CHAPTER 4

INTENSE RELATIVISTIC ELECTRON BEAM GENERATION STUDIES

IN THE PRESENCE OF PREPULSE

4.1 INTENSE GIGAWATT RELATIVISTIC ELECTRON BEAM GENERATION
IN THE PRESENCE OF PREPULSE

Intense gigawatt relativistic electron beam generation studies were carried out in a planar diode configuration in the presence of prepulse. It was found that with 400 kV on the diode a bipolar Prepulse of 60 kV peak and more than 800 ns duration arrives on the diode. The negative peak occurred about 600 ns before the main pulse and the positive peak about 200 ns before the main pulse [17]. Usually 100 kV/cm electric field is required to initiate plasma formation on the cathode surface. But due to poor vacuum and surface condition on the graphite cathode plasma formation can occur much below 100 kV/cm electric field. Also during the positive half of the Prepulse voltage some plasma can be generated at the anode surface. Because of the plasma expansion from the anode and cathode surfaces, the diode either short circuited before the main pulse arrived or the effective shape of the cathode changes which lowers the impedance of the 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, what plasma that is turned on may well 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. Cathode plasma can consist of a mixture with hydrocarbons on the
FIG. 4.1 Waveform of the electron beam voltage and current for 11.3 mm Gap, 70 mm dia cathode.

surface contributing significantly to its constitution [38]. Protons make up the majority the ion beam that is observed in most diodes.

FIG. 4.2 Marx generator output voltage with impedance mismatch.
Details of the experimental set up is given in Chapter 3.3. IREB generation studies have been carried out for graphite cathode of 70 mm diameter and AK gap ‘d’ was varied from 11 mm to 31 mm. A 30 cm diameter SS flange was used as an Anode. Pressure in the diode region was maintained at $4 \times 10^{-5}$ m.bar by a diffusion pump backed by rotary pump. Beam voltage was measured by a copper sulphate voltage divider of ratio (2K: 1) and beam current was measured by a self integrating Rogowski coil (5 V/kA) and B-dot probe. Initially ‘d’ was kept at 11.3 mm for 70 mm diameter cathode. At this gap diode impedance should match with the impedance of the Blumlein (~19 $\Omega$) for 300 kV beam voltage and can be calculated from Child-Langmuir Law. In this configuration the

![Waveform of the electron beam voltage and current for 21 mm Gap 70 mm dia cathode.](image)

FIG. 4.3 Waveform of the electron beam voltage and current for 21 mm Gap 70 mm dia cathode.
measured beam voltage was 57 kV [Fig. 4.1] though the Marx generator output voltage was 300 kV and beam current was as high as 40 kA. Also a large reversal seen in the Marx generator output voltage due to impedance mismatch between the diode and the Blumlein line [Fig. 4.2]. In this case the diode remains in the conduction phase for 30 ns duration then suddenly voltage rises to 57 kV. So the diode behaves as plasma filled diode but the impedance is much less than vacuum impedance. The Prepulse generated plasma completely covers the AK gap during the conduction phase. There was not much shot to shot variation in this case.

In order to avoid the prepulse effect the AK gap was increased much more than that given by the Child Langmuir Law. For 70 mm diameter cathode and 21 mm gap an IREB of 150 kV and 30 kA could be generated [Fig. 4.3] for 320 kV Marx generator voltage.

![Figure 4.4](image.jpg)

**FIG. 4.4** Marx generator output voltage with matched impedance.
In this case the short circuit phase is not seen but diode voltage still remains less than Marx generator voltage and reversal in the Marx generator voltage remains but less. Marx generator voltage was varied from 250 kV to 380 kV. It was seen that as we increase the Marx generator voltage diode voltage decreases and current increases with the consequent increase of Marx generator voltage reversal. For the same Marx generator voltage there is lot of shot to shot variation in the diode voltage and current due to the nonreproducibility of Prepulse generated plasma. In this case Prepulse generated plasma expands and reduces the effective AK gap consequently reducing the diode impedance [17].

For 70 mm diameter cathode and 23 mm gap similar behavior observed in the diode voltage and current. Various shots were taken varying the Marx voltage from 300 kV to 400 kV. For a constant 400 kV Marx voltage diode voltage varies from 100 kV to 225 kV and diode current from 25 kA to 40 kA for different shots.

