High Power Pulsed Electron Accelerators Development for Industrial Applications

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Abstract. Present paper describes the design and test results of indigenously developed electron beam pulsed accelerator, which is a kilo ampere linear injector: KALI-5000 having ratings of 1 MV, 80 kA, 100 ns, 80GW. It comprises of Marx generator, Blumlein pulse forming line (PFL) and relativistic electron beam diode. It is a single shot system. In view of numerous industrial and strategic applications of electron beam accelerators, BARC is actively pursuing the design and development of various kinds of accelerators viz. 10 MeV RF accelerators, 0.5 -3 MeV DC accelerator and 0.2-1 MeV pulsed electron accelerator. This paper presents the subsystem details of KALI-5000 and recent experimental results with electron beam emission.

1. Introduction

Applications of accelerators are no more limited to research & development studies or for defence utilization. Recent trends of accelerator usage include the irradiation of food, water, medical sterlization, surface treatment, high power microwave generation and radiography . The recent application of Intense Relativistic Electron Beam (IREB) technology to the generation of coherent electromagnetic radiation by (i) relativistic magnetron, (ii) electron cyclotron maser & (iii) free electron laser have already produced power levels over a wavelength band ranging from centimetres to few hundred microns. The collective ion acceleration with linear IREB is another field of application, where the accelerating field gradients are not limited by electrical breakdown, collective methods may eventually lead to the compact, economical acceleration of intense currents of light and heavy ions to hundreds of MeV/nucleon [1, 2]. Potential areas of such beams include controlled thermonuclear research, electronuclear breeding, basic nuclear physics and radiation shield testing.

In order to generate intense power electron beam pulses, BARC has developed various types of accelerators for plasma related research, flash radiography and high power microwave generation for shielding of electronic components & devices. Present paper deals with the design and development details of 1MV, 80kA, 100ns pulsed electron beam accelerator viz. KALI-5000. The details of the high voltage pulse power system to generate the high voltage and high current pulse & electron beam in conjunction with field emission type electron beam gun for HPM generation using microwave device like VIRCATOR are described. The main sub-systems of this accelerators are (i) 1.5 MV, 25 kJ Marx generator, (ii) 1 MV, 5 kJ, 100 ns Blumlein type pulse forming line (PFL), 1MV SF_6 sparkgap and (iv) 1MV, 80 kA, 100 ns REB diode. The photograph of the complete assembly of KALI-5000 is shown in Fig.1. It has been used to generate 40 GW of REB pulse. This system has been used for generation of electron beam pulses in experiments for one of the classic application of coherent electromagnetic radiation in the microwave portion of the electromagnetic spectrum, which extends from 3-5 GHz. The details of individual sub-systems and results are described below.

2. Construction of Pulsed Accelerator KALI-5000:

There are various devices to generate the high voltage pulses but most popular technique is Marx generator in which energy storage capacitors are charged in parallel and discharged through synchronized spark gap switching in series resulting in enhanced voltage and power [3]. Once the voltage pulse is generated, it is required to shape them into a flat top type so that when it is injected to the electron gun, same energy beam will be emitted during that time span. With this flat top pulse as input, the electron gun produces the pulsed electron beam, which can be used for various applications.

