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TABLE TOP, PULSED, RELATIVISTIC ELECTRON GUN WITH GV/m GRADIENT*

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Table Top, Pulsed, Relativistic Electron Gun with GV/m Gradient

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ABSTRACT

We present the design and performance characteristics of a compact, high voltage pulser with 150 ps rise time, 0.2 to 2 ns adjustable flat top and up to 1 MV amplitude on a 80 Ohm load or up to 0.5 MV on a 20 Ohm load, at 1 Hz repetition rate. Combination of a laser triggered SF_6 and a liquid gap is used to form the fast rising pulse and maintain a low jitter between the laser, external trigger, and the high voltage pulsed output. The dark current and breakdown studies with this pulse applied between the electrodes of a diode indicate that fields up to 1 GV/m could be supported by stainless steel and copper cathodes without breaking down. The dark current from a conditioned cathode in a background pressure of 10^{-7} Torr is below the detection limit of 0.5 mA of our system. Photoemission studies had been conducted with 300 kV applied between copper cathode and stainless steel anode seperated by 2 mm. KrF laser of 5 eV photon energy and 20 ns FWHM was used to irradiate the cathode. In these preliminary measurements, 3 nC charge and corresponding quantum efficiency of 3.5×10^{-4} have been obtained. Future plans include increasing the gradient to GV/m range, decreasing the laser pulse duration to ps and subps range and increasing the electron energy to a few MeV.

INTRODUCTION

In the past decade, there has been extensive research [1] in the development of low emittance, high brightness electron injectors for linear collider and free electron laser applications. RF injectors with a few nC charge in a few ps, with an emittance of ~1-5 π mm mrad are operational in a number of facilities [2-4]. The frequency of the RF and the design of the cavity are chosen to minimize the RF and space charge effects on the electron bunch so that low emittance, high brightness electron beam could be generated. Minimization of RF effects on emittance growth require a low RF frequency while minimizing the space charge effects require high field and hence high RF frequency. The design is hence a compromise between these two conflicting requirements. Some of these limitations could be overcome by using a large pulsed electric field at the cathode rather than a RF field. An added advantage of these high fields on metal surface is the lowering of the work function due to Schottky effect. The change in the work function is given by [5]

$$\Delta\phi = \sqrt{\frac{e}{4\pi\varepsilon_0}}(\beta E)^{1/2} \qquad (1)$$

where e is the charge of the electron, ε_0 is the dielectric constant of free space, E is the applied field and β is the field enhancement.

For a field of 1 GV/m, and a field enhancement factor of 3 [5], the change in the work function can be calculated to be ~2 eV. This opens up the possibility of using either the infrared or visible radiation to overcome the work function and to extract the electrons from low workfunction metals such as yttrium or magnesium. The complexity and cost of the laser system associated with the photocathode is then significantly reduced.

DESIGN OF THE PULSER:

The breakdown studies conducted by Juttner et. al. [7] and Mesyats et. al. [8] indicate that metals could withstand field gradients of a few GV/m if the duration of the field is ~ few ns. For HV pulses with pulse duration less than 10 ns, both cathode initiated and anode initiated breakdowns become less probable, the breakdown voltage become relatively insensitive to the cathode and anode materials, formation of microscopic craters due to explosive emission become less frequent and the erosion of the electrodes decreases significantly. Hence uniform field gradients of ~1 GV/m on macroscopic surfaces would necessitate a HV pulse with voltage amplitude ~ 1 MV, pulse duration of a few ns with subns rise and fall times. In addition, to extract photoelectrons, this pulse should be synchronizable to a laser beam. HV pulses synchronizable to the laser pulse within 150 ps had been achieved [9] by laser triggering high pressure gas closure switches. In this section, we describe the design of such a high voltage pulser constructed to meet these requirements.

A photgraph of the pulser is presented in Fig. 1. The pulser consists of three major sections: the low voltage pulse generator, the transformer and the high voltage transmission line with pulse sharpeners.

