Design of a Permanent Magnet Based Focusing Lens for a Miniature Klystron

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Abstract—Application of Permanent magnet technology to high frequency miniature klystron tubes to be utilized for space applications improves the efficiency and operational reliability of these tubes. But nevertheless the task of generating magnetic focusing forces to eliminate beam divergence once the beam crosses the electrostatic focusing regime and enters the drift region in the RF section of the tube throws several challenges. Building a high quality magnet focusing lens to meet beam optics requirement in cathode gun and RF interaction region is considered tobe one of the critical issues for these high frequency miniature tubes. In this paper, electromagnetic design and particle trajectory studies in combined electric and magnetic fieldfor optimizing the magnetic circuit using 3D Finite element method (FEM) analysis software is presented. A rectangular configuration of magnet was constructed to accommodate apertures for input and output waveguide sectionsand facilitate coupling of electromagnetic fields into input klystron cavity and out from output klystron cavity through coupling loops. Prototype lenses have been built and have been tested after integration with the klystron tube. We discuss the design requirements and challenges, and the results from beam transmission of the prototype lens.

Keywords— Beam transmission, Brillouin, confined flow, Miniature Klystron.

INTRODUCTION

One of the major challenges associated with beam focusing of high intensity space charged electron beam in high frequency miniature klystron tubes is achieving high field intensity in constrained longitudinal and transverse dimensions. Achieving high beam filling factor in millimetre scale drift tube aperture and shielding requirements for reducing beam boundary oscillations in cathode gun region further aggravates the design complexity.

Beam boundary oscillations in a linear beam tube are governed by Busch's theorem and Gauss's law [1]. At the beam boundary where $r = b$, the electric field, $Er(b)$, is given as

$$Er(b) = \frac{\eta I}{2\pi \mu_0 \varepsilon_0} \quad (1)$$

The relation given below represents the motion of the electrons on the outer edge of the beam under the influence of electric and magnetic fields:

$$\ddot{b} + b\omega_L^2 \left[1 - \left(\frac{B_C}{B}\frac{b_c^2}{b^2}\right)^2\right] - \frac{\eta I}{2\,\Pi\, i\, \mu_0 \varepsilon_0} = 0 \quad (2)$$

If we let,

$$a = \frac{1}{B}\left(\frac{2I}{\eta\,\Pi\,\mu_0\,\varepsilon_0}\right)^2 \quad (3)$$

Using the equilibrium radius beam equation can be written as,

$$\frac{\ddot{b}}{a} + \omega_L^2 \left[\frac{b}{a}\left(1 - \left(\frac{B_C}{B}\frac{b_c^2}{b^2}\right)^2\right) - \frac{a}{b}\right] = 0 \quad (4)$$

where,

Table 1: Symbol Notations for equation (1), (2), (3) and (4)

Symbol	Quantity
ω_L	Larmor frequency, = ⍰B/2
I	Beam current
B_C	Flux density at cathode position
B	Actual Flux density = mB_B for confined flow
m	Confinement factor
B_B	Brillouin Flux density
μ_0	Free space permeability
ε_0	Free space permittivity
η	Charge to mass ratio; • = e/m
a	equilibrium radius for a Brillouin Beam

The first term is proportional to the radial acceleration and, therefore, to the radial force on the electrons. When the space charge and centrifugal forces causing the beam to expand are equal and opposite to the magnetic focusing forces that compress the beam, the beam is in equilibrium and there are no forces causing it to expand or contract.Because of high sensitivity of beam to misalignments and RF perturbations, confined flow focusing is a preferred method for majority of klystrons [1],[2]. The primary benefit of confined flow focusing is that beam control is significantly better than Brillouin focusing. It is often convenient to refer the actual flux density used for focusing, B, to the Brillouin value, B_B, by a confinement factor m, where B= m $B_{B.}$ In confined flow focusing, a limited amount of magnetic flux passes through cathode gun region and thus the motion of electron beam is governed by both electrostatic as well as magnetostatic forces in this region.An optimized value of cathode fluxprevents translaminar electrons from crossing or coming close to the beam axis and improves the laminarity of the beam.

In the present case, a partially shielded permanent magnet focusing lens is designed with a confinement factor of 2.

A rectangular configuration of PM based lens of 130mm x 65mm transverse dimensions (perpendicular to tube axis) was designed to produce an axial magnetic field of 0.34 T in the RF section of the miniature klystron tube. It was integrated with the miniature klystron tube and tested for its beam transmission efficiency. Deviations from the circular configuration of magnet arrangement lead to the asymmetric field configuration in the cathode gun region and increases design complexities.

