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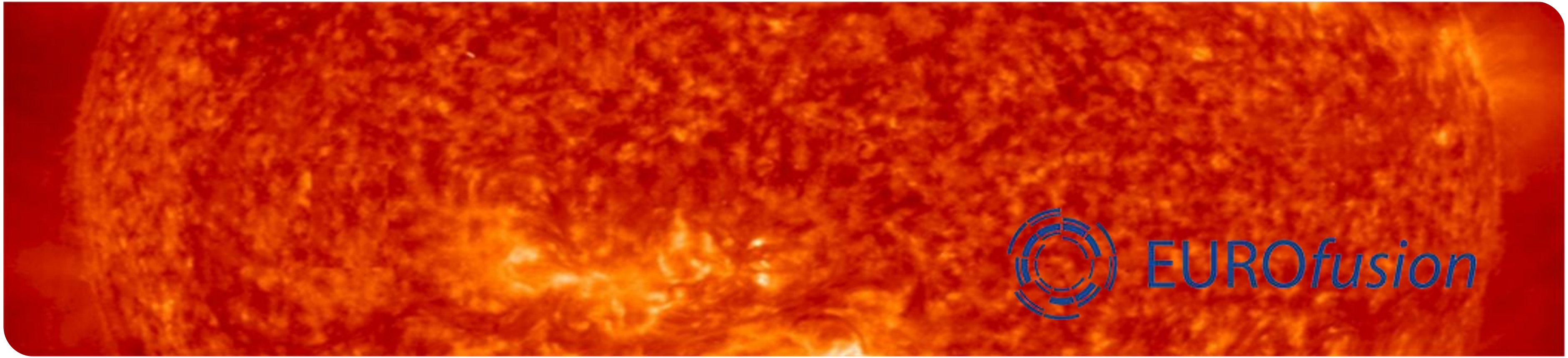
2023 Monitoring Meeting EUROfusion ENR Project (ENR-TEC.01.KIT)

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)

Stefan Illy on behalf of the ENR Project Team



Outline

- Introduction / Main Objective and Approach
- T1: Fundamental Theoretical Research on Individual Methods
  - Results on Injection Locking (T1.1)
  - Corrugated Cavity (T1.2)
- T2: Integrated Design Concepts
  - Second Harmonic Gyrotron Design (T2.1)
  - Higher Frequency Gyrotron Design for CTS (T2.2)
- T3: Possibilities for Proof-of-Principle Experiments
  - Manufacturing and Low-Power Test of the Quasi-Optical System (T3.1)
- Conclusion and Outlook

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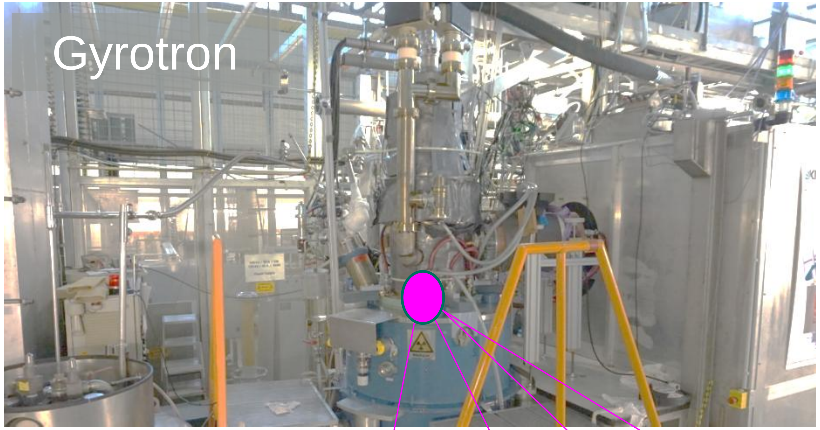
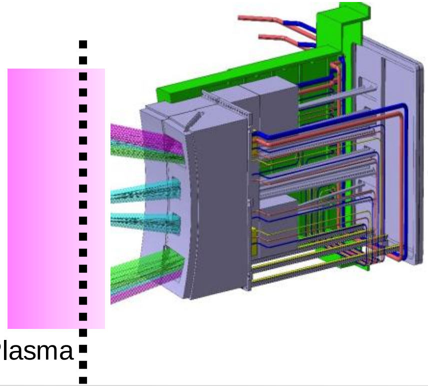
Introduction

