Indian J. Phys. **66B** (5 & 6), 639 – 650 (1992)

Relativistic electron beam generation and transport through low pressures gases

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Abstract : Intense pulsed relativistic electron beams (REB) are characterised by high pulse powers ranging from gigawatts to terawatts and have important applications in scientific research, industry and defence. Physical processes involved in the generation of these beams and aspects of diode design have been discussed. The transport of high power REB in low pressure gas channels, taking into consideration charge and current neutralization processes and plasma heating, is also discussed.

Keywords : REB, generation, transport in low pressure gases.

PACS Nos. : 41.80 Ee, 52.40 Mj

1. Introduction

In recent times, intense relativistic electron beams (REB) of a few tens of nanoseconds duration have been developed and studied extensively. Of particular interest are the beams with gigawatt to terawatt powers and beam voltages in the range 0.2–5 MV. The interaction of these high-power density beams with low pressure gases, is of considerable importance in the study of beam transport and plasma beating [1,2]. Both these areas of study have important applications in magnetic and inertial confinement fusion research. In addition to their role in the fusion research, high-power pulsed beams have also found important applications in the fields of (a) intense pulsed particle sources of electrons, ions and neutrons, (b) generation of X-rays, microwaves and laser radiation, (c) flash radiography, (d) collective acceleration of ions and (e) material studies.

Relativistic electron beams can be generated in a vacuum, a partial vacuum or a plasma-filled diode gap. The emission process [3] involves the formation of field emission initiated cathode-flare plasma from cathode whiskers. An anode plasma is also formed due to electron bombardment. The diode impedance is time dependent and is basically governed by the Child-Langmuir law with modifications due to movement of the cathode and anode plasmas. When the diode current is very high, the effect of the self magnetic field of the beam is also to be taken into account. For high powers exceeding 10^{10} W at 1 MV, para-potential models [4] taking into account beam pinching have been developed. The plasma and the gas filled diodes [5,6] have a unique advantage of controlling the beam pulse duration by a suitable choice of the plasma density or the gas pressure.

REB transport over distances exceeding 1 m is essential for many applications. A low-pressure gas channel offers a simple and efficient method of neutralizing the self electric and magnetic fields of beams, and enables the transport of very high-power beams. Optimization of beam and gas parameters [2,7], taking into account various beam-gas interaction phenomena like charge and current neutralization, and plasma heating, is important for efficient charge transport.

In Section 2, the physical processes involved in beam generation and some aspects of diode design are discussed. Beam-gas interaction and optimisation of beam and gas parameters for efficient charge transport are covered in Section 3. The conclusions emerging from these studies are presented in Section 4.

2. Relativistic electron beam generation

The pulsed beam technology, in the earlier stages, was developed for weapons simulation research. However the theoretical work of Winterberg [8] in 1968, indicating the possibility of producing an inertially confined thermonuclear plasma using intense electron beams, gave impetus to the development and study of intense relativistic electron beams at high beam energies. Technological advances in pulse power technology and particle beam generation resulted in the availability of intense pulsed beams up to terawatt power levels for studies and applications in the fields of scientific research, industry and defence. Table 1 shows typical beam parameters of interest for various applications.

Table 1. Typical beam parameters.

Partical energy	:	100 keV – 15 MeV
Beam current	:	1 kA - 1 MA
Beam current density	:	1 kA/cm^2 – 1 MA/cm^2
Pulse duration		10 ns – few μs
Beam radius		1 cm – 10 cm
Pulse power	:	10^9 W – 10^{13} W
Beam energy		100 J – 1 MJ

A. REB System :

A typical REB system for beam generation and transport studies is shown in Figure 1. The sub-systems are shown in the block diagram (Figure 1(a)) while details of the diode and drift region are shown in Figure 1(b). The main components of the system are (1) pulse power system, (2) field emission diode and (3) a drift tube for beam propagation and interaction studies.

In the pulse power system [9], a Marx generator is charged by a DC power supply. The Marx, in turn, pulse charges a pulse forming line to a high voltage. The pulse forming line is a co-axial transmission line or a Bluemlein line with deionised water or oil as the dielectric. The vacuum diode is connected to the pulse forming line through a transmission line feed and a high voltage spark gap.

