Karlsruhe Institute of Technology

High Power CW Gyrotron Development at KIT: Current Status and Future Prospects

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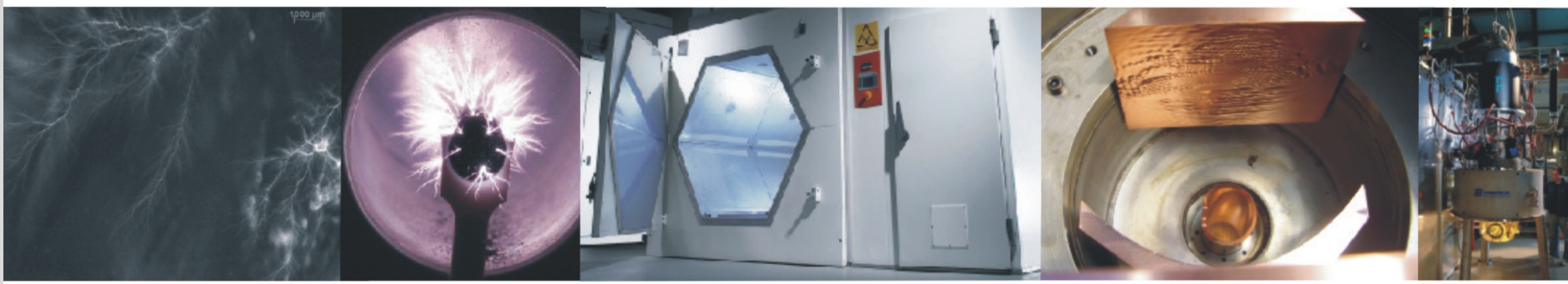
Presented at the 7th ITG-IVEW 2020

Institute for Pulsed Power and Microwave Technology (IHM), Karlsruhe Institute of Technology, Karlsruhe, Germany

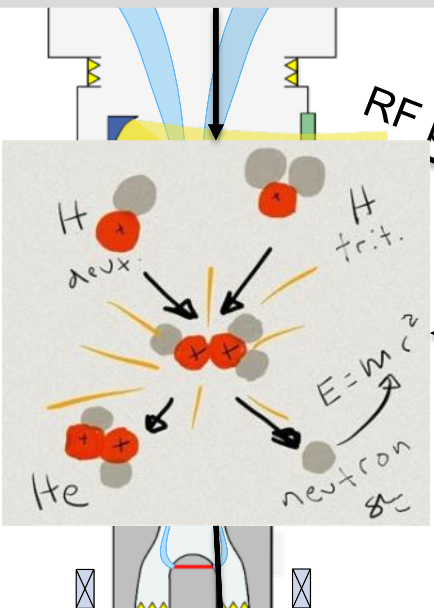


Outline

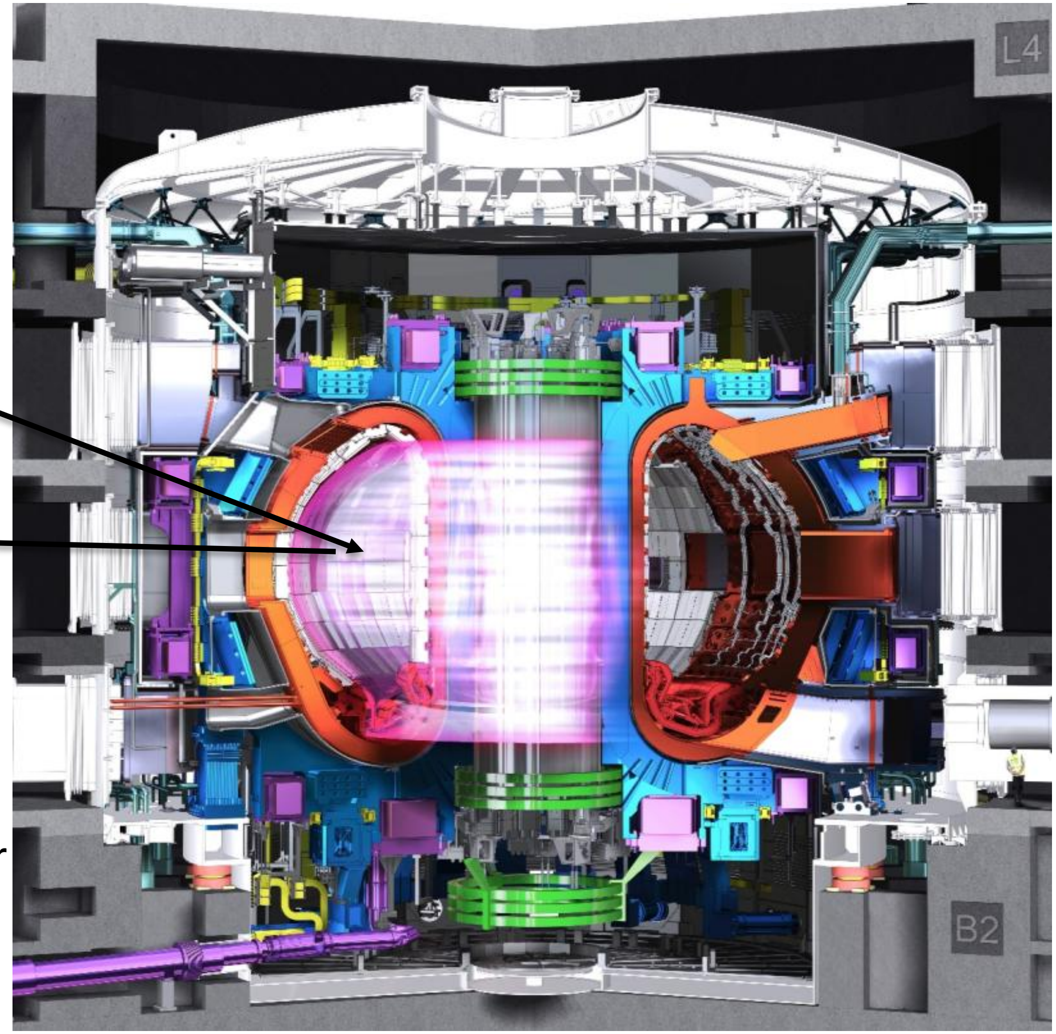
- Introduction
- Overview of components
- Principles of gyrotron interaction
- Main conceptual and technical challenges
- Gyrotron development at KIT
- Conclusion & Outlook

Introduction: Nuclear Fusion

Nuclear fusion: clean and steady state energy for next generations.



RF power



Gyrotrons are used as high power microw... on Cyclotr... g (ECRH).

Temperature: 100-200 **million** ℃

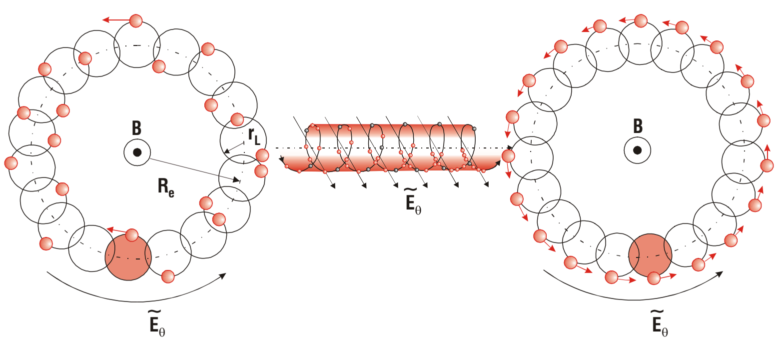
Introduction: Electron Cyclotron Resonance Heating (ECRH) and Current Drive

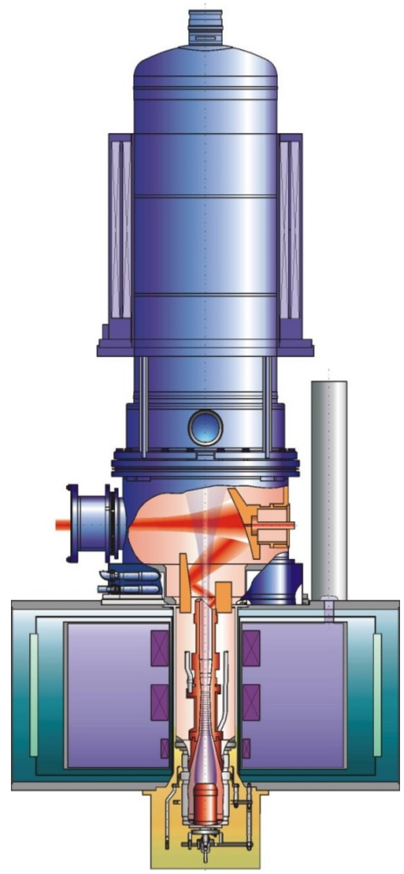
- In ECRH, a resonance between the electrons and RF waves is exploited.
- High-power mm-waves propagate through the plasma, power is deposited at the resonance location (energy-transfer to electrons). Electrons indirectly heat the ions, increasing the overall temperature of the bulk plasma.
- Advantages:
  - RF sources installed quite far from torus
  - Relatively small ports are needed
  - No antenna structures close to plasma edge
  - Good coupling, different inner regions of the plasma can be accessed
- Scenarios for plasma stabilization & current drive are possible.
- **Prominent example (under KIT responsibility):**

