DESIGN OF RELATIVISTIC MAGNETRON FOR HIGH POWER MICROWAVE GENERATION

Romesh Chandra, Sandeep Singh, Ankur Patel, S. R. Ghodke, Archana Sharma
Accelerator & Pulse Power Division, Bhabha Atomic Research Centre, Mumbai, 400085, India

Abstract

A Linear Induction Accelerator based upon magnetic storage, utilising magnetic switches has been made and it is capable of providing a 400 kV diode voltage, 4 kA beam current for 100 ns pulse duration with 100 Hz repetition rate. It operates in a very high repetition rate due to the use of magnetic switches in it. The lesser shot to shot variation make this system ideal for a Relativistic Magnetron operation, where a huge dependence of output power on applied voltage and applied current is observed. A relativistic magnetron with axial extraction is analytically designed and simulated for this system. This relativistic magnetron is expected to give a power of 100 MW per pulse when operated in its full rating. The design features of this relativistic magnetron are presented here. This magnetron was designed for an output microwave frequency of 2.52 GHz.

INTRODUCTION

Pulse power systems are widely used for High Power Microwave (HPM) generation, Flash X-rays (FXR) production and intense electron beam applications. The applications include circuit vulnerability testing, dynamic radiography of fast moving objects via FXR and colouring of precious gems using electron beams [1].

In the recent developments in pulse power techniques for HPM generation, Relativistic Magnetrons have shown the best efficiency amongst all the available high power microwave devices [2]. Relativistic magnetron basically consists of coaxially coupled cavities in which a high magnetic field (0.2 T to 0.6 T) is applied perpendicular to the electron beam trajectory. This applied magnetic field is just enough to restrict the electrons within the interaction region between the cavities and the cathode. The minimum value of the magnetic field that can be applied for a given geometry at a particular accelerating voltage of electrons is given by Hull Cut-off condition. The maximum value of the magnetic field is given by Buneman and Hartree relation [3].

Based upon the extraction method of the HPM from the cavities, relativistic magnetrons can be divided into two subcategories, one is with radial extraction and another is with axial extraction. In the magnetrons based upon the radial extraction, a radial slot is made in one of the cavities and HPM is extracted through a waveguide and is radiated in the medium through an antenna. In the axial type of extraction system a portion of HPM is extracted through each of the cavities axially and is then radiated through an antenna. Since normally magnetrons are operated in π-mode which has zero group velocity, HPM extraction made through tapered cavity antenna.

A Relativistic magnetron based upon axial extraction method has been designed and developed for linear Induction Accelerator-400 (LIA-400).

RELATIVISTIC MAGNETRON

Design of the magnetron was done using Charged particle simulation technique (CST) simulation software.

LIA-400 System

A repetitive pulse power system was developed which is based on the magnetic pulse compression (MPC) technique and inductive voltage adders (IVA) similar to LIA-200 developed earlier in BARC [4]. The advantage of these types of systems is that these systems have high rep rate and a better shot to shot variability compared to those spark gap switch based systems. [5].

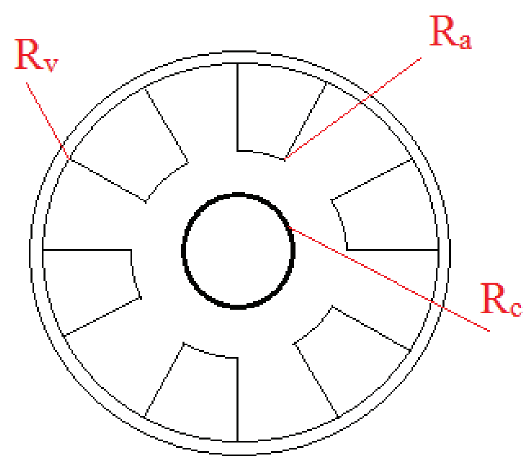

Figure 1: Simulated structure of the magnetron.

Simulation

Simulations were performed with the help of CST MS and CST PIC to get the frequency domain behaviour of this device. The simulation structure is given in fig.1. The values of R_c, R_a and R_v are 10 mm, 21.1 mm and 41.5 mm respectively. The length of the magnetron structure is 75 mm and is inside to the plane of the paper. Initially Eigen mode simulation was performed to get the Eigen modes of the six coupled cavities as shown in fig. 2. In all the modes obtained for the magnetron operation, π-mode operation with frequency 2.52 GHz was chosen because it is the only frequency which is non-degenerate. The electric field directions inside the cavity are shown in fig.3 for π-mode.

