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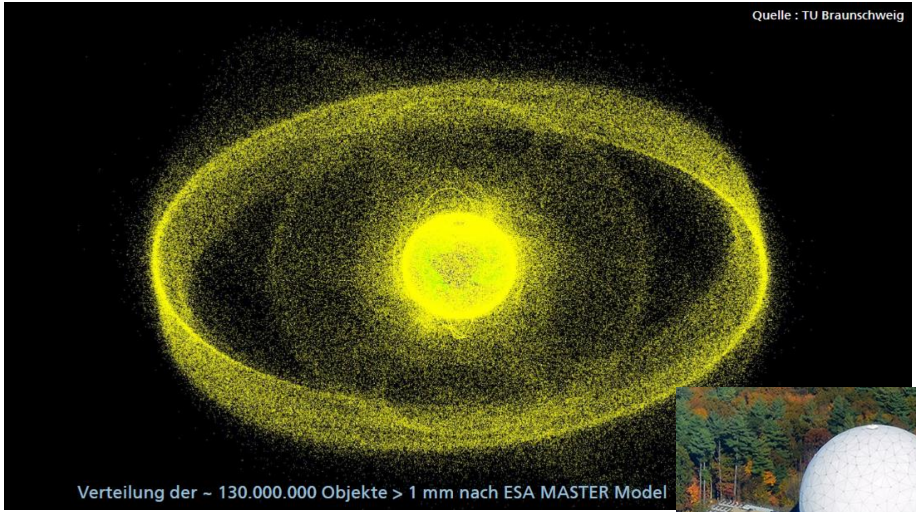
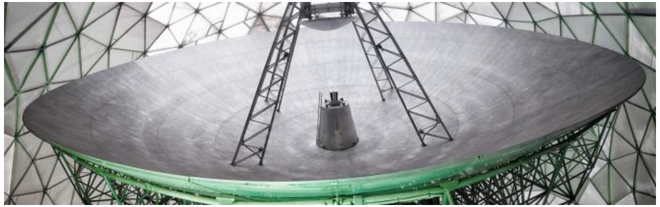
Physical Design of a CUSP-Type Electron Gun for a Broadband High-Power W-Band Helical Gyro-TWT

8th IVEW
2nd September 2022 - Max Vöhringer

Structure

1. Motivation
2. Introduction
3. Final Gun Design
4. Conclusion





Tracking and Imaging Radar (TIRA) (16.7 GHz)

Haystack Ultrawideband Satellite Imaging Radar (HUSIR) (96 GHz)

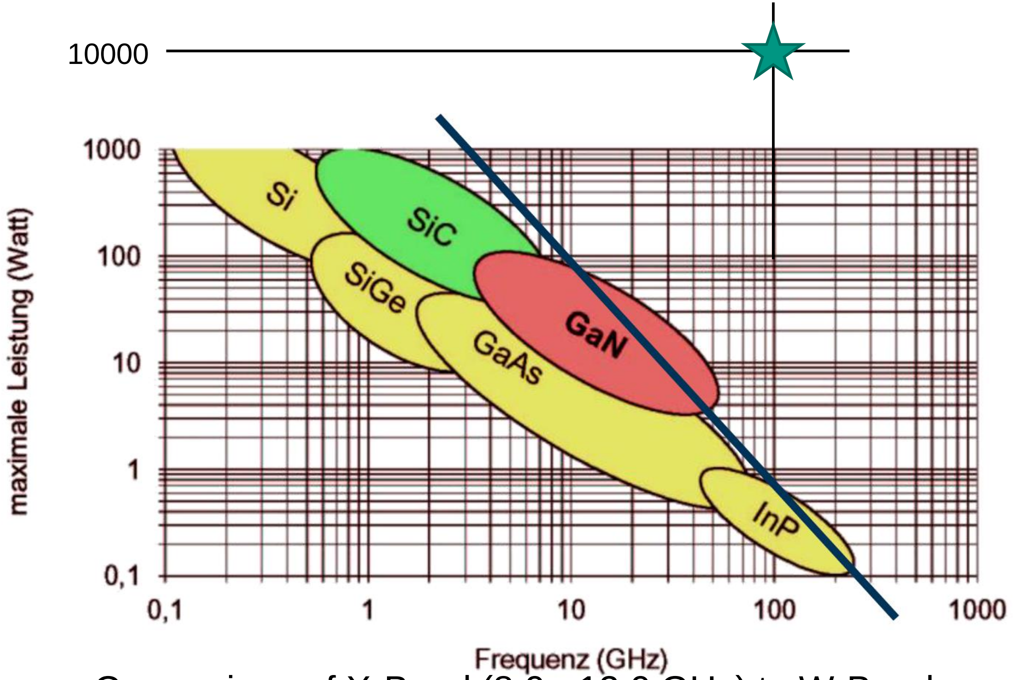
https://www.fhr.fraunhofer.de/en/the-institute/technical-equipment/Space-observation-radar-TIRA.html
https://orbitaldebris.jsc.nasa.gov/measurements/radar.html

1. Applications

Why W-Band (75 - 110 GHz)?

- Broadband radar applications
  - Better resolution
  - Atmospheric window
- Communication (e.g. 6G)
  - New frequency bands
  - Higher data rate
  - Higher directivity
- Spectroscopy