![Waveform of the electron beam voltage and current](image)

**FIG. 4.5** Waveform of the electron beam voltage and current for 31 mm Gap 70 mm diameter cathode.
At 31 mm gap the beam parameters obtained are 420 KeV, 22 kA, 100 ns [Fig. 4.5]. Reversal in the Marx generator voltage also decreases [Fig. 4.4]. There is no shot to shot variation in the diode voltage and current. Typical IREB diode waveforms are shown in Fig. 4.5 In this case the diode gap is large enough to eliminate the creation of Prepulse generated plasma. Electron beam diode impedance and Perveance values (as shown in Fig. 4.6) were obtained from the diode voltage and current waveforms. It has been observed that the time varying perveance increases and diode impedance decreases with elapsed time. This is due to the fact that the effective AK gap decreases due to cathode and anode plasma expansion. Till 115 ns beam perveance does not increase so rapidly, but after that perveance increase very rapidly also there is a distinct change in the impedance curve. We conclude that diode closes at that point. The pervenace value at that point is around 200 $\mu$Perv ($1 \mu\text{Perv} = 1 \times 10^{-6} \text{A}/\text{V}^{3/2}$). So we can consider the diode as a short if perveance value is more than 200 $\mu$Perv. By the word short means impedance of the diode is much less than the Blumlein impedance.

![FIG. 4.6 Diode impedance and beam perveance with time.](image-url)
As the Marx generator voltage increase the prepulse voltage also increases. If we change the AK gap keeping the Marx generator voltage same, the field due to prepulse at the diode gap increases. Preveance of the diode scales as $1/(\text{Anode Cathode Gap})^2$ as seen from Eq. 2.4. We have plotted the diode impedance and perveance values for various Marx Voltage / $(\text{Anode Cathode Gap})^2$ in Figs. 4.7 and 4.8 These values are obtained for 21, 23 and 31 mm AK gap and the Marx generator voltage was varied from 275 kV to 420 kV and calculated at the peak of diode voltage and current.

FIG. 4.7 Diode impedance for various Marx Voltage / $(\text{Anode Cathode Gap})^2$ kV/cm$^2$ at the diode.
It can be seen from Fig 4.8 that the perveance is more than 200 $\mu$Perv when the Marx Voltage / (Anode Cathode Gap)$^2$ is more than 56 kV/cm$^2$. So in order to avoid the short-circuit condition the value of Marx Voltage / (Anode Cathode Gap)$^2$ has to be kept below 56 kV/cm$^2$. Below 56 kV/cm$^2$ effect of Prepulse will be less and the diode can be operated with a better shot to shot reproducibility.
4.2 EFFECT OF CATHODE DIAMETER ON IREB GENERATION IN THE PRESENCE OF PREPULSE

To understand the effect of the cathode diameter on intense relativistic electron beam generation in the presence of a prepulse, we have carried out experiments with same AK gap but with various cathode diameters and diode voltages. Experiments were 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]. We have also investigated the shot to shot reproducibility of the diode voltage and current versus the prepulse generated plasma.

The electron space charge limited current in bipolar flow for an annular cathode is given by [11]

\[
I_A(t) = 1.86 \times 2\pi \varepsilon_0 \frac{m_i c^3}{e} \left( \frac{r_e}{d - 2vt} \right)^2 \left( \sqrt{\gamma_o} - 0.8471 \right)^2, \quad (4.1)
\]

where \( c \) is the speed of light, \( r_e = \left[ R_e^2 - (R_e - x)^2 \right]^{1/2} \) is an effective radius of the cathode, \( x \) is the thickness of the annular cathode, \( \gamma_o \) is the relativistic factor evaluated at the anode. So for both the planar and annular cathode the diode impedance decreases with the increase of cathode radius.

To study the prepulse effect on beam generation, the experiments were carried out in two phases. In phase I the beam generation experiments were carried out with planar cathodes of diameters 67 mm and 98 mm respectively.
FIG. 4.9 Marx generator output and Prepulse waveform along with the main voltage pulse for 280 kV diode voltage in Phase I experiment with 67 mm diameter planar cathode.

In the phase II experiment, the planar cathodes have been replaced by annular cathodes of 40 mm and 70 mm diameters. Thickness of the annular cathode was $x = 5$ mm. The cathode material was graphite and a 30 cm diameter SS plate was used as an anode.

The diode voltage waveform along with the Marx Generator output voltage waveform in the phase I with 67 mm diameter cathode is shown in Fig. 4.9. One can see a negative prepulse of peak voltage ~ 60 kV, ~ 500 ns duration and a positive prepulse of peak voltage ~ 50 kV, ~ 200 ns duration during the Marx generator erection or the Blumlein line charging. Let us define the diode voltage as $\varphi_d$, current as $I_d$, and the Marx generator voltage as $\varphi_M$. 
FIG. 4. 10 (a) The temporal behavior of the diode impedance in Phase I experiment with 67 mm diameter planar cathode. (b) Experimental perveance for Phase I experiment.
FIG. 4.11 The diode voltage and current waveform in Phase I experiment with 98 mm diameter planar cathode for (a) $\varphi_d = 334$ kV, (b) $\varphi_d = 306$ kV.
For phase I there was no shot to shot variation in the diode voltage and current for the same Marx generator voltage. Electron beam diode time varying impedance and perveance values were calculated using the voltage and current waveforms. The starting point or the zero time for perveance calculations was taken when the main voltage pulse is zero.