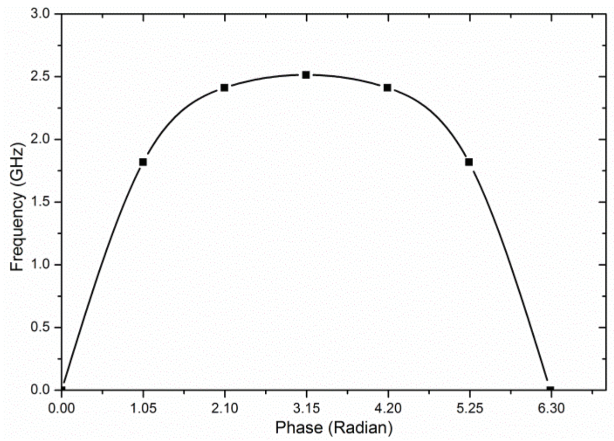

Figure 2: Dispersion curve for the six coupled cavities.

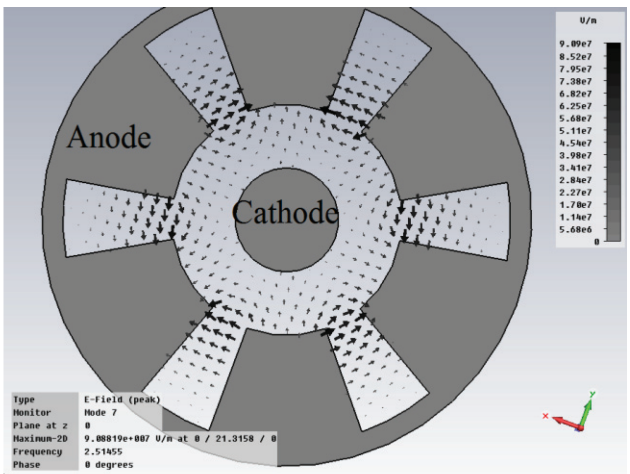

Figure 3: Π-mode field plot.

The electron velocity must correspond to this phase velocity. Once the phase velocity is known from equations (1) and (2), the values of the desired voltages and applied magnetic field can be calculated. These equations provide a set of diode voltage and magnetic field. One of the values may be chosen for the simulation.

$$B^2_{z,min} = \frac{8m}{e} V_A \left(\frac{r_a}{r_a^2 - r_c^2}\right)^2 \qquad (1)$$

$$\left(\frac{eV}{mc^2}\right) = \frac{eB_z\omega_n}{mc^2 n} r_a d_e - 1 + \sqrt{\left[1 + b_\varphi^2\right]\left[1 - \left(\frac{r_a\omega_n}{cn}\right)^2\right]}$$

where,

$$b_\varphi = \frac{I_z(kA)}{8.5} \ln\left(\frac{r_a}{r_c}\right) \qquad (2)$$

Here r_a and r_c are anode and cathode radius respectively. V_A is the applied voltage and n is 3 for π-mode. ω_n is the angular frequency for π-mode. The sets of possible solutions to equation (1) and (2) are plotted in Fig.4.

Particle in Cell (PIC) simulations were performed by taking a 400 kV operating voltage and 0.31 T magnetic field across the z-direction. The voltage pulse was taken to be rectangular with 5 ns rise time. Simulation was run for 50 ns duration. The current waveform obtained from simulation is shown in Fig.5.

The electrons emit from cathode as shown in Fig.8 (a) and start moving towards the anode. Due to external magnetic field these electrons start gyrating between anode and cathode. This space between anode and cathode is also known as the interaction space.

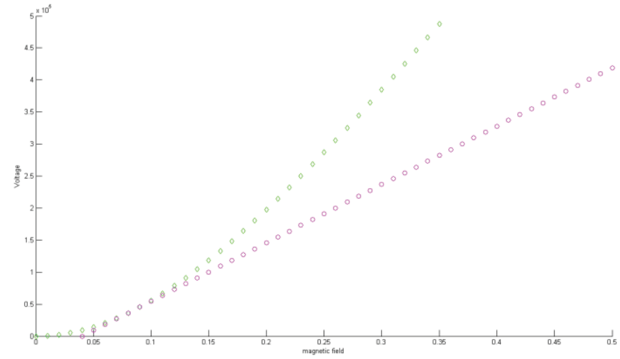

Figure 4: BH curve for this magnetron.

