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Design, Simulation and Experiment of a Cusp Electron Beam

for Millimeter Wave Gyro-devices

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Abstract: T*he design, simulation and experiment of a thermionic cusp electron gun that is to be used for millimeter wave generation will be presented. A cusp gun uses a non-adiabatic magnetic field reversal to obtain azimuthal motion on an electron beam resulting in an annular shaped, axis-encircling beam. The cusp gun was designed to generate a beam of 1.5A at 40kV with an adjustable velocity ratio of up to 3.0. The beam had a simulated axial velocity spread of 7.4% and alpha spread of 10.1%. The beam had an averaged radius of 0.35mm and beam thickness of 0.05mm which is ideal to drive sub-mm wave gyro-devices under investigation.*

Keywords: Cusp; electron gun; millimetre wave gyro-device; gyrotron.

Introduction

Gyro-devices are promising candidates for the generation of high power, high frequency, coherent radiation at wavelengths in the millimetre to sub-millimetre range. A few projects combining theoretical, numerical and experimental study of such devices are underway to generate or amplify radiation in this frequency range required for a number of applications. A W-Band Gyrotron Backward Wave Oscillator (gyro-BWO) based on a helically corrugated waveguide is simulated to achieve a 3dB frequency tuning band of ~84-104 GHz, output power of ~10kW [1,2]. A harmonic gyrotron operated at the 7th harmonic of the electron cyclotron mode and with a TE_{71} output mode has been designed to achieve ~500W at ~390GHz [3]. At the same time a W-band Gyrotron Traveling Wave Amplifier (Gyro-TWA) based on a helically corrugated waveguide is under design to achieve a maximum output power of ~5kW with a 3dB bandwidth of 90-100GHz [4].

Presented in this paper are the design, simulation and latest experimental results of a novel cusp electron beam source to drive the beam-wave interactions in the aforementioned Gyro-devices. This electron gun is required to produce an axis-encircling, annular shaped electron beam of current 1.5A, energy 40keV and a pitch alpha of up to 3 with the beam optimized for interaction in the cavities. The pitch alphas (velocity ratio α) of the electron beam generated by the cusp gun are chosen to be 1.65 and 1.2 respectively when driving the W-band gyro-BWO and gyro-TWA. The interaction between the second harmonic cyclotron beam mode and the TE_{21} like eigenwave based on the CRM instability allows broadband microwave growth to be

achieved both in the gyro-BWO and gyro-TWA. An alpha value of 3 can be obtained to drive the high harmonic TE_{71} mode gyrotron with an output frequency of 390GHz. When using a weakly relativistic electron beam the interaction coefficient is significantly reduced for the high harmonic cyclotron mode of operation. A high α can lower the starting current of the operating mode and lead to higher efficiency.

The cusp electron gun is a novel way of creating an axis-encircling annular electron beam ideal for use in harmonic gyro-devices. Conventional electron guns mainly used in gyro-devices are the Magnetron Injection Gun (MIG) and Pierce gun. Mode selectivity is poor in the MIG as the coupling for such a beam is strongest with the fundamental mode. In the Pierce gun case, a pencil line electron beam is kicked into an axis-encircling path. However, for this CW operation the Pierce gun would not be suitable as the kicker magnet is feasible primarily in pulsed mode. Due to the high power of the spent electron beam, an annular shaped electron beam is desirable for beam energy recovery using a depressed collector method because of the reduced power density on the collecting electrodes.

Design

A 'smooth' cusp formed by two coils without any magnetic shaping poles was used to generate the required axis-encircling electron beam because in this case the Larmor step is much larger due to the small amplitude of the cusp and small transverse velocity component (Fig. 1). This allows a field reversal over a longer distance.[5]
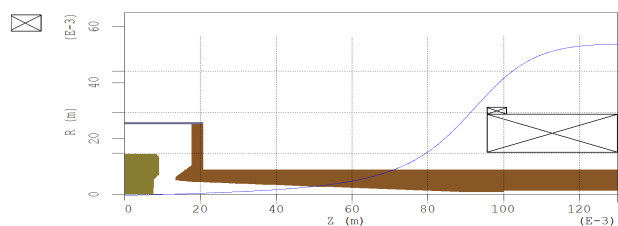

Fig. 1 A schematic showing the cusp gun, its magnetic coils and overlaid magnetic field profile.