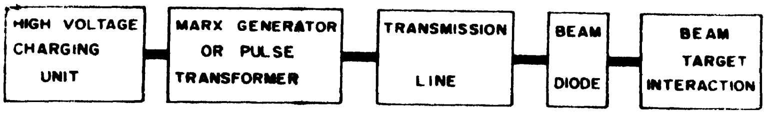

Figure 1(a). Block diagram of a typical REB system.

Sometimes a magnetically insulated vacuum transmission line is used as the transmission line feed. In some systems a Tesla transformer is used in place of the Marx generator.

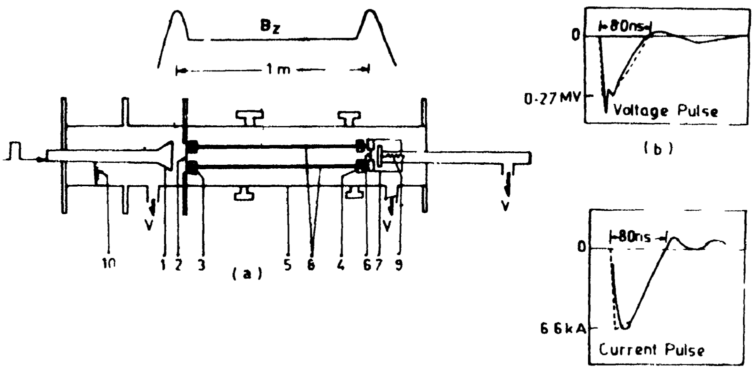

Figure 1(b). Schematic of REB diode and interaction region. 1-Cathode; 2,6–12.5 μm Ti foils; 3,4–Rogowski coils R_A, R_B; V-vacuum system; 5–drift tube; 7–Faraday cup; 8–return current rods; 9–current shunt; 10–$CuSO_4$ voltage divider.

The vacuum diode is a high voltage low impedance device with suitably designed dielectrics for mounting the cathode and anode electrodes. Graphite is most commonly used as the cathode material and the anode is usually a thin (12.5 μm) titanium foil which allows beam injection into the drift region with negligible energy loss. Frequently, a mirror type of magnetic field is used in the drift region to guide the REB as well as to confine the beam generated plasma. Fast response diagnostics are employed to characterise the beam and plasma parameters during the experimental investigations.

Some of the intense beam facilities developed in various countries are shown in Table 2.

B. Physics of beam generation :

REB can be generated in vacuum, partial vacuum or a plasma filled diode. In the following discussion, a vacuum diode is presumed unless otherwise specified. The REB diode (Figure 2), in its simplest form, consists of a planer cathode and a titanium foil anode. The anode is usually grounded and a negative high voltage is applied to the cathode. Pressure in the anode-cathode region is maintained at 10^{-5} Torr.

Table 2. Output characteristics of some intense beam generators.

Facility	Voltage MV	Current kA	Current duration ns	Power GW
Hydra, SNL, USA	1	1×10^3	80	1.0×10^3
Proto–II, SNL, USA	1.5	5.5×10^3	50	8.25×10^3
Angara I, USSR	2.5	4×10^2	60	1.0×10^3
Aurora HD, USA	12	1.6×10^3	120	1.9×10^4
Gamble II, NRL, USA	1	1.0×10^3	50	1.0×10^3
Reiden IV, ILE, Japan	1–2.5	1.0×10^3	50	2.0×10^3
Cornell USA	0.3–0.5	30–100	50–60	40
KALI-200, BARC, India	0.2	10	50	2
KALI–5000	1.0	75	50	75
BARC, Inida (under fabrication)				

The physical processes [10–13] leading to beam generation can be described in the following steps :

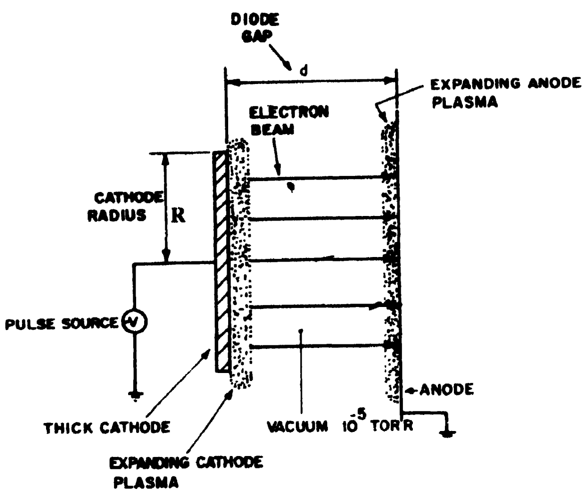

Figure 2. Schematic of REB diode.