Due to fluctuation in the emission process a white frequency signal is generated in the cavity. Among these noise frequencies, the coupled cavity chooses appropriate frequencies which are the Eigen modes of the total cavity. Now since the group velocity (dω/dk) of the π-mode frequency is zero, this frequency signal starts building up much more strongly than other Eigen mode signals. When this signal is very strong it starts affecting the electron motion and if the applied voltage and magnetic field are appropriate for π-mode operation (given by eqn. (1) and (2)), electrons and microwave signal become resonant and a huge field is obtained in the output. Fig.6. shows the output electric field profile with the time. Fig.7. gives the fast fourier transform of the electric field signal.

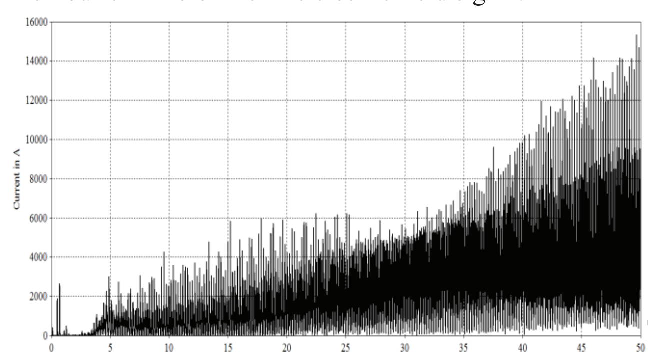

Figure 5: Total current passing through Anode cathode gap.

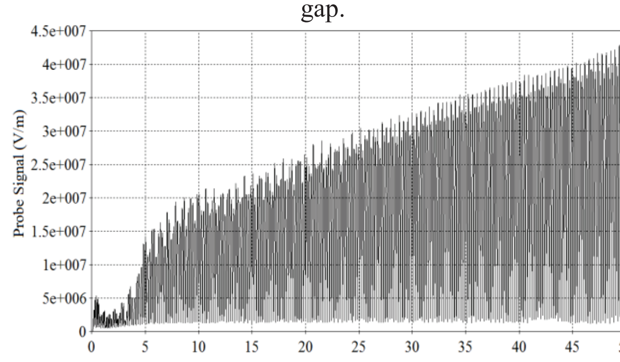

Figure 6: Absolute field recorded within one of the cavities.

ISBN 978-3-95450-142-7

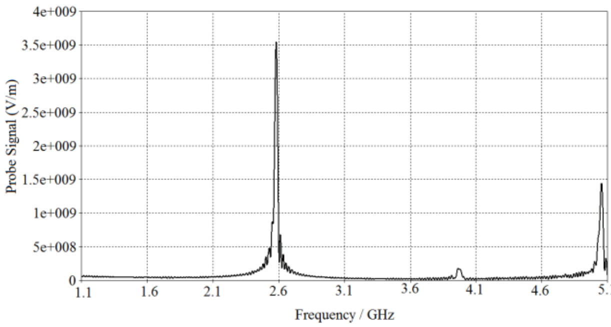

Figure 7: Frequency spectrum of the absolute electric field signal recorded as given in Fig.6.

Fig 8(a) shows the starting of the electron emission from the cathode. The applied voltage and the magnetic field values are so that the kinetic energy of the moving electron is just enough to reach at the anode. These electrons form a cloud in the interaction space and start moving collectively in the self produced radiofrequency fields. Fig. 8(b) shows the formation of electron cloud for 2π mode fields. At t=4.4 ns an electron cloud for π-mode is formed and is stable till the end of simulation. Fig 8(c) and 8(d) show the formation of electron cloud in π-mode, where three spokes of the electron cloud can be seen.