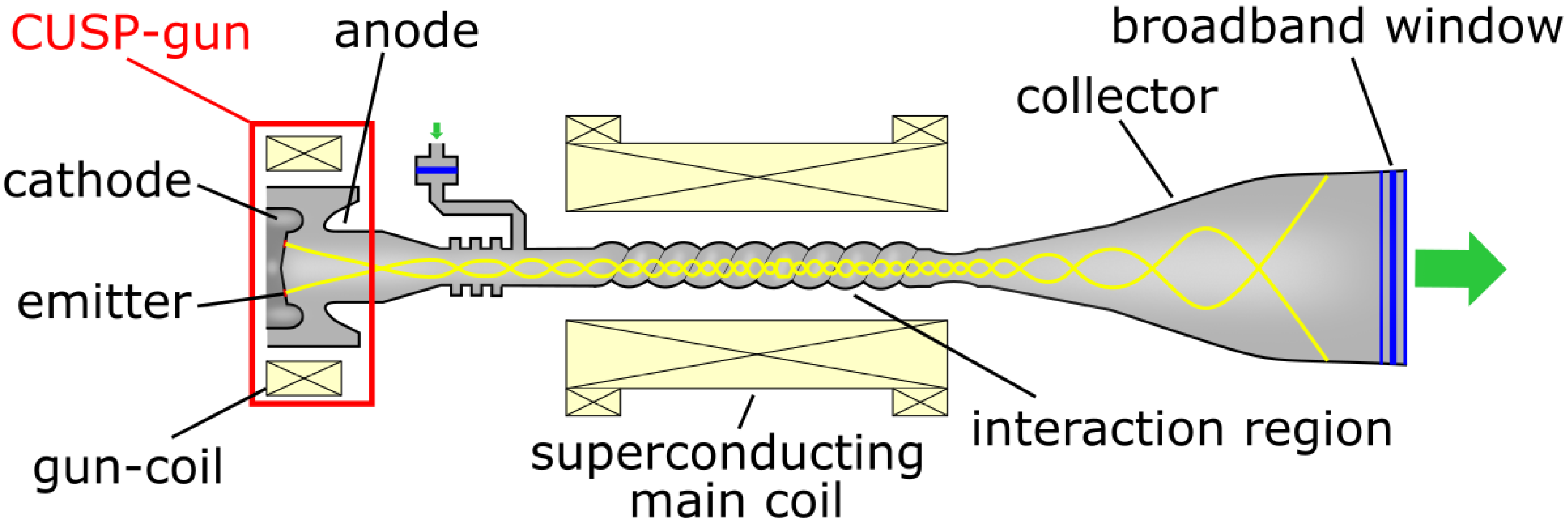
→ Development of an amplifier
  - Center frequency $94\ \mathrm{GHz}$
  - Bandwidth > 10 % of center frequency
  - $10\ \mathrm{kW}$ output power



Comparison of X-Band (8.0 - 12.0 GHz) to W-Band

M. G. Czerwinski and J. M. Usoff, “[illegible]

2. Gyrotron Travelling-Wave-Tube Amplifier



2. Interaction Region

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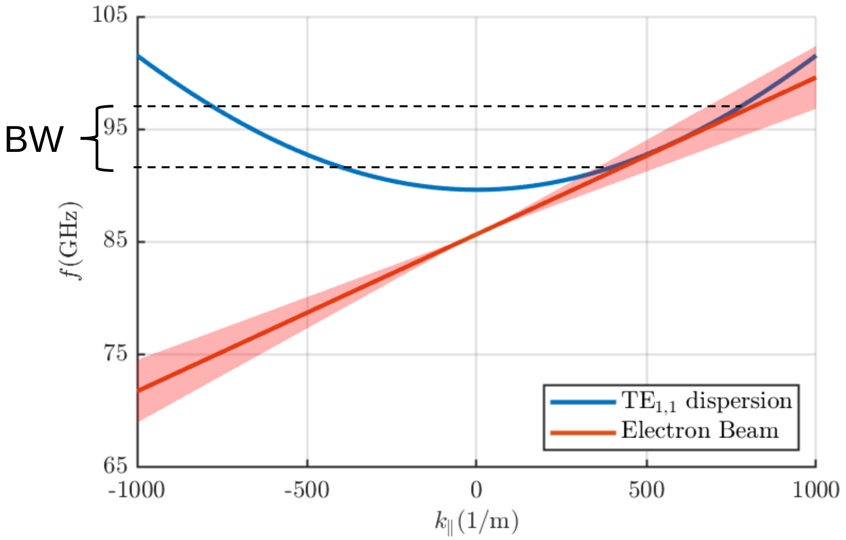
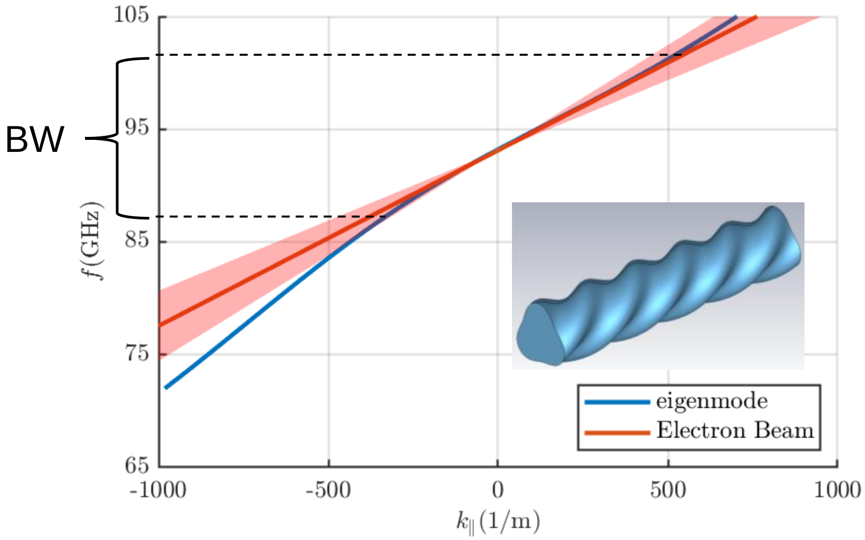
Circular Interaction Region



$$\omega \approx s\omega_c + k_\parallel v_\parallel$$

Helically Corrugated Interaction Region (HCIR)



