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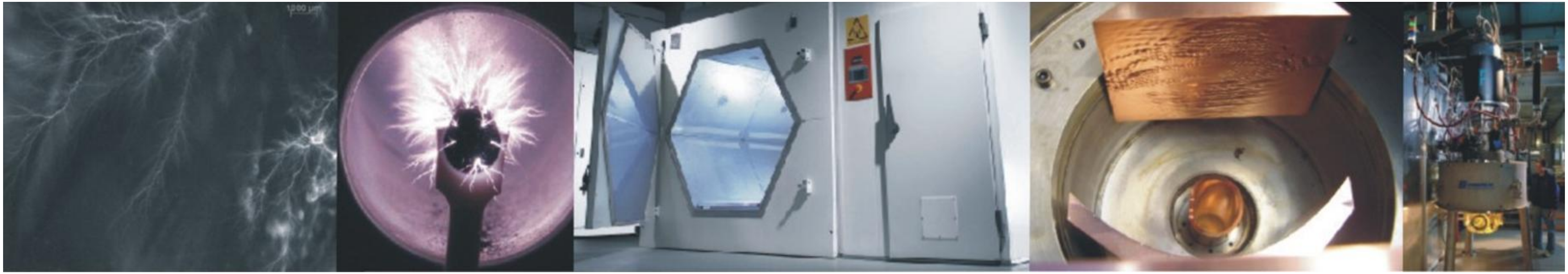

Novel dual-harmonic gyrotrons for DEMO featuring fast switching between distant frequencies: Concept elaboration and experimental demonstration of key elements

Stefan Illy on behalf of the KIT/NKUA ENR Project Team

EUROfusion

IHM
Institute for Pulsed Power and Microwave Technology (IHM)

1. Introduction
2. Theoretical Investigation of Fast Switching
   - Novel Concepts for Advanced Fast Switching Between Harmonics
   - Enhancement of Mode Selectivity using Profiled Corrugations
3. EU-DEMO Relevant Design
   - Cavity Design
   - Triode Gun
   - MDC
4. Experiments on Second Harmonic Operation

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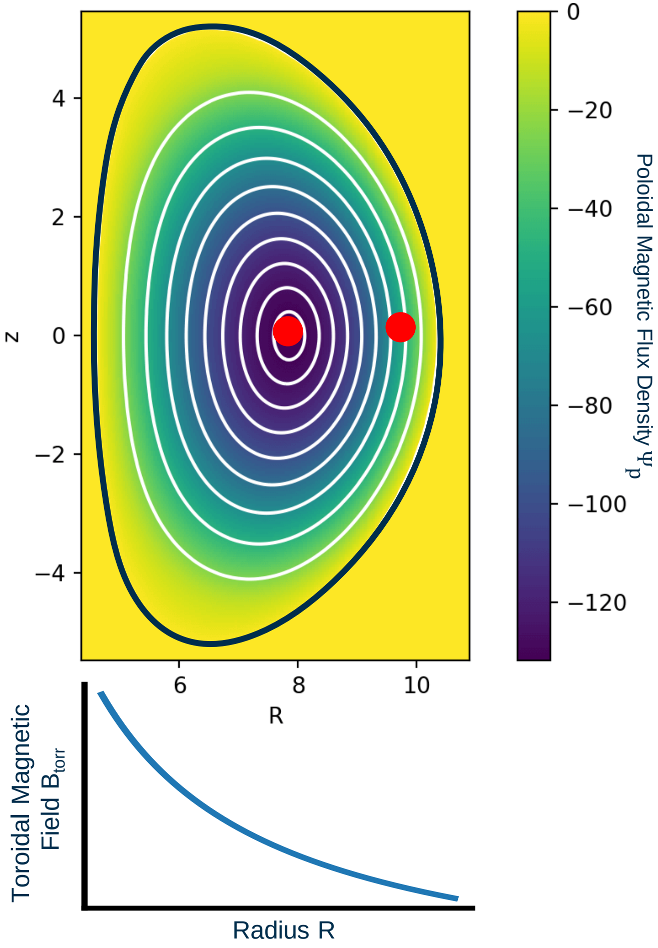
Introduction

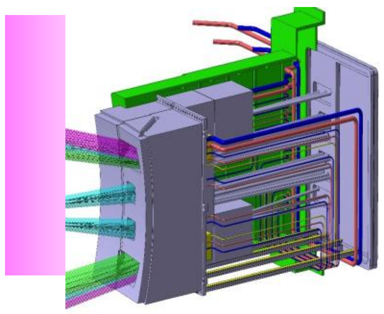
Problem: DEMO Radiative Instabilities

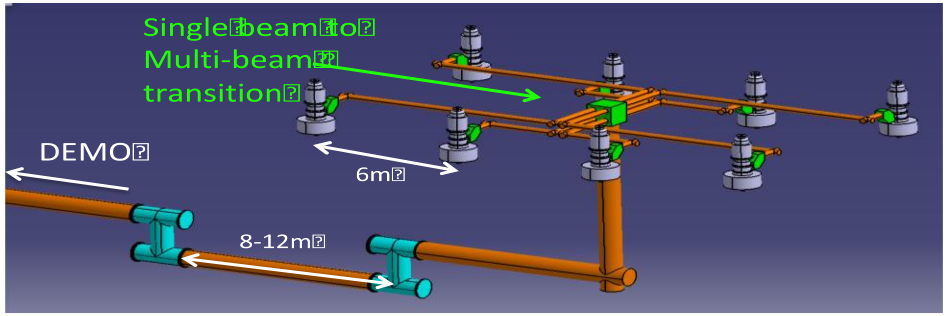
- Impurities at the plasma edge can lead to disruption.
- Magnetic field in the plasma depends on the radius ($\omega_c \propto B \propto 1/R$).
- Center heating (< 30 MW required) at high frequency and edge instability heating (> 70 MW) at a lower frequency needed.



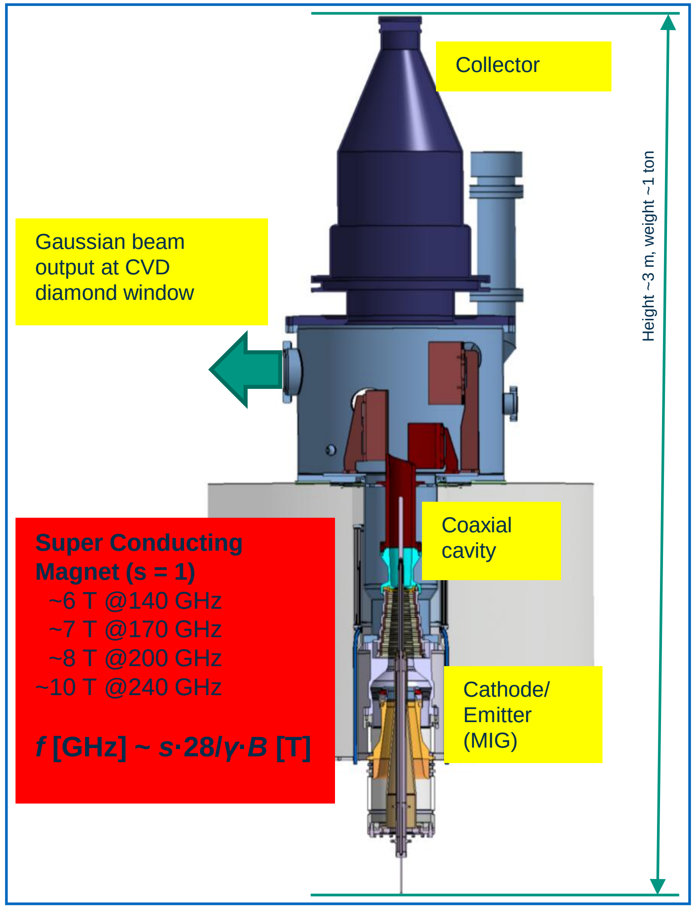
Key Components of the DEMO EC System

EC equatorial launcher





Quasi-optical transmission line (TL)

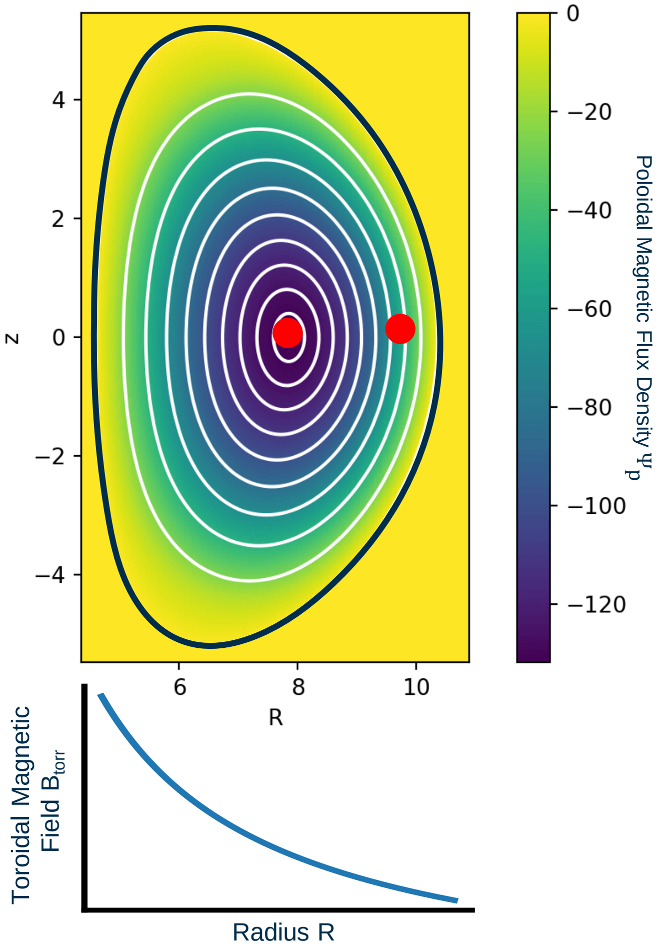


- Switching frequencies takes a long time, due to the large inductances of the magnet.

