EUROfusion Science Meeting on Results of Enabling Research Projects 2021-2024

New Generation of Megawatt-Class Fusion Gyrotron Systems Based on Highly Efficient Operation at the Second Harmonic of the Cyclotron Frequency (ENR-TEC.01.KIT)

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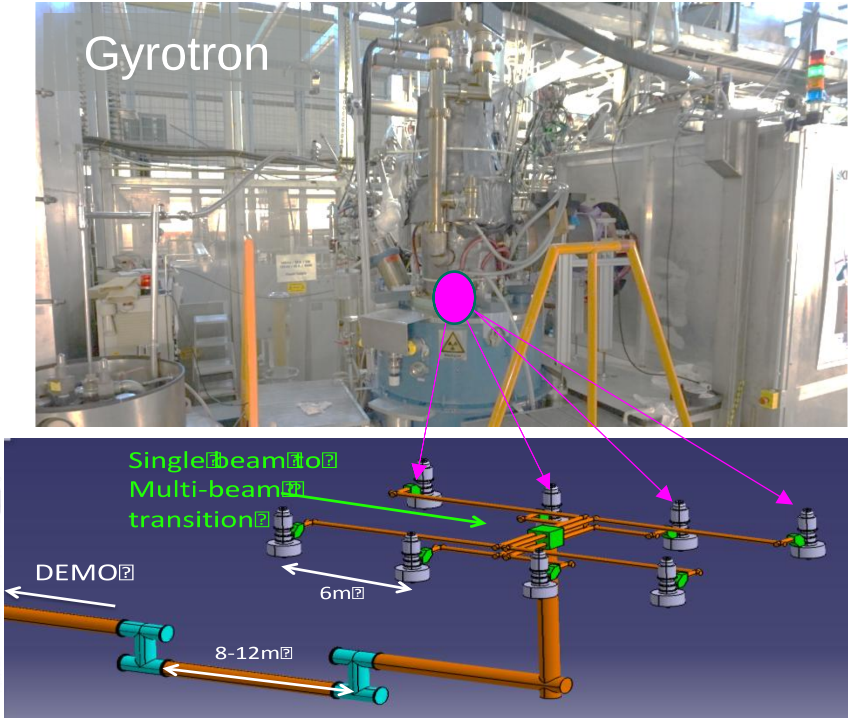
Outline

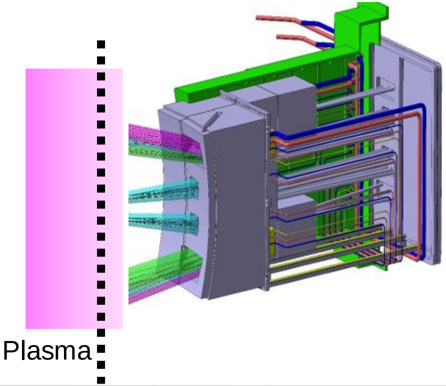
- Main objective and approach of the EUROfusion Enabling Research Project
- Three methods to obtain 2nd harmonic operation based on coaxial cavity technology
- Design and test of a bi-directional launcher for injection locking
- Enhancing the efficiency using a multi-stage depressed collector
- Conclusion, Possible Impact & Outlook

