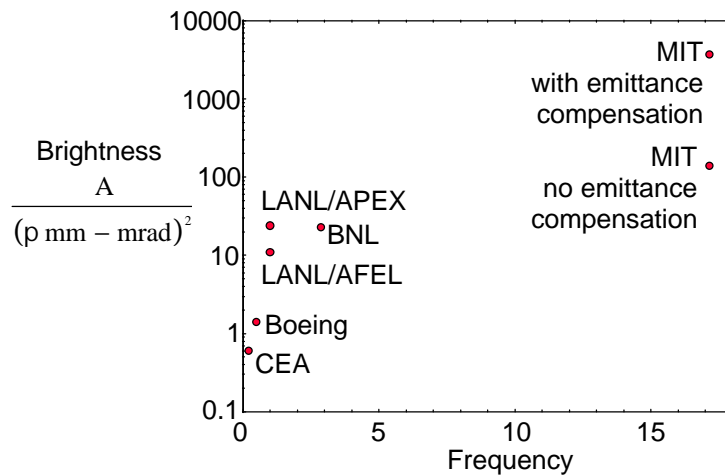


Figure 4. brightness frequency scaling

RF CAVITY AND TRANSPORT LINE

As shown in Fig. 1, the MIT 17 GHz RF gun is a traditional B.N.L.-style sidewall coupled 1.5 cell structure⁵. The RF gun is clamped, not brazed, and has been cold tested using a vector network analyzer. The measured parameters are given in Table 1. Note that the peak electric field is not measured directly but inferred from the energy balance equation.

Table 1 - rf gun measured parameters

Frequency	17.145 GHz (6*SLAC frequency)
Length	1.31 cm (1.5 cells)
Inner Diameter of Cavities	0.538"
Unloaded Quality Factor	1790
Loaded Quality Factor	808
Coupling Coefficient	1.22
Ratio of Peak to Average field	1.21
Material	OFHC Copper
Peak Electric Field at Cathode	250 MV/m (7.2 MW pwr into gun)

The RF gun requires a 7.2 MW, 50 ns pulse to reach the design level field strength of 250 MV/m on axis. The experiment utilizes a 17 GHz relativistic klystron amplifier constructed by Haimson Research Corporation⁶. The klystron is driven by a 580 kV, 1 μ s flattop modulator pulse. A Thomson CSF gun produces a 100 A pulse. The beam is space-charge limited and the gun perveance is 0.27 μ perv. The amplifier chain includes a TWTA to provide about 10 W to the klystron. The klystron gain is approximately 60 dB. A block diagram of the system components is shown in Figure 5.

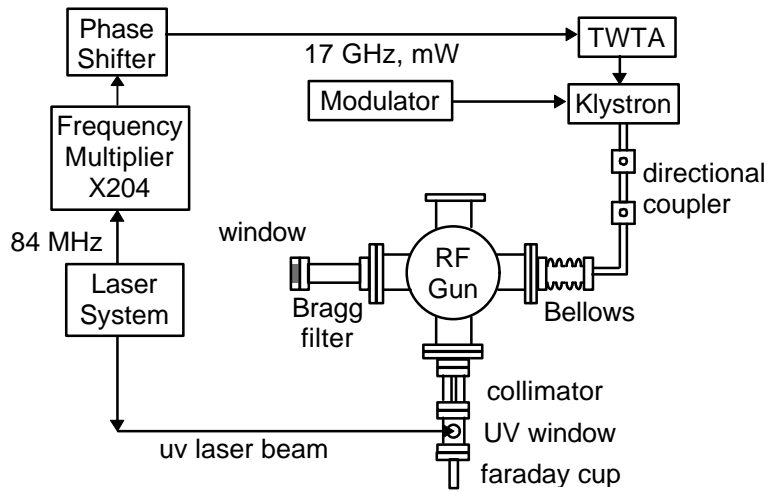


Figure 5. system block diagram

The klystron amplifier has been found to generate power in two 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 has been designed and installed on the RF gun coupling waveguide. This filter is reflective for frequencies in the range 16.7 to 17.1 GHz and is transparent for higher frequencies. The filter has eliminated one spurious mode and variation of magnetic optics has shifted the second mode so that it occurs after the microwave output pulse. The klystron power stability is better than $\pm 5\%$. The Bragg filter structure is shown in Figures 6 and 7. As shown in Figure 5, the microwaves transmitted through the Bragg filter and exit the RF gun vacuum vessel via a window. Note that the filter is not completely reflective at the operating frequency reducing the power coupled into the RF gun.

