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A HIGH CURRENT, HIGH GRADIENT, LASER EXCITED, PULSED ELECTRON GUN*

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Abstract

This paper describes a pulsed electron gun that can be used as an FEL, as an injector for electron linear accelerators or for rf power generation. It comprises a 1 to 5 MeV, 1 to 2 ns pulsed power supply feeding a single diode, photoexcited acceleration gap. Beam quality of a ~ 1 nC charge in ~ 1 GV/m field was studied. Computations of the beam parameters as a function of electrode configuration and peak electron current are presented together with descriptions of the power supply, laser and beam diagnostics systems.

1 BACKGROUND

Among the many important parameters that characterize an electron beam are energy, brightness, emittance and energy distribution. Current efforts in accelerator research and research in new beam applications put very strict demands on these parameters. RF photocathode electron guns are currently the preferred choice for the production of high brightness electron beams. These guns satisfy many of the requirements for advanced accelerator investigations and they are currently used extensively for that purpose. Typically, even with the use of linear emittance compensation schemes, photoexcited rf guns provide a normalized beam emittance of ~ 1.0 to 1.5π mm-mrad emittance at a total charge of < 0.5 nC and brightness of $\sim 10^{13}$ A/m²-rad² at energies up to 4.5 MeV, an average accelerating gradient of ~ 60 MV/m at an operating frequency of 3 GHz leads to a physical length of ~ 10 cm. An alternative approach to generating high brightness beams is acceleration of electrons in a pulsed, constant voltage, high (1GV/m) electric field. In this approach, a ~ 2 ns, 1 MV voltage pulse is applied to a simple diode configuration [1]. During this short time interval, the photocathode is excited by a laser pulse of < 100 ps duration. Since the voltage remains constant during the pulse, the electron gun essentially operates in a *dc. mode* with minimal change in voltage.

TECHNICAL APPROACH AND POWER SUPPLY DESIGN

The pulsed, high gradient, laser excited photocathode electron gun is based on the recent studies of voltage

breakdown conducted by Juttner et. al. [2] and Mesyats et. al. [3]. Their studies indicate that metals could withstand voltage gradients of a few GV/m if the duration of the field is \sim few ns. Voltage pulses in the range of - 800 kV to - 750 kV (1.6 GV/m to 1.5 GV/m), applied across a 0.5 mm gap in the BNL vacuum diode confirmed the above results. The dark current, measured using a Faraday cup, was very sensitive to the field at gradients of ~ 1.5 GV/m. There was no measured dark current at a field of ~ 1 GV/m.

A high gradient photocathode, laser excited, 1 MeV pulser/electron gun system based on this principal is currently undergoing tests at BNL. The voltage pulse, which is applied to a photodiode electron gun, must be synchronizable to the laser beam used to excite the photocathode. Synchronization of HV pulses to a laser pulse within 150 ps has been achieved [4] by laser triggering high pressure gas closure switches. Thus, a complete electron gun system would consist of a suitable laser system and a compact, high voltage pulse power supply feeding into a pulse shaping transmission line output that is terminated in a simple photodiode electron gun. This approach is compact, rugged, low cost, simple and elegant.

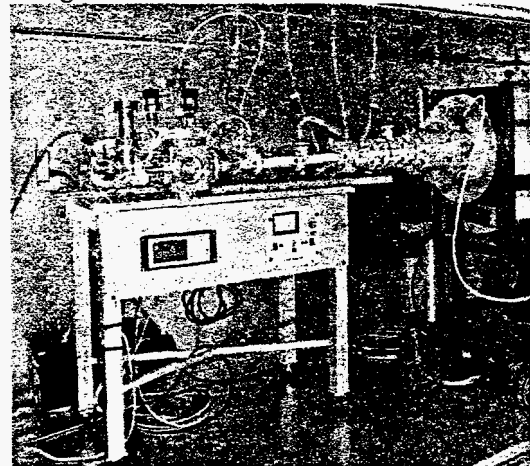


Figure 1. Photograph of the BNL, 1 MeV gun.

Figure 1 is a photograph of the high gradient pulsed gun system. This compact (1.5m x 1.5m x 1m) high voltage pulser/electron gun system consists of four sections: a low voltage pulse generator, a pulse transformer, which is seen on the right in the photo, a coaxial transmission line with pulse sharpening spark gaps

and the photodiode seen resting on a metal table.

We have determined that the 5 MeV pulser will be only slightly larger and will require somewhat higher power than the 1 MeV system that was discussed elsewhere in this report. Because it will use water or ethylene glycol and water as the insulating medium instead of transformer oil, the stored energy can be increased without a proportional increase in size of the overall system.

