

ECRH / Gyrotrons für die (Magnet-) Fusion



Deutsche Physikalische Gesellschaft e.V.

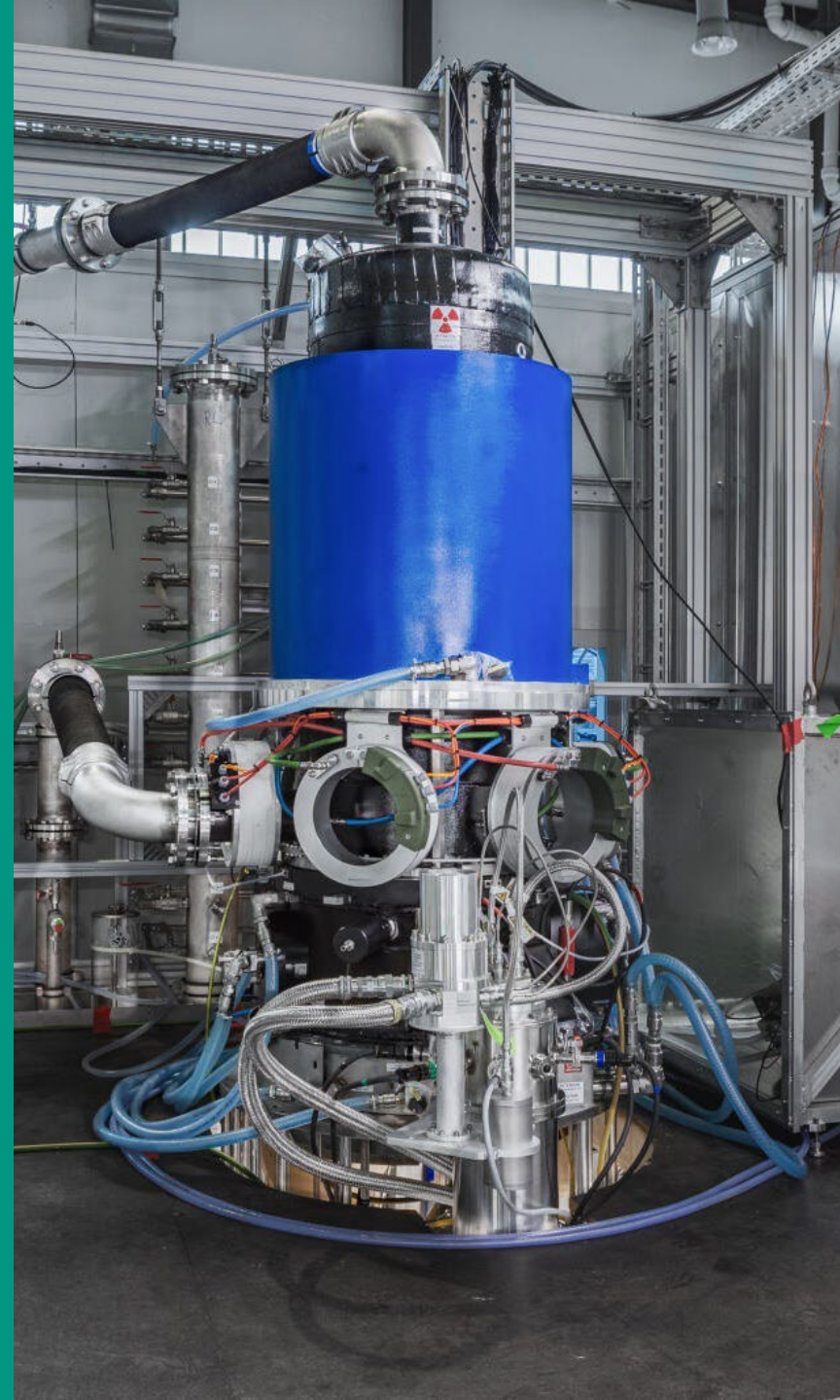
Arbeitskreis Energie (AKE)

Herbstsitzung 1./2. Oktober 2026

Physikzentrum Bad Honnef

John Jelonnek* on behalf of the gyrotron team

*john.jelonnek@kit.edu



Part of this work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

With funding from the:

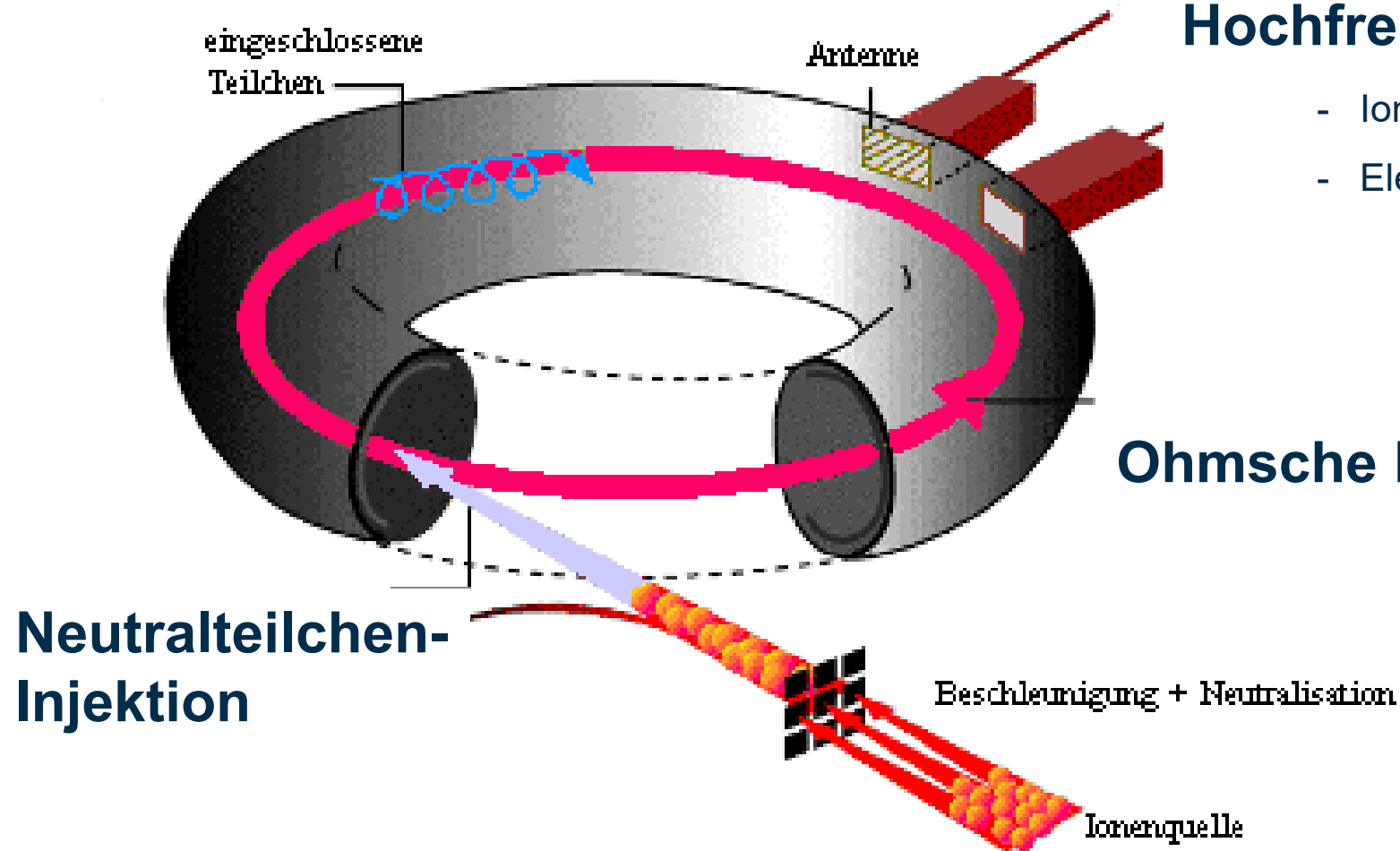


Federal Ministry
of Research, Technology
and Space



Grundlagen

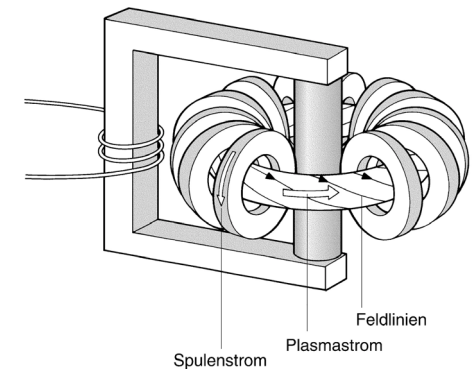
Plasmaheizverfahren für die Kernfusion



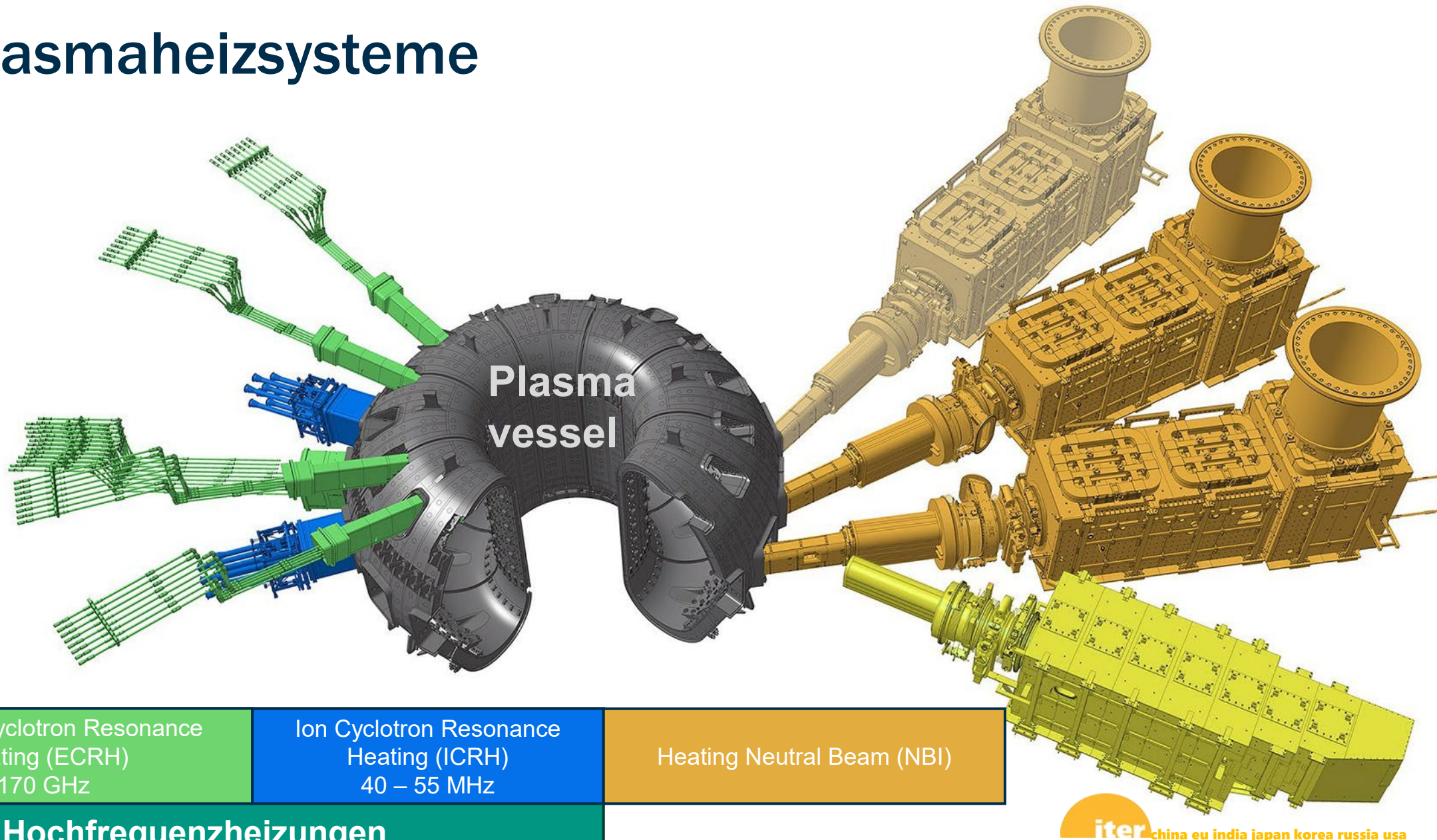
Hochfrequenzheizung

- Ionen-Zyklotronresonanz
- Elektronen-Zyklotronresonanz

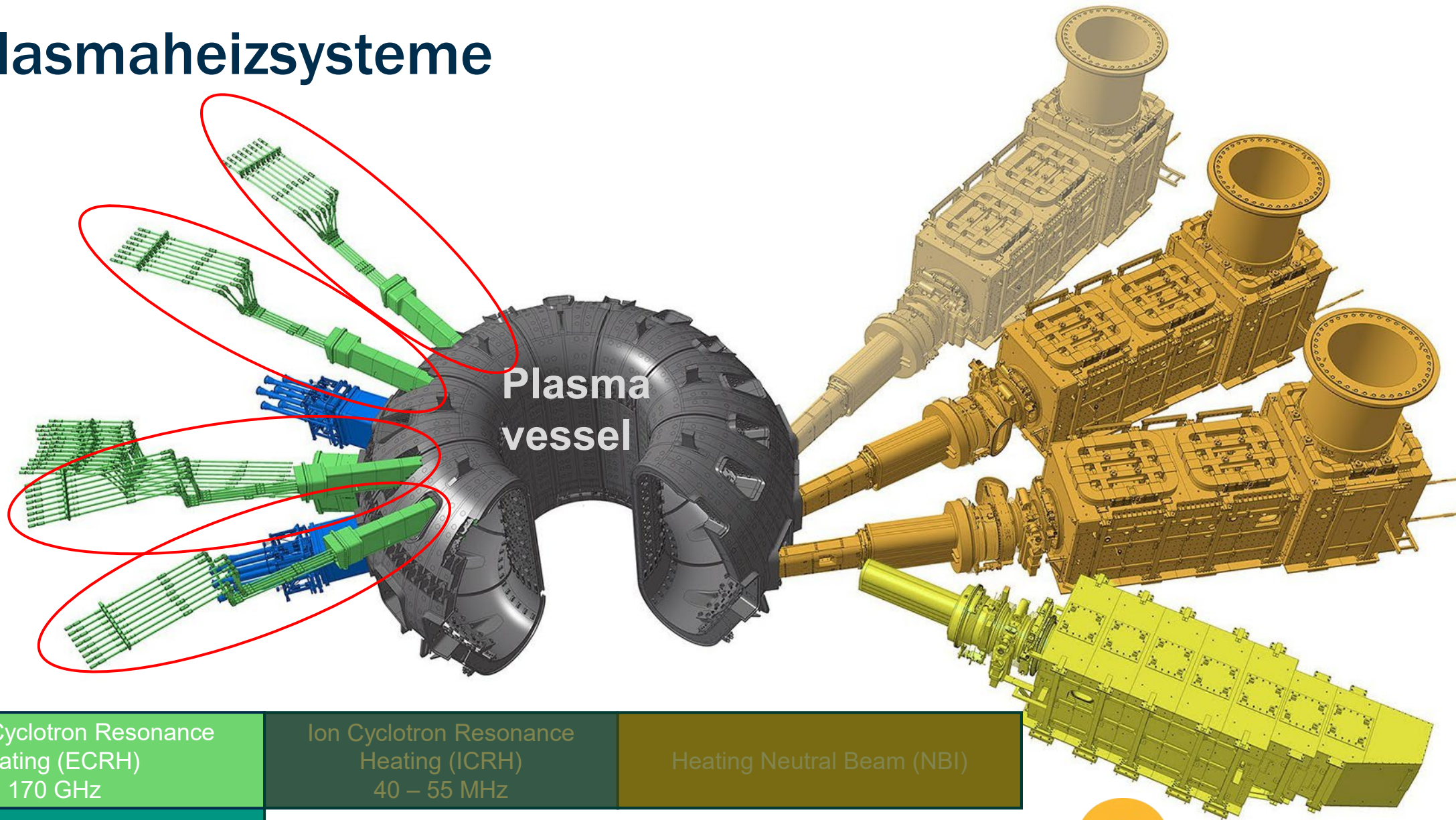
Ohmsche Heizung



ITER Plasmaheizsysteme



ITER Plasmaheizsysteme



Electron Cyclotron Resonance
Heating (ECRH)
170 GHz

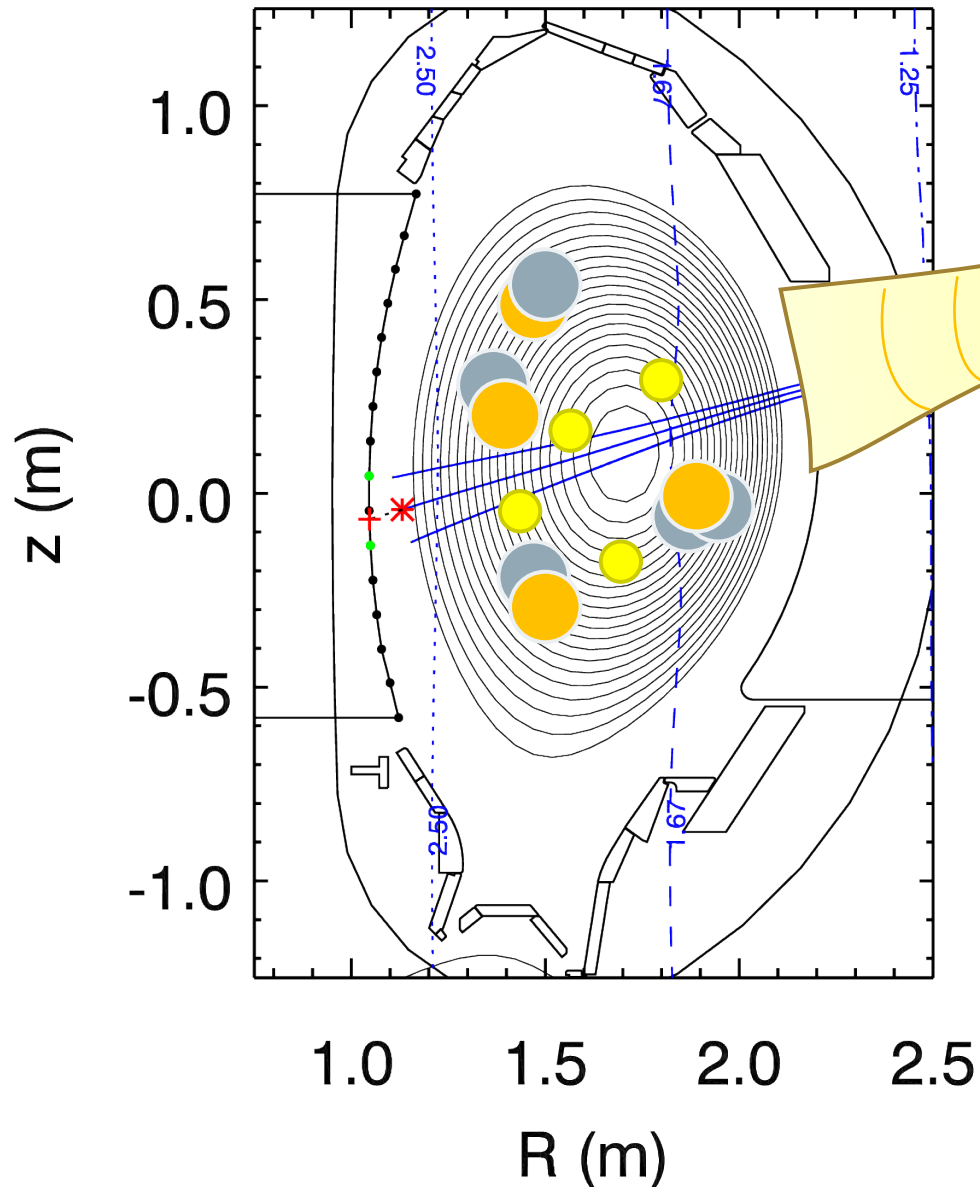
Mikrowellenplasmaheizung

Ion Cyclotron Resonance
Heating (ICRH)
40 – 55 MHz

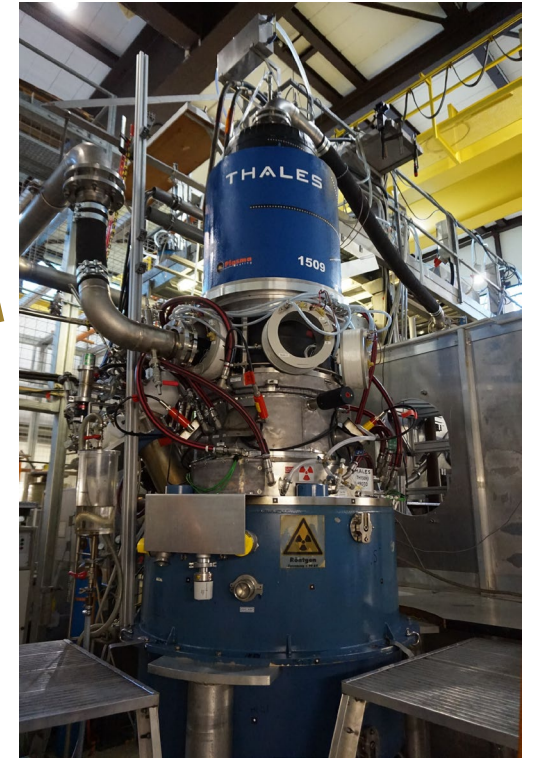
Heating Neutral Beam (NBI)



Mikrowellenplasmaheizung (ECRH)



ECH is used for:
(Auxiliary) Heating
(Auxiliary) Current drive
Control and stabilization
Diagnostics

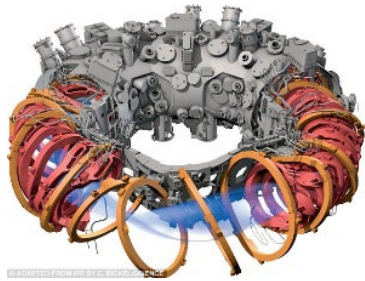


Mikrowellenerzeuger

Beispiel: ASDEX, IPP Garching

Considered Advances in EC Plasma Heating (< 2024)

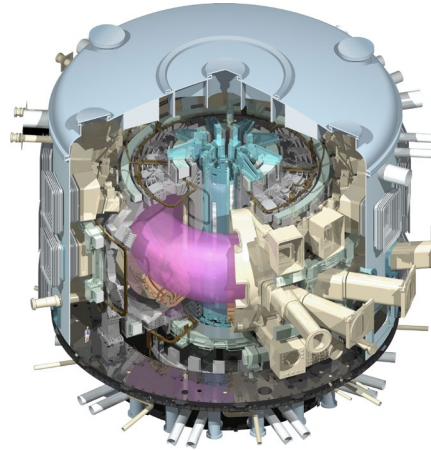
W7-X



$f_{EC} = 140 \text{ GHz}$
 $P_{EC \text{ Sources}} = 10 \text{ MW}$

IPP

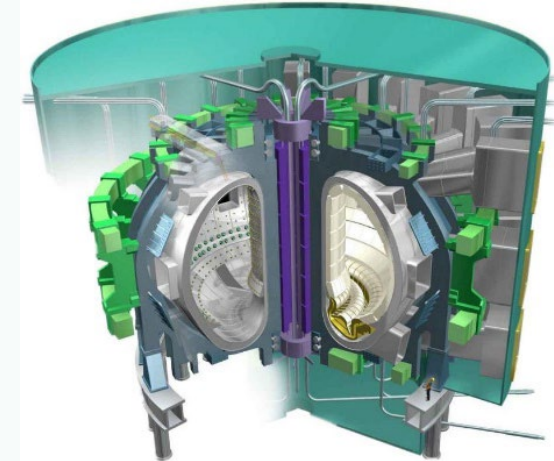
ITER/DTT



170 GHz
24 MW



EU DEMO

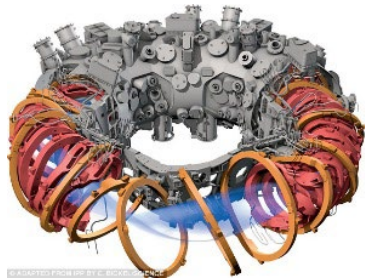


136 / 170 / 204 / 240 GHz
> 70 MW

- + multi-purpose operation
- + frequency steering into the plasma
- + operation at long pulses
- + sufficiently high plug-in efficiency

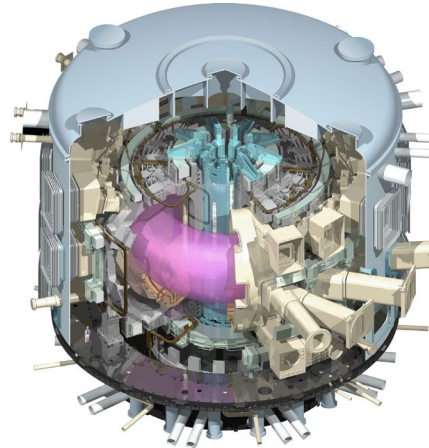
Split of Technology and Exciting Opportunities (>2024)