  10 MW ECRH system of the Wendelstein 7X stellarator at IPP Greifswald

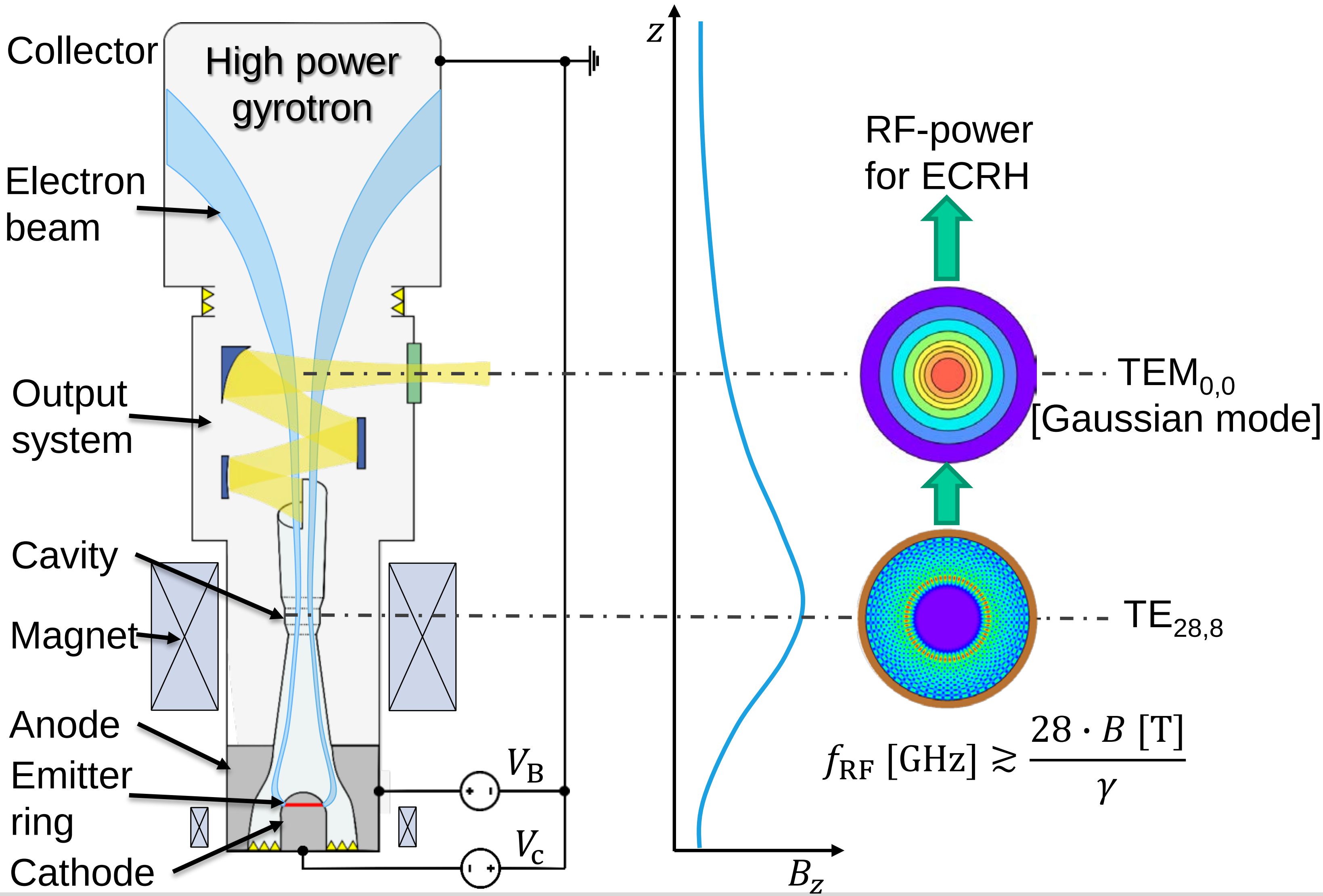
The Gyrotron – a Powerful mm-Wave Source

- Vacuum electron tube in a strong magnet
- Up to 2 MW RF power at frequencies of 70 ~ 170 GHz
- Efficiency: currently ~ 50 %
- „Gyrotron“ = „gyrating electron“