→ **Gyrotrons switchable between 1st and 2nd harmonic might be the solution!**

Problem: DEMO Radiative Instabilities

- Impurities at the plasma edge can lead to disruption.
- Magnetic field in the plasma depends on the radius ($\omega_c \propto B \propto 1/R$).
- Center heating (< 30MW required) at the 2^{nd} harmonic (s = 2) and edge instability heating (> 70 MW) at the first harmonic (s = 1).
- **Same gyrotron, launcher, window and transmission line for center & edge heating could be the solution.**



ENR Second Harmonic Gyrotron

Target: MW class gyrotrons operating at 1st harmonic (s = 1) and at 2nd harmonic (s = 2) of the electron cyclotron frequency

- Plasma center heating and mitigation of radiative instabilities with the **same gyrotron, transmission line and launcher.**
- Fast (sub-second) switching between distant frequencies.
- Two enabling technologies are addressed:

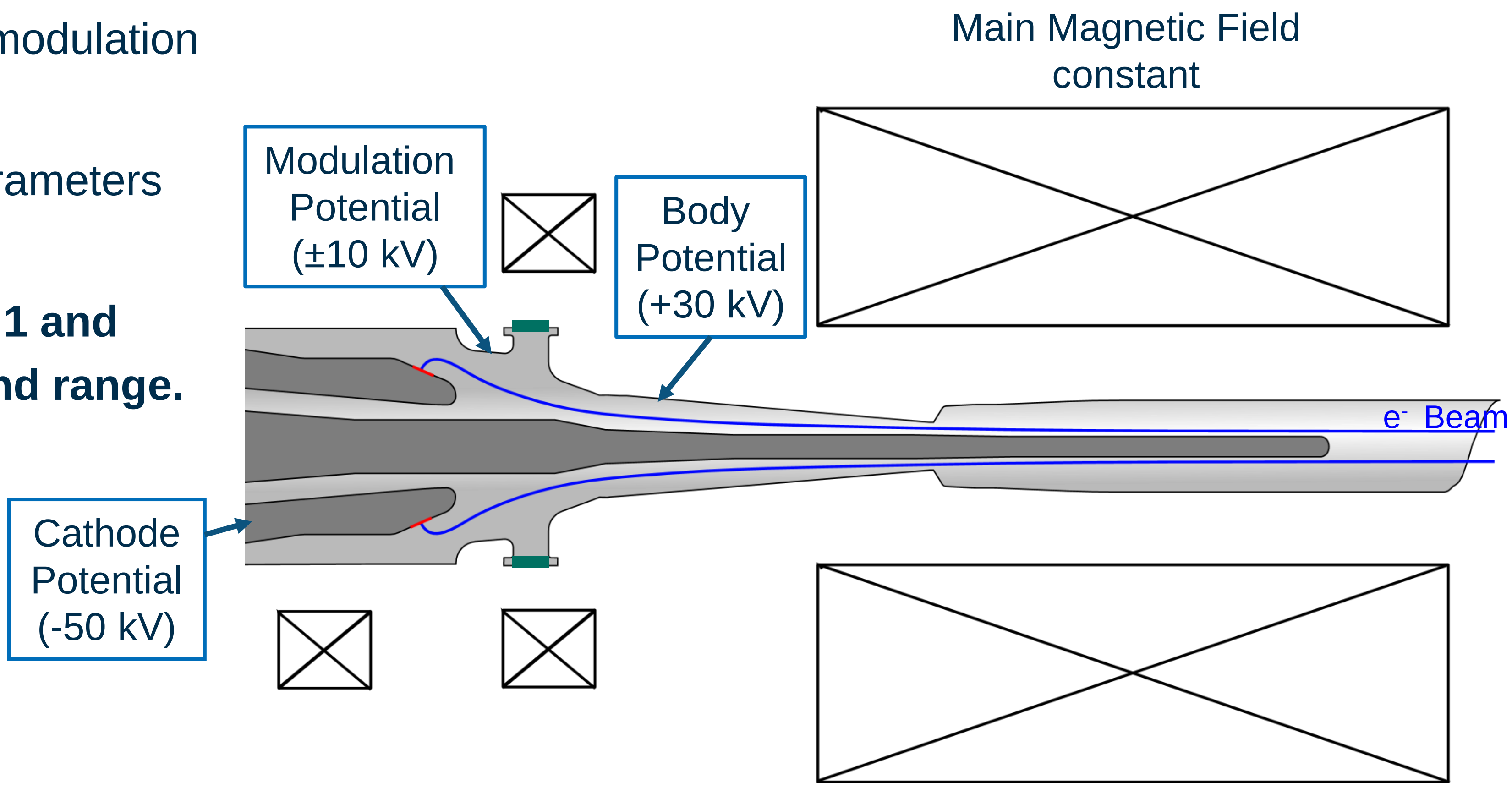
1. The coaxial-type cavity technology that is specifically adapted to the operation at 2nd harmonics in combination with advanced inner and outer corrugations.
2. The Multi-stage Depressed Collector (MDC) technology based on $E \times B$ drift concept.

Potential of saving ≳ 100 MW of installed spare power for EU-DEMO (Baseline 2019)

Theoretical Investigation of Fast Switching

Ultra-Fast Switching Using the Applied Voltages

- Variation of the accelerating and modulation anode voltage.
- Variation of the electron beam parameters (E_{kin}, $\alpha = v_{\perp} / v_z$).
- **Enables switching between s = 1 and s = 2 operation in the millisecond range.**



Novel concepts for advanced fast switching between harmonics

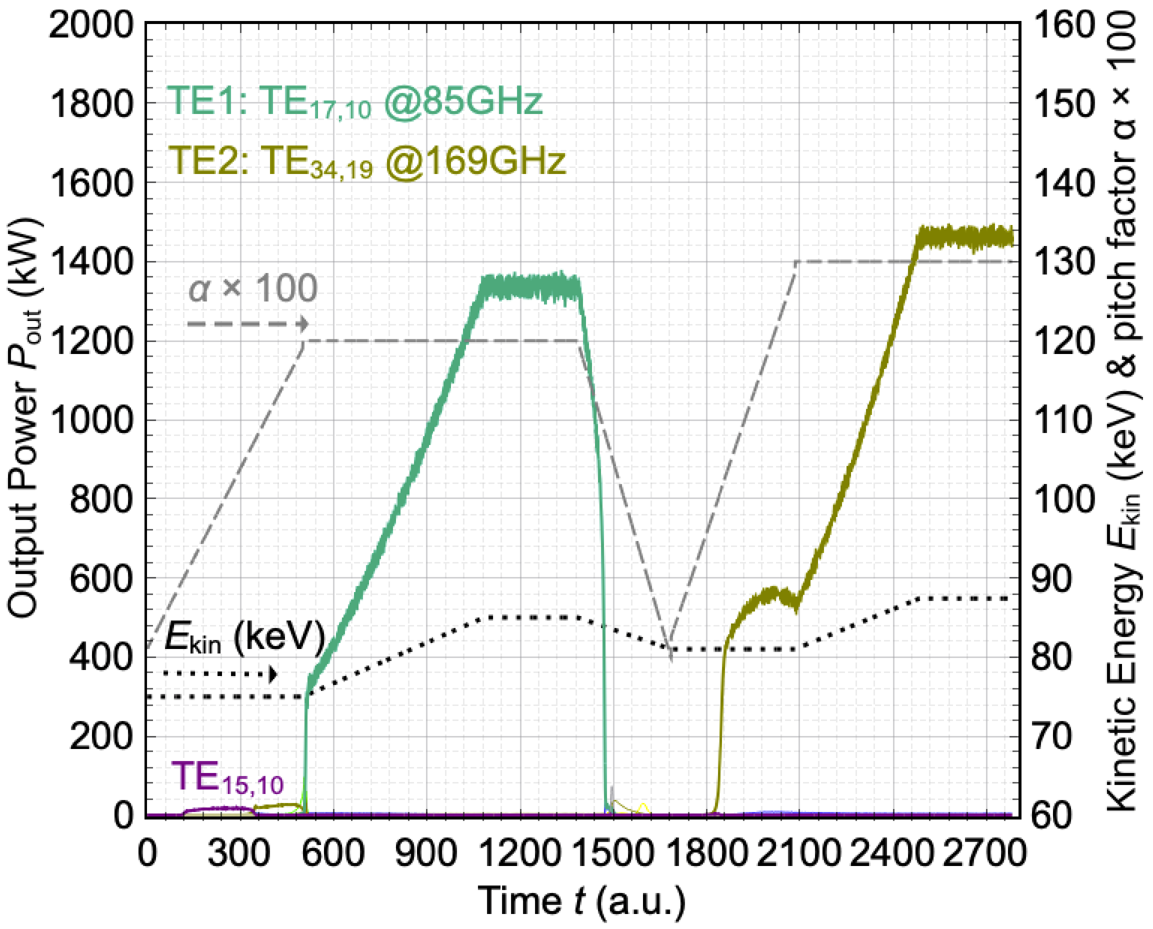
- Cavity (2nd harmonic TE2, 1.55 MW @ 170 GHz) tested for:
  - also 1st harmonic TE1 operation
  - the design of a fast-switching scenario
- Table I: Operating Points

	E_{kin} (keV)	I_b (A)	B_{max} (T)	Pitch factor α	*Eigenvalue*
$TE_{17,10}$	85	95	3.475	1.2	53.00
$TE_{34,19}$	87	95	3.475	1.3	105.19

- Table II: Performance

	P_{out} (MW)	efficiency	ρ_{out} (kW/cm²)	ρ_{in} (kW/cm²)
$TE_{17,10}$	1.35	18%	0.5	**1.35**
$TE_{34,19}$	1.45	19%	2.1	0.39

Multimode simulations demonstrate the fast-switching scenario between the TE1 and the TE2 mode by varying the electron-beam parameters (E_{kin}, α)