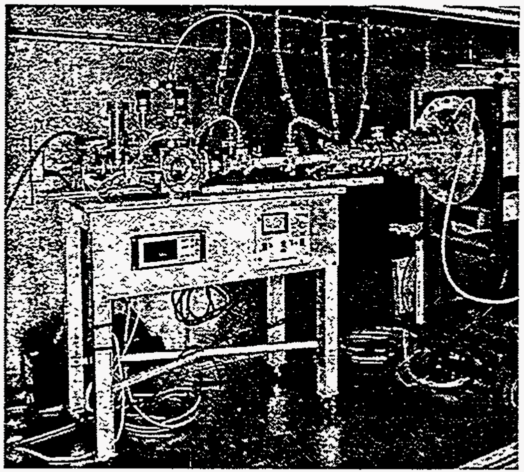

Fig. 1 Photograph of 1 MV pulser including the SF_6 gap, transmission line, diode and associated detection system and vacuum cell.

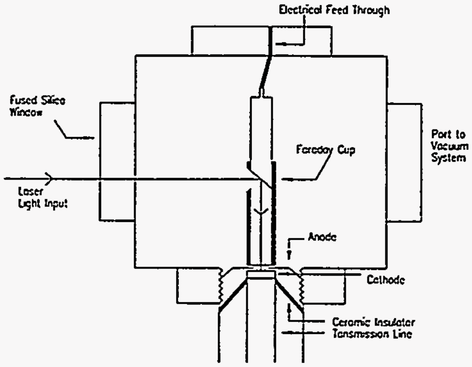

Fig. 2 Schematic of the vacuum cell containing the cathode, anode, and Faraday cup.

The low voltage pulse generator section is made up of a D. C. voltage source of 10 - 25 kV, a trigger generator and a low voltage switch. The trigger generator derives its trigger pulse from an external pulse generator that controls the timing of the rest of the system. The low voltage switch is a three electrode spark gap, with the central electrode connected to the trigger generator. The output of this low voltage system is fed to the primary of the high voltage transformer. the voltage regulator of the DC source can be used to vary the final voltage from the pulser.

The high voltage transformer is a Tesla transformer with a copper sheet as the primary and a 80 turn copper winding as the secondary, with the secondary immersed in transformer oil. The primary and the secondary windings of the transformer are designed to meet the resonant conditions. This enables a doubled voltage with polarity opposite to that of the primary to be applied to the diode at the end of the transmission line. The capacitance of the transformer is 1.5 nF, resulting in a rise time of ~500 ns for the high voltage pulse. The duration and the amplitude of the transformer output can be measured using a built in resistive divider with an attenuation coefficient of 18000.

The high voltage from the transformer is transmitted along a pulse forming line with two switches, a high pressure SF_6 gap and a liquid gap, to sharpen the rise and fall times of the HV pulse. The SF_6 gap consists of a hemispherical electrode connected to the HV transformer and a flat electrode connected to the transmission line with an electrically isolated stainless steel wire in the middle of the gap to aid in laser triggering. Two CaF_2 windows centered on the wire permit the laser to irradiate the wire normal to the gap. The gas pressure in this gap can be varied up to 150 psi, although most of the measurements were done at

90 psi. Since the voltage hold off increases with the pressure, the gas pressure could be used to vary the voltage delivered to the gun. Additional pulse sharpening is achieved by a self discharging liquid switch with 0.8-1.5 mm adjustable gap at the end of the pulse forming line. The duration of the pulse can be varied from 200 ps to 2 ns by changing the length of the pulse forming line.

A tapered line transformer, terminated at the cathode, doubles the voltage to 1 MV. The system could be used either with or without this tapered line depending on the required voltage range. Three calibrated capacitive dividers help measure the amplitude and duration of the voltage pulse along the transmission line, as well as to optimize the gap spacing for the required performance. They are located as follows: one is positioned before the liquid switch, one at the beginning of the transmission/transformer line and the third at the end of this line,. Both the transmission line and the capacitive divider lines were designed to accommodate the high frequencies encountered in this system.

The cathode at the termination of the line and the grounded anode held parallel to the cathode act as the diode for generating the electron bunch (Fig 2). Both the electrodes are removable and hence the performance of the diode for different electrode material, and geometry can be investigated without changing the characteristics of the applied voltage significantly. Alternately, for a given electrode material and geometry, the performance of the diode can be studied for various shapes and amplitudes of the voltage pulse, by changing the SF_6 gas pressure, the amplitude of the low voltage and the length of the pulse forming line, without breaking the vacuum. The pulser and the diode with its diagnostics are housed in an enclosure designed to filter the electromagnetic noise associated with such a system. This enables us to minimize the length of the cables to be used and possible distortion associated with the cables.

