CHAPTER 2

LITERATURE SURVEY

INTRODUCTION

This chapter 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. The intense electron beam is generated using the metal, metal-dielectric cathode,
from explosive emission plasma which is formed when the strong electric field $E \geq 10^7$ V/cm is
applied to the AK gap. Velvet or carbon fiber cathodes are characterized by surface flashover
plasma. Space charge limited electron emission occurs from the high density cathode plasma.
When the intense electron beam hits the anode, an anode plasma is produced. These cathode
and anode plasmas expand toward each other which causes the decrease in the diode
impedance. The diode closure occurs later in the pulse duration due to the expansion of these
plasmas. The plasma uniformity, space charge limited electron and ion emission from these
cathode and anode plasmas and the associated self magnetic fields controls various process
occurring in the high power vacuum diode. Section 2.1 describes space-charge limited electron
emission from an expanding plasma cathode. The electrode plasma expansion and the
impedance characteristic of the diode have also been included in this section. Section 2.2
describes multidimensional space-charge limited flow. Plasma-filled diode has been described
in section 2.3. Section 2.4 describes effect of prepulse on intense relativistic electron beam
generation. Electron beam quality and uniformity has been discussed in section 2.5. The shot
to shot reproducibility of the electron beam diode and its effect on electron beam quality has
been described in section 2.6.
Axial virtual cathode oscillator employed for high power microwave generation using the intense relativistic electron beams is presented in section 2.7. Various aspects of cylindrical electron beam diode and the coaxial virtual cathode oscillator have been described in section 2.8.

2.1 SPACE-CHARGE LIMITED ELECTRON EMISSION FROM AN EXPANDING PLASMA CATHODE

FIG. 2.1 High Power Electron beam Diode. Schematic geometries of typical sites of field enhanced electron emission.
The Relativistic Electron Beam Diode system consists of a planar, cylindrical or annular cathode and anode with a suitable gap enclosed in a vacuum chamber and connected to the pulse forming line. Fig. 2.1 shows the expanding cathode and anode plasmas in a planar high power electron beam diode. The anode is kept grounded. When a negative high voltage, short duration pulse is applied to the diode, a high electric field (~ $10^7$-$10^8$ V/cm) is produced at the cathode due to micro projections on the cathode surface. Electrons are pulled out of the surface by field emission. The micro projections blow up due to high local current density leading to rapid resistive heating and vaporization of cathode material. The vapour is easily ionized resulting in the formation of high density plasma near the cathode called ‘cathode plasma’. This cathode plasma spread over the cathode surface and acts as a rich source of electrons. This is known as Explosive Field Emission.

![Streak picture of cathode and anode plasmas](image)

**FIG. 2.2** luminosity of anode and cathode plasmas for the AK gap length of 5 mm using an annular cathode of outer radius 1.5 cm, 1mm thickness and an aluminum (Al) foil anode of 15 μm in thickness (300 kV, 35 kA, 50 ns) [11].
FIG. 2.3 Expanding plasma boundaries in the diode region as a function of time. Expanding plasmas are observed by their luminosity as shown in the previous figure [11].

The electron beam heats the anode material and causes desorption from the anode surface. The desorbed gases are rapidly ionized by the electron beam and by avalanching of the secondary electrons. Thus creating plasma near the anode surface called “anode plasma”. In general, around 0.2 kJ/g of the energy density deposited to the anode is enough to generate anode plasma. The plasmas expand radially and axially (typical expansion velocity of the plasma ~ 2-4 cm/µs which is ion acoustic velocity [38]) filling the gap with enough plasma to ‘short’ the diode. No beam current can be drawn after shorting. Figure 2.2 and 2.3 shows the expanding plasma boundaries in the diode region as a function of time [11]. The side-view images of plasma movement within the diode for the bare carbon fiber cathode are shown in Fig. 2.4. Fig. 2.5 shows the light emission from the diode with the CsI-coated carbon fiber cathode [39].
FIG. 2.4 Side-view images of plasma movement within the diode for the bare carbon fiber cathode. The anode appears on the right and the cathode on the left. Images (a), (b) and (c) were, respectively, captured at ~100 ns, ~200 ns and ~300 ns after the beginning of the HV pulse. The initial AK gap was 50mm and the anode was a stainless steel disc [39].

FIG. 2.5 Light emission from the diode with the CsI-coated carbon fiber cathode. Images (a), (b) and (c) were captured at ~100 ns, ~200 ns and ~300 ns after the beginning of the HV pulse, respectively. The anode appears on the right and the cathode on the left. The AK gap was 50 mm. Note that the light intensity increased only slightly as the voltage increased [39].

The diode current density $j_e$ at time $t$ during the pulse and total current $I_e$ are given by the Child-Langmuir law [6, 47, and 48]. For a plane parallel diode consisting of a cylindrical cathode of radius ‘r’ and a anode-cathode gap ‘d’ the $j_e$ and $I_e$ are given by,

$$j_e = \frac{4e_n}{9} \left( \frac{2e}{m_e} \right)^{1/2} \frac{V_{3/2}}{(d-vt)^{3/2}} = 2.33 \times 10^{-6} \frac{V_{3/2}}{(d-vt)^{3/2}},$$  \hspace{1cm} (2.1)$$

and

$$I_e = j_e \pi r^2 = 2.33 \times 10^{-6} \frac{\pi r^2 V_{3/2}}{(d-vt)^{3/2}},$$  \hspace{1cm} (2.2)$$
where \( V \) is applied voltage, \( v \) is the plasma expansion velocity, \( t \) is the time during pulse at which \( j_e \) and \( I_e \) are measured; \( e \) and \( m_e \) are electron charge and mass. However, in Eq. (2.2) the radius of the emitting area of the cathode plasma assumes constant which is in not correct in major cases. In that case the radius \( r \) in Eq. (2.2) modifies as \( r = r_o + vt \), where \( r_o \) is the initial emission radius.