Key Components of the DEMO EC System

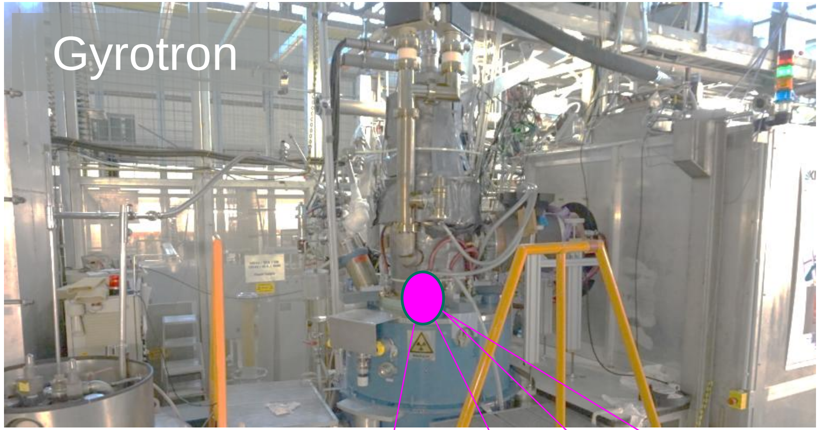


Quasi-optical transmission line

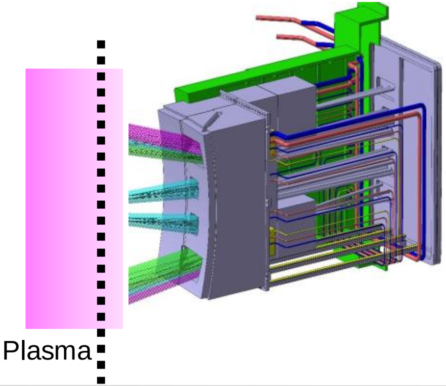
EC equatorial launcher

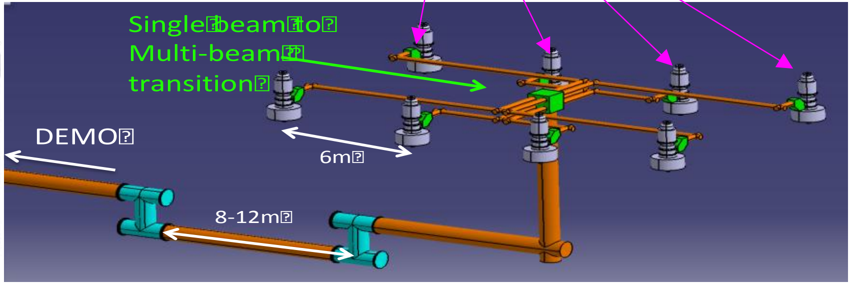


Key Components of the DEMO EC System

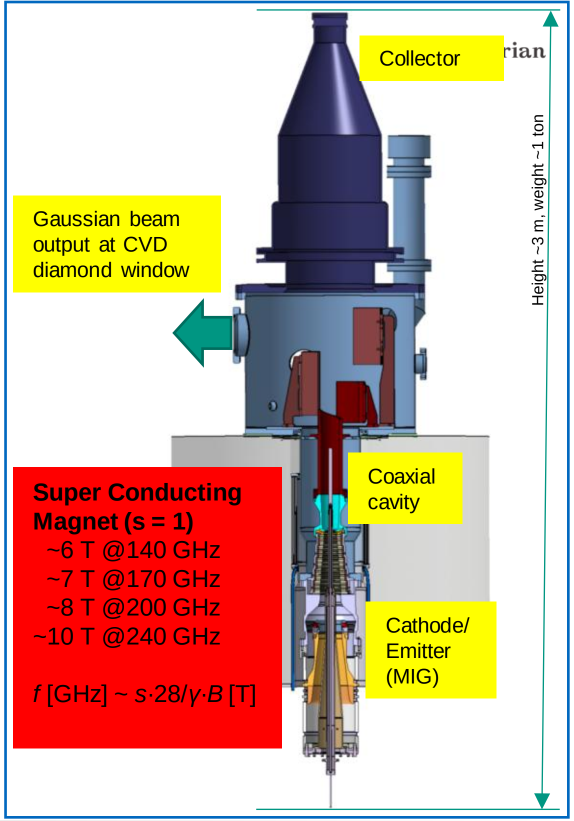


EC equatorial launcher

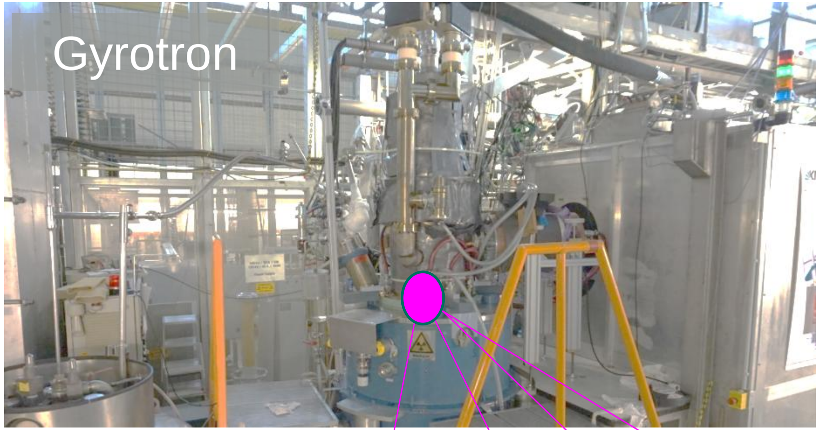




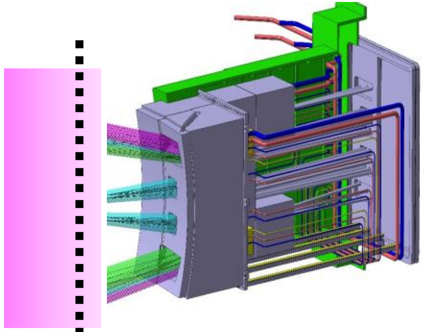
Quasi-optical transmission line

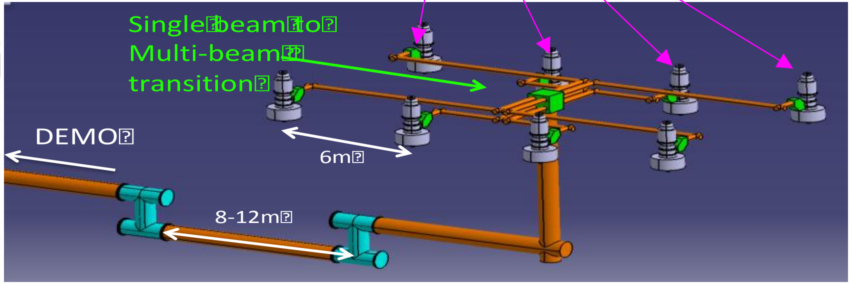


Key Components of the DEMO EC System

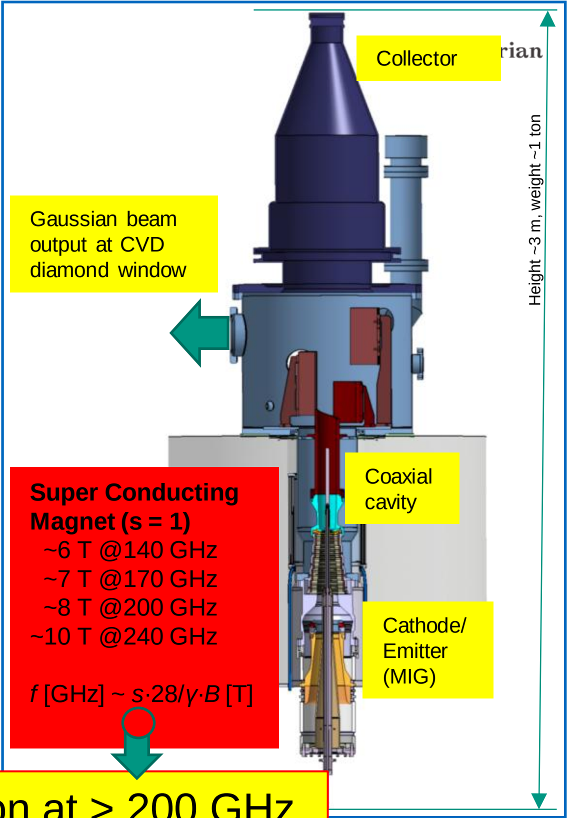


EC equatorial launcher





Quasi-optical transmission line



Gaussian beam output at CVD diamond window

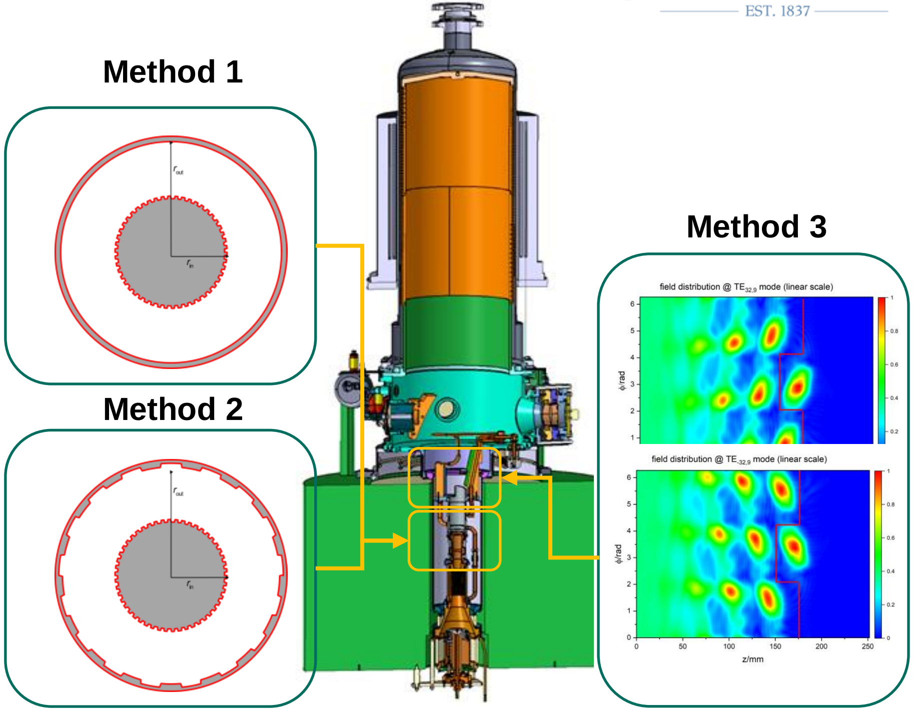
Super Conducting Magnet (s = 1)
~6 T @140 GHz
~7 T @170 GHz
~8 T @200 GHz
~10 T @240 GHz

$f\,[\mathrm{GHz}] \sim s \cdot 28/\gamma \cdot B\,[\mathrm{T}]$

The required magnetic field becomes an issue for operation at > 200 GHz
→ **Gyrotrons operating at 2nd Harmonic (*s*=2) might be the solution!**

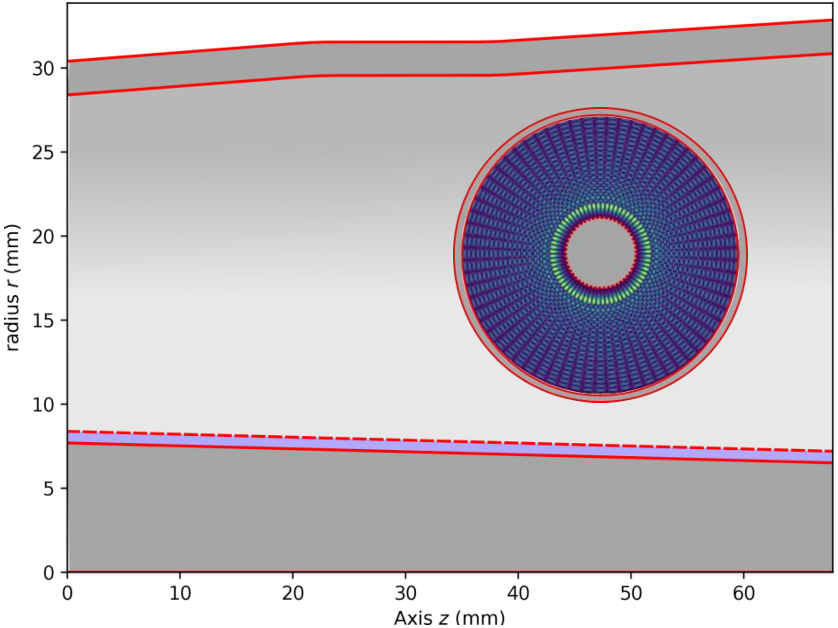
Main Objective and Approach

- *We aim for a completely new generation of highly efficient, megawatt-class fusion gyrotrons that will operate at the* ***2nd harmonic (s = 2)*** *of the electron cyclotron frequency*
- Gyrotron interaction possible when: $\omega = \boldsymbol{s}\underbrace{\frac{eB}{m_e\gamma}}_{\Omega_\mathrm{c}} - k_\mathrm{z}v_\mathrm{z}$
- Competition with fundamental competitors most critical
- Three main methods to suppress fundamentals:
  1. Coaxial cavity gyrotron with **inner** corrugations
  2. Coaxial cavity gyrotron with **inner & outer** corrugations
  3. Using **Injection locking** by an external signal with co and counter rotating quasi-optical launcher
- Apply a multi-stage depressed collector (MDC) to enhance efficiency



Method #1:
Inner Corrugations

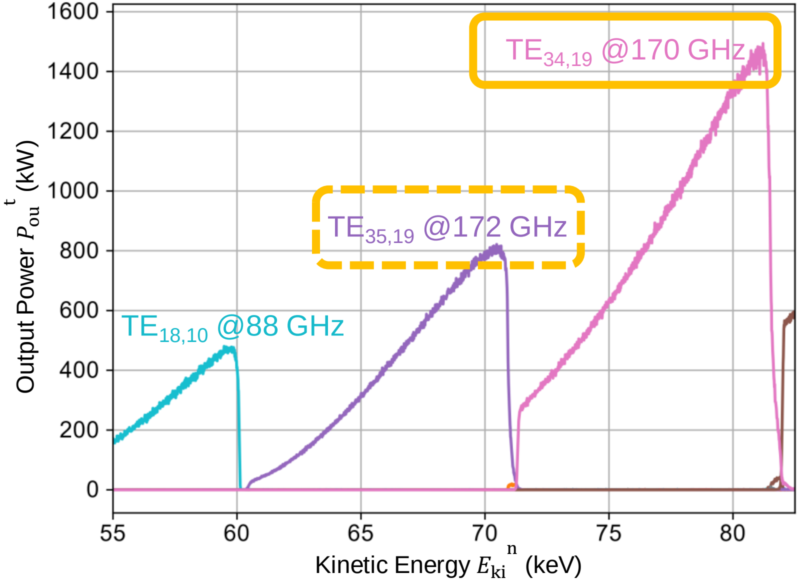
- Suppression of fundamental competing modes due to:
  - Tapered inner and outer conductor.
  - Special designed axial corrugations of the coaxial insert.
  - Lowered quality factor of competing modes.
- Only the fundamental competing modes are influenced.
- Very high-order modes can be excited (eigenvalue $\chi > 100$).
- Cavity designs at 170 GHz, 204 GHz and 280 GHz.



Method #1:

170 GHz Cavity KIT TE$_{34,19}$ Gyrotron

- Second harmonic cavity for fundamental KIT coaxial short-pulse TE$_{34,19}$ gyrotron [1] as basis.
- Output power above 1 MW possible with new cavity (obeying technical constraints).
- Electronic efficiency $\gtrsim$ 20%.
- Further power increase limited by thermal loading.
- **Experiments with KIT coaxial cavity gyrotron planned** (only new cavity and coaxial insert required!).