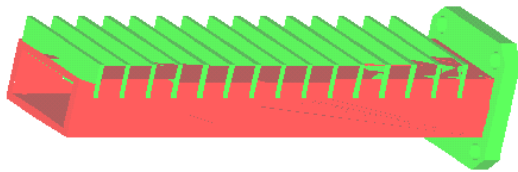


Figure 6. rendered Bragg filter

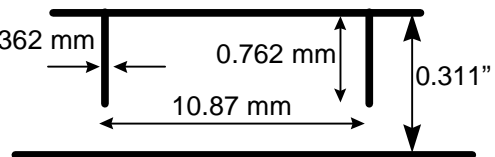


Figure 7. Bragg filter cross section

The phase stability of the klystron output is better than 5° measured using a phase discriminator. However, this measurement was limited by noise and the actual phase stability figure may be lower.

LASER

The illumination for the RF gun photocathode is produced by a Ti:Sapphire laser system. The laser system produces 2 ps, 1.9 mJ 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. The laser system parameters are summarized in Table 3.

Table 3. laser system parameters

Parameter	Design	Measured
Initial Wavelength	800 nm	800 nm
Tripled Wavelength	267 nm	267 nm
Repetition Rate	10 Hz	10 Hz
IR Energy per pulse	1.5 mJ	1.9 mJ
UV Energy per pulse	10 μ J	46 μ J
Energy Fluctuation (IR)	$\pm 10\%$	$\pm 10\%$
Pulse Length	2 ps	1.9 ps
Phase Jitter	< 1 ps	unknown
Timing Jitter	< 1 ns	< 1 ns
Polarization	> 99 %	> 99 %
Beam divergence	0.5 mrad	0.2 mrad
Laser Spot Radius	0.5 mm	1 mm
Beam pointing error	< 50 μ rad	< 50 μ rad
Modelock frequency	84 MHz (tunable)	84 MHz tunable

The pulses are frequency converted using the nonlinear optical properties of a 10 mm cube of KDP crystal for second harmonic generation to blue, 400 nm, light and a 5 mm cube of BBO crystal for sum frequency generation into the ultraviolet, 267 nm. The collinear arrangement of crystals shown in Figure 8 is possible since group velocity dispersion is not significant for 2 ps pulses in crystals of these sizes and walk-off is not significant.

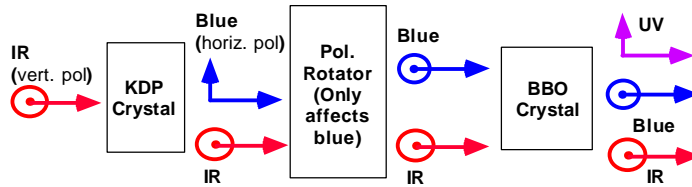


Figure 8. harmonic generation system

The UV pulses each contain up to 46 mJ of energy which is more than sufficient to create 0.1 nC from a copper cathode under the strong microwave field enhancement of the photoelectric effect. Equation 1 gives the dependence of quantum efficiency on field strength and wavelength for copper⁷.

$$h = A \left[\hbar \omega - f + \sqrt{\frac{eE}{4\pi\epsilon_0}} \right]^2, \quad A = 1.3 \cdot 10^{-3} / \text{eV}^2, \quad f = 4.65 \text{ eV} \quad (1)$$

The laser is located in a lab down the hall from the accelerator due to space constraints and requires stable beam transport over about 40 m to the RF gun. The beam is focused using a 5:1 reduction telescope to 2 mm diameter near the nonlinear optic crystals. The UV laser pulse is injected into the RF gun by means of a prism mounted inside a Faraday cup which faces the exit hole of the RF gun.

