EXPERIMENTAL STUDY OF AN UNNEUTRALIZED RELATIVISTIC ELECTRON BEAM TRANSPORTATION THROUGH THE WAVEGUIDES

Lalit Gupta, IPS Academy, Indore-452012

Y. Choyal, Prasad Deshpande, K. P. Maheshwari, Devi Ahilya University, Indore-452 001

S. C. Bapna, Raja Ramanna Centre for Advance Technology (RR-CAT), Indore-452 013

Abstract

The experimental results of unneutralized electron beam transportation in an evacuated cylindrical metallic drift tube have been obtained. Marx generator is used as a high voltage source to energize the cathode. A 300 keV, 2 kA, and 150 ns pulsed electron beam has been generated by the field emission diode. For axial guidance of the electron beam a 1 Tesla, 260 μs, guide magnetic field has been used. The guide-magnetic field is generated by the discharge of a capacitor bank into a solenoid. A synchronized circuit ensures the triggering of the electron beam at the instant when the axial magnetic field attains its peak value. Experimental studies of the electron beam transportation through various metallic tubes of different wall-materials, and different thicknesses in the presence of varying magnetic fields have been made. Our experimental results show that the transportation properties of the beam get substantially affected because of the different diffusivity of the guide magnetic field through the different materials, and different thicknesses of the wall of the drift tube.

INTRODUCTION

Over the last two decades high-current electron-beams are becoming useful tools in various areas. The applications of these beams have produced a number of advances that did not appear possible without them. With increasing machine capabilities it is very important to study the behavior and propagation of the electron beam [1]. The primary limitation to efficient transport of intense beams is the electrostatic potential depression which results from the electron beam space charge [2]. If the injected beam current exceeds the space charge limiting current of the guide/cavity a virtual cathode will form whose position and transparency are determined by several experimental parameters. High current electron beam can only be transported with the help of sufficiently strong axial guide magnetic field. In this paper we present several experimental results related to the injection of an intense electron beam into an evacuated drift space and its transportation. The experimental results related to the electron beam transportation through various metallic tubes of different wall-materials, and different thicknesses have been obtained. It is observed that the transportation properties of the beam get substantially affected because of the different diffusivity of the guide magnetic field through the different materials of the wall of the drift tube. It is well known that the un-neutralized beam self-

fields cause the beam to expand, while the B_0 supplies a restoring force. The equilibrium radius r_{b0} is

$$r_{b0}^2 = \frac{2P_\theta / m}{\left(\Omega^2 - 2\omega_e^2 / \gamma_0\right)^{1/2}} \qquad (1)$$

$\Omega = eB_0 / mc$ is cyclotron frequency, $\omega_e = \left(4\pi n_0 e^2 / m\right)^{1/2}$ is the beam plasma frequency and P_θ is the canonical angular momentum and there can be no equilibrium unless

$$\Omega^2 \ge 2\omega_e^2 / \gamma_0 \qquad (2)$$

For a 300 keV electron beam of density 10^{12} /cm^3, the magnetic field strength required for equilibrium is ~ 3.6 kG. Hence, axial guide magnetic field can easily satisfy the equilibrium condition for vacuum transportation of intense electron beams. For a solid, magnetized electron beam, the minimum beam size is given by

$$r_b = \sqrt{\left(8Ic^2\right)/\left(I_A \Omega_0^2 \gamma^2\right)}, \qquad (3)$$

where I is the beam current, I_A is the Alfven current, $\Omega_0 = eB / \gamma mc$ is the relativistic gyro frequency in the guide magnetic field.

