HeatQIS

Proxima Fusion

KIT

Diamond Materials
Advanced Diamond Technologies

Development of a 238 GHz Megawatt-Class Gyrotron within the BMFTR Project HeatQIS

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THALES

1837-2027 190 YEARS HELLENIC REPUBLIC National and Kapodistrian University of Athens

KIT

Project HeatQIS

- “Microwave-plasma heating for the stellarator power plant“ (Mikrowellen-Plasmaheizung für das Stellaratorkraftwerk)
- Project funded by the BMFTR to create necessary base technology for the ECRH-system until end of 2028.
- Consists of 3 work packages (WPs), covering key components from microwave source up to plasma coupling.

With funding from the:

Federal Ministry of Research, Technology and Space

- Alpha can achieve 9.5 T, thanks to HTS, giving it much better confinement
- Resulting challenge is that Alpha requires 238 GHz for ECRH with about 30 MW

Early 2030s



Alpha – The world’s first stellarator that will demonstrate net energy gain

2030s



Stellaris - The first stellarator power plant that will feed fusion electricity into the grid

Key Components of EC Plasma Heating Systems

EC Launcher (In-vessel)

First Containment System (FCS): Closure plates,
Safety Important Component/Class 1 (SIC-1)

Port Cell Trans

Port cell TL = Ex-ves
SIC-1 up to diamond window

FCS barrier
(Structural system)

HeatMIS WP 1(a):
238 GHz / 1,7 MW (100 s) gyrotron demonstrator

HeatMIS WP 2:
Diamond disks for gyrotron microwave power extraction and safety-critical torus windows

Diamond Windows

Steering options:
- Mechanical steering
- Electronic frequency steering

Plasma

HeatMIS WP 1(b):
Conceptual design of a HTS gyrotron magnet

HeatMIS WP 3:
Design of an Electron Cyclotron (EC) launcher for efficient microwave power coupling into the plasma

cher Design 2024



Gyrotron

Work Package „Gyrotron“ (WP 1a)

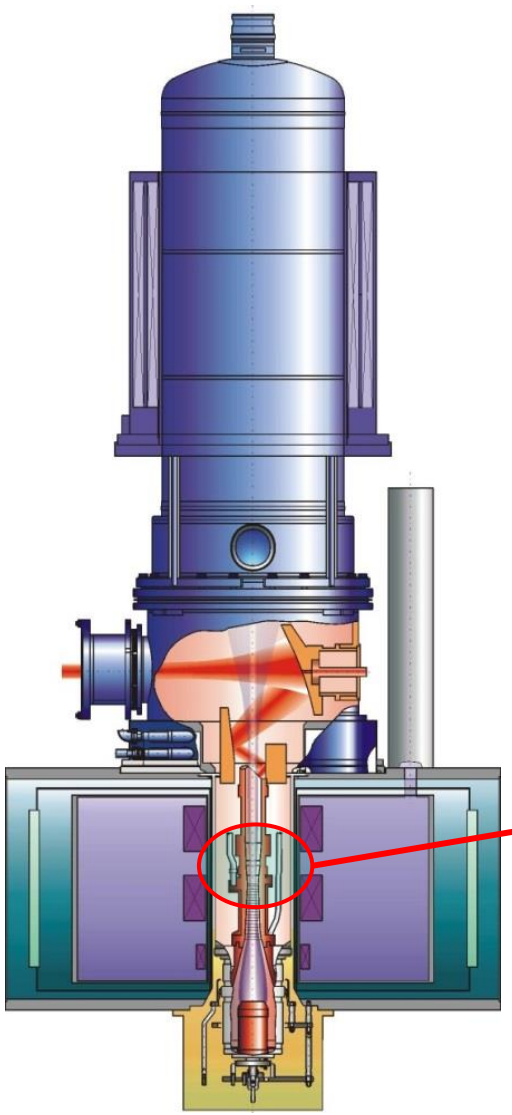
Design and manufacturing of a 238 GHz / 1.7 MW gyrotron demonstrator capable of long-pulse operation (up to 100 s)

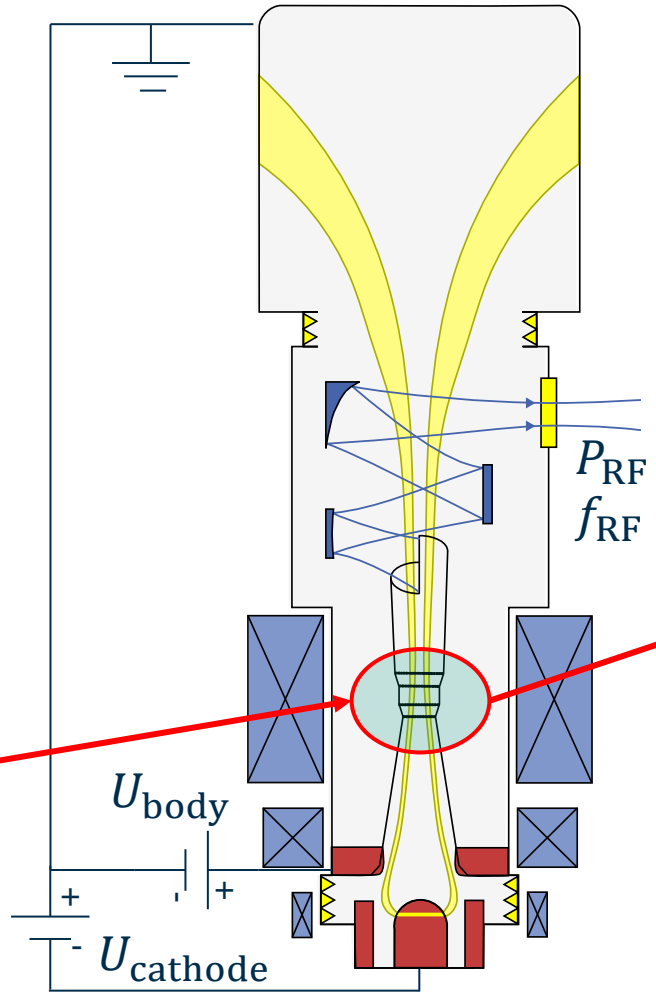
Objectives:

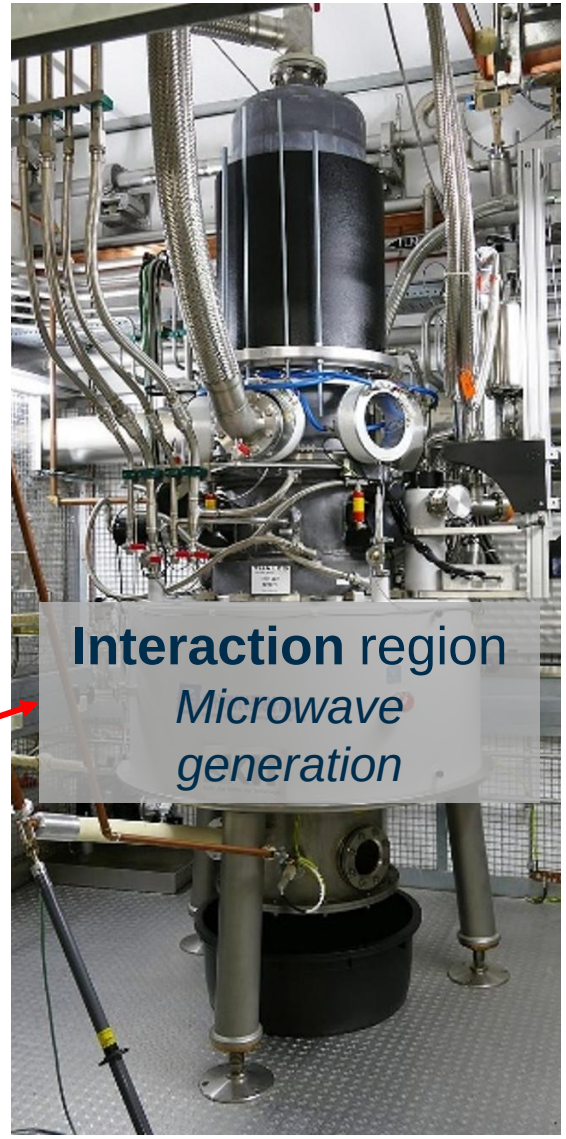
1. **Design:** Based on the EU 2 MW coaxial-cavity gyrotron for ITER (THALES TH1508), further optimized for **238 GHz operation** and manufacturability. — Q3, 2026
2. **Validation:** Experimental **low-power validation** of the quasi-optical system, followed by a **first proof-of-concept** and subsequent construction and testing of a **short-pulse demonstrator**. — Q4, 2026 / Q2, 2027 / Q4, 2027
3. **Industrial Gyrotron:** Support during fabrication of the **full-scale industrial gyrotron at THALES** under subcontract of Proxima Fusion, installation at KIT, and comprehensive acceptance testing. — Q3/Q4, 2028