TIMING

In order to produce a high quality electron beam, emission of the electron bunch via the photoelectric effect must be synchronized with the electromagnetic field inside the RF gun. Synchronization of the UV laser pulse with the microwaves in the RF gun has two components, amplitude and phase. Amplitude corresponds to cavity filling on a 50 ns timescale. Phase corresponds to the phase of the accelerating field on a 1 ps timescale. (A picosecond is 6 degrees of RF phase at 17 GHz.) These two physical constraints are illustrated in Figure 9.

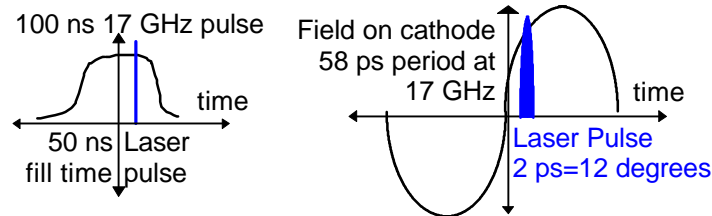


Figure 9. synchronization timescales

Phase synchronization is achieved via a somewhat novel approach. There is no external master clock or oscillator. The Ti:Sapphire oscillator is regeneratively modelocked. As laser pulses bounce back and forth in the cavity, a photodiode samples a small portion of the light. This signal is filtered, amplified, and used to drive an acousto-optic modulator. As a result, the frequency of modelocking is

determined by the optical length of the cavity. $f_{\text{Modelocking}} = \frac{c}{2L}$. The length of

the optical cavity is made stable by use of an INVAR metal tube which has a low thermal expansion coefficient. Typically, the frequency is 84 MHz plus/minus 0.1 ppm over hours of operation. The stability of the laser and the presence of the photodiode signal permit the use of the laser as the master clock. The 84 MHz photodiode signal is multiplied by 204 using solid-state electronics to 17 GHz for use as a milliwatt level input to the microwave amplifier chain.

Experimentally, the photodiode signal is taken out of the laser, amplified at the 84 MHz frequency, and transported to the RF gun control room via BNC cable. Next, the 84 MHz signal is converted to 17 GHz, phase shifted, and attenuated. The low power 17 GHz signal is then sent to the TWTA via WR-62 waveguide. As shown in Figure 10, spectral analysis of the derived 17 GHz signal is a narrowband, high quality signal with weak sidebands and wings.

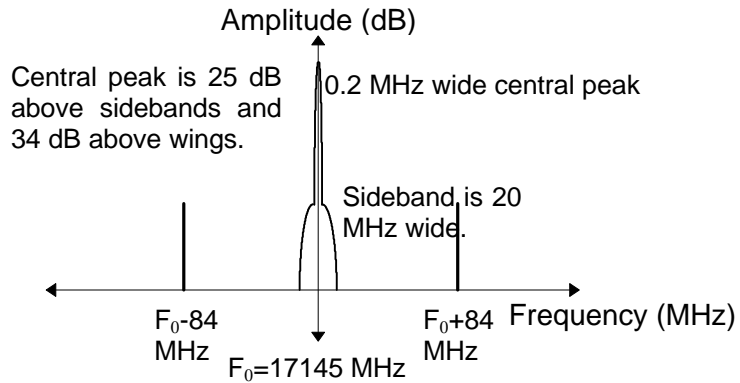


Figure 10. spectral analysis of derived 17 GHz

The synchronization of the laser pulse arrival to the correct amplitude of the electric field in the RF gun involves timescales from 1 second to 1 nanosecond. The sequence of events is shown in Figure 11. The klystron is operated at 1 Hz. The laser fires at 10 Hz. The buildup of the voltage in the high voltage modulator for the klystron requires approximately 150 ms. The buildup of energy in the YAG resonator requires about 140 μ s after the time the lamps energizing the rod are fired. The risetime of the current pulse from the modulator is about 2 μ s from the time the modulator fire command is sent. The laser pulses are 12 ns apart (84 MHz) and require about 500 ns to reach the RF gun from the time they are injected into the regenerative amplifier.