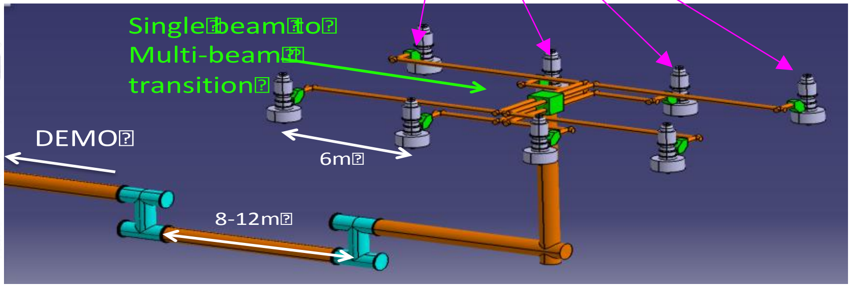
Key Components of the DEMO EC System



EC equatorial launcher



Plasma



Quasi-optical transmission line

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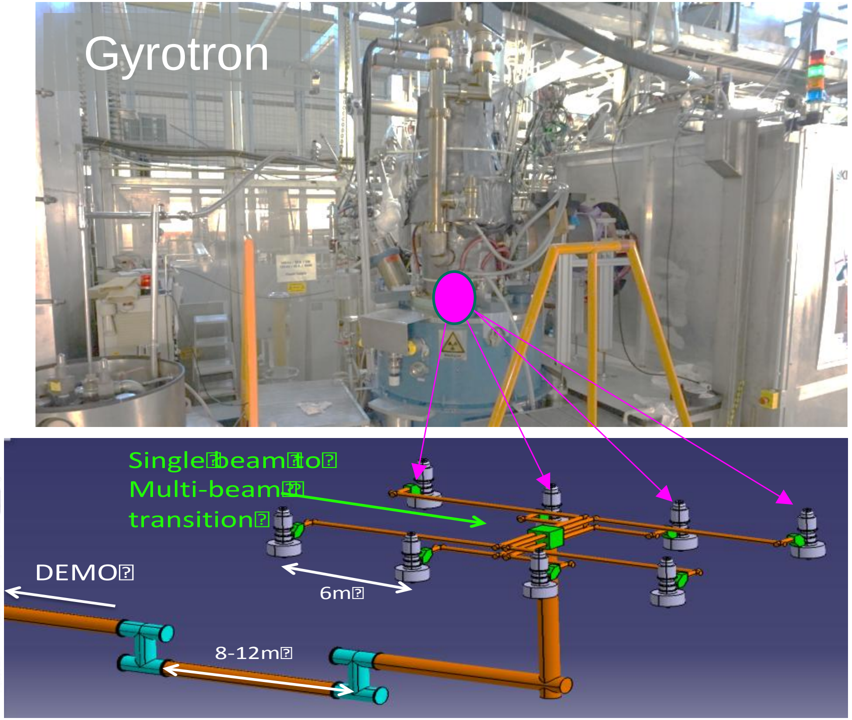
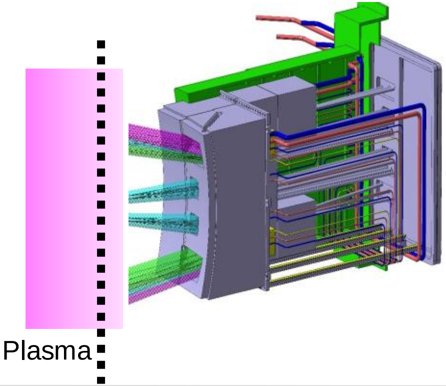
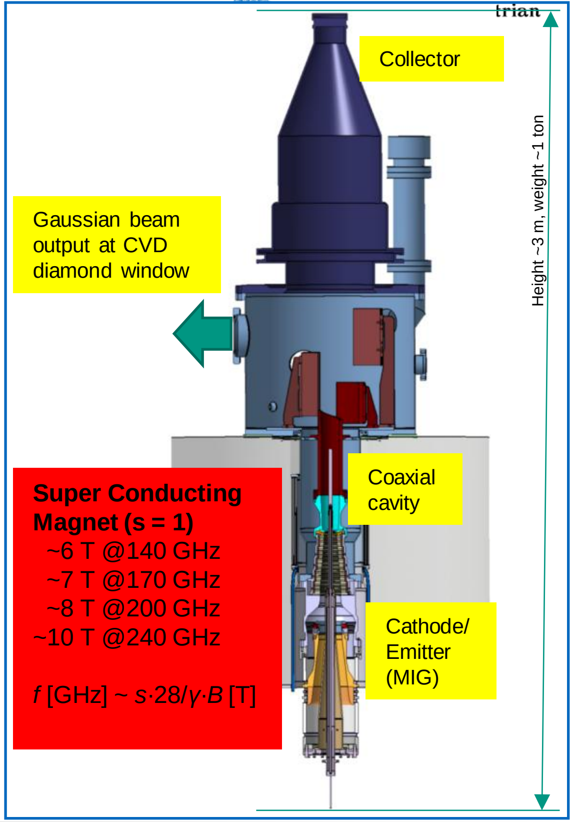
Key Components of the DEMO EC System



