A laser excited, sub-nanosecond, pulsed electron beam system is described. The system consists of a high voltage pulser and a coaxial triggered spark gap. The liquid spark gap discharges into a pulse forming line designed to produce a flat voltage pulse of 1 ns duration on the cathode of a photodiode. A synchronized laser is used to illuminate the photo-cathode to produce an electron beam with very high brightness, a short duration and with peak currents up to the space charge limit. The system can be configured to operate at energies from 1 MeV to 5 MeV and beam pulse widths from 10 ps to 200 ps with at least 10 nC charge in the electron beam. Initial operating experience with a prototype system is discussed.

PACS Codes: 29.27

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, photo-excited rf guns provide a normalized beam emittance of ~1.0 to 1.5 π mm-mrad 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 ( 1 GV/m) electric field. In this approach, a ~ 1 ns, 5 MV maximum voltage pulse is applied to a simple diode configuration. During this short time interval, the photo-cathode is excited by a laser pulse of < 100 ps duration. Since the voltage remains constant during the voltage pulse, the electron gun essentially operates in a dc mode with minimal change in voltage.

Technical Approach

The pulsed, high gradient, laser excited photo-cathode electron gun is based on the studies of voltage breakdown conducted by Juttner et. al and Mesyats et al. Their studies indicate that metals can 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.
Figure 1 is a schematic diagram of the 5 MeV, high gradient, pulsed electron gun. This compact (1.5m x 1.5m x 4m) high voltage pulser/electron gun system consists of a pulsed power supply and a laser system that is used to trigger the high voltage pulser and also to excite the photocathode of a diode electron gun. There is also provision for focusing the exiting electron beam onto a target or into an accelerator.

The pulsed power supply comprises four sections: a pulse transformer, a coaxial transmission line with pulse sharpening spark gaps and the photodiode. A laser pulse triggers the first coaxial line liquid spark gap.

**Design of the High Voltage Pulsed Power Supply**

The pulsed power supply and pulse forming line was designed in a collaboration between Brookhaven Technology Group, Inc. (BTG), Optoel Scientific and Innovation Company (OPTOEL) and BNL and constructed by OPTOEL in St. Petersburg, Russia. It is based on a Tesla transformer configuration.

A general view of the pulsed power supply is shown in Figure 2. Figure 3 is a photograph of it. The pulser is an integral unit comprising the following components:

- A metal casing
- A pulse generator (100 kV) for exciting the primary winding of the pulse transformer
- A pulse transformer
- A forming line for generating the short (~1 ns) high-voltage pulse
- An ignition trigger generator for triggering the four gas discharge switches
The welded casing forms the framework onto which all of the other parts of the pulser are mounted. The casing consists of four principal parts. The upper section, which is not sealed, houses a solid dielectric cylinder that forms a support for the pulse transformer winding. The side and end plates of this section of the casing are detachable to allow access to the components of the 100 kV pulse generator.
The section housing the 100 kV pulse generator is oil filled above the level of the four gas discharge switches. A detachable, oil filled assembly containing the ignition trigger generator is attached to the sidewall of this section. The charging cable is connected through a sealed connector in the back wall. A BNC connector for monitoring the voltage is also mounted on this unit.

The lower sealed section is for containment of the transformer oil during maintenance of the system. An pump system is provided to pump oil in or out of the system. The casing is supplied with wheels for moving the pulser and special supports are provided to hold the unit in its operational location. A grounding electrode for discharge of residual voltage from the capacitors is located in the oil filled section. A commercial, solid state, low voltage trigger generator is used to drive the system.

The high-voltage pulse transformer shown in Figure 5 is located inside a sealed solid dielectric cylinder made of 48 mm thick organic glass with an inner diameter of 420 mm and is filled with transformer oil. A diaphragm, separating the liquid spark gap from the pulse transformer, is mounted on the output end of this cylinder. The diaphragm contains one of the electrodes of the liquid spark gap that is mounted on its center. On the surface of this electrode, within the solid dielectric cylinder, a cylindrical electrode is attached. This forms the intrinsic capacitance of the pulse transformer.