**TABLE I.** Results of the phase I experiment with 67 mm diameter cathode showing prepulse voltages and time durations for three different shots.

<table>
<thead>
<tr>
<th>Marx output</th>
<th>Negative prepulse</th>
<th>Positive prepulse</th>
<th>Diode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (kV)</td>
<td>Reversal (%)</td>
<td>Voltage (kV)</td>
<td>Duration (ns)</td>
</tr>
<tr>
<td>320</td>
<td>17</td>
<td>67</td>
<td>500</td>
</tr>
<tr>
<td>320</td>
<td>17</td>
<td>53</td>
<td>500</td>
</tr>
<tr>
<td>362</td>
<td>17</td>
<td>90</td>
<td>500</td>
</tr>
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Fig. 4.10(a) shows the diode impedance versus time for two different shots. The diode perveance for two different shots is shown in Fig. 4.10(b). One can see that there is not much differences in the impedance and perveance curve for the two shots. Results of the Phase I experiments with 67 mm diameter cathode are shown in the Table I. The % reversal in the Marx generator output voltage waveform is calculated from the ratio between the first positive peak and the peak Marx generator voltage. One can see from the Fig. 4.10(a) that the initial impedance for \( D_j = 290 \) kV voltage is less than that for the case with \( D_j = 280 \) kV voltage. This is because of the fact that the negative prepulse voltage for \( D_j = 290 \) kV voltage is higher than the case with \( D_j = 280 \) kV voltage. The estimated bipolar SCL current [see chapter 5, Eq. (5.2)], with plasma velocity \( v = 0 \), for 290 kV diode voltage is only 3.8 kA, much less than the measured current 19 kA. This implies that the electrode plasma closure is an important effect in this experiment. It was also found that, at \( D_j = 362 \) kV, and with a corresponding negative prepulse voltage of 90 kV, the time varying diode perveance remains same as of Fig. 4.10(b).
The reversal in the Marx output voltage was ~ 17%, same as the case with $\phi_m = 320$ kV. This suggests that the prepulse generated plasma expansion has little effect in this experiment.

For 98 mm cathode diameter, the diode voltage was less than the Marx generator output voltage and some shot to shot variation in the diode voltage and current were measured for the same Marx generator voltage. Also a large reversal seen in the Marx output voltage is due to impedance mismatch between the diode and the Blumlein line. The estimated bipolar SCL current [see chapter 5, Eq. (5.2)], with plasma velocity $v = 0$, for 169 kV diode voltage is only 3.6 kA. This indicates the effect of the prepulse on the diode voltage and current. Results of the Phase I experiments with 98 mm cathode diameter is shown in the Table II.

<table>
<thead>
<tr>
<th>Marx output</th>
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<tr>
<td>Voltage (kV)</td>
<td>Reversal (%)</td>
<td>Voltage (kV)</td>
<td>Duration (ns)</td>
</tr>
<tr>
<td>334</td>
<td>58</td>
<td>67</td>
<td>500</td>
</tr>
<tr>
<td>306</td>
<td>45</td>
<td>53</td>
<td>500</td>
</tr>
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</table>
FIG. 4.12 (a) The temporal behavior of the diode impedance in Phase I experiment with 98 mm diameter planar cathode for two different Marx generator voltages. (b) Experimental perveance for Phase I experiment for two different Marx generator voltages.
The diode voltage and current waveforms for two different Marx generator voltages are shown in Fig 4.11(a) and Fig 4.11(b). Fig. 4.12 (a) shows the diode impedance versus time for the two different Marx generator voltages. Experimental perveance for two different Marx generator voltages are shown in Fig. 4.12(b). One can see from the Fig.4.12 (b) and Fig 4.11(a) that for the shot with $\varphi_u = 334$ kV voltage the diode closes at much earlier time $\sim 90$ ns as compared to $\varphi_u = 306$ kV. Fig. 4.12(a) shows that till $\sim 15$ ns from the beginning of the diode voltage rise the diode impedance for $\varphi_u = 334$ kV is less than for $\varphi_u = 306$ kV. This is probably due to the fact that the negative prepulse voltage is large for $\varphi_u = 334$ kV voltage and the prepulse generated cathode plasma expanded to a larger distance than it expands at $\varphi_u = 306$ kV, even though the positive prepulse voltage amplitude and duration was more for $\varphi_u = 306$ kV. This implies that the positive prepulse voltage has little effect on the diode perveance.