→ higher bandwidth

→ better resilience against velocity spreads

2. Electron Beams at the Interaction Region

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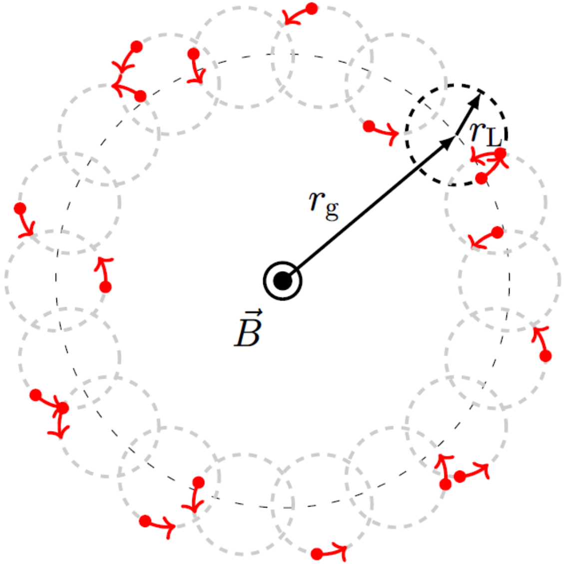
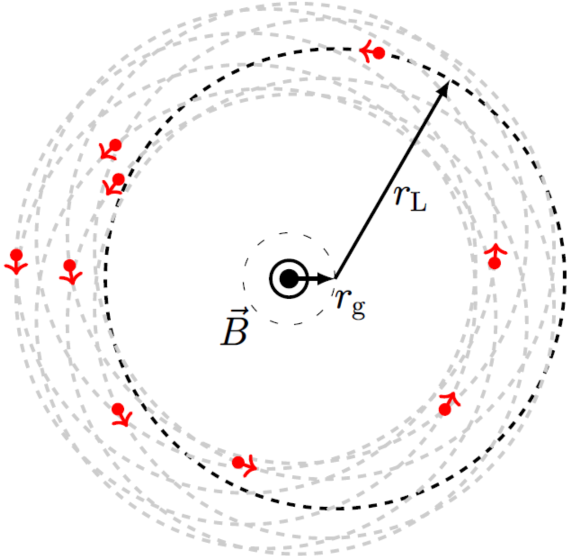
Small Orbit Beam



- Usually used in high power gyrotrons
- Interacts with higher order modes

Large Orbit Beam



- Only interact with $TE_{s,1}$-modes
- Remember: Eigenmode of HCIR similar to $TE_{2,1}$
  $\rightarrow s = 2$: 2nd – harmonic operation

2. Generation of Electron Beams

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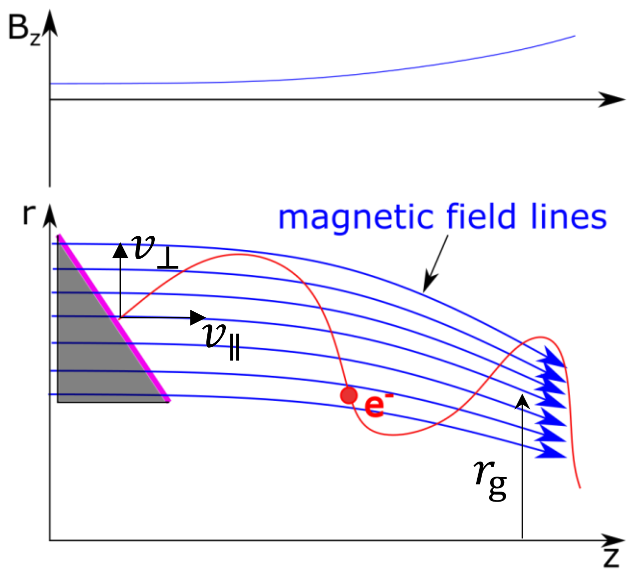
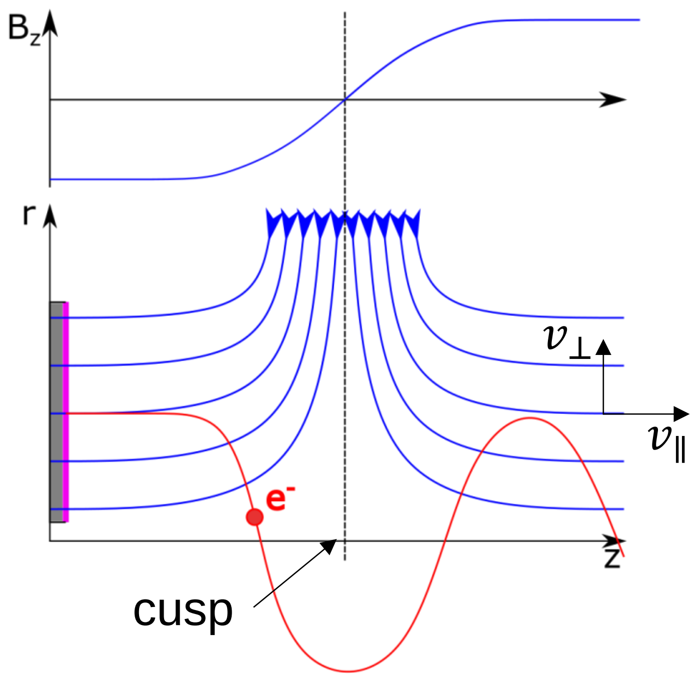
Small Orbit Beam