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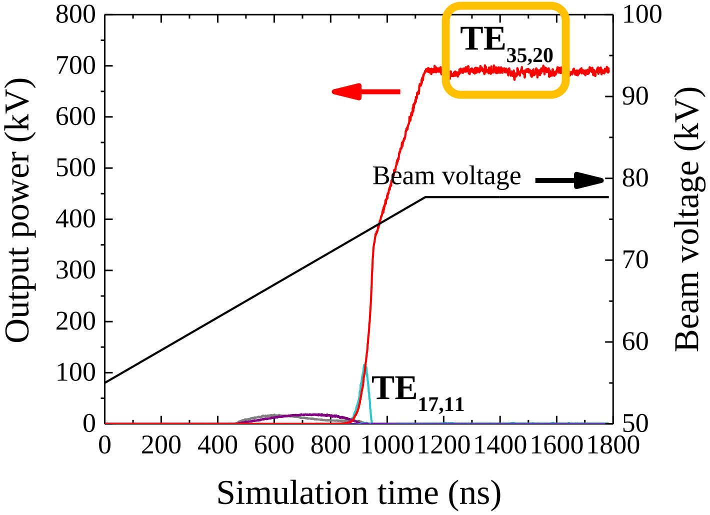
[1] T. Ruess *et al.*, ‘Performance Expectation and Preparation of the First Experimental Campaign of the KIT 2 MW 170/204 GHz Coaxial-Cavity Gyrotron’, in *2021 22nd International Vacuum Electronics Conference (IVEC)*, Apr. 2021, pp. 1–2. doi: 10.1109/IVEC51707.2021.9722448.

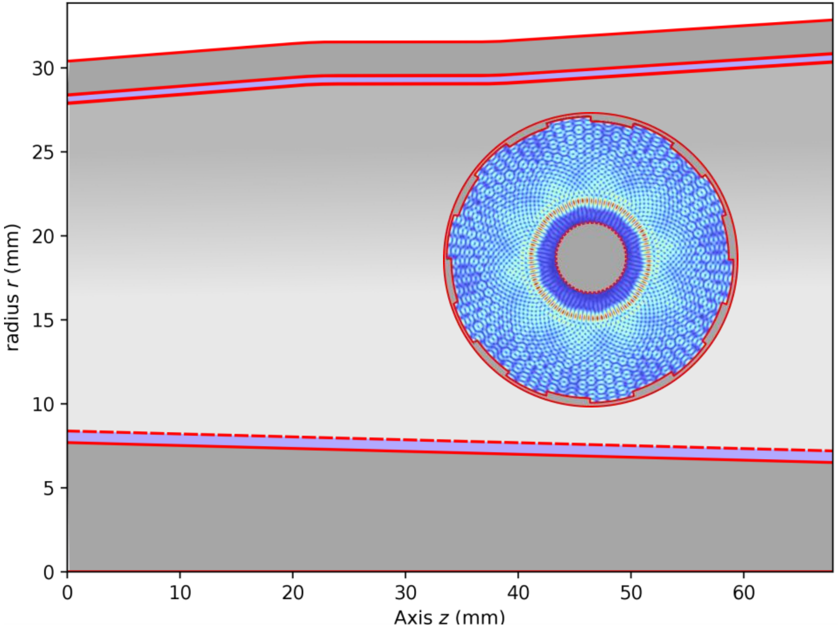
Method #1:
Coaxial-cavity for 280 GHz

- Additional challenges for higher frequencies:
  - Ohmic loading increases with frequency ($\rho \sim f^{2,5}$).
  - Smaller resonator dimensions, reduced clearance of e-beam vs. inner conductor.
- **Coaxial-cavity design with TE$_{35,20}$ ($\chi \cong 110$)**
  - Maximum output power **0.7 MW**.
  - Electronic efficiency **η_{el}=15%** (total efficiency can be increased to **47%** if a MDC with η_{col}=80% is used).
  - Ohmic loading: **ρ_{out}=2.15 kW/cm^2**, **ρ_{in}=0.33 kW/cm^2**.
  - Significant challenge w.r.t precise insert manufacturing and alignment (R_{coax}≈5.5 mm) and proximity of the insert and e-beam (~0.5 mm).



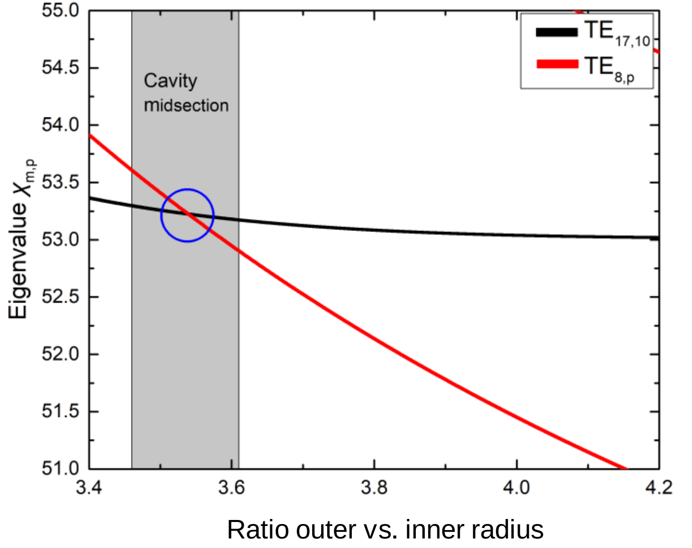
Method #2:
Inner & Outer Corrugations

- Introduce outer wall corrugations to enhance operating stability.
- Degeneration of critical fundamental modes due to coupling with low order modes.
- Outer corrugations designed such, that the operating mode is **not** affected.



Mode-Converting Outer Corrugations
Illustrative example: mode & geometry selection

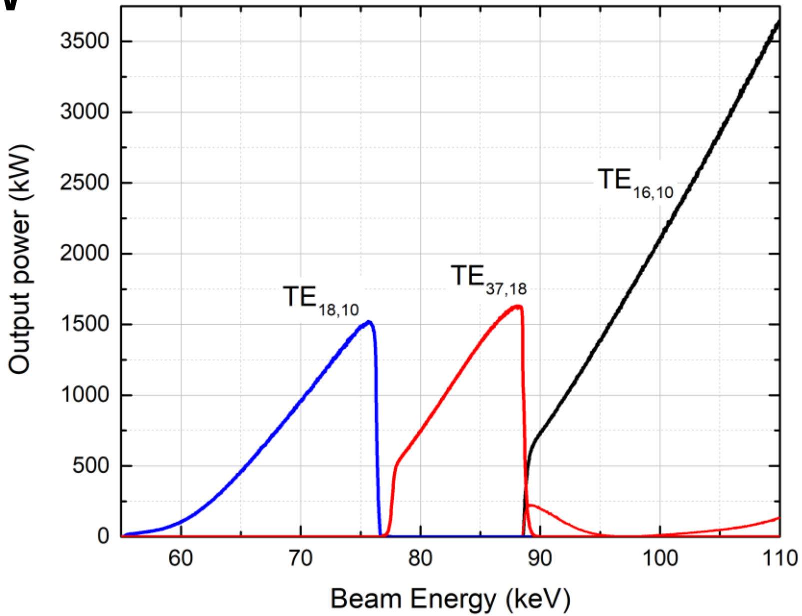
- A detailed design strategy has been derived*.
- $TE_{37,18}$ was selected as operating mode. It **cannot** be excited with insert corrugations only.
  (Main 1st harmonic competitor is $TE_{17,10}$).
- The appropriate converting coupling of $TE_{17,10}$ was achieved by introducing *M*=25 outer corrugations.
- Resulting cavity dimensions are almost the same as these of the existing 2MW-170GHz KIT one.



*D. V. Peponis *et al.*, "Design of MW-Class Coaxial Gyrotron Cavities With Mode-Converting Corrugation Operating at the Second Cyclotron Harmonic," in *IEEE Transactions on Electron Devices*, vol. 70, no. 12, pp. 6587-6593, Dec. 2023, doi: 10.1109/TED.2023.3326431

Mode-Converting Outer Corrugations
Illustrative example: performance

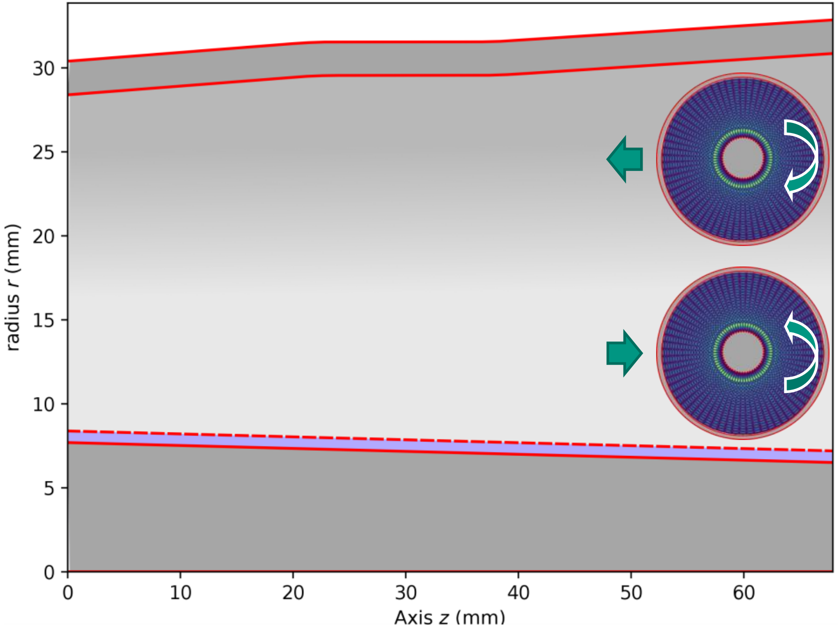
- $TE_{37,18}$ at 170 GHz was excited with $\boldsymbol{P_{out}}$ **=1.3 MW** @ $\boldsymbol{\eta}$**=22%** electronic efficiency (I_b=80 A).
- Ohmic loading within technological constraints.
- By investigating other operating points (E_b~130 keV, I_b~80A) we were able to obtain $\boldsymbol{P_{out}}$**= 1.95 MW @** $\boldsymbol{\eta}$**=20%**.



