Chapter 15

Intense Relativistic Electron Beam (REB) Diodes

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The high voltage pulse of few 10s of nanoseconds duration from the pulse power driver is converted into intense relativistic electron beam (IREB) in a vacuum diode/chamber called REB diode. The electron beam has peak voltage and currents depending up on the operating parameters of the source driving it and the diode parameters set. There will be cathode and anode assembly separated by a suitable gap – anode cathode (A-K) gap across which the high voltage pulse is applied. The electron beam is generated by the process of explosive electron emission (EEE). The high voltage pulse causes a very high field of the order of $10^4 – 10^5$ kV/cm on the micro tips of the cathode surface and electrons start coming out by field emission. The current density at the micro tips will be very high and as a result, the tips vaporise due to rapid resistive heating. The electrons ionise the vapour and creates dense plasma next to the cathode surface termed as “cathode plasma.” This plasma extends across the surface area of the cathode and supplies the high current electron beam. The current will be space charge limited (SCL). The electrons generated are accelerated towards the anode and they cause desorption of anode materials due to impact heating. This leads to the formation of anode plasma. Both anode and cathode plasmas expand towards each other (with a typical expansion velocity of 1 – 6 cm/µs) and finally short the A-K gap. After this, beam cannot be extracted. The REB diode can have different geometries depending on the application – flash X-ray (FXR) generation, high power microwave (HPM) generation and so on.

15.1. REB Diode Design

The REB diode design should be done keeping in mind the non linear particle trajectories as well as the self consistent electric and magnetic fields. There will be space charge forces and self generated or applied fields existing inside the diode. The voltage, current and pulse width of the diode is estimated from the output requirement of the particular application, say dose and power in the case of FXR and HPM generation respectively. This fixes the diode geometry and pulse power ratings. Then numerical simulations have to be carried out to evaluate the I-V characteristics for the specific geometry in the operational range. The field stress analysis of the diode has to be carried out to check whether the dimensions selected have any unwanted emissions within the diode other than the cathode emitting surface. There are benchmarked simulation tools available for field stress analysis and for particle emission and tracking.

The high voltage – vacuum interface are mainly two types: radial insulator for $V \leq 1$ MV and metal dielectric graded insulator for $V > 1$ MV. Figure 1 shows the schematic of the two types of insulators. The grading is done to distribute the diode voltage evenly along the interface and to prevent surface flash over breakdown. The empirical formula for calculating the average electric field (kV/cm) is given by [1]

$$\langle E_{br} \rangle t^{1/6} A^{1/10} = 175 \tag{15.1}$$

where t is the time duration in ns and A in cm^2 is the area of the insulator.

The weakest point from where the breakdown can initiate is the triple point (insulator-vacuum-metal joining point).

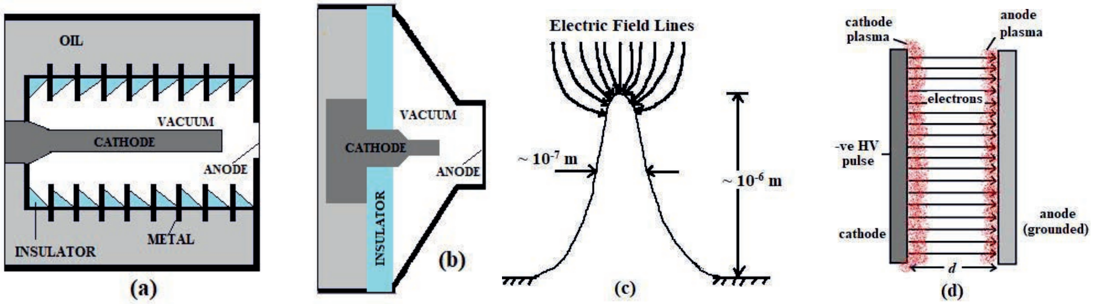

Figure 15.1. Schematic of (a) axial insulation structure (b) radial insulation structure (c) micro protrusion and E field enhancement at tip, (d) plasma expansion in planar diode.

There are mainly three different diode geometries – planar, annular and cylindrical.

15.2. Planar REB Diode

In the case of a planar diode with cathode of radius 'r_c' and 'd' as the distance between cathode and anode, the current density j_{1D} and current I_p for an applied voltage V are given by,

$$j_{1D} = \frac{4\in_o}{9}\left(\frac{2e}{m_e}\right)^{1/2}\frac{V^{3/2}}{d^2} = 2.33\times10^{-6}\frac{V^{3/2}}{d^2} \tag{15.2}$$

$$I_p = j_e \times \pi r^2 = 2.33\times10^{-6}\frac{V^{3/2}\pi r^2}{d^2} \tag{15.3}$$

Here v is the velocity of plasma expansion and e the charge of electron and m_e the mass of electron. If t is the instantaneous time where I_p is measured, the d^2 terms in Eqs. (15.2) & (15.3) have to be replaced by $(d\text{-}vt)^2$.

With the expanding anode and cathode plasmas with a velocity v, d^2 has to be replaced with $(d\text{-}vt)^2$.