CATHODE STUDIES

We studied the advantages and disadvantages of different cathode materials with regard to voltage hold-off, ruggedness[5], reliability and effect on system cost and performance. LaB_6 , semiconductor and simple metal cathodes were considered. All but the metals were dropped from consideration because only metals offer the important advantages of ease of preparation, relative insensitivity to contamination, long lifetime, and fast response time. The biggest disadvantage of simple metals is their relatively high work function which necessitates use of UV irradiation of the cathode to obtain reasonable electron yield. However, the gun being developed for this project will be used in a very high gradient diode in which the average electric field is $\sim 1 \text{ GV/m}$. In this high field, the change in work function due to the Schottky effect results in a reduction in the work function of $\sim 2\text{eV}$, where we have used $\beta = 3$ [6]. This leads to the possibility of using longer wavelength radiation to overcome the reduced work function, hence reducing the cost of the laser system.

The investigation of cathode materials showed that with proper surface preparation, voltage hold-off of 1 GV/m without dark current or voltage breakdown could be maintained and a QE in the range of $3\text{E-}3 < \text{QE} < 5\text{E-}3$ could be achieved with a simple copper cathode

ELECTRODE DESIGN AND BEAM DYNAMICS

We used computer simulations to determine the influence of electrode design, laser power and cathode current density distribution on beam dynamics. Since the pulsed, high gradient, laser excited approach to electron source design offers the possibility of achieving greatly improved beam quality (defined in terms of emittance, brightness and energy spread), the study was designed to determine beam quality and the predicted beam behavior for very short ($\sim 300 \text{ fs}$ to 1.0 ps) pulses in a 1 GV/m field. The simulations assumed the voltage pulse ($\sim 1 \text{ ns}$) is constant during the current pulse interval, which was varied from 300 fs to 10 ps . (These limits are imposed by available laser systems and not any known limitation of the computer codes.) In addition, the calculations were designed to explore the effects due to cathode geometry and space charge on the 6 dimensional phase space. The beam dynamics calculations explored the importance of transition effects, which dominate the leading and trailing ends of the bunch; the onset of space charge limited emission; beam behavior leading up to the space charge

limit; and the optimum cathode geometry.

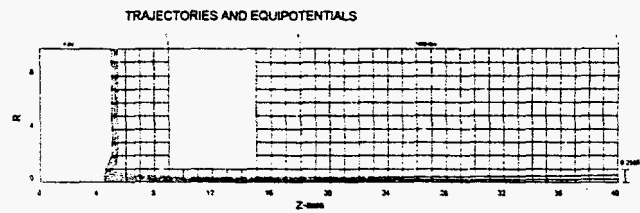


Figure 2. Geometry of the 1 MeV, 1 GV/m Diode

Figure 2 shows an example of the *standard* geometry used in the calculations. 1 MV potential is applied across a 1 mm gap of an axially symmetric diode. The cathode, which in this example is curved with a radius of 1 mm, is illuminated with a laser with transverse radius of 0.25 mm. The phase space of the beam is calculated along with the rms. emittance Parameters that were varied included the electric field, cathode radius of curvature, anode radius and total current. Since photoexcitation provides the means to control the laser intensity profile, which in turn determines the current density profile at the cathode, the calculations also examined effect of hollow, Gaussian and uniform cathode current density.

Although we had use of the PIC code MAFIA through our collaboration with BNL, the problem of simulating the transport of a 1 nC short pulse beam in a 1 GV/m field was less expensive and faster when an electrostatic code PBGUN was used to explore the parameter space prior to performing full time-dependent calculations. To test the region of validity of the electrostatic code we compared the simulations of the electron optical characteristics at the middle section of a short bunch using electrostatic and PIC computer codes and found excellent agreement [7].

For our constant beam size of 0.25mm. radius at the cathode the emittance for a given peak beam current (or equivalent bunch length at a charge of 1nC) the beam quality was insensitive to changes in cathode curvature, anode exit aperture or field gradient. However, with a flat cathode the beam divergence and thus the beam size at a given location is large (requiring external focusing to attain the desired spot size), as compared to the case of a curved cathode. A 1 mm. radius of curvature was used for many of the beam studies and this produced a beam waist between 1mm. and 2mm. beyond the anode exit plane. Due to the effects of space charge, the waist size and position varies with peak current (or pulse duration), growing larger and moving towards the cathode as the peak current is increased. Increasing the beam radius at the cathode affects the waist size (which is typically $< 150 \mu\text{m}$) and position and allows for a higher peak current for a given cathode current density distribution. It is necessary to either reduce the total charge and/or increase the beam size at the cathode in order to attain higher peak currents or sub-picosecond pulse duration. MAFIA calculations show that at a peak current of 100A a pulse duration of 0.3ps is attainable.