Four copper bus bars wound around the outside wall of the solid dielectric cylinder serve as the primary winding of the pulse transformer. These buses are connected in parallel to the 100 kV pulse generator. In order to prevent breakdown between the bus bars or between the bus bar and casing, the copper bus bars are wound with fluoroplastic foil.
The secondary winding consists of 80 turns of copper wire of 3 mm in diameter wound upon a cone made of organic glass. The cone is fixed within the solid dielectric cylinder, with its smaller diameter contacting the electrode of the intrinsic capacitance.

A dielectric pipe, of inner diameter 55 mm, hermetically separated from the inside space of the pulse transformer, is mounted along the cylindrical axis of the pulse transformer. Within this pipe there is a quartz rod (30 mm in diameter) for the purpose of transporting the laser pulse into the liquid spark gap.

Filtered dielectric fluid flows in the gap between the outer surface of quartz rod and the inner surface of dielectric pipe and into the liquid commutator switch. This method of construction makes it possible to take out the quartz rod and the focusing system from the pulse transformer without draining oil from the pulse transformer. The optical transport arrangement is shown in Figure 6.

The optical system consists of a focusing lens 1, the light guide 2 and the adjustable mirror 3. The lens 1 is rigidly fastened onto the light guide 2 which consists of two rods with a diameter of 30 mm made of different laser neodymium glasses: a phosphate glass with a length of 400 mm and bevel of ~2° (pos.2.1) and a silica glass with a length of 630 mm and a bevel of ~5° (pos.2.2). A screw coupling connects the rods, 4, which are made of polyamide. The chamfers prevent radiation reflected from the ends of the rods coming back to the laser system as well as preventing interference noise effects. Dielectric liquid flows through the slots in the centering rings and around the light guide thus preventing
electrical breakdown along the light guide surface due to the strong electrical field. Seals on the metal flange, 5, which embraces the output end of the rod 2.2, provide the hermetic seal. When the seals are tightened the lens 1 and the light guide 2 are rigidly coupled. This allows a change in the lens focal position relative to the surface of the liquid spark gap ground electrode, within a range of 8 mm, by translating the light guide (with the lens inside the spark gap casing) driven by the flange 5, along its axis.

The internal space of the coupling 4 and the holder 1 is filled with pure transparent liquid in order to decrease Fresnel losses and prevent burning of the surfaces of the optical elements.

The biconvex sapphire lens 1 (n=1.76) with a diameter of 25 mm has different surface radii R1=35mm and R2=60mm. This allows a variation of the effective focal length within a range of 30 to 60 mm, depending on the degree of filling with liquid and on the lens orientation. The lens is 20 mm from the end of the light guide, 2.1, to prevent damage of the light guide end by the focused reflected flash from the spark.

The adjustment mirror 3 is rigidly fastened onto the flange 5 by means of a 2 dimensional adjustment unit. The adjustment procedure consists of centering light from an alignment laser onto mirror 3 and adjusting the pilot-laser beam by the mirror 3 to hit the center of lens 1. Alternatively, acoustic adjustment can be made by adjustment of the Nd laser beam by a snap of the laser induced spark. At the liquid spark gap, the spark in the liquid may be observed visually via the sighting windows in the housing. Experimental investigations have shown that stable laser triggering of the liquid spark gap with nanosecond jitter is obtained with a laser pulse energy of 20 to 30 mJ, pulse duration FWHM 200 ps and radiation divergence less than 1 mrad.

Figure 6. Optical transport system for the laser beam
A general view of the pulse forming line is shown in Figure 7. It consists of a number of components arranged in sequence:

- A liquid commutator switch controlled by the laser
- A charging inductance
- A forming line
- A self-breakdown liquid discharge switch
- A section of transporting coaxial line
- A transforming line (10 Ohm - 160 Ohm)
- A load of 160 Ohm
- A separating vacuum window.

The Laser triggered liquid commutator switch is a hermetically sealed two-electrode system filled with clear dielectric fluid. The high-voltage electrode has a central hole (of about 3 mm in diameter) on its axis to allow for passage of the ignition laser beam. It is also possible to start the commutation radially through a window in the casing of the liquid commutator switch.