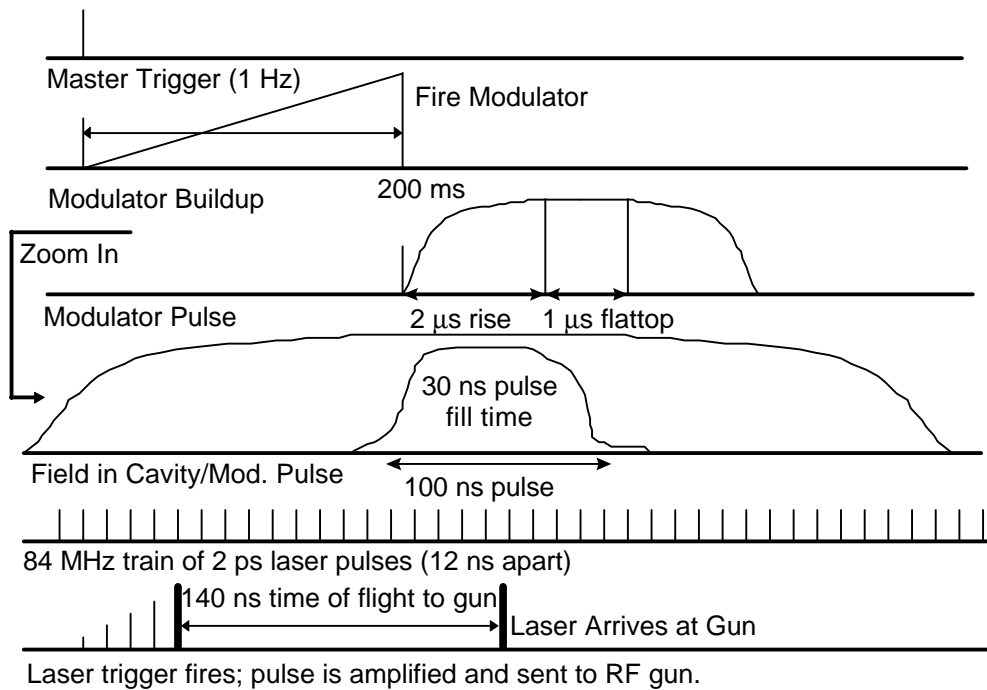


Figure 11. rf gun timing sequence

In order to synchronize these time scales, the laser is used as the master trigger. The laser produces two timing signals, lamp and Q-switch. The lamp signal occurs synchronously with the firing of the YAG lamps and therefore precedes the arrival of the laser pulse by $140 \mu\text{s} \pm 12 \text{ ns}$. The variation of the delay comes from the spacing between laser pulses. The lamp signal fires at 10 Hz. A divide-by-ten box is used to send the charge/fire command pair to the klystron modulator. This permits the coarse synchronization of the klystron gain to the laser pulse arrival (to within 12 ns). The second timing signal from the laser is the Q-switch signal. The laser electronics phase lock to the 84 MHz photodiode signal in order to select a pulse to inject into the regenerative amplifier. As a result, the Q-switch signal precedes the laser pulse arrival at the RF gun by $500 \text{ ns} \pm 1 \text{ ns}$ (perhaps less jitter, unobservable using existing oscilloscopes.) The Q-switch signal is used to turn on and off the microwave drive for the klystron by modulating the TWTA voltage grid and a microwave pin diode switch. Using this scheme, we have observed $< 1 \text{ ns}$ timing jitter between laser pulse arrival at the gun and the microwave input to the klystron. Laser synchronization is verified using an infrared photodiode located near the RF gun which detects scattered light from a turning mirror.