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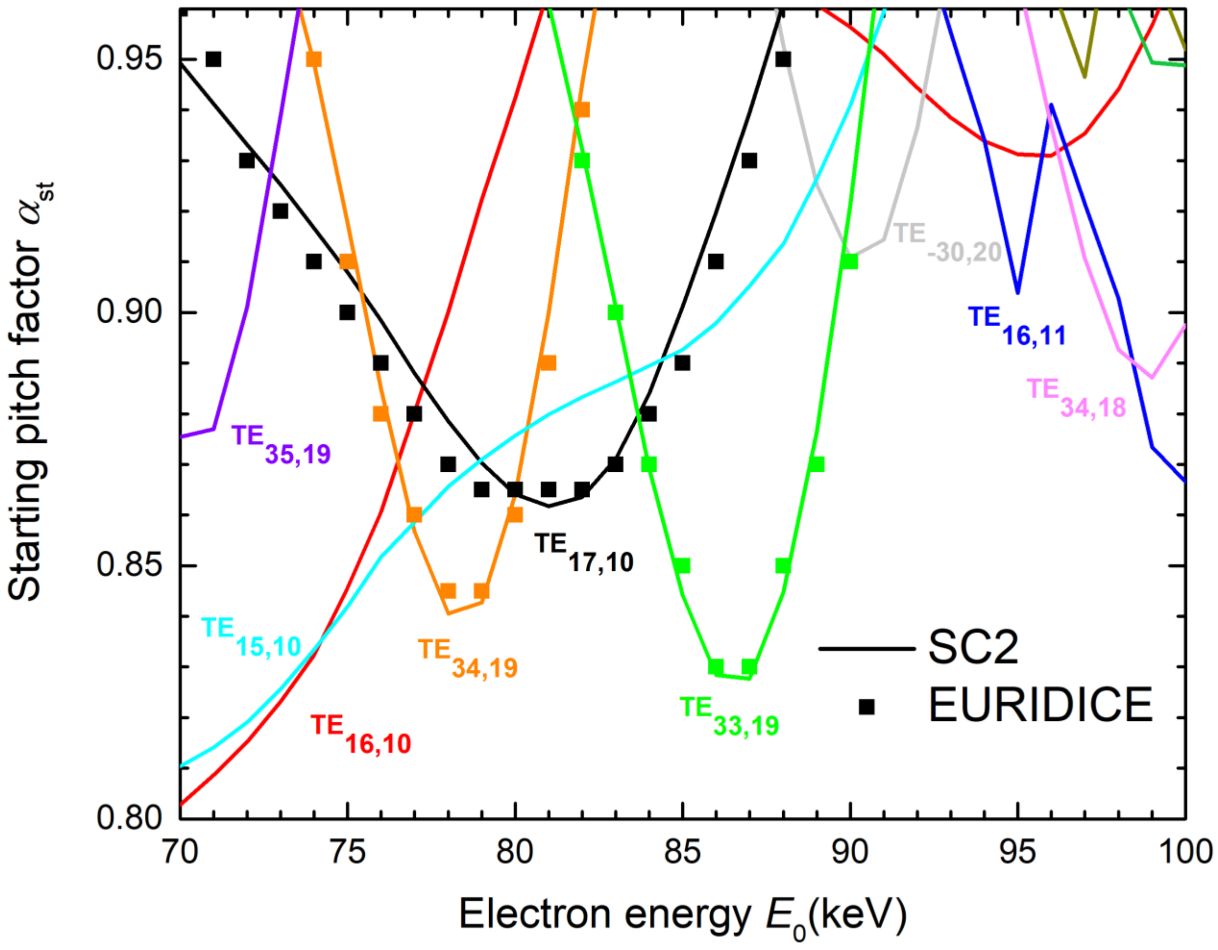
New Modelling Tool for Starting Pitch Factor Calculation

- The numerical code SC2 has been developed for the calculation of the starting pitch factor and the starting current of a TE mode in gyrotron cavities.
- SC2 has been validated by comparison with EURIDICE and TWANGlinspec.
- The knowledge of the starting pitch factor identifies practical gyrotron startup scenarios with a triode-type electron gun that can mitigate mode competition, especially in high-power gyrotrons.



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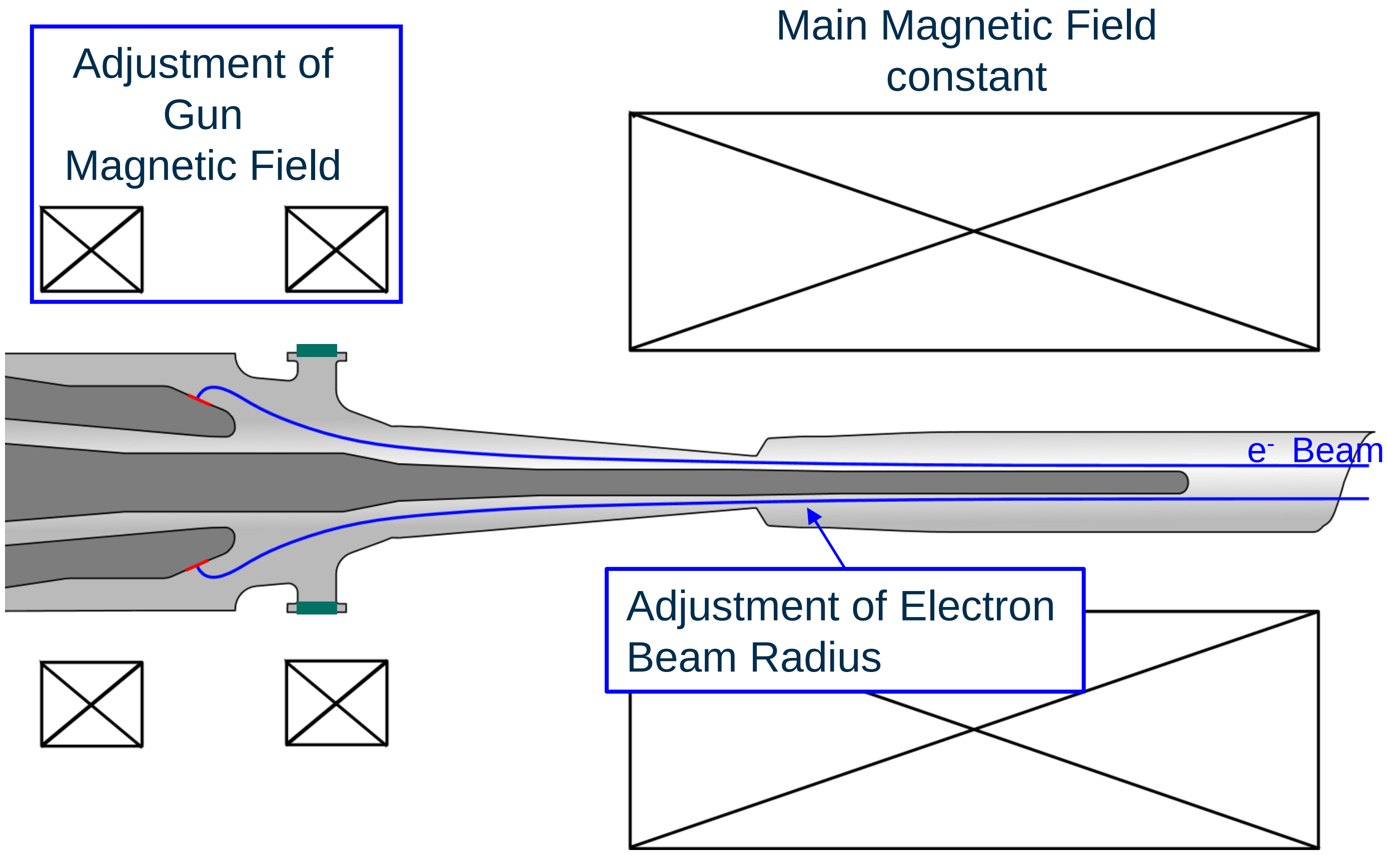
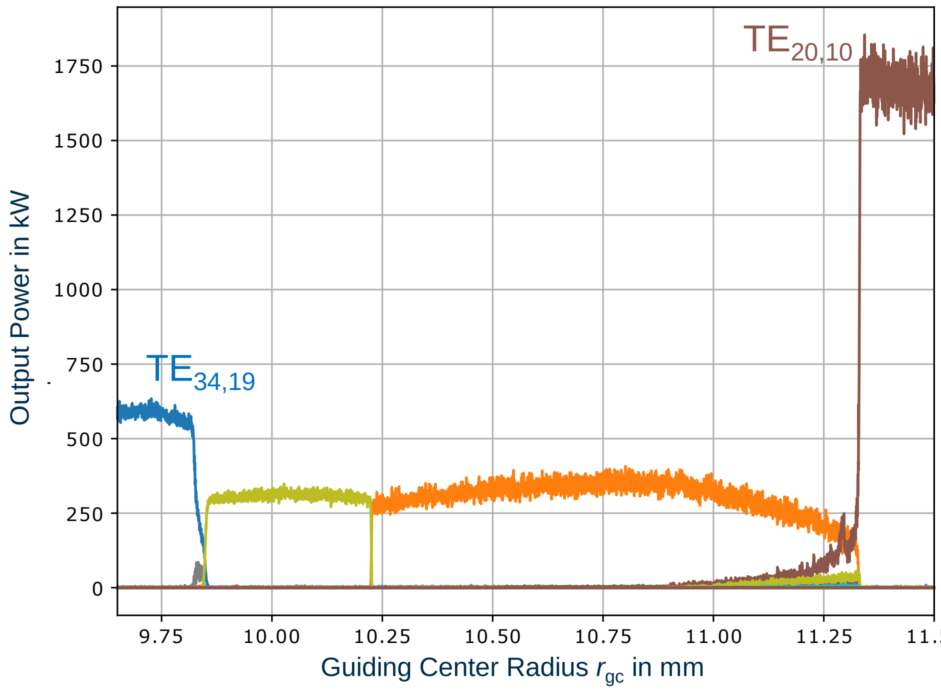
Fast Switching the Guiding Center Radius (Tuning the Gun Coils)

- Switching time in the multiple seconds range.
- Gyrotrons can be used for plasma startup (at s = 2) and then switched for RI mitigation (at s = 1).
- Varying the magnetic field at the emitter changes the electron beam radius in the cavity.
- Hysteresis effect, depending on sweep direction could lead to a suppression of the second harmonic operating mode.

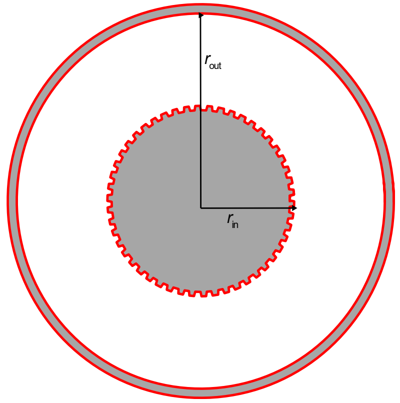


Fast Switching the Guiding Center Radius (Tuning the Gun Coils)

- Main magnetic field coil remain unchanged.
- Transition from $\mathrm{TE}_{34,19}$ mode (170 GHz) to $\mathrm{TE}_{20,10}$ (86.6 GHz) mode.
- Magnetic field at the emitter changes from 88.8 mT ($\mathrm{TE}_{34,19}$) to 107.6 mT ($\mathrm{TE}_{20,10}$).
- Non-optimal for the quasi-optical (QO) output system
  - Reflection of -15 dB at the window expected
  - Difference in relative caustic radius: 0.32 ($\mathrm{TE}_{34,19}$) → 0.35 ($\mathrm{TE}_{20,10}$).
- Output power:
  - Second-harmonic operation: 600 kW
  - Fundamental operation : 1.7 MW
- Recommended to also re-ramp the accelerating voltages after tuning the gun coils.

