Intense Gigawatt Relativistic Electron Beam generation
Studies in Planar and Cylindrical Diodes

SYNOPSIS

Intense gigawatt relativistic electron beams (IREB) with beam energies greater than 100 kilo electron volts, beam currents tens to hundreds of kiloamperes and duration few tens of nanosecond to few microsecond have found applications in the field of high-power microwave generation (HPM) [1], free electron lasers [2], flash X-ray (FXR) generation [3], and surface modification [4] etc. For all these applications, the intense electron beam is generated in REB diode by the explosive field emission process. When a high electric field (> 100 kV/cm) is applied on a cathode surface, electrons are emitted from the surface by field emission process. Due to resistive heating of the sharp points on the surface, an expanding plasma layer (called cathode plasma) is formed on the cathode surface in a few ns. When the intense electron beam hits the anode, anode plasma is produced. Space charge limited electron and ion emission occurs from these electrode plasmas. Movement of electrons, ions, electrode plasmas, plasma uniformity and associated self magnetic fields control various processes occurring in the high power vacuum diodes. Considerable experimental and theoretical work [5] has been done in the study of beam generation processes but the information available is far from complete. The numerous applications of these large devices, often insufficiently understood, create a need for establishing rules as precise as possible. An attempt has been made in this thesis to understand the beam generation process under various diode configurations and also production of HPM using these beams.

Chapter 1 of this thesis introduces the subject of intense relativistic electron beam generation in vacuum. Based on the review of available literature on the beam generation process, it is felt that plasma expansion velocities and presence of a high voltage pulse (known as pre pulse) before the main power pulse control the magnitude and duration of the beam produced. Consequently, the following problems were identified for investigation in this thesis.

a) Intense Gigawatt Relativistic Electron Beam generation studies in the presence of prepulse in planar and cylindrical diodes.
b) Prepulse suppression techniques.

c) Measurement of electrode plasma expansion velocity from the perveance data during the main pulse using the bipolar space charge limited flow model.

d) Generation and measurement of HPM power from axial and coaxial virtual cathode oscillator.

Chapter 2 of this thesis presents a review of the literature available on the various aspects of the intense gigawatt relativistic electron beam generation and its application on High Power Microwave generation.

A typical pulse power system consists of a primary charging device like Marx Generator (MG) or Tesla Transformer (TT), a pulse forming line, either Blumlein line or a simple two electrode coaxial line, spark gap switches, electron beam diodes as a load and peaker.

Fig. 1 shows the elements of the unified circuit for the production of nanosecond high-power pulses. An MG charges a primary energy store (capacitor or line) within about 1µs. The pulsed charging of an energy store enables one to use nonconventional liquids for insulation of MG's, such as water, glycerin, castor oil, and not just transformer oil. Besides, it is possible to work with much stronger electric fields, allowing one to reduce the overall dimensions of the device and to use a nontriggered spark gap as the main switch. The primary energy store is discharged through the main switch into a pulse-forming line, which in turn is discharged through a peaker into a transmission line. The transmission line is connected to a load through another peaker. The load can be the diode of an accelerator of electrons or ions, a gas laser, the resonator of a high-power microwave generator, a z-pinch shell, the diode of a high-power x-ray generator, etc.

The circuit in Fig. 1 is a generalized one, since, depending on the parameters of the pulse and its purpose, some or other elements can be absent. In particular, the second peaker, as a rule, is used not only to shorten the pulse rise time, but also to reduce the amplitude of the prepulse. The latter, if an electron diode is used as a load, results in the occurrence of premature explosive electron emission and undesirable filling of the diode with plasma before the arrival of the main pulse. Therefore, in some circuits where the prepulse does not play a role, the second peaker may be absent. The transmission line can serve simultaneously as an impedance converter, for example, an exponential strip or coaxial line. In some generators, there is no
peaker at all, and the pulse, after pulse-forming line, arrives immediately at the load. For example KALI 5000 pulse power system does not have a peaker.