PERFORMANCE OF THE PULSER:

As shown in the timing diagram Fig.3, a pulse generator (Stanford Research System DG 535) acts as the master clock and two suitably delayed trigger pulses trigger the laser and the HV pulser. The laser beam, derived from a KrF laser, was focused between the stainless steel wire and the high voltage electrode of the SF_6 gap such that the beam nearly fills the gap between the two.

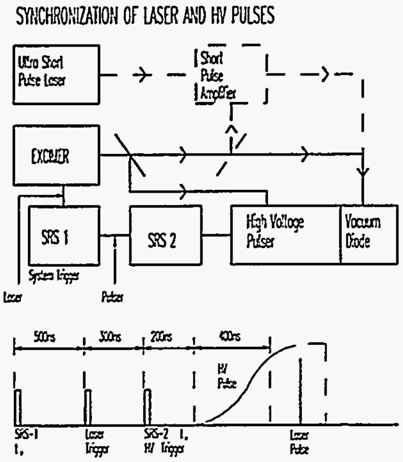

Fig. 3 Timing diagram of the system. SRS 1 is the master clock. The laser is triggered by a signal from SRS 1 suitably triggered and the pulser is triggered by SRS 2 driven by SRS 1.

The typical laser parameters were, energy: 75 mJ, spot size: 2 mm x 0.2 mm, pulse duration: 20 s and laser wavelength: 248 nm. As shown in Fig 4, with 90 psi of SF_6, the optimum delay between the arrival of the laser at the gap and the breakdown of the gap was ~30 ns, with jitter of 0.7 ns. The maximum voltage amplitude measured at the last probe was 0.9 MV. A 5:2 mix of argon:SF_6 at this pressure reduces the voltage by 10% and jitter to 0.5 ns and the delay to 5 ns. Since this jitter value includes the fluctuations in the laser energy and hence the trigger time, the real jitter between the laser and the HV pulse is expected to be much smaller than the measured 0.5 ns. Jitter values of ~150 ps have been reported [9] with similar arrangements. The pulse shape, shown in Fig 5., indicates that the duration of the pulse is ~0.7 ns, rise and fall times are ~150 ps, and the fluctuation in the voltage amplitude in the flat region is negligibly small.

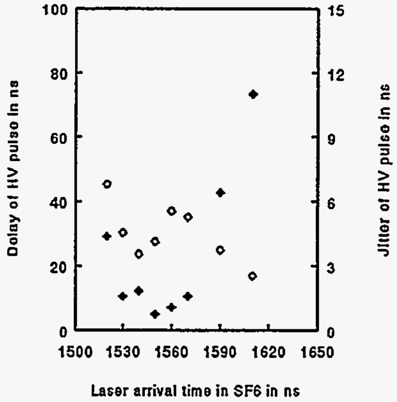

Fig. 4 Delay (o) and jitter (+) of the HV pulse with reference to the laser pulse for 90 psi of SF_6

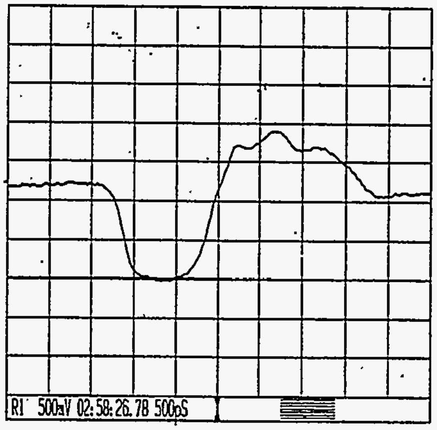

Fig. 5. Shape of the high voltage pulse. The maximum amplitude is 0.9 MV and deconvoluted rise and fall times are ~150 ps.

DARK CURRENT STUDIES:

The dark current measurements were done with the pulser in the self trigger mode, without the laser irradiating the SF_6 gap. This enabled us to apply the maximum field on the diode. two different cathode materials, stailess steel and copper, were tested for their voltage hold off properties and dark current emission. Fields exceeding 1 GV/m could be applied to both the cathodes. As can be expected, the dark current depended criticall on the background pressure between the electrodes. The dark current from stainless steel after conditioning, in a field gradient of 0.7 MV/m, was below the detection limit of our our system even at background pressures of ~10^{-3} Torr. Copper on the other hand yielded a dark current of 200 A under similar conditions. When the background pressure was reduced to 10^{-7} Torr, the dark current fell below the detection limit of our system, 0.5 mA.