Quasi-optical transmission line

EC equatorial launcher





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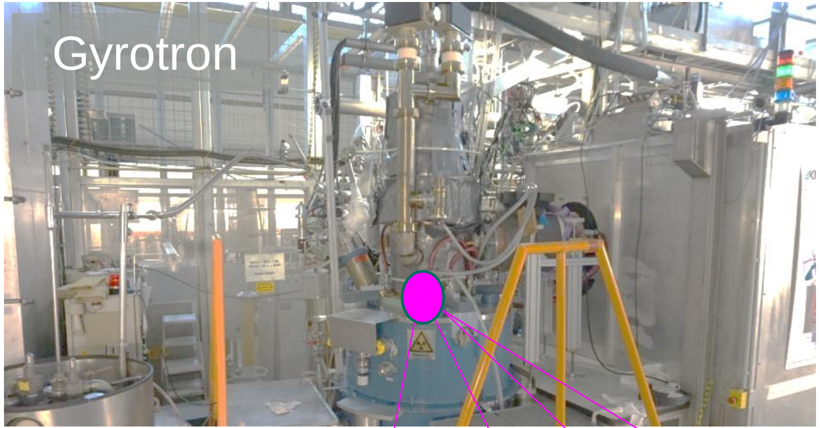
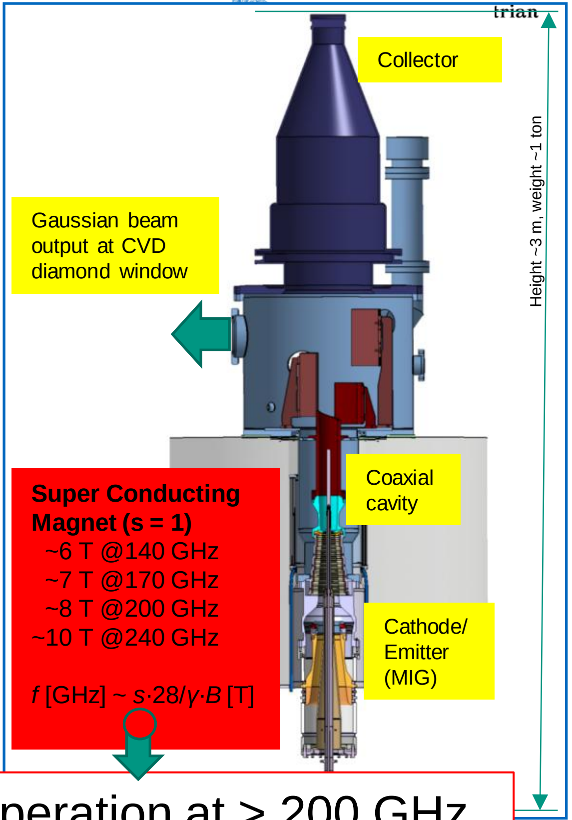
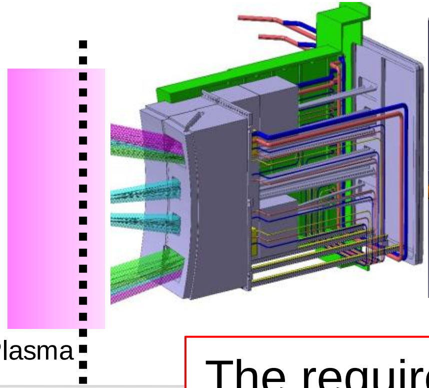
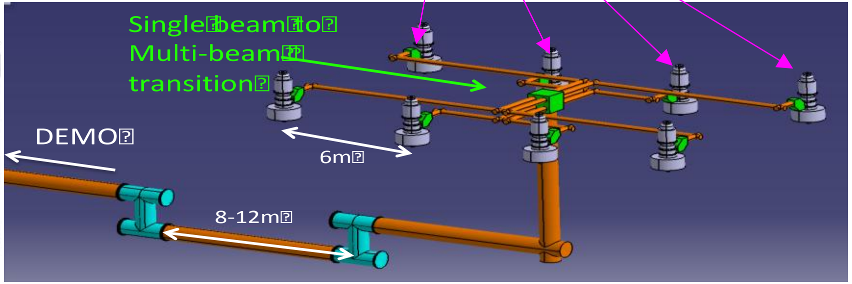
Key Components of the DEMO EC System





EC equatorial launcher



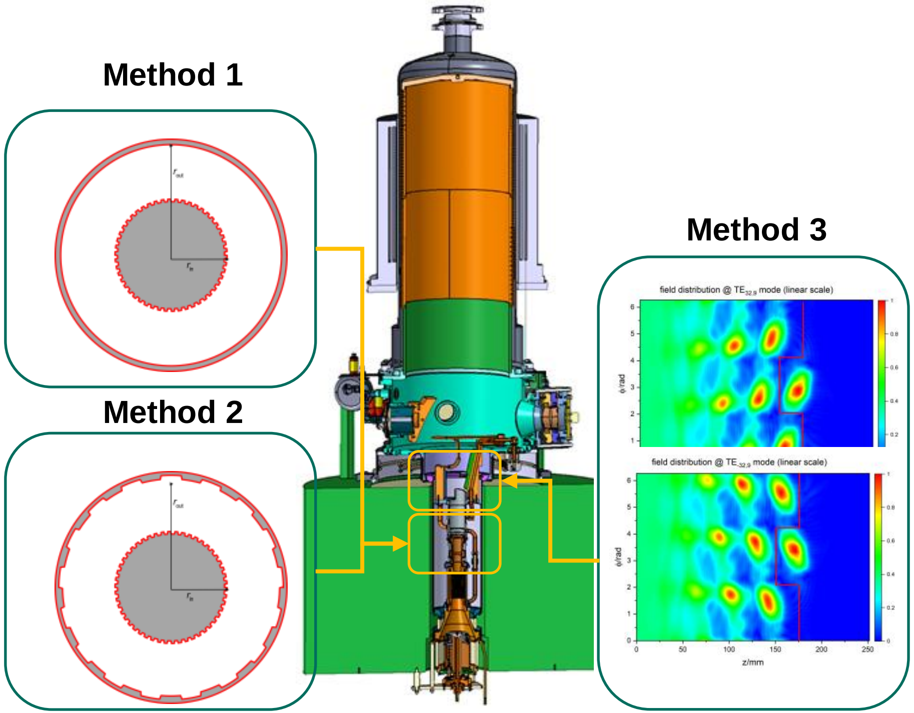


Quasi-optical transmission line

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: $\omega = \boldsymbol{s}\underbrace{\frac{eB}{m_e\gamma}}_{\Omega_c} + k_z v_z$
- Competition with fundamental competitors most critical
- 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