1. Design

The Gyrotron – A Powerful Microwave Source







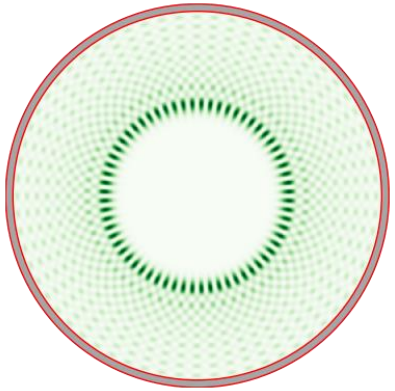
Typical performance:

- Output power: ≥ 1 MW
- Frequency: ≥ 100 GHz
- Efficiency: ~ 50 %

Interaction based on relativistic EC resonance:

$$f_c = \frac{1}{2\pi}\frac{e\,B_z}{\gamma\,m} \approx 28\,\frac{\mathrm{GHz}}{\mathrm{T}} \cdot \frac{B_z}{\gamma}$$

Energy transfer to a high order transverse electric (TE) mode:



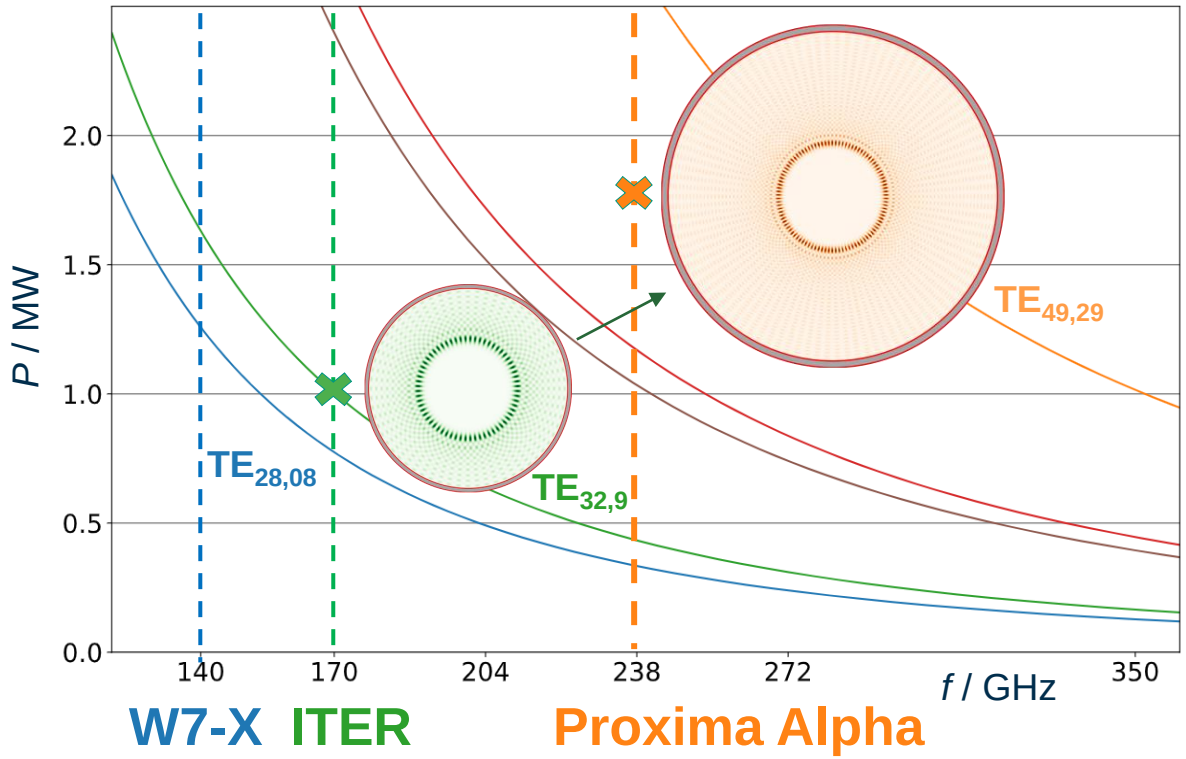
Power vs. Frequency Considering Specific Mode Orders