PHOTOEMISSION STUDIES:

The cathode used for these measurements was OFC II copper. The surface preparation is described in detail elsewhere [10]. The anode is a stainless steel cup with a 2 mm diameter hole in the middle for laser irradiation and extraction of electrons. The electrode gap for these measurements were 2 mm. The charge is collected at the Faraday cup consisting of a 3/8" copper rod and copper sleeve fitted tightly over it. The end of the copper rod was cut at 45° and polished to mirror finish and was used as the reflector for introducing the laser beam onto the cathode. A small cut out in the copper sleeve facilitates the transport of the laser beam. The signal from the Faraday cup was measured by the 7 GHz oscilloscope. The entire arrangement was maintained in 10^{-7} Torr pressure.

The laser beam irradiating the SF_6 gap was split into two parts by passing it through a CaF_2 window. The beam transmitted through the window was used to irradiate the gap, while the reflected fraction was used to irradiate the photocathode. The arrival time of the laser at the gap was adjusted for maximum voltage and minimum jitter. The gap pressure was adjusted such that the voltage at the cathode was 300 kV. The photocathode beam was optically delayed so that both the laser and the HV pulse arrive at the cathode synchronously. The beam was then focussed by a lens such that the smallest spot size is at the anode hole to reduce beam loss. The diameter of laser spot on the cathode was ~1 mm. The photoelectric signal from the Faraday cup is shown in Fig.4. The integrated charge arriving at the Faraday cup was 3 nC. The refelctivity of the copper mirror at this wavelength was measured to be 25%. If one assumes that the electrons emitted in the high field alone arrive at the Faraday cup, the energy of the laser beam intercepted by the cathode during this time is ~ 42 μJ. The quantum efficiency of the cathode can then be calculated to be 3.5×10^{-4}, comparable to the value obtairied at the ATF [11] with copper cathode in a field gradient of 120 MV/m. Measurement of photocurrent in GV/m gradient is currently underway.

COMPUTER SIMULATIONS:

Results of computer simulations using MAFIA to predict the gun performance under different diode geometries are shown in Table 1. The parameters for the simulations are: parallel plate diode geometry, 1 nC charge, flat top charge distribution in both r and z with 10 ps bunch length and 100 µm diameter, and 1 MV on the cathode. The emittance was monitored in three locations along the beam path, in front of the anode (ε_1), immediately after the anode (ε_2) and after a drift distance of 7 mm (ε_3). As can be seen from Table 1, the lowest value of 0.5 mm mrad for ε_3 is obtained for a gap spacing of 1-3 mm and a hole size of 2 mm. This emittance may further be reduced if the diode geometry, bunch length, and charge distributions are optimized.

Table 1

Gap mm	**Hole Radius** mm	ε_1 mm-mrad	ε_2 mm-mrad	ε_3 mm-mrad
1	1	0.2	0.3	0.7
2	2	0.3	0.4	0.6
1	2	0.2	0.3	0.5
2	2	0.2	0.4	0.5
3	2	0.4	0.4	0.5
4	2	0.4	0.5	0.6

CONCLUSION:

In conclusion, a high voltage pulser capable of delivering up to 1 MV with a duration of ~1 ns and rise and fall times of ~0.15 ns has been constructed and tested. Copper and stainless steel cathodes have been tested to withstand 1 GV/m gradient. Under background pressures of 10^{-7} Torr, the dark current is below the detection limit of our system. Preliminary photoemission studies with 5 eV photons of 20 ns duration and field gradients of 150 MV/m have yielded up to 3 nC and a quantum efficiency of 3.5×10^{-4}, in agreement with previous results. Computer simulations indicate that electron beams with 1 nC charge, ps bunch length and 0.5 mm mmrad emittance can be obtained with this diode. Future plans include increasing the field gradient to GV/m range, decreasing the laser pulse duration to ps and subps ranges and increasing the energy of the electron beam to a few MeV.

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