Alignment of the subcomponents in the high frequency tubes also demands tight tolerances. Ifthe axis of the electron beam is not aligned with the axis of the magnetic field which could happen if the electron gun was misaligned during tube fabrication. Thegun axis could be either off center or tilted with respect to the axis of the tube. Other causes for misalignment include errors in cathode, grid, or control electrodepositioning or non-uniformities in magnetic pole piece material. The result of beammisalignment is that the entire beam spirals about the magnetic field axis at thecyclotron frequency. [2]

Electromagnetic Analysis and Simulations

Electron gun simulation studies – Space charge analysis

'3D SCALAspace charge' software has been used for estimation ofbeam current by thermionic emission from cathode surface. Work function and temperature of the cathode surface were defined for calculation of emission current density by applications of child's law. Fig 1 shows the electron gun model consisting of cathode (red), BFE (green) and anode (yellow) for space charge analysis.

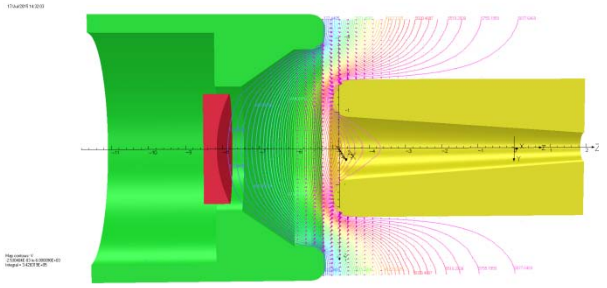

Fig1: 3D SCALA model for electron gun of miniature klystron [Electric potential (V) distribution]

Magnetostatic Simulations

'3D TOSCA magneto statics' software has been used for estimation of magnetic field pattern for a permanent magnet solenoid lens. Full model of the focusing lens is solved and Dirichlet boundary condition is applied to arrive at the solution.

Axially magnetized block magnets of trapezoidal shape placed in a particular configuration in aluminum housing, generate the desired axial magnetic field in the beam aperture. Trapezoidal shaped magnets were chosen to increase the magnetic volume when placed in a polar array. End flanges, made out of soft magnetic steel, shape the field distribution along the beam line and alsoprovide the requisite radial fields at the entrance and exit of the RF interaction region. The end flanges mate with the inherent pole pieces brazed on to the cavity at both ends of the RF interaction region [4]. Cover shields are designed to limit the fringe magnetic field in the cathode gun and collector region. Special care in the design of the shield ensured that the electron beam from its inception at the cathode to its end at the collector does not encounter a field reversal in the direction of the axial magnetic field. This is important in case of permanent magnet based design of solenoid focusing systems, as axial magnetic field reverses its direction twice along its travel in the axial direction. End flanges and shield design need to ensure that the field reversal regions are outside of the beam interaction region [4]. Optimization studies have been performed to maximize the magnetic field intensity in the focusing lens aperture by varying the profile of the soft magnetic steel flanges. Outer dimension of the focusing lens is constrained throughout the design of the magnet assembly. Shield dimensions are optimized for desired magnetic flux intensity in cathode gun and the collector region.

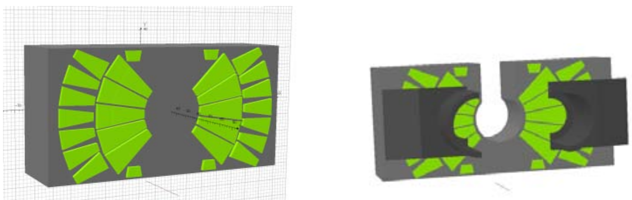

Fig 2: (a)Permanent magnet assembly housed in an aluminium casing, (b) Permanent magnet assembly with soft magnetic steel

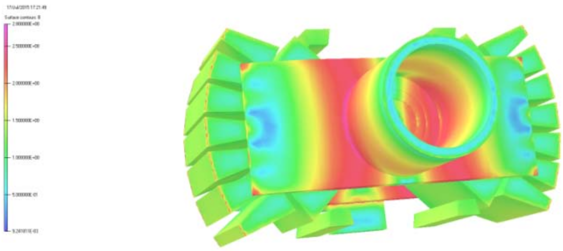

Fig 3: 3D TOSCA Magneto static Model for Permanent magnet focusing lens for miniature Klystron (surface B field plot)

A permanent magnet focusing lens assembly with a partially shielded gun region is designed and developed to produce an axial peak field of 0.34T in the magnet aperture. High energy density rare earth magnets have been used in the design of this solenoid to reduce the magnet volume. Magnet sprocket is inserted from top of the Klystron tube. An alignment tube is mounted on the body of the klystron tube to guide the sprocket and align its axis with the tube. Soft iron flanges are slid from sides and axially aligned with the inherent pole pieces on gun and collector side. Special jigs were fabricated to assemble and guide the soft iron flanges in place. Fig 4 shows simulated values of axial magnetic field profile for the magnet assembly with and without shield. Addition of the shield reduces the peak axial field obtained in the magnet aperture, but shifts the field reversal point away from the beam interaction zone.