Output power of the enhanced cavity with outer corrugations. TE$_{37,18}$ is clearly excited

Method #3:
Injection Locking

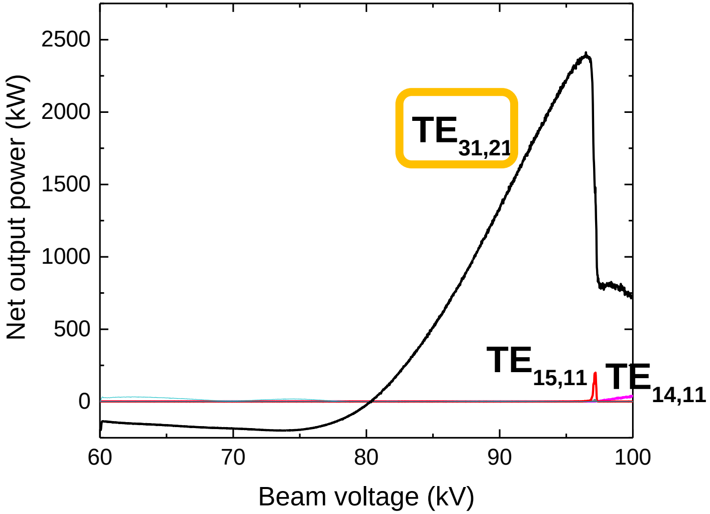
- Inject external driving signal into cavity (from quasi-optical launcher side).
- Enforce oscillation of the operating mode.
- Bi-directional, dual rotation launcher necessary.
- High input power required for sufficient locking bandwidth.
- Slight reduction of the cavity quality factor needed for increased locking bandwidth.



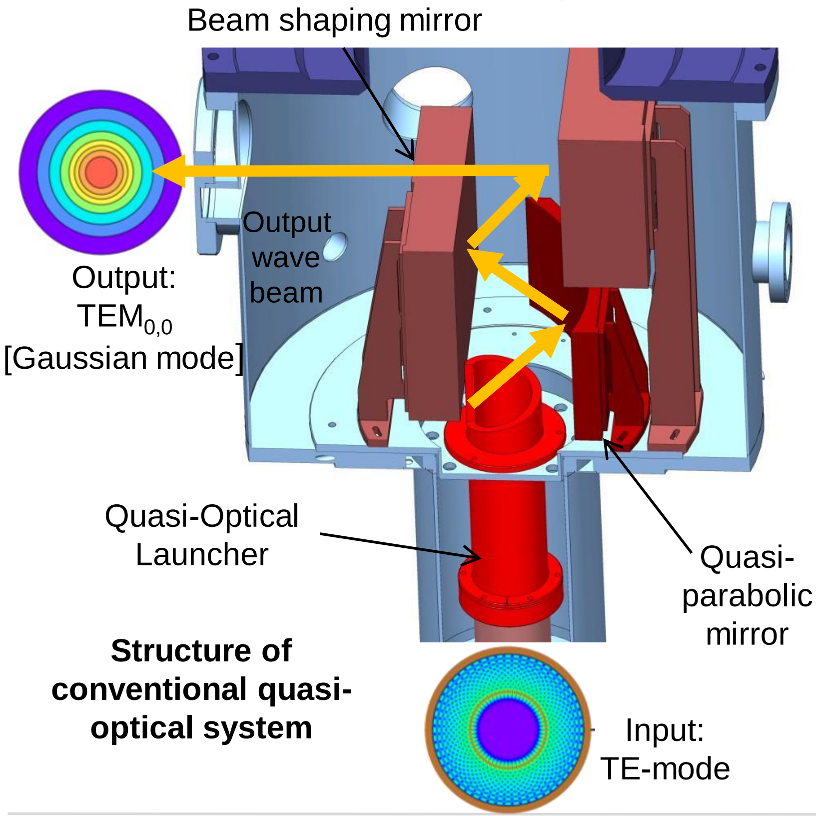
Method #3:
Injection Locking for 170 GHz coaxial cavity

- Initial design for 170 GHz with $TE_{31,21}$ ($\chi \sim 108$).
- Numerical simulation results:
  - Injected power **200 kW** (-11 dB). Lower power in the order of 100 kW is required to excite the mode.
  - 2.55 MW of total output power,
    → **2.35 MW net output power**.
  - 21% of electronic efficiency.
  - Ohmic loading 2.2 kW/cm^2 at the outer wall.
  - Ohmic loading 0.37 kW/cm^2 at the coaxial insert.

Multi-mode simulation considering 93 modes (first- and second-harmonic competitors).



Method #3:
Research on Coupling Systems for Injection Locking



Beam shaping mirror

Output wave beam

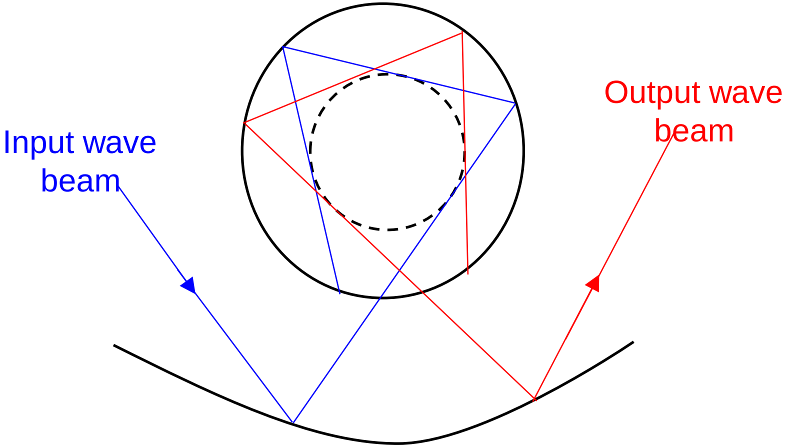
Output: $TEM_{0,0}$ [Gaussian mode]

Quasi-Optical Launcher

Quasi-parabolic mirror

Input: TE-mode

Structure of conventional quasi-optical system



Input wave beam

Output wave beam

Bi-directional launcher for co- and counter-rotation operating modes used for phase locking operation.

Method #3:
Research on Coupling System for Injection Locking

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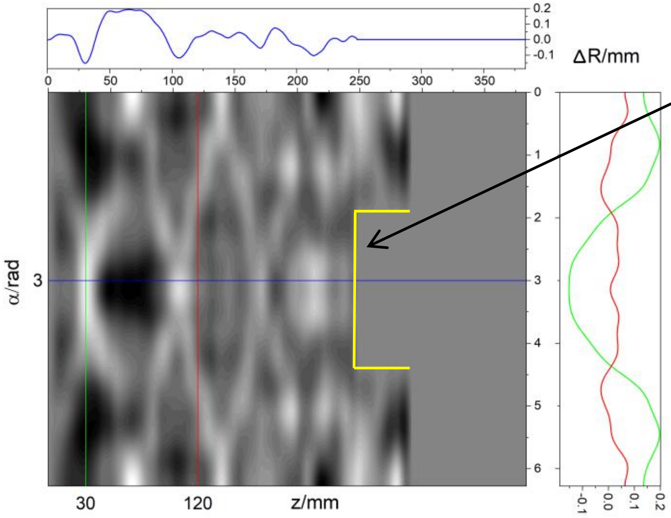
Design of a bi-directional *Mirror-line* launcher

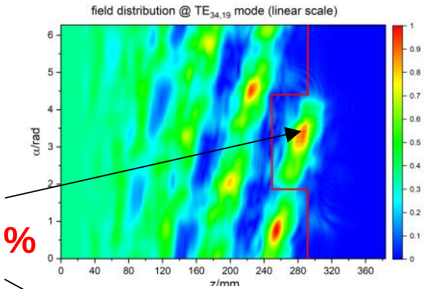
for co- ($TE_{34,19}$ mode) and counter- ($TE_{-34,19}$ mode), 170 GHz:

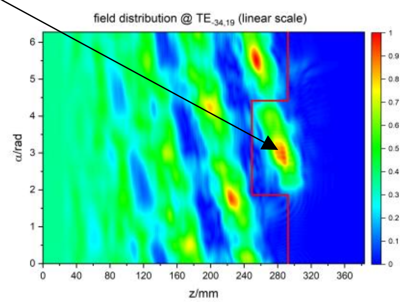
Profile on unrolled launcher wall:



Rectangular cut
(not helical)