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<td>Voltage (kV)</td>
<td>Reversal (%)</td>
<td>Voltage (kV)</td>
<td>Duration (ns)</td>
</tr>
<tr>
<td>320</td>
<td>30</td>
<td>80</td>
<td>500</td>
</tr>
<tr>
<td>278</td>
<td>25</td>
<td>53</td>
<td>500</td>
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Also the reversal in the Marx generator output voltage is less for the case $\varphi_u = 306$ kV due to the smaller negative prepulse voltage. The reason for the shot to shot variation in this experiment may be because of a decrease in the uniformity of the prepulse generated plasma with the corresponding increase in the cathode diameter.

In the phase II, for both the cathode diameter some shot to shot variation in the diode voltage and current were measured for the same Marx generator voltage. But the diode peak voltage
obtained for 40 mm diameter cathode is much larger than the 70 mm diameter cathode. Results of the Phase II experiments are shown in the Table III and Table IV. The estimated bipolar SCL current from Eq. (4.1), with plasma velocity $v = 0$, for 346 kV diode voltage is only 0.9 kA. The diode voltage and current waveforms for two different Marx generator voltages are shown in Fig. 4.13(a) and Fig. 4.13(b). One can see from the Fig. 4.13(b) that the voltage waveform is associated with few spikes which can be considered as noise. Fig. 4.14 shows the diode impedance versus time for two different Marx generator voltages. One can see from the Fig. 4.14 that the diode impedance obtained for $\phi_m = 278$ kV is much higher than that for $\phi_m = 320$ kV as the prepulse voltage is much higher for the second case.

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<tr>
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<td>Duration (ns)</td>
</tr>
<tr>
<td>320</td>
<td>48</td>
<td>67</td>
<td>500</td>
</tr>
<tr>
<td>348</td>
<td>48</td>
<td>67</td>
<td>500</td>
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The estimated bipolar SCL current for 70 mm cathode diameter from Eq. (4.1), with plasma velocity $v = 0$, for 231 kV diode voltage is only 1.1 kA.
FIG. 4.13 The diode voltage and current waveform in Phase II experiment with 40 mm diameter annular cathode for (a) $\varphi_u = 278$ kV, (b) $\varphi_u = 320$ kV.
The diode voltage and current waveforms for two different Marx generator voltages are shown in Fig 4.15(a) and Fig 4.15(b). The diode voltage waveform for this case is always noisy. Fig. 4.16 shows the diode impedance versus time for two different Marx generator voltages. One can see that till ~ 15 ns from the beginning of the diode voltage rise the diode impedance for $\phi_d = 348$ kV is less than for $\phi_d = 320$ kV, even though the negative prepulse voltages were same. Probably because of the fact that the uniformity of the prepulse generated plasma was not similar for both the cases. It is interesting to note that the reversal in the Marx generator output voltage is same for the two cases. But the reversal is large as compared to the 40 mm diameter annular cathode.

FIG. 4.14 The temporal behavior of the diode impedance in Phase II experiment with 40 mm diameter annular cathode for two different Marx generator voltages.
FIG. 4.15 The diode voltage and current waveform in Phase II experiment with 70 mm diameter annular cathode for (a) $\phi_a = 320$ kV, (b) $\phi_a = 348$ kV.
FIG. 4.16 The temporal behavior of the diode impedance in Phase II experiment with 70 mm diameter annular cathode for two different Marx generator voltages.

4.3 IREB GENERATION IN HIGH POWER CYLINDRICAL DIODE IN THE PRESENCE OF PREPULSE

The experimental setup used is shown in Chapter 3.3. The cylindrical diode consists of an annular cathode and grounded mesh anode. A graphite cathode with outer diameter of 13.7 cm and a copper mesh anode of 8.6 cm diameter were used for the cylindrical diode. The graphite cathode has a 2 cm emission length. To study the prepulse effect on beam generation in a high power cylindrical diode, the experiments were carried out in three phases. In phase I the cathode inner diameter was set to 12.3 cm with the radial AK gap of 1.85 cm. The diode chamber was evacuated using a diffusion pump backed by a rotary pump. The vacuum in the diode chamber was $\leq 6 \times 10^{-5}$ mbar. In the phase II experiment,
FIG. 4.17 (a) Voltage waveform in the Phase I experiment. (b) Current waveform in the Phase I experiment.
FIG. 4.18 (a) The temporal behavior of the diode impedance in Phase II experiment. (b) Experimental and theoretical perveance for Phase II experiment. Solid triangle represent perveance for 310 kV Marx voltage and open circles represent 240 kV Marx voltage. Continuous line represents theoretical perveance.
FIG. 4.19 (a) The temporal behavior of the diode impedance in Phase III experiment. (b) Experimental and theoretical perveance for Phase III experiment. Solid circles represent perveance for 250 kV Marx voltage and open circles represent 320 kV Marx voltage. Continuous line represents theoretical perveance.
the cathode inner diameter was set to 11.9 cm with the radial AK gap of 1.65 cm. In phase III experiment, the cathode inner diameter was set to 11 cm with the radial AK gap of 1.2 cm. For the phase I there was no shot to shot variation in the voltage and current for the same Marx generator voltage. One can see from Fig. 4.17 (b) that the diode current starts at positive prepulse, i.e., there is a plasma formation at the cathode during the prepulse with negative polarity. Also, one can see the rise in the impedance at the beginning of the accelerating pulse, which indicates on plasma prefilled mode of the diode operation with a fast plasma erosion.

