The Design of a 390 GHz Gyrotron Based on a Cusp Electron Gun

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***Abstract*—The design and simulation of a harmonic gyrotron based on a cusp electron gun is presented. The gyrotron is operated at the 7th electron cyclotron harmonic with an output frequency of ~390 GHz and mode pattern of TE_{71}. A large orbit electron beam with an energy of 40 keV, beam current of 1.5 A and an adjustable pitch alpha from 1 to 3 from a cusp gun is used to drive the beam-wave interaction. Smooth cylindrical waveguide and slotted structures have been studied as interaction cavities. Theoretical analysis and numerical simulation results of these structures will be presented.**

I. INTRODUCTION AND BACKGROUND

MICROWAVE radiation sources are one of the crucial technologies for modern society. High power sub-millimeter wave sources have attracted significant interest recently due to their potential applications in electron cyclotron resonance heating, plasma diagnostics, space radar systems, communication systems, materials science and medical technology [1,2].

The gyrotron is well known as a coherent millimeter wave source capable of high power and high frequency output which is extendable to the Terahertz (THz) frequency region. But as the output frequency increases, both larger magnetic fields and reduced size of interaction regions are needed when operating at the fundamental cyclotron mode. An alternative approach to generate high frequency radiation is to work at higher cyclotron harmonics. A large orbit electron beam is favorable in harmonic gyrotrons. The cusp gun designed for this gyrotron has been optimized for generating such a beam with minimum velocity spread and scalloping in the beam trajectory at a beam energy of 40keV, beam current 1.5A and a pitch alpha from 1 to 3.

A THz microwave source based on a harmonic gyrotron and a cusp electron gun is currently being studied at Strathclyde University. When using a weakly relativistic electron beam, the interaction coefficient is significantly reduced when operating with a high harmonic cyclotron mode. A slotted cross-section structure [3] has been studied as a possible solution to this problem. Both numerical and experimental studies will be carried out to study its effects on the starting current and the interaction efficiency of the operating mode.

II. CUSP GUN

A cusp electron gun works by passing an electron beam through a non-adiabatic magnetic reversal from negative to positive amplitude. Invariance of the magnetic moment results in a large orbit, annular electron beam[4]. Such a beam is desirable in a harmonic gyro-device. For example such an electron beam when used in the Cyclotron Resonance Maser (CRM) interaction with a TE_{nmq} mode will interact with the nth harmonic of the cyclotron mode only. This results in better mode selection and hence mitigated parasitic interactions. The beam is also ready for CW operation as it does not need a kicker magnet and the efficiency of the millmetre wave source can be increased with the use of energy recovery.

The 3D PiC code Magic was used to simulate and optimize the design of the cusp electron beam source. The geometry of the cusp gun including the resultant beam trajectories are shown in Fig. 1.

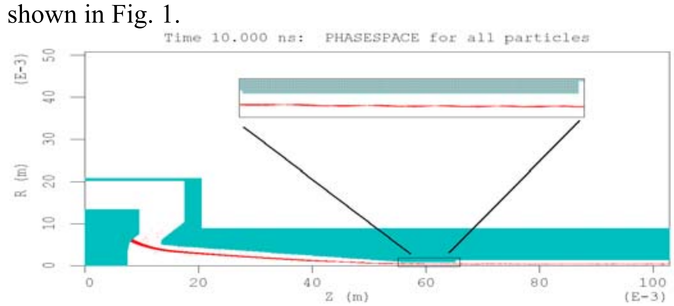

Fig. 1 Simulated cusp gun and resultant beam trajectories.

In the simulation, the position, size and current of the two coils, the shape and dimension of the focusing electrode, the gap distance between the cathode and anode as well as the anode focusing electrode could be adjusted to optimize the velocity spread and scalloping in the downstream region at the designed beam parameters. A 3D view of the beam trajectories and their projections in the axial and transverse planes are shown in Fig. 2

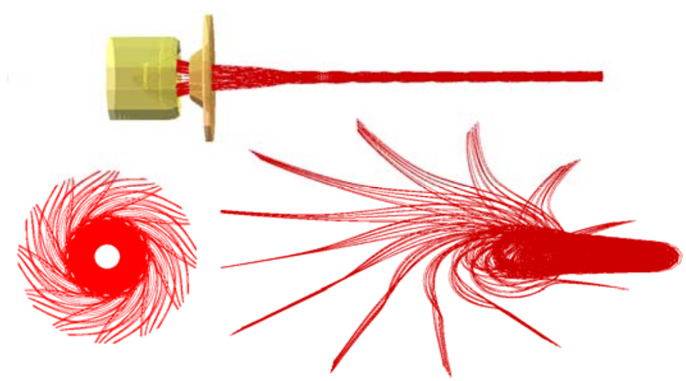

Fig. 2 Electron beam trajectories and their projections in the axial and transverse planes.

III. DISPERSION AND GROWTH RATE

A gyrotron operates through a fast cyclotron wave interaction, which takes place near the frequency cut off region of the waveguide mode as shown in the dispersion diagram Fig. 3. The dispersion diagram illustrating the beam-wave interaction gives many important parameters of the device.

In the diagram the TE_{71} cylindrical waveguide mode is interacting with the 7th harmonic of the electron cyclotron mode of a beam with a velocity ratio α=2 at a magnetic field of 2.09 T. The radius of the cylindrical waveguide is 1.06 mm.