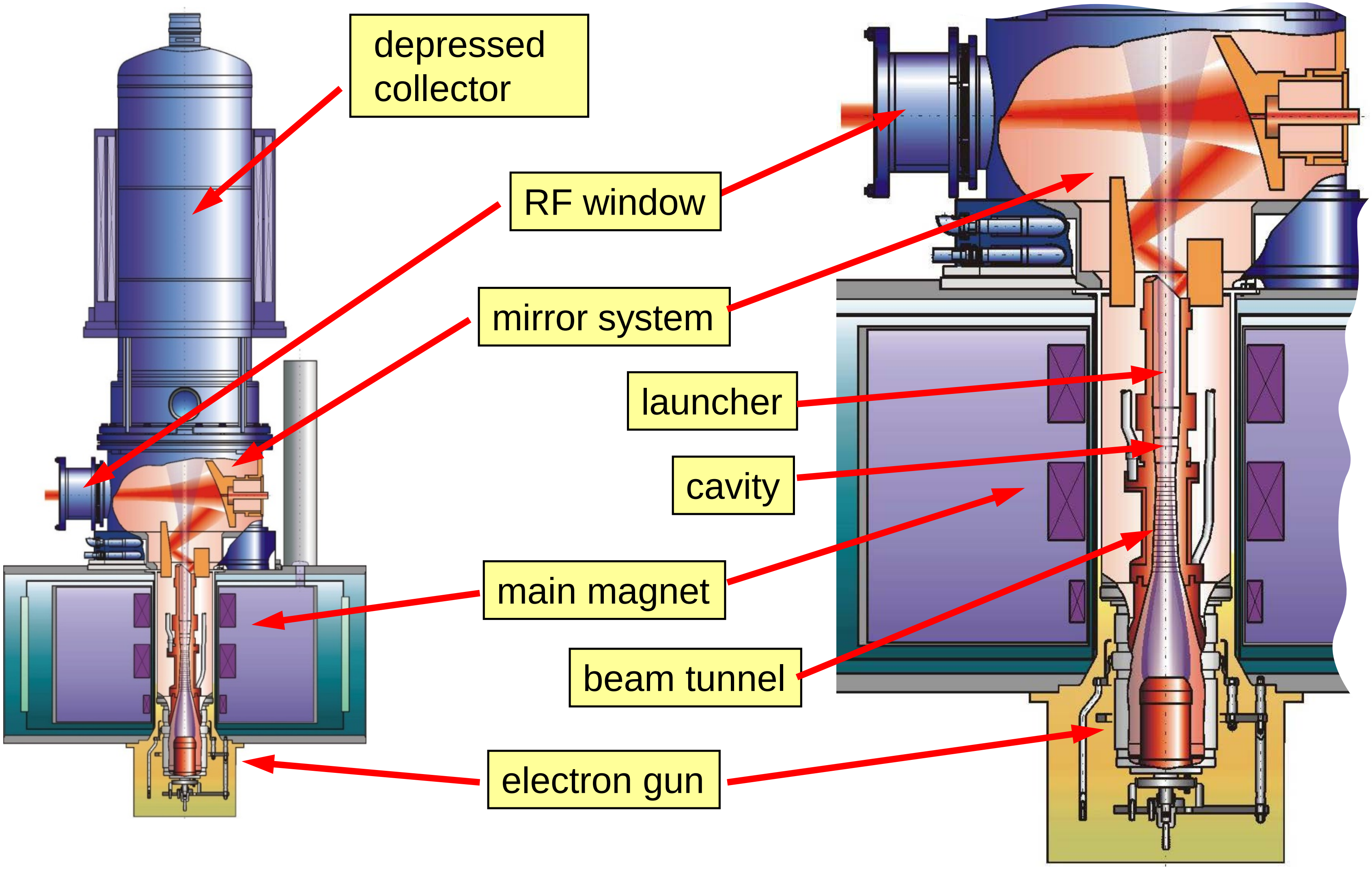




Introduction: High Power Gyrotrons



The Gyrotron – Overview of Components



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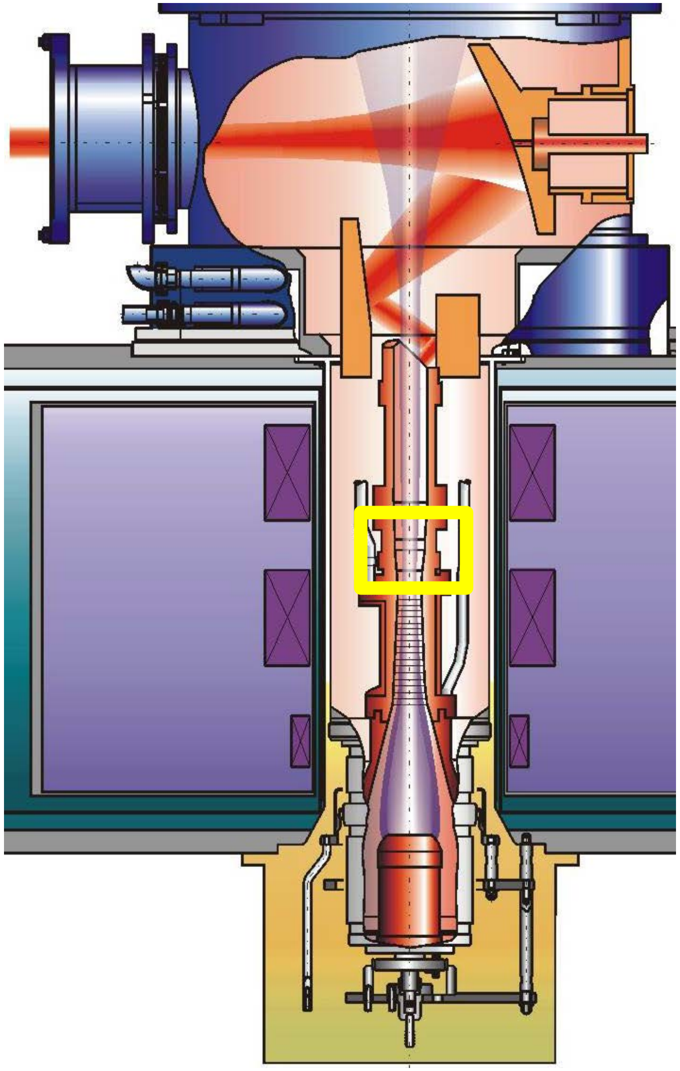
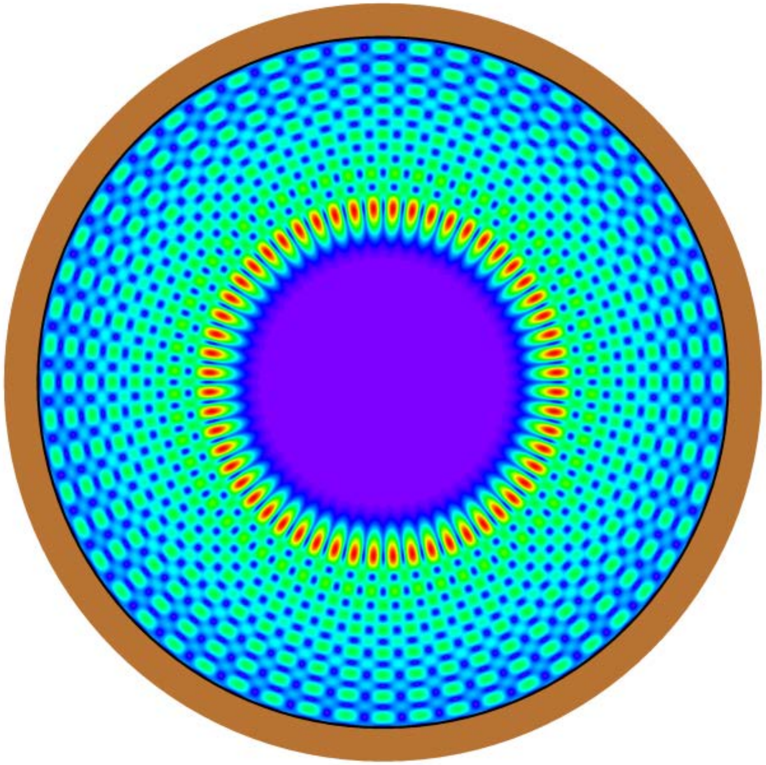
The Gyrotron Cavity



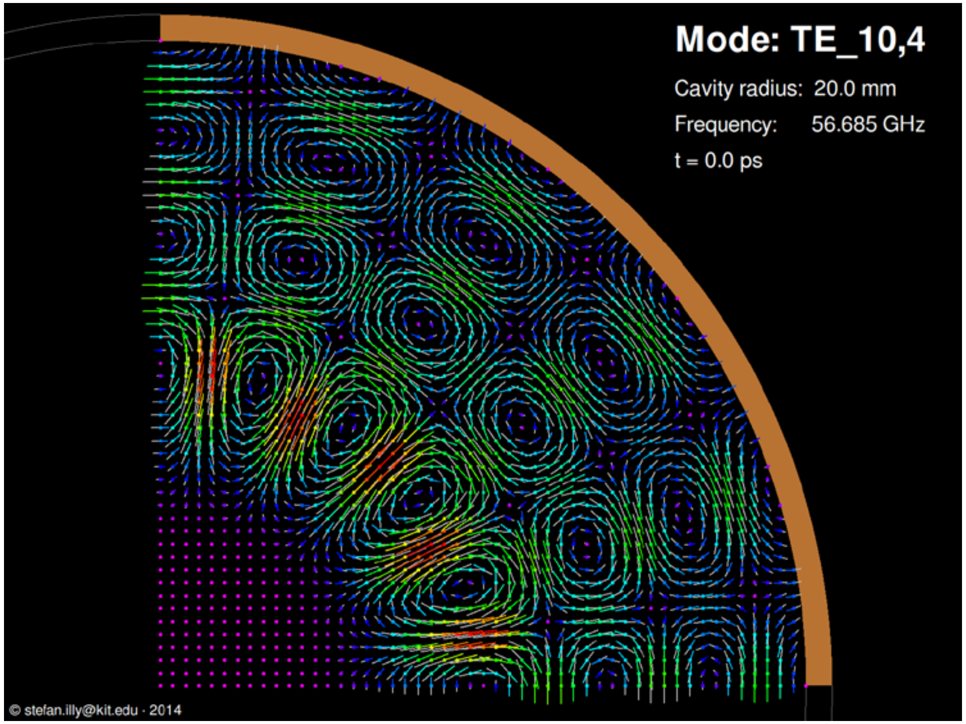
Electromagnetic wave modes in cylindrical waveguides

Standing wave, azimuthal: sine function (periodic pattern)
radial: Bessel functions

$TE_{28,8}$ Mode (abs. value of E-field)



$TE_{10,4}$ Mode (vector representation)



Number of propagating modes: $N \propto (D/\lambda_0)^2$ (with *D*: Diameter, λ_0: free space wavelength)

Electron-Cyclotron-Interaction

relativistic cyclotron frequency

$$\Omega_c = \frac{eB}{m_e\gamma} \approx 2\pi \frac{28\mathrm{GHz} \cdot B/\mathrm{T}}{\gamma}$$

relativistic factor

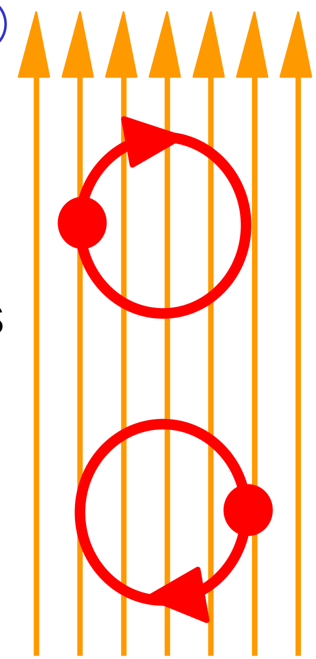
$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}} \approx 1 + \frac{W_{kin}}{511keV}$$

high frequency field with (angular) frequency ω_{rf}

magnetic field **B** $\otimes$

<u>Deceleration</u>
electron loses energy
-> γ decreases

<u>Acceleration</u>
electron gains energy
-> γ increases

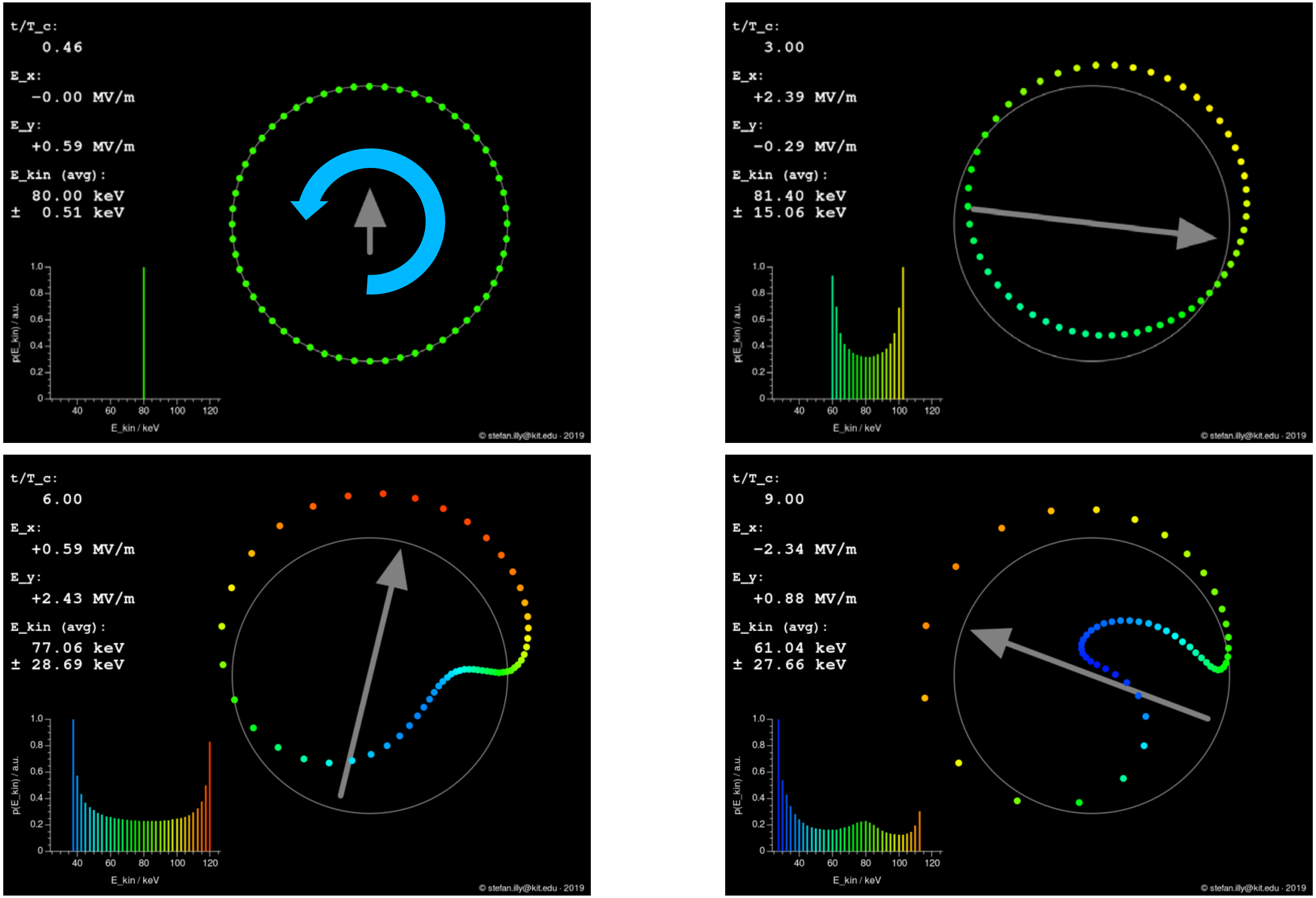


	$\omega_{rf} > \Omega_c$	$\omega_{rf} < \Omega_c$
Deceleration	$\Omega_c \uparrow$ $\Delta\Lambda \downarrow$	$\Omega_c \uparrow$ $\Delta\Lambda \uparrow$
Acceleration	$\Omega_c \downarrow$ $\Delta\Lambda \uparrow$	$\Omega_c \downarrow$ $\Delta\Lambda \downarrow$

Principle of the electron-cyclotron-interaction: When ω_{rf} is slightly higher than Ω_c, electrons remain longer in the phase position where they lose energy, because the change of phase per cycle decreases in this position ($\Delta\Lambda$).