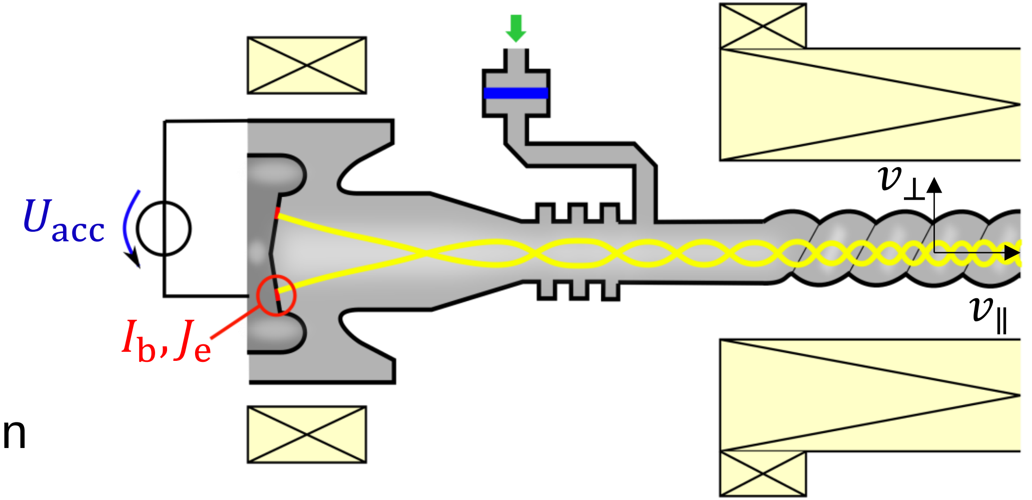


Large Orbit Beam



3. Goals for the CUSP-gun

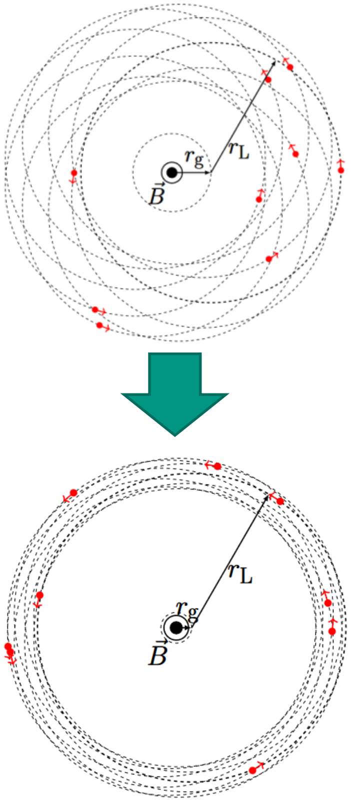
- Pitch factor $\alpha = \frac{v_\perp}{v_\parallel} = 1.0$
- Acceleration voltage $U_{\mathrm{acc}} = 50\ \mathrm{kV}$
- Electron beam current $I_{\mathrm{b}} = 1.5\ \mathrm{A}$
- Emitter current density $J_{\mathrm{e}} < 4\ \frac{\mathrm{A}}{\mathrm{cm}^2}$
- Magnetic flux density at the interaction region $B_{\mathrm{zi}} = 1.82\ \mathrm{T}$



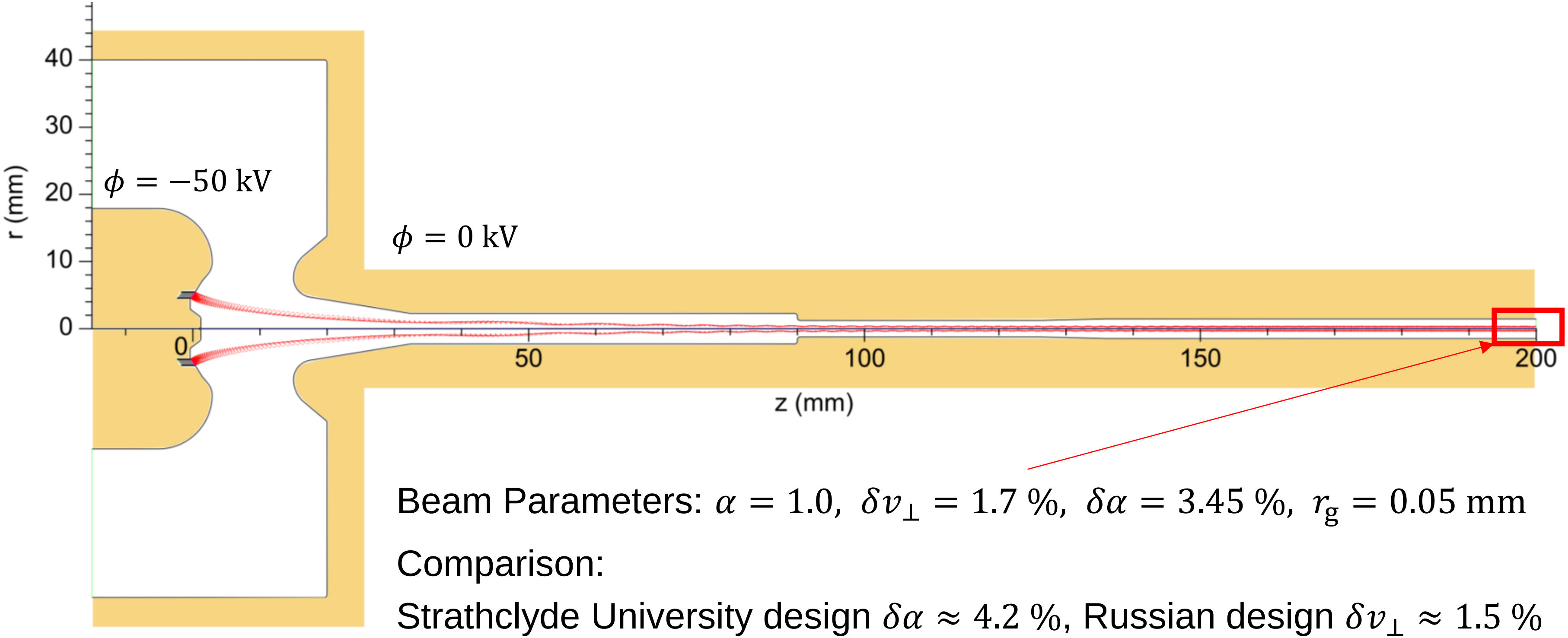
3. Electron Beam Quality

What defines a high quality electron beam and why?

- Small spread $\delta\alpha \leq 10\ \%$ (RMS) for a high bandwidth
- Smallest possible guiding center radius r_{g} for a good mode selectivity.