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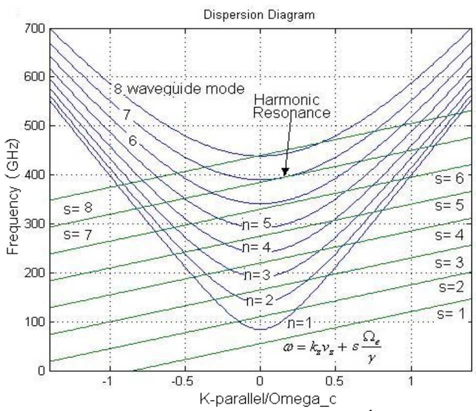


Fig. 3 Dispersion of the 390 GHz, 7th harmonic TE_{71} mode Gyrotron.

The growth rate of this interaction is shown in Fig. 4.

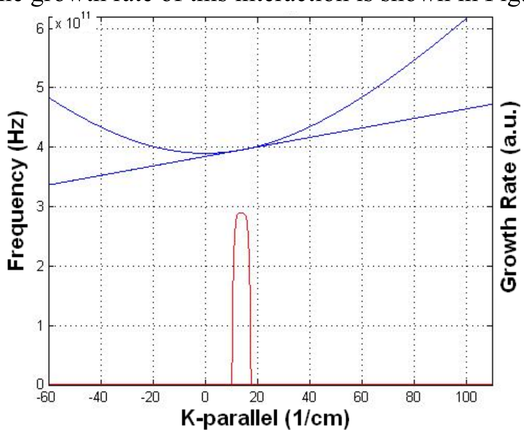
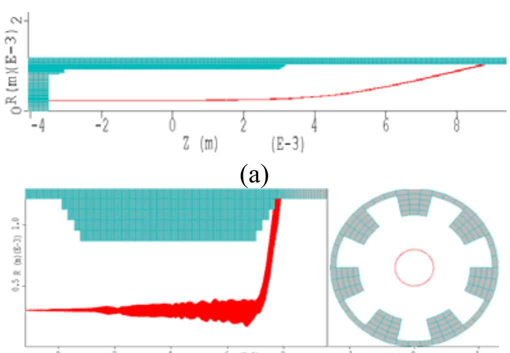


Fig. 4 The growth rate at the 7th harmonic interaction.

IV. RESULTS

The 3D PIC (Particle in Cell) code MAGIC was used to simulate the harmonic gyrotron interaction. Cross-sectional geometries of both smooth and slotted structures are shown in Fig. 5.

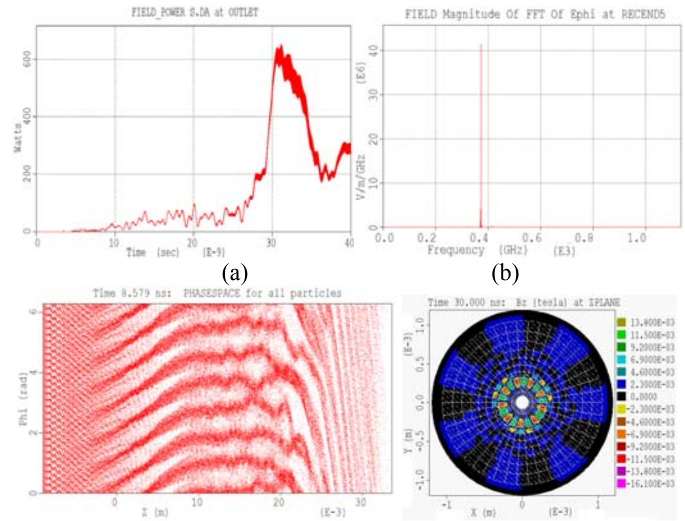


(a)

(b)

Fig. 5 Cross-sectional geometries with simulated electron beam trajectories: (a)-smooth; (b)-slotted.

A simulation result of the interaction between a 40 kV, 1.5 A large-orbit annular electron beam with the TE_{71} waveguide mode in the smooth waveguide is shown in Fig. 6. The electron distribution in the phase space (6c) indicates the interaction occurred at the 7th harmonic of the electron cyclotron mode. From the diagram an output power of 600 W at a frequency of ~390 GHz was achieved.



(a) (b)

(c)

Fig. 6 Simulation results of the 7th harmonic gyrotron in a smooth cavity: (a)-output power, (b)-output spectrum and (c) electron distribution in phase space and (d) B_z pattern at resonance

The dispersion curve of the slotted structure with 1.24 mm outer and 0.88 mm inner radius was simulated using MAGIC for the TE_{71} mode and is shown in Fig. 7. This was found to be in very good agreement with the analytical calculated results also shown in Fig.7.

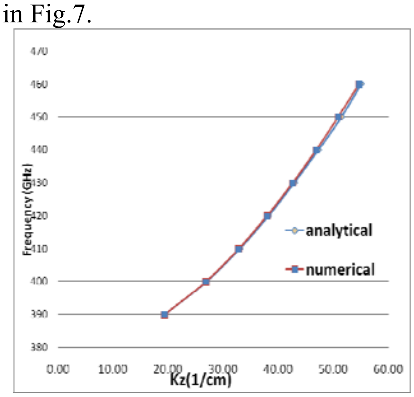


Fig. 7 Simulated and calculated dispersion of TE_{71} mode in the 7-vane slotted structure.

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