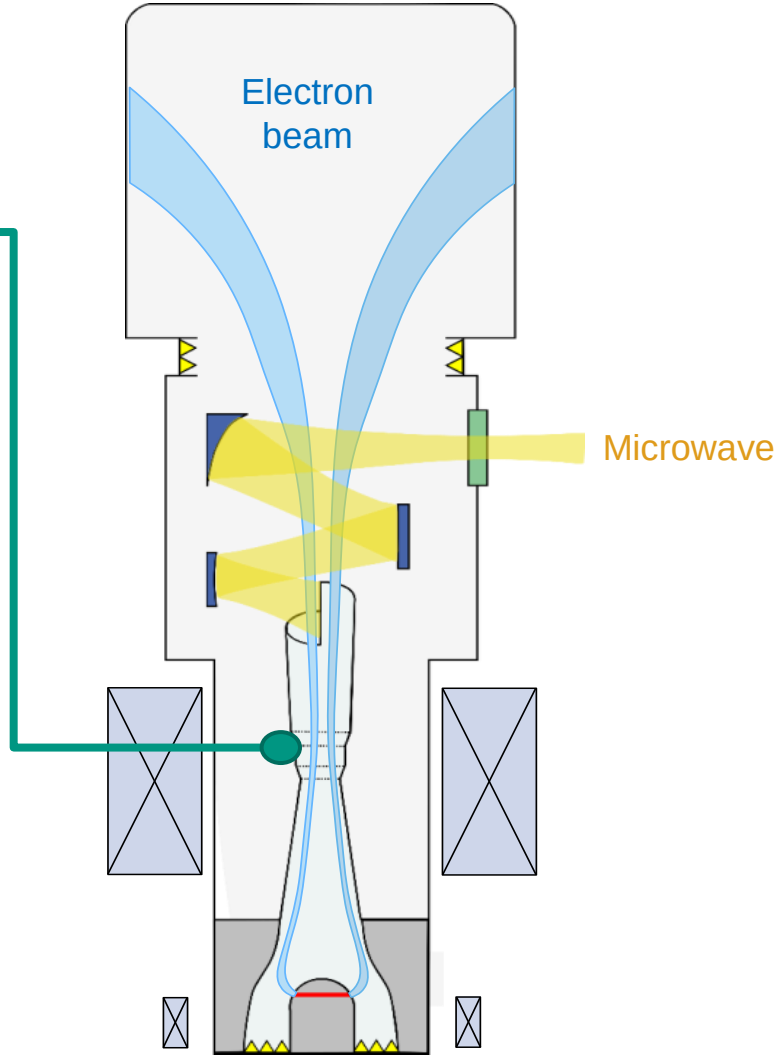
Cavity

Thermal wall loading $\sim f^{2.5}$

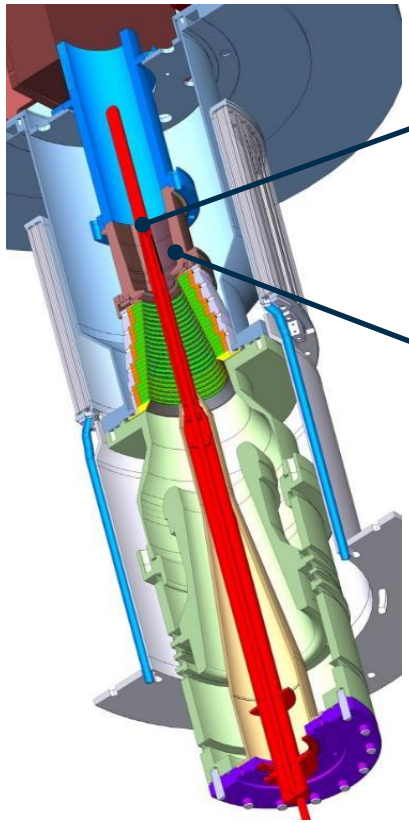
(limited to ≤ 2 $\frac{\mathrm{kW}}{\mathrm{cm}^2}$ by cooling system)

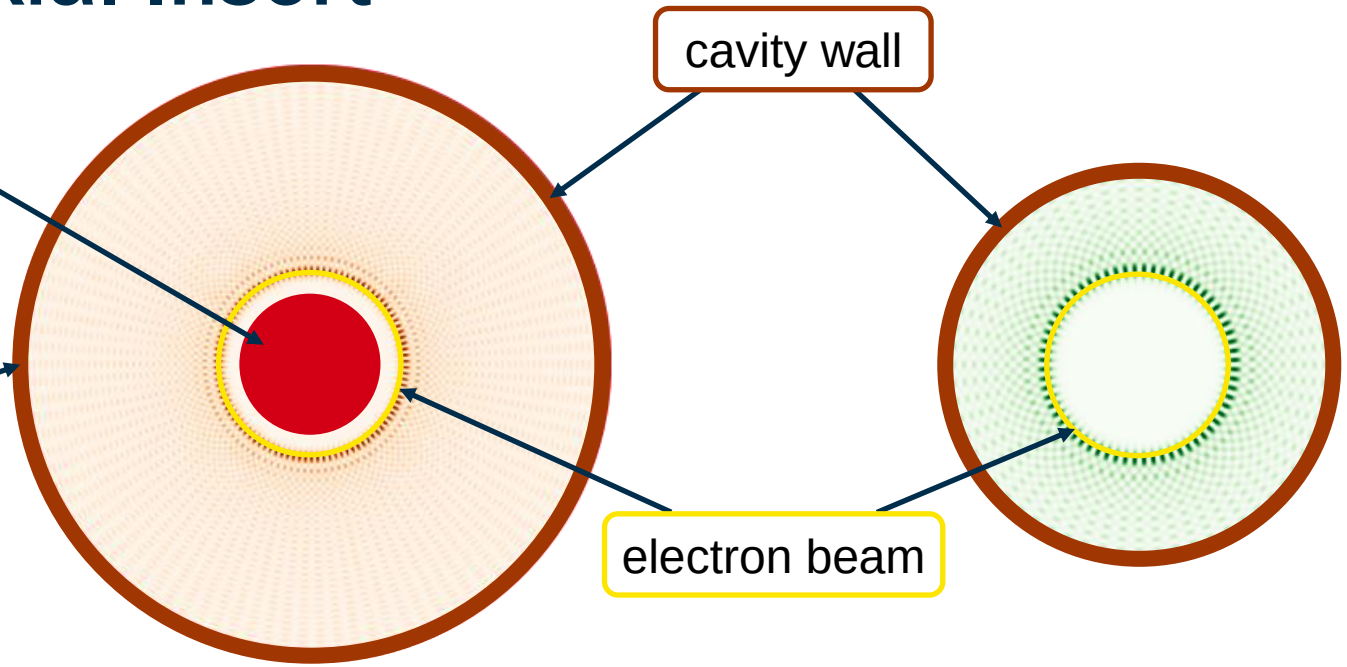
→ Need for very high-order TE mode





Design Concept - Coaxial Insert





238 GHz 1.7 MW $TE_{49,29}$ mode <u>coaxial</u> cavity
R_{cavity} = 31.65 mm; R_b = 10.2 mm; R_{ins} = 8.78 mm

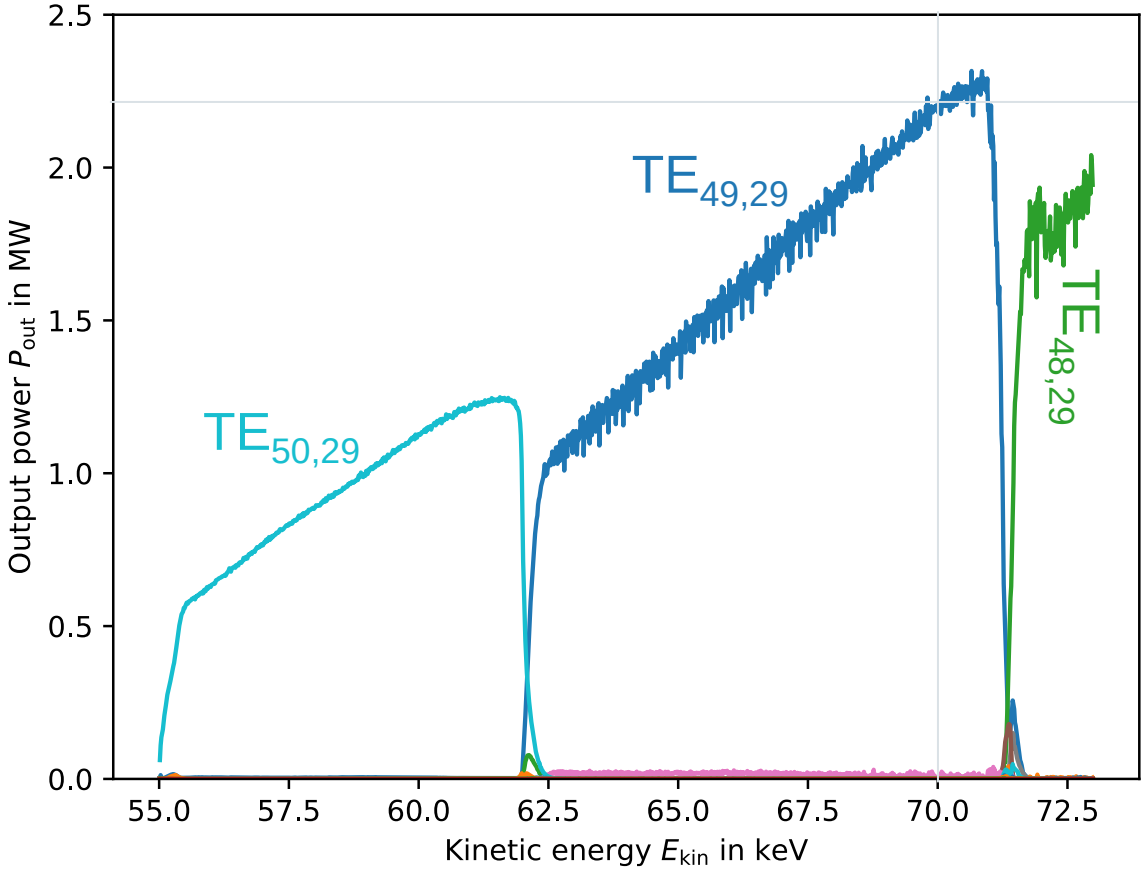
170 GHz 1 MW $TE_{32,9}$ mode <u>hollow</u> cavity
R_{cavity} = 19.22 mm; R_b = 9.44 mm