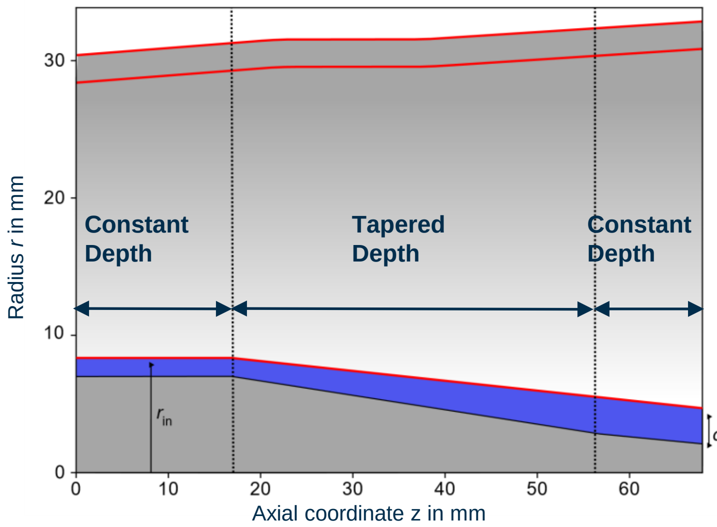


Enhancement of Mode Selectivity
Profiled Inner Corrugations

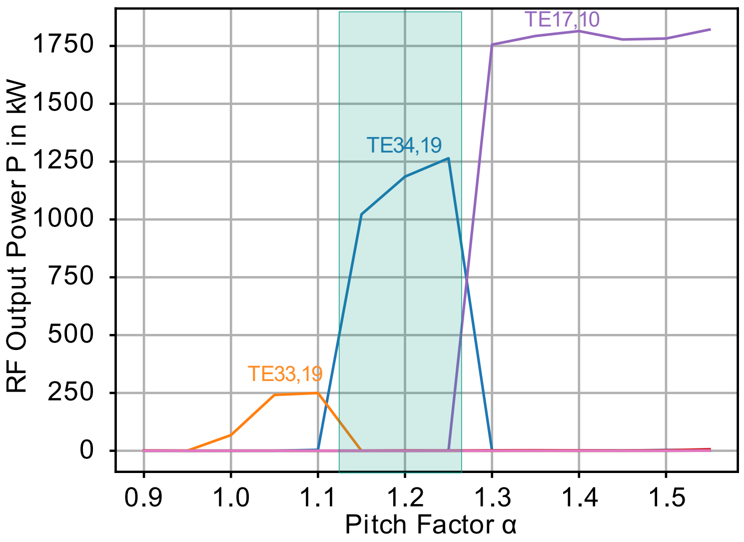


Target: Better suppression of the fundamental competing modes

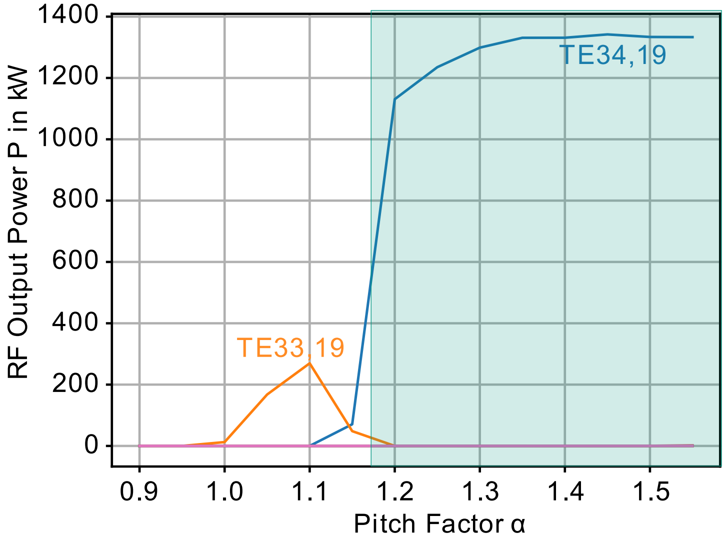
- Introduce a novel concept for tapered impedance corrugations.
- Increase drop of the eigenvalue along the cavity axis.
- Decrease of the diffractive Q factor → Increase of the starting current.
- Relaxed tolerance requirements.