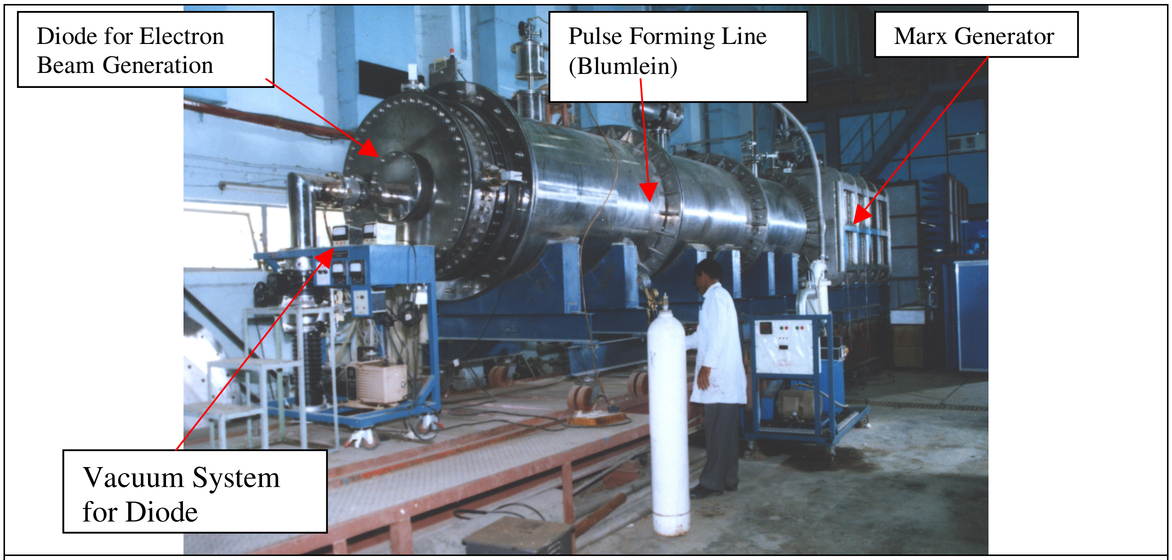


Fig.1: Photograph of 40GW Pulsed Accelerator

The schematic of this pulsed electron beam accelerator is presented in Fig.2. It comprised of high voltage ± 50 kV DC charging power supply followed by an impulse generator based on plus minus charging type Marx generator. The output pulse is shaped

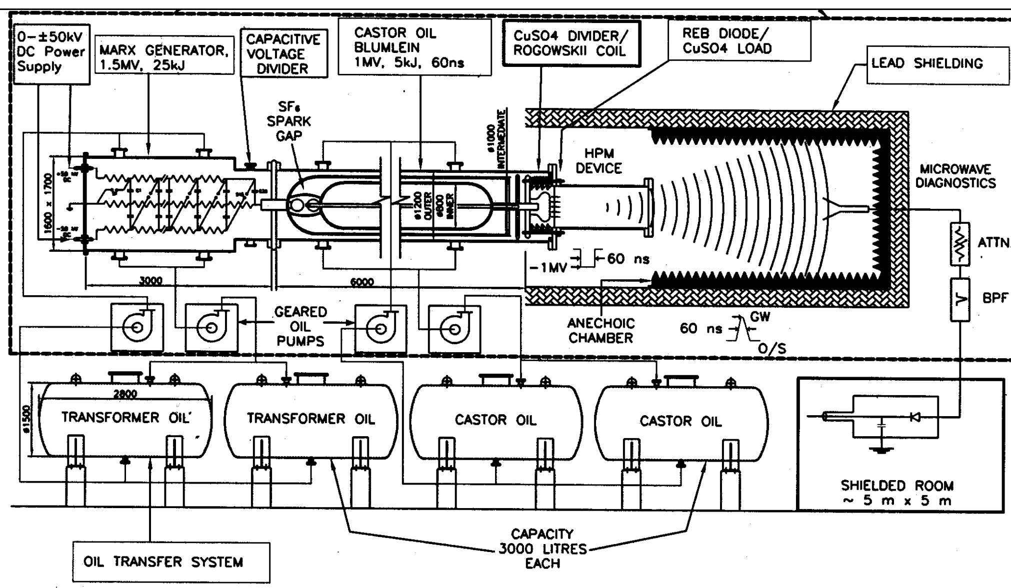


Fig.2. The schematic diagram of the pulsed electron beam accelerator KALI-5000

through a Blumlein type pulse forming line and terminated across a field emission type electron gun. The whole assembly has been put on rails for ease in assembly and maintenance point of view. The descriptions of main sub-systems are as follows:

2.1 1.5MV, 25kJ, Plus Minus Marx Generator

The Marx principle is the transient series connection of a number of electrostatic energy storage capacitors. The key to the Marx operation lies in the triggering of the series-connecting switches. Designs can be made more compact where pulse durations are short, or where liquid or special gas environment can be provided. But, as designs are made more compact, two problems arise: breakdown hazards increases and the inter-stage capacitances increase, with the result that 2-electrode gaps can be triggered by operating them very close to self breakdown, thus reducing the pre-fire safety factor. Therefore it is necessary to devise improved arrangements for triggering the series connecting switches and accommodating the higher electric stresses in large compact Marx generators. In present scheme, plus-minus charging type Marx generator is used for pulse charging of Blumlein as shown in the general scheme of this system in Fig.2.

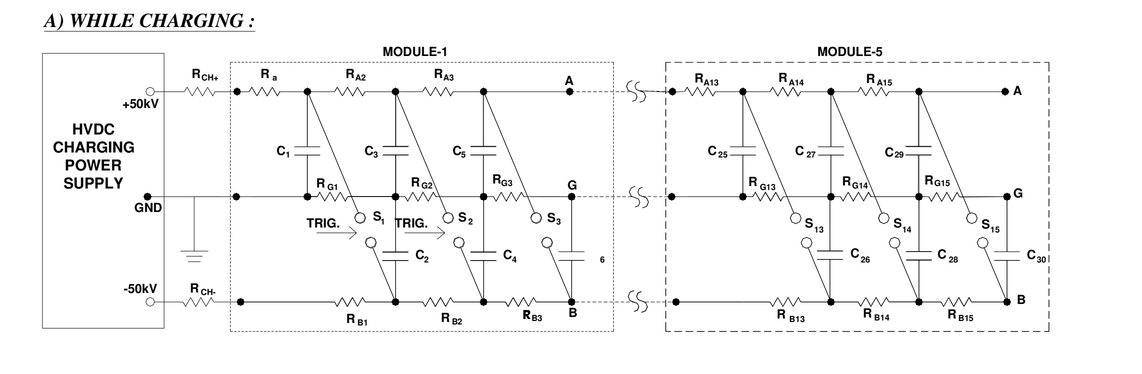


Fig.3(a). Schematic of Plus Minus Marx Generator while charging

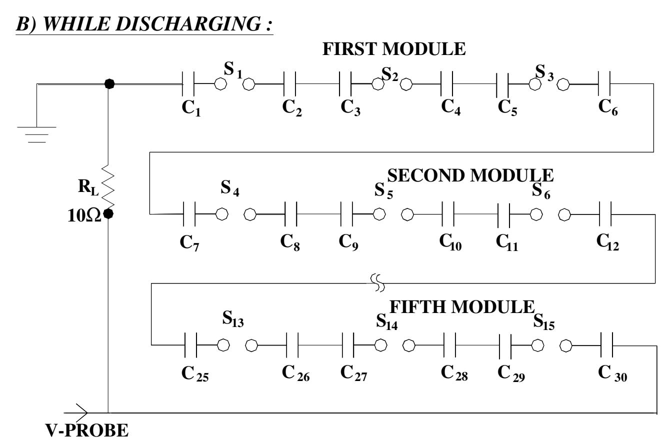


Fig.3(b). Schematic of Plus Minus Marx Generator while discharging in series

The main advantages of plus-minus charging are: (i) the number of spark gaps is halved compared to a conventional Marx of single polarity charging. This results in lower inductance, less complexity and increased reliability, (ii) it enables efficient use of three electrode triggered gaps with central electrode held at mid potential thereby producing uniform field & high insulation value and (iii) when compared to single polarity 100kV charging, the insulation requirement to ground is reduced to half. The schematic of the Marx generator based on plus-minus charging is shown in Fig.3(a) while charging and as in Fig.