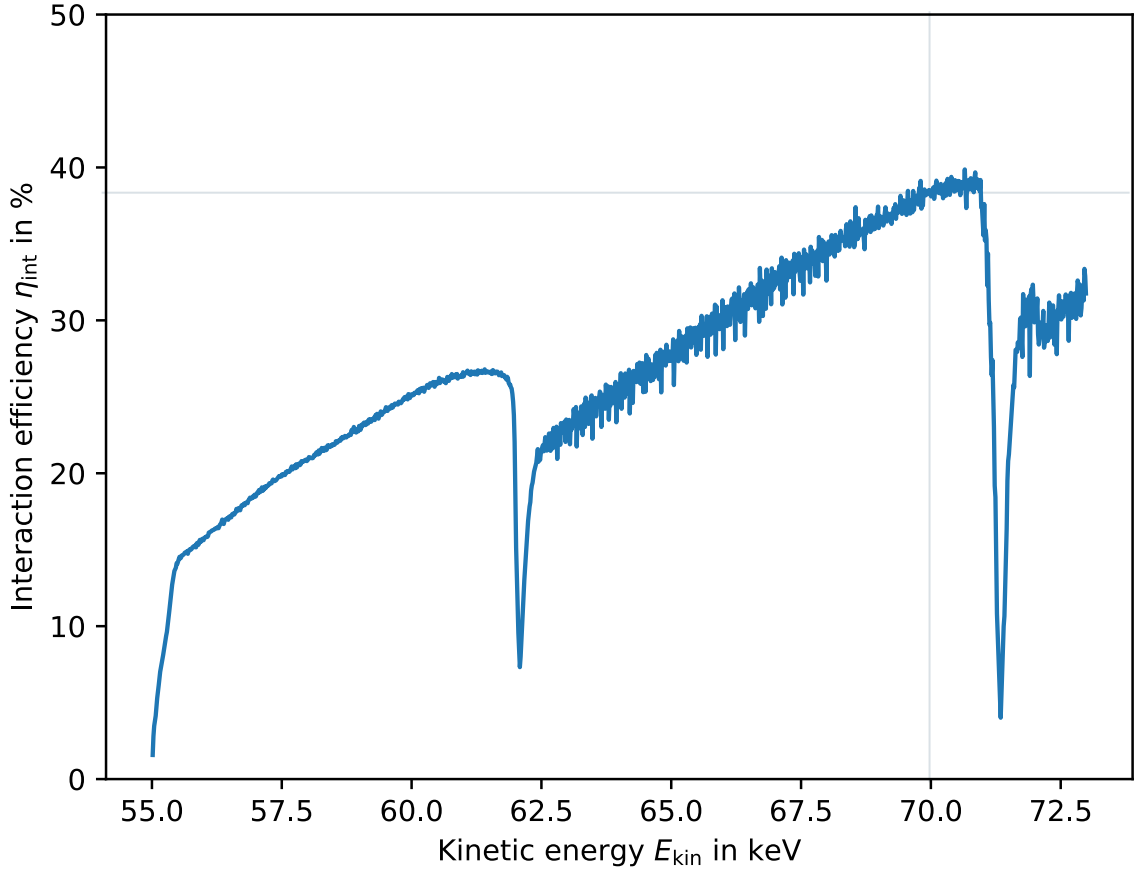
+ Reduced mode competition
+ Reduced voltage depression
– Additional risk of misalignment and thermal loading

+ Simpler design
+ Verified technology
– Lower operating mode

Gyrotron Startup Simulation

- ROCK[1]: in-house, time-dependent self-consistent multimode interaction model
- e^--beam – wave interaction taking 200 competing modes into account

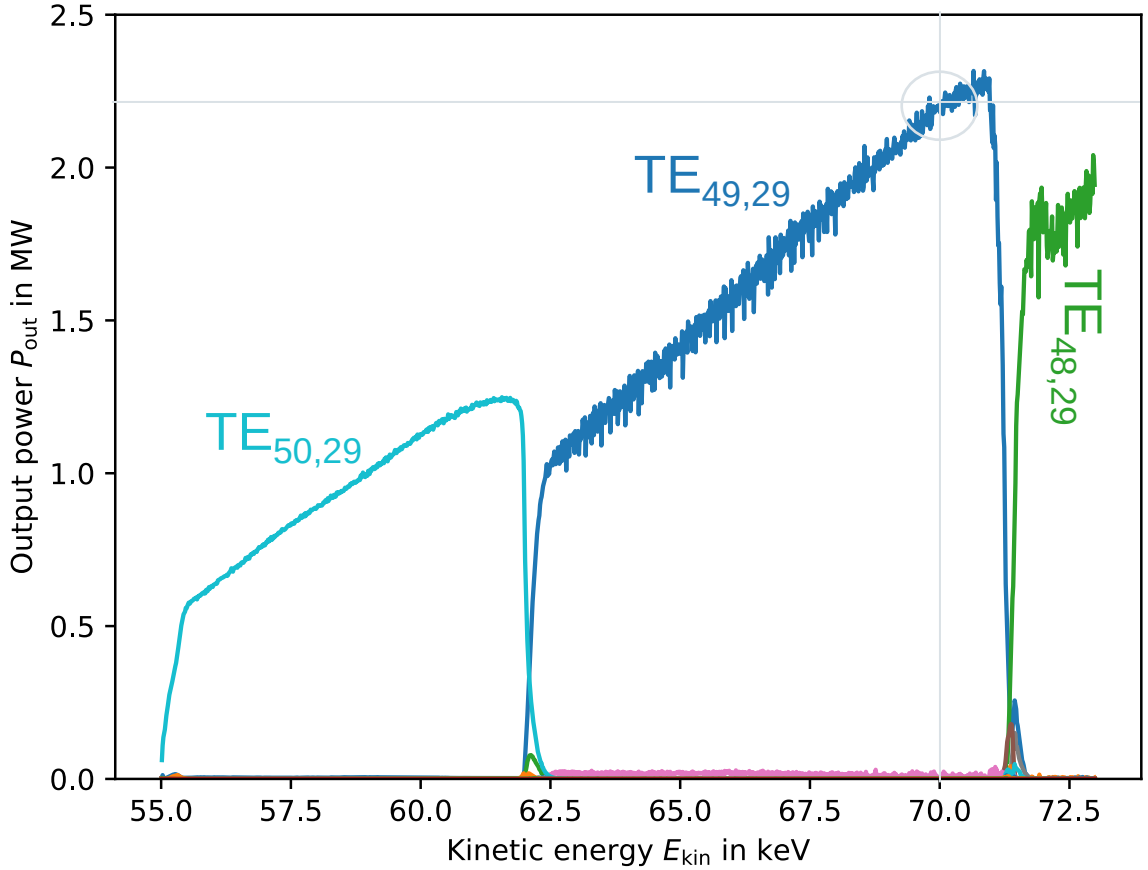




[1]: C. Wu *et al.*, ROCK: a flexible gyrotron cavity simulation toolkit using an accuracy-improved time-dependent self-consistent multimode interaction model, *Journal of Infrared, Millimeter, and Terahertz Waves*