W7-X



IPP

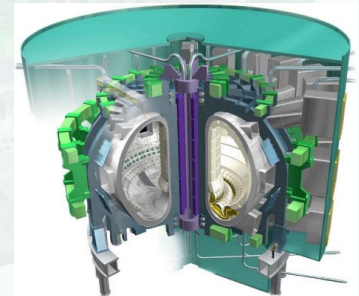
ITER/DTT



EU



Low-Field Devices with large footprint



≤ 200 GHz

136 / 170 / 204 GHz

> 70 MW



UKAEA STEP



≥ 240 GHz, ≥ 1 MW

High-Field Compact Devices

$f_{EC} = 140$ GHz

$P_{EC\ Sources} = 10$ MW

Before 2030

15-18 MW

≥ 1.5 MW power per gyrotron
(up to 2 MW per unit)

170 GHz

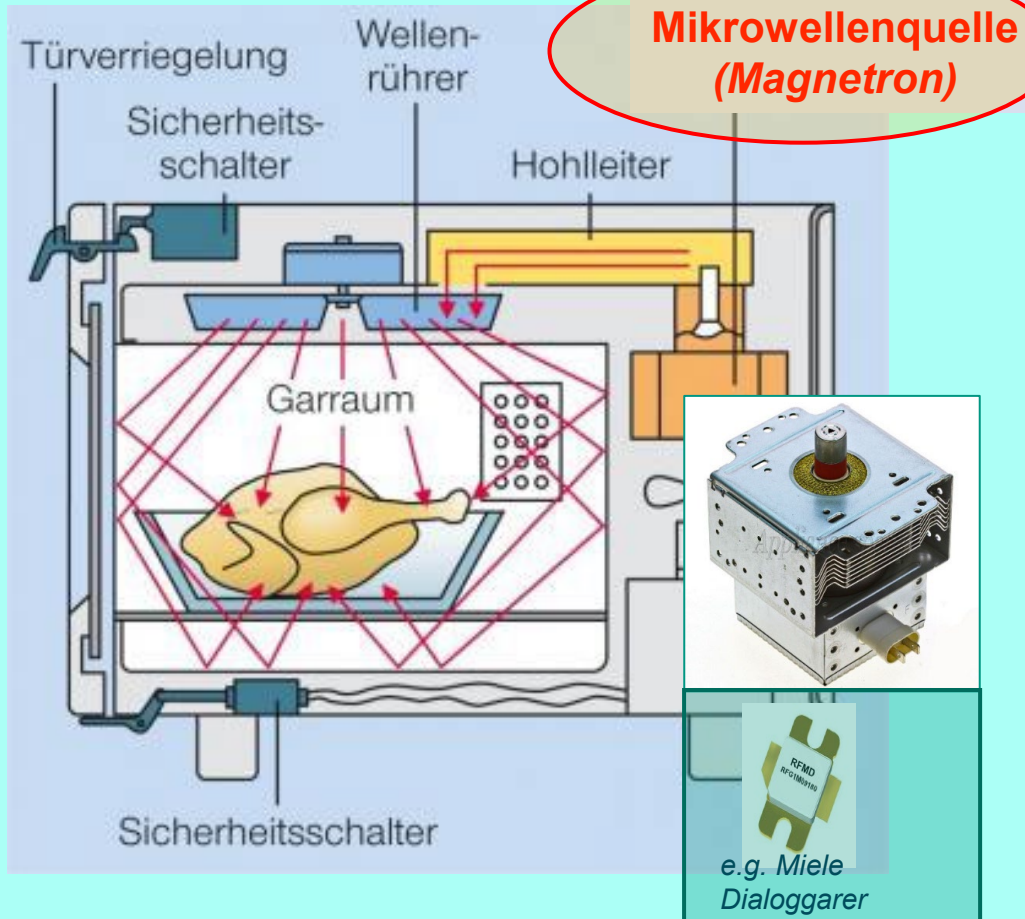
24 MW

80 MW

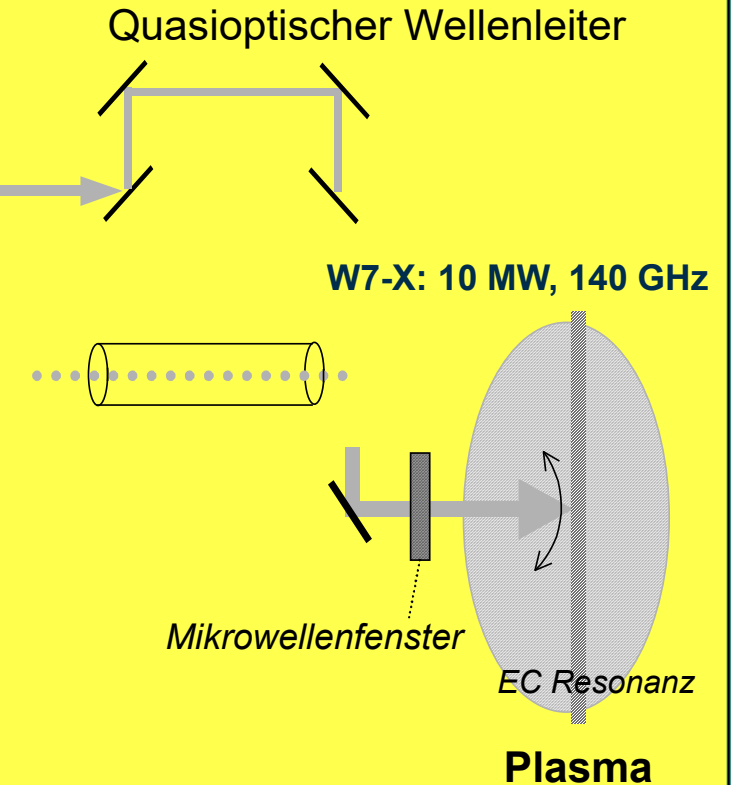
Large gyrotron arrays

Haushaltsmikrowelle versus ECRH: Schlüsselkomponenten im Vergleich

Haushaltsmikrowelle: 1 kW, 2.45 GHz



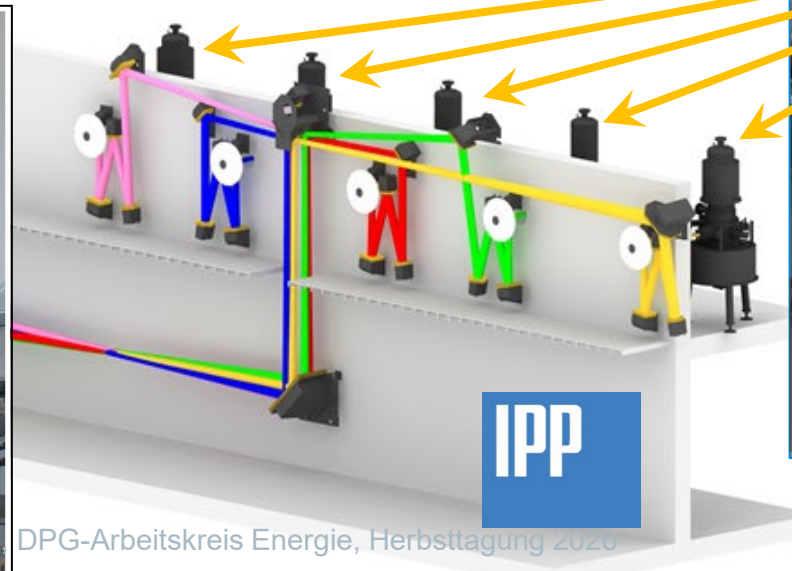
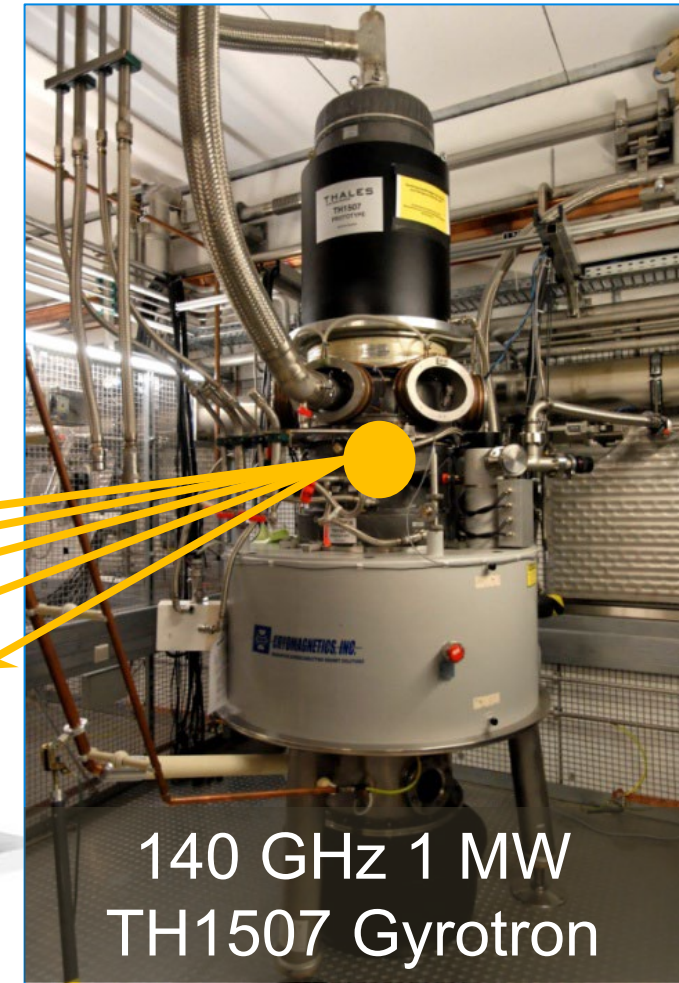
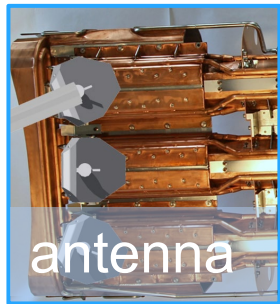
EC Heizsystem bei der Kernfusion



ECRH Heizsystem an Wendelstein 7-X (W7-X)

1998: KIT/IPP Projekt Mikrowellenheizung für W7-X (PMW)

H. P. Laqua et al., "The ECRH-Power Upgrade at the Wendelstein 7-X Stellarator", EPJ Web of Conferences, 2023), <https://doi.org/10.1051/epjconf/202327704003>



Alternative ECRH Installation (ITER)

EC Launcher (In-vessel)

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

Port Cell Transmission Line (TL) (Ex-vessel)

Port cell TL = Ex-vessel FCS: SIC-1 up to diamond window

FCS barrier
(Structural system)

Steering options:

- Mechanical steering
- Electronic frequency steering

Plasma

Diamond
Windows



EUROfusion DEMO Launcher Design 2024



Gyrotron

Die Wahl einer geeigneten Mikrowellenquelle

Moving towards Multi-Megawatt Class Sources

**Solid
State**

Vacuum tubes

$P \cdot f^2 \sim \text{const.}$



**< 500 W
@ 2.45 GHz**

Moving towards Multi-Megawatt Class Sources

Solid State

Vacuum tubes

$P \cdot f^2 \sim \text{const.}$

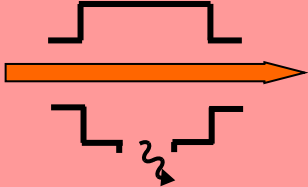


< 500 W, 2.45 GHz



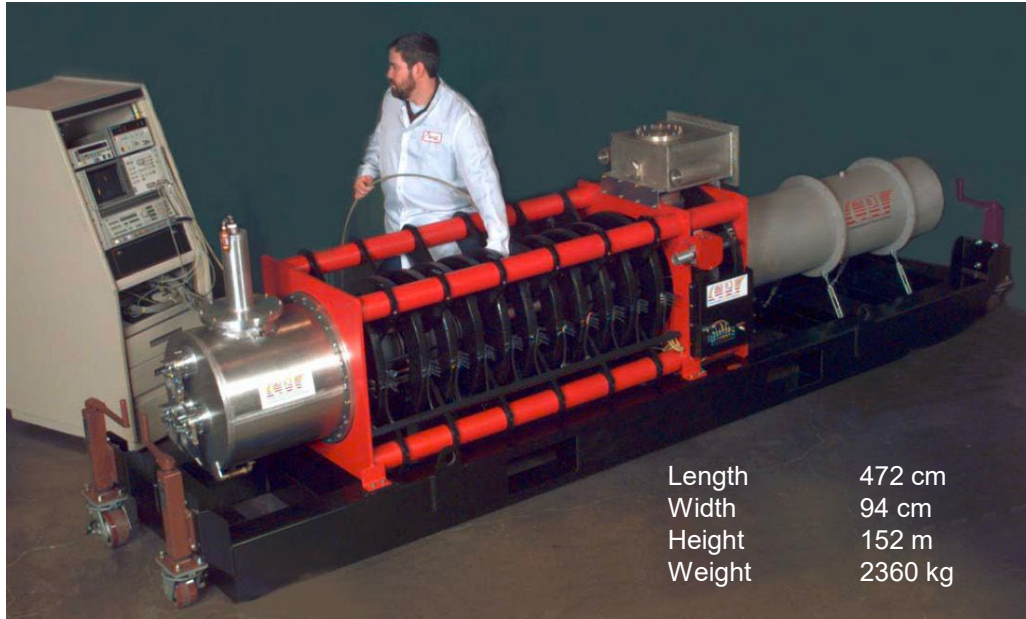
**Magnetron
1 - 20 kW pulsed,
2.45 GHz**