3(b) while discharging. It can be seen that the inductance of capacitors and sparkgaps only play crucial role in the output pulse shape, besides interconnections between stages. Therefore efforts are made to minimise the inductance of the circuit and used components. In present scheme, the 15 stage modular plus minus 50 kV charging type Marx generator is adopted. These modules consists of 30 numbers of energy storage capacitors rated 0.70µF, 50kV each, 15 numbers of sparkgap switches of pressurised nitrogen gas insulated media with Bruce profile stainless steel electrodes and nichrome wire wound resistors of 2.5kΩ and 20kΩ for charging and ground isolation resistances respectively. The low inductance capacitors are arranged in "Z" configuration, which requires minimum, module-to-module insulation.

The high voltage DC charging of the capacitors is transformed into a short duration and high power pulse by the external triggering of first spark gap switch followed by sequential firing of rest of the switches. It facilitates the output voltage pulse to be 30 times more than the charging voltage level and FWHM is limited to 1µs. The voltage pulse on a dummy load of 10 Ω is measured by copper-sulphate voltage divider ($CuSO_4$) on a wide band (500MHz) storage oscilloscope. In order to see the erection of Marx in sequence, two modules are used with charging voltage of ±10kV. The photograph of the assembly of 5-module Marx generator is shown in Fig. 4(a). Typical wave -shapes of individual and two modules in series are shown in Fig.4 (b) & 4(c). Modules 1&2, 2&3, 3&4, and 4&5 are erected in series and their sequential firing has been confirmed. All Marx components are immersed in transformer oil and sparkgap switches are enclosed in Perspex assembly in pressurized nitrogen gas medium. The output voltage of the Marx generator can be varied by varying the pressure of the sparkgap switches. It has been housed in a stainless steel tank of 1.7 m width x 1.6 m height x 3 m length. The charging resistors (R) of conventional Marx generator can be replaced by inductors (L) for repetitive application, to (i) reduce power loss and heat in the oil insulation used for the Marx generator, and (ii) allow faster charging of Marx capacitors and hence enhancing the repetitive pulse capability of Marx Generator.

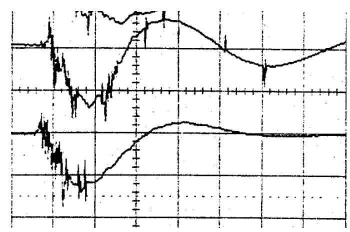


Fig. 4(b) Module-1 & Module-2 Voltage pulses, ~ (60kV peak).

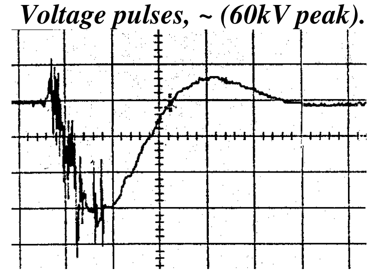


Fig.4 (a). Assembly of Marx Module of KALI-5000 Pulse Power System

Fig. 4(c) Erected voltage pulse of two Modules-1 & 2 (~120kV)

2.2. 1 MV, 12 Ω Castor Oil Blumlein

In a pulse power system, transmission line could be defined as power amplifier, which receives the energy to be stored at low average power over a long period of time and delivers the stored energy at high average power over a short period of time. The transmission line could take one of the numerous well-known geometries like two electrode simple pulse forming line in strip line or coaxial geometry, five electrode Blumlein line in strip-line geometry or stacked configuration of simple or Blumlein lines. The dielectric could be (a) solids like polyethylene or Mylar impregnated with oil, water or $CuSO_4$ solution, (b) liquids like transformer oil, caster oil, de-ionized water or glycerin. The transmission line in the present pulse power system is a three electrode coaxial Blumline with castor oil as the dielectric. When the Marx generator is triggered and erected, the resulting stepped up voltage then charges the Blumlein to a peak voltage V_p, where further shaping of the pulse takes place. Pulsed charging of this line enables to make the system compact. When the PFL is charged to the voltage corresponding to the preset breakdown voltage of SF_6 spark gap S_2, it breaks down & discharges the stored energy into a matched dummy $CuSO_4$ load of 17 Ω for testing purpose or into beam diode for generation of relativistic electron beam (REB). Reversing the polarity of the HVDC supply can reverse the polarity of the output pulse.