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Calculations also show that at high current (>100A), the beam behavior is dominated by space charge and fringe fields and not by thermal effects. However, at low current (10 A or 1 nC/100ps), other effects including surface roughness, and photon energy appear to play a more significant role.

The most important result of the time dependent MAFIA calculations was the information regarding longitudinal effects. At higher current density, space charge forces in the beam cause the leading and trailing ends to have greater and lesser energy, respectively, with respect to the center of the bunch. (This is for constant laser intensity for the pulse duration). This energy spread is in addition to any energy change due to voltage variation during the beam pulse. For a 1 nC, 10 ps pulse, the calculated energy spread due to this effect is ~ 0.2%. However, relatively few electrons (only those near the ends of the bunch) contribute to this energy spread. Therefore, we do not expect it to have a strong effect on the beam quality. We conclude that there will be no difficulty in producing a 1 MeV or a 5 MeV beam with extremely good beam quality.

For the 1mm radius of curvature cathode and a constant current density distribution, the calculated beam emittance (geometric) at a distance 2.25 mm beyond the anode aperture was found to be $< 0.1 \pi$ mm-mrdn for a beam current of 100 A (1nC/10ps). Thus the beam brightness is $\sim 10^{16}$ A/m² - rdn². These values exceed existing sources by an order of magnitude in emittance and two orders in brightness.

LASER SYSTEM

We will use an existing laser system available at BNL for our program. It comprises a Nd:YAG laser of pulse duration ~10ns, providing ~450mJ energy at a wavelength of 1064nm from which a part of the energy (~10%) is split off to amplify the laser used to excite the electron gun cathode. The remaining energy is frequency converted to trigger the SF₆ filled, pressurized spark gap of the pulsed power supply. The laser illuminating the cathode is a colliding pulse, mode locked Dye laser, which operates at a wavelength of ~ 632 nm and has an output energy of ~200pJ - 500pJ. The output is fed to a pulse stretcher and then to a Dye laser amplifier that is pumped by the Nd:YAG laser. This is then frequency converted and pulse compressed to give a variable pulse width of 300fs to 100ps, with an energy of 8 - 30 μ J. to drive the photocathode of the electron gun.

BEAM DIAGNOSTICS

In order to fully characterize the electron beam emerging from the pulsed diode gun, it is necessary to measure the total charge, the beam size and divergence, or emittance, and, ideally, the bunch length. The measurement is best made as close as possible to the exit aperture in order to minimize space charge effects in the drift space. Methods to determine all of these parameters

were investigated.

Charge: Total charge is the easiest of the above-beam parameters to measure. It is merely necessary to stop the electron beam in a Faraday cup and to measure the voltage developed across a suitable terminating resistor.

Emittance: Beam dynamics computations show that the beam emittance will be $< 0.1\pi$ mm-mrdn at an energy of 1 MeV and may be less at 5 MeV. Although it will be difficult to measure this emittance, we have calculated that measurements can be made using an insertable pepper pot with enough subsequent drift length to resolve the transverse phase space information.

Longitudinal Phase Space and Pulse Length In our investigation of diagnostic methods, we explored a direct method of measuring the electron bunch length by utilizing a radiofrequency transverse deflecting cavity to deflect the electron beam so that the resulting beam width increase measured on a phosphor screen some distance downstream of the deflecting cavity gives us a direct measure of the electron bunch length. A radiofrequency cavity operating in the TE₁₀₂ mode at a frequency of 2856 MHz has previously been used to measure the ~5 to 10 ps electron bunches at the Brookhaven National Laboratory Accelerator Test Facility. We studied the design of a similar rf cavity operating at a frequency (synchronous with the drive laser) of around 10 GHz. We would allow the beam center to reach the cavity center as the magnetic field passes through zero. Then the front and rear of the electron beam experience equal and opposite deflections so that, after a suitable drift distance, a measurement of the beam size would give a value related to the bunch length.