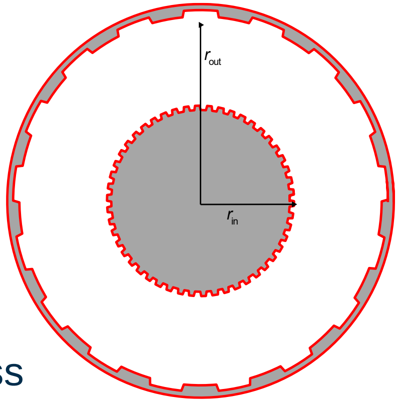
Constant Corrugation Depth

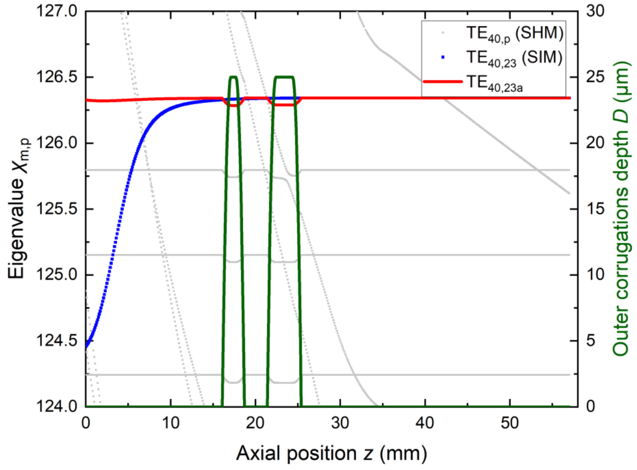


Variable Corrugation Depth

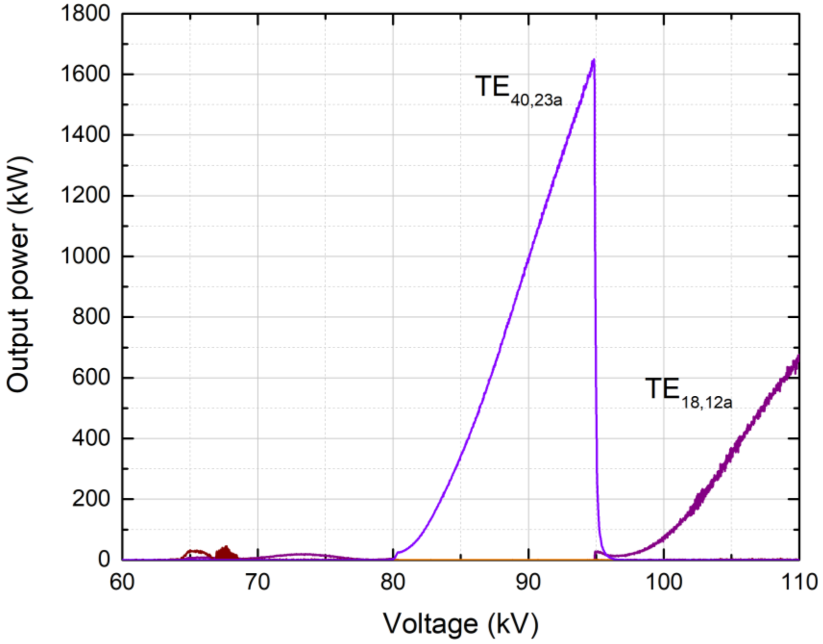


Enhancement of Mode Selectivity
Profiled Outer Corrugations



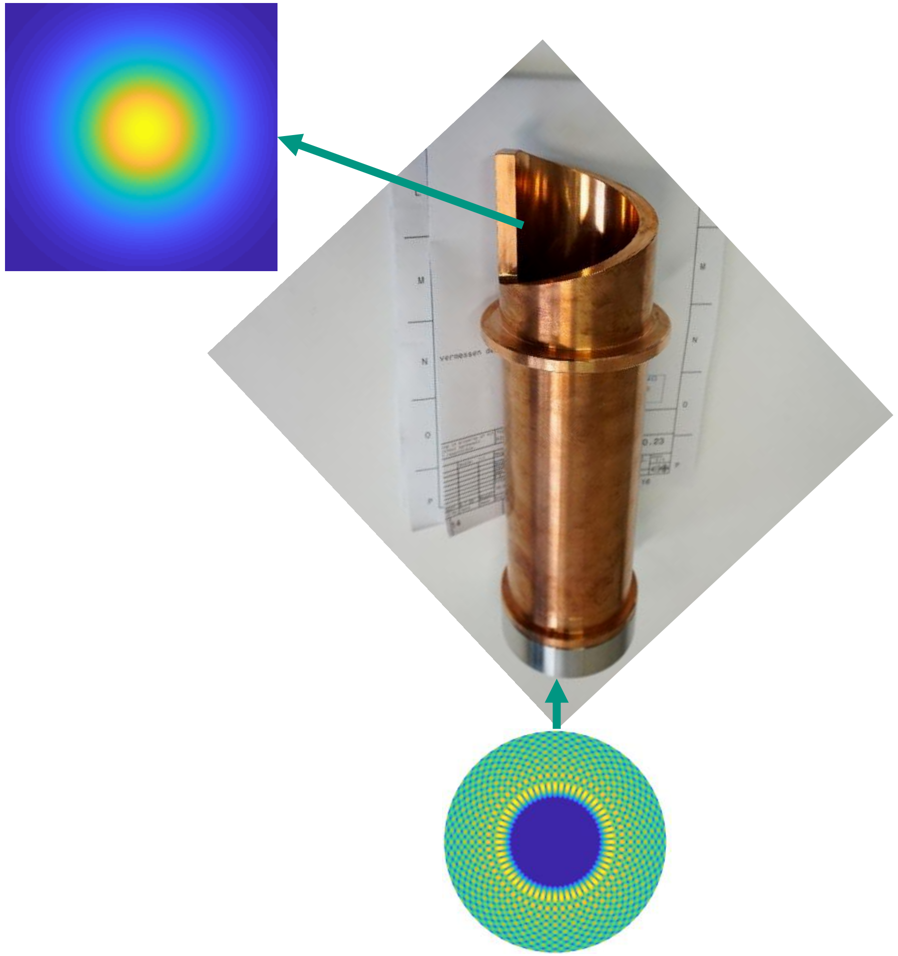


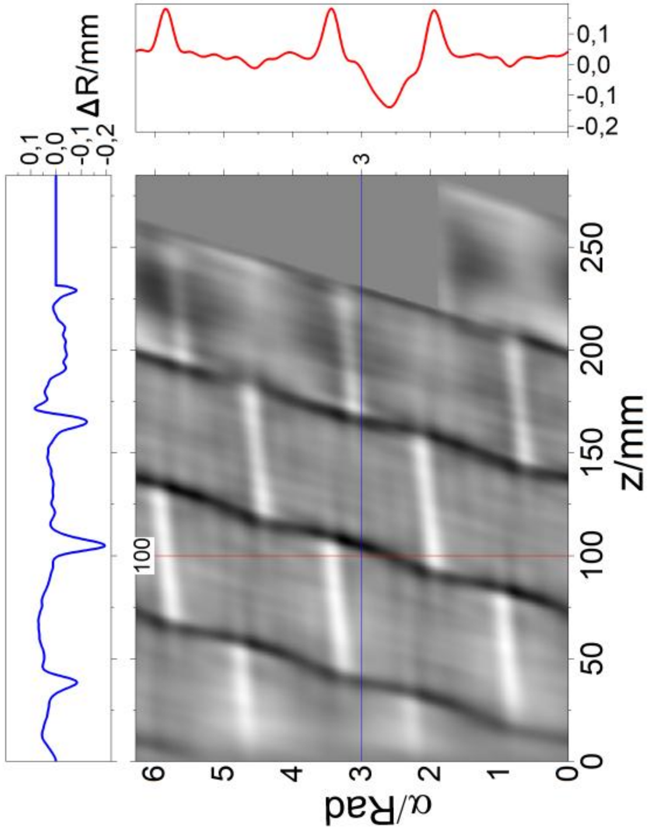
- To reach eigenvalues above χ=125, a new scheme of axially profiled azimuthal corrugations was proposed and studied.
- Such corrugations should be localized on the axis to selectively suppress only the major competing modes while leaving the operating one unaffected.
- The transition from the smooth wall to profiled corrugations is performed smoothly to avoid any undesired reflections and mode conversion.
- As an illustrative example, the excitation of $TE_{40,23}$ (χ=126) at 204 GHz and at second harmonic have been used.
- Main 1st harmonic competing modes are $TE_{19,12}$ and $TE_{19,13}$.
- $TE_{40,23}$ cannot be excited with corrugations only on the insert (without profiling $TE_{19,12}$ suppresses $TE_{40,23}$).
- Performance:
  - P_{out}=1.65 MW,
  - η=22%,
  - Ohmic loading below technological limits (ρ_{out}=2.09 kW/cm^2, ρ_{in}=0.24 kW/cm^2).



Studies on dual-harmonic launchers and quasi-optical system

A mirror-line launcher for the TE17,10 mode @ 85.66 GHz and the TE34,19 mode @ 170.05 GHz

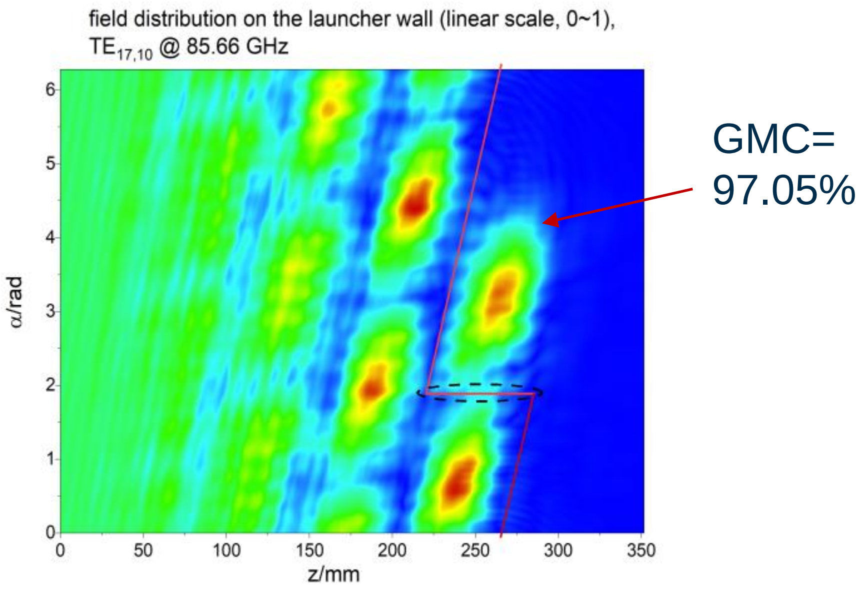


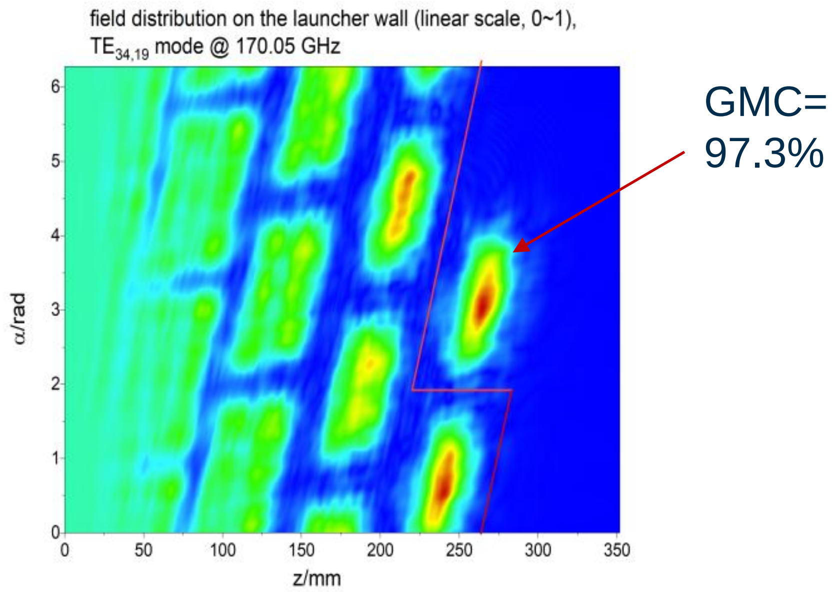


Studies on dual-harmonic launchers and quasi-optical system

A mirror-line launcher for the TE17,10 mode @ 85.66 GHz and the TE34,19 mode @ 170.05 GHz

GMC: Gaussian Mode Content





Field distributions on launcher wall, operating in the $TE_{17,10}$ mode @ 85.66 GHz (left) and in the $TE_{34,19}$ mode @ 170.05 GHz (right).

Disadvantages:

- The RF beam @ 85 GHz could not be focused very well (due to the wavelength @ 85 GHz, which is two times larger compared to the 170 GHz case) → relatively large power density at the launcher cuts.
- Relatively strong reflection on the straight cut @ 85 GHz, "ripple" appears on the field on launcher wall.

EU-DEMO Relevant Design

Detailed cavity design including sensitivity studies

- Requirements for dual-harmonic operation:
  - maximum 1% difference in caustic radii ($|\delta R_C| < 1\%$)
  - maximum 1% deviation of the window reflection coefficient from zero ($\delta R_{ref} < 1\%$)
  - $80 < \chi_{m,p} < 110$ for TE2
- Table III: Reduced list* of candidate modes for dual-harmonic operation from a Python code

TE1 / TE2	R_c/R_o	$\lvert\delta R_C\rvert$	δR_{ref}
$TE_{17,10}$ / $TE_{34,19}$	0.3	0.77 %	0.23 %
$TE_{20,07}$ / $TE_{40,13}$	0.4	0.91 %	0.32 %
$TE_{23,06}$ / $TE_{46,11}$	0.5	0.94 %	0.34 %

*Three cases with relative caustic radii of 0.3,0.4 and 0.5 are considered sufficient to cover all relevant cases

- The $TE_{17,10}$ / $TE_{34,19}$ mode pair: promising candidate, but limited by high ρ_{in}, despite cavity modifications.
- The $TE_{20,07}$ / $TE_{40,13}$ mode pair: single mode simulations indicate high ρ_{in} during TE1 operation.
- The $TE_{23,06}$ / $TE_{46,11}$ mode pair: indications of compatibility with CW dual-harmonic operation.

Detailed cavity design including sensitivity studies

- Table IV: Operating Points & Performance

	E_{kin} (keV)	I_b (A)	B_{max} (T)	Pitch factor α	*Eigenvalue*
$TE_{23,06}$	86	72	3.482	1.29	46.84
$TE_{46,11}$	89	74	3.482	1.28	92.80

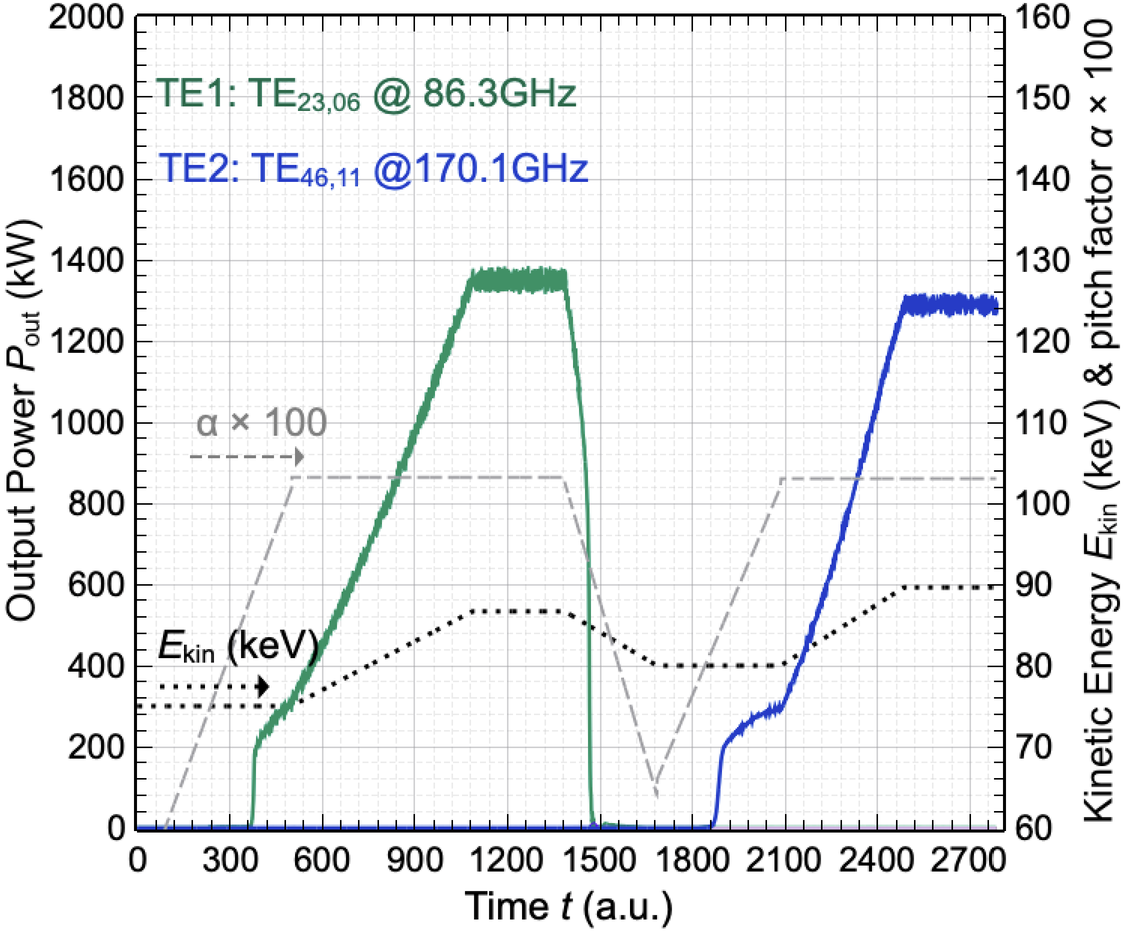
	P_{out} (MW)	Efficiency	ρ_{out} (kW/cm^2)	ρ_{in} (kW/cm^2)
$TE_{23,06}$	1.35	22%	0.65	0.36
$TE_{46,11}$	1.30	20%	2.4	0.08