The diode impedance \( Z_d \) is given by,

\[
Z_d = \frac{V}{I_e} = \frac{136}{V^{\frac{1}{2}}} \left( \frac{d - vt}{r^2} \right)^2 \text{ (V in MV)} ,
\]

The perveance expression for the electron flow in the planner region of the diode can be defined by

\[
P = \frac{I_e}{V^{\frac{1}{2}}} = 2.33 \times 10^{-6} \frac{\pi r^2}{(d - vt)} .
\]

So the perveance is related to the effective diode geometry. If the electron flow remains unneutralized, the cathode emission area, the effective diode separation and the beam envelope are the only parameters which can affect the perveance. These interpretations are strictly valid only in the nonrelativistic limit. But the error associated will be small if the electron kinetic energy is less than 500 KeV [40].

The plasma expansion largely determined by the thermal and electrical properties of the cathode material (which determine the specific energy required to cause cathode flare formation) as indicated in Eq. (2.5), which has been found to give good agreement with experiment [41] if the resistivity is taken to be in the range 30–100 times its room temperature value.

\[
v = \sqrt{\frac{4j_{ke}}{\lambda_0 - 1}} E , \text{ where } E = \frac{j^2 I_e \kappa}{\pi^2 \rho}
\]
\[ \lambda_a \] adiabatic parameter, 1.24 [42] for a plasma (1.67 for atomic gas);

\[ \kappa \] resistivity;

\[ E \] thermal energy (per unit mass) heating the solid whisker;

\[ j \] emission current density;

\[ t_d \] transition time to explosion;

\[ \rho \] density of the cathode material.

Information about the velocity, creation time, and closure rate of the diode plasmas emerging from the electrode surfaces has been measured by streak cameras [11] and by detail analysis of the diode perveance and impedance variations with time [40]. Fig. 2.6 illustrates plasma expansion velocity calculated from the temporal behavior of the diode perveance [40]. Double-exposure interference holography has been used to measure the temporal and spatial dependence of plasma densities and velocities in IREB diodes [43]. The exposure variation of the fringe pattern and motion of plasmas between pictures taken at different times during the pulse have indicated plasma velocities vs spatial position that varies from \(10^6\) to \(10^7\) cm/sec [43]. In the near-UV range the plasma expansion speed in vacuum IREB diode has also been measured by the Doppler-shift and by the time-of-flight methods [38]. The maximum observed speed of \(2.4 \times 10^7\) cm/sec for the \(C^{+3}\) ions lead to the estimation of the electric field probably in the range of 1-6 kV/cm.

Maenchen et. al. [44] using interferometry, observed velocities of up to 30 cm/\(\mu\)s 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) Johnson et al. [45] have reported that an expansion velocity of 5 to 10 cm/\(\mu\)s throughout the voltage pulse was required for their surface-flashover anode plasma in order to explain the temporal impedance decrease. In higher power diodes the
higher plasma-pressure gradient may result in a fast plasma expansion [46]. Expansion velocities of 5 cm/μs correspond to the ion thermal velocity of 25-eV protons.

FIG. 2.6 Plasma expansion velocity calculated from diode perveance. A best fit was obtained when the plasma velocity was set equal to 2.8 cm/μs [40].

2.2 MULTIDIMENSIONAL SPACE-CHARGE LIMITED FLOW

Space-charge-limited (SCL) flows in diodes have been an area of active research since the pioneering work of Child and Langmuir [47, 48] in the early part of the last century. Indeed, the scaling of current density with the voltage to the 3/2’s power is one of the best-known limits in the fields of nonneutral plasma physics, accelerator physics, sheath physics, vacuum electronics, and high power microwaves. The physics of SCL flows and emission appear throughout the literature of plasma physics. These theories, however, focus typically on SCL
flows in one-dimension only. Recently lot of studies has been carried out to extend the classical Child-Langmuir law to finite dimension [49].

Recent particle-in-cell (PIC) Calculations [50] have shown that for a spatially constant current density strip the true limiting current can exceed the one dimensional limiting current by a significant degree. These calculations used an emission method called “overinjection.” A current density, that is constant over the entire strip $w$, is emitted into the diode. This current density $J$ is progressively increased until a virtual cathode is observed. In other words, the calculations are repeated until the greatest current is found that allows the beam to propagate without reflected particles. This current is then interpreted as the limiting current as it satisfies the original expectations of Child and Langmuir, namely the largest current with laminar, steady-state flow. This case have relevance to various physical emission mechanisms, such as thermionic and photoemission, where the maximum emitted current density is specified by conditions other than the applied voltage (i.e., when not running completely space charge limited).

The enhancement in constant current density that can be injected over a finite strip on the cathode without virtual cathode formation can be synthesized from the PIC data in the following empirical scaling law: [50]

$$\frac{J_{CL}(2-D)}{J_{CL}(1-D)} = 1 + 0.3145 \frac{w}{d} + 0.0004 \left(\frac{w}{d}\right)^2,$$

for $w/d$ as small as 0.1. Equation (2.6) clearly recovers the Child–Langmuir result in the one-dimensional limit as $w/d$ goes to infinity. Lau recently derived a similar result from first principles for the case of $w/d$ on the order of one or greater where the last term in Eq. (2.6) is negligible [51]. For a planar strip, he found $J_{CL}(2-D)/J_{CL}(1-D) = 1 + (d/\pi w)$. The agreement
with Eq. (2.6) is excellent. Furthermore, he extended the theory to describe other geometries, the most important being a circular patch of radius $R$. In this case, the scaling becomes $J_{CL}(2-D)/J_{CL}(1-D) = 1 + (d/4R)$. PIC calculations similar to Ref. 50 verified this scaling for $R/d$ on the order of one and greater. Equation (2.6) and the analytic results presented herein give valuable rules of thumb for the onset of virtual cathode formation in two-dimensional flows.