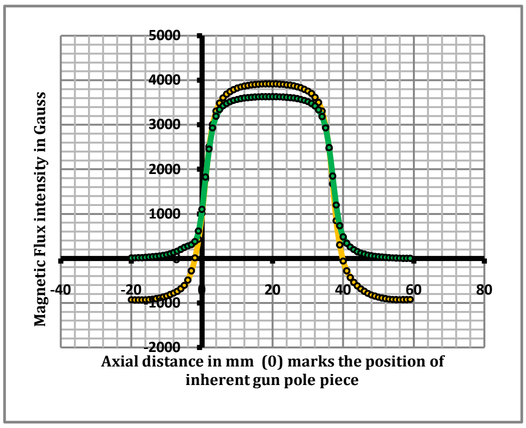

Fig. 4. Magnetic field profile along the logitudnal axis of the miniature Klystron ('0' position marks the inherent gun pole pieces position). Yellow line indicates the B field profile without shield and green line indicates the profile with shield on Gun and collector side

Particle trajectory simulations in combined Electric and magnetic fields

In engineering analysis and design of electromagnetic coupled systems, many phenomena have to be considered in order to predict a technical device's behavior realistically. In order to tackle the physical interactions, the study of the coupled problems is an important step. Multi-physics simulations using 3D FEM program OPERA-3D were carried out for study of beam behavior in combined electrostatic and magnetostatic fields for miniature Klystron tube [5].

Combined field tracking is used analyze the beam behavior under influence of combined electric and magnetic fields. The electron beam current is calculated in an iterative fashion using Child's law to simulate electron emission off the cathode using FEM electron gun program OPERA-3D/SCALA. The output of the 3D FEM magnetostatic/TOSCA is a table of magnetic fields on all the points/nodes in the solution region [5]. The results of the magnetostatic solver are coupled to electron gun program and the final output is a six dimensional phase space matrix. The six dimensions are specified by the particle's x, y, z position as well as its vx, vy, vz relativistic velocity components. Beam current was calculated at various points in the RF interaction region and collector region and percentage transmission was calculated with respect to the injected current at the exit of thermionic cathode.

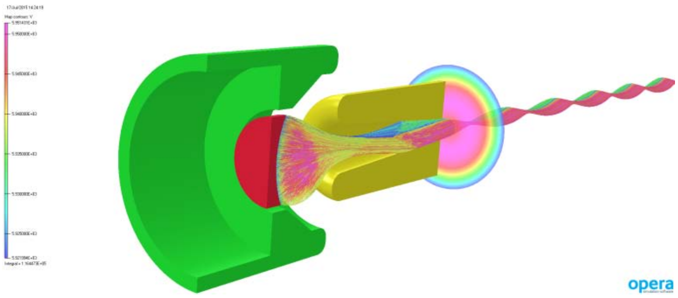

Fig. 5. Particle trajectory under the incfluence of combined elctric and magnetic fields. Current values at required axial locations are calculated by intersecting trajectories with a polar patch.

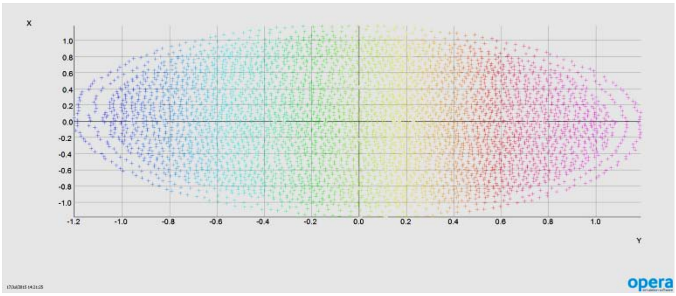

Fig. 6. Beam profile in X-Y plane at the exit of RF intercation region (in the collector region)

Beam Transmission Results

Constructed magnet assembly was integrated with the miniature klystron tubeand tested for its beam transmission efficiency [3]. 85% transmission was achieved at full beam energy of 5.6KeV. Deviations from the circular configuration of magnet arrangement lead to the asymmetric field configuration in the cathode gun region increases design complexities. To limit the beam boundary oscillations in the transition region when the beam leaves the electrostatic focusing regime and enters the drift region in the RF section some amount of shimming is incorporated in the magnetic field profile. The shimming field obtained by few extra magnets in the gun and the collector region nullifies imbalance in the field which hinders with the un-intercepted beam travel through the drift tube. Best beam transmission is achieved when the tube is aligned properly with the magnet sprocket. Alignment is one of the most critical issues in the miniature klystron tubes due to spatial constraints. In the rectangular magnet configuration it was observed that shimming action at a particular energy does not lead to same beam transmission at all beam energies. Various test configurations were tried to study the effect of shimming magnets on the beam transmission.

