A NOVEL, HIGH GRADIENT, LASER MODULATED, PULSED ELECTRON GUN

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ABSTRACT

This paper describes a high current, fast pulsed, laser excited, electron gun. This gun, which is being designed to operate at energies between 1 and 5 MeV, forms the basis for research in linear colliders, Free Electron Lasers, cellular biology, molecular science, materials science, and the study of transient phenomena in the sub-nanosecond time frame. The electron source will generate an electron beam of brightness approaching 10^{16} A/m^2 rad^2, which is 2 orders of magnitude greater than the present level of 10^{14} A/m^2 rad^2, a parameter highly sought after for future linear colliders and short wavelength FELs. It will also be used to study properties of materials in the presence of high fields such as dark current emission and high voltage breakdown characteristics that will provide information critical to the development of high frequency accelerating structures. In addition, using Bremsstrahlung radiation from these ultra short relativistic electrons, the gun is expected to be an efficient source of x-ray photons for imaging transient effects in biological samples, microlithography and micromachining. These excellent beam qualities will be augmented for the first time by the simplicity and compactness of the device resulting in an efficient, affordable product with superior performance and unique capabilities.

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 1.5 π mm-mrdn emittance at a total charge of < 0.5 nC and brightness of ~ 10^{13}A/m^2-rdn^2 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 [i]. 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 APROACH 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. [ii] and Mesyats et. al. [iii]. Their studies indicate that metals could withstand voltage gradients of a few GV/m if the duration of the field is ~ 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 BNLiv. 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 [v] 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.

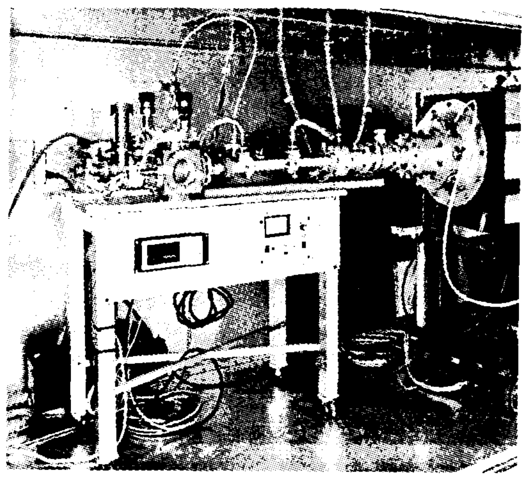

Figure 1. Photograph of the BNL 1 MeV gun.

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 expect the 5 MeV pulser to be larger in diameter but approximately the same length as the 1 MeV system and that it will fit into a RFI enclosure similar to that seen in Fig. (1).

CATHODE STUDIES

We studied the advantages and disadvantages of different cathode materials with regard to voltage hold-off, ruggedness[vi], 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 ~ 1 GV/m. In this high field, the change in work function due the Schottky effect results in a reduction in the work function of ~2eV, where we have used β. = 3[vii].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, a field of 1 GV/m without dark current or voltage breakdown could be maintained and a QE in the range of 3E-3 < QE < 5E-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 (~300 fs to 1.0 ps) pulses in a 1 GV/m field. The simulations assumed the voltage pulse (~ 1ns) 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.

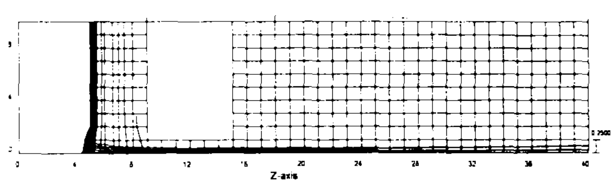

Figure 2.Geometry of the 1 MeV, 1 GV/m Diode

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 PBGUNS 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 [viii-ix].

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 < 150μ 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. 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 π mm-mrdn for a beam current of 100 A (1nC/10ps). Thus the beam brightness is~10^{16} A/m^2 - rdn^2. These values exceed existing sources by an order of magnitude in emittance and two orders in brightness.

Laser System

The dual purposes of the laser system in this gun are:

1. irradiating the photocathode to release photoelectrons, and
2. triggering the high voltage switch to synchronize the voltage pulse and the photocathode laser at the cathode.

The beam parameters for these two applications are distinctly different. The parameters of the photocathode laser are:

Pulse duration: Adjustable from 0.3-10 ps

Laser energy: tens of μJ if a QE of ~10^{-4} is assumed for the cathode

Laser photon energy: 2-4 eV

The trigger laser specifications depend critically on the design of the HV switch. Axial triggering of high pressure SF_6 gas with ~10 mJ of 248 nm radiation with ~10 ns pulse duration has resulted in sub-nanosecond jitters. Transverse triggering under similar conditions with ~90 mJ laser energy has also resulted in sub-nanosecond jitter. We will use an existing laser system available at the Instrumentation Division at Brookhaven National Laboratory. The laser system is shown schematically in Figure 3.

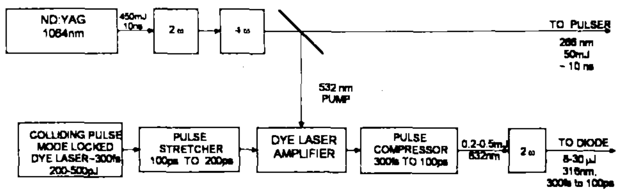

Figure 3. Schematic of the laser system.

CONCLUSION

Construction of a 5 MeV pulser based on the design and simulations discussed here will be built and tested by the authors. The beam energy, emittance and brightness will be measured.

This work is supported by U.S. Department of Energy contracts DE-AC02-98CH10886 and DE-FG02-97ER82336.

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