The relativistic beam current that can be allowed through a wave-guide is governed by the relation

$$I_b = \frac{I_A}{2\ln(r_0 / r_b)}\left(\gamma_b^2 - 1\right)^{1/2} \frac{\gamma_c - \gamma_b}{\gamma_b}$$

where $\gamma_b = \left(1 - v_b^2 / c^2\right)^{-1/2}$, γ_c is related to cathode potential $\phi_c : \gamma_c = 1 + e\phi_c/mc^2$, $I_A = 4\pi\varepsilon_0 mc^3 / e = 17.1\,kA$, r_0 is the mean waveguide radius. For the chosen parameters of the beam and the waveguide a plot of I_b vs γ_b for $\phi_c = -300$ kV, $r_b = 0.5$ cm and $r_0 = 1.5$ cm is shown in **figure 1**. The maximum steady-state current that the waveguide will allow is given by

$$I_{scl} = \frac{I_A}{2\ln(r_0 / r_b)}\left(\gamma_c^{2/3} - 1\right)^{3/2} \quad ;$$

and is referred to as the space charge limiting current. This idealized value represents an upper limit.
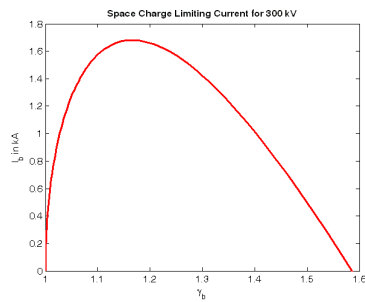
Figure 1: The dependence of beam current, I_b on γ_b for $\phi_c = 300$ kV, $r_b = 0.5$ cm, $r_0 = 1.5$ cm.
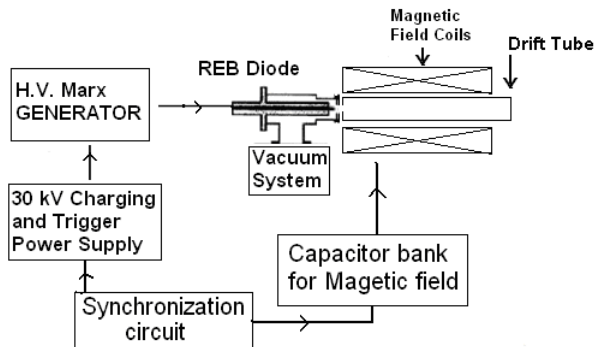
EXPERIMENTAL SET-UP

Figure 2: Experimental set-up for electron beam generation and its transportation

The schematic diagram of experimental set-up used in these studies is shown in **figure 2**. The electron beam is generated by a 20 stage, 300 kV Marx generator [8]. For the initial charging voltage of magnitude 25 kV, we get 230 keV, ~ 2 kA electron beam of 150 ns pulse duration. Voltage and current rise time of electron beam is observed to be ~ 30-40 ns. A diode assembly consisting of a stainless steel (SS) cathode and 3 mm thick, 300 mm long SS drift tube of 20 mm and 40 mm diameter is used in the experiment. The anode cathode gap is 7 mm. The pressure in both the diode and drift tube is maintained at 5×10^{-5} Torr. The magnetic field is provided by the discharging of a 210 μF capacitor bank through a 34 μH solenoid load. The period of discharge is sufficiently long (260 μ s) to allow complete field penetration through the drift tube and provide a constant magnetic field over the electron pulse duration. We have repeated these experiments with tubes of different thicknesses and with different wall materials (SS, Al and copper).

RESULTS AND DISCUSSION

In the beginning of the performance of the beam transportation experiment through the smooth wall waveguide we charged the Marx generator up to a maximum of 15 kV. The output (~ 150 kV) of the Marx generator was applied to the cathode of the diode to generate an electron beam. The electron beam signatures were obtained immediately after its generation on a thermal paper fixed at the anode at a distance of 7 mm from the cathode. Initially the experiment was performed

Other

in the absence of any guide magnetic field. The beam spot is shown in **figure 3a** and the beam size (diameter) is 16 mm.
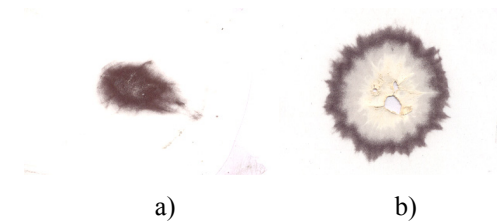

a)   b)