The diode impedance is time varying. The impedance is given by

$$Z_d = \frac{V}{I_e} = \frac{136}{V^{1/2}}\frac{(d-vt)^2}{r^2} \tag{15.4}$$

The diode perveance which is a measure of the space charge effects on the beam dynamics is given by

$$P_{planar} = \frac{I_p}{V^{3/2}} = 2.33\times10^{-6}\frac{\pi r^2}{(d-vt)^2} \tag{15.5}$$

Perveance is affected by the geometrical parameters if there are no space charge effects. This is valid only in the non relativistic voltage levels (< 500 kV).

The generation of anode plasma and ions current streaming towards the cathode causes bipolar flow in the diode. Then the diode current given by Eq. (15.3) has to be multiplied by a factor of 1.86.

15.3. Annular REB Diode

Annular cathodes are used in self planar pinch Flash X-ray diodes as well as in the foil less backward wave oscillator (BWO) devices. The SCL current in the case of an annular cathode is given by

$$I_A = 2\pi\frac{\varepsilon_0 m_e c^3}{e}\left(\frac{r_c}{d-2vt}\right)^2\left(\sqrt{\gamma_0}-0.8471\right)^2 \tag{15.6}$$

where c is the speed of light, r_c is effective radius of the cathode, γ_0 is the relativistic factor .

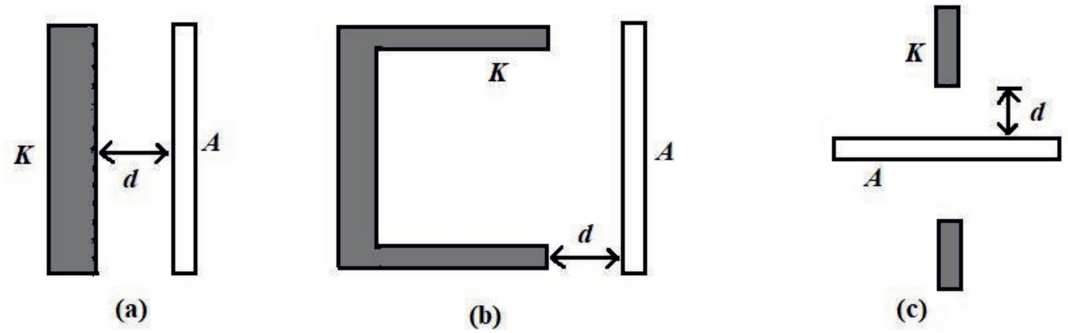

Figure 15.2. Schematic of (a) planar (b) annular & (c) cylindrical diodes. *K* stands for cathode, *A* for anode and *d* is the distance between anode and cathode.

15.4. Cylindrical REB Diode

REB diodes in cylindrical geometry are used in industrial/Rod Pinch FXR diodes, coaxial vircator etc. Langmuir-Blodgett law gives the one dimensional SCL current per unit length for cylindrical diodes for an applied voltage V.

$$j_{1D} = \left(\frac{8\pi\varepsilon_0}{9}\right)\left(\frac{2e}{m_e}\right)^{1/2}\frac{V^{3/2}}{r\beta^2} \tag{15.7}$$

Here β depends on the ratio of r/r_c. The SCL current for an emission length of 'h' will be

$$I_c = j_{1D}\times(h+2d) \tag{15.8}$$

It should be noted that the emission length will be (h + 2d) instead of h as a result of the two-dimensional edge contribution to the current. There will be current enhancement because of bipolar flow and I_c will increase by approximately 1.86 times. This applies for non relativistic voltages and where the cathode to anode radius ratio is unity and further increases with r_c/r_a increment. But as the voltage goes above 500 kV, this factor comes down.

15.5. Electron Beam Pinching

The electron flow is parallel to the electric field lines at lower voltages and current levels and the current here is space charge limited (SCL). As the beam current increases, self generated magnetic field becomes prominent and the bean starts bending or pinching. The transition to magnetically limited (ML) current occurs when the relativistic gyro radius of the electron beam is equal to the A-K gap separation. Here the current first becomes weakly pinched and then strongly pinched depending up on the current values. The ion space charge caused by anode plasma is crucial in the early formation of the pinch. The self magnetic pinch (SMP) diodes can have two geometries, planar self pinch (SP) and rod pinch (RP). There is a threshold current called critical current, I_{crit} to be attained for pinching to start. In the case of the planar self pinch diode, it is given by

$$I_{crit}(kA) = 8.5\alpha \frac{r_c}{d}(\gamma^2 - 1)^{1/2} \tag{15.9}$$

where α is an empirical scaling factor ~ 2 due to bipolar flow caused by the increased ion fraction and γ is the electron relativistic factor. Usually in SP diodes, $r_c >> d$ and this makes sure a high ion current. The SP normally operates at lower impedance levels. In the case of RP diodes, I_{crit} is given by

$$I_{crit}(kA) = \frac{8.5\alpha}{\ln\left(\frac{r_c}{r_a}\right)}(\gamma^2 - 1)^{1/2} \tag{15.10}$$

'α' for a RP diode is proportional to the ratio r_c/r_a and also to the ion current fraction. It can vary from 1 and go as high as 3. There are some applications which require the extraction of electron beams in to the vacuum region. A foil less diode can be used in such cases. The beam does not pass through the anode here, but is guided by an external magnetic field. The formation of anode plasma due to electron impact heating is not a concern here and relativistic magnetron and BWOs use foil less diodes.

References

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