Interaction Mechanisms in Linear Beam Tubes

Electron Motion	Wave-Electron Synchronism	Interaction Scheme	Structure Size	RF Oscillators and Amplifier
$\dot{\vec{v}}_{\perp} = 0$	cherenkov $v_{el} \geq v_{\parallel} = \omega/k_{\parallel}$		$\leq \lambda$	TWT, BWO Magnetron
	transition radiation			Monotron Klystron

Comparison of Physical Sizes of MW-Class Energy Converters

1 MW, 700 MHz Klystron (CPI VKP-7952)

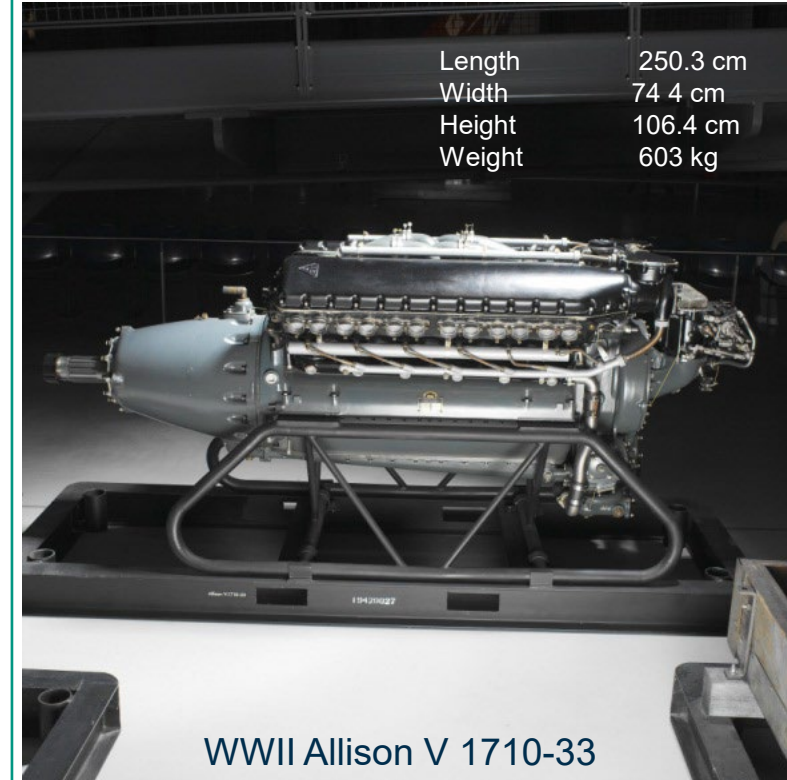


Length 472 cm
Width 94 cm
Height 152 cm
Weight 2360 kg

1000 kW (1 MW) ~ 1380 hp

- Acceleration Voltage 95 kV (max.)
- Beam Current 21 A (max.)
- Efficiency 65 %
- Dissipation loss of collector ~540 kW CW

0.78 MW WWII Aircraft Engine



Length 250.3 cm
Width 74.4 cm
Height 106.4 cm
Weight 603 kg

WWII Allison V 1710-33

776 kW (0,776 MW) ~ 1040 hp

- Fuel consumption: ~130 gallons (492 l)/h

1 PS ~ 0,986 hp ~ 0,735 kW

Moving towards Multi-Megawatt Class Sources

***Solid
State***

Vacuum tubes

Conventional vacuum tubes

Power · (Frequency)² ~ const.



Magnetron
1 - 20 kW pulsed,
2.45 GHz

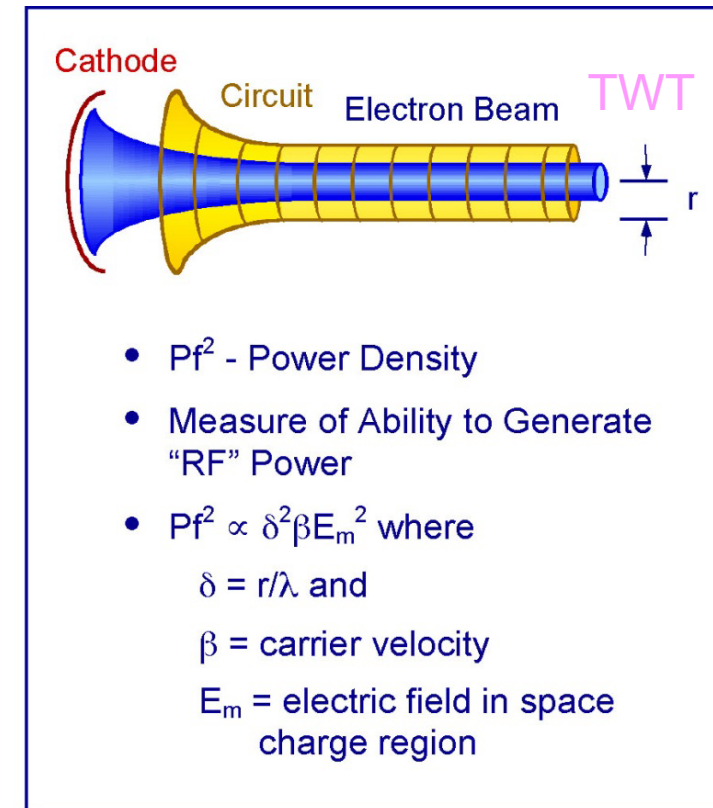
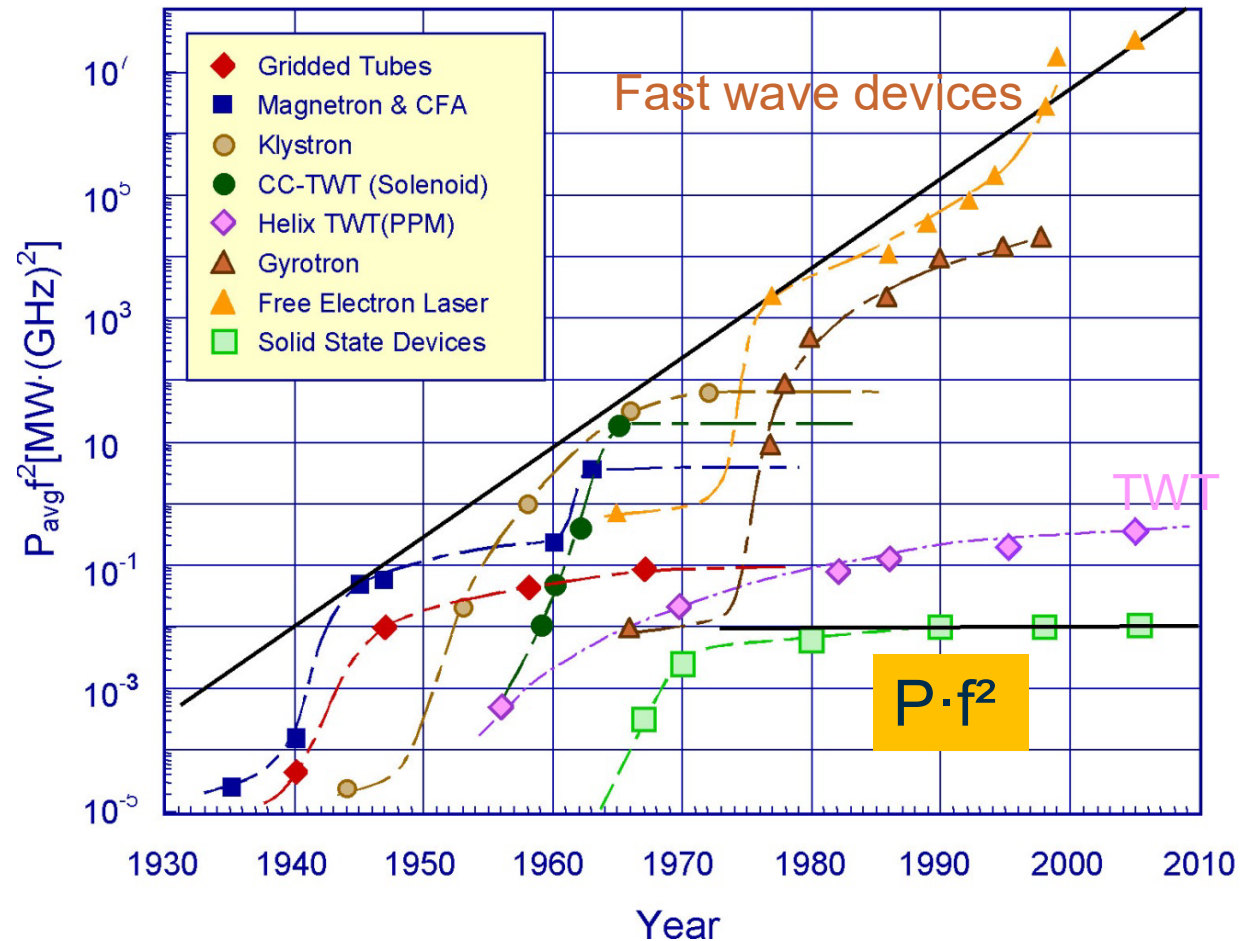


Klystron

MW-level pulsed, 0.3 - 3 GHz

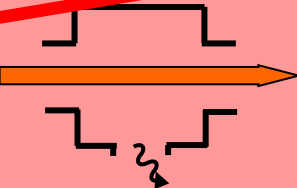
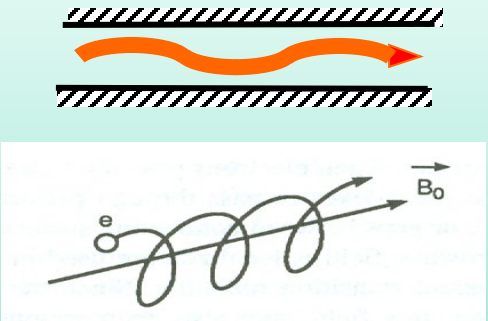
Conventional vacuum tubes depend on resonant structures ($\sim \lambda/2$) and on the interaction close to metal structures $\ll \lambda$

Power-Frequency Law for Classical Vacuum Tubes: Power · Frequency² ≈ Const.

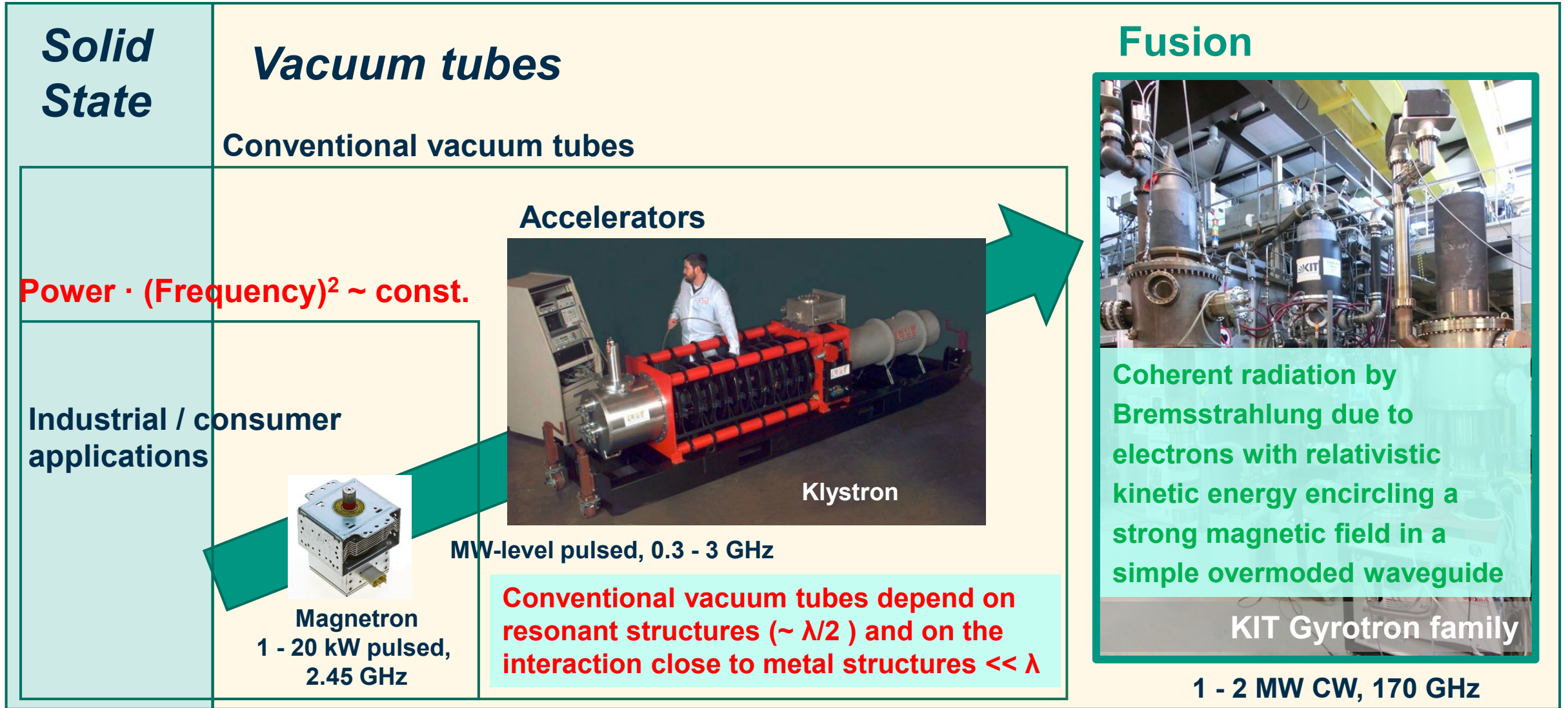


Source: B. Levush, et al, „Vacuum Electronics: Status and Trends“, Aerospace and Electronic Systems Magazine IEEE (2007)