i) When the pulse high voltage is applied across the diode, a high electric field (10^7–10^8 V/cm) is established at the whiskers on the cathode surface. The whiskers blow up due to the high local current density drawn and the consequent resistive heating. The vapour of the cathode material thus formed is ionized by the electrons resulting in the formation of a plasma, called the cathode flare plasma [14], which servés as the source for electron emission.

ii) Electron bombardment heats the anode resulting in the release of absorbed gases as also the evaporation of the anode material. The desorbed gases are rapidly ionized by the electron beam and by avalanching, leading to the formation of the anode flare plasma.

iii) The high density flare plasmas expand radially and axially with typical velocity of 2–4 cm/μs. The electron emission is governed by the time dependent spacing between the flare plasmas and will cease when the diode is shorted due to the meeting of the plasmas.

The electron current density is given by the Child-Langmuir relation. For plane parallel diode consisting of a cylindrical cathode of radius R and a vacuum gap d to the flat anode, the beam current density [13] J_b at a time, t, is given in MKS units by

$$J_b\,(\mathrm{A/m^2}) = \frac{2.34 \times 10^{-6}}{(d - vt)^2}\, V^{3/2}$$

where V is the applied voltage, in volts and ϑ is the plasma closure velocity.

In terms of impedance Z, the above equation can be written as

$$Z\ (\mathrm{Ohms}) = \frac{136\,(d - vt)^2}{V^{1/2}\, R^2}$$

where V is in units of million volts (MV).

The measured diode impedences [15] agree within a factor of 2 with the Child-Langmuir impedence.

At high beam currents, the self magnetic field begins to modify the electron flow and tends to pinch the flow pattern around the axis. The critical current I_c above which this pinching occurs is given by Friedlander *et al* [16,12] as

$$I_c\,(\mathrm{A}) = 8500\ \beta\, \Gamma\, (R/d)$$

where β is the ratio of the velocity of the electron to the velocity of light in vacuum and Γ is the relativistic factor defined as $\Gamma = \left(1 - \beta^2\right)^{-\frac{1}{2}}$.

For beam current $I_b > I_c$, due to self magnetic effects, the electron flow is no longer orthogonal to the equipotentials and the beam electrons tend to flow parallel to the equipotentials to get focussed around the axis. The saturated parapotential current I_{bp} was obtained by Creedon [17] by approximating to pinched flow pattern by relativistic Brillouin flow. The expression for I_{bp} for planar geometry is given by

$$I_{bp} = 8500\ \Gamma\,(R/D)\,\ln\left[\Gamma + \left(\Gamma^2 - 1\right)^{\frac{1}{2}}\right].$$

Creedon was able to obtain reasonable agreement with impedence measurements for diodes operating at 1 MV in the 1–4 ohm regime. Goldstein *et al* [18] gave a similar expression based on forward focussed flow while Cooperstein and Condon [19] obtained an empirical expression which fits their data.

The parapotential expression is applicable for power levels of 10^{10}–10^{11} W at 1 MV and does not scale up to powers of terrawatts and the impedances obtained by experiment do not agree with values predicted. At these higher powers, ion flow also becomes important and analytical treatment was given by Goldstein and Lee [20] and computer simulation was used by Poukey [21].

These results set the lower limit on diode impedence for efficient conversion of source energy at 1 ohm and 1–2 TW. Thus higher power particle beam drivers for fusion [16] and other applications require modular structure with each diode operating at 1–2 TW. Particle beam fusion accelerator PBFA at Sandia Laboratory has been designed to have 36 beams to give 100 TW for D–T pellet fusion applications.

Most of the facilities developed are for producing short duration (~50 ns) electron beam pulses. However, high power long pulse (~1 μs) electron beams have potential for plasma heating in solenoidal trap [22]. Recent studies by Arzhannikov *et al* [23] reported from USSR, indicate the successful generation of 1 MeV beam pulses of 10 μs duration. High efficiency λ (~75%) of energy transfer from a capacitor storage to electron beam with total energy of about 150 kJ has been attained in these experiments where long anode-cathode gaps of 5–8 cm with an axial magnetic fields of 1.0 T were used.