The fluid in the commutator is continuously circulated through a closed cycle by means of a pump. Each cycle the liquid passes through a mechanical filter for removing the particles produced during the discharge. The flow of cleaned fluid is arranged so that the part containing particulate matter does not flow into the zone where the laser beam passes.

The next volume contains a charging inductance which is followed by the forming line. The forming line is fastened onto a conical insulator by the use of a connecting screw. In order to lighten the construction, the forming line is hollow. A capacitance sensor
mounted above the forming line serves as a monitor for checking the voltage on the forming line. The end part of forming line forms the electrode of a self-breakdown liquid commutator switch. The ring-shaped electrodes allow us to achieve a multi-channel breakdown and also to reduce the inductance of discharging circuit. The second electrode of the self-breakdown commutator switch is the input end part of the transporting and transforming line.

The fluid volume within the self-breakdown commutator switch is hermetically separated from the neighboring volumes by means of O-rings on the supporting insulators, so that fluid from the discharge circuit is not able to mix with that from the neighboring sections. For removing the particles produced during discharges in the fluid, the mixture circulates through a mechanical filter like that in the controlled liquid commutator switch. The spark gap distance may be varied within the range 0 - 8 mm. It is adjusted by rotation of a coupling nut mounted on the casing of one of the sections.

The transporting line is step-wise transformed into a transforming line by changing the diameter from 78 to 6 mm. A matching load of about 160 Ohm, made up of a cone of carbon resistors, is connected to the end of the 6 mm diameter section.

The last unit in the system of high-voltage pulse formation is a conical ceramic vacuum window. There is a screw hole on the axis of the center electrode to allow for mounting of the photo-cathode.

### Laser System

The basic requirements for the laser system are:

1. The energy, energy density and wavelength of the laser beam triggering the liquid gap required to minimize the jitter between the HV pulse and the photo-cathode laser.

2. The energy and wavelength of the laser required to deliver ~ 1 nC from the cathode.

3. A timing system to synchronize the HV and laser pulses at the cathode so that photoelectrons of constant energy are generated for each pulse and the timing jitter is low enough for this beam to be injected into an accelerator for additional energy gain.

4. An optical system that would integrate these requirements and allow us the flexibility in providing different laser pulse lengths and temporal distributions.

Two laser systems were built and tested with the pulser. The first system uses a picosecond Nd:YAG laser as a master oscillator followed by two stages of amplification, giving a 150 ps pulse at the liquid spark gap of the pulsed power supply. The oscillator is mode locked using an electro-optical system with negative feedback by means of a high voltage photodiode and a Pockles cell. Gate pulses applied to this Pockles cell provide Q-modulation. This provides a stable pulse train of 8 - 12 pulses of 150 ps duration. To
generate single ps pulses a second Pockle cell based on a DKDP crystal is arranged within a resonator and a pulsing mirror extracts a single pulse. A Marx generator using solid-state components is used to drive the laser. The time period of this master oscillator is ~ 5 ns.

The time jitter of a single picosecond laser pulse is the same ~ 5 ns and the energy variation is ~ 10% for a pulse energy of ~ 0.5 mJ. After correction of its divergence by a telescope, this single pulse is transported into a two-pass Nd:YAG laser amplifier. A pulse duration of 100 – 200 ps at a pulse energy of ~ 20 mJ was found to be optimal in providing stable, low jitter triggering of the triggered liquid spark gap of the high voltage.

![BNL Laser System Diagram]

Figure 8 BNL Laser System

The second laser system is an adaptation of that used to trigger the SF₆ gas spark gap of the 1 MeV BNL pulser. The system is shown schematically in Figure 8. It comprises a Nd:YAG laser of pulse duration ~10 ns, providing ~450 mJ energy at a wavelength of 1064 nm 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 liquid 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 ~200 pJ – 500 pJ. 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 300 fs to 100 ps, with an energy of 8 - 30 µJ, to drive the photo-cathode of the electron gun.

**Initial Operating Experience**

The first tests on the system were carried out as part of the acceptance test for the pulsed power supply system.
Test of the trigger generator.