Gaussian mode content: **93.65 %**





Power content of injected $TE_{-34,19}$ mode at cavity: 85.45%

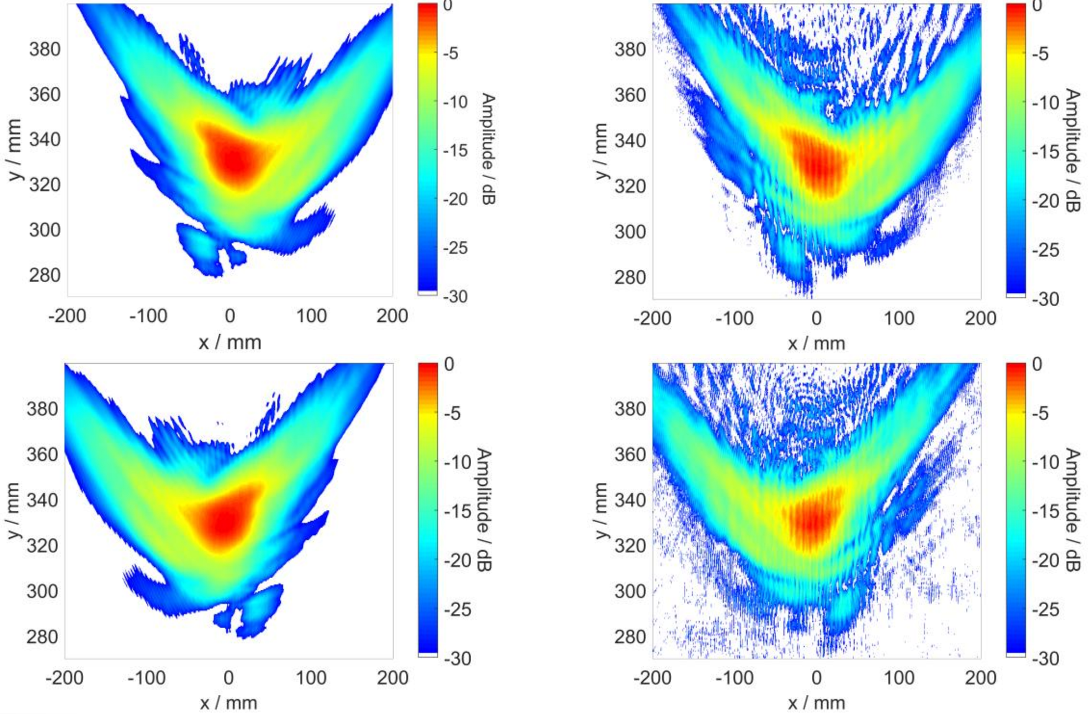
Low-power Test of the Bi-directional Quasi-Optical Launcher

Measurements performed with the KIT 170 GHz $TE_{34,19}$ mode generator

Simulation **Measurement**

Co-rotating

Counter-rotating

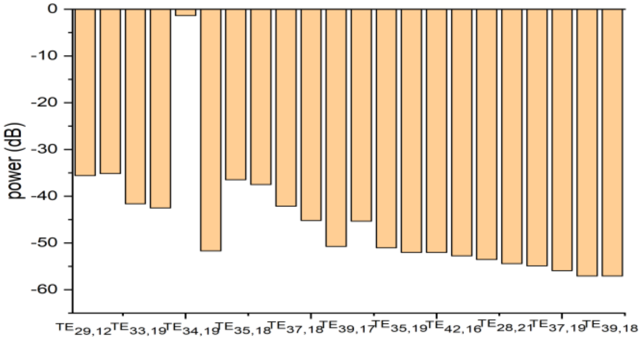


Investigation of the mode purity at the entry of the launcher when an ideal Gaussian mode is injected into the q.o. system

The mirror system designed for the coaxial-cavity, 2MW, $TE_{34,19}$-mode gyrotron is used to transform the RF beam radiated into the mirror-line launcher for the $TE_{\pm 34,19}$ mode. The GMC of the RF beam is calculated to be 93% at the output window. The fields in the mirror system and in the launcher have been calculated using the in-house code KarLESSS.

Relative power content of the different modes under consideration (in %).

power	**1.66**	**1.75**	**0.83**	**0.75**	**85.45**	**0.26**	**1.5**	**1.33**	**0.78**	**0.55**	**0.29**
mode	$TE_{29,21}$	$TE_{31,20}$	$TE_{33,19}$	$TE_{34,18}$	$TE_{34,19}$	$TE_{34,20}$	$TE_{35,18}$	$TE_{36,18}$	$TE_{37,18}$	$TE_{40,18}$	$TE_{39,17}$
power	**0.54**	**0.28**	**0.25**	**0.25**	**0.23**	**0.21**	**0.19**	**0.18**	**0.16**	**0.14**	**0.14**
mode	$TE_{38,18}$	$TE_{35,19}$	$TE_{33,18}$	$TE_{42,16}$	$TE_{32,20}$	$TE_{28,21}$	$TE_{36,19}$	$TE_{37,19}$	$TE_{31,21}$	$TE_{39,18}$	$TE_{33,20}$

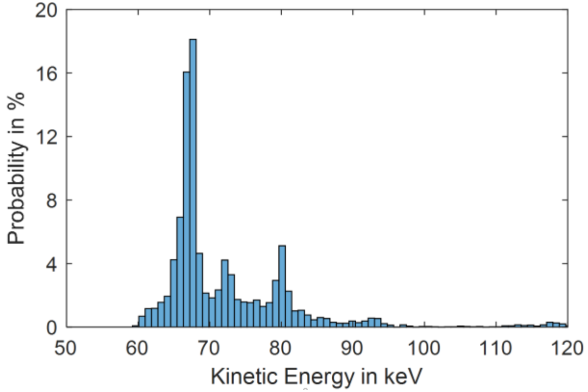


Interaction simulations show:

- ~85 % content of driving mode is sufficient for 2nd harmonic operation
- Additional spurious modes even suppress unwanted fundamental interaction!

Increasing the Gyrotron Efficiency:
First of its Kind Multi-Stage Depressed Collector - Theory

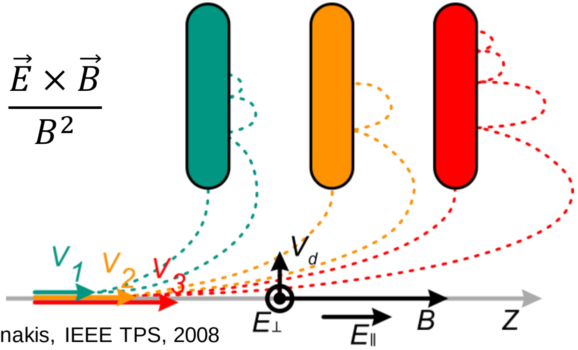
- Energy of the spent electron beam is recovered in depressed collectors
- Electrical efficiency of the overall tube is increased
- Single-stage collector efficiency is limited by:
  - Slowest electron
  - Widely spread energy spectrum



➡ Multi-stage depressed collector

- Sorting electrons based on ***E*×*B* drift**
- Spatial separation according to the kinetic energy
- Reduced thermal losses
- Increased collector & gyrotron efficiency

$$\overrightarrow{v_d} = \frac{\vec{E} \times \vec{B}}{B^2}$$

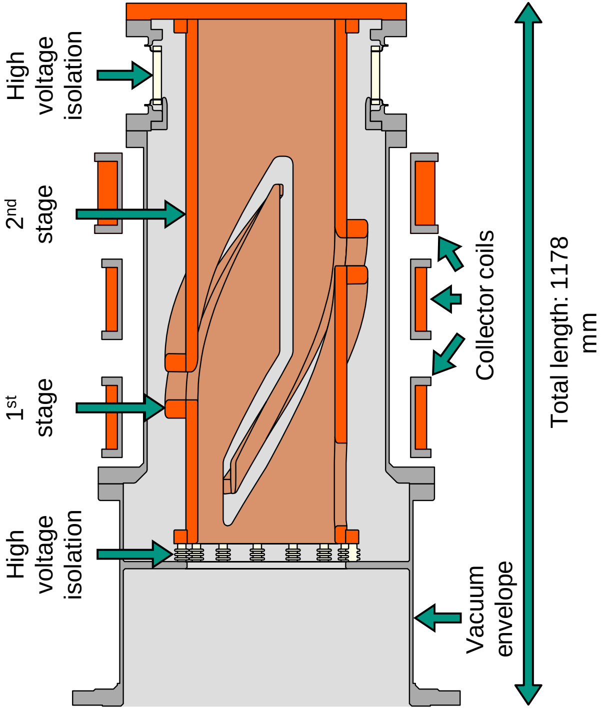


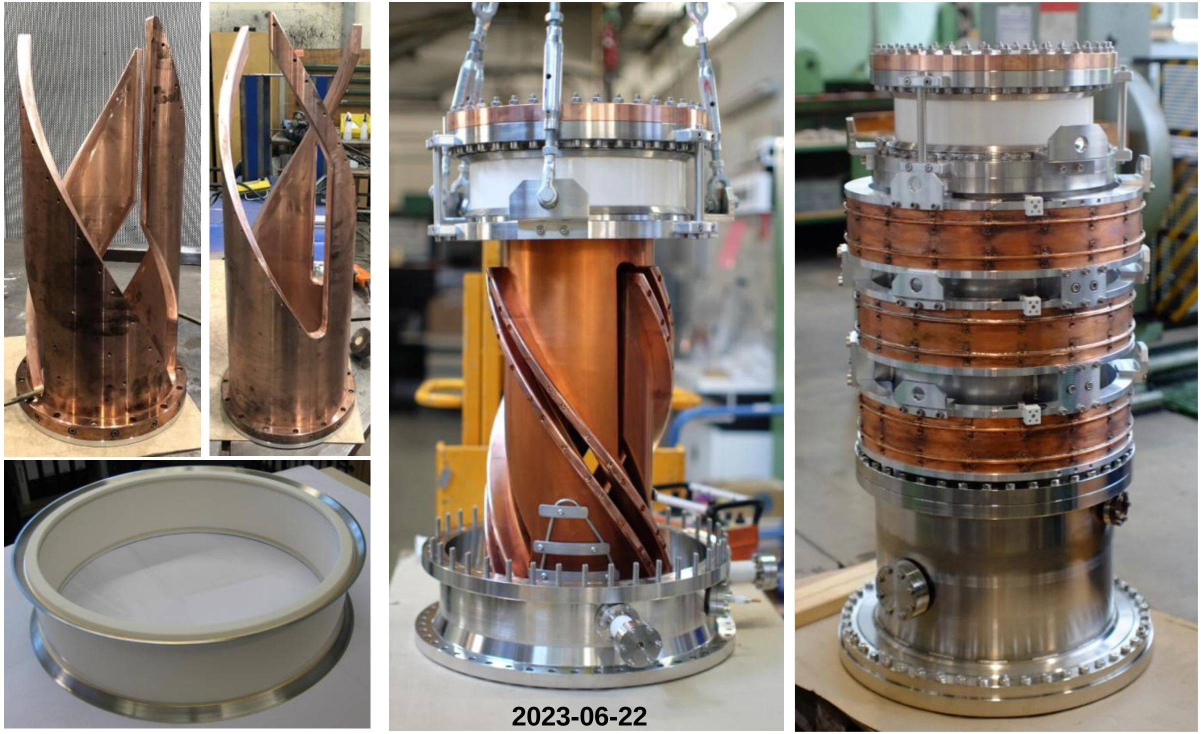
I. Gr. Pagonakis, IEEE TPS, 2008

Increasing the Gyrotron Efficiency:

First of its Kind Multi-Stage Depressed Collector - Realization

Short-pulse prototype, electron beam splitting / sorting based on *E*×*B* drift



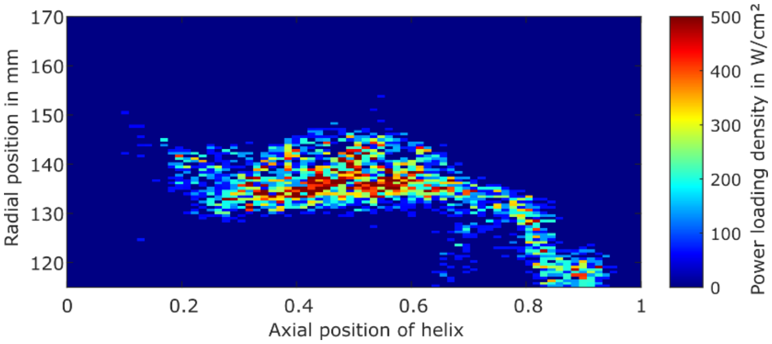


B. Ell et al., “Mechanical Design of the Short Pulse E×B Drift Two-Stage Depressed Collector Prototype for High Power Gyrotron”, IVEC, 2021, DOI: 10.1109/IVEC51707.2021.9722425

Multi-stage Depressed Collector
Compatibility with 2nd harmonic operation

- Design of the short-pulse MDC prototype is compatible with 2nd harmonic operation
- Depression voltages: 45.9 kV on first stage
  62.8 kV on second stage
- High collector efficiency: 85.3 %
- Low reflected current: 30 mA

- MDC is fabricated, mounted on W7-X upgrade shortpulse gyrotron; Experiments in KIT FULGOR test-stand currently running.



Power loading density on the first electrode

Conclusion

- The obtained results indicate that high-power / high frequency second harmonic gyrotrons for fusion applications can be possible (based on enhanced coaxial cavity technology and optional injection locking).
- This offers completely new opportunities for plasma heating and control at high magnetic fields.
- The reduced electronic efficiency can be compensated by a multi-stage depressed collector.
- We also aim for experimental verification (based on the existing short-pulse 170 GHz gyrotron at KIT).

Possible Impact on Mainstream EUROfusion Program

- Of interest, when fusion reactors will be operated at very high magnetic fields (at the moment not the case for the current design of the EUROfusion DEMO reactor).
- Also of interest, if ECRH/ECCD system operates at the 2nd harmonic (example: W7-X).
- Can be useful for specific types of diagnostics at frequencies significantly above the ECRH/ECCD frequency (e.g. Collective Thomson Scattering / CTS – at moderate power levels).
- Fast switching of frequency may be helpful to heat / control / stabilize different areas of the plasma without the (costly) need for different sets of tubes (→ **Outlook**).

Outlook

- New ENR project started: “*Novel dual-harmonic gyrotrons for DEMO featuring fast switching between distant frequencies: concept elaboration and experimental demonstration of key elements”.*
- Two different 170 GHz cavities compatible with the KIT test stand have been designed in detail and will be used in the upcoming experiment for demonstration of MW-class operation at the 2nd harmonic.
- Ultra-fast switching between the 2nd-harmonic mode $TE_{34,19}$ and the 1st-harmonic mode $TE_{17,10}$ was achieved in numerical simulations. The investigations of more appropriate mode pairs relevant for CW operation is ongoing.
- Preliminary results on depth profiling of outer corrugations show that higher-order TE modes can be excited in MW power level at the 2nd cyclotron harmonic.

Publications

First Author	Title of work	Journal / Conference	Doc. Type	DOI or status of paper
D. V. Peponis	Design of MW-class coaxial gyrotron cavities with mode-converting corrugation operating at the second cyclotron harmonic	IEEE Transactions on Electron Devices	Paper	10.1109/TED.2023.3326431
I. G. Chelis	High-Frequency MW-Class Coaxial Gyrotron Cavities Operating at the Second Cyclotron Harmonic	IEEE Transactions on Electron Devices	Paper	10.1109/TED.2024.3356472
L. Feuerstein	Design of a Second Harmonic MW-Level Coaxial Gyrotron Cavity	2023 24th International Vacuum Electronics Conference	Conference	10.1109/IVEC56627.2023.10156958
L. Feuerstein	MW Level 280 GHz 2nd Harmonic Coaxial Gyrotron Cavity with Variable Corrugation Depth	2024 25th International Vacuum Electronics Conference	Conference	10.1109/IVECIVESC60838.2024.10694886
S. Illy	Progress in the Design of Megawatt-Class Fusion Gyrotrons Operating at the Second Harmonic of the Cyclotron Frequency	2023 48th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)	Conference	10.1109/IRMMW-THz57677.2023.10299170
S. Illy	Design Proposals for Megawatt-Class Fusion Gyrotrons Operating at the Second Harmonic of the Cyclotron Frequency	2024 22nd Joint Workshop on Electron Cyclotron Emission (ECE) and Electron Cyclotron Heating (ECRH)	Conference	
L. Feuerstein	Design of a MW Level 2nd Harmonic Coaxial Gyrotron Cavity with Variable Corrugation Depth of the Inner Conductor	2024 9th ITG International Vacuum Electronics Workshop (IVEW)	Conference	
S. Illy	Design Concepts for Megawatt-Class Fusion Gyrotrons Operating at the Second Harmonic of the Cyclotron Frequency	2024 33rd Symposium on Fusion Technology	Conference	

Acknowledgements

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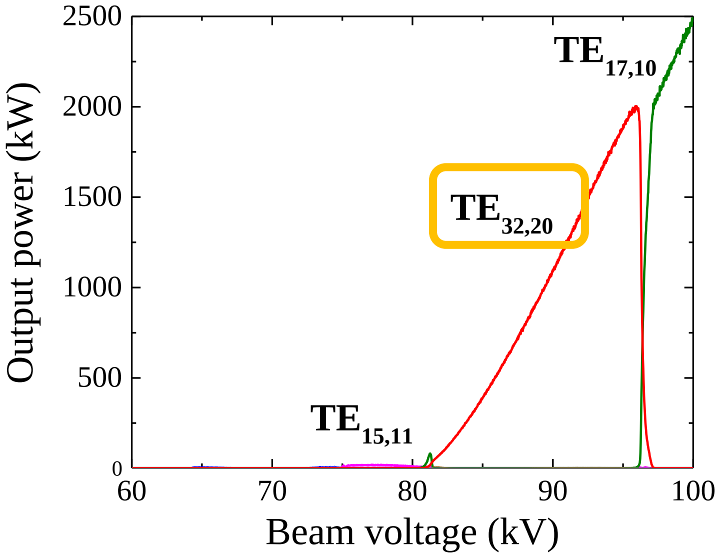
Thank you for your attention!

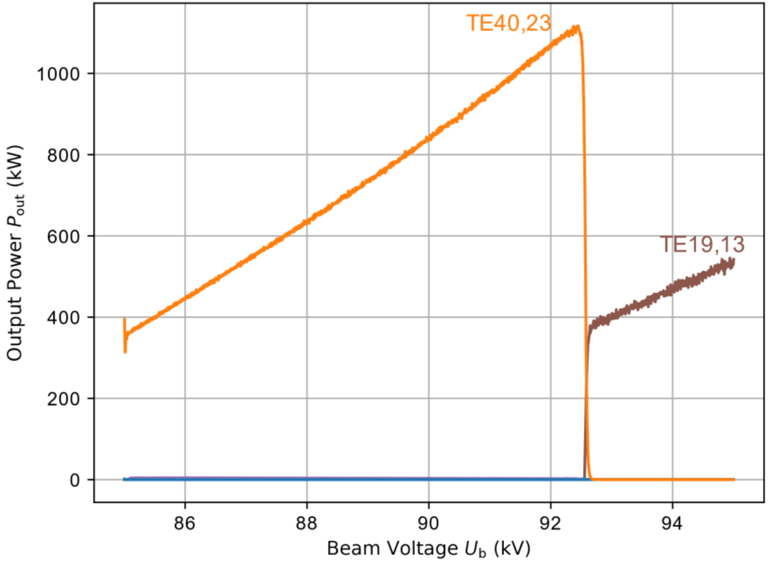
Backup Slides

Method #1:
Coaxial-cavity design for 170 GHz

- **Example design with $TE_{32,20}$ ($\chi \cong 106$)**
  - Proper design of the coaxial insert needed to excite the mode.
  - Maximum output power **2.0 MW**.
  - Electronic efficiency η_{el}**=22%**.
  - Total efficiency can be increased to **58%** (with MDC η_{col}=80%).
  - Ohmic loading of outer wall and insert:
    - ρ_{out}**=2.05 kW/cm²**
    - ρ_{in} **=0.19 kW/cm²**.
- Same level of performance with other modes of similar eigenvalue (e.g. $TE_{31,20}$, $TE_{29,21}$, $TE_{34,19}$).