- The new cavity design is:
  - Optimized for: High interaction efficiency at both harmonics.
  - Tested for:

    a. Safe margins from modeloss by independent increase of beam parameters (E_{kin}, I_b, α).

    b. Stable Performance under cavity deformation.

Multimode simulations (75 modes are included) demonstrate the fast switching-scenario between the TE1 and the TE2 mode by varying the electron beam parameters



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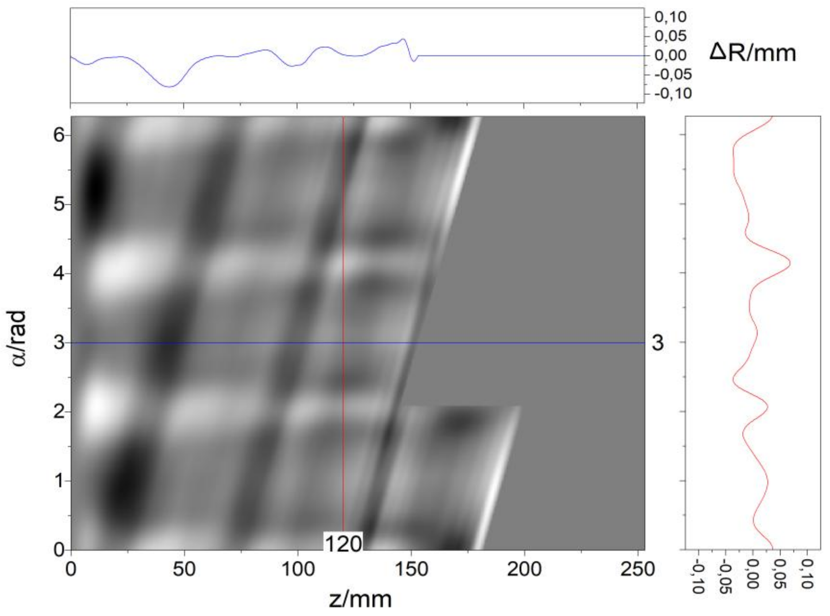
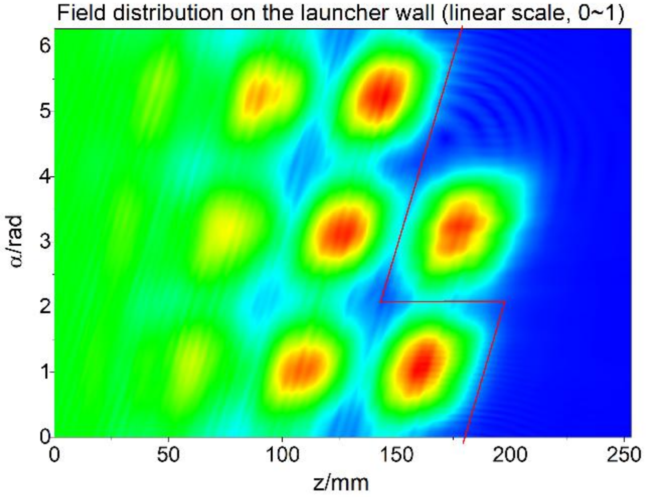
Design of a Quasi-Optical System for Harmonic Modes Launcher

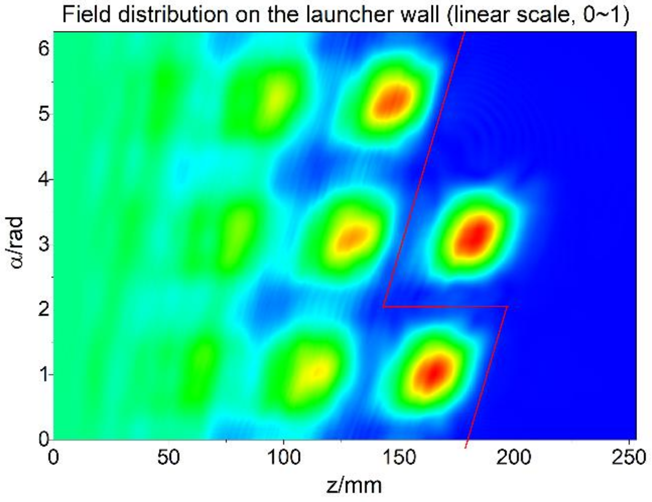
- A **hybrid-type** launcher has been designed for the $TE_{46,11}$ mode @ 170 GHz and the $TE_{23,06}$ mode @ 85.66 GHz
- The launcher length is 213.12 mm, the slope of taper is 0.002, launcher radius at the entry of the launcher is 27.86 mm.



First Harmonic



Second Harmonic



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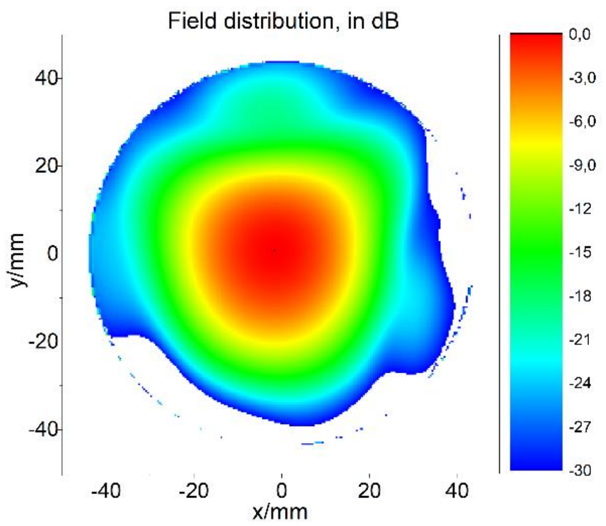
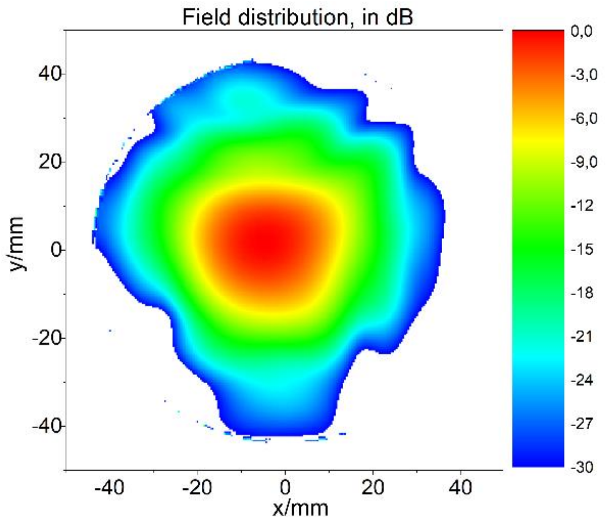
Design of a Quasi-Optical System
Mirror System

- A mirror system with a quasi-parabolic mirror, and two quadratic mirrors has been designed.
- Excellent Gaussian Mode Content (GMC) at first (**98.37%**) and second harmonic (**97.86%**) operation.
- Beam waists first harmonic :
  - $w_{0,x}$=19.98 mm @ 2 mm after the window
  - $w_{0,y}$=20.49 mm @ 34 mm before the window
- Beam waists second harmonic :
  - $w_{0,x}$=17.75 mm @ 231 mm after the window
  - $w_{0,y}$=14.57 mm @ 261 mm before the window.
- Astigmatism has to be compensated by matching optics unit (MOU).

First Harmonic

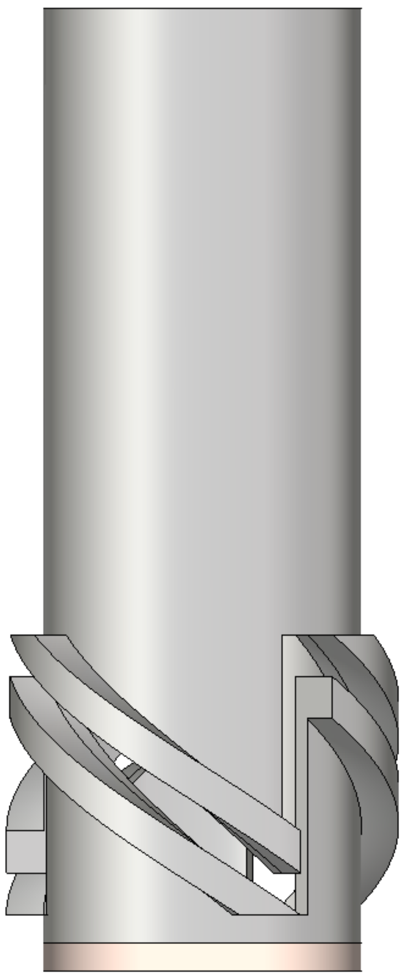


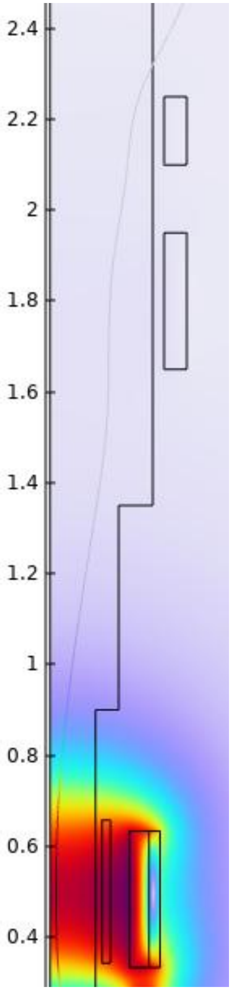
Second Harmonic



Design of a CW Multistage Depressed Collector (MDC)