![Diagram](image)

*Figure 1. Elements of the unified circuit for the production of nanosecond high-power pulses: 1 - Marx generator, 2 - capacitive energy store, 3 - pulse-forming line, 4 - transmission line, 5 - load, 6 - main switch, 7 - first peaker, 8 - second peaker*

In actual pulsed power systems, a voltage pulse of about 10%–30% of the main pulse voltage appears across the vacuum diode at about 300–800 ns before the arrival of the main pulse. This pulse is known as a prepulse and appears in the charging cycle of the Blumlein pulse forming line. This prepulse is produced due to the charging inductor connected between the central and outer electrodes of the Blumlein. The prepulse voltage becomes more pronounced due to the imbalance of the charging lines of the Blumlein. Presence of prepulse in the pulse power systems [6, 7] poses some problem in the beam generation process. The onset of the prepulse prior to the arrival of the main pulse in the IREB diode leads to the evaporation of cathode whiskers and subsequent launching of significant amount of plasma and neutral vapors into the vacuum diode region. The plasma thus created affects the performance of the IREB generation significantly [7]. In the past, beam generation studies were carried out in IREB diode in the presence of a prefilled plasma of different densities [8]. The beam generation mechanism in the presence of a prepulse is not exactly the same as that of the earlier works on plasma filled diodes.

For shorter pulse duration < 100 ns and at the comparatively low current density ~10 A/cm² electron flow remains unipolar [9]. However at the higher current density greater than few hundreds of A/cm² electron flow becomes bipolar [10]. The charge neutralizations of the electrons by the ions allows approximately 1.86 times the current to flow as compared to single species Child–Langmuir, with the limiting electron current independent of the ion mass [6].

The anode and cathode plasma, can cross the diode gap, resulting in collapse of the diode impedance during the high voltage pulse. This behavior adversely affects the diode performance, limits the duration of the electron beam pulse and results in poor efficiency of
coupling between the electron beam diode and the pulse power system. From the plasma luminosity measurement it was seen that a cathode plasma appears on the cathode surface immediately after the rise of the beam current at about $t=20$ ns [11]. An anode plasma on the anode surface has been seen to be formed at $t=30$ ns [11]. The cathode plasma expands at 1.8-4.2 cm/$\mu$s and the anode plasma expands at 2.6-9.4 cm/$\mu$s for various AK gaps [11].

To delay the impedance collapse of the diode, it has been suggested to use cesium iodide (CsI) coated carbon fiber cathode and heat the anode [12] at 800–1200 K. Heating the anode may reduce the amount of gas that is desorbed and thereby reduce the amount of plasma exploding in to the diode region [12]. CsI coating produces slower and/or more uniform cathode plasma through easier emission at lower electric field [12].

IREB’s have been used extensively to generate HPM using Virtual Cathode Oscillator (VIRCATOR) device. In a VIRCATOR device IREB’s are injected into drift tube in excess of the space charge limited current. In this case, a virtual cathode forms and reflects electrons back toward the accelerator. This is an inherently unstable situation, and it leads to quite efficient production of electromagnetic radiation. The self space charge of the electrons forms a deep electrostatic well, which results it the virtual cathode. Power levels between 10 MW and several gigawatts at frequencies in the range of 2-13 GHz, with electron beam power conversion efficiencies between 1.5 and 14 % have been reported.

**Chapter 3** of this thesis describes the experimental setup and procedure. KALI 1000 (Kilo Ampere Linear Injector) (300 kV, 20 kA, 100 ns) and KALI 5000 (1MV, 60 kA, 100 ns) pulse power system has been used to investigate the various aspects of IREB generation. KALI 5000 pulse power system has been operated without a prepulse switch (or peaker) to study the effect of prepulse on IREB generation. The typical electron beam parameters studied in this thesis were 200-450 keV, 10-40 kA, 100 ns with few hundreds of A/cm$^2$ current density. A copper sulfate resistive voltage divider has been developed to measure the diode voltage. A self integrating Rogowski coil and a B-Dot probe has been designed and developed to measure the fast rise time diode current. In order to generate HPM using the IREB, axial and coaxial vircators have been designed and developed.

**Chapter 4** of this thesis presents the IREB generation studies in the presence of prepulse. To understand the prepulse effect on the relativistic electron beam diode, beam generation experiments have been carried out with various AK gaps and voltages. Electron beam
generation mechanism in the presence of the prepulse has been analyzed by the expansion of the prepulse generated plasma and plasma filled diode. Increasing the AK gap reduces the prepulse electric field and eventually drops it below the explosive emission threshold and eliminates its creation. As this threshold is approached, the plasma that is turned on may be non-uniform as explosive sites become few and far between. This will make the cathode plasma very dependent on surface preparation and the resulting plasma will be wispy, spotty, and very nonreproducible. For perveance more than 200 \( \mu \text{Perv} \) we can consider the diode as short. The diode can be considered short if the Marx voltage/(Anode Cathode Gap)^2 is more than 56 kV/cm^2. Below 56 kV/cm^2 the effect of the prepulse will be negligible.