PIC calculations are carried out to find out the current and the current density of a finite-width, space-charge-limited electron beam in two-dimensional, parallel-plate geometry [32]. The results obtained show that the total current follows a universal function of the dimensionless parameter $w/d$ that can be described empirically as

$$I = 1 + \frac{0.23033 - 0.00665}{w/d} \cdot \left(\frac{w}{d}\right)^2. \quad (2.7)$$

![Figure 2.7](image)

**FIG. 2.7** Variation of the diode perveance $P$ normalized to Child–Langmuir values $P_{CL}$ with the dimensionless geometrical parameter $d_a/R_e$. Data obtained with 20 (open circles), 60 (full circles), and 100 mm (triangles) diameter velvet explosive emission cathodes are shown. The fitting curve (solid line 1) is calculated in accordance with Eq. (2) in Ref. 36. The dashed line 2 is a result of a PIC modeling of the finite width, infinite length diode (See Ref. 32). The dotted curve 3 is calculated from Eq. (2.7).
At present, there is no analytical theory for the most commonly used planar diodes with circular cathodes that would allow determination of perveance $P$ at arbitrary AK gap $d_{ak}$ and cathode radius $R_k$. An experimental investigation of the explosive emission planar diodes with $R_k$ comparable to $d_{ak}$ therefore becomes important for the analysis of experimental data and for validation of theoretical models. The dependence of $P/P_{CL}$ on $d_{ak}/R_k$ that combines all of the experimental data obtained with 20, 60, and 100 mm-diameter velvet cathodes is shown in Fig. 2.7. A good matching of the simulation curve Eq. 2.7 with experimental data could be obtained in the relation [36]

$$\frac{P}{P_{CL}} = a \left[ a_{i} + b_{i} \left( \frac{d_{ak}}{R_i} \right) + c_{i} k \left( \frac{d_{ak}}{R_i} \right)^2 \right], \quad (2.8)$$

where $a = 0.75$ as above, and $k = 7.2$ (see curve 3 in Fig. 2.7). While the coefficient $a_o$ takes account of the initial nonuniformity of the cathode emission, the coefficient $k$ allows the 2D simulation results to be applied to the 3D diode configurations.

![FIG. 2.8 Geometry and relevant parameters for the baseline 2D emission simulation [33.]](image)
Figure 2.9 shows the current density emitted at the cathode surface (normalized to the analytic 1D Child-Langmuir value) as a function of position along the cathode (normalized to AK gap distance) for a sampling of emission strip widths (W) and gap distances (D) [33]. FIG. 2.8 displays the geometry and relevant parameters for the baseline 2D emission simulation [33].

At the beam edge of a flat cathode, there exists no space charge just outside the beam in order to help drive the normal electric field at the last emission point to zero; thus, one can posit that extra space charge is emitted (above the 1D Child-Langmuir limit) in order to help drive this local field down. From the scans it is apparent that these high current density “wings” at the beam edge scale with the emission strip width divided by gap distance, W/D (i.e., scans with the same W/D value overlay on the graph). In addition, as the emission strip narrows (W/D ≤ 1), even the current density at the center of the beam begins to rise above the analytic 1D predicted value. (Such W/D scaling was previously seen by Luginsland et al. [50] when simulating uniform current density transported in a comparable 2D geometry. Emitted current
density wing structure is independent of applied magnetic field, $B_y$, for tested values of 0, 0.05, 0.1, 0.5, and 0.8 T.

To examine how these increased current density wings might affect total current, emission from some portion of the cathode has been suppressed in two different fashions and changes in the total current has been monitored. In the first method, the baseline 4-cm-wide emission region has been divided into 40 separate, equal-width subregions. As the portion of each subregion that is allowed to emit systematically decreased, little effect is seen on the total current emitted until nearly all of the cathode emission area has been turned off. This behavior is shown in the upper trace of Fig. 2.10.

![Active Emission Area Effect on Total Current](image)

FIG. 2.10 Reduction of total emitted current due to the reduction of an allowed emission area on a 4-cm-wide cathode strip. The current is normalized to the simulation result for emission from 100% of the cathode area. The cathode is divided into 40 individual sections which are gradually turned off (discrete patches), or a sole nonemitting hole is allowed to expand from the cathode center (central hole) [33].

Almost 80% of the full emission area current can be supplied by a mere 20% of emitting cathode area due to the ability of the enhanced current density wings to compensate for the paucity of emission area. In the second method, this effect was further examined by suppressing emission from only a central portion of the cathode. The nonemitting portion was
gradually increased in size as the total current was monitored (also shown in Fig. 2.10). From the figure it is clear that the 2 sets of wings present at the two edges of the nonemitting portion cannot compensate for the nonemitting area nearly as well as the 40 sets of wings available in the discrete patches case. Such an effect has direct relevance to understanding space-charge-limited emission from explosive emission cathodes, plasma cathodes, ferroelectric cathodes, photocathodes, and even thermionic cathodes (if operating well above the temperature limited regime). Ferroelectric emission is electron emission from the plasma formed at the surface of ferroelectric as a result of non-complete surface discharges [33a]. *Many small portions of the emission surface may be completely inactive before a significant change is detected in the observed total current.* In a plasma-based cathode (including explosive or ferroelectric emission) such an effect may be masked due to plasma filling in the gaps between emission sites. Nevertheless, as these cathodes are driven into regimes where the plasma is cooler and less dense, the total current emitted is not expected to change even if the plasma no longer completely fills the gaps between emission sites. This effect must be taken into account when developing an understanding of a plausible death mechanism for such cathodes. If a sole region ceases to emit and then continues to enlarge in area, one would expect to see a nearly linear reduction in the total current. If the emission is instead being provided by numerous microsites, many such sites could be turning off and on multiple times during the life of a given cathode with little or no effect on the observed total current.

It was found experimentally 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 [34]. Three cathodes are reported, each cathode has a corona bushing surrounding the emitting surface. The inner
diameter of the bushing is 14.9 cm, and the width of the bushing annulus is 2.8 cm and the axial thickness of the bushing is 2.54 cm. The bushing has a full radius in the axial dimension. The bushings for these short pulse lengths are aluminum which has been painted with Glyptol paint.

Therefore, the electron emission in high-current diode almost always occurs from the plasma boundary according to the space charge law. The currents which are obtained "above" space-charge law is simple due to edge effect, i.e., non validity of ID approximation and, respectively, larger current of electrons is required to screen enhanced electric field.