3. Developed Electrode Geometry

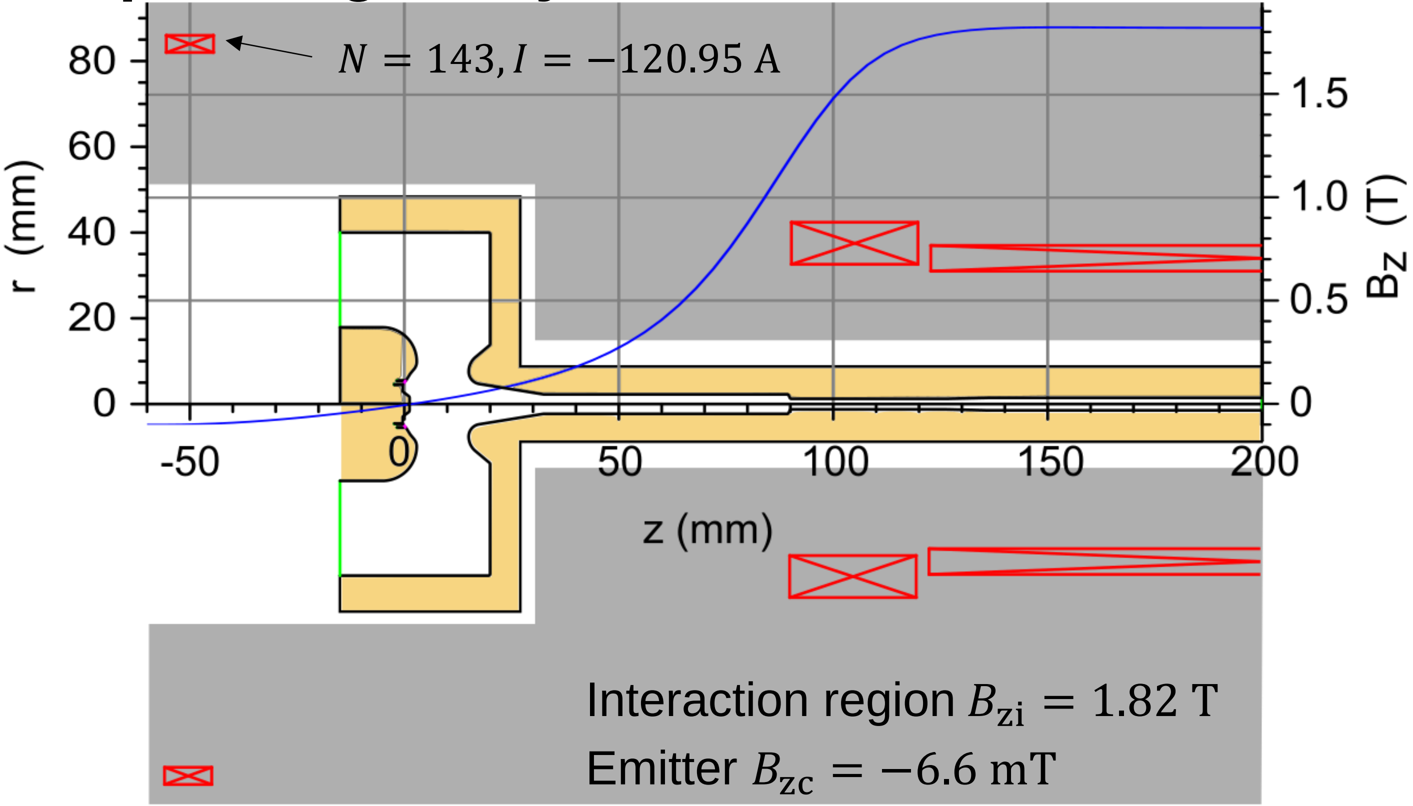


Beam Parameters: $\alpha = 1.0,\ \delta v_\perp = 1.7\ \%,\ \delta\alpha = 3.45\ \%,\ r_\mathrm{g} = 0.05\ \mathrm{mm}$

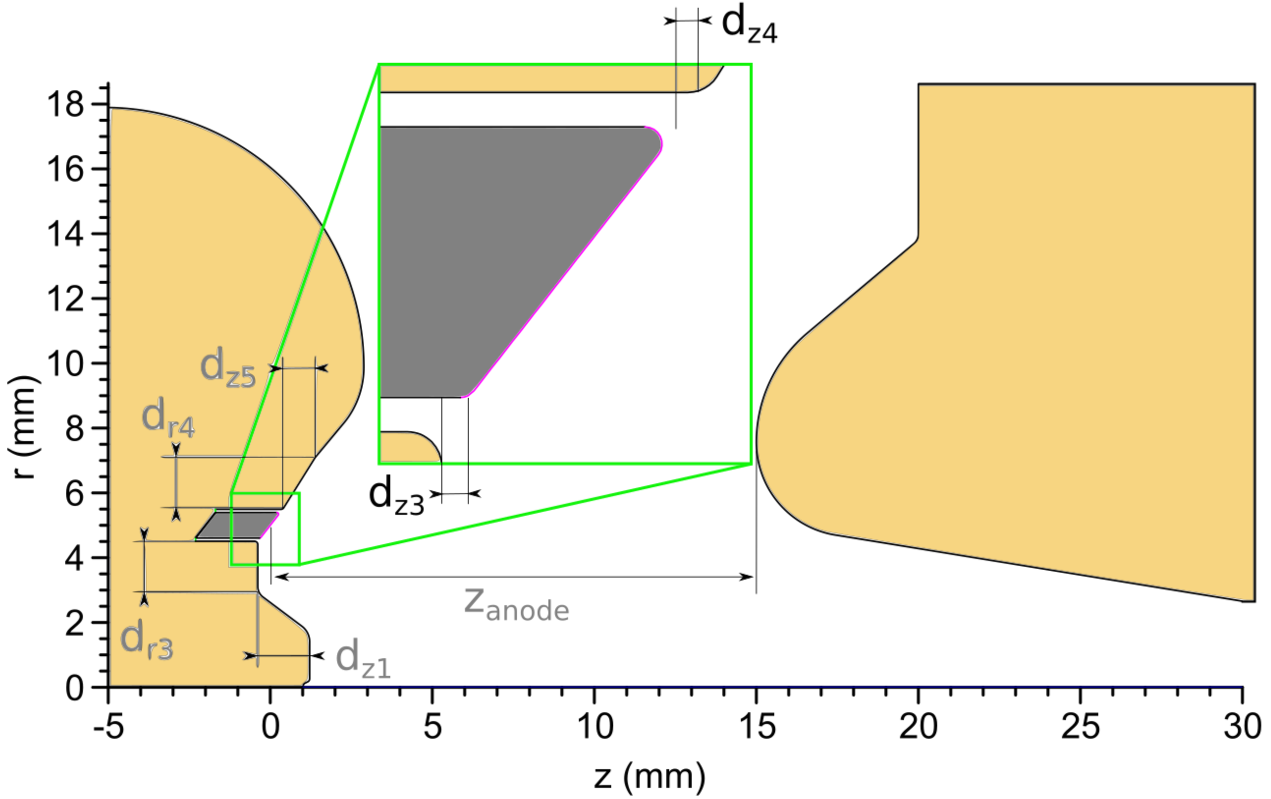
Comparison:

Strathclyde University design $\delta\alpha \approx 4.2\ \%$, Russian design $\delta v_\perp \approx 1.5\ \%$

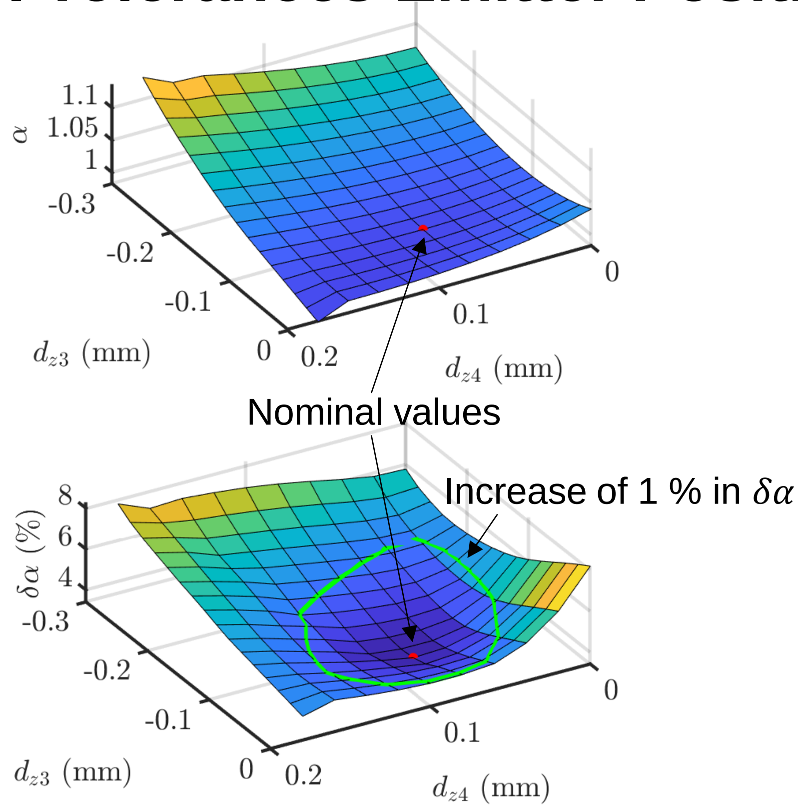
3. Developed Magnet System

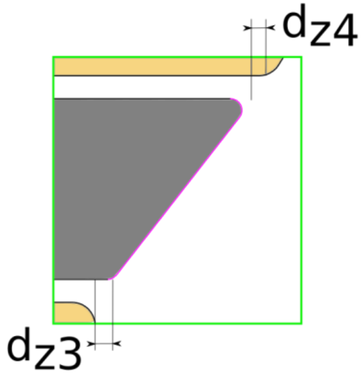


3. Tolerances



3. Tolerances Emitter Position





Parameter	Nominal Value	Tolerance
d_{z3}	-78.1 µm	± 80 µm
d_{z4}	78.1 µm	± 60 µm

→ Tight tolerances

→ Thermal expansion of the emitter has to be considered

3. Offset between tube and coil system

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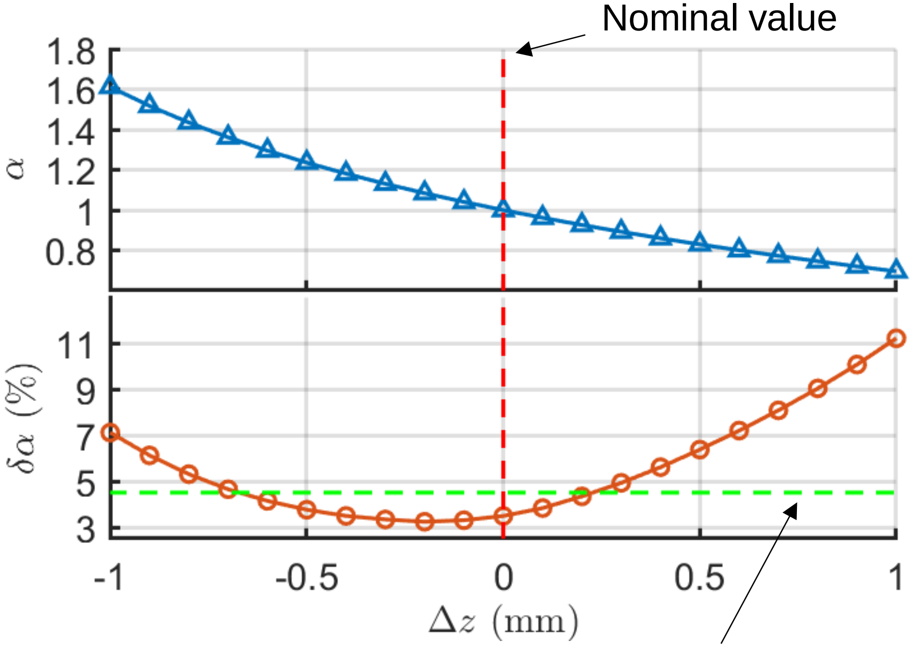
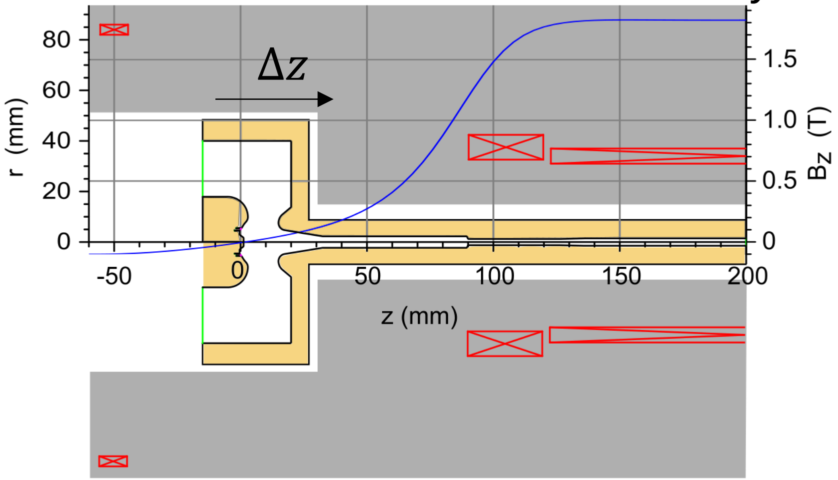