Gyrotron Startup Simulation

- ROCK[1]: in-house, time-dependent self-consistent multimode interaction model
- e^--beam – wave interaction taking 200 competing modes into account



Operation point parameters	Value
P_{out}	2.2 MW
η_{int}	38.4 %
B	9.365 T
r_{beam}	10.2 mm
E_{kin}	70 keV
I	82 A
$\alpha = \frac{\beta_\perp}{\beta_\parallel}$	1.15

Required electron beam parameters

[1]: C. Wu *et al.*, ROCK: a flexible gyrotron cavity simulation toolkit using an accuracy-improved time-dependent self-consistent multimode interaction model, *Journal of Infrared, Millimeter, and Terahertz Waves*

Coaxial Triode Electron Gun at 238 GHz

- Objective: Use existing 170 GHz coaxial triode MIG and operate it in 238 GHz test setup for first proof-of-concept
- Challenge: Achieving high enough pitch factor $\alpha = \frac{\beta_\perp}{\beta_\parallel} \approx 1.15$ in the cavity

$$\beta_\perp = \frac{b^{\frac{3}{2}} \cos(\Theta)}{c} \frac{E}{B\gamma}$$

E: electric field at emitter

B: magnetic field at cavity

γ: relativistic factor

b: magnetic compression

Θ: emitter angle

c: speed of light

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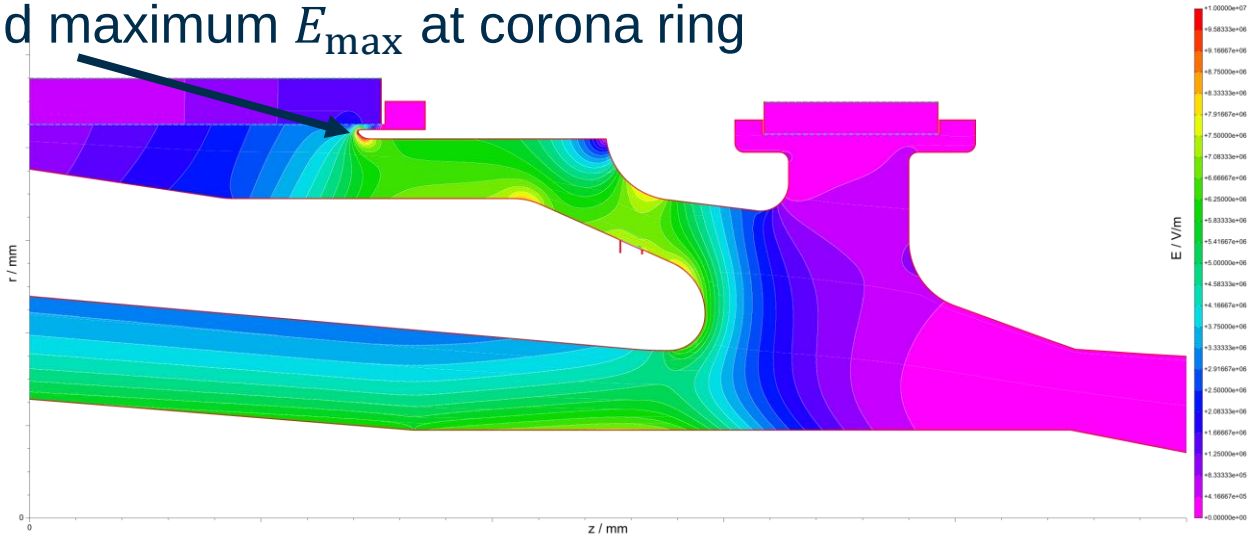
γ: relativistic factor

b: magnetic compression

Θ: emitter angle

c: speed of light

- Increased electrical field due to high magnetic field may cause arcing
- Electrical field maximum $E_{\max}$ at corona ring



Electron Gun Arcing

- Objective: Use existing 170 GHz coaxial triode MIG and operate it in 238 GHz test setup for first proof-of-concept
- Challenge: Achieving high enough pitch factor $\alpha = \frac{\beta_\perp}{\beta_\parallel} \approx 1.15$ in the cavity

$$\beta_\perp = \frac{b^{\frac{3}{2}} \cos(\Theta)}{c} \frac{E}{B\gamma}$$

- Increased electrical field due to high magnetic field may cause arcing
- Electrical field maximum $E_{\max}$ at corona ring

	U_{cat}	U_{mod}	U_{body}	B	γ	$E_{\max}$
Voltage standoff test	-80 kV	0 kV	0 kV	5 T	–	139 $\frac{\text{kV}}{\text{cm}}$
Operation point	-47.5 kV	23.1 kV	25 kV	9.365 T	1.137	123 $\frac{\text{kV}}{\text{cm}}$

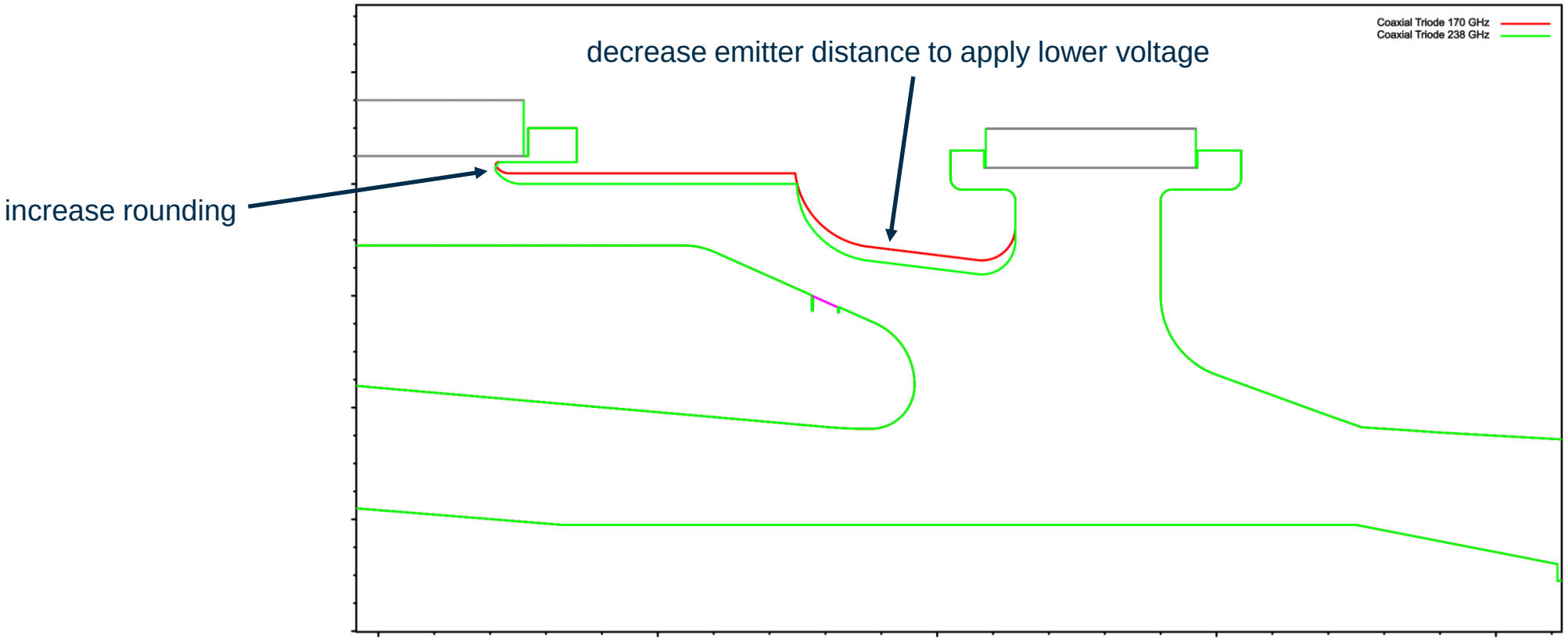
- Gun suitable for proof-of-concept, but not for industrial gyrotron