FIG. 2.11 Optical images showing the electron beam uniformity for each cathode: (a) the velvet cathode, (b) the tufted carbon fiber cesium iodide cathode, and (c) the carbon slat cathode. Note that the slatted cathode has very nonuniform emission, although the current wave form for it is nearly identical to the two cases of more uniform emission.
The significant feature of these results is that while the emission area can vary considerably between three cathodes, the current amplitude can be the same and nearly indistinguishable merely by measuring the total current (Shown in Figs. 2.11 and 2.12). This result is consistent with theoretical results described above, which indicate that edge effects play a significant role in the emission process [33]. In particular, the field enhancement at the edges where there is no emission offsets the lack of emission in other regions of the cathode. Therefore, it is not necessary to conjecture extensive plasma formation on the cathode surface to achieve space charge limited flow. Further, it is notable that merely measuring the current wave form may not be sufficient to estimate emission uniformity.

![Current and voltage traces from the experiment: (a) applied diode voltage, (b) current traces for the three cathodes. A is the velvet cathode, B is the tufted carbon fiber cesium iodide cathode, and C is the carbon slat cathode. Note the similarity in the current wave forms for the same applied voltage.](image)
2.3 PLASMA-FILLED DIODE

In plasma filled diode (PFD) the injected plasma initially causes the vacuum diode to behave like a short circuit. As the diode current increases, some combination of magnetohydrodynamics (MHD) effects, plasma thinning, and plasma erosion cause the diode impedance to increase [24]. If the initial plasma density is low, the diode can increase to its vacuum impedance. If the initial plasma density is high, a small effective AK gap can form that allows the diode to operate at much lower impedance than possible with the initial vacuum.
A typical diode current and diode voltage drop obtained from Particle in Cell simulation for case with spatially uniform plasma density $n = 10^{13} \text{ cm}^{-3}$ hydrogen plasma fill and SCL electron emission from cathode surface is shown in Fig. 2.13 [24].

The high voltage opening phase of a PFD with an emitting cathode can be described by the following arguments. When a high voltage is applied at the anode cathode gap containing low density plasma a collisionless sheath form over the cathode [24, 21]. At low currents flow is one dimensional and the behavior can be explained by a one dimensional model. Electron emission occurs from the high density cathode plasma via field emission and whisker-explosion mechanisms as discussed in the previous section.

FIG. 2.14 PFD configuration tested on Gamble II. Dashed lines indicate current flow direction [25].

The electrons in the plasma are initially repelled by the large negative potential of the cathode to some well defined distance, producing a transient sheath [52]. This occurs before the ions have time to respond to the applied potential. The bare ions, exposed in the transient sheath, are accelerated by the potential and rapidly absorbed at the cathode. The ion current then quickly becomes space charge limited. If the pulse duration is short enough compared to the reciprocal of the ion plasma frequency then a steady-state sheath will not form. Let us assume that our pulse duration is short and a sheath of thickness $x$ exists between the cathode plasma
at voltage $-V$ and the field free bulk plasma. Across this sheath flow space charge limited ion and electron currents given by [21]

FIG. 2.15 Data from the highest dose-rate PFD shot on Gamble II (solid lines), compared with data from a shot with no plasma (dashed lines). (a) Generator current waveforms. (b) Diode voltage waveforms. (c) Diode impedance waveforms. (d) X-ray (dose rate) signals. The vertical line indicates the time of maximum X-ray signal for the PFD shot [25].

$$j_i = 1.86 \left( \frac{4 \epsilon_0}{9} \right)^{1/2} \frac{2e}{m_i} \frac{V^{3/2}}{x^2}, \quad (2.9)$$

$$j_e = \left( \frac{m_i}{m_e} \right)^{1/2} j_i, \quad (2.10)$$

where $m_i$ and $m_e$ are the ion and electron masses, $e$ is the electron charge, $\epsilon_0$ is the vacuum permittivity.

If the ion current is much greater than the saturation current

$$j_i \sim n \left( \frac{kT_e}{m_i} \right)^{1/2},$$

where $n$ is the plasma density.
Then the sheath boundary must move into the plasma to provide ion flux given by

$$j = ne \frac{dx}{dt}.$$  \hspace{1cm} (2.11)

But the short circuit phase of the PFD cannot be explained by the above argument [24]. Plasma-filled diodes have been employed for producing high dose-rate bremsstrahlung over small areas [25]. Fig. 2.14 shows PFD configuration tested on Gamble II pulse power generator. Fig. 2.15 displays the data from the highest dose-rate PFD shot on Gamble II (solid lines), compared with data from a shot with no plasma (dashed lines) [25]. Prepulse generated plasma can completely fill the diode gap if the anode cathode gap is small and the diode behaves as a PFD. PFD operation is very similar to plasma opening switch which was extensively investigated in many laboratories [25a].

## 2.4 EFFECT OF PREPULSE ON INTENSE RELATIVISTIC ELECTRON BEAM GENERATION

Beam generation studies were carried out in Sandia National Laboratories, U.S.A, with HERMES I (MV, kA, 100 ns) pulse power system in the presence of prepulse [53]. Figure 2.16 shows modelled Marx-Blumlein charging voltage and raw prepulse voltage on the Blumlein inner conductor, for a peak operating voltage of 1.7MV on PIM machine at AWE, UK[54]. The erratic tube behavior was characterized by low impedance and unrepeatable spatial distribution of the electron stream. It was hypothesized that the prepulse voltage causes plasmas to form inside the tube. These plasmas then act as electron sources during the main pulse. Thus, the apparent geometrical shape of the cathode was not the electron emitting shape during the main pulse.

An experiment was conducted to determine the approximate voltage level at which the plasma formation occurs by simulating the prepulse voltage across a tube structure. A Marx generator
A device capable of generating 500 kV, 300 ns pulse was assembled and operated across the HERMES I X-ray tube. During the experiment the time coincidence between the voltage trace and the plasma glow was verified by a streak camera. A typical AK gap of approximately three inches was used for these experiments. A summary of data is given in Table. I

TABLE I. Voltage levels at onset of prepulse plasmas for various cathodes.