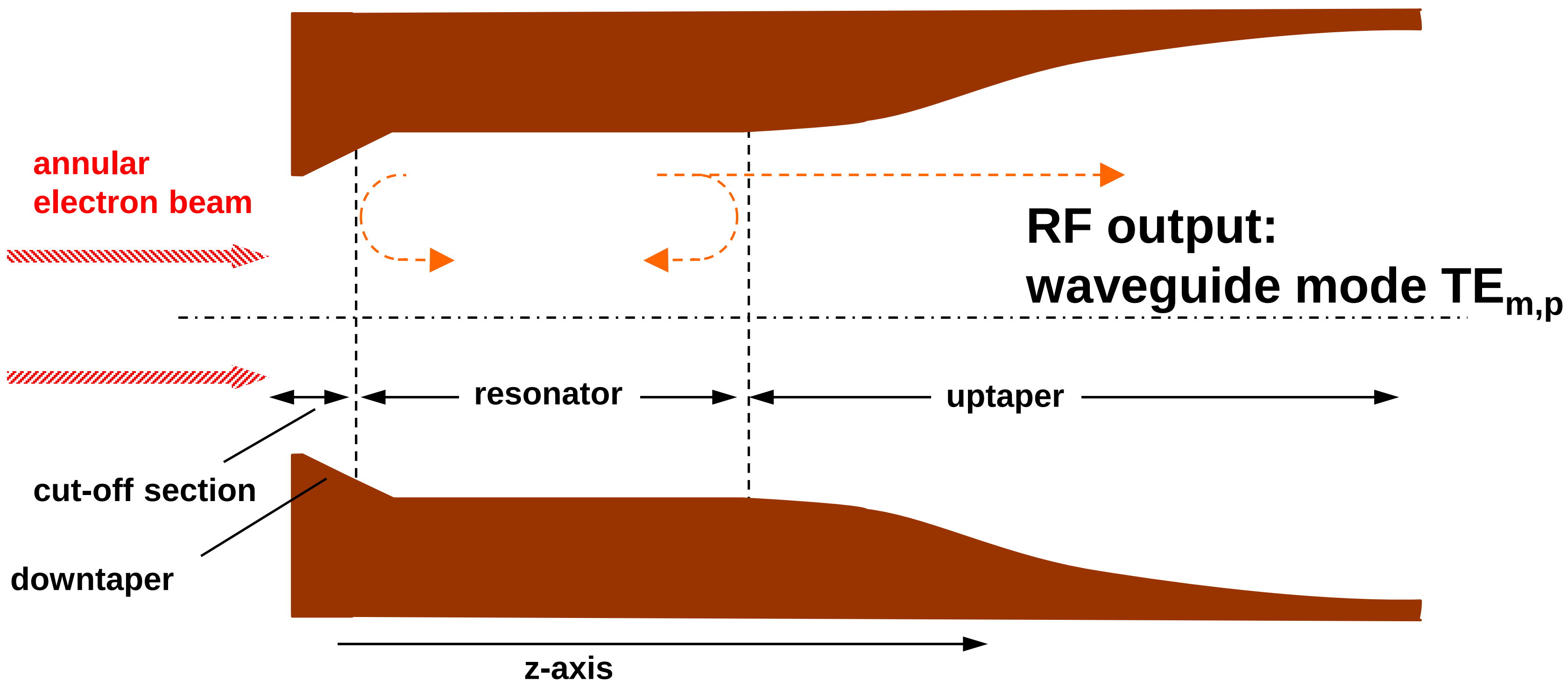
The electron-cyclotron-interaction is a relativistic effect!

Gyrotron Cavity:
Bunching of Gyrating Electron Beam in Rotating Electric Field



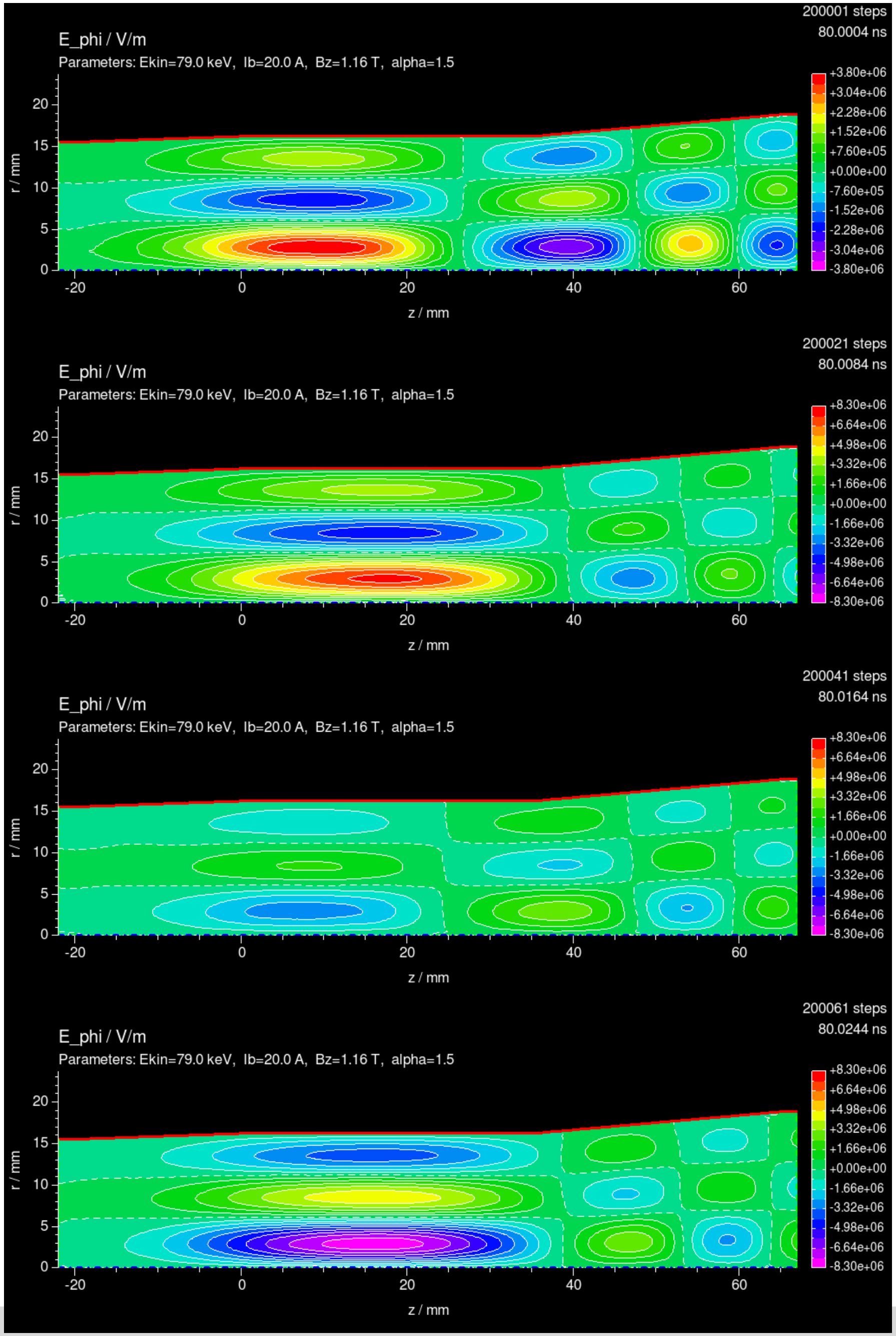
Resonator (Cavity)

- Open waveguide resonator (hollow waveguide or coaxial)
- Downtaper at the electron entrance to minimize RF power traveling towards the gun: The operating mode is reflected.
- Non-linear uptaper at the exit to increase the diameter.



2D PIC Simulation of the gyrotron interaction

($TE_{0,3}$ mode, electron beam placed at the first radial maximum)



Main Conceptual & Technical Challenges (I)

- Higher frequency (> 200 GHz) at high power (1.5 MW and above):
  - Needs very high order modes → problems with mode concurrency, mechanical tolerances & alignment, enhanced demand on electron gun
  - KIT concept: coaxial-cavity gyrotron, longitudinally corrugated insert suppresses critical neighboring modes;

    Example: 2 MW, 170 GHz $TE_{34,19}$ coaxial-cavity gyrotron
- Most critical thermomechanical challenges:
  - Resonator (≈ 2 kW/cm² peak loading, risk of plastic deformation / damage)

    → studies are ongoing to enhance the cooling capabilities
  - Collector (≥ 5 kW/cm² instantaneous peak loading)

    → sweeping of the electron beam is required (but: fatigue problems!)