<u>Design criteria:</u>

The length of the transmission line is selected depending on the output pulse duration. From the given values of voltage (V), current (I) and duration (T) of the pulse at the load, the basic design equations used for the calculation of coaxial line parameters are given below [4]:

Velocity of Propagation $V_p = C/\sqrt{\varepsilon_r}$

Length of the line $L = 2.\tau.C/(2\sqrt{\varepsilon_r})$

where C = velocity of light = 3.10^8 m/s

ε_r = relative permeability = 5 for castor oil

$2.\tau$ = pulse duration = 100ns

Characteristic Impedance

$Z_0 = \{60/\sqrt{\varepsilon_r}\} \ln\{R_2/R_1\}\ \Omega$

where ε_0 = permeability of free space and

ε_r = relative permeability,

R_2, R_1= outer / inner radii of cylinders

The peak breakdown stress is given by

$$E_{BD} = \frac{V}{R_1 . \ln\{R_2/R_1\}} \text{ MV/cm}$$

where V = applied voltage in MV, R_1 is in cms and E_{BD} = Breakdown stress in MV /cm.

Characteristic Impedance and the peak breakdown stress are depended upon the ratio of $\{R_2/R_1\}$. The ratio of $\{R_2/R_1\}$ should be selected close to 2.7 to take advantage of polarity effect. The length of the Blumlein is selected to match the required pulse duration of ~100 ns. The S.S. 304L stainless steel tubes and plates are selected for fabrication of transmission line due to their welding properties under corrosion conditions and high voltage withstand capability. For 1MV, 80 kA, 100ns with impedance of 12 Ω, the resulting coaxial line parameters like length (L), inner radius (R_1), intermediate radius and outer radius (R_2) are 4 m length, inner cylinder radius of 0.4 m, intermediate cylinder radius of 0.5 m and outer cylinder radius of 0.6 m respectively. However due to additional inductance of charging inductor and connecting lead to REB diode, the impedance increases, which results in increased duration (100ns) & reduced current (40kA). The energy stored in this Blumlein, is switched through SF_6 sparkgap and the output pulse is applied to REB diode for beam generation. The photograph of charging / isolation inductor is shown in Fig.5(a) at the diode end and Fig.5(b) presents the SF_6 sparkgap chamber connected with Blumlein at Marx end.

Before filling the castor oil, Blumlein chamber was degassed and after filling the oil again it was degassed for 4-5 days and then it was kept for 2 more days to settle down before using for experiments. The charging inductor of 1μH is used to charge the inner capacitor formed by inner & intermediate cylinders until Blumlein sparkgap fires. This pipe is used for SF_6 gas inlet to SF_6 sparkgap chamber. This sparkgap chamber is made of Perspex cylinder with nylon tie rods to have pressurized gas as the insulating medium. It is a self breakdown type sparkgap which connects the intermediate cylinder to innermost cylinder. The stored energy is transferred through the innermost cylinder to electron-gun.