<table>
<thead>
<tr>
<th>Cathode Type</th>
<th>AK Gap</th>
<th>Tube Pressure</th>
<th>Average Breakdown</th>
<th>$t_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(in.)</td>
<td>(Torr) x 10^4</td>
<td>(B.D) Voltage (kV)</td>
<td>(ns)</td>
</tr>
<tr>
<td>Single Sharp Needle</td>
<td>2-3/4</td>
<td>3.5</td>
<td>180</td>
<td>300</td>
</tr>
<tr>
<td>Multipoint</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sharp Needles</td>
<td>3</td>
<td>3.6</td>
<td>180</td>
<td>300</td>
</tr>
<tr>
<td>Blunted</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Needle</td>
<td>3</td>
<td>4</td>
<td>250</td>
<td>300</td>
</tr>
<tr>
<td>Round Lucite Insert</td>
<td>3</td>
<td>2.3-2.5</td>
<td>170</td>
<td>400</td>
</tr>
<tr>
<td>Long Lucite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cathode</td>
<td>2-3/4</td>
<td>10</td>
<td>No B.D at 455 kV</td>
<td>&gt; 2 $\mu$s</td>
</tr>
<tr>
<td>Hemisphere End</td>
<td>2-3/4</td>
<td>2.8</td>
<td>No B.D at 460 kV</td>
<td>&gt; 2 $\mu$s</td>
</tr>
</tbody>
</table>

The conclusions from these tests were:

1. Considerable ionization can occur in the AK gap which distorts the apparent electron emitting shape of the cathode.
2. There exists at least a factor of three in the breakdown voltage between sharp pointed and smooth blunt cathodes.

3. Short blunt Lucite cathodes ionize at levels similar to sharp pointed metal rods.

4. Only a negative pulse was used on these experiments. The prepulse actually alternates polarity and lower breakdown voltages probably occur during actual machine operation.

In subsequent experiments, a simple Hemispherical tipped or blunt cathode has been utilized to minimize plasma formations.

![FIG. 2.16 Modelled (a) Marx-Blumlein charging voltage and (b) raw prepulse voltage on the Blumlein inner conductor, for a peak operating voltage of 1.7MV on PIM machine [54].](image)

Another experiment has been carried out by D. A. Phelps et. al. [55] at Maxwell Laboratories, San Diego, California, U.S.A, to control impedance of the relativistic electron diodes with externally applied prepulse. In this paper, a technique for externally introducing a typically 100 kV, low power conditioning pulse prior to the main pulse of a low impedance relativistic electron diode is described. The typical electron beam parameter was 1 MV, 1 MA, 50 ns. For various cathode geometries, the breakdown field, closure velocity, and time-dependent
impedance established by this external prepulse is measured and compared with an empirical model of space charge limited emission from a hydro-dynamically expanding plasma. The best results were obtained with one and four ring razor blade cathodes which produced very symmetric emission for over 100 kV/cm stresses. The prepulse impedance collapses with a roughly 2.3 cm/μs closure velocity, producing a 15 Ω -25 kV diode just prior to the main pulse. After about 25 ns of the main pulse, Child's Law scaling predicts an 2 Ω impedance which is consistent with the data. Noticeably, the main pulse impedance collapses a little faster (about 4 cm/μs, probably due to the creation of anode plasma by the high current density). Experimental evidence is presented that the high current accelerator impedance is effectively controlled by the relative time delay between the start of the prepulse and the main pulse. The reason for this impedance control lies in the fundamental emission efficiency, plasma closure velocity and approach to space charge limited emission of a given diode geometry in the presence of sufficient prepulse electric field. In addition to determining the proper pre-shot timing, this external prepulse is useful for checking the diode gap setting (since the closure velocity is repeatable to with 5 % if the emission efficiency is good); for checking the diode pressure near the cathode (i.e., the presence of local outgasing, that could ruin a. shot, usually shows up as premature flashover of the prepulse insulator); and finally, for removing surface contaminants from the primary cathode-anode regions (the first few prepulse firings normally exhibit earlier gap closure then the quite repeatable subsequent shots-evidently due to the removal of volatile impurities).

Effect of prepulse has also been observed on ASTERIX [56] high voltage (6 to 7 MV), ~ 60 Ω, 50 ns pulse generator at Centre d’Etudes de Gramat (CEG) in Gramat, France. With 4 MV on the diode, a positive prepulse of 365 kV peak voltage > 100 ns duration was predicted. The
peak occurred about 250 ns before the main pulse and generated an electric field on the cathode four times greater than the 100 kV/cm normally required to initiate plasma formation on the cathode surface. When operated without a prepulse switch the current oscillated between +500 to -1000 A starting about 500 ns before the main pulse. The diode impedance was near zero at the start of the main pulse and only increased to a peak of about 20 Ω during the pulse. This behavior was consistent with a plasma filled diode [24], the result of the prepulse current. The prepulse in the ASTERIX Rod-Pinch Diode Experiments has been minimized by a vacuum prepulse switch [56].

So there are some reports available on effect of prepulse on electron beam diode but those are done either by simulating the prepulse voltage across a diode structure [53] or by externally applied prepulse voltage [55]. Also many literatures are available on prepulse suppression by various techniques [16]. There are no reports available on systematic study of intense electron beam generation in the presence of prepulse.

2.5 ELECTRON BEAM QUALITY AND UNIFORMITY
Quality and uniformity of the electron beam is an important factor in context to its usefulness in high power microwave generation [2, 29]. Experimental results show that the carbon fiber cathode can improve the electron beam quality and dramatically enhance the beam-to-microwave efficiency of the reflex triode vircator [2]. It was found that the beam-to-microwave efficiency increased from about 4%–6% in the case of the stainless steel cathode to over 10% in the case of the carbon fiber cathode. Experimental results indicate that the plasma forming on the carbon fiber cathode is more uniform as a result of the surface flashover discharge along the whole surface of the carbon fiber. But, the electron emission of the metal cathode is confined to the tips of the emitters on the cathode, which obviously differs from the electron emission mechanism of the carbon fiber cathode. In addition, the slower plasma expansion velocity was achieved with the cathode made with carbon fibers, and the electron beam extracted from the carbon fiber cathode has a higher quality than the case of the stainless steel cathode [2]. Fig. 2.17 (a) shows needle-shaped annular carbon fiber cathode. Fig. 2.17 (b) displays the photo of nylon target bombarded once by beam emitted by a stainless steel
cathode and the Fig. 2.17 (c) shows the photo of nylon target bombarded once by beam emitted by a needle-shaped annular carbon fiber cathode [2].