![Prepulse waveform](image)

**FIG. 4.20** Prepulse waveform along with the main voltage pulse for 240 kV Marx voltage in Phase II experiment.

In the phase II, the diode voltage was less than the Marx generator output voltage and some shot to shot variation in the diode voltage and current were measured for the same Marx voltage. This indicates the effect of the prepulse on the diode voltage and current. Results of the Phase II experiments are shown in the Table I. Fig. 4.18 (a) shows the diode impedance...
versus time for two different Marx generator voltages. Experimental perveance for two different Marx generator voltages is shown in Fig. 4.18 (b). One can see that after 110 ns, the perveance increases rapidly as compared to the case of the phase

![Graph showing perveance versus time for two different Marx generator voltages.](image)

**FIG. 4.21** Prepulse waveform along with the main voltage pulse for 250 kV Marx voltage in Phase III experiment.

This shows that AK gap closure occurs after 110 ns. It is interesting to note that the time varying experimental perveance values were the same for the two shots except theirs values between 20 ns and 80 ns of the diode voltage. Since the prepulse voltages were similar for the two cases, the effective diode geometry did not changed much due to the prepulse generated plasma expansion. Fig. 4.20 shows the prepulse waveform for 240 kV Marx generator voltage.

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Results of the Phase III experiments are shown in the Table II. For the Phase III, the diode voltage obtained was less than the Marx generator output voltage also some shot to shot variation in the diode voltage and current were measured for the same Marx generator voltage. Fig. 4.19 (a) shows the diode impedance versus time for the two different Marx generator voltages. Experimental perveance for two different shots, one with $\phi_m = 320$ kV and another with $\phi_m = 250$ kV are shown in Fig. 4.19 (b). One can see from the Fig. 4.19 (b) that already at the beginning of the main voltage pulse the initial perveance for $\phi_m = 320$ kV is larger than for case $\phi_m = 250$ kV.
This is due to the fact that the negative prepulse voltage is large for \( \varphi_u = 320 \) kV voltage and the prepulse generated cathode plasma expanded to a larger distance than it expands at \( \varphi_u = 250 \) kV, even though the positive prepulse voltage amplitude and duration was more for \( \varphi_u = 250 \) kV (Fig. 4.21 and Fig. 4.22). This implies that the positive prepulse voltage has little effect on the diode perveance. The reason for this may be that the explosive emission threshold for copper anode mesh is higher than for the graphite cathode. After \( \sim 100 \) ns, the perveance for \( \varphi_u = 320 \) kV increases rapidly showing AK gap closure.

The comparison of the Phase III experiment with previous planar diode experiment with 1.13 cm AK gap, shows that in the case of the planar diode the prepulse generated plasma completely fills the AK gap and the diode behaves as plasma filled diode. 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

<table>
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<th>Negative prepulse</th>
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<td>250</td>
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<td>400</td>
<td>60</td>
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completely fill the diode gap, resulting in $\geq 170$ kV diode voltage. Let us note, that the current density in the planar diode experiment was in the range $0.2 - 1.0$ kA/cm$^2$, similar to the measured peak current density for the present cylindrical diode experiment, $0.2 - 0.6$ kA/cm$^2$. 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.

4.4 ELECTRON BEAM GENERATION WITH A BIPOLAR PULSE IN A HIGH POWER CYLINDRICAL DIODE

In the present experiment, KALI 5000 system has been operated without a prepulse switch which results in generation of the bipolar high-voltage prepulse. The experimental setup used is shown in Chapter 3.3. The cylindrical diode consists of an annular cathode and grounded mesh anode. A graphite cathode with outer diameter of 13.7 cm and a copper mesh anode of 8.6 cm diameter were used for the cylindrical diode. The graphite cathode has a 2 cm emission length. The inner diameter of the graphite cathode is 11 cm with the radial AK gap of 1.2 cm. The diode diagnostics employed were aqueous copper sulphate resistive divider for the diode voltage, and B-Dot probe for the diode current measurement. The inductive correction due to the transmission line inductance of 14 nH from the resistive divider to the cathode edge is less than a few percent since the $dI/dt$ is typically $0.14-0.27$ kA/ns in the present experiment. The diode chamber was evacuated to $\leq 8 \times 10^{-5}$ mbar using a diffusion pump backed by a rotary pump. During the positive voltage pulse the copper mesh act as an explosive emission electron source. Whereas during the negative voltage pulse the outer graphite electrode acts as a cathode.
FIG. 4.23 (a) The diode voltage waveform. (b) The diode positive and the second negative voltage waveform with the corresponding current waveform.
The diode voltage waveform is shown in Fig. 4.23 (a). During the first ~ 400 ns the diode voltage is negative with the peak voltage of ~ 70 kV, then the diode voltage changes to positive for ~ 200 ns duration and again negative for ~ 100 ns duration.

