CHAPTER 1
INTRODUCTION

Intense gigawatt relativistic electron beams has received considerable attention during last 40 years due to its use in such diverse applications as high-power microwave generation (HPM) [1, 2], free electron lasers [3], flash X-ray (FXR) generation [4], and surface modification [5] etc. The intense relativistic electron beam (IREB) is generated from the cold cathode by explosive electron emission process, and the electron emission occurs from the plasma which is formed on the cathode surface when the strong electric field $E \geq 10^7$ V/cm is applied to the anode-cathode (AK) gap [6]. Intense pulsed relativistic electron beams were first developed to provide sources for flash X-radiography to simulate nuclear weapon effects in the laboratory. J. C. Martin [7] and his colleagues at Atomic Weapon Research Establishment (AWRE), Aldermaston, UK did pioneering work in this area in early 1960’s. The first experimental investigation of IREB’s was reported by Graybill and Nablo [8] in 1966 and similar experiments were carried out in many laboratories. Since that time lot of developments has taken place in pulsed power technology during last 40 years, IREB’s with beam currents upto 10 MA, powers of $10^{13}$ Watt and energies of $10^6$ Joule are presently available for experiments. The numerous applications of these large devices, often insufficiently understood, create a need for establishing rules as precise as possible.

KALI 1000 and KALI 5000 (Kilo Ampere Linear Injector) pulse power system has been used to investigate the various aspects of IREB generation in planar and cylindrical diodes. KALI-5000 consists of a 1.5 MV, 25 kJ Marx generator [9], [10] 1 MV, 5 kJ Blumlein type transmission line, and 60 kA electron beam diode with voltage and current diagnostics. KALI-1000 (Maximum output voltage 300 kV, output impedance 15 $\Omega$, and pulse duration 100
ns). consists of a radial tesla transformer, a water transmission line and electron beam diode with voltage and current diagnostics.

When the intense electron beam hits the anode, an anode plasma is produced. These anode and cathode plasma, however, can cross the diode gap, resulting in collapse of the diode impedance during the high voltage pulse. The diode closure occurs later in the pulse duration due to the expansion of these plasmas. 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 $t = 20\, \text{ns}$ [11]. An anode plasma on the anode surface has been seen to be formed at $t = 30\, \text{ns}$ [11]. Expansion velocity for cathode plasma may be different than for the anode plasma. The plasma expansion velocity has been calculated from the temporal behavior of the AK gap.

Impedance collapse due to expansion of the electrode plasmas in the AK gap is a well-known phenomenon and has been studied by various authors, both theoretically [12] and experimentally [13]. For shorter pulse duration < 100 ns, and at the comparatively low current density ~ 10 A/cm$^2$ electron flow remains unipolar [14]. But at the higher current density > few hundreds of A/cm$^2$ electron flow becomes bipolar [15]. In this thesis the operation of a diode has been investigated in the bipolar regime to understand the effect of plasma expansion on the impedance of the diode. 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 [13] 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 [13]. CsI coating produces
slower and/or more uniform cathode plasma through easier emission at lower electric field [13].

Presence of prepulse in the pulse power systems [6, 16] poses some problem in the beam generation process. In order to achieve full voltage at the diode, impedance of the diode should match with the impedance of the pulse forming line. But the presence of prepulse could reduce the diode impedance significantly. 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 (PFL). This prepulse is produced due to the charging inductor connected between the central and outer electrodes of the Blumlein PFL. The prepulse voltage becomes more pronounced due to the imbalance of the charging lines of the Blumlein PFL. A bipolar prepulse voltage of ~ ± 90 kV peak voltages has been recorded at the diode [17].