Several key factors must be present to achieve a low-emittance electron beam, not the least of which is a uniform electric field across the emitting surface of the cathode [57]. Cathodes that emit nonuniformly have large nonuniformities in the electron space charge, independent of the emission mechanism. Hence, the radial-electric field across the cathode surface is also nonuniform, as required by the boundary conditions between regions of high and low space charge. Cathodes with poor uniformity develop large radial-electric fields at the emission surface. These electric fields impart transverse momentum to the electrons as they accelerate toward the anode, increasing the emittance. It was shown that, the cathodes with the lowest turn-on field for emission exhibited the best uniformity and the lowest emittance [29]. The cesium iodide (CsI) coated carbon fiber cathode is compared to polymer velvet, metal-dielectric, and carbon-slat cathodes. However, most of the cathodes typically suffers from large amounts of outgassing, nonuniform emission, and very high emittance.

FIG. 2.18 (a) Macroscopic photograph and (b) SEM image of the CsI carbon fiber cathode. The cathode consists of carbon fibers that have been attached to a carbon surface. These fibers are then coated with a CsI salt. The SEM is at 50-times magnification with the fibers of 6-μm diameters [59].
The CsI-coated carbon fiber consistently shows the best emission uniformity of all four cathode types [29]. It was shown that, the uniformity and emittance are related for all of these cathodes. In general, the more uniform the electron emission, the lower the emittance of the cathode. The CsI coating makes a significant improvement over the uncoated cathodes. Cesium iodide serves to eliminate impedance collapse, as well as to reduce the turn-on field and greatly reduce the neutral outgassing. Furthermore, the CsI coating eliminates flaring on the cathode surface, thus improving the uniformity of the emission. The reduction of nonuniformities acts to reduce the normalized emittance for the cathodes [58]. Figure 2.18 shows macroscopic photograph and SEM image of the CsI carbon fiber cathode. The cathode consists of carbon fibers that have been attached to a carbon surface. These fibers are then coated with a CsI salt. The SEM is at 50-times magnification with the fibers of 6-μm diameters [59].

The main advantages of the carbon-fiber cathode are its nanosecond timescale turn-on, relatively good vacuum compatibility, long lifetime, and the unnecessity of an additional power supply for its ignition. However, in spite of the intensive experimental research carried out by different groups, the nature of the electron emission (either field emission or plasma emission) has still remained unclear [59a, 59b, 59c]. The same concern is related to the influence of CsI coating on the carbon-fiber cathode operation. For instance, in the recent review by Shiffler et al., [59] both emission phenomena are used to characterize the operation of the CsI coated carbon-fiber cathode.
FIG. 2.19 AFRL relativistic magnetron normalized average (rms) RF power waveforms for the cases of POCO graphite, CsI-coated carbon velvet on a graphite substrate (conventional processing), and uncoated low-hydrogen carbon velvet on a graphite substrate (high-temperature processing) cathodes [59].

FIG. 2.20 Uniformity data from an uncoated (a) and a CsI coated (b) carbon-on-epoxy cathode. Regions of intense are red and regions of low emission are blue. The uncoated cathode shows flaring, or nonuniform emission [58].
Figure 2.19 shows AFRL relativistic magnetron normalized average (rms) RF power waveforms for the cases of POCO graphite, CsI-coated carbon velvet on a graphite substrate (conventional processing), and uncoated low-hydrogen carbon velvet on a graphite substrate (high-temperature processing) cathodes [59].

Several research have been performed on carbon fiber cathodes [60]–[63]. These cathodes have consisted of either bare carbon fiber or carbon fiber with a coating of cesium iodide (CsI) [64]–[66]. CsI not only is well known as an emitter of ultraviolet (UV) radiation when stimulated properly, but also has the advantage that the cesium has a very low first ionization potential of 3.89 eV [67]–[70]. Carbon fiber has the advantage of low outgassing, which keeps the gas evolution and thus plasma formation in the diode to a minimum [39, 71]–[73]. The addition of the CsI and its subsequent UV emission and low ionization potential contributes to the photoemission and field emission of electrons early in the diode voltage pulse. These emitted electrons allow the diode to turn on quickly and uniformly, presumably limiting the effects of explosive emission and plasma formation in the diode. Thus, CsI-coated carbon fiber cathodes would appear to have many good characteristics as electron emitters for long pulse cathodes [66, 74]. Figure 2.20 displays uniformity data from an uncoated and a CsI coated carbon-on-epoxy cathode. Regions of intense are red and regions of low emission are blue. The uncoated cathode shows flaring, or nonuniform emission [58]. However it is still doubtful that UV emission influences on plasma formation and electron emission [59a]. Coating by CsI simply allows one to achieve more uniform flashover surface plasma formation and heavy Cs and I ions make this plasma expansion slower [59a].

Figure 2.21 displays false-color images of the cathode plasma generated by explosive emission processes in a vircator high-power microwave source (300 kV, 5-8 kA, 60 ns). Three different
cathode materials are shown [75]. The images show the plasma formation to be fairly uniform across the surface of all three cathode types.

![False-color images of the cathode plasma generated by explosive emission processes in a vircator high-power microwave source (300 kV, 5-8 kA, 60 ns). Three different cathode materials are shown. The camera intensifier gate width was 200 ns. Each cathode was attached to a brass plate which is located at the top of each image. The anode structure is seen at the bottom of each image. The spacing between the anode and cathode was 10 mm. The images show the plasma formation to be fairly uniform across the surface of all three cathode types. The light emission from the brass attachment plate in the milled aluminum cathode case indicates that differences in either the delay time or peak voltage required for emission for this particular cathode design allowed points on the brass to explosively emit [75].](image)

Spatial uniformity of electron emission from velvet cathodes has been measured by observing the distribution of electrons hitting the anode in a planar high-voltage diode [76]. It is shown that unless all electrons move parallel to the diode axis, the electron distribution measured at the anode does not represent the cathode emission pattern. Here, parallel trajectories were achieved by applying a strong, uniform axial magnetic field. A 5 ns gated ICCD camera recorded light from a fast anode scintillator. The emission from two brands of velvet was found to be mostly concentrated in small spots with density of about 55/cm². The pixel-to-pixel standard deviation of the emission amounted to at least 16%. Figure 2.22 shows images of the anode scintillator with magnetic field and without magnetic field.
FIG. 2.22 Images of the anode scintillator: (a) with magnetic field; (b) without magnetic field. Line profiles shown were taken along horizontal diameters [76].