Initial tests included timing jitter and output signal amplitude measurements of the trigger generator. The time jitter of the trigger generator was measured in relation to a trigger pulse from a pulse generator.

The 20 kV trigger generator was triggered with pulses having an amplitude of +12 V. At the 20 kV generator output the pulse delay in relation to the starting pulse was about 300 ns, the jitter being about 50 ps. The total pulse duration is about 6 ns and the output timing jitter is less than 2 ns with a charging voltage in the range of 30-40 kV. At a charging voltage of 30-40 kV the output pulse amplitude to the primary of the pulser was 75 kV.

Test of the 100 kV generator.

In these tests, the time jitter of each of four channels in relation to the trigger pulses was measured as well as the recharge voltage amplitude of the storage capacitors. During the tests the 100 kV generator was connected to an equivalent load. The pulses were transferred from the voltage dividers in each of four channels of the 100 kV generator to an oscilloscope triggered by pulses coming from another channel of the master timer. The charging voltage of the trigger generator was about 38 - 39 kV. The charging voltage of the 100 kV generator can be varied from ~ 30 to 90 kV. The measured time jitter of each of the channels in relation to the trigger pulse and to the other channels was less than 10 ns.
Test of the high-voltage transformer.

The high-voltage transformer was tested in two stages. In the first stage the high-voltage capacitance divider was calibrated by charging the storage generator with the 100 kV generator with the gap length of the high-voltage liquid discharger being set to 10 mm. In the second stage the transformer was tested during investigations on the whole system, the gap length of the high-voltage liquid discharge being varied in the range from 10 mm to 30 mm.

Laser triggered operation of the high-voltage spark gap with at a gap length of 1 cm.

Controlled operation of the liquid spark gap was achieved with the use of Nd:YAG laser radiation at a wave length of 1.06 µm with pulse duration 160 ps and pulse energy of 10-20 mJ. The radiation was sent in along the pulser axis from the side of the negative electrode. Experiments have shown that for an applied voltage of 1 MV, the starting time spread depends on the following:

- the spark shape;
- the dimensions of the spark;
- the location of the focus;
- the purification grade of the liquid in the discharge gap;
- the voltage level with respect to the self-breakdown voltage.

The lower the delay time, the less was the time spread. Liquid impurities increased the starting time spread. In order to provide stable operation of the discharger, the pulse repetition frequency was not higher than 1 pulse in 30 s.

Figure 10. output of the transformer (triggered spark gap).

Figure 11, Self-breakdown liquid spark gap.

A characteristic oscilloscope trace of the voltage sensor on the transformer secondary winding for an applied voltage of 1 MV is shown in Figure 10. Figure 11 shows the
voltage pulse at the second self breakdown liquid gap and Figure 12 the corresponding voltage at the end of the forming line.

![Graph](image)

**Figure 12. Voltage waveform at the end of the pulse forming line.**

**Investigation of laser triggered discharge with a 25 mm gap and with a laser pulse duration of 160 ps.**

In this investigation the laser pulse similar to that used for a 10 mm gap was used. The applied voltages were as follows:

- 1. 1.3 - 1.5 MV at a charging voltage of 60 - 65 kV.
- 2. 1.8 MV, at a charging voltage of 70 - 73 kV.
- 3. 2.0 - 2.2 MV, at a charging voltage of 80 kV.

At the first voltage the starting delay was about 40 ns and the starting time spread was ~ 5 ns. At the higher voltages the starting delay decreased to 20 - 25 ns, with the time spread being less than 1 ns. An optimum spark length of 2 - 3 mm and focal position of 3 - 4 mm from the positive electrode was determined. This resulted in a starting time spread of 1 ns. Further investigations with the short pulse duration laser confirmed that with increasing pulse energy the starting time spread is reduced.