Arc during voltage standoff test in air

Design of a New Modulation Anode

- Improvement of modulation anode for industrial gyrotron
- U_{mod} decreased to $5.3\ \mathrm{kV}$ and E_{max} decreased to $70\ \frac{\mathrm{kV}}{\mathrm{cm}}$



2. Validation

“Cold” Measurements of Quasi-Optical Output Couplers

- Quasi-optical output couplers have to be verified before installation into gyrotrons
  - Fabrication tolerances of launcher and mirrors
  - Alignment of the Gaussian beam in the window plane
- Verification in “cold” measurements (without a gyrotron) in the low power regime → mode generator necessary

- Challenges:
  - Excitation of the cavity modes without the gyrotron electron beam
  - High number of propagating modes: $N \approx 2.55 \cdot \left(\frac{2 \cdot r_{\mathrm{mid}} \cdot f_{\mathrm{op}}}{c_0}\right)^2$

    e.g. 1.7 MW 238 GHz $TE_{49,29}$-mode gyrotron with

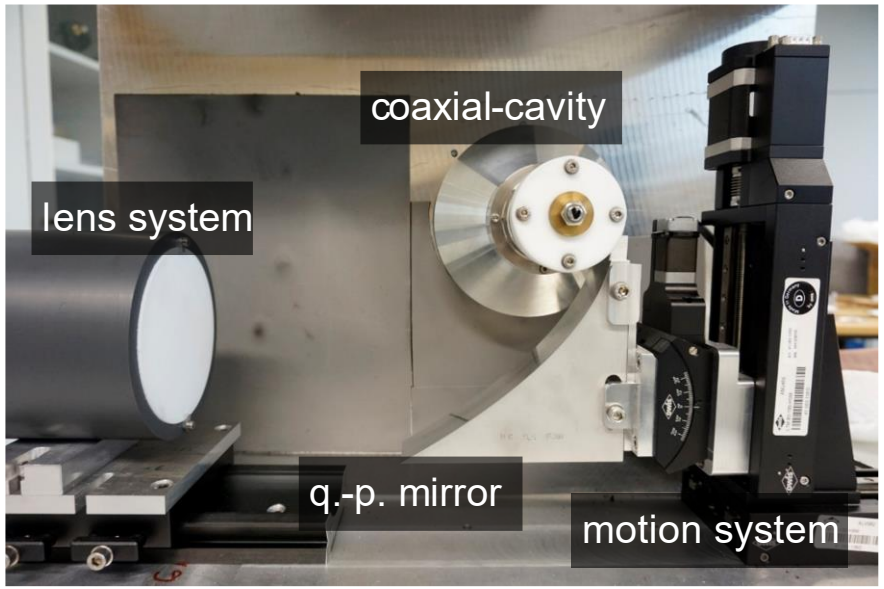
    $r_{\mathrm{mid}} = 31.65\ \mathrm{mm}, \mathrm{N} \approx 6439$

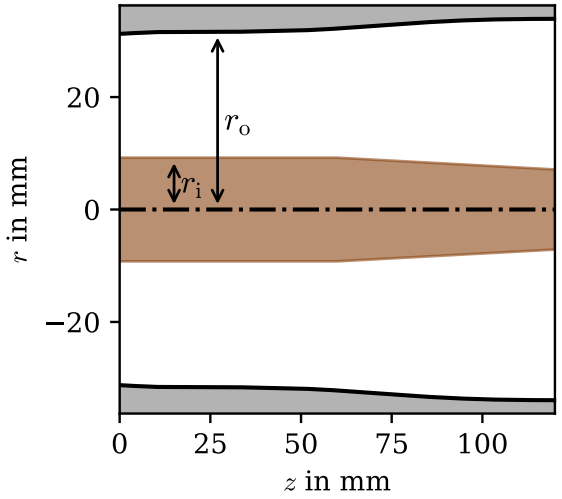


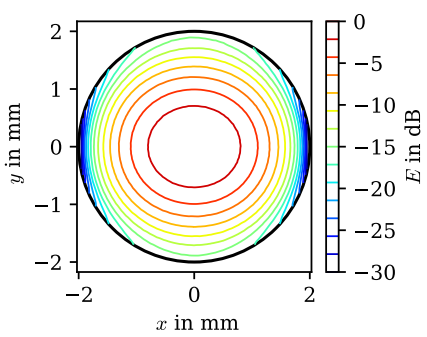
$TE_{49,29}$-Mode Generator for Low Power Tests[2]

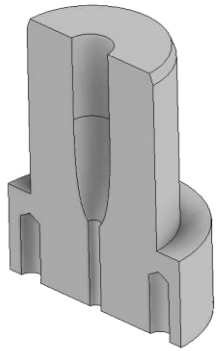
Improved motion system
- Improved accuracy
- Better repeatability

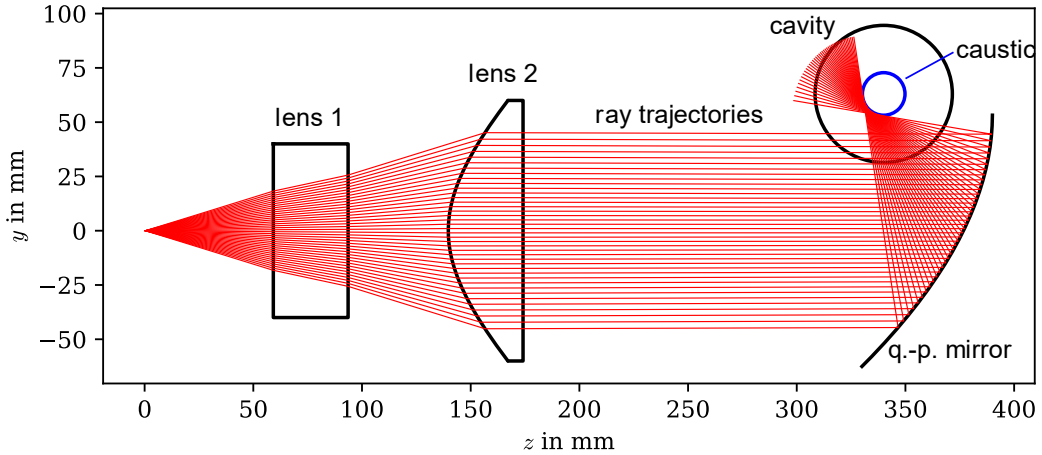
Optimized lens system
- 238 GHz horn
- New lenses











New coaxial cavity
- Highly optimized inner contour for excitation of the $TE_{49,29}$-mode

[2]: M. Misko *et al.*, Quasi-Optical Mode Generator for the Verification of a 238 GHz TE49,29-Mode Gyrotron Launcher Antenna, *10th VDE ITG International Vacuum Electronics Workshop (IVEW)*

FULGOR: The World's Only Gyrotron Test Facility for 240 GHz, 2 MW CW Gyrotrons



Virtual tour: https://www.ihm.kit.edu/Rundgang-Fulgor

Gyrotron output power

- 2 MW (CW)
- 4 MW (3600 s)
  in dual-output configuration
  (additional cooler + test box)

Gyrotron operating frequency

- up to 240 GHz
  (**with 10.5 T SC magnet**)