2.6 THE SHOT TO SHOT REPRODUCIBILITY OF THE ELECTRON BEAM DIODE

FIG. 2.23 Histogram showing the variation in current for a carbon velvet, cesium-iodide-coated cathode. Other cathode produces similar results with variation in standard deviation and skewness [31].
The shot to shot reproducibility of the intense electron beam diode is an important property both for single shot or repetitive operation [60]. Good shot-to-shot reproducibility is a requirement for many environments. In fact, there is a statistical correlation between emission uniformity and the shot-to-shot variation in diode current [31]. The current waveforms can provide some assessment of cathode emission uniformity if the data is of a statistical nature taken over thousands of shots rather than examining single shot waveform shapes. Comparing to the data in [34], one finds that the standard deviation and skewness of the current histograms increase as the cathode emission becomes less uniform. As the emission uniformity decreases, the variability of the current increases significantly. Perhaps this appears obvious; however, the demonstration in a controlled simulation environment strengthens the conjecture that shot-to-shot variability can provide a viable surrogate for emission uniformity. The shot to shot variation in current is because of the fact that the nonemission areas vary randomly on a shot-to-shot basis [31]. As these areas vary randomly, cathode emission comes from a combination of small patches and larger, relatively uniform segments, resulting in significant variability in the measured current.

TABLE II Statistical data for the shot to shot variation in the diode current.

<table>
<thead>
<tr>
<th>Cathode Type</th>
<th>Standard Deviation</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Slat</td>
<td>200</td>
<td>-0.72</td>
</tr>
<tr>
<td>Polymer Velvet</td>
<td>120</td>
<td>0.137</td>
</tr>
<tr>
<td>Tufted Cesium Iodide Coated</td>
<td>60</td>
<td>0.06</td>
</tr>
<tr>
<td>Carbon Fiber</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cesium Iodide Coated Carbon Velvet</td>
<td>12</td>
<td>0.015</td>
</tr>
</tbody>
</table>
The shot to shot variation of cathodes consist of a carbon slat cathode, polymer velvet cathode, a tufted carbon fiber cathode with the individual fibers bundles coated with cesium iodide (CsI) salt have been studied. The histogram showing the variation in current closely resembles a Gaussian, with a slight skewness to the curve as shown in Fig. 2.23. Statistical data shows that the slat cathode being the least uniform and the cesium-iodide-coated carbon velvet being the most uniform [31]. Statistical data for four different types of cathodes are summarized in Table II. But the shot to shot variation in the diode perveance has not been studied so far. The shot to shot variation in the diode voltage and current due to the prepulse generated plasma has also not been studied so far.

2.7 HPM GENERATION FROM VIRTUAL CATHODE OSCILLATOR USING IREB

It was known that, in planar gaps with self-consistent account for space charge under certain conditions, a so-called virtual cathode (VC) forms [6]. Figure 2.24 shows axial virtual cathode oscillator. For a long time this phenomenon was not applied in practice. During the 1970s the situation changed when high-current relativistic electron beam technology reached the level which provided $10^4$-$10^6$ A beams at 0.1-10 MeV acceleration energy quite easily. Then, certain proposals emerged for employing VC-based devices in various technical applications (for example, ultra-short-pulse current generation with VC discharges [77] and ion collective acceleration with a moving VC [78]).

However, the most important VC-based device application is the generation of super-powerful microwave pulses. This idea was first published by Kapetanakos et. al., who suggested one version of such a device-the reflex triode [79]; later, Sullivan proposed another microwave device based on the VC-the Vircator [80].
The merits of VC-based microwave devices include simple design and device control with an external microwave signal. Moreover, VC-based microwave devices are one of the high power devices which can operate without external magnetic fields, making them competitive with other classes of microwave devices, especially for repetitive pulse radiation sources. Figure 2.25 shows an axial vircator with HPM diagnostics [81].

In a virtual cathode device, there are two possible sources of microwave radiation; one from electrons oscillating between the real cathode and virtual cathode and the other from the oscillating electron cloud or virtual cathode [82].
The electron reflection frequency \( f \) is given by \( f = 1/4T \), where \( T \) is the transit time of electrons to move back and forth between the cathode and anode. The transit time is given by \( T = \int_0^\infty (dz/\nu) \), where \( \nu \) is electron velocity, and \( d \) is the distance between the anode and cathode. The oscillation frequency, \( f_v \), for the virtual cathode ranges from \( \omega_p/2\pi \) to \( 5\omega_p/4\pi \), where \( \omega_p \) is the electron beam plasma frequency [77] defined by \( \omega_p = \sqrt{n e^2/m \varepsilon_0} \). Here, \( n \) is electron density, \( -e \) is electronic charge, \( m \) is electron mass, \( \varepsilon_0 \) is vacuum permittivity, and \( \gamma \) is relativistic energy factor.

The vircator’s have been studied extensively by various authors both theoretically [83] and experimentally [84, 81, 85]. Much of the research in recent years has been focused on increasing the efficiency of microwave generation [2]. Many experimental studies have been carried out on the vircator in order to improve its beam-wave energy conversion efficiency. Despite these efforts, the highest efficiency is still limited to several percent. To improve the vircator efficiency various cathode materials have been investigated [2, 86]. It was found that the beam-to-microwave efficiency increased from about 4%–6% in the case of the stainless steel cathode to over 10% in the case of the carbon fiber cathode [2]. Figure 2.26 shows Vircator microwave power and frequency versus various initial AK gap distances \( d \) [81]. Double gap vircator also has superior parameters as compared with commonly used vircators [81a]. Figure 2.27 shows microwave signal and time-varying effective AK gap distance \( d_{\text{eff}} \) along with the diode voltage \( V_d \) and diode current \( I_d \) under initial AK gaps 2 mm and 5 mm, respectively [81].
FIG. 2.26 (a) Vircator microwave power and (b) frequency versus various initial AK gap distances $d$ [81].