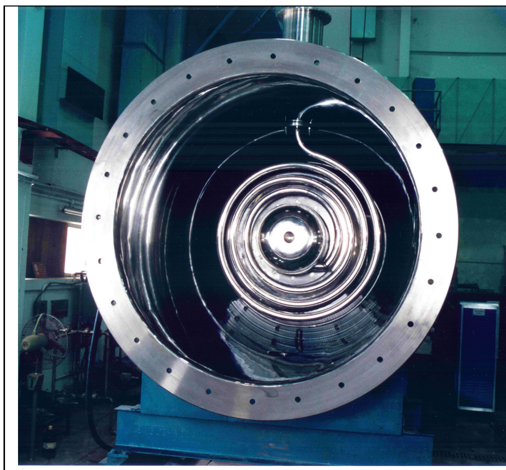


Fig.5(a). Photograph of Charging / isolation Inductor

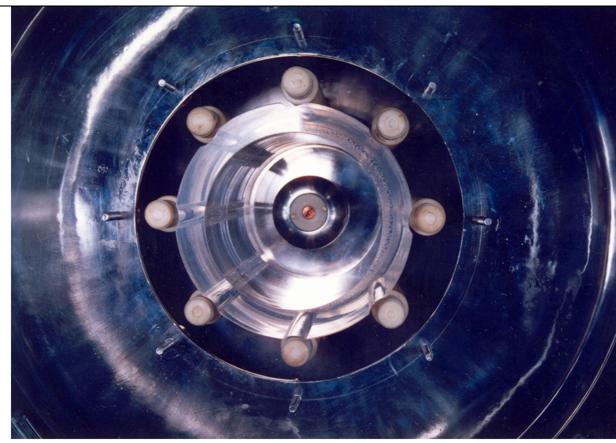


Fig.5(b). Photograph of SF_6 sparkgap Chamber

2.4 Electron Gun:

The schematic of the REB generation is shown in Fig. 6(a). It is a field emission diode made of graphite cathode and anode is of copper mesh. Diameter and gap are adjusted to give required characteristics impedance of the diode. Current through the diode is measured by Rogowski coil and voltage by $CuSO_4$ solution based voltage divider [5]. This graphite cathode is used for generating the intense pulse electron beam of 800-1000 keV, ~40GW, 0-70 kA, ~100 ns. These Relativistic Electron Beams are useful for the generation of High Power Microwaves (HPM) and Flash X Rays (FXR) [2]. The pulsed HPM is generated by injecting electron beam in to microwave devices such as Beam plasma interaction {Fig. 6(a)}, Vircator {Fig.6(b)} & backward wave oscillator {Fig.6 (c)}. The parameters of frequency, peak power, efficiency for these devices are 1-100GHz / 1-100MW / 0.1-1% / 1-10 GHz/1-20GW/1-5%, 10-50 GHz/0.1-1GW/10-50% respectively. HPM power up to 500MW has been generated using another system of relatively low power, named KALI-1000 in a virtual cathode oscillator {VIRCATOR} at beam parameters of 200-250keV, 10-15kA, ~100ns. To upgrade the output power now KALI-5000 system has been used at 600 keV and 70kA, 100ns beam pulse were obtained as shown in Fig.7 (a) & Fig.7(b) respectively. This electron beam pulse has been used to generate HPM in VIRCATOR mode and 1 GW power level in S-Band frequency have been achieved. It will also be used for generating highly powerful X rays (Flash X rays) as shown in Fig.6(d).