C. Plasma and gas filled REB diodes :

Most of the experimental results are based on the vacuum diode in which pressure is maintained at 10^{-5} Torr. In order to increase the current in the diode, plasma and gas filled REB diodes have been investigated. Miller *et al* [5] have reported that when plasma of density 10^{13}–10^{14} cm^{-3} is injected in the cathode-anode gap, impedence of the diode collapses rapidly during the pulse duration and more current can be drawn. Pulse shaping studies in gas filled relativistic electron beam diode have been reported by Mittal *et al* [6] in which voltage and current pulse duration can be varied from 60 ns to 10 ns when pressure is changed from 10^{-5}–10^{-1} Torr.

Thus using the formulation described in this section, REB of desired paremeters can be designed. Since the physics of beam generation has evolved from the experiments only, this description provides the basic guidelines. Scaling laws for higher power beams do not exist and hence only experiments can determine the beam properties.

3. Beam transport through low pressure neutral gases

REB transport is basically governed by the intense self electric and magnetic fields of the beam in addition to any externally applied fields. Because of the very high self-fields, transport of high current beams in vacuum requires expensive high magnetic fields over large volumes. On the other hand these beams can be conveniently transported through neutral gas and plasma channels where the necessary charge and current neutralization could be achieved. As the beam traverses a gas it causes ionization and the ion-background neutralized the beam charge to a degree depending on the charge neutralization factor f_e which is given by the ratio of the ion density to beam electron density. During this time, the electrons produced by ionization are assumed to leave the beam-channel owing to the large radial electric field caused by the beam space-charge and transport is governed by the reduced self electric field and self-magnetic field. When forces due to these fields balance, the beam transports in a force-free condition and the input beam divergence controls the beam expansion. However, the force-free condition is not a stable one as further charge neutralization takes place. When the beam charge is fully neutralized, further ionization leads to the formation of a plasma. Under the influence of induced electric field generated by time varying beam current, a plasma current is driven. With the flow of the plasma current the net current I_n is given by the algebraic sum $(I_b + I_p)$ of beam and plasma currents. In the rising part of the beam current pulse, the induced plasma current flows in the reverse direction to the beam current. However, in the fall portion of the beam current pulse the plasma current decreases and finally changes direction due to the changes in E_z direction and flows in the same direction as the beam current. The current neutralization factor f_m is the ratio of the plasma current to the beam current. The transport, after fractional current neutralization is governed by the magnetic field produced by the net current.

A. Beam parameters and limiting currents

In order to understand beam transport and interaction with gases the limiting currents that are important are defined below :

The space charge limiting current [24], I, arises from the radial electric field due to space charge and for vacuum propagation, is given by

$$I\,(\mathrm{kA}) = 17\left(\Gamma^{\frac{2}{3}} - 1\right)^{\frac{3}{2}}\left[1 + 2\ \ln\left(\frac{R}{R_b}\right)\right]^{-1},$$

while R_b is the beam radius and R is the radius of drift tube in which the beam is propagating. The limiting current can be increased by reducing the space charge field by introducing a neutralizing ion background. For instance, if f_e is the fractional charge neutralization given by $f_e = n_+ Z/n_b$ where n_+ and n_b are ion and beam electron densities and Z is the ion charge state, then I is given by

$$I\,(\mathrm{kA}) = 17\left(\Gamma^{\frac{2}{3}} \cdot 1\right)^{\frac{3}{2}}\left[1 + 2\ \ln\left(\frac{R}{R_b}\right)\right]^{-1}, \quad (1 - f_e)^{-1}.$$

Another limiting current which is of great importance in transport studies is the Alfvén current [25], I_A, which is the maximum current that can be propagated after a beam is completely charge neutralized.

This limiting current arises as a result of the self magnetic field preventing forward motion of electrons and is given by

$$I_A\,(\mathrm{kA}) = 17\ \beta\,\Gamma.$$

The ratio of beam current to Alfvén current is given by

$$I_b / I_A = N e \beta c / I_A,$$

where N is number of beam electrons per unit length. Expressing N in terms of the Budker parameter $\nu = N e^2 / 4\pi\varepsilon_0 mc^2$

$$I_b / I_A = \nu / \Gamma.$$

The beam parameter ν/Γ is a measure of the importance of self fields. For $\nu/\Gamma << 1$ the magnetic effects are negligible and transport is governed by space charge and its neutralization. For $\nu/\Gamma > 1$ the magnetic effects dominate and transport is only possible when the magnetic effects are neutralized.