In order to study the effect of prepulse on cathode diameter, an intense relativistic electron beam has been generated from planar and annular graphite cathodes at a fixed 25 mm AK gap in the presence of prepulse. A bipolar prepulse voltage has been recorded at the diode. It was found that the positive prepulse voltage has no significant effect on the diode perveance and impedance. Annular graphite cathodes of 40 and 70 mm diameters and 98 mm diameter planar graphite cathodes are not very suitable for reliable operation in the presence of prepulse.

High Power Cylindrical diodes have been employed for intense relativistic electron beam generation in coaxial virtual cathode oscillator [13] and in high resolution radiography sources [3]. Intense relativistic electron beam has been generated in a high power cylindrical diode in the presence of prepulse. A bipolar prepulse voltage has been recorded at the diode. The amplitude and the time duration of the prepulse voltage vary with the Marx generator voltage. It was found for the AK gap \( \leq 1.65 \) cm that there is shot to shot variation in the cylindrical diode voltage and current for the same Marx generator voltage. It was shown that the positive prepulse voltage has no significant effect on the diode perveance. For the cylindrical diode the prepulse generated plasma decreases the impedance of the diode and, respectively, increases the diode perveance. However, one can conclude that the plasma dose not completely fill the diode gap, resulting in \( \geq 170 \) kV diode voltage.

Studies have been carried out to generate intense electron beam in the cylindrical electron beam diode when subjected to a high voltage bipolar pulse. In the positive voltage pulse, a copper mesh acts as a source of electrons. The diode perveance in the positive voltage pulse linearly increases with time due to the increase in the emission area. The electrode plasma closure is a small effect on the positive voltage pulse. During the negative voltage pulse, the
diode impedance decreases with time due to the plasma expansion. Thus, even though there is a plasma formation on the anode during the positive voltage pulse, the electron beam can be generated from the graphite cathode in the negative voltage pulse with a modest perveance ($1.1 \times 10^{-4} \text{ A/V}^{3/2}$).

So the effect of prepulse is more pronounced in the planar cathode of higher diameter due to a decrease in the uniformity of the prepulse generated plasma with the corresponding increase in the cathode diameter. The effect of the prepulse is less pronounced in the cylindrical diode as compared to planar diode that allows one to operate the cylindrical diode with the AK gap $\leq 1.85$ cm. Annular cathodes are not very suitable for reliable operation in the presence of prepulse.

In order to reduce prepulse voltage to an acceptable level ($\leq 5\%$), prepulse switches are used after the pulse forming line [7]. It is also possible to reduce prepulse by introducing a surface flashover switch into the conductor feeding the diode in vacuum. IREB generation studies were carried out with a Perspex cathode holder. The dielectric cathode holder acts as a surface flashover switch. It was found that corrugated Perspex of length $\geq 35$ mm can eliminate the prepulse voltage but affects the rise time of the diode voltage. The prepulse voltage reduces significantly ($\leq 10\%$) when an inductance is added to the charging circuit of the Blumlein line. But with an added inductance the slower rise time ($\sim 2 \mu s$) of the Marx charging voltage can increase the jitter in the output switch and increase the voltage stress in the Blumlein line. With an added inductor at the charging circuit of the Blumlein line the KALI 5000 system can be operated up to $\sim 400$ kV with an acceptable level of prepulse voltage. In order to operate the diode up to 1 MV a low capacitance gas prepulse switch has to be installed after the pulse forming line.

Chapter 5 of this thesis presents the electrode plasma expansion velocity measurements for various diode configurations and diode voltages. We have measured the electrode plasma expansion velocity from the perveance data for various diode configurations. The time varying electron beam diode impedance and perveance were measured in a planar diode for 18, 25 and 31 mm AK gaps. For 31 mm AK gap the anode and cathode plasmas expand at 9.5 cm/µs toward each other. The peak current density in this case was $J = 401 \text{ A/cm}^2$. Such a high plasma expansion velocity has also been observed with carbon nanotube cathode [14] with a high current density $J = 309 \text{ A/cm}^2$, the plasma velocity reported $v = 9.1 \text{ cm/µs}$. It was found
that the plasma expansion velocity decreases for lower AK gap. It may be possible that the higher electric field at lower AK gap is slowing down one of the two plasmas. It was also found that for the same AK gap the plasma expansion velocity increases with the increase of the diode voltage due to an increase in the corresponding current density.