Figure 3 Electron beam spot at a distance of 7 mm from its occurrence and charging voltage of Marx generator is limited to a) 15 kV and b) 25 kV
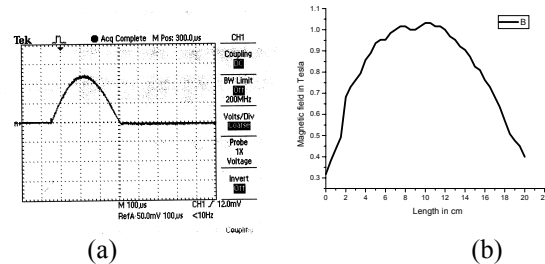

(a)   (b)

Figure 4: Temporal and spatial profile of 10 k Gauss magnetic field

However, the beam got completely lost at some distances in the drift tube in the absence of any guide magnetic field. We performed our further studies on beam transportation in the drift tube along the axis in the presence of the guide magnetic field. The profile of the guide magnetic field (both temporal and spatial) is shown in **figure 4**. This 260 μs magnetic field pulse is synchronized with the 150 ns electron beam as shown in **figure 5b** where the channel 1 corresponds to the electron beam while the channel 2 shows the magnetic field. The output voltage waveform of the electron beam for 15 kV charging voltage is shown in **figure 5a**.

The signatures of the electron beam at different distances in the drift tube along the axis in the presence of axial guide magnetic field of intensity 10 k Gauss (1.0 Tesla) are shown in **figure 6**. At a distance of 1.7 cm from the cathode the beam spot is shown in **figure 6a**. We give our results of beam transportation at a distance of 5.7, 10.7, 15.7 and 20.7 cm from its occurrence as shown in **figure 6b-e** respectively. As expected, the beam size within the tube is found to be smaller than as shown in figure 3a, at the entrance of the drift tube. The reason is that the magnetic field in the solenoid is not uniform and it is maximum at the center of solenoid and half at the ends as shown in spatial profile of the solenoid in figure 4b. Therefore the magnetic field at the entrance end of the solenoid is 5 k G. At this field the beam is confined and beam size (diameter) reduces up to 8 mm. Further at a distances 5.7 cm from the cathode the beam sees stronger field (~7.5 kG) and the beam size reduces up to 4.0 mm as shown in **figure 6b**.
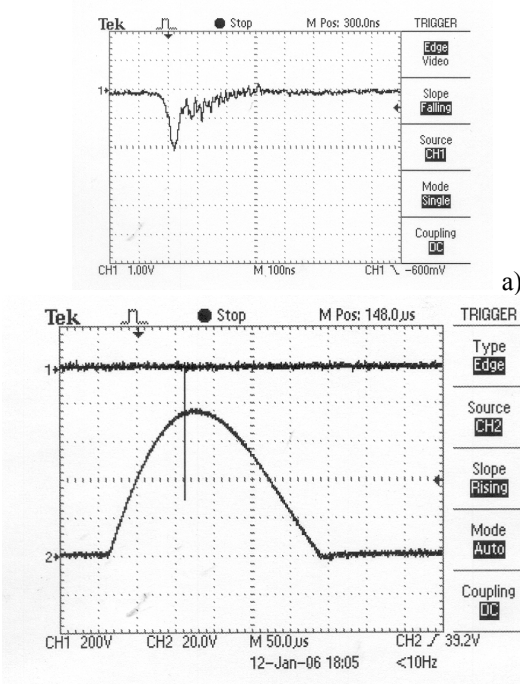
a)

b)

Figure 5: a) Output voltage waveform of electron beam, V_c =15 kV, B=10 kG and b) Synchronization of the 150 ns electron beam with 260 µs magnetic field.