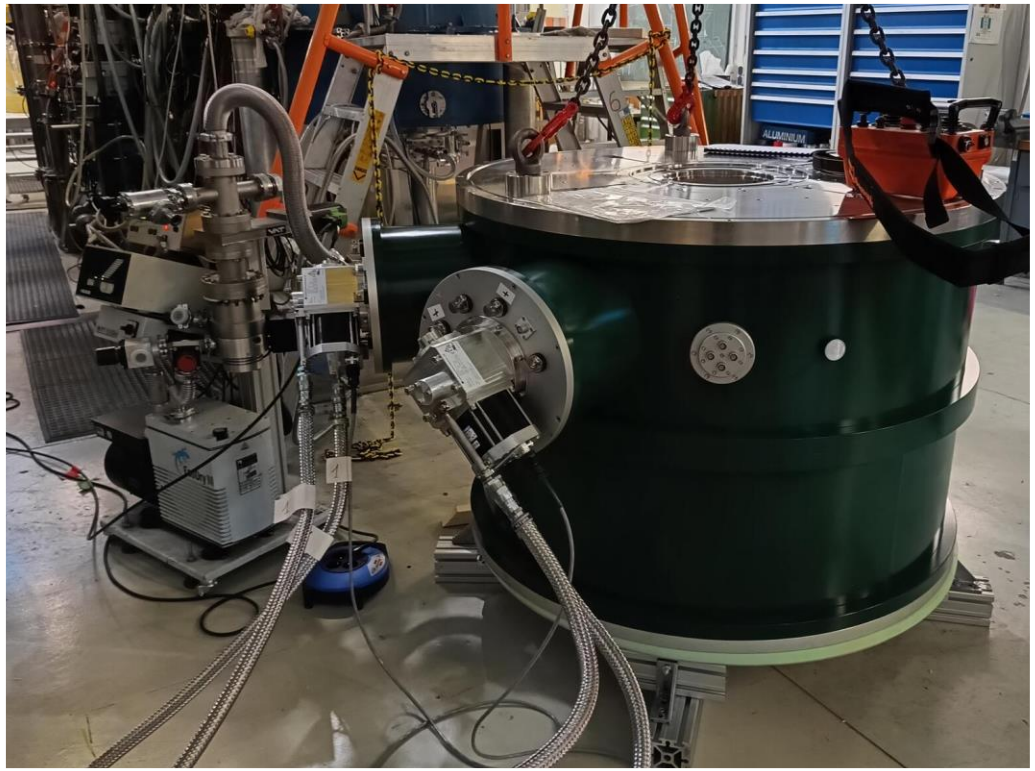
Gyrotron total efficiency

- > 60 %
  (using multi-stage depressed collector (MDC) for energy recuperation)

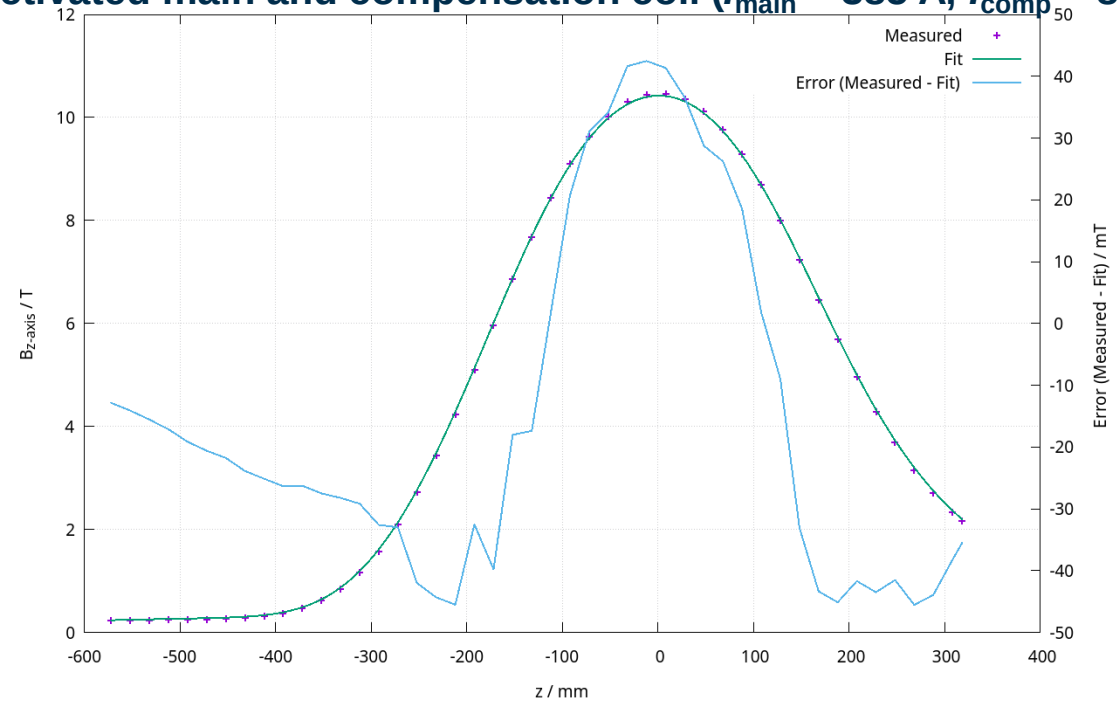


Magnetic System Overview

- Magnet system by Cryogenics with 10.5 T peak at main coil
- 4 independent steerable coils
- Warm bore hole of 240 mm diameter
- Distance between emitter and center of main coil 419.5 mm

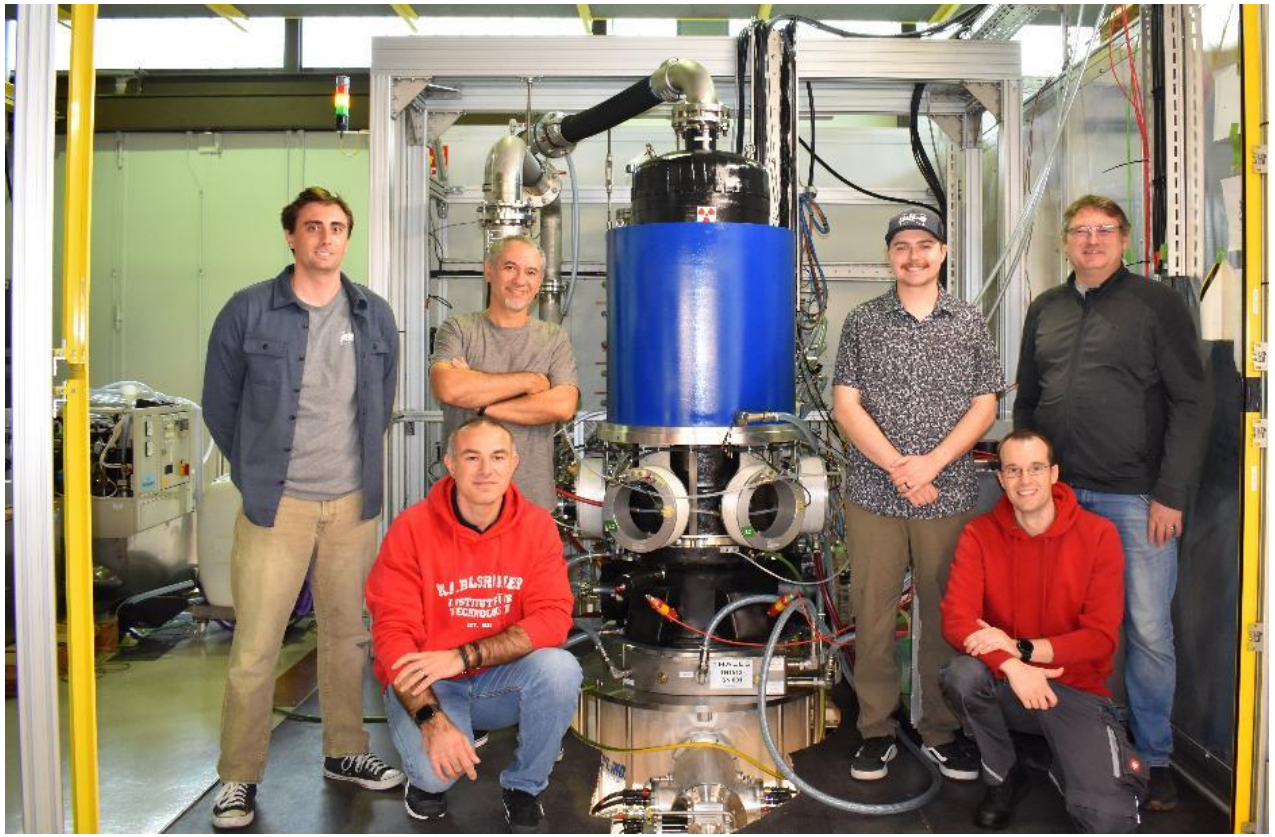


Measured field profile vs. calculated profile at full field with activated main and compensation coil (I_{main} = 385 A, I_{comp} = 85 A)