**Investigation of laser triggered operation of the liquid spark gap with a 25 mm gap and with a laser pulse duration of 5 ns.**

Operation with a laser pulse duration up to 5 ns and energy up to 50 - 60 mJ was attempted. The voltage used was 2 MV and the charging voltage was 68 kV. These experiments showed a significant increase of the starting time spread by up to 10 ns. With this longer laser pulse there is evidence of micro-bubble formation probably due to
acoustic cavitations. These disturbances have a relaxation time of several seconds so that a subsequent laser pulse induces a partial collapse of previously generated micro-bubbles leading to scattering of the laser beam and thus erratic switching. This increases the time jitter. With short (150 ps) laser pulses, self focusing occurs within the cylindrical long laser channel and also the micro-bubbles within the beam do not have sufficient time for expansion.

Test of self-breakdown of the liquid spark gap.

Tests were carried out with gap lengths in the range of 1.5 - 3.5 mm. The larger the gap, the longer the voltage pulse front at the generator output as well as the line charging time. At a voltage of 2.5 MV, the optimum gap was found to be 2.5 to 2.8 mm. This gap resulted in an output pulse of the required time parameters and 5 MV amplitude. The starting time spread for the self-breakdown liquid switch discharger was found to be less than 0.1 ns.

Beam Dynamics Computations

Various computational programs were reviewed in order to determine the ones best suited to our study. Those under consideration included, PBGUN, and MAFIA. Since the BNL group working on a 1 MV pulsed gun test system had been using MAFIA for their studies, we decided to use their MAFIA results to evaluate the effectiveness of programs developed for dc beams in attaining our design objectives. A number of comparisons between MAFIA and PBGUN simulations indicated that for dc up to ~300 A, PBGUN results were in excellent agreement with MAFIA data for determination of \( r, r' \) phase space. Therefore, in the interests of time and economics we used the pc based program PBGUN for our beam dynamics studies, while making specific comparison with BNL MAFIA runs where appropriate. Since PBGUN is a dc beam program, no energy spread data is obtained from it.

Computational Methods

In order to separate the effects of space charge and radial electric field effects resulting from the fringing field at the exit aperture of the anode, computations were carried out with a simulated metal boundary across the exit aperture as well as with an open aperture as in a practical application. At low current, 1 A or less, where space charge can be neglected, a closed exit aperture gives us a measure of the focusing effect of a curved cathode, while at higher current it shows the effect of space charge.

Results for 3MeV, 4MeV and 5MeV Electron Beams

Computations were carried out for both a flat and curved cathode configuration, using a constant current density distribution as input. Different beam currents, exit apertures and cathode beam radii were investigated, all for a fixed gap length of 5 mm. Thus the gradient at the cathode was 1 GeV/m for 5 MeV electron beam energy, 800 MeV/m for 4 MeV beam energy and 600 MeV/m for 3 MeV beam energy. Although there was some improvement in the beam divergence with the use of a curved cathode, the change in going from flat to curved cathode was far less dramatic than for the 1 MeV case. This is
because the gap to exit aperture ratio is 5 to 10 times larger for these calculations so the effect of the fringing field at the exit aperture is reduced. Also, the fringing fields have less affect on the higher energy beam. Therefore, we decided to use the data from flat cathode computations as input for any beam transport calculations.

The calculations are summarized in Table II. For the majority of the calculations the peak electron beam current was maintained at 100 A and the anode exit aperture was set at 1 mm. The electron beam radius at the cathode was either 125 µm or 250 µm. It can be seen that for 100 A peak electron current the smaller beam radius resulted in smaller beam size and less divergence at a monitor point ~2 cm. from the anode exit aperture. This naturally gave rise to a lower emittance value. At this current level space charge is not a significant effect.

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<th>Cathode</th>
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<th>Beam Radius (µm.)</th>
<th>Anode Exit Aperture Radius (µm.)</th>
<th>Divergence (mrad)</th>
<th>Emittance (µm.mrad)</th>
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Table II. Calculated beam radius, divergence and emittance for 3, 4 & 5 MeV electron beams for a flat cathode and uniform charge density distribution.

Summary

Initial tests of the 5 MV pulser has demonstrated that with a suitable laser system it is possible to achieve an output voltage with sub nanosecond jitter. Providing that the same laser with suitable frequency multiplication and pulse compression is used to excite a photo-cathode, an electron gun suitable for injecting beam into an rf accelerator section would be feasible.

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