CONCLUSION

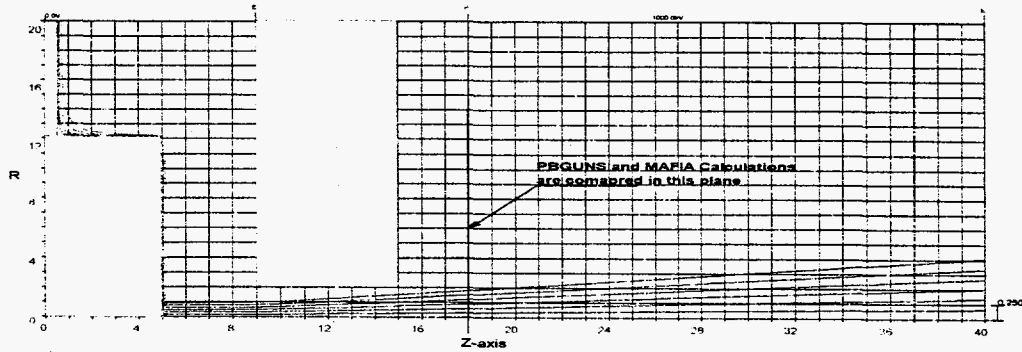
The Phase I study has demonstrated that it will be possible to achieve beam emittance $< 1 \pi$ mm-Rad and brightness $\sim 10^{15}$ A/m²Rad² with a 1 MeV electron beam and for pulse amplitude up to ~600 A and pulse duration from 1 ps to ~ 100 ps. These results are more than an order of magnitude improvement over existing electron guns.

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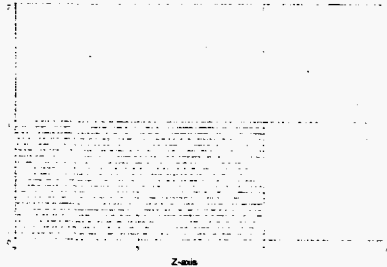
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PBGUNS Simulations

TRAJECTORIES AND EQUIPOTENTIALS

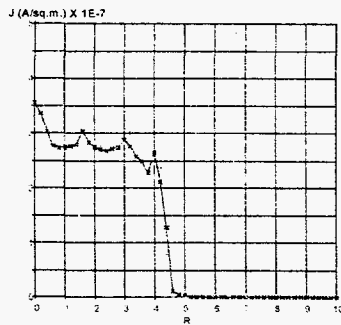


CATHODE CURRENT DENSITIES



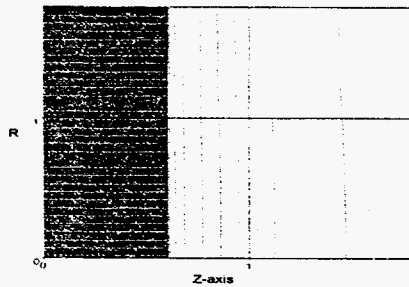
Z-axis

b. Cathode current distribution.
EXIT PLANE CURRENT DENSITY DISTRIBUTION



c. Current density at exit (E3).

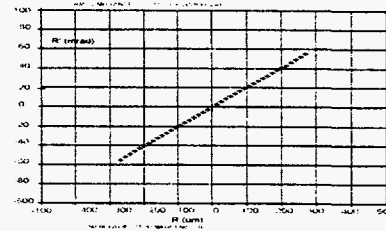
FINE MATRIX EQUIPOTENTIALS



d. Cathode equipotentials.

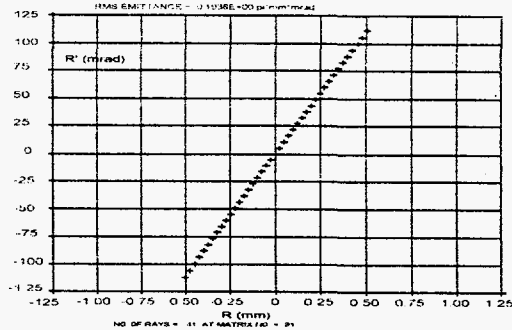
a

EMITTANCE PLOT



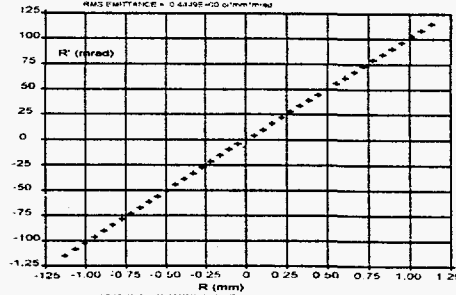
e. Phase space plot at anode (E1)

EMITTANCE PLOT



f. Phase space plot after anode (E2).

EMITTANCE PLOT



g. Phase space plot at end (E3)