At -1.0 cm   At - 5.0 cm   At -10.0 cm
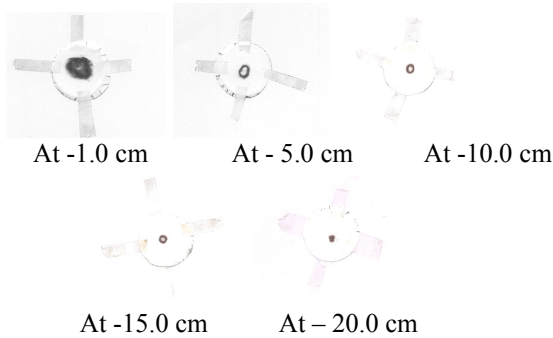

At -15.0 cm   At – 20.0 cm

Figure 6: Electron beam spots at various distances from the beam emergence in SS drift tube of thickness 20 mm along the axis, for the charging voltage of Marx is V_c =15 kV, and magnetic field B = 10 k Gauss

Further moving in the drift tube up to 10.7 cm from the cathode (i.e. at the centre of the solenoid) the beam sees here the strongest field (10 kG) and beam size reduced up to 3.0 mm. The corresponding beam spot is shown in **figure 6c**. The beam spot size remains unchanged upto a distance of 15.7 cm validating the uniformity of the axial magnetic field upto this distance. At the exit end of the drift tube (20.7 cm form the cathode) the beam size is very small with very less intensity. Initially the beam is very intense and is able to burn the thermal paper uniformly leaving a black imprint.

At -1.0 cm   At -5.0 cm   At -10.0 cm

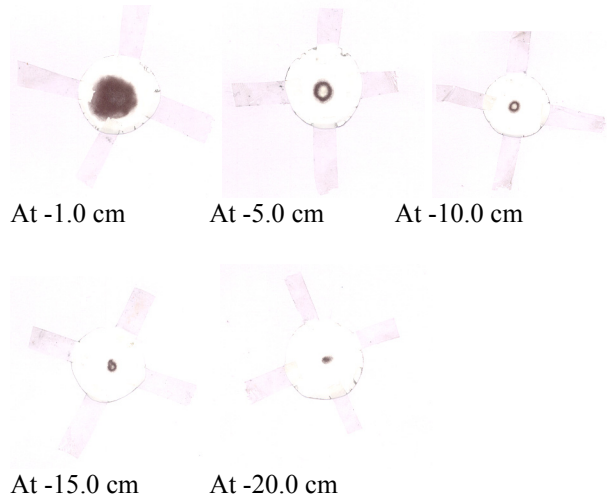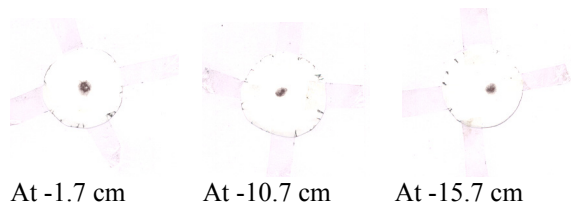
At -15.0 cm   At -20.0 cm

Figure 7 Electron beam spots at various distances from the beam emergence in SS drift tube of thickness 20 mm along the axis, for the charging voltage of Marx is V_c =15 kV, and magnetic field B = 7.5 k Gauss

At -1.7 cm   At -10.7 cm   At -15.7 cm

Figure 8 Electron beam spots at various distances from the beam emergence in SS drift tube of thickness 20 mm along the axis, for the charging voltage of Marx is V_c =15 kV, and magnetic field B = 2.5 k Gauss