No detectable current is recorded in the diode during the initial negative diode voltage. Fig. 4.23 (b) shows the diode positive, and the second negative voltage waveform along with the corresponding current wave form. The diode peak voltage and current obtained in the positive and negative voltage pulse were 142 kV, 7.3 kA and 143 kV, 11.2 kA, respectively. One can see a sharp decrease and increase in the negative voltage pulse [Fig. 4.23 (b)]. At the same time, however, there are no changes in the current waveform. It may be due to a partial surface
breakdown either along the voltage divider surface or along the interface insulator. It is understood that this partial surface breakdown introduces error in the voltage measurement of the negative voltage pulse.

![Image](image_url)

**FIG. 4.25** The temporal behavior of the diode perveance for negative voltage pulse. The dashed line is the perveance calculated from Langmuir-Blodgett law.

One can see from Fig. 4.23 (b) that the diode current starts at the positive voltage pulse after ~80 ns from the initial rise in the diode voltage. This indicates that the explosive emission threshold for the copper mesh is ~ 95 kV/cm and the plasma formation occurs after ~ 80 ns. Because of this high explosive emission threshold, ~ 70 kV positive
FIG. 4.26 (a) The temporal behavior of the diode impedance for positive voltage pulse. (b) The temporal behavior of the diode impedance for negative voltage pulse.
prepulse voltage had no significant effect on the diode perveance in our earlier experiment described in the previous section. One can also see from Fig. 4.23 (b) that before the onset of positive current, the diode current is slightly negative. The latter indicates that there is a plasma formation at the graphite cathode during the first negative voltage pulse. In the subsequent discussion, the negative voltage pulse refers to second negative voltage pulse only.

At the time of maximum current during the positive pulse, the diode voltage $V = 130$ kV, if we use the initial radii of the electrodes (with no gap closure) and assume a 2 cm emission length (the length of the anode during the positive pulse). The SCL current from Langmuir-Blodgett law (See chapter 5) for these parameters is 5 kA, close to the measured value of 7.3 kA. This indicates that electrode plasma closure is a small effect in the positive voltage pulse.

The diode perveance $P$ is defined as, $I = PV^{1/2}$ where $I$ is the diode SCL current. The experimental perveance derived from the positive diode voltage and current is shown in Fig. 4.24 where it is compared with the perveance calculated according to Langmuir-Blodgett law. One can see that perveance increases linearly with time. Initially the diode gap is close to 1.2 cm, but the emission occurs over only a fraction of the cathode area. This area increases as the current increases and the perveance increases due to the increase of the emission area.

During the negative pulse, the diode voltage is about -100 kV at the time of peak current. The estimated SCL current from Langmuir-Blodgett law is 2.9 kA, much less than the measured peak current 11.2 kA. So during the negative voltage pulse diode current increases due to the plasma expansion. The time varying perveance for negative diode voltage and current is shown in Fig. 4.25. Fig. 4.26 (a) and Fig. 4.26 (b) shows the diode impedance versus time for positive and negative voltage pulses, respectively. During the positive voltage pulse, the diode
impedance decrease with time due to the increase in the emission area. But during the negative voltage pulse, the diode impedance decreases with time due to the plasma expansion. Therefore 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 (~$1.1 \times 10^{-4}$ A/V$^{3/2}$).

4.5 PREPULSE SUPPRESSION TECHNIQUES

4.5.1 Prepulse Suppression using a dielectric cathode holder

In general, the best method to avoid prepulse is the use of spark gap switch or additional transmission line. The magnitude and polarity of the prepulse allowed are a function of the type of application of the electron beam diode. In order to reduce prepulse voltage to an acceptable level prepulse switches are used after the pulse forming line [16]. Depending upon the particular diode, various low capacitance prepulse switches have been used, for example, water, oil and gas switches. It is also possible to reduce prepulse by introducing a surface flashover switch into the conductor feeding the diode in vacuum [110], [56]. It can reduce prepulse by a factor of a few or so up to about 10, depending upon the geometry [16]. In order to see the feasibility of a surface flashover prepulse switch in the KALI 5000 electron beam diode we have operated the diode with corrugated Perspex cylinder at the cathode holder.
FIG. 4.27 Schematic of the experimental setup showing Perspex cathode holder and the electron beam diode.