Due to azimuthal symmetry of the magnetic and electric field, conservation of the electron canonical angular momentum [6] gives rise to an axis encircling beam. The electrons gain transverse velocity mainly due to $V_z \times B_r$ force in the cusp region. It is possible to show that the alpha value of the beam

in the downstream uniform B field region is governed by Eq. (1):

$$\alpha = \frac{V_\perp}{V_z} = \sqrt{\frac{-r_c^2 \omega_c \omega_0}{V^2 + r_c^2 \omega_c \omega_0}} \qquad (1)$$

Here V and ω are electron velocity and cyclotron frequency, subscripts '$\perp$', 'z' denote transverse and z components, '0' and 'c' the final and cathode region respectively.

Simulations

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 its magnetic field profile is shown in Fig. 1. 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 and the shape of the anode could be adjusted to optimize the beam quality in the downstream region. The emitted beam current, transported current and electron energy, velocity, pitch alpha and its spread were simulated and monitored at a position in the downstream uniform B-field region.

The simulated beam trajectories are shown in Fig. 2. It clearly shows that an axis-encircling beam was obtained.
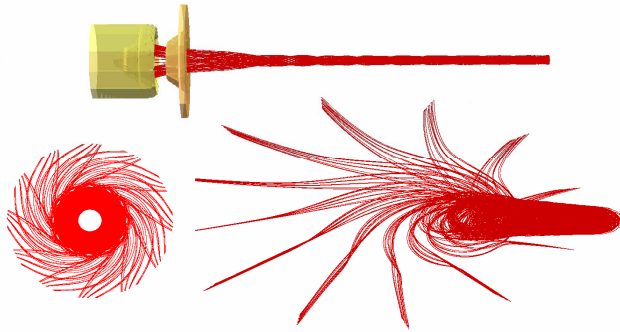

Fig. 2 Simulation results showing the shape and trajectories of the electron beam from the cusp gun.

The alpha value of the electron beam can be adjusted by adjusting the magnetic field amplitude at the cathode or/and at the downstream uniform region as governed by Eq. (1). Simulation predicted the large orbit electron beam has an inner and outer diameter of 0.6mm and 0.7mm at an alpha value of 1.65 when in the downstream, uniform magnetic field region (B_0=2.1T). The spread of the alpha is ~10% as shown in Fig. 3.
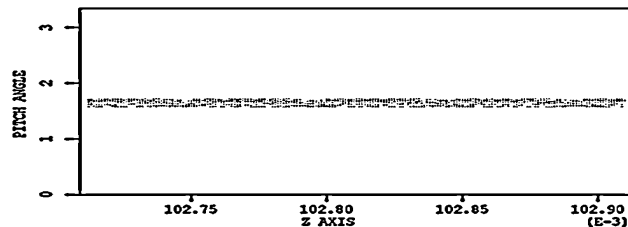

Fig. 3 Velocity pitch angle of the cusp beam.

Experiment

The construction of the cusp electron gun and various components including magnetic coils, cathode and diode are completed. The diagnostics of the electron beam including a fast, high voltage divider and a Faraday cup for beam voltage and current measurements are designed as well. A scintillator method will be used to measure the beam cross-sectional shape and size hence the velocity ratio α. The experimental measurements will be given and compared with the theoretical and simulation results.

Conclusion

Optimized design for a cusp electron gun for use in sub-mm Gyro-devices is presented. The cusp gun was designed to generate a beam of 1.5A at 40kV with an adjustable velocity ratio of up to 3.0. The beam had a simulated axial velocity spread of 7.4% and alpha spread of 10%. The beam had inner and outer diameters of 0.6mm and 0.7mm at an alpha value of 1.65 which is ideal to drive sub-mm wave gyro-devices under investigation.

Acknowledgments

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