One method used to increase microwave output involves tuning the cavity in which the vircator is housed [86]. Reflecting strips are placed downstream of the microwave output which reflects a portion of the microwaves back toward the virtual cathode. The oscillations of the vircator are then improved by the upstream traveling waves. This method has been used successfully in the past on the reflex triode and cylindrical vircators [37]. Several different cathodes and anodes have been tested with different diagnostics. It has been shown that the metal and carbon fiber cathodes have uniform current emission in both time and space. The carbon fiber and the aluminum etched cathode both recorded higher peak microwave power then the velvet with no signs of degradation over the lifetime test. A Tantalum anode constructed with a honeycomb hole pattern has been tested to provide similar results with the original stainless steel weave meshes at a greater lifetime potential. It has also been shown the anode transparency has a significant effect on peak microwave power. Reflector tests have also shown some success in amplifying the peak microwave power [86].
FIG. 2.27 Microwave signal and time-varying effective AK gap distance $d_{\text{eff}}$ along with the diode voltage $V_d$ and diode current $I_d$ under initial AK gaps $d$ are (a) 2 mm and (b) 5 mm, respectively [81].

2.8 CYLINDRICAL ELECTRON BEAM DIODE AND COAXIAL VIRTUAL CATHODE OSCILLATOR

High Power Cylindrical diodes have been employed for intense relativistic electron beam generation in coaxial virtual cathode oscillator [Fig. 2.28] (Vircators) [37] and in high resolution radiography sources [4]. In fact, the coaxial vircator presents a cylindrical diode which consists of an annular cathode and grounded mesh anode [87]. Figure 2.29 shows a coaxial Vircator with HPM diagnostics [88].

![Coaxial virtual cathode oscillator](image)

Fig. 2.28 Coaxial virtual cathode oscillator.

In the vircator device an electron beam is accelerated in the diode gap where pulsed high voltage is applied between the anode and the cathode. The beam passes through the anode,
which is usually a thin foil or a mesh, and is injected into the area on the other side of the anode. When the beam current is higher than the space-charge-limited current of this area, a virtual cathode is formed at a certain position that reflects a certain part of the electron beam. The position of the virtual cathode and the ratio of beam reflection depend very much on the electron energy.

Therefore, if the electron energy is modulated at a given frequency, both the virtual cathode position and reflected beam current will oscillate at the same frequency. The electron energy can be modulated by an electromagnetic field and the same field may interact with the modulated reflection current because they have the same frequency. In this interaction, if the phase relation is such that the electromagnetic field obtains energy from the modulated current, the result will be field amplification by the virtual cathode oscillation [89]. It is obvious that the amplitude of the beam current modulation and the strength of the electromagnetic field are very important to the beam-field interaction. The interaction is between the electron beam...
current and the radial electric field of the waveguide mode. Compared with the axial vircator, the coaxial vircator is expected to have the following advantages.

1) Due to the absence of the end wall of the waveguide, the electromagnetic field may also exist in the diode area and give rise to stronger beam modulation than that which only exists in the waveguide. In other words, the interaction area is extended from the waveguide to include the diode area.

2) The electron movement is only in the radial direction which eliminates the loss carried by the transmitted electron beam (through the virtual cathode) in the axial vircator. In addition, any modification of the waveguide configuration close to the vircator would not affect the electron beam behavior, in contrast with inevitable variation of the space-charge limited current in the axial vircator. The modification of the waveguide configuration can be planned in order to increase the feedback of the electromagnetic wave to the vircator.

3) Due to the large area of the diode gap, the current density is significantly reduced compared with the axial vircator. As a result, the damage on both the cathode and the anode is decreased,

FIG. 2.30 Typical oscilloscope traces of the diode voltage, current, and microwave [37].
allowing longer lifetime of the electron beam diode, which is especially important for repetitive operation.

For these advantages coaxial vircator has been studied extensively by various authors both theoretically [90, 91] and experimentally [37, 92-93, 88]. The measured microwave frequency and peak power in a coaxial vircator have been investigated to be about 3.34 GHz and 1.57 GW, respectively. Using the bar reflector, the power conversion efficiency from the electron beam to the microwave is enhanced from 28.9% up to 45.4% [37]. Figure 2.30 shows a typical oscilloscope traces of the diode voltage, current, and microwave in a coaxial vircator [37]. Figure 2.31 shows the field magnitude of FFT at the output port used for frequency measurement [37]. Figure 2.32 shows plot of microwave frequency and power according to the variation of AK gap distance in the coaxial vircator without a reflector [37]. Figure 2.33 illustrates the power conversion efficiency (from the electron beam to the microwave) enhancement using the bar reflector at the wave guide [37].
At the heart of the coaxial vircator technology is the cylindrical electron-beam diode where electrons are accelerated by strong electric fields. For design of the pulsed power systems that power the diode, it is useful to be able to predict the diode current for a given voltage and geometry. The space charge limited current in a cylindrical diode in one dimension can be described by the Langmuir-Blodgett law [94]. The Langmuir-Blodgett law has been extended to two dimensions by performing 2D particle in cell simulations [95]. But the results are limited to low voltage and low current regime (few kilovolts and few Amps).

Approximate analytical solutions for the space charge limited current in 1D and 2D cylindrical diodes are also calculated by various authors [96, 97]. When the self magnetic field of the electron beam is large enough for the electron Larmor radius to be comparable to the anode cathode gap spacing, space charge theory breaks down and the diode current becomes Magnetically Limited [98]. At the low currents, the self magnetic fields can be ignored and the charged-particle flow in the diode is space charge limited [98]. Particle in cell simulations of charged particle flows of cylindrical pinch beam diodes can be found in Ref.28, 99 and also in Ref.98.
Although several works has been carried out in connection with the intense relativistic electron beam generation in cylindrical electron beam diodes, the electrode plasma expansion and the effect of prepulse are not studied in detail. Another important issues concerning vacuum diodes is the increase of the perveance of the electron beam, which effects various applications, including high power microwave generation, transport of high current electron beams, and production of intense bremsstrahlung. The temporal behavior of perveance of the cylindrical electron beam diode is also not studied in detail.

FIG. 2.33 Plot of (a) microwave frequency and (b) power according to the variation of the reflector position [37].