BEAM DIAGNOSTICS

Existing electron beam diagnostics are limited to a high speed Faraday cup shown in Figure 12. The Faraday cup is designed as a tapered 50Ω transmission line with a type N connector⁸. The hole in the central conductor serves to reduce secondary emission noise and allows passage of the UV laser beam into the RF gun. It has been found that the Faraday cup produces anomalous signals about 1 V in magnitude unrelated to the presence of electrons, when high power microwaves are present. Therefore, the signal to noise ratio of the Faraday cup was dramatically improved when isolated from microwaves and other electronic noise using a narrow metal collimator acting as a cutoff waveguide. With a 1.95" long, 0.2" i.d. collimator in place, the noise level on the Faraday cup was about 15 mV.

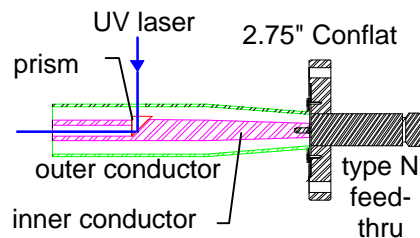


Figure 12. faraday cup

HIGH POWER OPERATION

High power tests of the RF gun with the klystron indicate consistent filling of the RF cavity and the generation of field gradients up to 180 MV/m without

breakdown. Occasional breakdown of the RF gun is observed at higher powers corresponding to field gradients up to 250 MV/m.

The laser photodiode signal has been frequency multiplied to 17 GHz and used to drive the klystron. Using the laser derived 17 GHz signal, over 10 MW stable power output has been demonstrated. The RF gun cavity has demonstrated stable filling using the laser derived megawatt microwave pulses. The laser pulse arrival has been synchronized with the RF gun cavity filling at the sub-nanosecond level. This time scale corresponds to the amplitude of the electric field in the RF gun as explained previously. The IR laser beam has been transported to the experimental area, converted to UV, and injected into the RF gun.

MEASUREMENT OF DARK CURRENT EMISSION

The reduced noise level on the Faraday cup diagnostic made it possible to observe the variation of dark current emission from the RF gun with field strength in accordance with the Fowler-Nordheim law. See Figure 13.

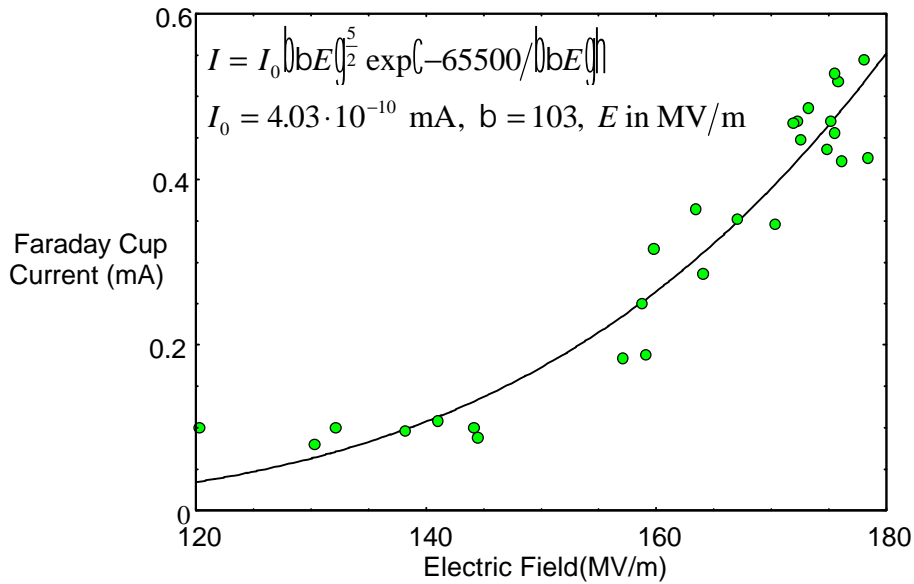


Figure 13. dark current data

EXPERIMENTAL RESULTS ON LASER-INDUCED ELECTRON BEAM EMISSION

The most important achievement in the 17 GHz RF gun experiment has been the demonstration of laser induced emission. Production of an electron beam from the 17 GHz RF gun at M.I.T. marks the first successful operation of a photocathode RF gun at a frequency higher than 3 GHz. The goal of laser induced emission was expected to be signaled by the appearance of an extremely brief Faraday cup signal whose width would be dictated by the capacitance of the