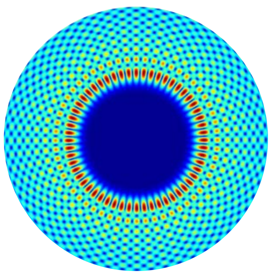
Main Conceptual & Technical Challenges (II)

- Multi-Frequency Operation:
  - Needs compatible operation modes
  - Quasi-optical output system must be capable to convert different modes
  - Diamond output window must match the different frequencies
    (→ Brewster window, demonstrated at KIT)
- Enhancing overall efficiency (to values above 60%)
  - → Use a multi-stage depressed collector (MDC) to recover electron energy

KIT Fusion Gyrotron Family

Past – Present – Future

W7-X, Greifswald



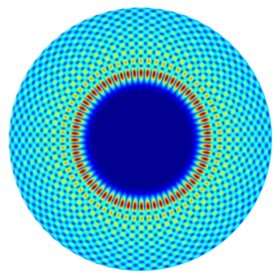
$TE_{28,8}$

Operating frequency	**140 GHz**
RF output power	1 MW (1800 s)
Overall efficiency	<50 %

In Operation

Upgrade to 1.5 MW in Progress

ITER, Cadarache

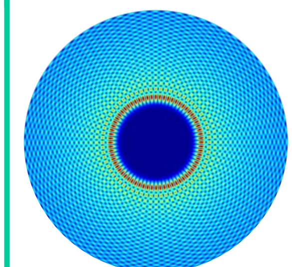


$TE_{32,9}$

170 GHz
1 MW (3600 s)
50 %

Final development phase

DEMO (EUROfusion)



$TE_{34,19}$

170/204/(238) GHz
2 MW (CW)
Target: >60 %

Research phase

KIT Gyrotron Development for W7-X

ECRH System for W7-X

Additional W7-X series tube (SN8)

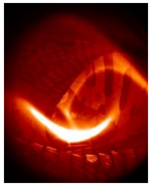
P_{RF} = 960 kW, η = 44 %

Launcher

Quasi-optical transmission

IGVP, Stuttgart

Window

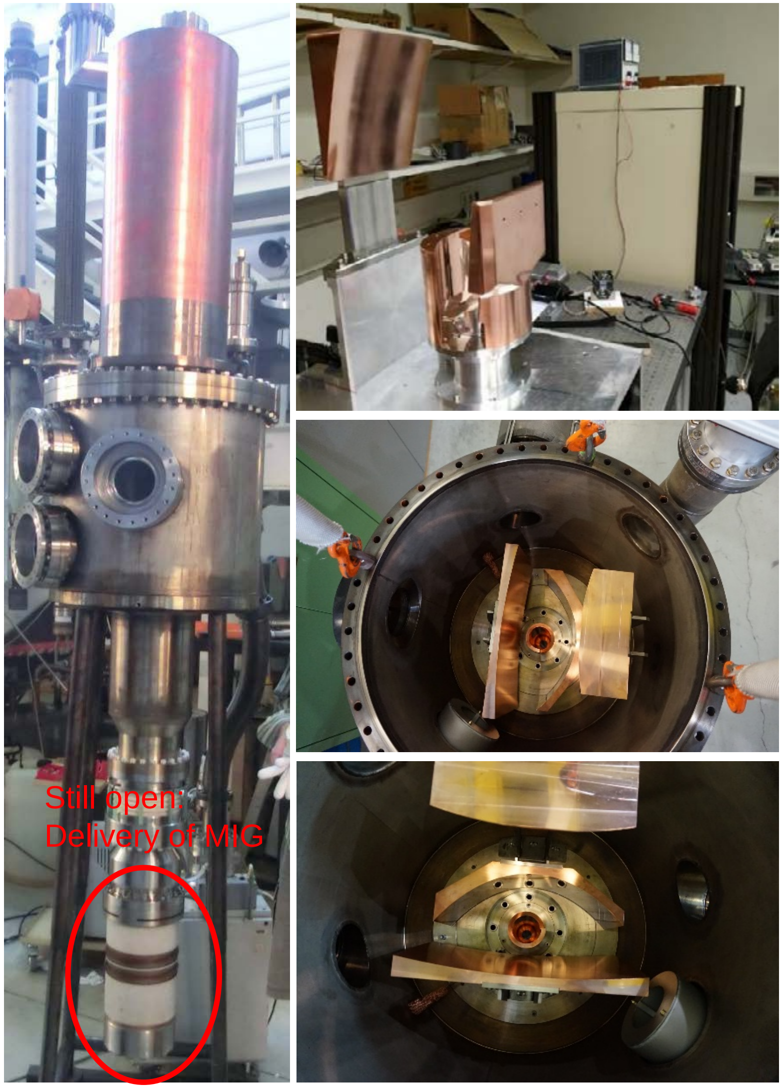


2015: Start of W7-X operation with a fully operational ECRH system

2016: IPP installed an additional tube (SN8) based on the successful operation

2018: Total delivered power up to 7.7 MW, up to 100 s @ 2 MW

Project “W7-X HIPOWER”



Goal: Increase of the ECRH Power to **15 – 18 MW** by procuring of new gyrotrons with up to **1.5 MW** output power.

- ***„Be in time, keep costs and risks low!“***
  Higher output power by using smart „upgrades“, keeping the overall construction and interfaces
- Construction and test of a modular short pulse prototype gyrotron as a basis for the series tube

Status:

Design is finalized, the operation mode is $TE_{28,10}$

The short pulse prototype tube waits for delivery of the MIG by Thales, „old“ SC Magnet is already installed in the test stand
(Risk „Corona-lockdown“)

Delivery of the first cryogen-free 5.7 T magnet is foreseen for 2021

The industrial tube is ordered by Thales, final production will start after test with the short pulse tube

Operation of a W7-X Gyrotron at 175 GHz

- Purpose: provide a microwave source for Collective Thomson Scattering (CTS) experiments.
- Further details: presentation of Laurent Krier (next session)

KIT Gyrotron Development for ITER

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EU ITER 170 GHz 1 MW Gyrotron

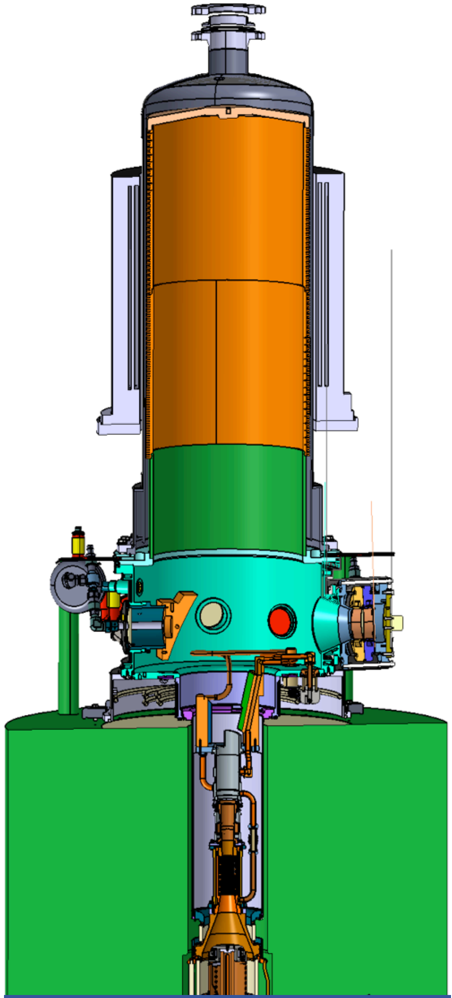
KIT SP prototype

The EU 2-step approach:

Short-pulse (ms) prototype

to validate the physical design

> 1.4 MW (ms)



3D schematics

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EU ITER 170 GHz 1 MW Gyrotron

KIT SP prototype

The EU 2-step approach:

Short-pulse (ms) prototype

to validate the physical design

> 1.4 MW (ms)

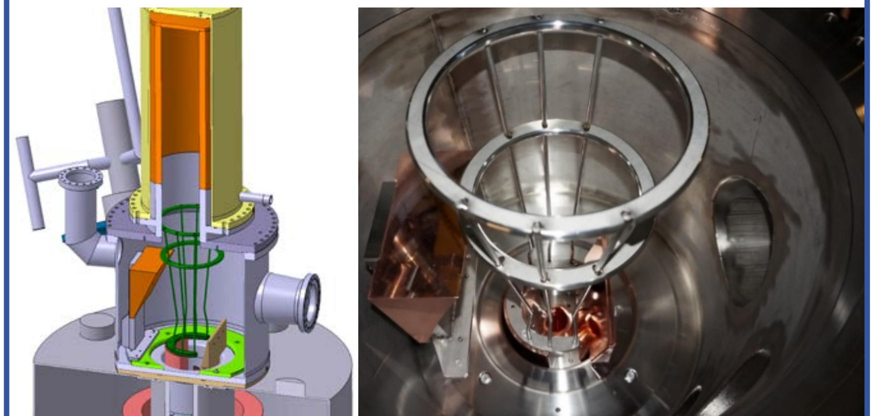
to verify the ITER requirements

- **KIT (< 180 s)**
- EPFL-SPC (3600 s)