Including Bremsstrahlung as Possible Interaction Mechanism

Electron Motion	Wave-Electron Synchronism	Interaction Scheme	Structure Size	RF Oscillators and Amplifier
$\dot{v}_{\perp} = 0$	cherenkov $v_{el} \geq v_{\parallel} = \omega/k_{\parallel}$		$\leq \lambda$	TWT, BWO Magnetron
	transition radiation			Monotron Klystron
$\dot{v}_{\perp} \neq 0$	Bremsstrahlung $\omega = k_{\parallel} v_{\parallel} + \Omega_c$		$\gg \lambda$	Gyrottron FEL

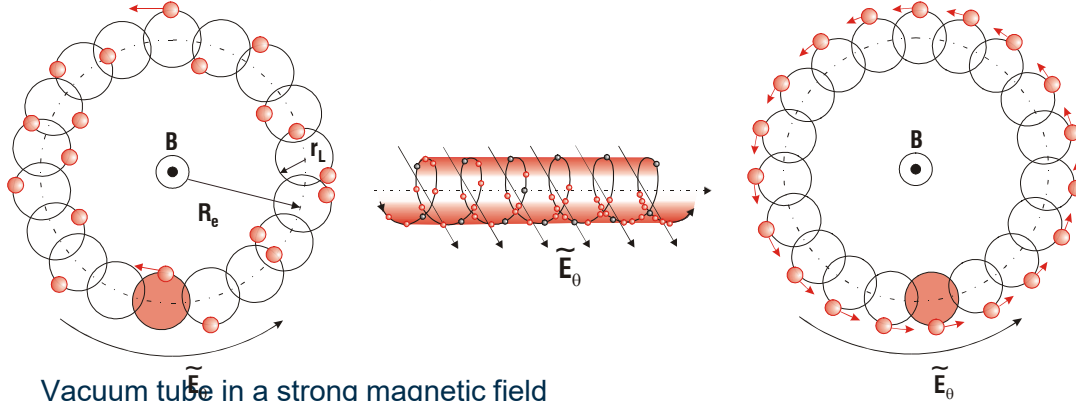
Moving towards Multi-Megawatt Class Sources



Gyrotron Grundlagen

The Gyrotron – A Powerful Fast Wave Device

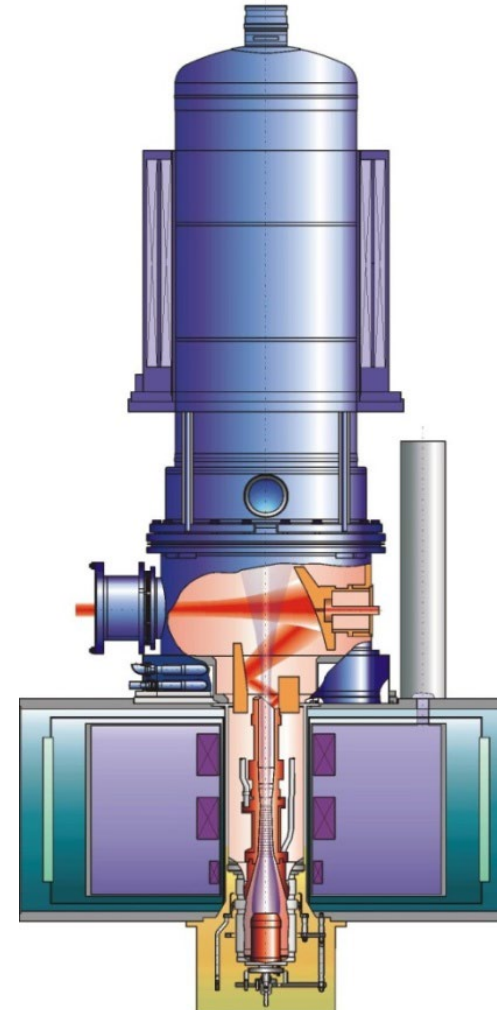
- „Gyrotron“ = „Gyrating electron“^O



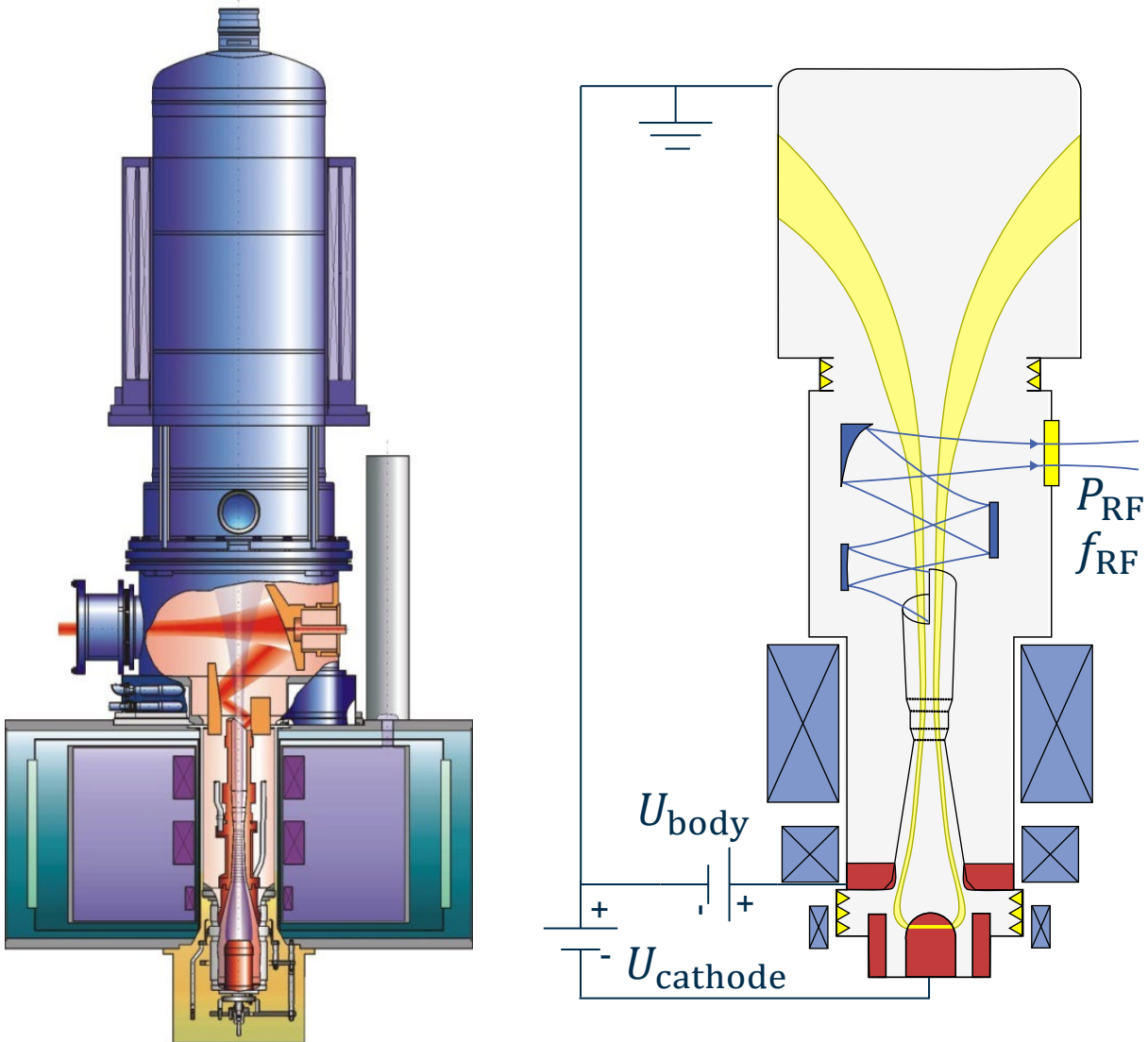
- Vacuum tube in a strong magnetic field

$$f_c[\text{GHz}] = \frac{1}{2\pi} \frac{e B_z}{\gamma m} \approx \frac{28}{\gamma} \cdot B_z[\text{T}]$$

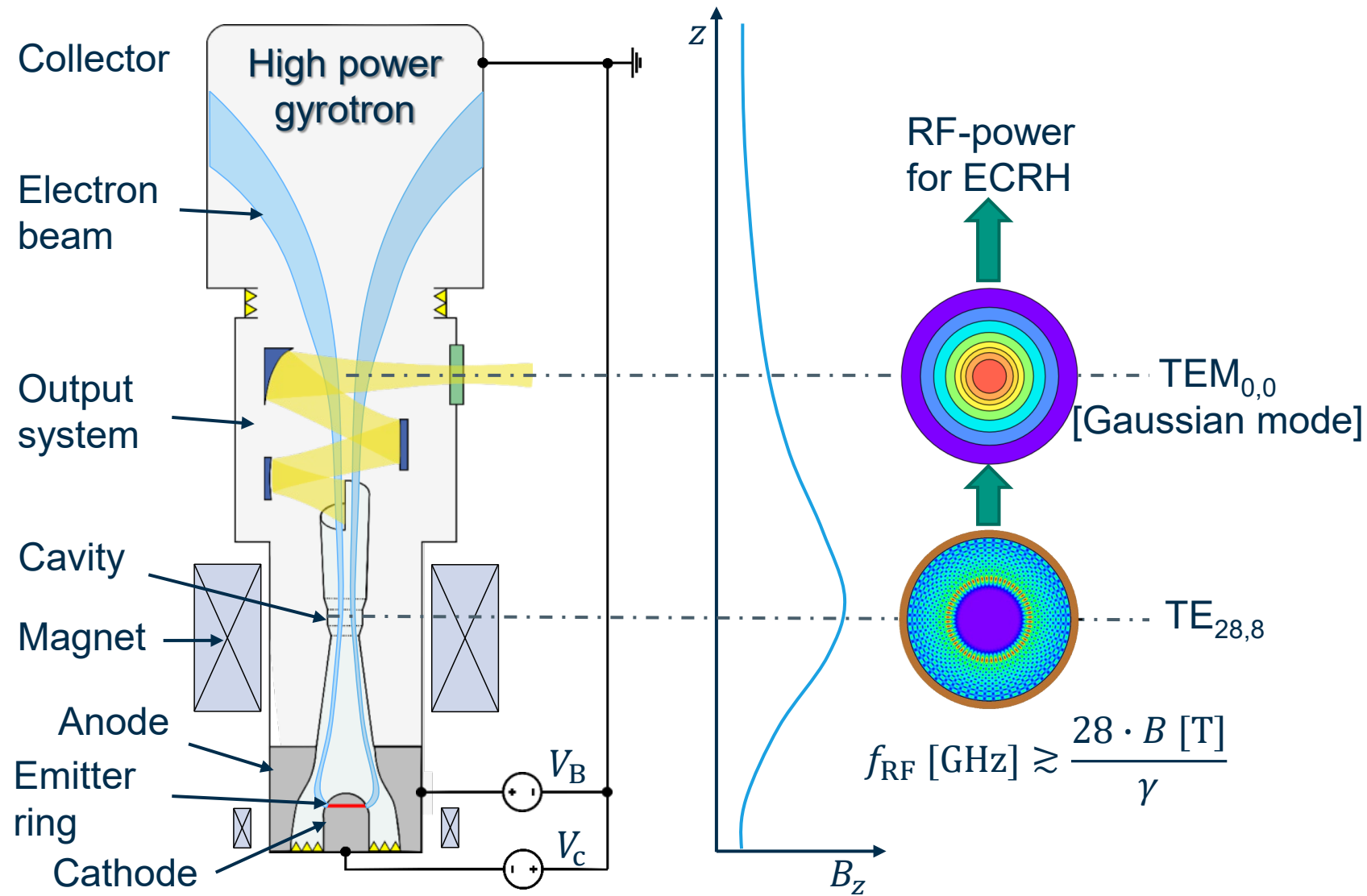
- Fast wave device $\rightarrow k_0 \sim k_c$
- Typical performance of high power fusion devices:
 - Output power: > 1 MW CW
 - Frequency: ~ 100 - 200 GHz
 - Efficiency: ~ 50 %