We repeated the above experiment with a lower values of the magnetic fields viz. 7.5, 5, 2.5 kG at the centre of the solenoid while keeping the Marx charging voltage same 15 kV. The corresponding results are shown in figure 7 and 8. For the magnetic field 2.5 k Gauss, the beam does not travel up to the end of the drift tube. We get the signature of the electron beam up to the three forth length of the drift tube. As we reduce the magnetic field below 2.5 k Gauss the beam does not travel into the drift tube.
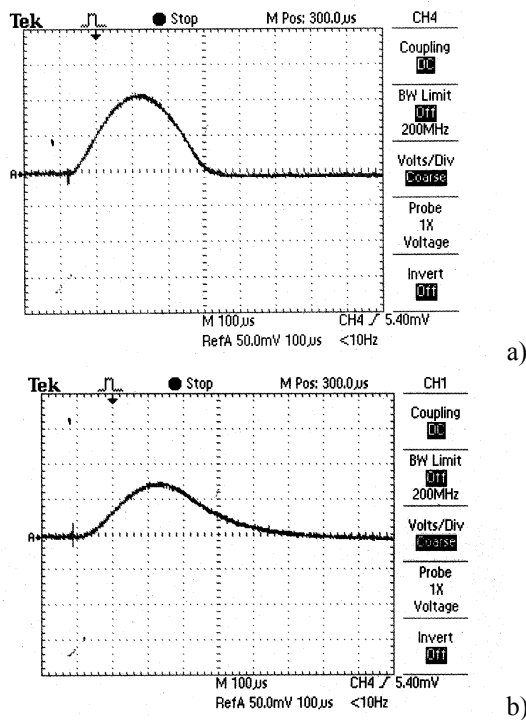
Other

a)

b)

Figure 9: Magnetic field diffusion profiles in SS drift tube with wall thickness a) 3.0 mm, and b) 9.0 mm

We repeated the beam transportation experiment for all the above values of magnetic field with charging the Marx up to 25 kV. And we see the same observations. The results of beam spots at various distances of travel in the drift tube and the magnitude of the guide axial magnetic field are summarized in the table 1. We have also performed the magnetic field diffusion experiments with the different wall thickness of the SS drift tube (3 and 9 mm) as well as copper and Aluminum drift tubes. The results are shown in **figure 9.** And we conclude that the SS tube is better for beam propagation. Because the magnetic field in copper and Aluminum tube is diffuses a lot. In copper tube the magnetic field reduced up to 90 % and we get only 10 % field while in SS we get 85% magnetic field.

CONCLUSION

In conclusion we find that for injected currents in excess of the space charge limit a guide magnetic field is needed for relativistic beam transportation through a drift tube. In the absence of any axial magnetic field the formation of virtual cathode hampers the beam transportation and the beam gets reflected. The expansion becomes more pronounced as the field strength is

decreased below the equilibrium criterion leading to severe loss of beam particles to the drift tube wall.

REFERENCES

[1] M. Friedman, "Formation of a Virtual Cathode by a Relativistic Electron Beam flowing through a cavity", Applied Physics letters, Vol. 24, No. 7, 1 April 1974.

[2] R. B. Miller and David C. Straw. "Propagation of an unneutralized intense relativistic electron beam in a magnetic field" Journal of Applied Physics, Vol. 48, No.3, March 1977.

[3] Miller R. B., 1982, *An introduction to the physics of intense charged particle beams* (New York: Plenum Press).

[4] V. I. Krementsov, P. S. Strelkov and A. G. Shkvarunets, "Neutralization of the space charge and magnetic field of a relativistic electron beam upon injection into a plasma in a homogeneous magnetic field", Sov. J. Plasma Phys., Vol. 2, pp. 519-523, 1976.

[5] L.S. Bogdankevich and A.A. Rukhadze, "Stability of Relativistic Electron Beams in a Plasma and the Problem of Critical Currents," Soviet Phys. Us-pekhi, Vol. 14, pp. 163-179, 1971.

[6] A. F. Alexandrov, L.S. Bogdankevich, and A. A. Rukhadeze, "Principles of plasma electrodynamics", Chap.9, Sec.4, Springer-Verlag, Berlin, 1984.

[7] J. A. Swegle, J. W. Poukey And G. T. Leifeste, "Backward Wave Oscillators with rippled wall Resonators: Analytic Theory and Numerical Simulation", Phys. Fluid, Vol 28, pp 2882-2894, 1985.

[8] Y. Choyal, Lalit gupta, et al, development of 300 kV Marx generator, Sadhna Journal of engineering, Vol 30, Part 6, pp757-764, Dec. 2005