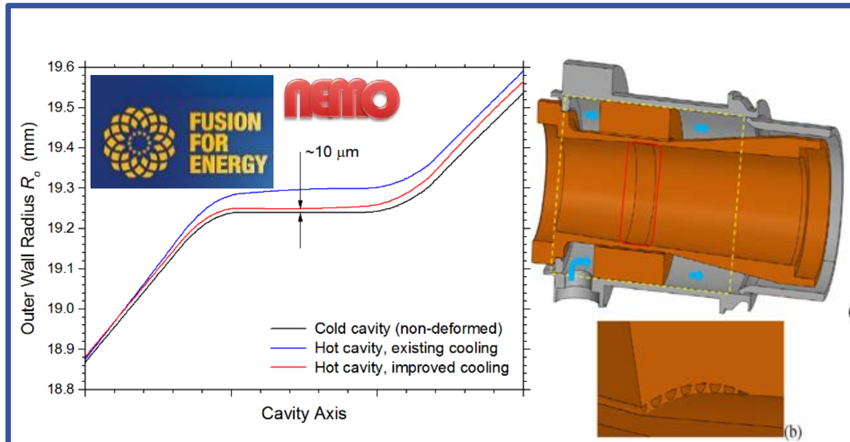
Further Details: Presentation by Alberto Leggieri (invited talk in next session)

Industrial prototype

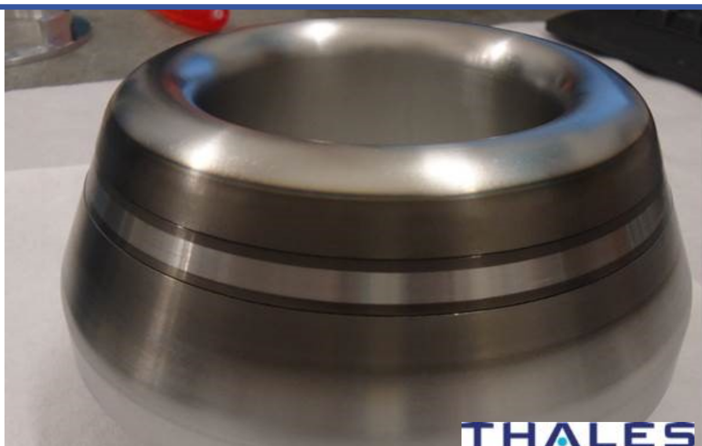
Breakthroughs for Future ITER Gyrotrons



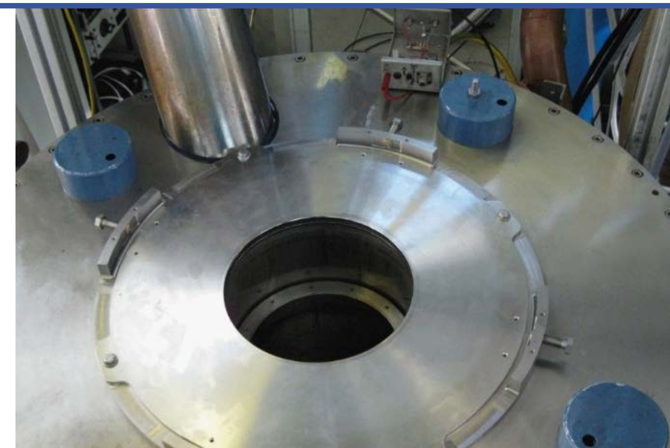
New methods for energy recovery



New and advanced cooling techniques



Advanced emitter technologies



Innovation in alignment procedures

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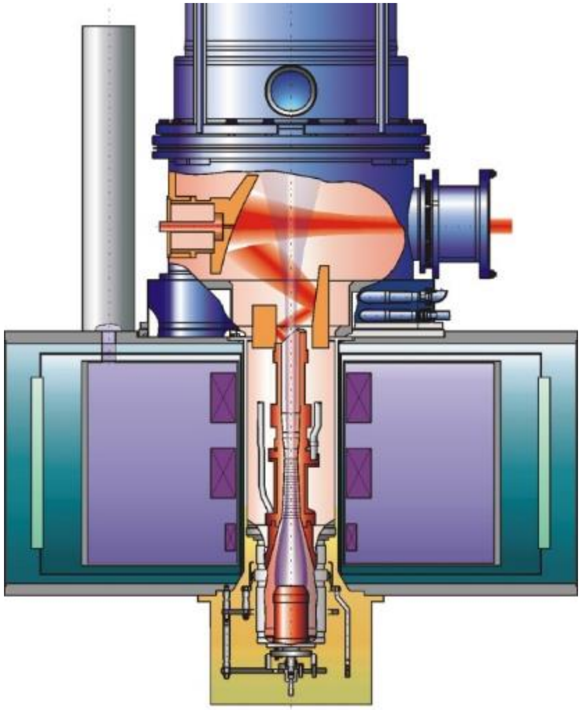
KIT Gyrotron Development for DEMO

Conventional vs. Coaxial Gyrotron Technology

Conventional

+ Simpler design
+ Verified technology

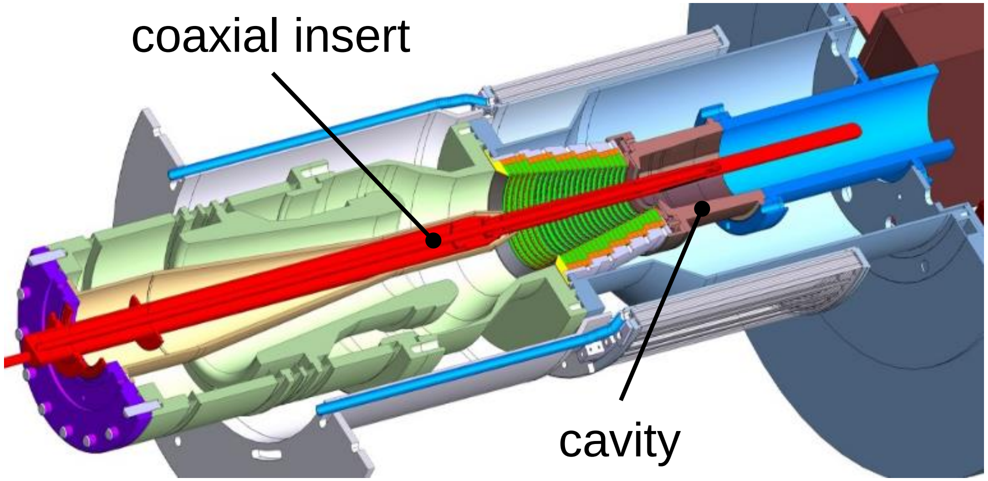


Coaxial

+ Reduced mode competition
  → operation at very high-order mode
+ Reduced voltage depression

higher output power

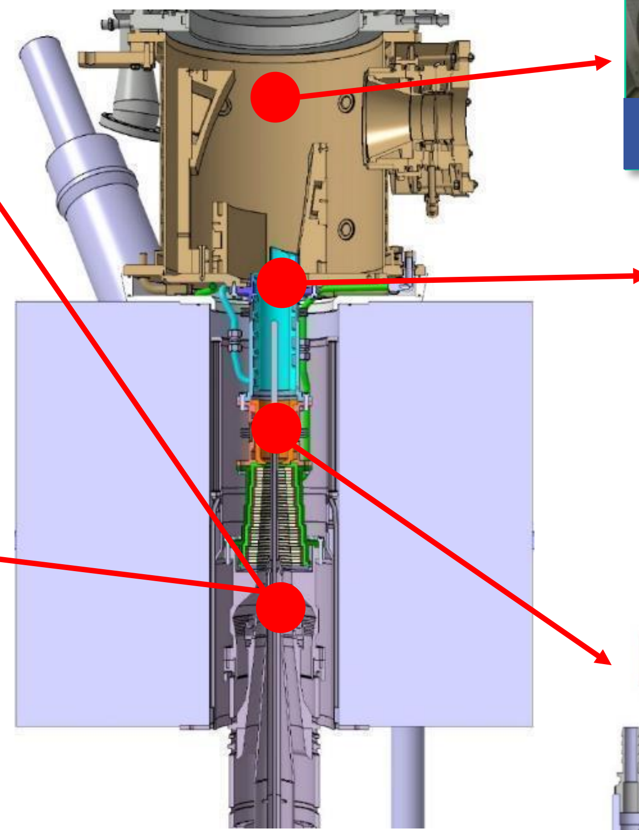
– coaxial insert:
  additional risk of misalignment and thermal loading



KIT 2 MW Coaxial-Cavity Long Pulse Development

KIT 2 MW LP pre-prototype

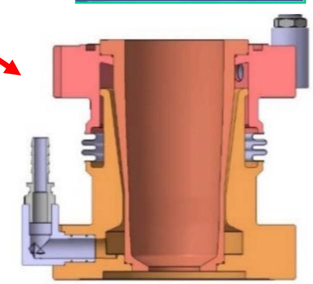
KIT Inverse MIG implementing new cathode configuration