B. Beam transport models :

The influence of charge neutralisation of beam transport was treated theoretically by Lawson [26] and numerical studies on beam transport over 1 m in various gases in 10^{-3}–1 Torr pressure range were reported by Miller *et al* [27] and Iyyengar and Rohatgi [28]. A general envelope equation which includes the effects of self fields, external uniform solenoidal field and scattering by background gas was developed by Lee and Cooper [29]. Current neutralization models taking into consideration beam impact ionization, electron avalanching and two stream instability were developed by Swain [30], Hammer and Rostoker [31] and others to explain net current measurements.

The work of Briggs *et al* [32] shows that two stream instability and electron heating are important mechanisms for ionization build up in the 10^{-2}–1 Torr region. The recent model on beam transport by Iyyengar and Rohatgi [33] takes into account (a) ionization by beam electrons, plasma electrons and avalanching, (b) charge and current neutralization and (c) plasma heating by return current and two stream instability. The effect of rise time and pulse width on charge transport was also studied by Iyyengar and Rohatgi [34] using the above model. The results (Figure 3) indicate that charge transport is higher for short rise times and longer pulse widths at an optimum pressure in the range 0.1–0.2 Torr for argon and hydrogen.

C. Experimental results of beam transport :

Charge transport results for two beams with ν/Γ of 0.05 (0.35 MeV, 25 kA) and 1.0 (1.5 MeV, 3 kA) were reported by Miller *et al* [27] and compared with calculations. While the agreement is good for the low ν/Γ beam, the calculated charge transport is higher for the beam with $\nu/\Gamma = 1$, indicating the necessity of taking into consideration current neutralization in calculations. The experimental results of Yonas and Spence [35] for 200 keV, 50 ns ($\nu/\Gamma \approx$ 10) beam at 0.1–1.0 Torr indicate complete current neutralizaiton and $(\nu/\Gamma)_{\rm net}$ of unity agreeing with the modified Lawson model.

Increase of transport efficiency with longitudinal magnetic field has been reported by Bzura and Limbe [36] for a 400 keV, 60 kA beam. An increase from 65% (no field) to 85% with 2 KG field at 0.5 Torr of air for transport of 2.5 m was reported. The results of transport of 200 keV, 200 kA, 50 ns beam in a solenoidal field upto 28 kG, reported by Stalling *et al* [37] for gas pressures of 0.3 to 1.5 Torr indicate an optimum value of magnetic field (≈9 kG for these experiments). The fall of efficiency at higher magnetic field has been attributed to lack of current neutralisation. The experiments of Bolduc and Patterson [38] with 2 MeV, 10 kA beam in a single ended magnetic mirror (5 kG uniform field and 3.7 mirror ratio) at 500 m Torr air over 50 cm show a fluence (energy per unit area) increase by a factor of 2.7. Experimental results and numerical calculations [33] of the transport of 0.27 MeV, 6.6 kA, 40 ns beam in argon and hydrogen in the pressure range of 0.01 to 1.0 Torr are

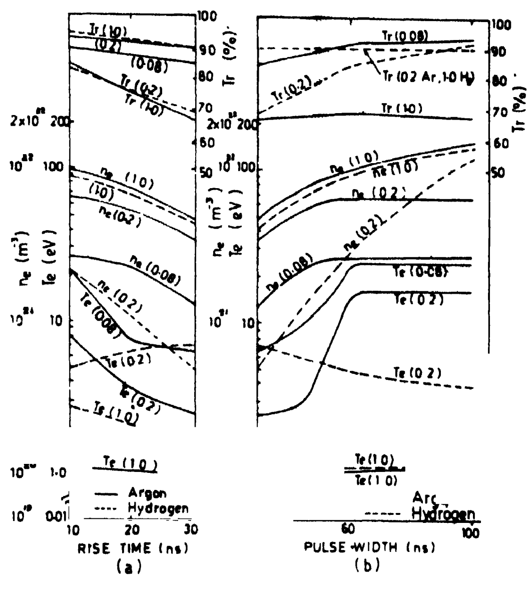

Figure 3. Effect of (a) rise time and (b) pulse width of a 1 MeV, 15 kA REB interacting with argon and hydrogen The electron density, electron temperature, and charge transport are indicated by n_e, T_e and T_r respectively Numbers in parentheses indicate pressure in Torr

shown in Figures' 4 and 5 respectively. The importance of current neutralizaiton in calculations is seen in Figure 4 (curves b and c). For pressures in 0.1 to 1.0 Torr the net current (Figure 4a) is seen to be decreasing due to increasing plasma currents. As the net current decreases, the charge transport is also reduced (Figure 4b) since the self-magnetic focussing force (proportional to net current) decreases. The breakdown time shown in Figure 4b is the time when rate of change in plasma current is equal to rate of change of beam current implying full current neutralizaiton.