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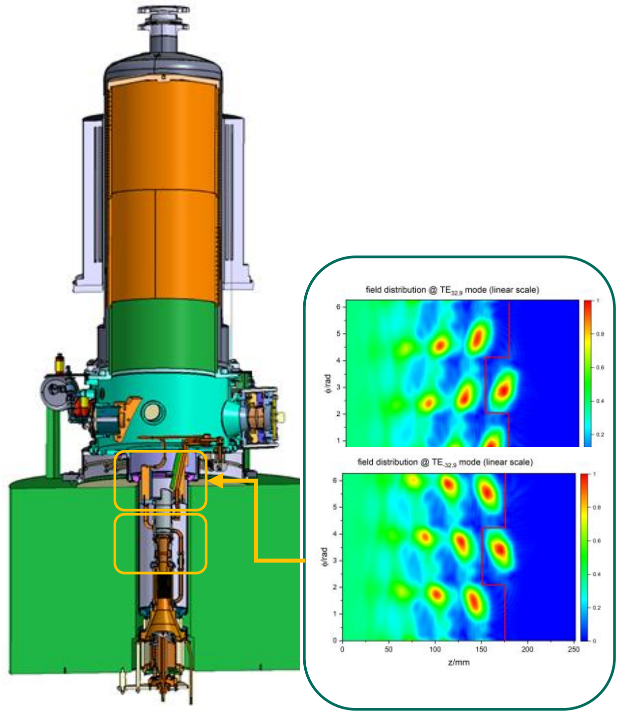
T1.1
Results on Injection Locking



T1.1.1: Fundamental theoretical studies on injection locking

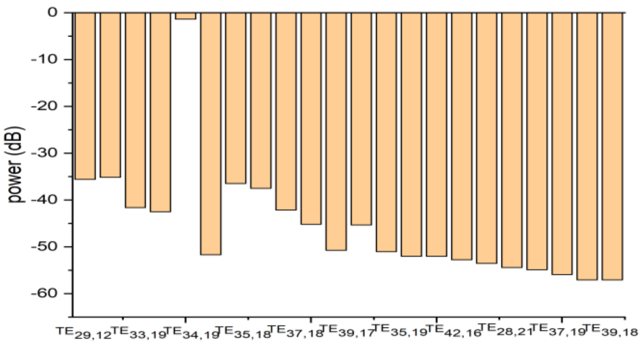
- Cavity design for $TE_{37,18}$ mode at 170 GHz has been used as "testbed" for combining the outer corrugation concept with injection locking (see T1.2.1).
- Baseline performance (without injection locking) with I_b=70 A:
  - **1.3 MW** at $\boldsymbol{\eta}$**=22.1%** electronic efficiency.
  - Ohmic loading: ρ_{in}=0.17 kW/cm^2 / ρ_{out}=1.73 kW/cm^2.
- With injection locking: Output power gain is nearly negligible:
  - With P_{inj}=50 kW we obtain $\boldsymbol{P_{out}}$**=1.47 MW** at $\boldsymbol{\eta}$**=25%**.
  - But the wall loading is high: **2.5 kW/cm^2**.
  - Only interesting if cavity cooling capabilities can be enhanced!

T1.2.2: 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 the mirror-line launcher for the $TE_{\pm34,19}$ 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!

T1.1
Corrugated Cavity

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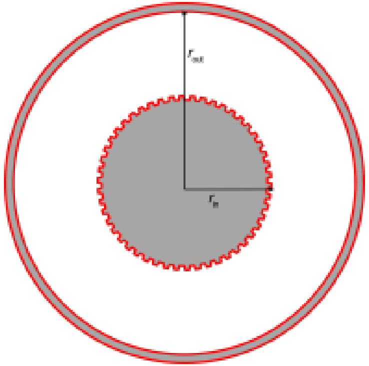
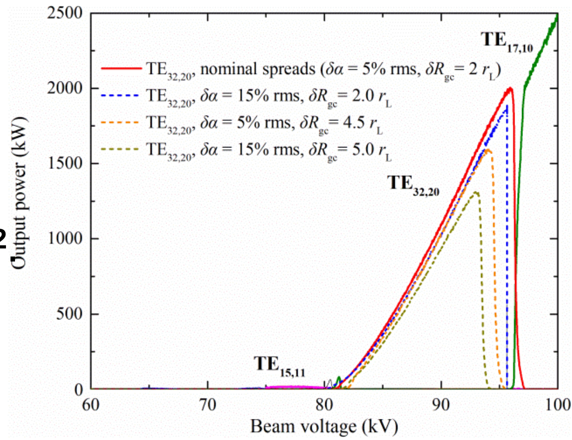
T1.2.1
Cavity designs with impedance corrugations (only inner / no outer corrugations)