Coaxial-cavity MIG using new emitter technology

Mirror Box

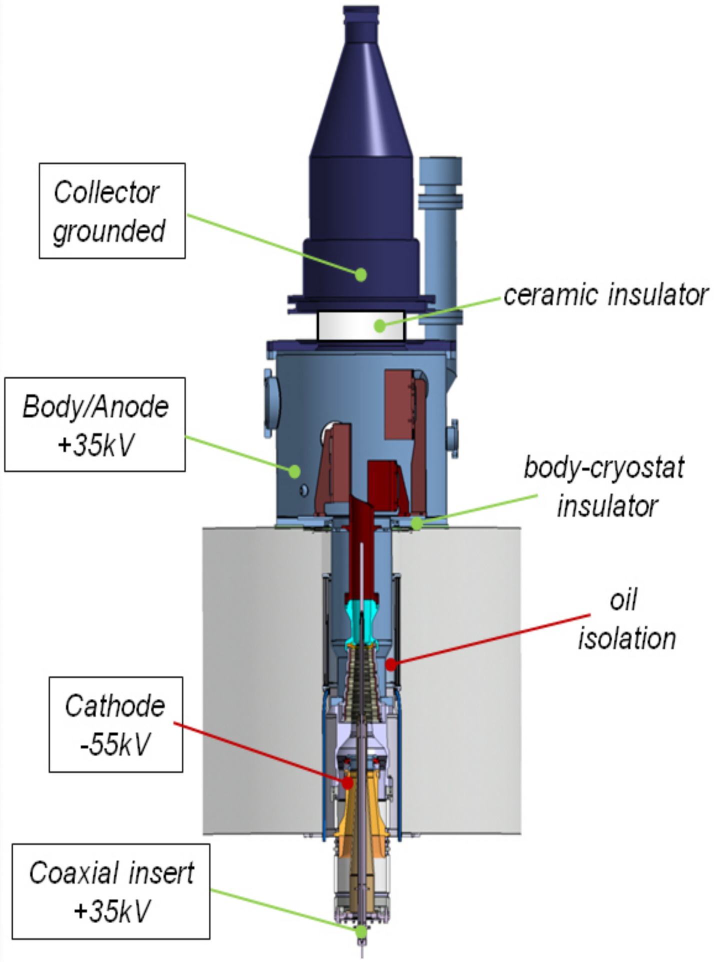
Launcher



Cavity using advanced cooling structure

2 MW, 170 GHz Coaxial-Cavity Gyrotron

Specifications	
Parameter	**Value**
Operating mode	$TE_{34,19}$
Output Power	2 MW
Operating Frequency	170 GHz
Nominal Beam Current	75 A
Accelerating Voltage	90 kV
Cavity Magnetic Field	6.87 T
Total Efficiency (SDC)	> 50 %
Gaussian Beam Content	> 95 %



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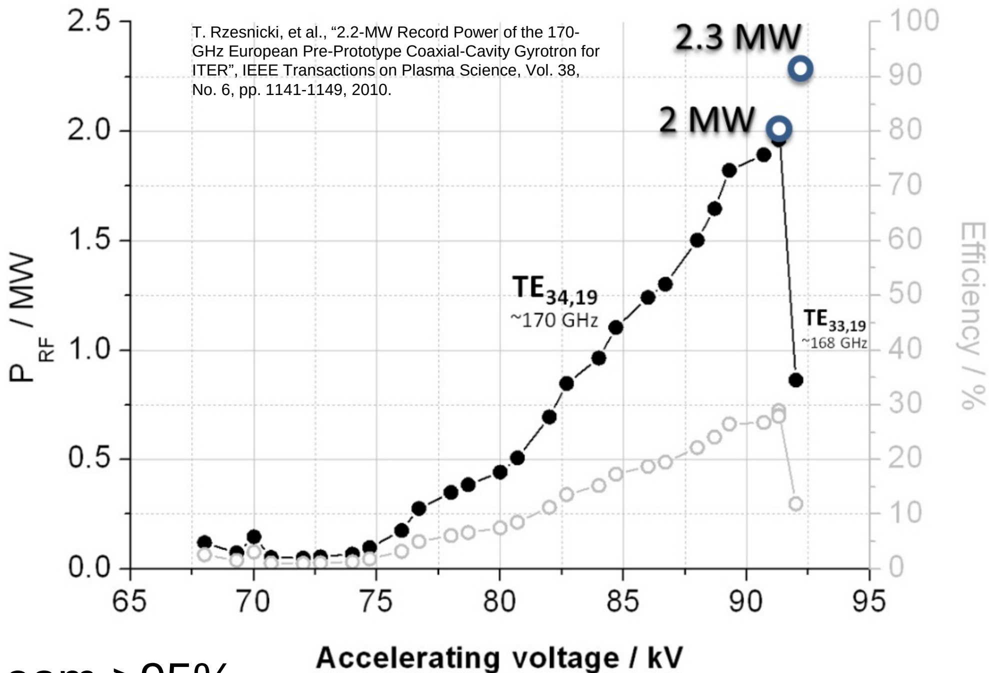
Results of the SP 2 MW Pre-Prototype Tube

- 2.0 MW, 91 kV, 77 A, efficiency ~28.5% (non-depressed) ~1.5ms *(pulse length limited by non-cooled components)*
- 2.3 MW, 92 kV, 84.7 A, efficiency 29.5% (non-depressed), pulse length ~0.6ms
- No parasitic oscillations have been observed
- Measured stray radiation level ~4%



- Gaussian mode content of the RF beam >95%
- Results with depressed collector close to the nominal operating parameters: ~1.9 MW, 51kV + 39kV (depression), 76A, efficiency ~47%, ~3ms
- Latest results: longer pulses with new triode gun: **~ 1.7 MW / ~ 47 % at 20 ms**
  ~ 1.3 MW / ~ 45 % at 50 ms

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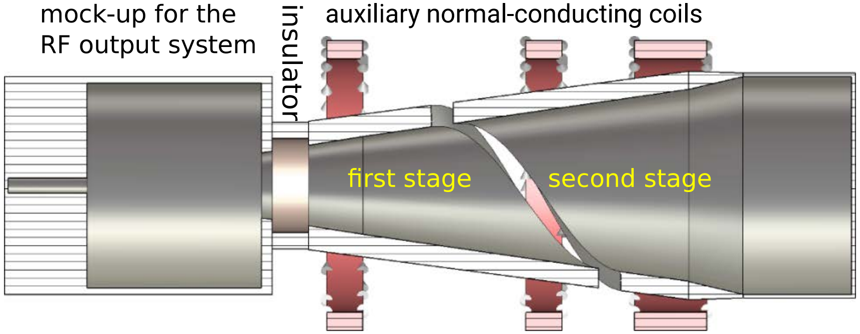
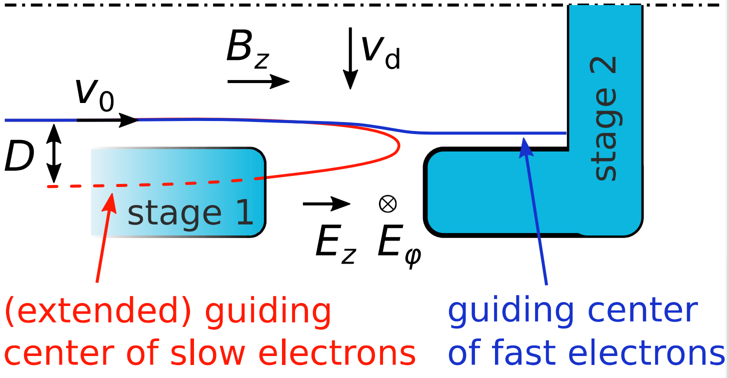
MDC: Increasing Efficiency

- Motivation: A Multi-staged Depressed Collector (MDC) can increase the overall gyrotron efficiency above 60 %.
- Proposed design: MDC based on *E*×*B* drift, using azimuthal *E*-field by helical electrodes



- Simulation results
  - Two stages:
    η_{col} = 78 % $\Rightarrow$ $\boldsymbol{\eta_{gyrotron}}$ **~ 63 %**
    Extendable to more stages
  - Very good handling of secondary electrons.
  - Excellent stability against radial stray magnetic fields and electron beam misalignment.



➡ Preparation of proof-of-Principle experiment under progress

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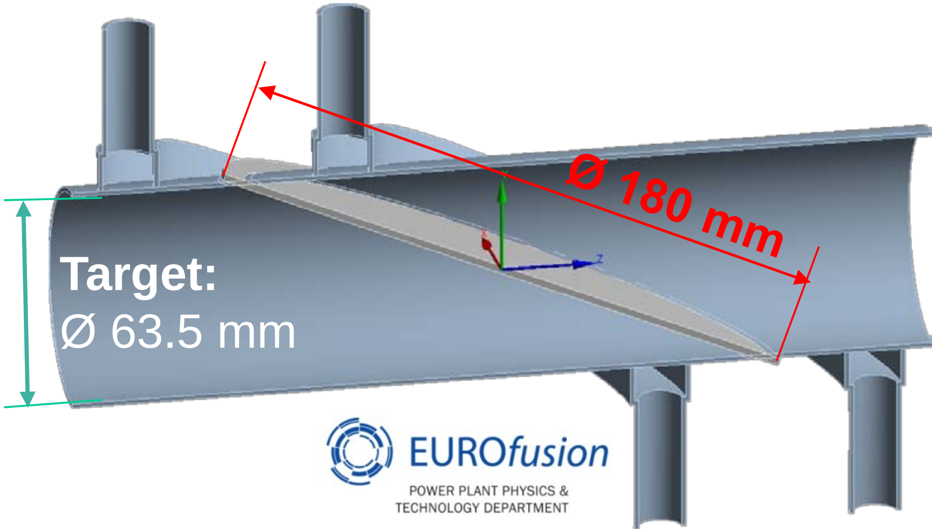
Development of a 170 / 204 GHz Coaxial Cavity Gyrotron

- Motivation: multi-frequency gyrotrons offer enhanced flexibility in terms of plasma control & current drive
- More details: see presentation by Tobias Ruess (same session)

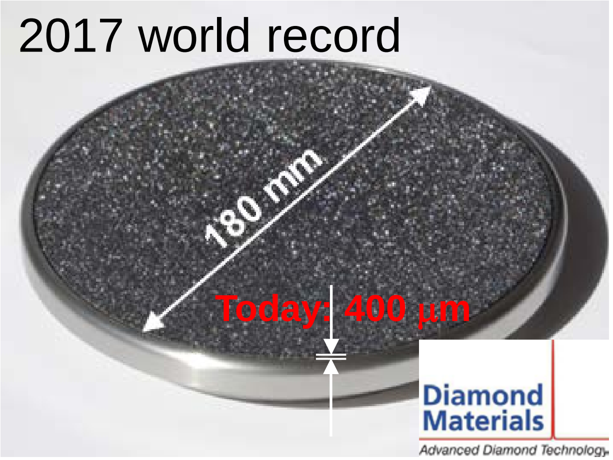
Towards Future High-Power RF Broadband Windows with Lowest Losses (In collaboration with KIT-IAM)

Karlsruhe Institute of Technology

- **Polycrystalline CVD-Diamond Disk Brewster-Angle Windows**
  → Key: Manufacturability of very large-size **(Ø 180 mm, 2 mm)** disks



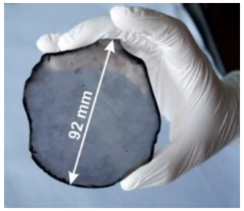
EUROfusion
POWER PLANT PHYSICS & TECHNOLOGY DEPARTMENT



Diamond Materials
Advanced Diamond Technology

- **Ultra low-loss single-crystal CVD-diamond disks for very high power (>2 MW) and lowest losses**
  (in collaboration with University of Augsburg).

