Development of a CUSP-Type Electron Gun for a W-Band Helical Gyro-TWT

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***Abstract*—To drive a broadband gyro-TWT with a helically corrugated interaction region, a high-quality axis-encircling electron beam is required. In this publication, a CUSP-type electron gun, capable of generating such a beam, is developed for a 94 GHz helical gyro-TWT. The design was optimized using the electron-beam-optics code *ESRAY* [1]. The final electron gun is optimized for the generation of an electron beam with a 50 kV beam voltage, 1.5 A current, and a pitch factor of $\alpha = 1.0$ with an RMS spread as low as 3.49 %. Additionally, tolerance studies, including the influence of deviations in the emitter position and the surface roughness of the emitter, are performed.**

I. Introduction

In the age of semiconductors and integrated circuits, vacuum microwave devices, in particular gyro-devices, are used to generate high output power for millimeter and sub-millimeter waves. This is achieved by utilizing the relativistic electron cyclotron maser (ECM) interaction principle [2].

A special type of gyro-device is the gyro-TWT with a helically corrugated interaction region (HCIR), also called helical gyro-TWT [3]. In Fig. 1, a diagram of a typical helical gyro-TWT is shown. This type of gyro-TWT requires a so-called CUSP-type electron gun [4-7], in which an axis-encircling large-orbit electron beam (LOB) is generated by a non-adiabatic reversal of the magnetic field (cusped magnetic field). Then the LOB is compressed and guided by a static magnetic field towards the HCIR. In the HCIR, the dispersion of the operating composite eigenmode is tailored to allow a resonant beam-wave interaction over a significantly increased bandwidth compared to classical gyro-devices with cylindrical interaction regions. At the same time, the sensitivity to velocity spreads in the electron beam is reduced. A further benefit of the operating eigenmode in the HCIR is its ability to resonantly interact with the LOB at the second cyclotron harmonic. Therefore, the required magnetic field is reduced by a factor of two, which is particularly advantageous at frequencies in the sub-THz range.

In this work, the design of a CUSP-gun for a W-band helical gyro-TWT with an output power of 10 kW is presented. The utilized methodology for the systematic design of the CUSP-gun is given.

II. Methodology

The beam quality of a CUSP-gun is mainly determined by the cusped magnetic field. The magnetic cusp is usually located close to the ring-shaped electron emitter and is created by placing a so-called gun-coil with the opposite field to the main coil behind the emitter. In Fig. 2, the aforementioned gun-coil, geometry, and magnetic field for a helical gyro-TWT with CUSP-gun are shown.

In axially symmetric and static fields, the canonical

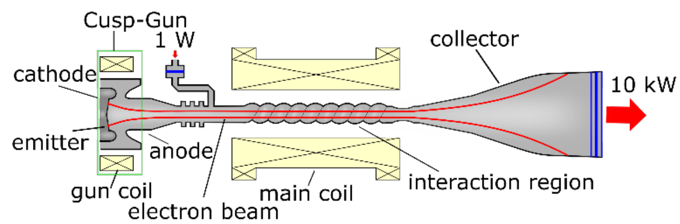

Fig. 1. Gyro-TWT cross-section

azimuthal (θ) angular momentum is calculated using [8]

$$P_\theta = m\, r^2\, \dot{\theta} - \frac{e_0\, \Psi}{2\, \pi}, \qquad (1)$$

with the elementary charge e_0, the relativistic electron mass m, and the magnetic flux Ψ through a circle of radius r. This momentum is conserved over the entire electron trajectory.

For the generation of a beam with small spreads $\delta\alpha$ of the pitch factor $\alpha = v_\perp / v_\parallel$, a constant canonical angular momentum over the emitter surface is required [5]. It is assumed that an emitted electron has no azimuthal velocity ($\dot{\theta} = 0$), which is valid if the θ component of the static electric field is zero. According to the second term in (1), the same flux Ψ is required for all positions along the emitter in order to emit all electrons

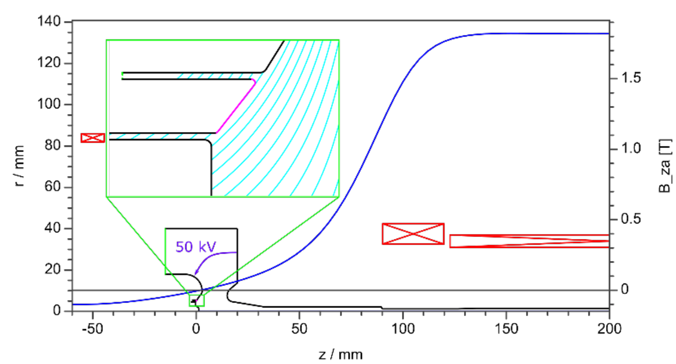

Fig. 2. On axis magnetic flux density (blue) and magnetic field lines (cyan) at the emitter generated by the solenoids (red).

with constant P_θ. This results in magnetic field lines parallel to the emitter surface, as shown in Fig. 2. Due to the gun-coil, the magnetic flux density has its minimum behind the emitter and increases towards the interaction region. This results in diverging magnetic field lines towards the CUSP-point ($B_z = 0$). Therefore, the emitter radius has to increase along z to achieve a constant magnetic flux. This results in an emitter that is tilted toward the axis of symmetry.