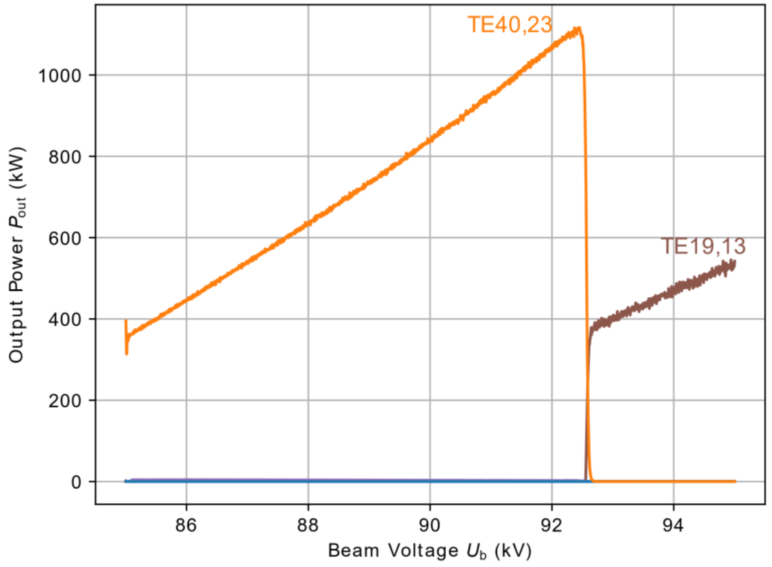
Coaxial-cavity designs for 170 GHz

- Detailed design considerations have been developed*.
- Systematic investigation of candidate modes and categorization in mode families.
- Cavity designs have been completed for different modes:
  - $TE_{32,20}$, $TE_{34,19}$, $TE_{31,20}$, $TE_{29,21}$.
  - Similar performance: **2.0 MW** output power**, 22%** electronic efficiency (can be increased to **~60%** by MDC with η_{col}=0.8).
  - Acceptable Ohmic loading: ρ_{out}<**2.2 kW/cm²**, ρ_{in}≈**0.2 kW/cm²**
  - Operating modes robust against high electron beam spreads (up to at least **15% rms spread in *α*** and up to about **five Larmor radii** uniform guiding center spread).



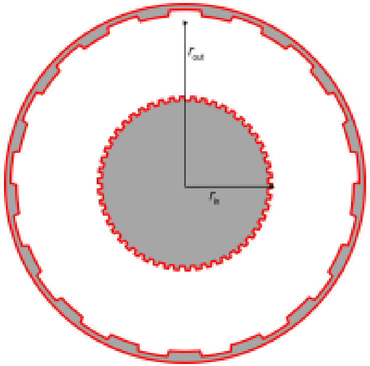
*I. G. Chelis *et al.*, "High-frequency MW-class coaxial gyrotron cavities operating at the second cyclotron harmonic," in *IEEE Transactions on Electron Devices*, vol. 71, no. 13, Jan. 2024, doi: 10.1109/TED.2024.3356472

Coaxial-cavity for $TE_{40,23}$ 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 η_{elec}~ 20 %
- More than 1 MW output power can be reached (with security margin)

T1.2.1
Mode-Converting Outer Corrugations



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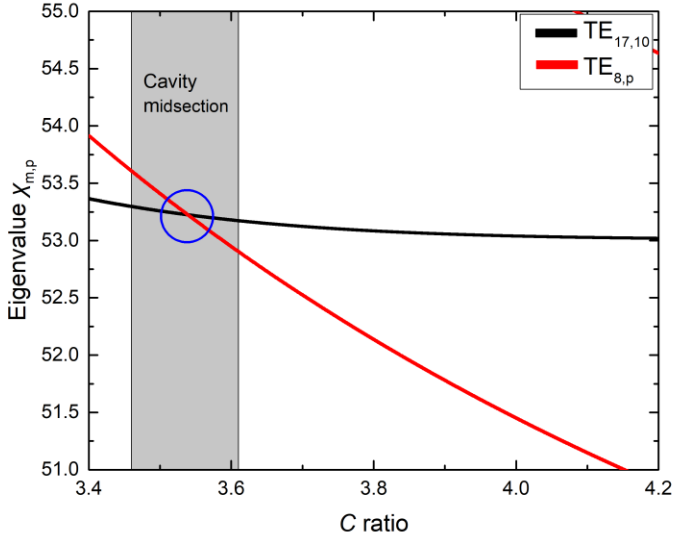
Mode-Converting Outer Corrugations
Illustrative example: mode & geometry selection