measurement system, a few ns, and whose area would correspond to the total charge emitted from the RF gun. This signal would appear different from dark current signals whose duration would be commensurate with RF drive pulse lengths. Also, breakdown signals on the Faraday cup would be wider, appear in the absence of the laser, and would be accompanied by a rise in pressure.

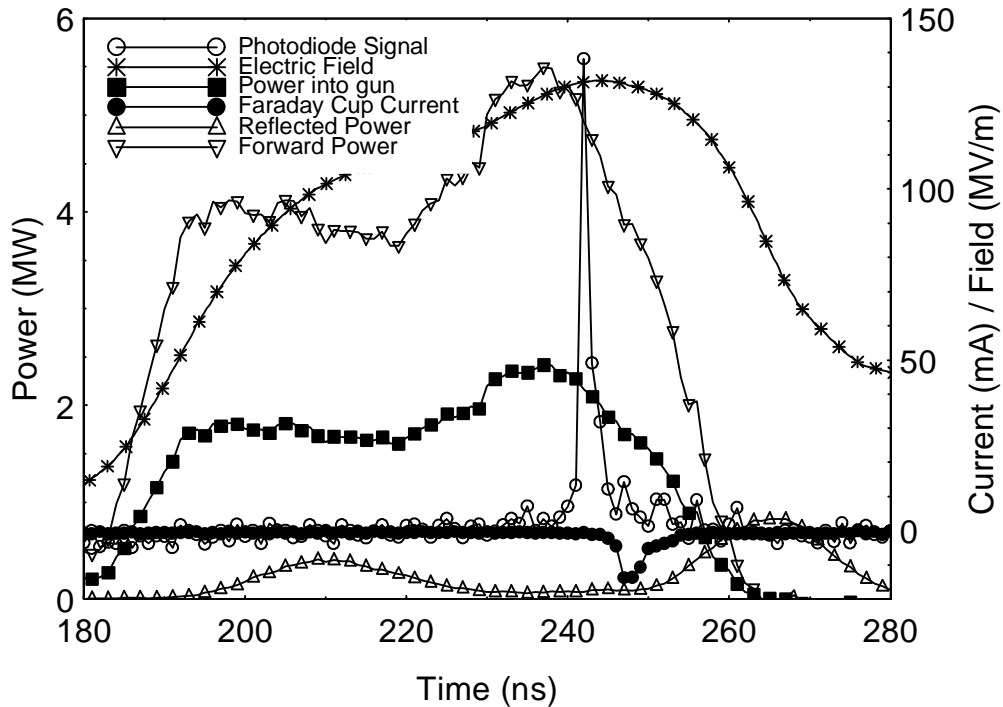


Figure 14. observation of laser induced electron beam emission (Faraday cup signal)

Pulses matching the expected signature were observed the first time the system was operated using the collimator on the Faraday cup. As shown in Figure 14, an extremely narrow, about 4 ns long, negative Faraday cup signal follows the positive photodiode signal by about 6 ns. This delay is consistent with the physical location of the photodiode detector relative to the RF gun and Faraday cup. UV pulses were measured to be about 20 mJ. The integrated Faraday cup signal indicates 0.12 nC of charge, consistent with theoretical expectations. The calculated electric field for this shot was 130 MV/m at the time of laser injection. These Faraday cup signal spikes are present only when the laser beam is injected into the RF gun.