In reality, it is difficult to achieve a constant magnetic flux along the entire emitter. Therefore, the magnetic flux at the inner and outer rim of the emitter is evaluated by approximately

$$\Psi(z) \approx B_z(z)\, \pi\, [r_e(z)]^2 \qquad (2)$$

and used as a starting point for the optimization process to achieve a minimal $\delta\alpha$. The other inputs of the optimization are the position and current of the gun coil, as well as the radius r_c and angle of the emitter. For the design shown in the following, the electron-beam-optic simulation tool *ESRAY* [1] is used for this numerical optimization procedure.

III. Final Design

For the investigated helical gyro-TWT, a magnetic flux density of 1.82 T in the HCIR is required. The helical gyro-TWT should be operated with an electron beam with a kinetic energy of 50 keV and a pitch factor of $\alpha = 1.0$.

In Fig. 3, the final electrode geometry is shown. It is the result of extensive numerical optimizations. Here the aforementioned tilted emitter can clearly be seen. Additionally, a nose was added below the emitter to focus the electrons [5]. The resulting beam parameters are $\alpha = 1.0$, $\delta\alpha = 3.49$ % (RMS), and a guiding center radius $r_g = 49.8$ µm.

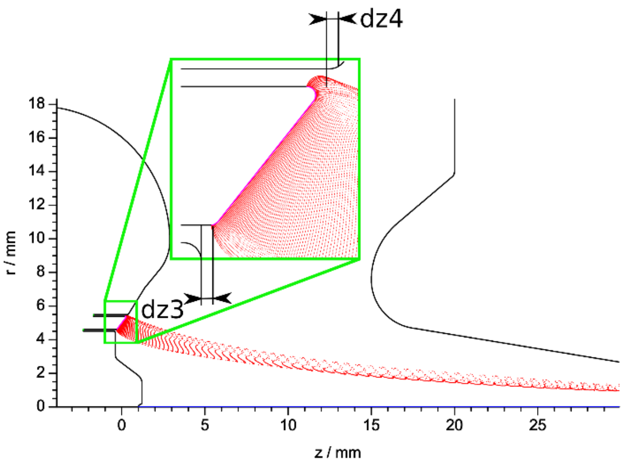

Fig. 3. Final cathode and anode design (black) with electrons (red) released by the emitter (magenta) and axis of symmetry (blue).

The optimizations have shown that slight changes in the electrode geometry have only a small influence on the beam parameters. More critical is the position of the emitter with respect to the surrounding cathode, defined by dz3 and dz4 in Fig. 3. The effect of a deviation from the nominal values on α is minimal. However, the effect on the spread $\delta\alpha$ is significant, as shown in Fig. 4. Here, the iso-line (green) for a 1 % increase

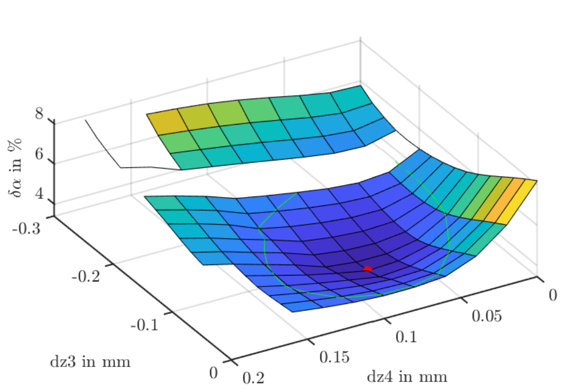

Fig. 4. Dependency of $\delta\alpha$ on dz3 and dz4. The red dot shows the nominal values for dz3 and dz4. The green contour marks an increase of 1 % in $\delta\alpha$

in $\delta\alpha$ can be seen. To stay under the defined upper limit of 4.5 % for $\delta\alpha$, a deviation of ±80 µm for dz3 and ±60 µm for dz4 can be tolerated.

IV. Emitter Surface roughness

In the initial optimization steps, a smooth emitter surface was considered to focus on the influences of the geometry and magnetic flux density on the beam parameters. However, real emitters have a surface roughness of several µm, which has a strong influence on $\delta\alpha$. As seen in Fig. 5, the spread $\delta\alpha$ increases significantly, even with low emitter roughness. Therefore, the overall beam quality does strongly depend on the achievable surface roughness of the emitter.

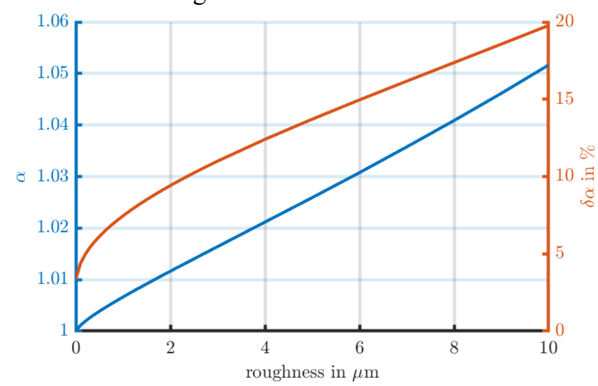

Fig. 5. Influence of the emitter roughness on the beam parameters.

V. Conclusion

The proposed methodology for the design of a CUSP-gun resulted in comparable parameters to the ones in [6] and [7]. Investigating the manufacturing tolerances resulted in a small acceptable deviation for the emitter position with respect to the cathode. Additionally, the dominant influence of the emitter surface quality has been shown.

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