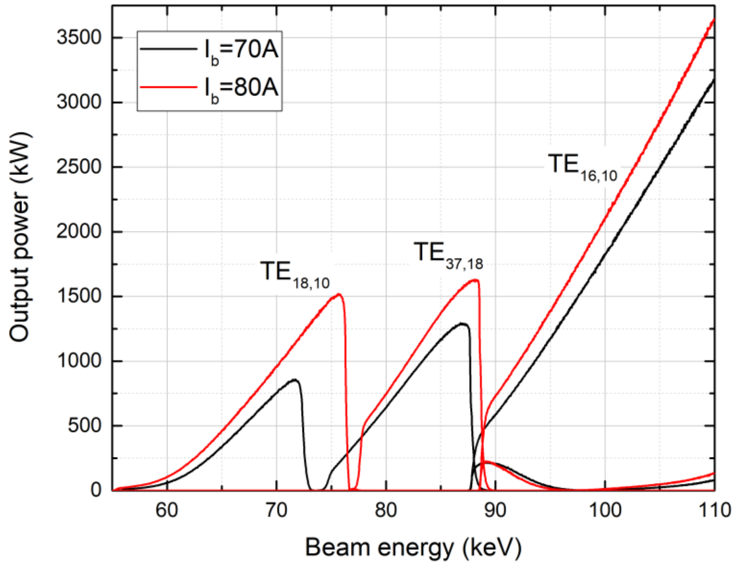
- A detailed strategy has been derived*.
- $TE_{37,18}$ was selected as operating mode. It **cannot** be excited with insert corrugations only. (Main 1st harmonic competitor is $TE_{17,10}$).
- The appropriate converting coupling of $TE_{17,10}$ was achieved by introducing *M*=25 outer corrugations.
- 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 $\boldsymbol{P_{out}}$ **=1.3MW** @ $\boldsymbol{\eta}$**=22%** electronic efficiency.
- Ohmic loading within technological constraints.
- By investigating other operating points (E_b~130 keV, I_b~80A) we were able to obtain $\boldsymbol{P_{out}}$**=1.95MW @** $\boldsymbol{\eta}$**=20%**.
- **MW-Class second harmonic operation has been achieved by introducing outer corrugations.**



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

T1.2.2
Enabling Research on Multi-Frequency Operation

T1.2.2 Multi-Frequency Operation

Target modes: $TE_{34,19}$ (170 GHz) and $TE_{40,23}$ (204 GHz)

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- Challenging to suppress fundamental competitors in both operating modes
- Different approaches:
  - Using thick inner conductor → High losses at the coaxial insert
  - Using a corrugation depth at the insert between $0.4\ \lambda_{17}{}^{0}{}_{\mathrm{GH}}{}^{\mathrm{z}}$ and $0.4\ \lambda_{20}{}^{4}{}_{\mathrm{GH}}{}^{\mathrm{z}}$ → High competition with fundamental modes
  - Using a tapered corrugation depth 0.77 mm to 0.60 mm → In simulations possible, but highly susceptible to tolerances

→ **Separate cavities necessary for 170 GHz and 204 GHz 2nd harmonic operation**

T2 Integrated Design Concepts
T2.1 Second Harmonic Gyrotron Design

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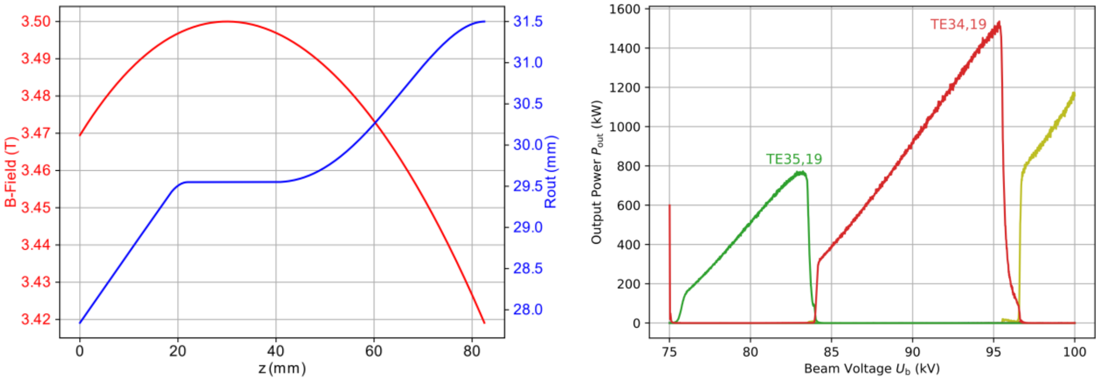
Steps towards Experiment

- Design of non-linear uptaper

Outer wall profile of the proposed $TE_{34,19}$ cavity (left) and corresponding start-up curve reaching 1.4 MW microwave output power (right).



- Research on existing Magnetron Injection Guns (MIGs) and magnet systems
- Investigation of resilience of operation against beam impurities and tolerances

Research on Existing MIGs

For $TE_{34,19}$, 170 GHz Operation

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- Target values for e-beam:
  r_{gc} = 9.6 mm, α = 1.2
- Possible magnet systems:
  - KIT test stand with 6.7 T Oxford Instruments magnet
  - KIT FULGOR test stand with procured 10.5 T Cryogenic magnet
- Existing MIGs
  - Diode type MIG → High Pitch Factor Spreads
  - Triode type MIG → Increased Flexibility

Magnet System	Oxford Instruments Magnet		FULGOR Magnet
Electron Gun Type	Diode Gun	Triode Gun	Triode Gun
E_{kin} / keV (StdDev)	81.31 (0.31 %)	95.71 (0.11 %)	92.56 (0.12 %)
Pitch Factor (StdDev)	1.16 (42.12 %)	1.22 (14.22 %)	1.25 (13.30 %)
r_{gc} / mm (StdDev)	9.71 (0.86 %)	9.62 (0.82 %)	9.62 (0.75 %)
***B* / T**	3.45	3.5	3.5