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 [16]. Due to the presence of the prepulse, a plasma with a density of $10^{13}$ cm$^{-3}$ is produced in the diode gap [18]. This plasma is in addition to the plasma produced at the surface of the cathode ($\geq 10^{18}$ cm$^{-3}$) when the main pulse appears across the gap [19, 20]. Accordingly the beam generation process is governed by the presence and movement of prepulse created plasma and the main plasma created at the cathode surface. In the past, beam generation studies were carried out in IREB diode in the presence of a prefilled plasma of different densities [21]-[25]. 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. Unlike the plasma filled diode, the prepulse initiated plasma is not homogeneously distributed within the AK gap of the IREB diode. In order to avoid effect of prepulse on IREB generation it has been suggested to use a prepulse switch [26] or increase the anode cathode gap [17] or reduce the prepulse voltage to a consistent level of less than 5% [27].

To understand the prepulse effect on the relativistic electron beam diode, beam generation experiment were carried out with various AK gaps and voltage. Beam generation and flow mechanisms in the diode are affected by the presence of the prepulse generated plasma in the AK gap. Experiments were carried out with same AK gap but with various cathode diameters and diode voltages. Experiments were also carried out with planar and annular graphite cathodes. Annular cathodes are used in self-magnetically pinched diodes to produce smaller diameter electron beams at the anode [28]. The shot to shot reproducibility of the diode voltage and current versus the prepulse generated plasma has been investigated for planar diode configuration.

It was also shown that there is a statistical correlation between emission uniformity and the shot-to-shot variation in diode current [31]. The perveance expression for the electron flow in the planar diode can be defined based on the Child-Langmuir (CL) “3/2” law [6]. The CL law is correct for nonrelativistic voltages and cathode dimensions much larger than AK gap. If the cathode radius is comparable with the diode gap, however, the diode perveance may be significantly larger [32] than that determined from the classical CL law. It was shown both theoretically [33] and experimentally [34] that a large percentage of the cathode can fail to take part in the emission process and yet the voltage and current can appear identical from the case in which the entire cathode contributes electrons to the emission process. Merely
measuring the current and voltage waveform may not be sufficient to estimate the emission uniformity [34]. But the current waveforms can provide some assessment of cathode emission uniformity if the data is of a statistical nature taken over large number of shots rather than examining single shot waveform shapes [31]. It was shown that the standard deviation and skewness of the current histograms increase as the cathode emission becomes less uniform [31]. Several factors may affect the perveance of the diode with explosive emission cathodes. The most important of these are the cathode plasma expansion, vacuum electric field [35], ion flow from the anode and electron backscattering [36].

IREB’s from a planar diode has been used to generate HPM in an axial vircator [1] configuration using KALI 1000 pulse power system. HPM pulse has been successfully detected using wide band double-ridge horn antenna, RF cable and diode detector setup. The estimated HPM peak power was ~ 59.8 dBm (~1 kW) (within the effective aperture area of the receiving antenna) at 7 m distance from the vircator window. The corresponding diode peak voltage and current was 256 kV and 9 kA respectively.

High Power Cylindrical diodes have been employed for intense relativistic electron beam generation in coaxial virtual cathode oscillator (Vircators) [37] and in high resolution radiography sources [4]. In order to enhance the conversion efficiency of High Power Microwaves the Coaxial Vircators have been proposed [37]. In fact, the coaxial vircator presents a cylindrical diode which consists of an annular cathode and grounded mesh anode. To understand the prepulse effect and plasma expansion characteristics on the cylindrical electron diode experiments were carried out with various AK gaps and voltages. The shot to shot reproducibility of the diode voltage and current versus the prepulse generated plasma has
been investigated. The intense electron beam generation studies have been carried out in the cylindrical electron beam diode when subjected to a high voltage bipolar pulse. Finally IREB’s from a cylindrical electron beam diode has been used to generate HPM in a coaxial vircator [37] configuration using KALI 5000 pulse power system in the presence of significant prepulse voltage. The HPM radiation was received by a double-ridge horn antenna located a distance 4 meter away from the output window and after suitable attenuation given to a diode detector. 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).