AuDiaTec
AUGSBURG DIAMOND TECHNOLOGY GMBH



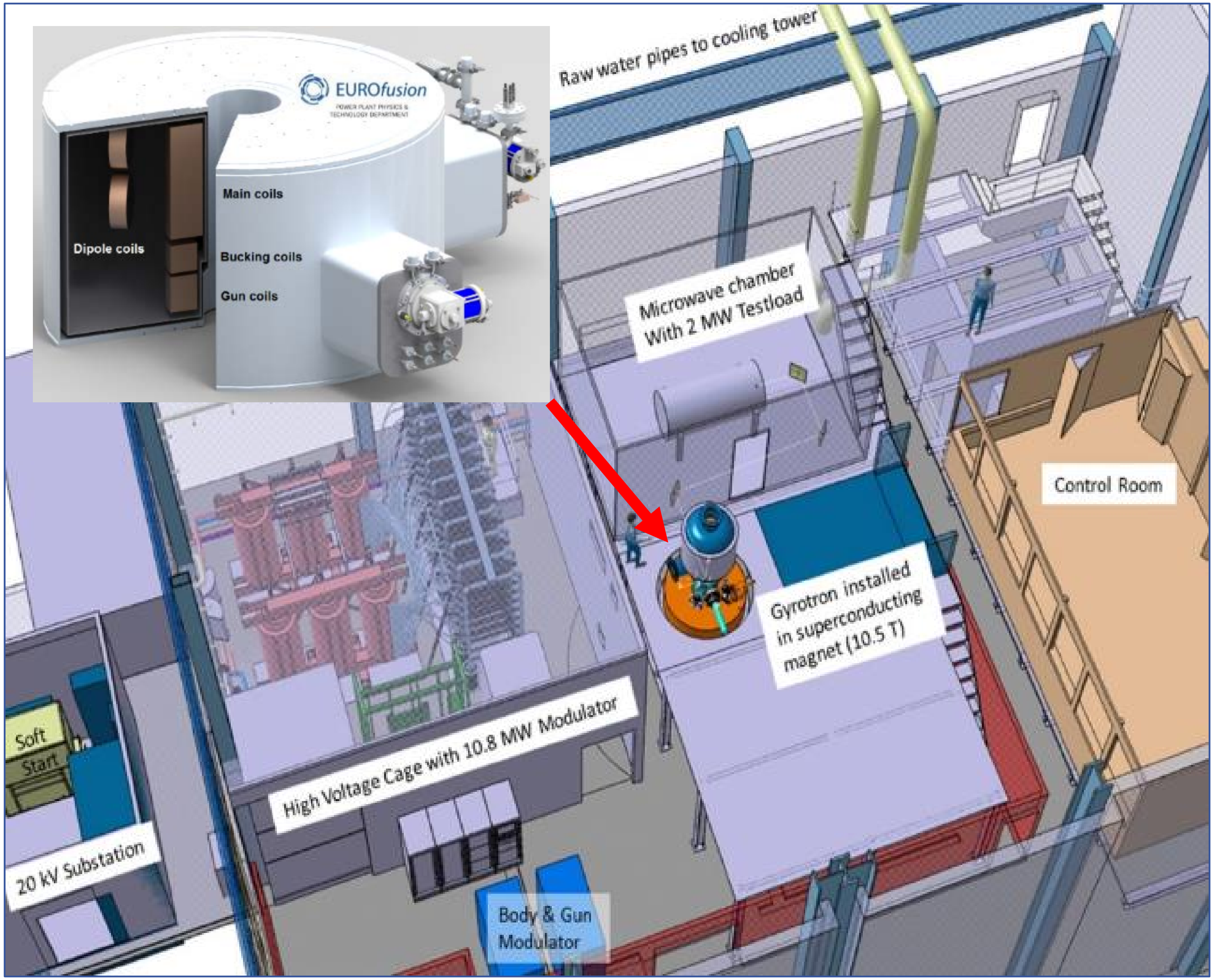
New Gyrotron Test Stand FULGOR
(Fusion Long-Pulse Gyrotron Laboratory)

Capabilities:

- 10 MW DC in
- 1x2 MW RF out
  2x2 MW (2nd step)
- up to 240 GHz
- MDC operation

Key components:

- 10 MW HV DC PS
  → READY
  (Body P.S. will be ordered May, 2020)
- 10.5 T SC magnet
  → @ 3Q'2020



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Conclusion & Outlook

- Gyrotron oscillators can generate mm-wave power in the MW region with high efficiency
- With these mm-wave sources available, ECRH is considered today a primary choice for fusion reactors
- The KIT capabilities (design, construction, manufacturing and testing) provide a solid basis for future high power gyrotron development

Main Future Challenges

- Reliability and versatility of the sources must be increased
- Even higher power per unit (at even higher frequency) is desirable and requires developments like the coaxial cavity gyrotron

Thank you for your attention!

Acknowledgement

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Backup Slides

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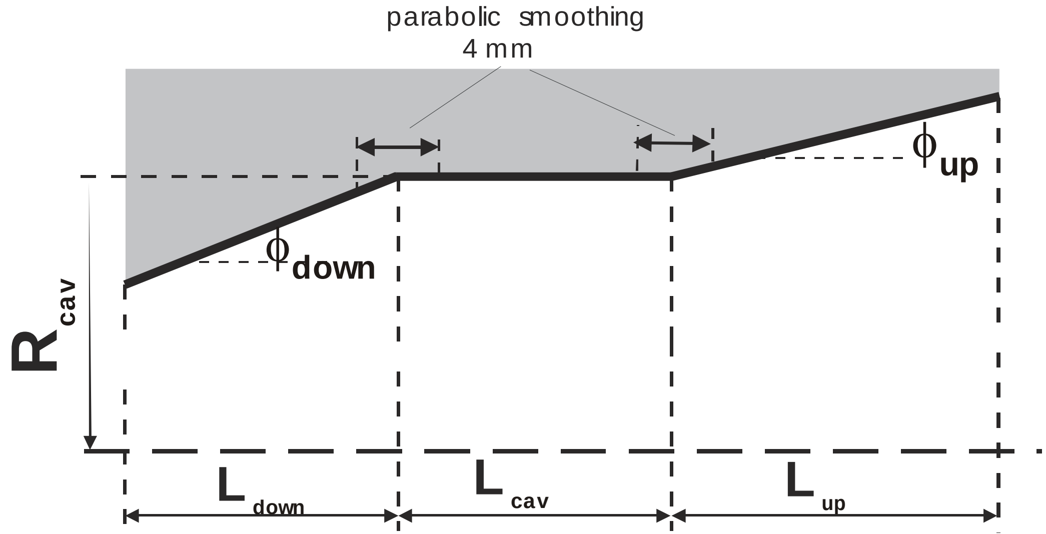
Gyrotron Cavity Example



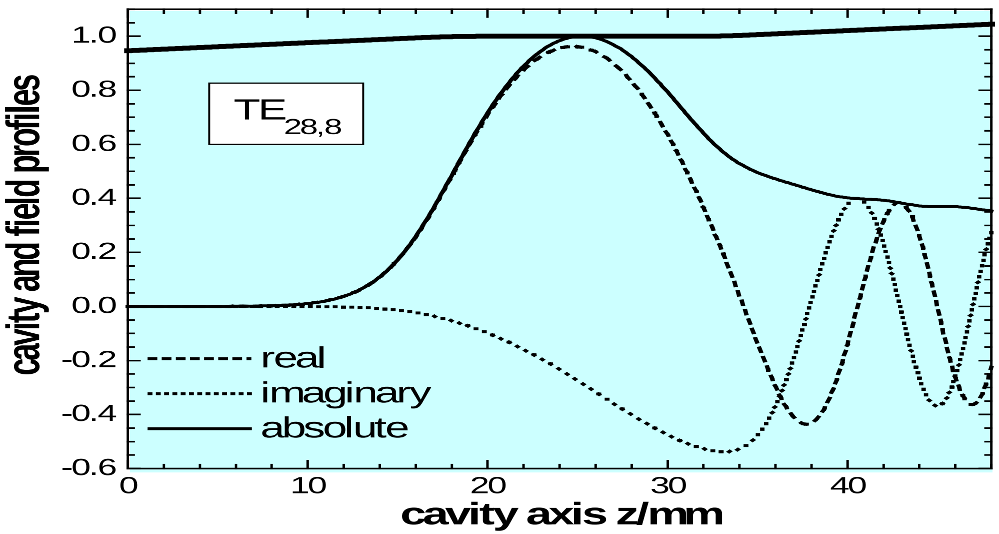
example for 1 MW, 140 GHz (λ_0= 2.14 mm) gyrotron:

L_{cav} = 14.5 mm

R_{cav} = 20.48 mm

R_{beam} = 10.1 mm

quality factor = 855 (cold)



Field distribution in the cavity region