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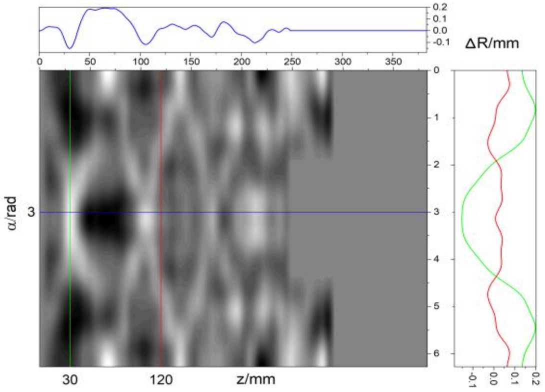
Design of a 2-way launcher system

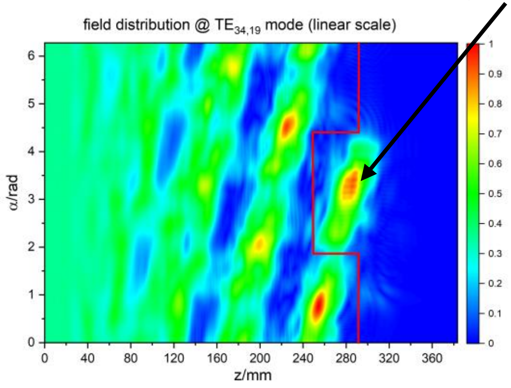
The method for the optimization of mirror-line launchers has been successfully improved for the conversion of the $TE_{\pm m,n}$ with ratio of caustic to the launcher radius to be approximately 1/3.

Example: a mirror-line launcher for the $TE_{\pm 34,19}$ modes (ratio of caustic to launcher radius is about 0.323) @170GHz.

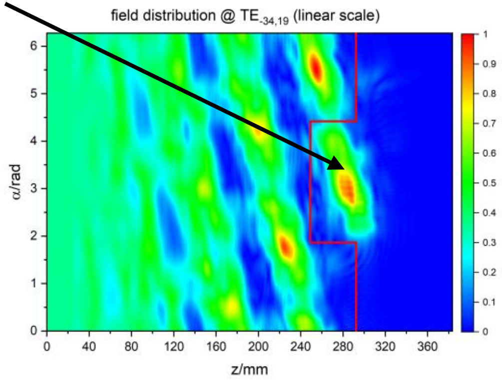


wall profile of the launcher for $TE_{\pm 34,19}$ mode

GMC: 93.65 %



Field distribution on the wall ($TE_{34,19}$)



Field distribution on the wall ($TE_{-34,19}$)

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Design of a suitable Multi-stage Depressed Collector (MDC)

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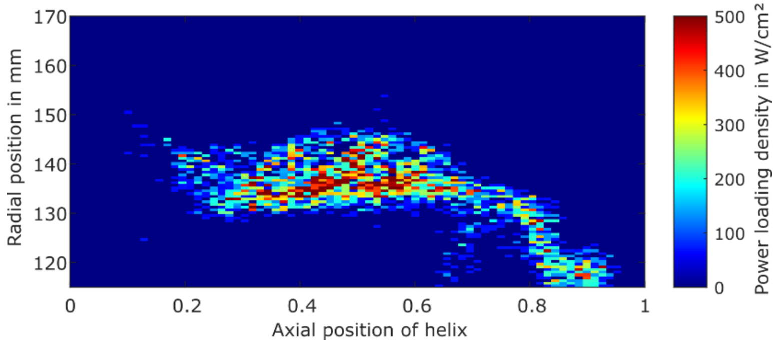
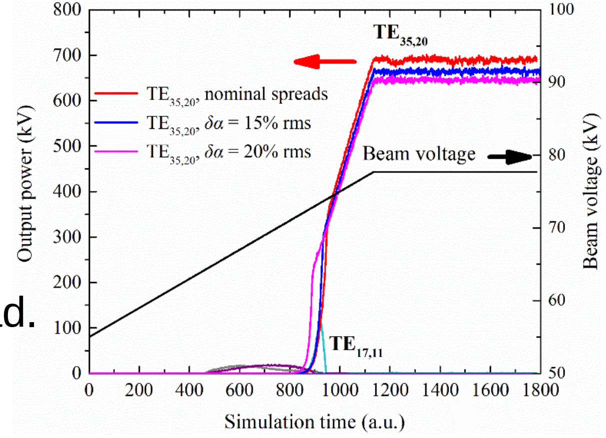
- Design of the short-pulse MDC prototype is compatible
- Depression voltages: 45.9 kV on first stage
  62.8 kV on second stage
- High collector efficiency: 85.3 %
- Low reflected current: 30 mA
- MDC is fabricated and ready for experiments