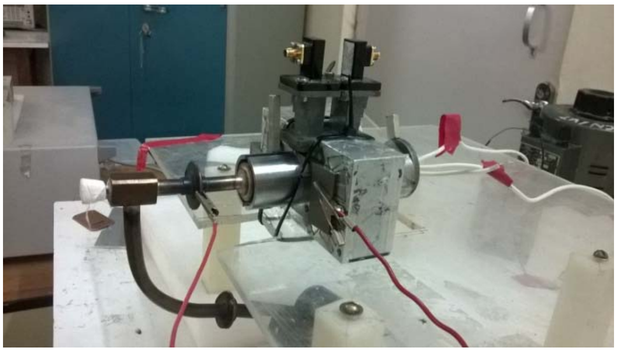

Fig. 7. Prototype miniature klystron tube integrated with developed magnet assembly

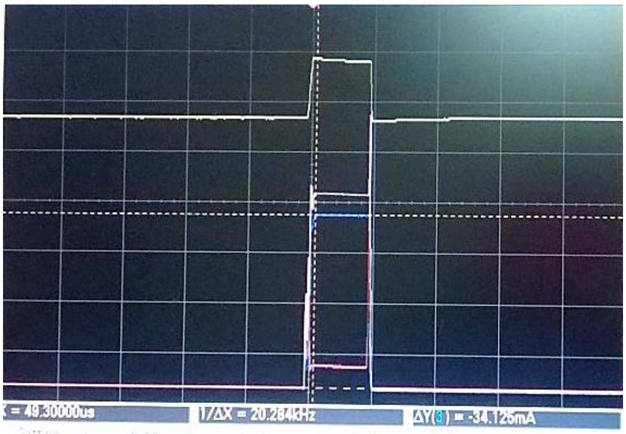

Fig 8. Transmitted current snapshot at Beam energy of 5KeV

Conclusion

The proto-type Permanent magnet focusing lens was integrated with prototype miniature klystron tubeand 85 % beam transmission was achieved [3]. Further studies are in progress to find out the action and influence of shimming magnets on higher order harmonics in the primary field. Combined field studies for particle trajectory will be used in future to predict the location and size of shimming magnets. The beam absorbed in the collector is considered to play a vital role in the RF power amplification at the output cavity. For better power efficiency, the entire beam needs to be rendezvous with the collector after transferring the energy to the output cavity. R&D efforts are being directed towards increasing the beam transmission above 90%.

Table 2 : Summary of the beam transmission results on miniature klystron tube integrated with Permanent magnet focusing lens

Beam Energy (KeV)	Transmitted current (KeV)	Total current (mA)	% Transmission
2	36	40	90
3	68	73	93.15
4	103	110	93.68
5	143	154	92.8
5.6	153	180	85

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References

1. S. Gilmour, Jr., "Klystrons,Travelling WaveTubes, Magne-trons, Crossed-Field Amplifiers,and Gyrotrons" 2011 ARTECH HOUSE, pp.133-199.
2. S.I. Molokovsky A.D. Sushkov, "Intense Electron and Ion Beams" Springer Berlin Heidelberg NewYork, vol. A247, pp. 175-197, May 2005.
3. Joshi, L.M. Pal, D. ; Kant, D. ; Ratan, S. ; Choudhury, A.R. ; Jindal, V. ; Jangid, S. ; Sharma, S. ; Meena, R. ;Nangru, S.C. ; Sharma, R.K. ; Sharma, S.M. ; Arya, S., "Development of a 300W peak power J-band klystron," Vacuum Electronics Conference (IVEC), 2010 IEEE International.
4. Y. Fuwa, Y. Iwashita, H. Tongu, S. Ushijima, Kyoto University, Uji, Kyoto, Japan, "PERMANENT MAGNET FOCUSING SYSTEM FOR KLYSTRONS"Proceedings of IPAC2012, New Orleans, Louisiana, USA
5. OPERA v10.0 user guide and reference manual.