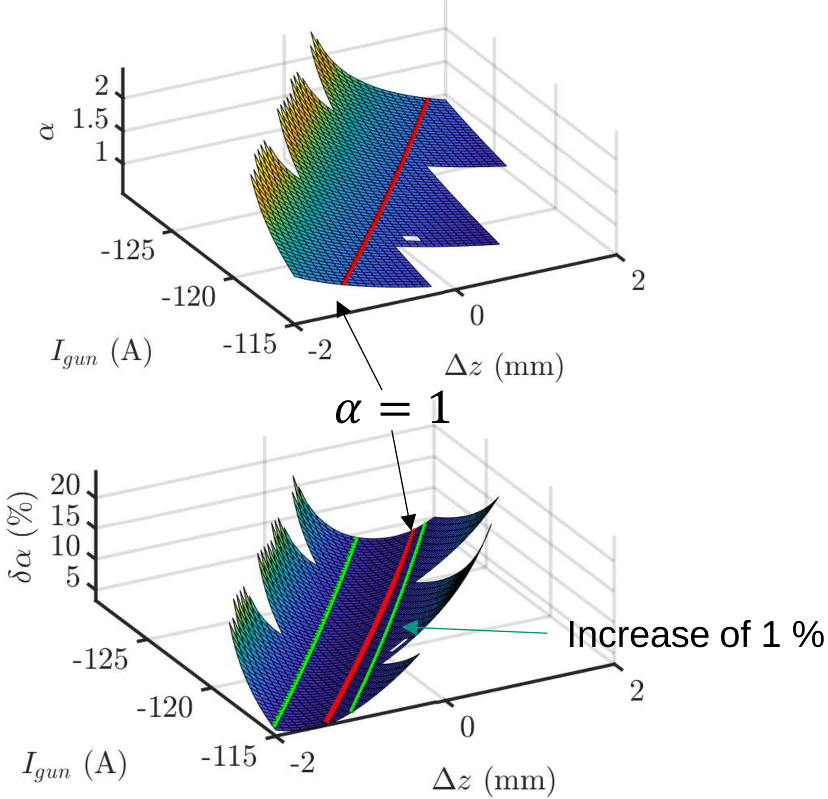
- Offset Δz between tube and coil system



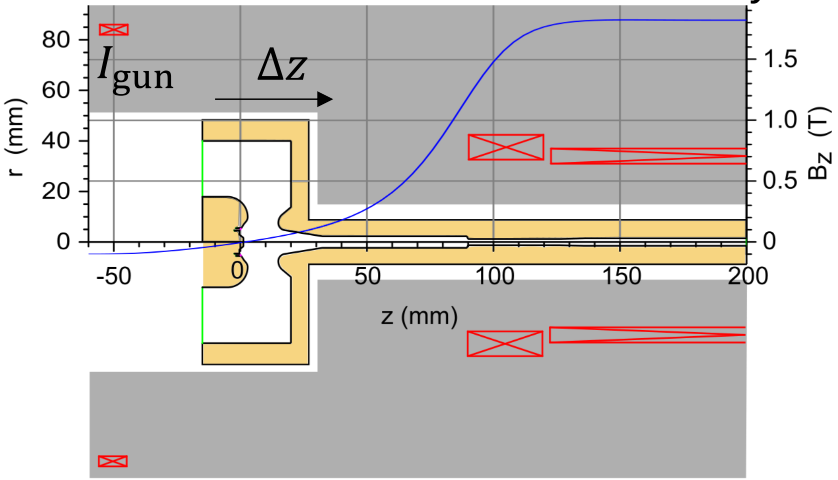
$$-0.7\ \text{mm} < \Delta z < +0.25\ \text{mm}$$

→ small tolerance compared to the length of the tube

3. Offset and gun-coil current



- Offset Δz between tube and coil system



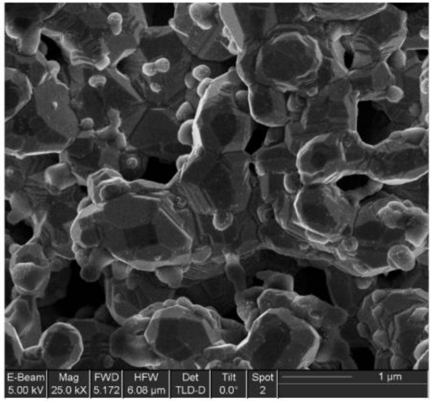
- Without compensation

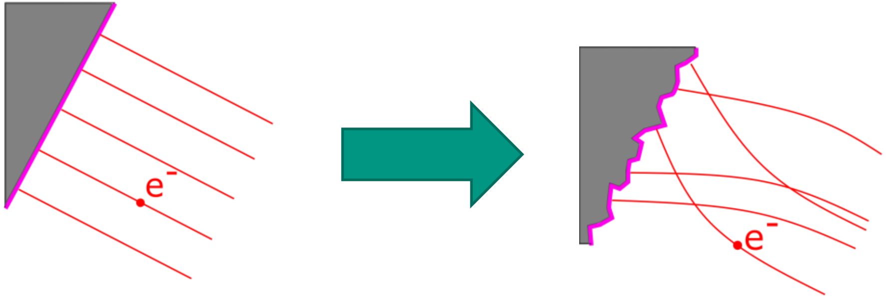
  $-0.7\ \text{mm} < \Delta z < +0.25\ \text{mm}$