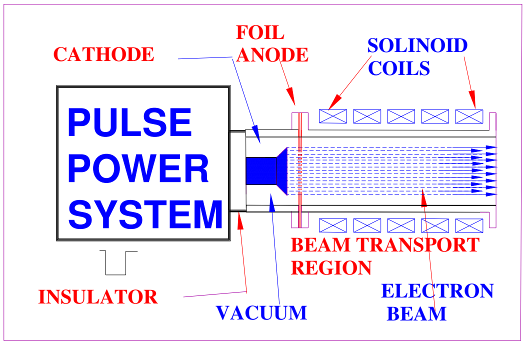


Fig.6 (a). REB Generation by Graphite cathode & Foil Anode

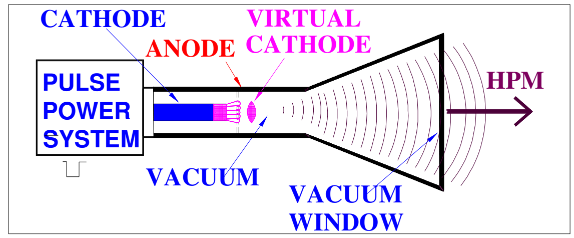


Fig.6 (b).Schematic of Vircator device for HPM Generation

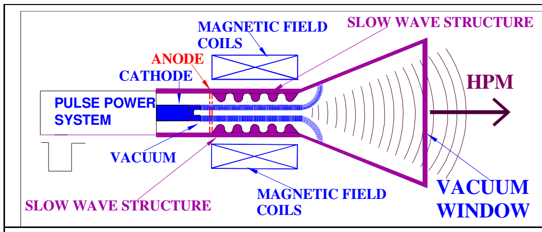


Fig.6 (c).Schematic of BWO device for HPM Generation

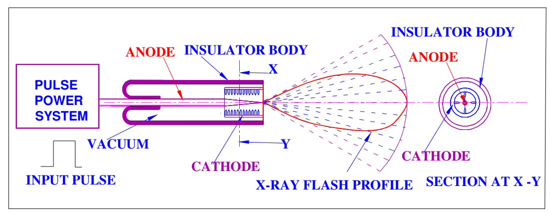
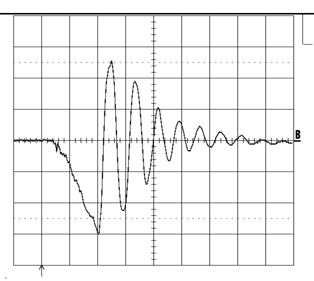


Fig.6 (d). Schematic of Flash X-Ray Generation

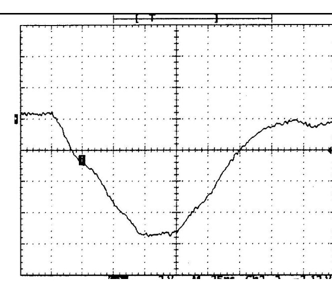
2.5 Operation and Results of KALI-5000 system:

With 2-2.5kg/cm^2 pressure of SF_6 gas, the peak output voltage obtained is 600kV & current pulse is 70kA as shown in Fig.6 (a) & 6(b). For pulse measurement of current and voltage in sub-microseconds, Rogowski coil and CuSO4 voltage divider are used respectively along with 200MHz storage oscilloscope.



Scale:200kA/division, 500ns/division

Fig. 7(a) Marx generator output voltage waveform. Peak Voltage= 600kV. T= 500ns.



Scale:20kA/division, 25ns/division

Fig. 7(b) Field Emission diode current I_{max} = 70kA at 600kV. FWHM = 100ns.

Advantages of Rogowski coil is (1) sub-nano second rise time, 2) the output is position independent, 3) the output is frequency independent, 4) it responds only to currents threading the coil, 5) good linearity between input and output, 6) no loading on the circuit, 7) no branching of the circuit for measurement.

The frequency response of conventional dividers will be distorted due to distributed capacitance of the high voltage arm. The $CuSO_4$ divider has good high frequency and low frequency response. It is immune from the effects of stray inductance and capacitance due to large area and higher resistivity compared to carbon film resistors [6]. The output voltage of this copper sulphate divider is terminated with a 50 Ω terminator, which is the characteristic impedance of cable used to damp the oscillations. Thus in a carefully designed column following features are achieved: (i) constant divider ratio, (ii) wide bandwidth, (iii) linearity in ratio vs frequency, or amplitude, (iv) high voltage sustaining capacity, (v) better signal to noise ratio, and (vi) large energy dissipation.

3.0 Conclusions

This 1MeV, 80kA, 100ns pulsed electron accelerator has been tested up to 600kV, 70kA, 100ns, 25GW power level. This powerful electron beam can be used for various strategic and industrial applications.

4.0 Acknowledgement

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5.0 References

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