Method #1:
Coaxial-cavity for $\mathrm{TE}_{40,23}$ 204 GHz Operation

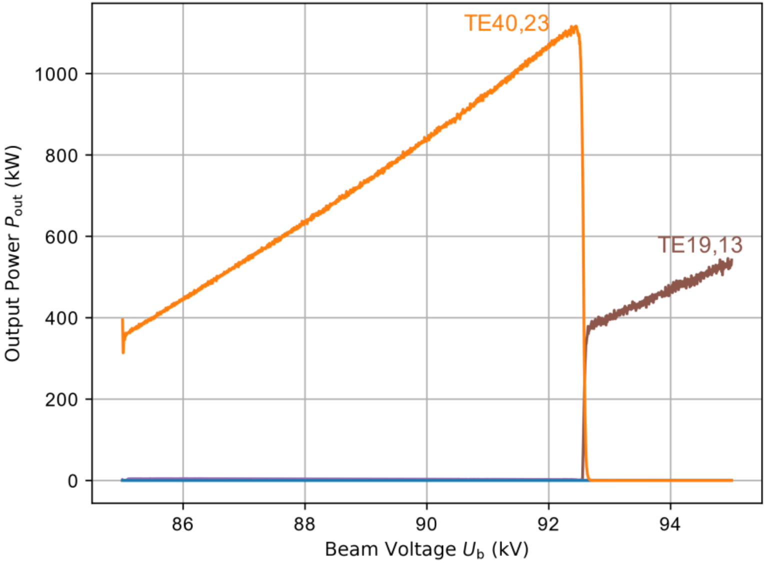


- Operating point
  - U_b = 90 kV
  - I_b = 60 A
  - r_{gc} = 9.52 mm
  - α = 1.2
  - B = 4.21 T
  - Spreads:
    $\delta\gamma = 0.10\ \%;\ \delta\alpha = 8.0\ \%;\ \delta r_{gc} = 2.0\ \%$
- Electronic efficiency $\eta_{elec} \sim$ 20 %
- More than 1 MW output power can be reached (with security margin)

Method #1:
280 GHz Cavity

- Additional challenges for higher frequencies:
  - Ohmic loading increases with frequency ($\rho \sim f^{2,5}$)
  - Smaller resonator dimensions
  - Less beam spacing to the inner conductor
- Coping strategies:
  - Higher order operating modes
  - Closer to whispering-gallery mode-types
- Output power of 0.5 MW to 0.7 MW possible at 280 GHz

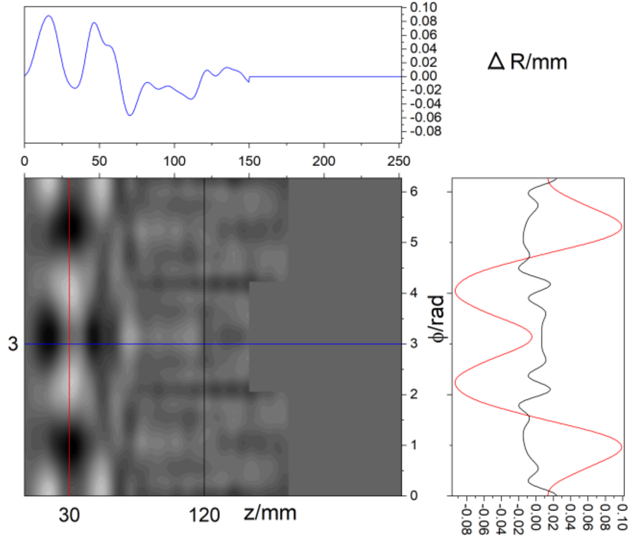
Results for high order volume-mode:

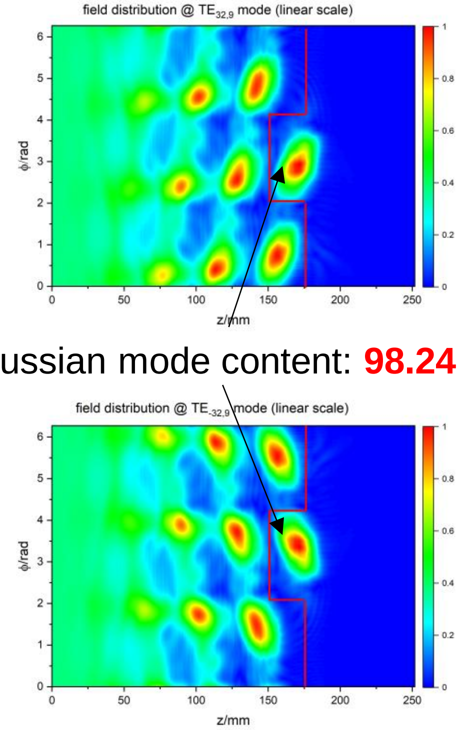


Method #3:
Research on Coupling System for Injection Locking

Design of a bi-directional *Hybrid-type* launcher
for co- ($TE_{32,9}$ mode) and counter- ($TE_{-32,9}$ mode), 170 GHz

Profile on unrolled launcher wall:



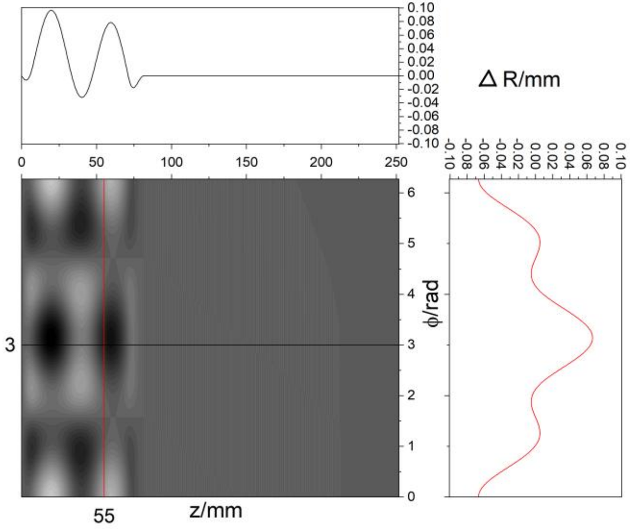


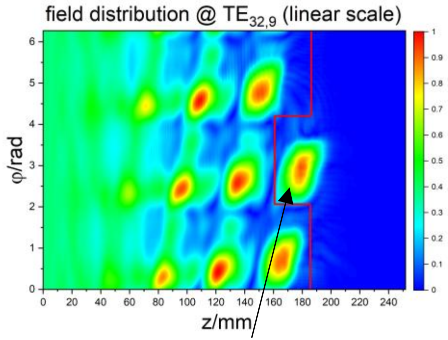
Gaussian mode content: **98.24 %**

Method #3:
Research on Coupling System for Injection Locking

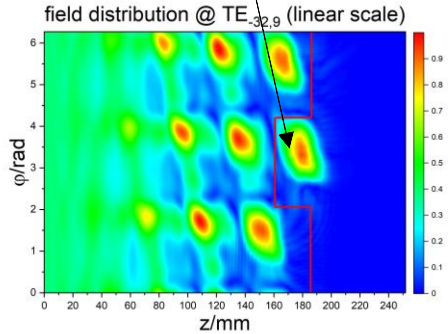
Design of a *Denisov-type* launcher
for co- (TE$_{32,9}$ mode) and counter- (TE$_{-32,9}$ mode), 170 GHz

Profile on unrolled launcher wall:





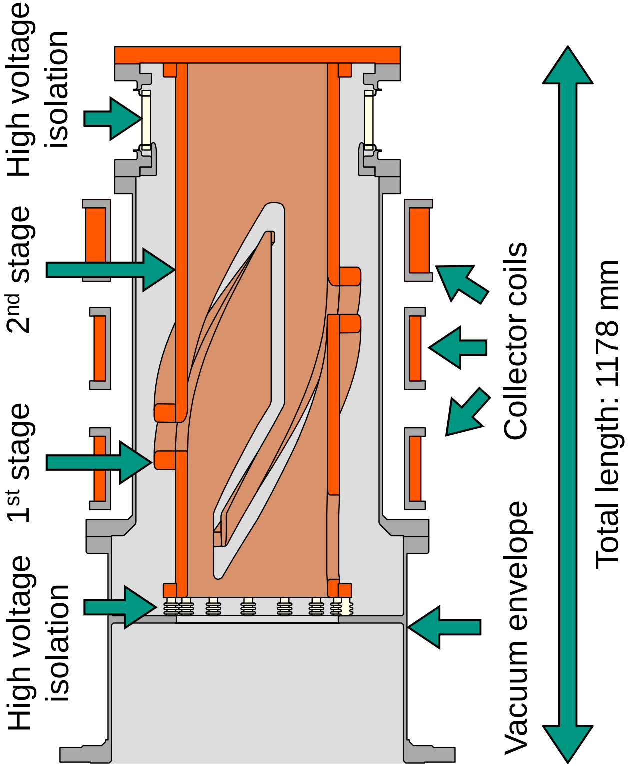
Gaussian mode content: **96.65 %**



Collector Prototype

- Prototype two-stage collector is built
  - Validation of *E*×*B* drift concept
  - Short pulse operation
  - Optimized for fundamental operation

- Operation possible at 2nd harmonic
  - 1st depression potential: 44 kV
  - 2nd depression potential: 63 kV
  - Gyrotron efficiency enhancement: 24 % → 67 % (without RF losses)
  - Low reflected current: 0.027 %
  - Power loading 1st stage: 94 kW