- With compensation by I_{gun}

  $-2.0\ \text{mm} < \Delta z < +2.0\ \text{mm}$

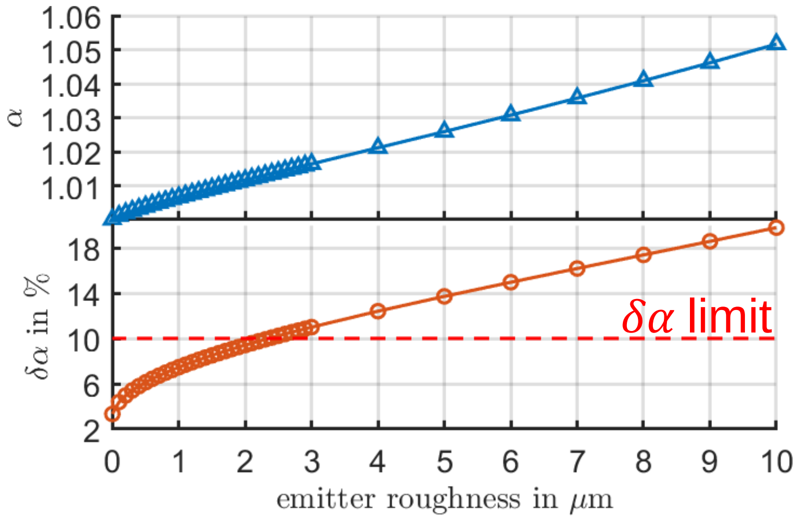
3. Emitter Roughness





$$\delta\alpha = 3.45\ \%$$

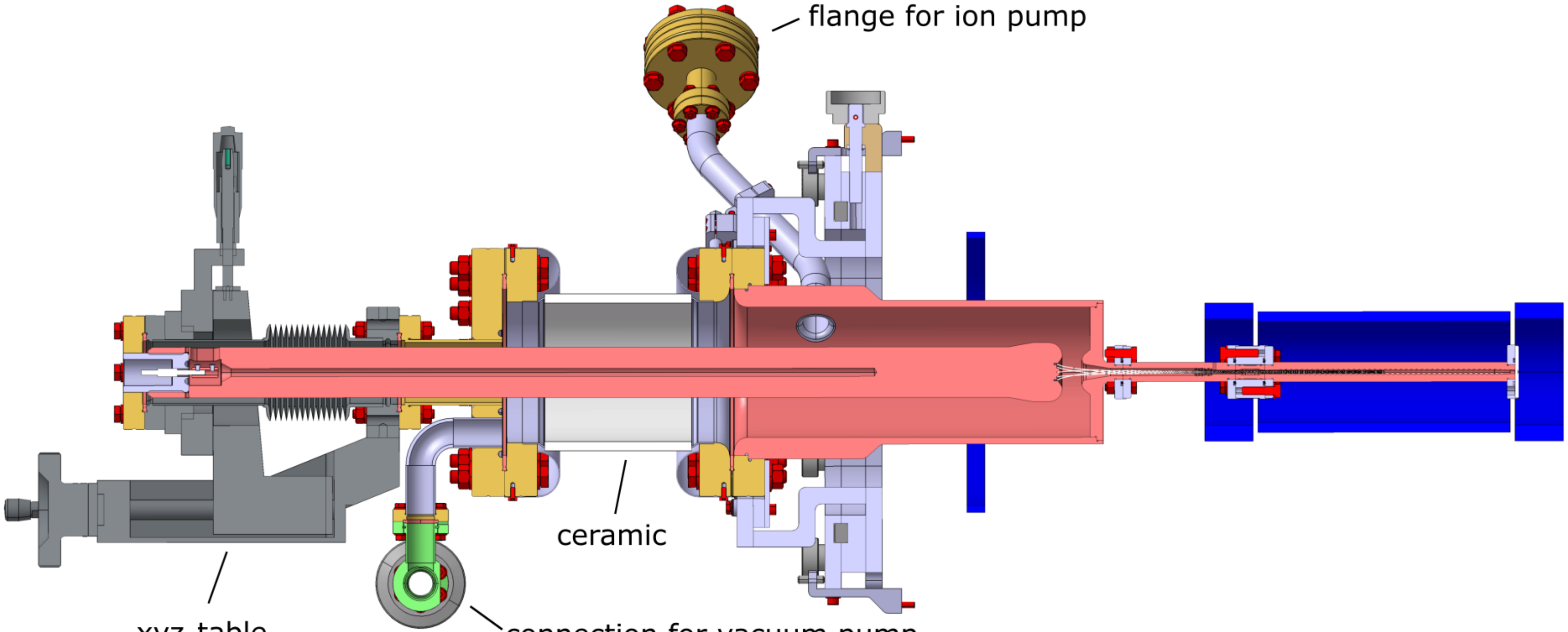
D. M. Kirkwood et al., "Frontiers in Thermionic Cathode Research," *IEEE Transactions on Electron Devices*



- With increasing surface roughness the pitch factor spread increases rapidly

→ A $\delta\alpha \leq 10.0\ \%$ can be reached up to a surface roughness of $2.3\ \mu\text{m}$.

3. Mechanical Realization



Drawing by Niklas Wirth

4. Conclusion

Goal: Design a CUSP-type electron gun with a spread $\delta\alpha \leq 10\ \%$.

- The final CUSP-gun with realistic coil configuration achieves a spread $\delta\alpha = 3.45\ \%$.
- Pitch factor spread of $\delta\alpha < 10\ \%$ for a surface roughness $< 2.3\ \mu\text{m}$.

→ Similar beam quality compared to Russian and UK designs

V. N. Manuilov, "Cusp Guns for Helical-Waveguide Gyro-TWTs of a High-Gain High-Power W-Band Amplifier Cascade," *Journal of Infrared, Millimeter, and Terahertz Waves*,
L. Zhang, "Cusp electron gun with modulation electrode for a THz gyro-amplifier," Sep. 2019, pp. 1–2. doi: 10.1109/IRMMW-THz.2019.8874517.