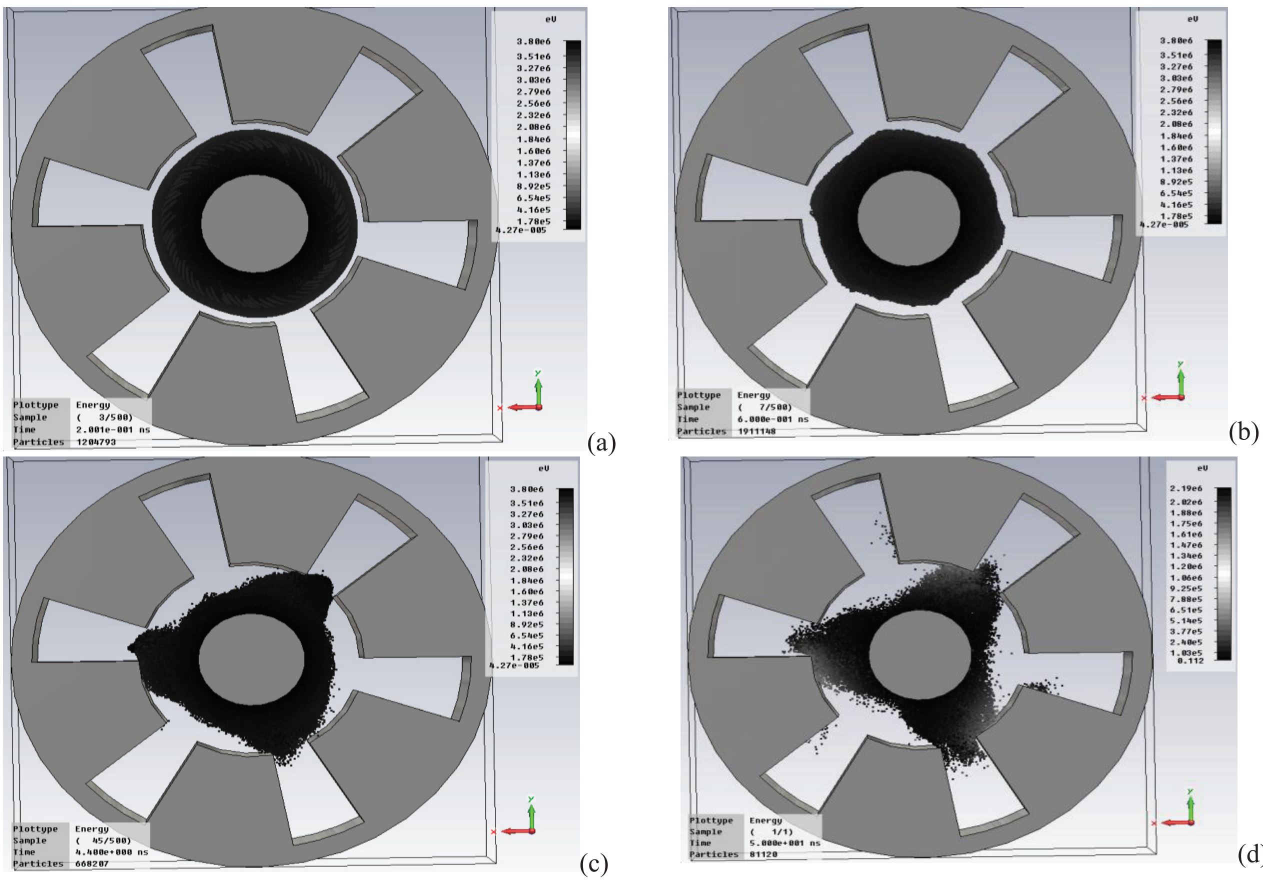

Figure 8:(a) Electron emission and it's trajectory in magnetic field. (b). 2π mode spoke formation. (c) π-mode spoke formed at t=4.4 ns and (d) at t=50 ns.

CONCLUSION

A relativistic magnetron with axial extraction has been designed using CST simulation software. The π-mode frequency was 2.52 GHz as simulated from Eigen mode solver. In PIC simulation this frequency comes 2.54 GHz. A stable operation of the magnetron in π-mode was seen throughout the simulation. This system will be tested with LIA 400 system for a 400 kV diode voltage and 4 kA beam current and it is expected to give 100 MW power.

REFERENCES

[1] J. Benford, "Space Applications of High-Power Microwaves", IEEE Trans. Plasma Sci., vol. 36, no. 3, pp. 569–581, Jun. 2008.

[2] M. I. Fuks and E. Schamiloglu "70% efficient relativistic magnetron with axial extraction of radiation through a horn antenna", *IEEE Trans. Plasma Sci.*, vol. 38, no. 6, pp.1302 -1312 2010.

[3] Y. Y. Lau et al. "A re-examination of the Buneman–Hartree condition in a cylindrical smooth-bore relativistic magnetron", Physics of Plasmas 17, 033102, 2010.

[4] Archana Sharma et al. "Preliminary results of Linear Induction Accelerator LIA-200", Journal of Instrumentation, Volume5, May 2010 *JINST 5 P05001.*

[5] Romesh Chandra et al. "Explosive Emission Properties of Cathode Materials in Relativistic Electron Beam Generation" Accepted IEEE plasma science.

ISBN 978-3-95450-142-7