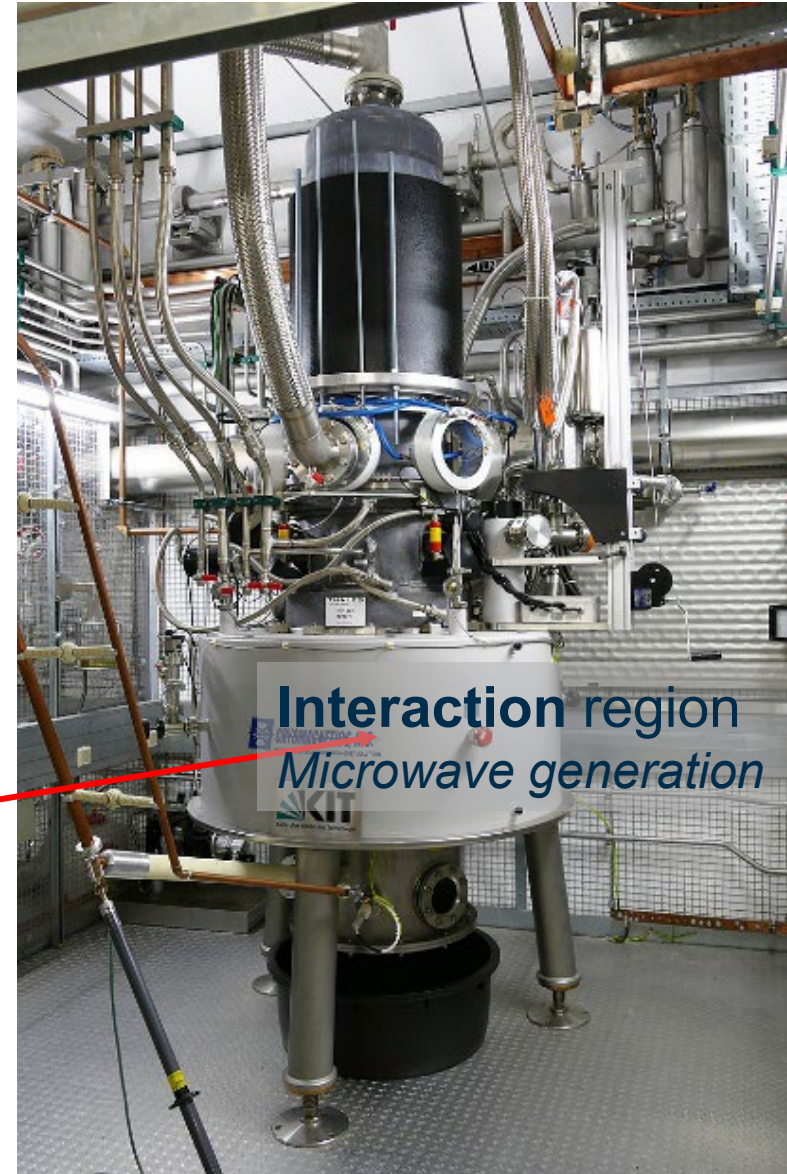
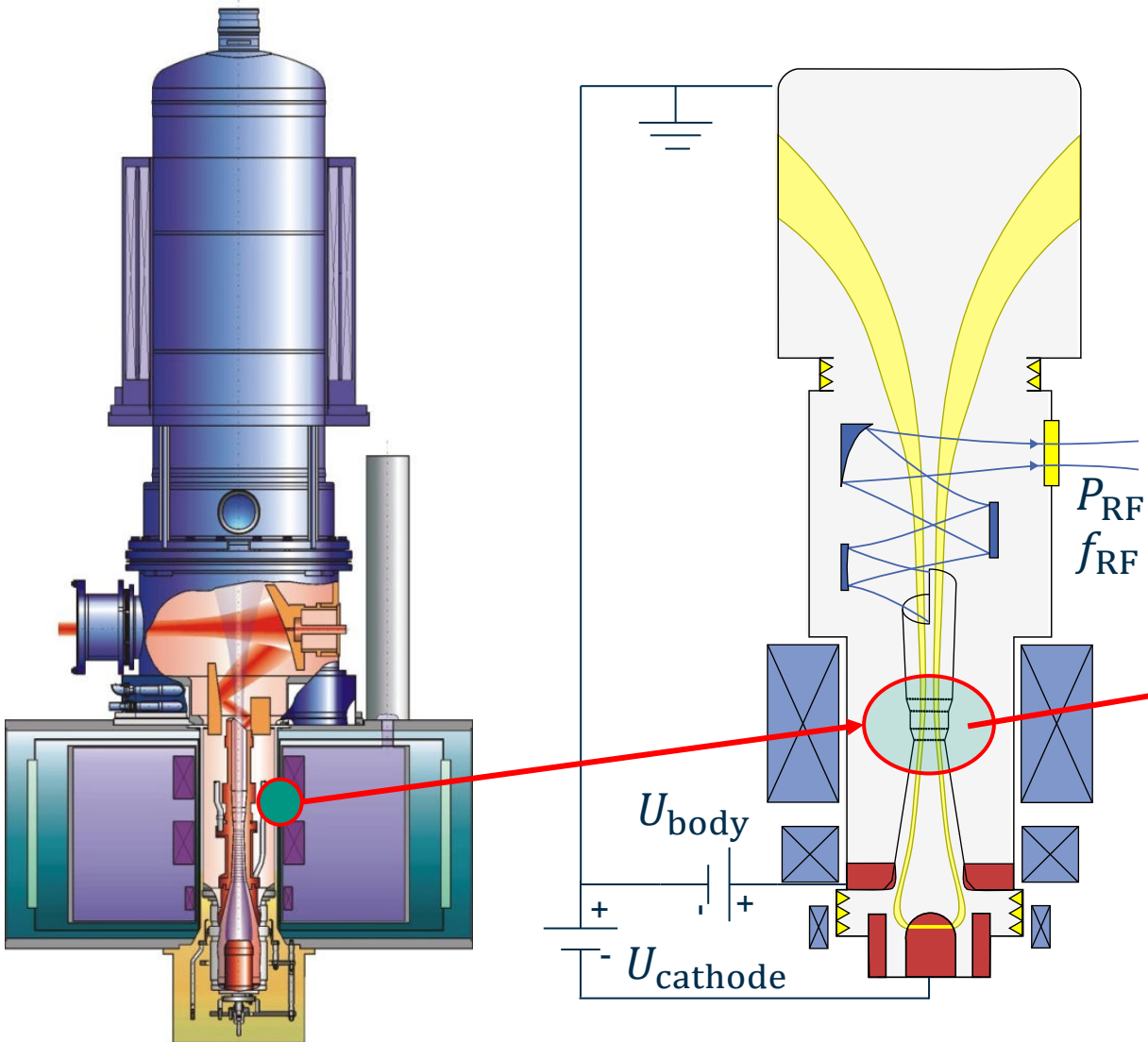
The High Power Gyrotron



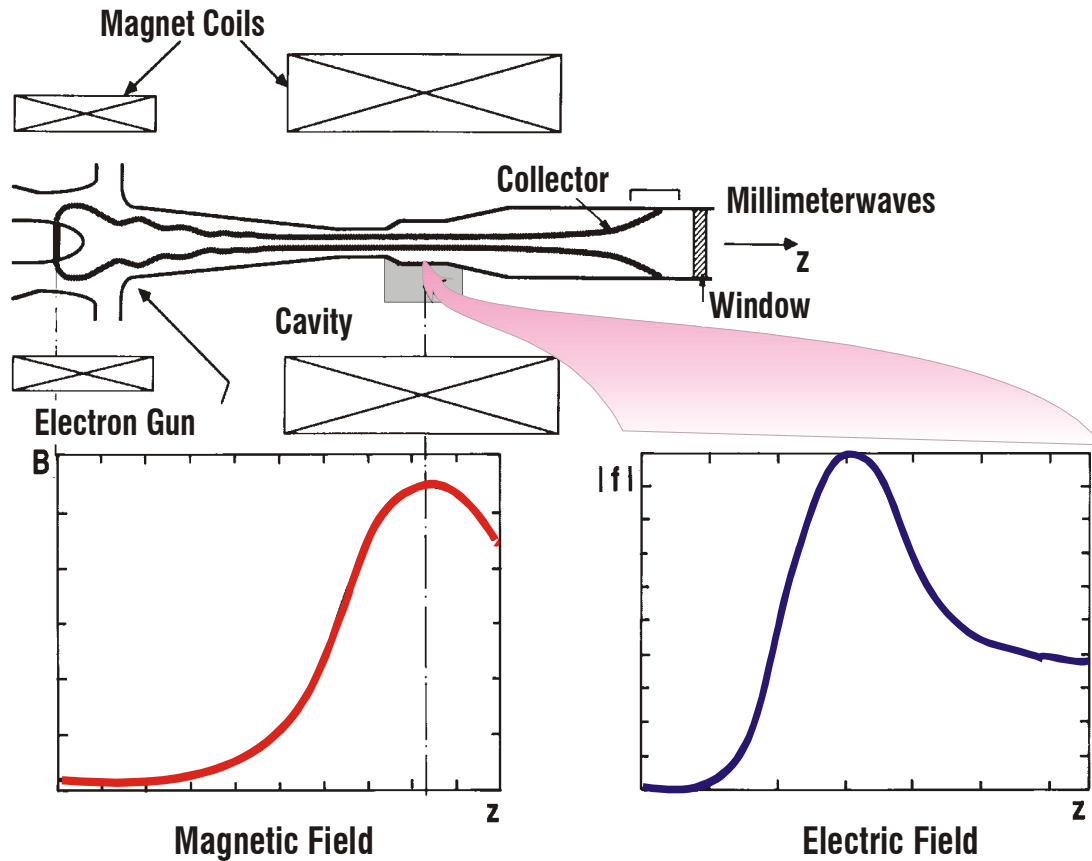
Gyrotron Oscillator at a Glance



Region of Energy Conversion



Axial Profiles of Magnetic and Electric Field Components



Circular Waveguide:
(TE_{mn} -Mode)

$$\lambda_{wg} = \frac{\lambda_0}{\sqrt{1 - \left(\frac{X_{m,n}c}{D\pi f}\right)^2}}$$

High Order Mode, Fast Wave ($v_{ph} > c$)