The experimental setup used is shown in Fig.4.27. A cylindrical graphite cathode has been connected to the SS cathode holder by a corrugated Perspex cylinder of 26 mm maximum diameter and 10 mm minimum diameter. The cathode diameter was 66 mm. An aluminum disk of 1.5 mm thickness was connected to the backside of the cathode by metal screws. Effective length of the Perspex cylinder can be changed by changing the position of the aluminum disk with respect to the cathode. The location of the prepulse switch is very important, if the switch is placed too close to the cathode prepulse could couple through the capacitance of the switch and would not be reduced enough. If the switch were placed too far
backward, the diode insulator and voltage divider would be exposed to UV from the flashover, resulting in a breakdown [56].

TABLE I. Results of the experiment with 66 mm diameter cathode showing diode voltage and current for various AK gaps and Perspex insulator length.

<table>
<thead>
<tr>
<th>Anode-Cathode Gap (mm)</th>
<th>Perspex Insulator Length (mm)</th>
<th>Diode Voltage (kV)</th>
<th>Diode Current (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>24</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>9</td>
<td>27</td>
<td>26</td>
<td>39</td>
</tr>
<tr>
<td>12</td>
<td>28</td>
<td>43</td>
<td>42</td>
</tr>
<tr>
<td>14</td>
<td>29</td>
<td>59</td>
<td>42</td>
</tr>
<tr>
<td>15</td>
<td>30</td>
<td>100</td>
<td>32</td>
</tr>
<tr>
<td>18</td>
<td>35</td>
<td>180</td>
<td>26</td>
</tr>
<tr>
<td>25</td>
<td>40</td>
<td>180</td>
<td>15</td>
</tr>
</tbody>
</table>

Intense relativistic electron beam generation studies have been carried out for 66 mm diameter graphite cathode and the AK gap has been varied from 6 mm to 25 mm and the Perspex insulator length has been varied from 24 mm to 40 mm. Results of the experiments are shown in Table I. Fig. 4.9 shows the Marx generator output and the bipolar prepulse waveform along with the main voltage pulse when the cathode is connected to the pulse forming line by a conducting rod. For 9 mm AK gap with 27 mm Perspex length there is no prepulse voltage in the diode voltage waveform, but the diode voltage is less ~ 26 kV and the current is quite large ~ 39 kA. Also some prepulse current is recorded before the main current pulse. Also at 6 mm AK gap and 24 mm Perspex length similar prepulse current has been observed though there was no prepulse voltage. This suggests that the 27 mm length Perspex is not sufficient to stop the prepulse arriving at the diode and during the prepulse voltage itself the diode AK gap has been filled with cathode plasma resulting in a very low voltage at the diode. Usually a 60 kV bipolar prepulse voltage has been seen at the diode at 300 kV Marx generator voltage [17].
Therefore surface flashover can occur at an electric field < 20 kV/cm due to the bipolar nature of the prepulse voltage [111]. At 12 mm AK gap and 28 mm Perspex length similar prepulse current has been recorded but a negative prepulse voltage of peak 40 kV and 200 ns duration was also present at the diode voltage. For 14 mm AK gap with 29 mm Perspex a negative prepulse of peak voltage ~ 16 kV with ~ 300 ns duration arrives at the diode either due to capacitive coupling or due to the surface flashover at the Perspex insulator. At 15 mm AK gap and 30 mm Perspex length a 30 kV peak bipolar prepulse voltage has been recorded at the diode.

To get a higher voltage at the diode we increase the diode gap to 18 mm and increase the Perspex length to 35 mm. The diode peak voltage and current obtained in this experiment were 180 kV and 26 kA [Fig. 4.28]. No prepulse voltage or current has been observed in this case. One can see from the Fig. 4.28 that till $t = 50$ ns the diode voltage rises slowly to ~ 40 kV then suddenly rises to ~ 350 kV then the diode current also started rising at $t = 70$ ns. This indicates that till $t = 70$ ns, surface flashover did not occur at the 35 mm length Perspex insulator. But before the breakdown of the Perspex insulator diode voltage rises slowly to ~ 50 kV due to the capacitive coupling. Also little current is recorded in this low voltage phase of the diode, showing plasma formation on the cathode surface. With the increase of the Marx generator voltage, diode current increases up to ~ 40 kA but the diode voltage remains almost same. Fig. 4.29 shows the diode voltage and current waveform for 18-mm AK gap with a higher Marx generator voltage.

Fig.4.30 shows the diode voltage and current waveform for 25 mm AK gap with 40 mm Perspex. In this case diode voltage has been measured before the dielectric cathode holder but inside the diode chamber only. One can see from the Fig. 4.30 that at $t = 60$ ns diode voltage
suddenly drops to ~ 150 kV. This is because of the fact that the diode voltage, measured before the Perspex insulator, increase to 330 kV, since by that time surface flashover has not taken place. At $t = 60$ ns the voltage breakdown takes place across the Perspex surface and the diode current started rising at the same time.