Further evidence for the identity of the Faraday cup spikes is given by multiple pulse emission. Imperfect dumping of the regenerative amplifier cavity occasionally produces multiple UV laser pulses of reduced energy about 10 ns apart in time. These multiple pulses are observed on the photodiode diagnostic and in some cases produce multiple Faraday cup spikes with the same temporal structure.

Table 2. beam properties

Parameter	Design	Measured
Bunch Charge	0.1 nC	0.12 nC
Kinetic Energy	2 MeV	≈ 1 MeV
Bunch Length	0.5 ps	-
RF Injection Phase	12°	-
Current Density at Cathode	6.7 kA/cm^2	$\approx 2 \text{ kA/cm}^2$
Emittance (normalized rms)	$0.47 \pi \text{ mm-mrad}$	-
Energy Spread	0.18 %	-
Peak Current	210 A	≈ 100 A
Brightness	$9.9\text{E}13 \text{ A/(m-rad)}^2$	-

FUTURE PLANS

Short term plans focus on phase locking and beam quality measurement. Existing beam measurements are summarized in Table 2. To date, phase locking of the laser to the microwave field in the RF gun has not been demonstrated. Approximately 1 in 6 shots demonstrate laser emission regardless of the setting of the phase shifter in the microwave chain. This percentage is consistent with random phasing of the laser relative to the microwaves. Sources of phase jitter are being investigated.

A Browne-Buechner magnetic energy spectrometer employing a Faraday cup as a detector has been constructed and will be installed on the RF gun beamline. The use of a pepper pot or beam position monitor is being considered for emittance measurements. Pulse length measurement is planned using an RF kicker cavity.

Long term plans include modifications to improve the performance of the 17 GHz RF gun. While scaling laws indicate very high beam quality at 17 GHz without magnetic focusing, beam quality can be further improved (see Figure 2 theory data points for MIT experiment) with the implementation of a solenoidal magnetic field⁹. Typically a bucking coil to zero the field at the cathode and a second solenoid for focusing are used. Scaling laws indicate the need for about 1 T strength field for emittance compensation. Permanent magnets may be suitable considering the small field volume required. Iron pole pieces will be needed to concentrate magnetic flux.

It would be useful to implement a brazed RF gun to reduce power consumption and increase the maximum attainable accelerating gradient. In order to predict the microwave properties of a brazed RF gun from mechanical dimensions to sufficient accuracy, theoretical work is being done on the coupling of the RF gun to the WR-62 waveguide via holes in a finite thickness wall. The axisymmetric code, URMEL, is used to model the unperturbed 1.5 cell resonances and field structure. This data, combined with the quasi-analytical theory for the coupling hole polarizability accurately reproduces the measured S_{11} data for the RF gun. Figure 15 illustrates the theoretical prediction of the RF gun reflection

coefficient. Despite careful modelling, a brazed gun will probably require tuners since a 25 μ m error in the radius of a cavity will produce approximately 30 MHz shift in the 17 GHz resonance. Symmetrization of RF fields is being investigated by the adoption of coupling holes on two sides of a racetrack geometry¹⁰.

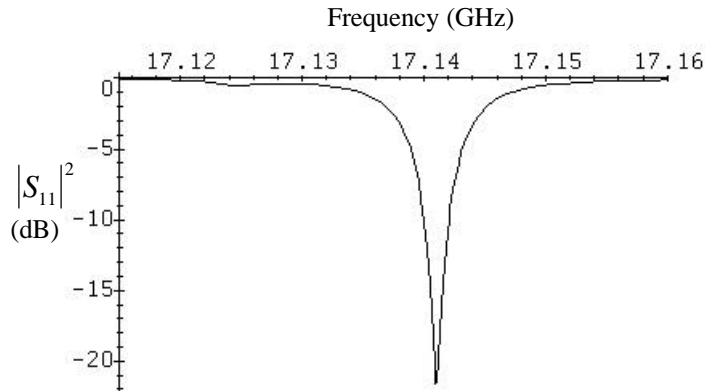


Figure 15. reflection coefficient for rf gun

ACKNOWLEDGMENTS

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