Cutoff-Frequency: $D = \frac{c}{\pi} \cdot \frac{X_{m,n}}{f}$

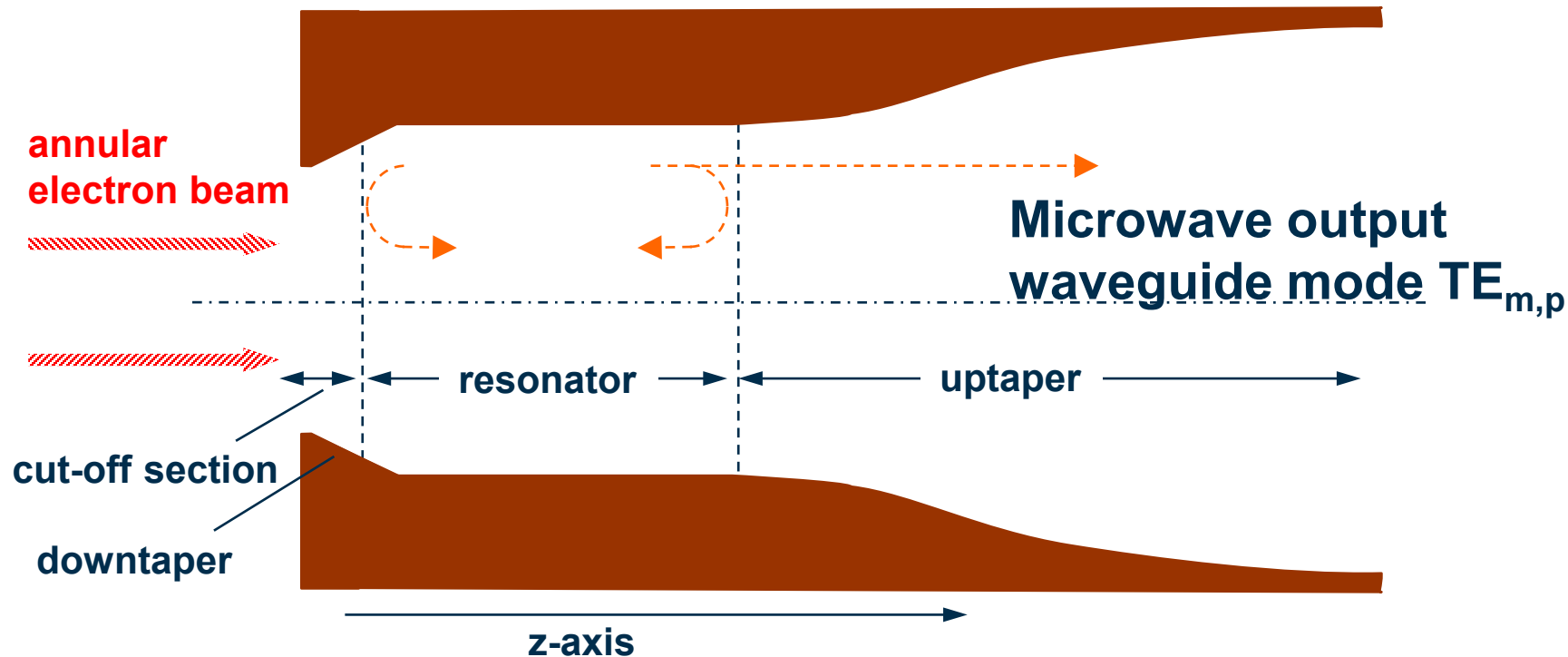
$$D(mm) \approx 95.4269 \frac{X_{m,n}}{f(GHz)}$$

Example: $TE_{22,6}$ ($X_{m,n} = 45.624$) at 140 GHz

$$D \approx 31.1mm$$

Resonator / Cavity

- Open waveguide resonator (hollow waveguide or coaxial)
- **High-order TE mode operating close to cut-off (fast wave!)**
- Downtaper at the electron entrance to minimize microwave power traveling towards the MIG: The operating mode is reflected.
- Non-linear uptaper at the exit to increase the diameter towards the launcher



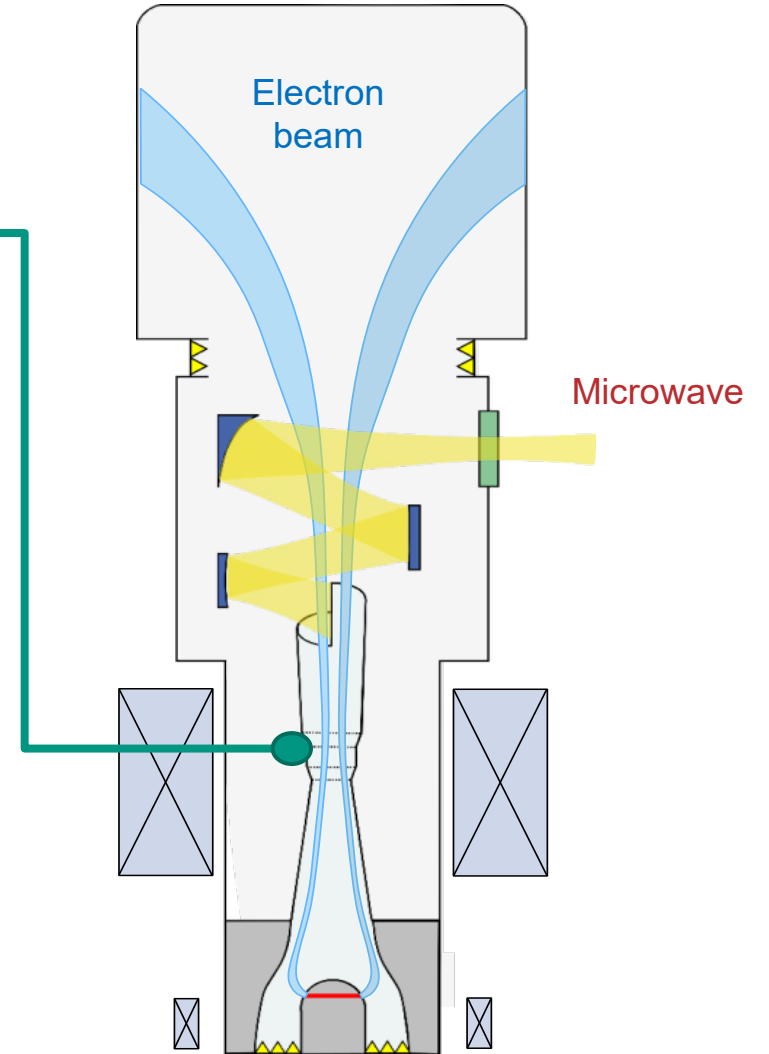
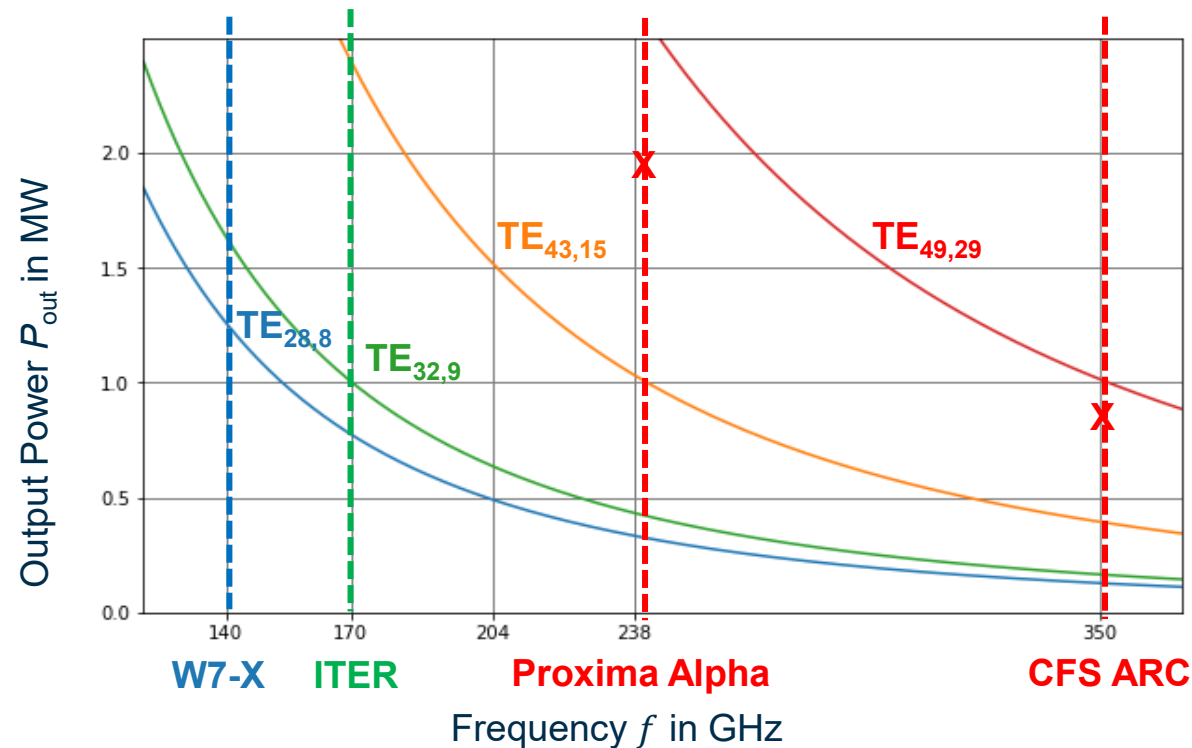
Power vs. Frequency Considering Specific Mode Orders

Cavity

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

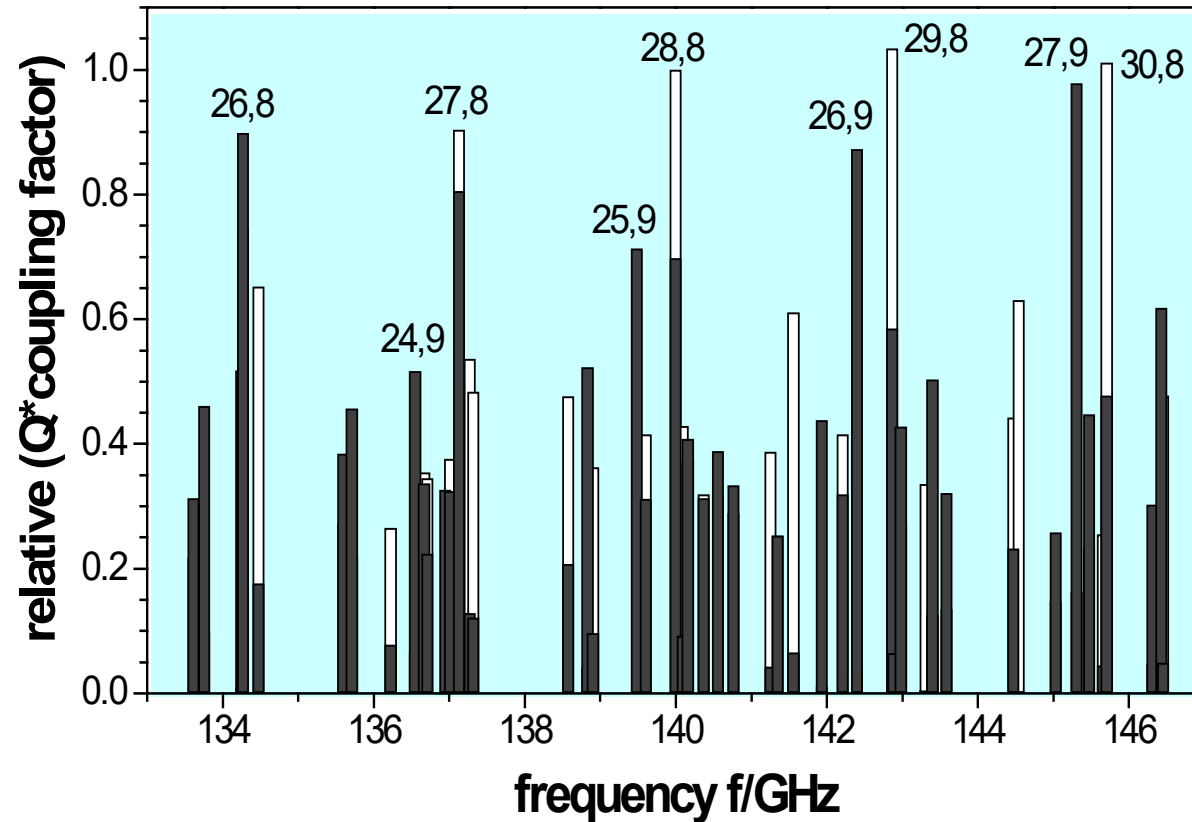
(limited to $\leq 2 \frac{\text{kW}}{\text{cm}^2}$ by cooling system)

→ Need for very high-order TE mode

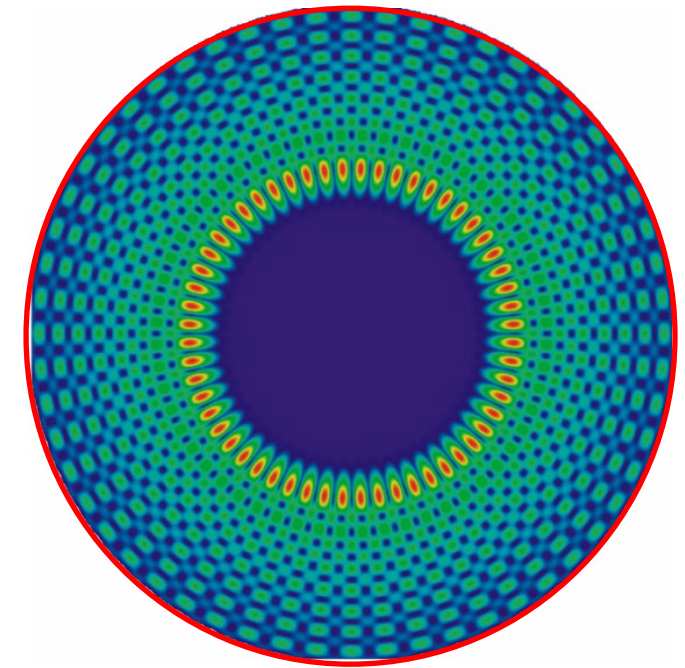


Mode Spectrum in the Cavity

MW gyrotrons use highly overmoded resonators
-> dense spectrum of relevant modes



wall losses @ 1 MW:
 $\sim 2 \text{ kW/cm}^2$



TE_{28,8} mode



Gyrotron F&E

ITER – The Way to New Energy



1985

Former US President R. Reagan and President of the former Soviet Union M. Gorbatschow agree to work together for a common future.