3. Industrial Gyrotron

GA DIII-D 117.5 GHz, 1 MW (10 s) Gyrotron THALES TH1512[3]



GA DIII-D 117.5 GHz, 1 MW CW	
f	117.5 GHz
B_c	4.7 T
P_{rf}	1 MW
Mode	$TE_{24,8}$
Efficiency	42%
Pulse length	10 s
Magnets	Cryo free SCM - Cryomagnetics
Goal	FAT

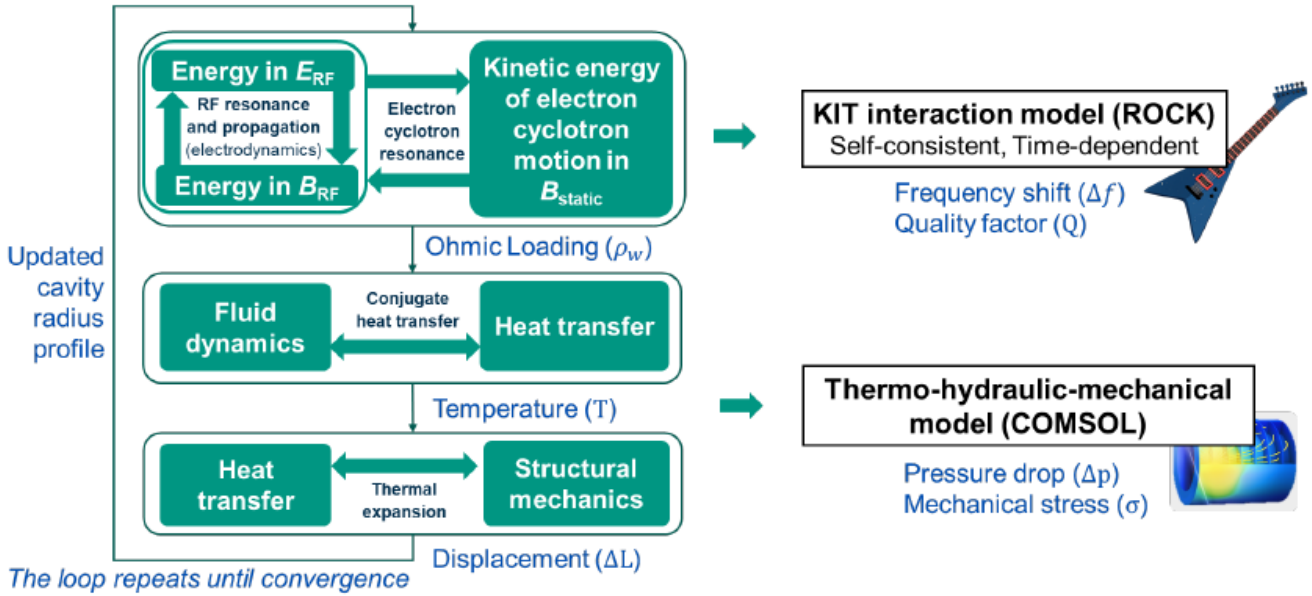
[3]: A. Leggieri *et al*., "The **Thales TH1512**: A New 117.5 GHz 1 MW Continuous-Wave Industrial Gyrotron for the DIII-D Tokamak," 2026 IEEE International Vacuum Electronics Conference (IVEC), Monterey, CA, USA, 2026, pp. 18-19, doi: 10.1109/IVEC65405.2026.11555899

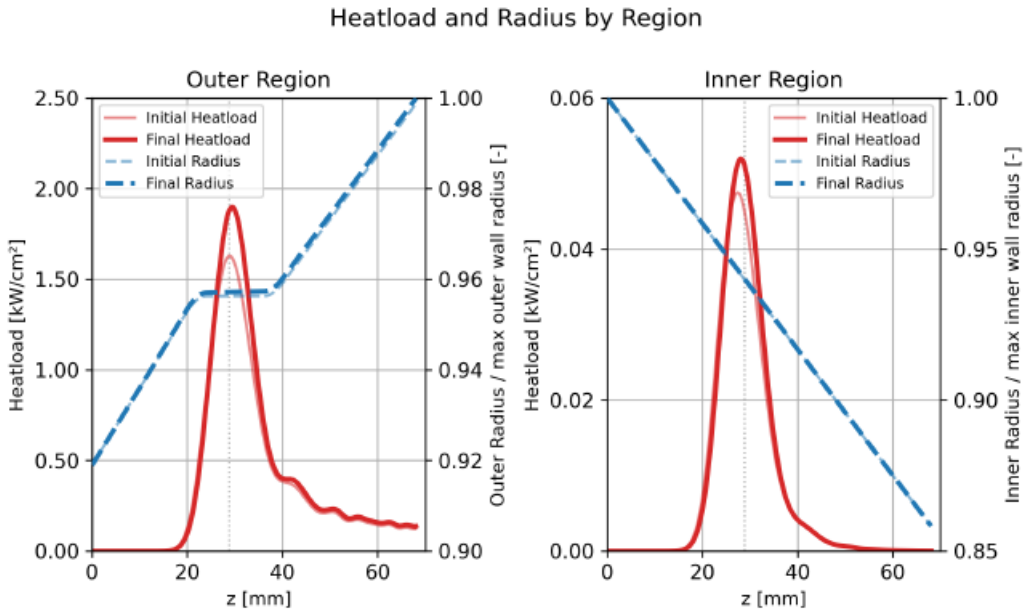
Accompanying Simulations for CW-Gyrotron

Impact of transition effects to continuous wave before steady-state operation is reached

- Cathode current boosting
- Neutralization
- Thermal expansion:

Schematic representation of **G-AMP**[4] (**G**yrotron cavity **A**utomated **M**ulti**P**hysics simulation tool





[4]: R. G. Bertazzoni *et al.*, Predictive Capabilities of G-AMP for High-Power CW Gyrotron Cavities: An Automated Non-linear Multi-Physics Simulation Framework, *submitted to Fusion Engineering and Design (FED)*

Thank you for your attention!

Want to know more about current gyrotron development?
Today's poster session in "Studio 1":

S. Illy "Fast Switchable Dual Harmonic Gyrotron Operation for Versatile Plasma Heating and Stabilization"

B. Ell "KIT Development on Gyrotron Mulltistage Depressed Collectors"

S. Stanculovic "KIT's integrated pproach to progressive cooling of cavities in fusion MW-class gyrotrons"

E. Deliprimis "Simulations estimating space-charge neutralization level in the 1.5 MW and 1 MW 140 GHz gyrotrons for the W7-X stellarator"

34th SOFT 2026

34th SYMPOSIUM ON FUSION TECHNOLOGY

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