The plasma expansion velocity has also been measured for cylindrical diode for three different AK gaps using a time dependent Langmuir-Blodgett space charge limited flow model. Electron beam diode perveance was measured for 1.85, 1.65, and 1.2 cm AK gaps. It was found that for 1.85 cm radial AK gap the anode and cathode plasmas expand at 5 cm/μs toward each other. Plasma expansion velocity decreases for 1.2 cm AK gap.

Using interferometry, observed velocities of upto 30 cm/μs has been reported in axial plumes of anode plasma in a pinch-reflex diode operating at 1.5 MA and 1.5 MV. In an applied B-ion diode (1.7 MV, 1.7 MA) an expansion velocity of 5 to 10 cm/μs throughout the voltage pulse was required for surface-flashover anode plasma in order to explain the temporal impedance decrease [15]. In higher power diodes the higher plasma-pressure gradient may result in a fast plasma expansion [15]. Expansion velocities of 5 cm/μs correspond to the ion thermal velocity of 25-eV protons.

Chapter 6 of this thesis presents HPM generation and measurement from axial and coaxial virtual cathode oscillator. HPM generation studies have been carried out using the pulsed power generator KALI 1000. The typical electron beam parameter was 200 kV, 14 kA, 100 ns. High power microwave has been detected by neon lamp discharge by HPM illumination when placed a few meter distances from the vircator window. Microwave power has been optimized by changing the AK gap. It was found that the peak power occurs around 6 mm AK gap. HPM measurements were done using zero bias Schottky diode detectors along with a horn antenna and sufficient attenuation so as to reduce the power level below the power rating of the diode detector. Various components used in the diagnostics were calibrated using standard modulated RF source. The estimated microwave peak power is ~1 kW (within the effective aperture area of the receiving antenna) at 7 m distance from the vircator window.

HPM generation studies were carried out with a coaxial vircator using cylindrical electron beam diode in the presence of significant prepulse voltages. For 1.2 cm diode gap HPM has got more peak power as the diode detector was getting saturated even when the antenna has been placed at around 4.5 meter distance from the vircator output window. At this place the
measured HPM peak power was more than 20 dBm (within the effective aperture area of the receiving antenna). The estimated peak power of the Coaxial Vircator was more than 1 MW.

Chapter 7 presents summary and conclusions. Based on the above studies following conclusions were made.

a) It was shown that intense gigawatt relativistic electron beams can be generated in the presence of significant prepulse voltages in planar, annular and cylindrical diodes with a larger gap than that estimated by the space charge limited law.

b) It was found that for lesser AK gap there is shot to shot variation in the diode voltage and current for the same Marx generator voltage due to the nonreproducibility of the prepulse generated plasma.

c) Inserting a dielectric at the cathode holder could be a very effective method to reduce prepulse voltage at the electron beam diode, but it increases the rise time of the diode voltage and reduces the effective electron beam pulse width.

d) In the case of the added inductance to the Blumlein circuit, the slower rise time reduces the prepulse voltage from 32% to $\leq 10\%$. A gas prepulse switch is required to increase the diode voltage up to 1 MV.

e) It was found that during the main pulse the diode impedance collapses due to plasma expansion from the cathode and anode surfaces. Electrode plasma expansion velocities are measured from the perveance data for planar and cylindrical graphite cathodes. It was found the plasma expansion velocities vary from 3.4 to 9.5 cm/$\mu$s for various diode configurations and diode voltages.

f) HPM has been generated from axial and coaxial virtual cathode oscillator using the IREB and the HPM power has been measured using a diode detector and receiving horn antenna set up.

Finally some suggested future work is being outlined.

a) Beam generation studies should be carried out with a gas prepulse switch.

b) Cathode and anode plasma expansion velocities should be measured more accurately with a streak camera.

c) Plasma expansion velocities should be measured for other cathode materials like velvet and carbon fiber and CsI coated cathodes.
d) HPM generation and measurements should be carried out with more accurate diagnostcs.

Present work has contributed to a better understanding of intense gigawatt relativistic electron beam generation process and it’s usefulness towards HPM generation. The results of the study are useful in the design of a reliable and efficient large electron beam system and HPM devices.

REFERENCE


**List of Publication during Ph.D. work**


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