- MDC development for increased efficiency
- Triple helix $E \times B$ design with magnetic field sweeping
- Compact MDC due to reduced magnetic field
  - Inner electrode radius: 150 mm
  - Length of $E \times B$ region: 300 mm

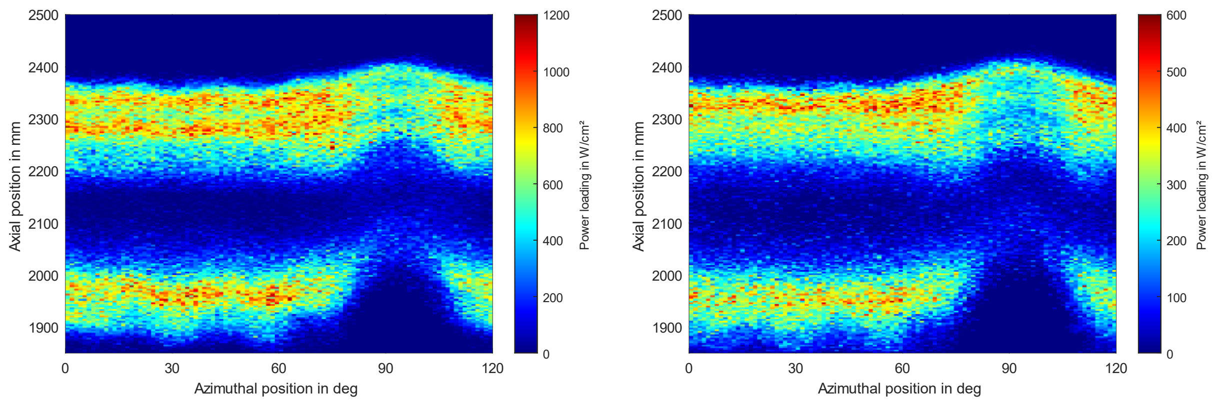




Design of a CW Multistage Depressed Collector (MDC)

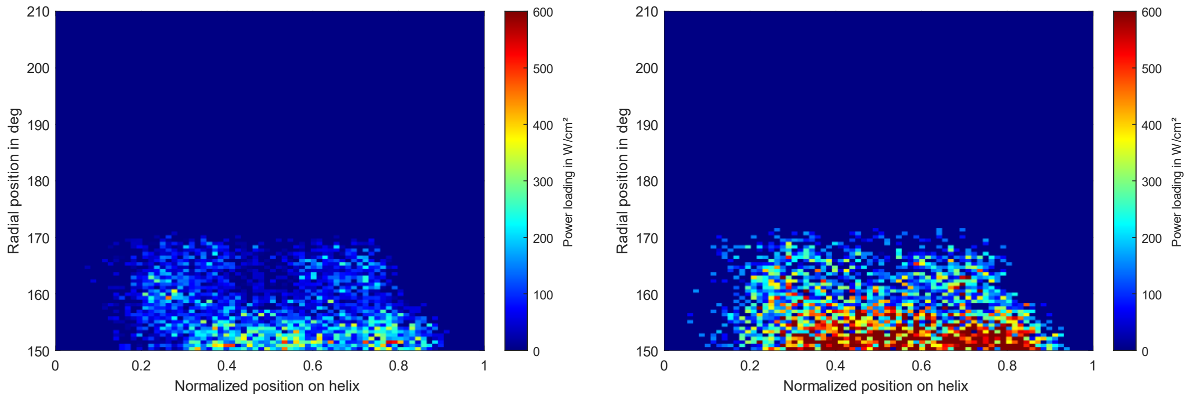
- MDC development for increased efficiency
- Triple helix $E \times B$ design with magnetic field sweeping
- Compact MDC due to reduced magnetic field
  - Inner electrode radius: 150 mm
  - Length of $E \times B$ region: 300 mm
- Operating points with identical collector potentials
- Excellent performance for second harmonic operation:
  - First harmonic: η_{col} = 66.1 % → η_{tot} = 42.8 %
  - Second harmonic: η_{col} = 84.2 % → η_{tot} = 57.7 %
- Optimization potential of magnetic field profile
  - Improve wall load uniformity
  - Reduce reflected current

Second Stage



First Harmonic | Second Harmonic

First Stage



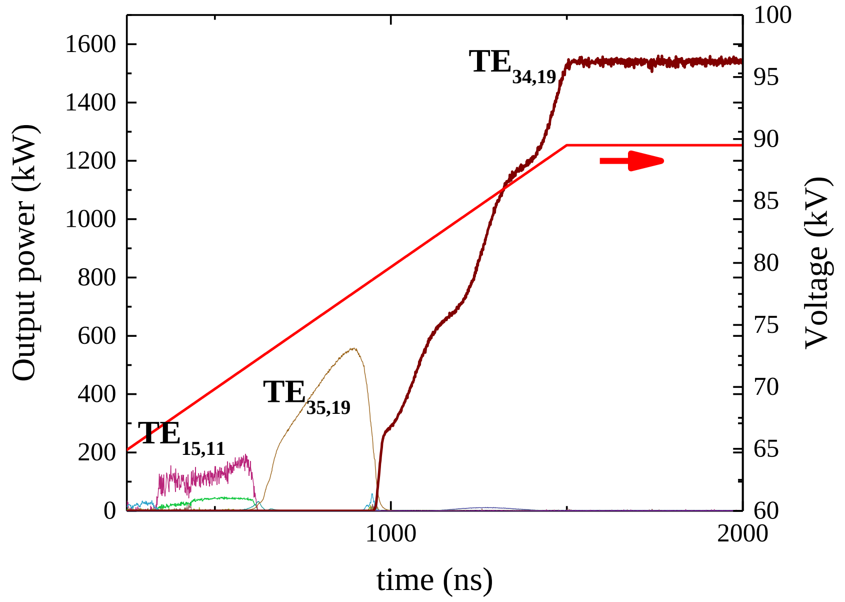
First Harmonic | Second Harmonic

Experiments on Second Harmonic Operation

Cavity Design for Experimental Verification

- A detailed 2nd-harmonic $TE_{34,19}$ coaxial cavity design for the upcoming experiment was performed targeting to MW-class operation.

- **Simulated performance**:
  - Output power at cavity exit P_{out}=1.55 MW.
  - Interaction efficiency η = 23 %.
  - Outer ohmic loading ρ_{out} = 2.08 kW/cm^2.
  - Inner ohmic loading ρ_{in} = 0.36 kW/cm^2.

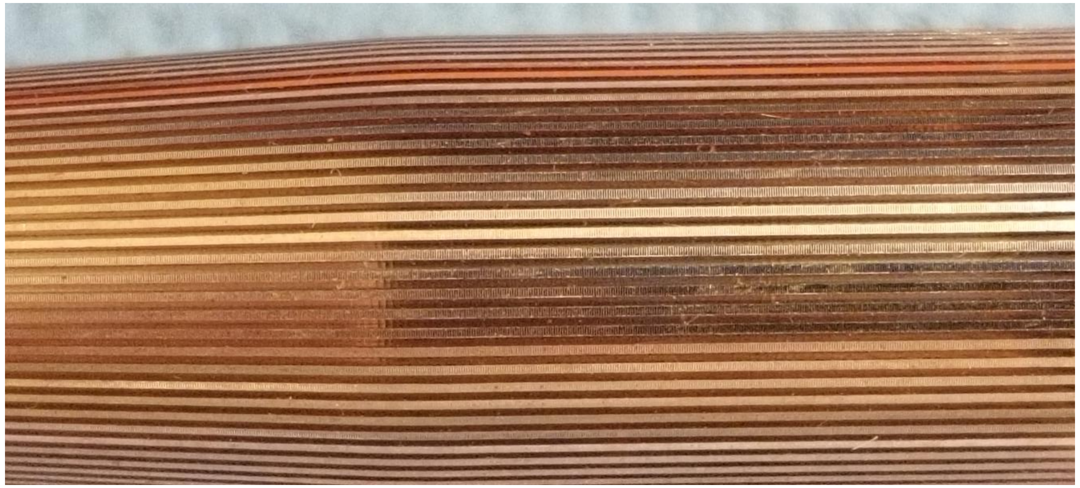


Simulation results showing stable excitation of the 2nd-harmonic operating mode $TE_{34,19}$ in diode startup. A large number of 100 1st- and 2nd-harmonic competitor modes are included in the simulation. Assumed spreads: 6% rms in pitch factor, 2.0 Larmor radii uniform guiding center spread.

- **Sensitivity analysis** was performed against many parameters. Excellent mode stability with respect to:
  - Velocity beam spreads (stable MW-class excitation of the 2nd-harmonic mode up to α-spread of 15% rms).
  - Magnetic field value B_{nom} and displacement z_{disp} (-1.0% < $(B – B_{nom})/B_{nom}$ < 0.5%, -6 mm < z_{disp} < +15 mm).
  - Coaxial insert and e-beam radii (8.57 mm < R_{coax}< 8.77 mm, 9.47 mm < R_{beam} < 9.73 mm).