![Graph](image)

**FIG. 4.28** Diode voltage and current waveform for 18 mm AK gap and 35 mm Perspex insulator.

With the increase of the Marx generator voltage both the diode current and voltage increases. Fig. 4.31 shows the diode voltage and current waveform for 25 mm AK gap with a higher Marx generator voltage. One can see from the Fig. 4.31 that in this case breakdown across the Perspex insulator occurs at an earlier time $t = 40$ ns and consequently the diode current started rising earlier than the previous case.
FIG. 4.29 Diode voltage and current waveform for 18 mm AK gap and 35 mm Perspex insulator with a higher Marx generator voltage.

FIG.4.30 Diode voltage and current waveform for 25 mm AK gap and 40 mm Perspex insulator.
Therefore 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 pulsewidth.

### 4.5.2 Prepulse Suppression by adding an Extra Inductance to the Charging Circuit of the Blumlein Line

To compare the diode operation with other technique of prepulse mitigation an inductance has been added to the charging circuit of the Blumlein line. In the case of the added inductance to the Blumlein circuit, the slower rise time reduces the prepulse voltage from 32% to $\leq 10\%$. In this case a 67 mm diameter graphite cathode and a Tantalum disk has been used as an anode.
One can see from the Fig. 4.32 that in this case the Blumlein charging time has increased from 800 ns (Fig. 4.9) to ~ 2 \( \mu s \) and there is no significant prepulse voltage. Some prepulse voltage is recorded during the beginning of the Blumlein charging but this prepulse voltage appears around 1.7 \( \mu s \) prior to the main voltage pulse and will have no effect on the diode operation.

### 4.6 CONCLUSIONS

An intense relativistic electron beam has been generated without a prepulse switch. 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 voltage and eventually drops it below the explosive emission threshold and eliminates its creation. For the same Marx generator voltage there is lot of shot to shot variation in the diode voltage and current due to the nonreproducibility of prepulse generated
plasma. For perveance more than 200 μPerv 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 less and the diode can be operated with a better shot to shot reproducibility.

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. For the planar cathode, the beam parameters obtained are 340 keV, 24 kA, and 100 ns at a 680 A/cm$^2$ current density. With an annular cathode, 346 keV, 10 kA, and 100 ns electron beam could be generated at a 3.4 kA/cm$^2$ current density. The peak electric field in the diode varies from 58 to 138 kV/cm.

A bipolar prepulse voltage has been recorded at the diode. The amplitude of the negative prepulse voltage increases with the Marx generator voltage but the time duration remains the same. A maximum of 32% negative prepulse voltage has been recorded at the diode. Both the time duration and the amplitude of the positive prepulse voltage decrease with the increase in the Marx generator voltage. The highest positive prepulse voltage is 17% of the peak diode voltage. The voltage reversal in the Marx generator output signal is higher for the 98 mm diameter planar cathode compared to that for the 67 mm diameter cathode. Also there is no shot to shot variation for the 67 mm diameter planar cathode. It was found that the positive prepulse voltage has no significant effect on the diode perveance and impedance. Reversal in the Marx generator output voltage is higher for the annular cathode compared to the planar cathode. Also the Marx reversal increases with the cathode diameter for both types of cathodes due to a decrease in the diode impedance. For the same Marx generator voltage, there is lot of shot to shot variation in the diode voltage and current in the annular cathode. 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. The effect of prepulse is more pronounced in the cathode of higher diameter due to a decrease in the uniformity of the prepulse generated plasma with the corresponding increase in the cathode diameter.

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 some 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. 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.

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 ($\sim 1.1 \times 10^{-4}$ A/V$^{3/2}$).

Intense relativistic electron beam has been generated in a planar diode with a dielectric cathode holder. Electron beam generation studies have been carried out for various AK gaps. The length of the Perspex insulator has been varied from 24 mm to 40 mm. It was found that for
the Perspex length < 35 mm prepulse voltage appears at the diode either due to capacitive coupling or surface flashover at the Perspex insulator surface at the prepulse voltage itself. This surface flashover occurs at an unexceptionally low flashover fields could be because of the bipolar nature of the prepulse voltage. No prepulse voltage has been recorded at the diode for the Perspex length ≥ 35 mm. But due to the pre breakdown time delay in the surface flashover across the insulator the rise time of the diode voltage increases. The diode current started rising after ~ 50 ns from beginning of the diode voltage, this reduces the effective pulse width by 50 ns. Inserting a dielectric at the cathode holder could be a very effective method to reduce prepulse at the electron beam diode, but it increases the rise time of the diode voltage and reduces the effective electron beam pulse width. The prepulse voltage reduces significantly (≤ 10%) when an inductance is added to the charging circuit of the Blumlein line and much higher diode voltage has been obtained for the same AK gap.