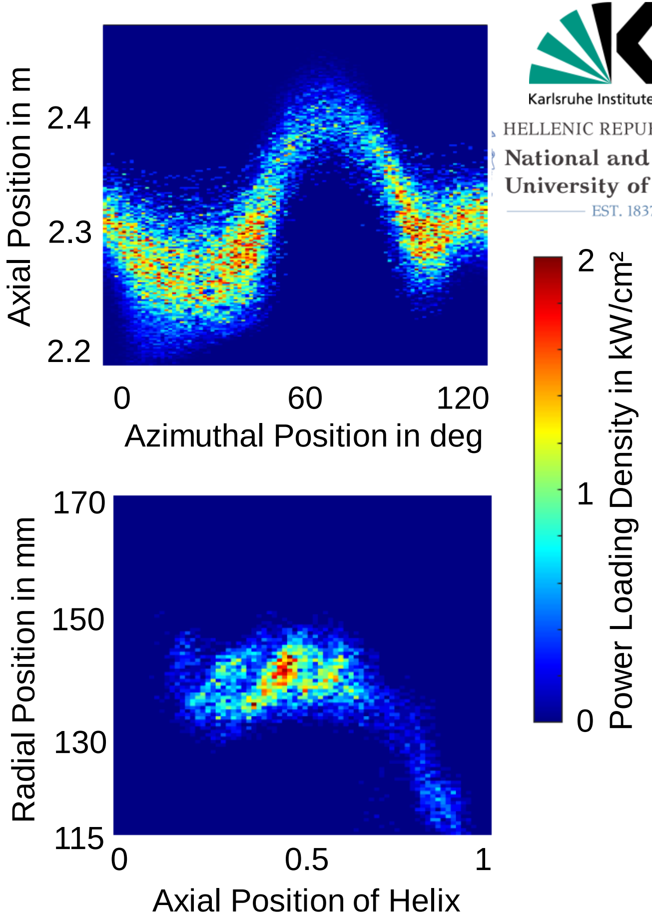


Collector Prototype Limitation

- Power loading density of short pulse prototype up to 2 kW/cm²
- Limit for CW at 500 W/cm²

Outlook:

➡ New design concept for Continuous Wave (CW)
  - Increased collector size
  - Implementation of sweeping system for 2nd stage
  - Operation point with reduced power on 1st stage
  - Optimized design for harmonic operation



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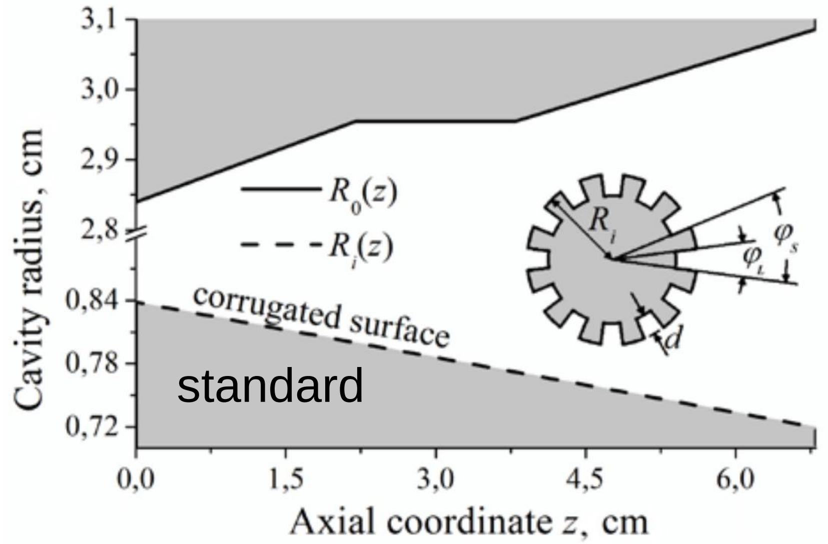
Inner and Outer Corrugations

Inner corrugations (insert)

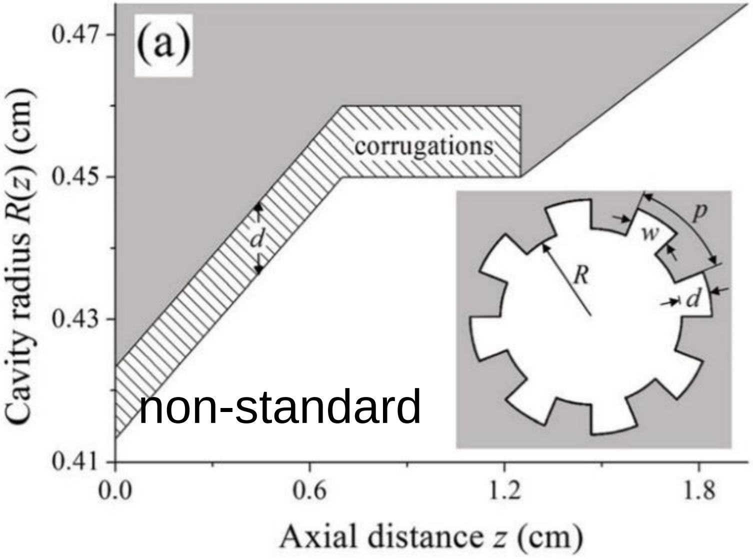


standard

Effect due to impedance corrugation

→ ***Attenuates unwanted modes***

Outer (wall) corrugations



non-standard

Effect due to mode conversion

→ ***Converts energy to other modes***

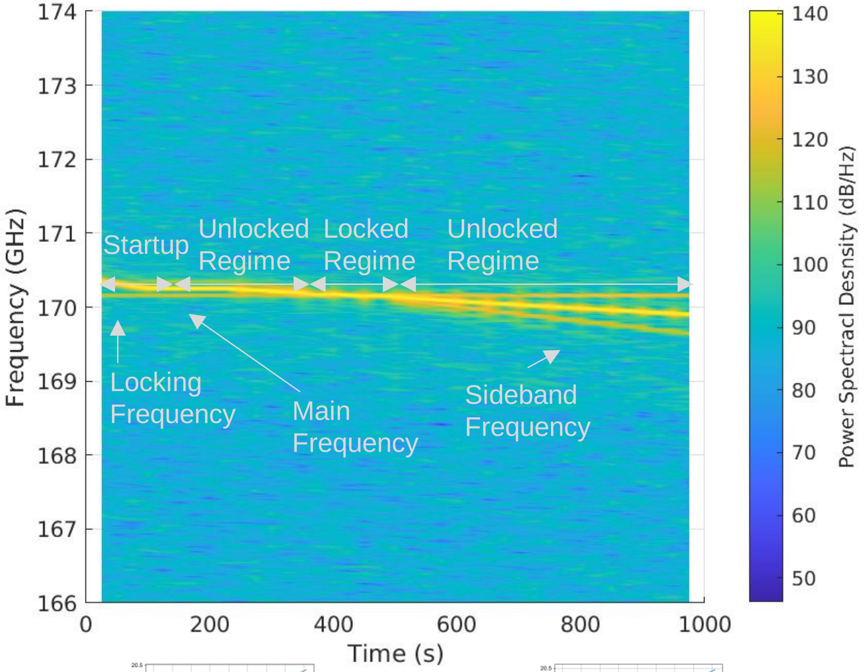
Fundamental KIT Coaxial 2 MW Gyrotron

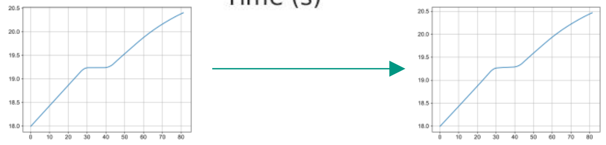
- Operating mode $TE_{34,19}$
- Frequency 170 GHz
- Output power 2 MW
- Magnetic field **6.9 T** → **3.45 T**
- No second harmonic operation possible, because of the fundamental competitors

→ **New cavity design for second harmonic interaction necessary**

Injection Locking with Thermal Expansion

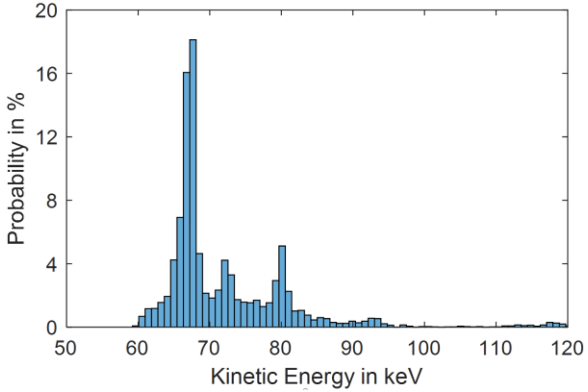
- Sweep of geometry from original cavity to thermal expanded cavity profile
- Injection signal:
  - Frequency: 170.15 GHz
  - Injection power: 4 kW
- Pull-in range can be described by Adlers relation





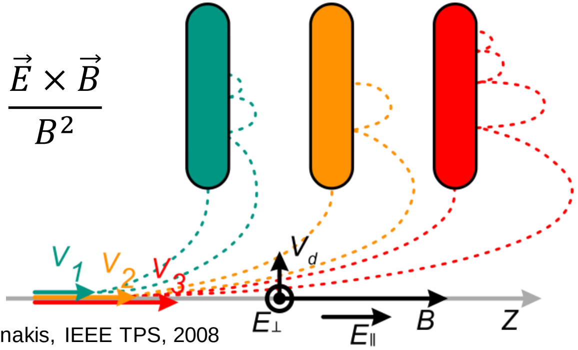
Increasing the Gyrotron Efficiency:
First of its Kind Multi-Stage Depressed Collector - Theory

- Energy of the spent electron beam is recovered in depressed collectors
- Electrical efficiency of the overall tube is increased
- Single-stage collector efficiency is limited by:
  - Slowest electron
  - Widely spread energy spectrum



➡ Multi-stage depressed collector
- Sorting electrons based on ***E*×*B* drift**
- Spatial separation according to the kinetic energy
- Reduced thermal losses
- Increased collector & gyrotron efficiency

$$\overrightarrow{v_d} = \frac{\vec{E} \times \vec{B}}{B^2}$$



I. Gr. Pagonakis, IEEE TPS, 2008