Experiments in Preparation
Design and Manufacturing

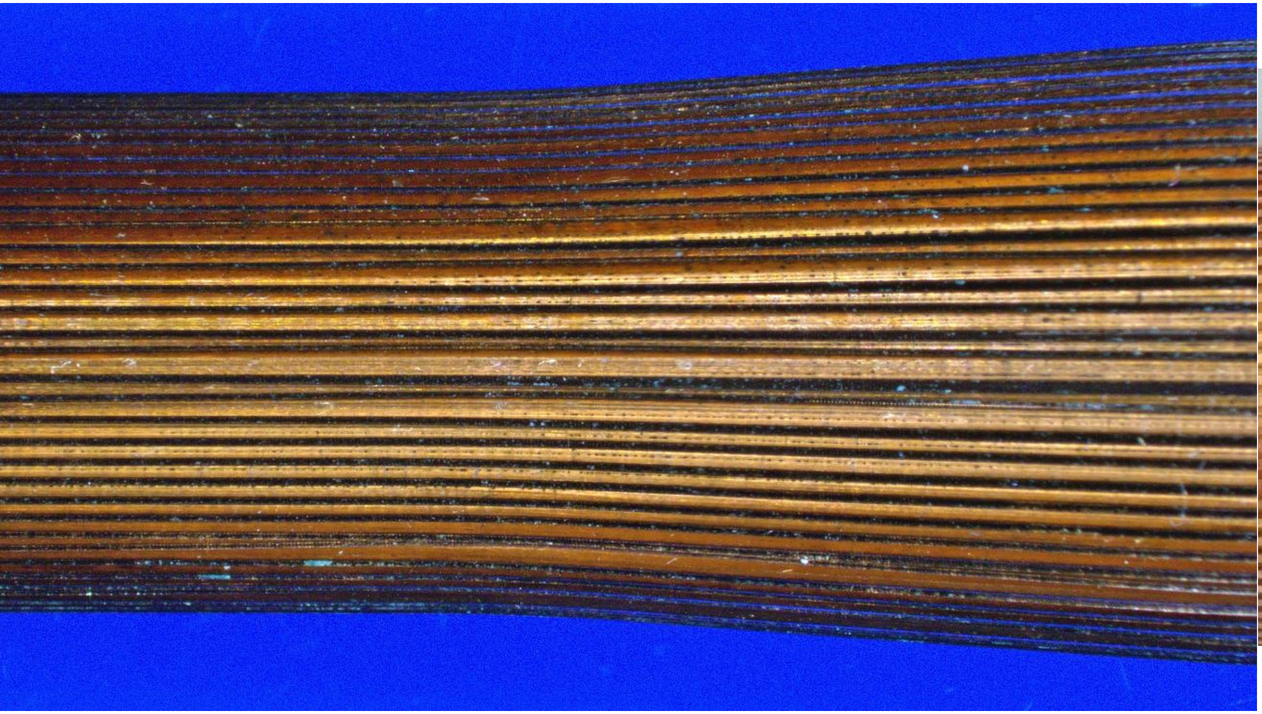
- Manufacturing of a short pulse cavity.
- Novel mechanical design and manufacturing of a modular insert.
- Challenging design of impedance corrugated insert tip.
- Two attempts needed to manufacture the corrugations.



Insert Manufacturing

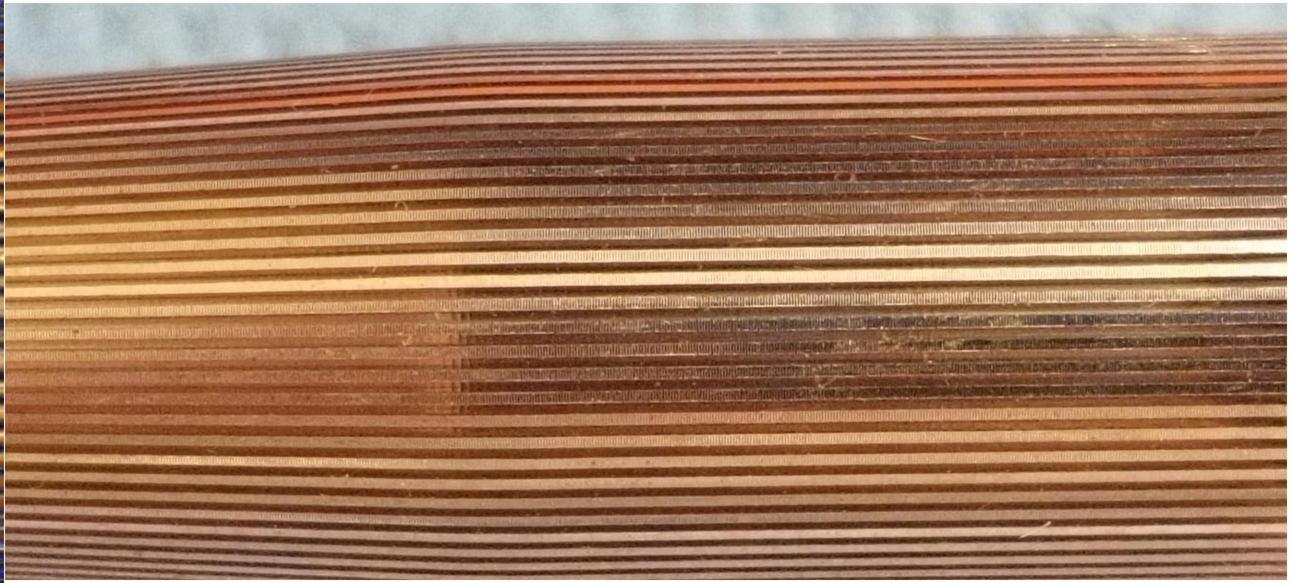
First Attempt

(June – July 2025)



Second Attempt

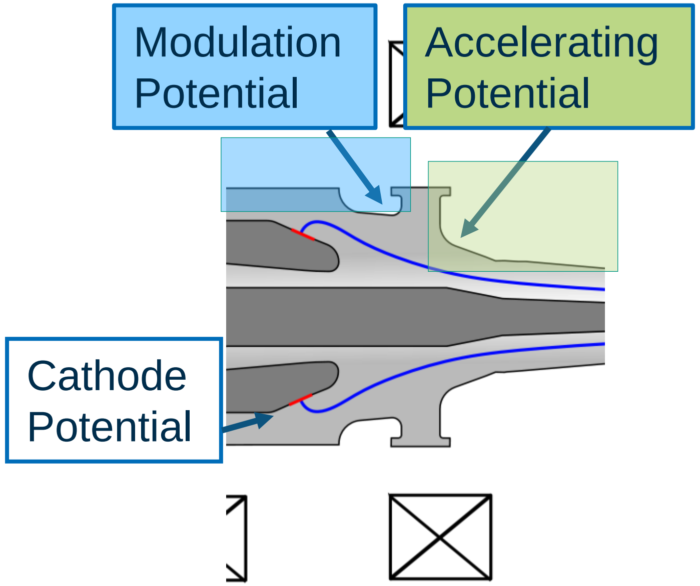
(September – October 2025)

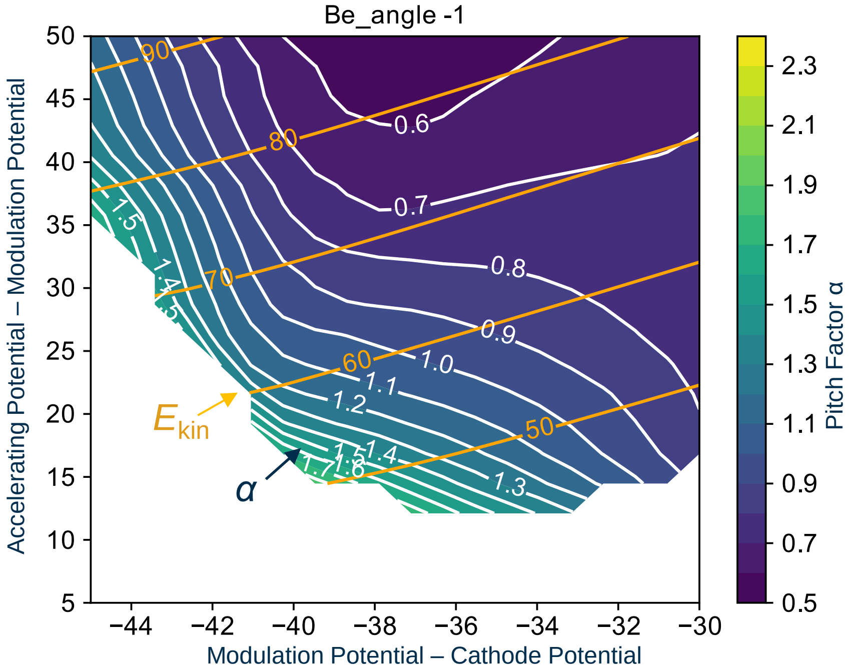


Grooves applied by a slitting cutter: constant depth 0.7 mm, slit width 0.3 mm

Experiments in Preparation
Electron Gun

- KIT triode gun was validated in June 2025 for fundamental operation and high beam currents.
- Challenging operation of the KIT triode gun.
  - Operation at half of the designed main magnetic flux density.
  - Low E_e field at the emitter to counteract high transverse velocities
    $\beta_\perp \propto \frac{1}{r_\mathrm{gc}} \frac{E_\mathrm{e}}{B_\mathrm{e}}$.
- High laminarity of the electron beam.
- High pitch factor spreads expected.
- Operation with reduced accelerating voltage and power to reduce spreads.





Experiments in Preparation Installation

- Installation of the manufactured parts in the KIT short pulse coaxial prototype finished.
- Superconducting magnet cooled down.
- Conditioning phase has started.
- **Target: World first second harmonic gyrotron experiment with a power of close to 1 MW.**

Conclusion

Conclusion

- Theoretical results on the “ultra-fast” switching approach very successful.
- Novel tools to calculate starting pitch factor and new approach for dual harmonic quasi-optical launcher were developed.
- Excellent gaussian mode content for both harmonics possible.
- Efficiency > 50 % for both harmonics can be reached using an MDC.
- Experiments will start **end of November.**

Publications

- C. Argyropoulos et al. ‚*A self-consistent linearized model and code for the calculation of the starting pitch factor of TE modes in gyrotron cavities*‘, Physics of Plasmas, 2025, (submitted).
- L. Feuerstein et al. ‚*Enhanced Suppression of First Harmonic Competing Modes in Harmonic Coaxial Gyrotron Cavities with Tapered Corrugation Depth* ‘, (ready for submission).
- S. Illy et al., ‘*Technical Concepts for Megawatt-Class Fusion Gyrotrons Operating at the Second Harmonic of the Cyclotron Frequency*’, 26th International Vacuum Electronics Conference (IVEC), Apr. 2025.
- L. Feuerstein et al., ‘*Design Strategies for Second Harmonic Gyrotrons in Nuclear Fusion Applications*’, 16th German Microwave Conference (GeMiC), Mar. 2025.
- L. Feuerstein et al., ‘*MW Level 280 GHz 2nd Harmonic Coaxial Gyrotron Cavity with Variable Corrugation Depth*’, Joint International Vacuum Electronics Conference and International Vacuum Electron Sources , Apr. 2024.
- S. Illy et al., ‘*Design Proposals for Megawatt-Class Fusion Gyrotrons Operating at the Second Harmonic of the Cyclotron Frequency*’, 22th Joint Workshop on Electron Cyclotron Emission (ECE) and Electron Cyclotron Resonance Heating , Apr. 2024.

KIT

Backup

T2.2 Profiling on Outer Corrugations (2)

- By examining the eigenvalue spectrum, it has been found that only by localizing the outer corrugations at specific C ($\frac{R_{\text{out}}}{R_{\text{in}}}$) range the main 1st harmonic competing modes can be suppressed, while the operating mode remains unaffected.
- The specific C range is translated to specific z range → localization.