Power loading density on the first electrode

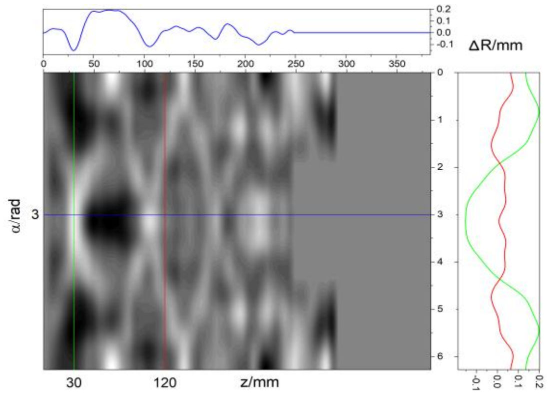
T2.2 Coaxial-cavity design for 280 GHz

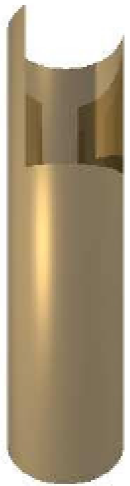
- A high-frequency cavity design for Collective Thomson Scattering has been developed.
- Very high-order mode $TE_{35,20}$ has been used (eigenvalue ≈110).
- Achieved performance:
  - **0.7 MW** output power, **15%** electronic efficiency (can be increased to **~50%** by using a MDC with η_{col}≈0.8).
  - Ohmic loading: ρ_{out}=**2.15 kW/cm²**, ρ_{in}=**0.33 kW/cm²**.
  - Design robust against high electron beam spreads (up to **20% rms** spread in α). More prone to guiding center spread.
- Concern about proximity of electron beam to coaxial insert (~**3.5 Larmor radii**). Precise manufacturing and alignment is required for such high frequencies.



T3.1 Manufacturing and low-power test of the two-way quasi-optical system

- An external company has been contacted, a first price estimate for an aluminum based $TE_{34,19}$ dual beam launcher has been received.
- The design data has been brought into the format required for production, the procurement will be launched soon.
- The existing KIT $TE_{34,19}$ mode generator will be used for low power tests.





Conclusion and Outlook

- During 2023, significant progress has been made for the defined tasks, including the optimization of tools and methods.

- Outlook: continuation according to task specifications. Main focus on:
  - Further Optimization of a $TE_{34,19}$ cavity design for a proof-of-principle experiment.
  - Procurement & cold measurement of the two-way 170 GHz launcher system.
  - Studies with respect to possibilities for frequency step-tunability of second-harmonic gyrotron cavities (T1.2.3 shifted from 2023 to 2024).

Publications

First Author	Initials	Title of work	Journal / Conference	Doc. Type	DOI or status of paper	Pinboard ID
D. V. Peponis	DPS	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	36005
I. G. Chelis	ICS	High-Frequency MW-Class Coaxial Gyrotron Cavities Operating at the Second Cyclotron Harmonic	IEEE Transactions on Electron Devices	Paper	Revised version submitted	36063
Feuerstein	L.	Design of a Second Harmonic MW-Level Coaxial Gyrotron Cavity	2023 24th International Vacuum Electronics Conference	Conference	10.1109/IVEC56627.2023.10156958	34576
Feuerstein	L.	MW Level 280 GHz 2nd Harmonic Coaxial Gyrotron Cavity with Variable Corrugation Depth	2024 25th International Vacuum Electronics Conference	Conference	submitted	-
Illy	S	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	34899

Backup Slides…

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ENR-TEC.01.KIT-T004 2024-01-01 – 2024-05-31

Task 1 - Fundamental theoretical research on individual methods

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- *T1.2 Corrugated cavity*
  - *T1.2.1 Enabling research on corrugations for second harmonic operation (D. Peponis)*
    - Completion of the development of generic design strategies for efficient MW-class operation at second harmonic, taking into account the findings of previous years' activities.

ENR-TEC.01.KIT-T004 2024-01-01 – 2024-05-31

Task 3 - Possibilities for proof-of-principle experiments

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- *T3.1 Manufacturing and low-power test of the quasi-optical system (S. Illy)*
    - The manufacturing of the mock-up quasi-optical system will be completed.
    - The manufacturing of the mode generator will be completed.
    - The performance of the coupling system in terms of coupling efficiency and mode purity will be experimentally evaluated.
- *T3.2 Theoretical investigation on and initial experiment of the possibility to use a megawatt-class gyrotron as driver oscillator (S. Illy)*
    - Concerning the driver oscillator for the injection locking the 2 MW 170 GHz 100 ms modular coaxial cavity gyrotron will be used. The gyrotron operates in the existing Oxford Instruments superconducting (OI) SC magnet which is placed in the existing old test stand in close vicinity to the new FULGOR test stand where the second harmonic gyrotron will be hosted. The required power for the injection locking is expected to be less than 100 kW.
    - The operating parameters for the operation of the coaxial cavity longer pulse gyrotron at a significantly lower power levels than the nominal one will be theoretically investigated.
    - Experiments will be performed to verify the theoretical results.
- T3.3 *Study for the required upgrade of the test stands to support the injection locking experiments (S. Illy)*
    - For the implementation of the injection locking the operation of the second harmonic gyrotron placed in the new FULGOR test stand must be synchronized with the operation of the driver oscillator which will be placed in the old gyrotron test stand in KIT. For this purpose, the necessary upgrade of the test stands will be evaluated and a fundamental implementation proposal will be made.
    - An approach will be proposed for the fundamentally necessary modifications of the common control system for both power supplies. An initial proposal on how to synchronize the triggering of both power supplies.
    - Several ideas will be theoretically investigated for the systems required for the transmission of RF beam from the driver gyrotron towards the second harmonic gyrotron.