As seen in Figure 5, the mirror magnetic field (1.5 kG–1.0 kG– 1.5 kG) is seen to enhance the peak calculated transport from 70% to 90%. The higher values of experimental

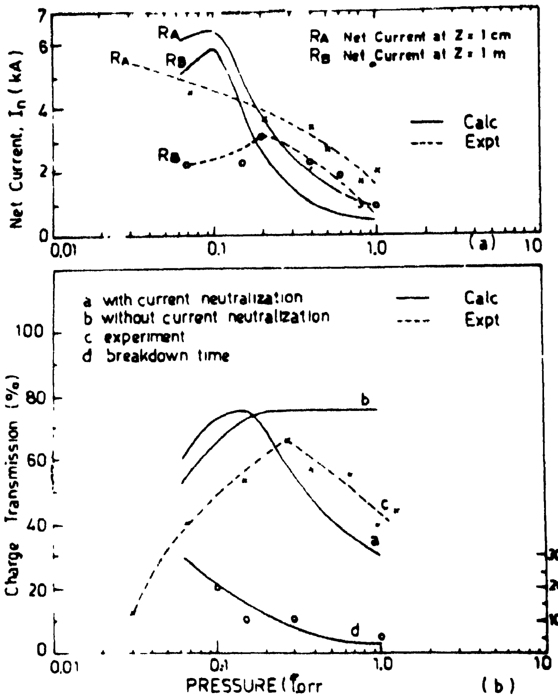

Figure 4. Comparison of calculated and measured charge transport, net current, and breakdown time t_B for 0 27-MeV, 6.6-kA, 40-ns electron beam transport in argon.

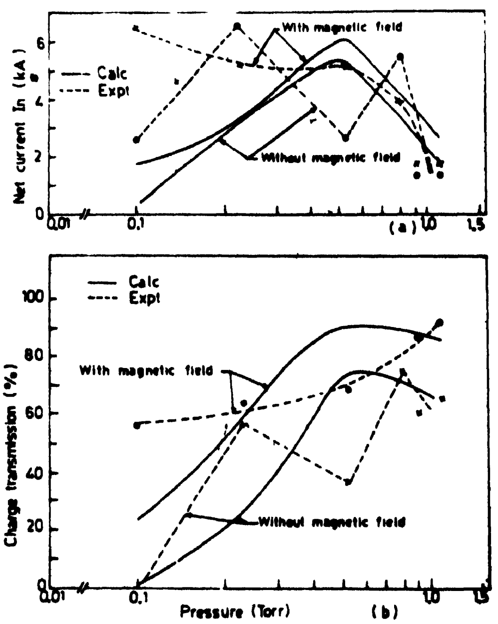

Figure 5. Calculated and measured charge transport and net current for 0.29-MeV, 6.3-kA, 40-ns electron beam in hydrogen, without and with a mirror magnetic field of 1.5–1.0–1.5 kG.

transport at lower pressure (0.1–0.3 Torr) have been attributed [33] to possible current multiplication due to two stream instability in this low pressure region.

4. Conclusions

Intense pulsed electron beams with power in the giga watt to tera watt range have been generated from field emission initiated flare plasma cathodes. The impedence of these REB diodes is time varying due to plasma motion and obeys the Child-Langmuir emission law for beam currents upto about 100 kA. At higher currents parapotential flow and ion flow have also to be taken into consideration and computer simulation of electron trajectories is necessary to understand diode behaviour.

Transport of these beams over distances exceeding 1 m is important for many applications including plasma heating and fusion research. These beams can be efficiently transported in low pressure neutral gases where beam-gas interaction leads to neutralization of self electric and magnetic fields of the beam. It is necessary to take into account beam parameters as well as beam plasma interaction phenomena like induced plasma current, plasma heating and instability growth to optimise efficient change transport.

Acknowledgment

The author wishes to thank Drs K C Mittal, A S Paithankar and V K Rohatgi for many fruitful discussions.

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