2006

Ceremony for the signing of the contract for the construction of the International Thermonuclear Experimental Reactor (ITER) at the Elysee Palace, Paris, France.



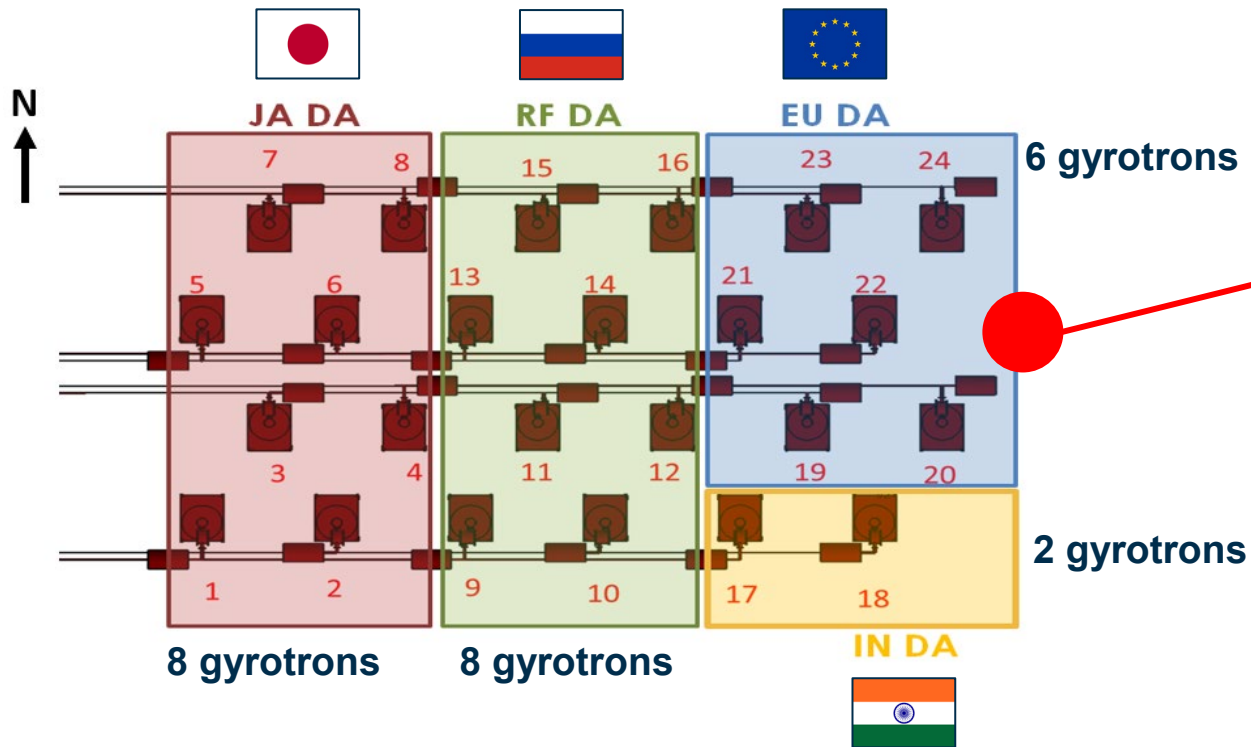
2024

ITER construction status at Cadarache, France

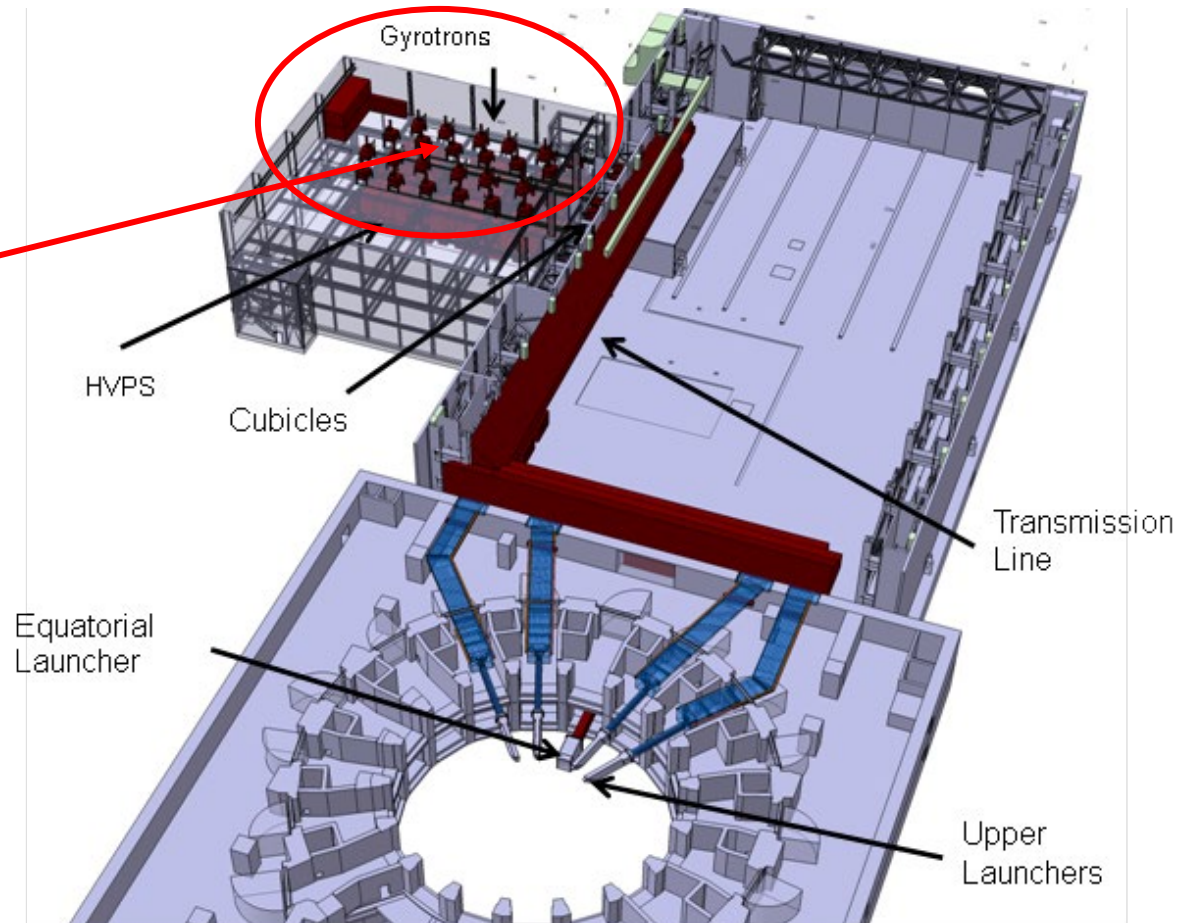


<https://www.world-nuclear-news.org/Articles/China-completes-ITER-magnet-support-components>, 2023

International Gyrotron Installation at ITER



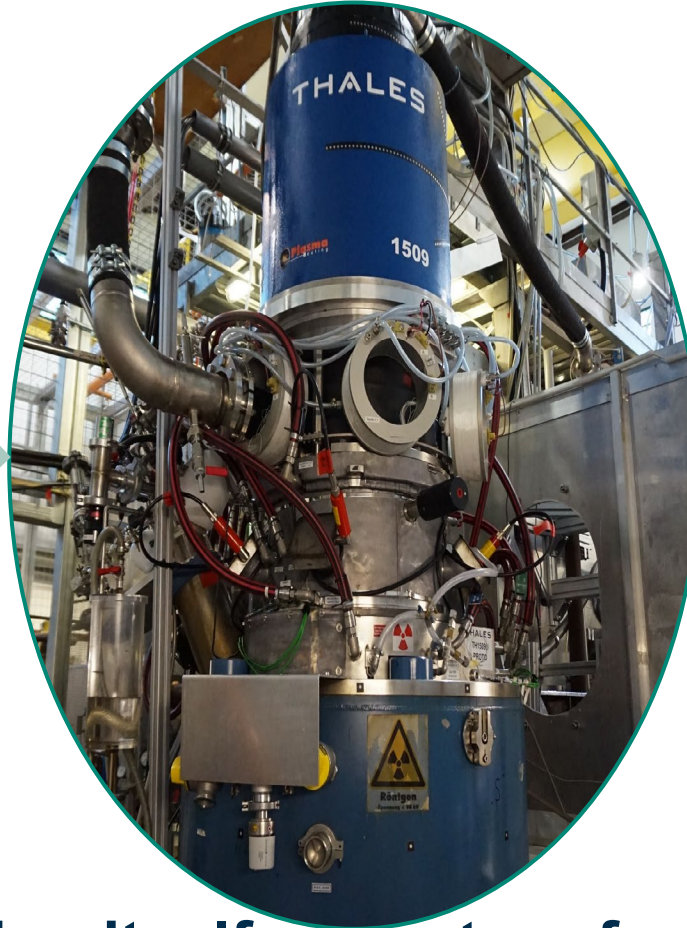
= 24 · 1 MW, 170 GHz gyrotrons



KIT Gyrotron Collaboration with Industry

KIT

- Fundamental concepts
- Simulation tools
- Measurements tools and facility
- „Physical“ design
- Pre-prototypes
- Experimental verification

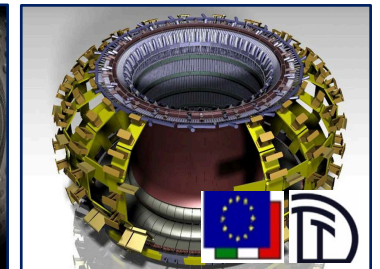
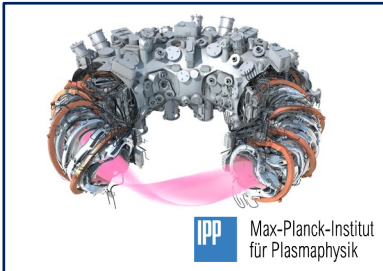
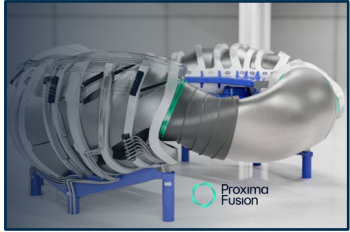


THALES

- Design for Manufacturability and Reliability
- Mechanical frame
- Thermo-mechanical design
- Key components manufacturing
- Integration and final assembly
- Conditioning

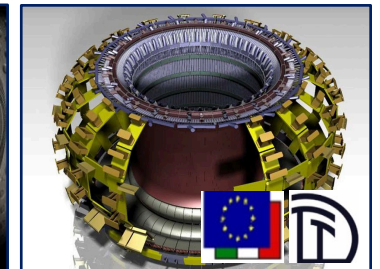
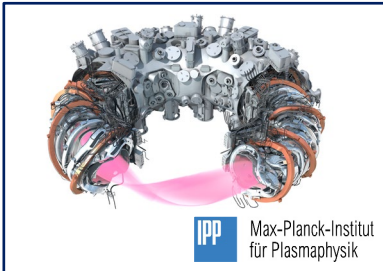
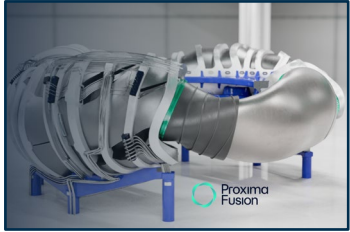
KIT is considering itself as partner for design and validation

Gyrotron Research and Development at KIT



- **Member of European Gyrotron Consortium (EGYC) for ITER**
- Partner of IPP for 1 MW and **1.5 MW / 2 MW developments for W7-X (BMFTR HiPMiB)**
- **EUROfusion tasks leader for gyrotron R&D**, leading the 2 MW coaxial-cavity gyrotron technology, Multistage Depressed Collector (MDC), operation at 2nd harmonics, electronic stability and frequency control
- Lead in test and validation of megawatt-class gyrotrons (**FULGOR**)
- Partner in gyrotron developments for European and worldwide nuclear fusion experiments such as **TCV, CEA/WEST, DTT** and **GA/DIII-D**
- **Project coordinator for BMFTR project HeatQIS** together with **PROXIMA Fusion, Diamond Materials** and **THALES** towards 238 GHz gyrotrons, EC launchers and windows

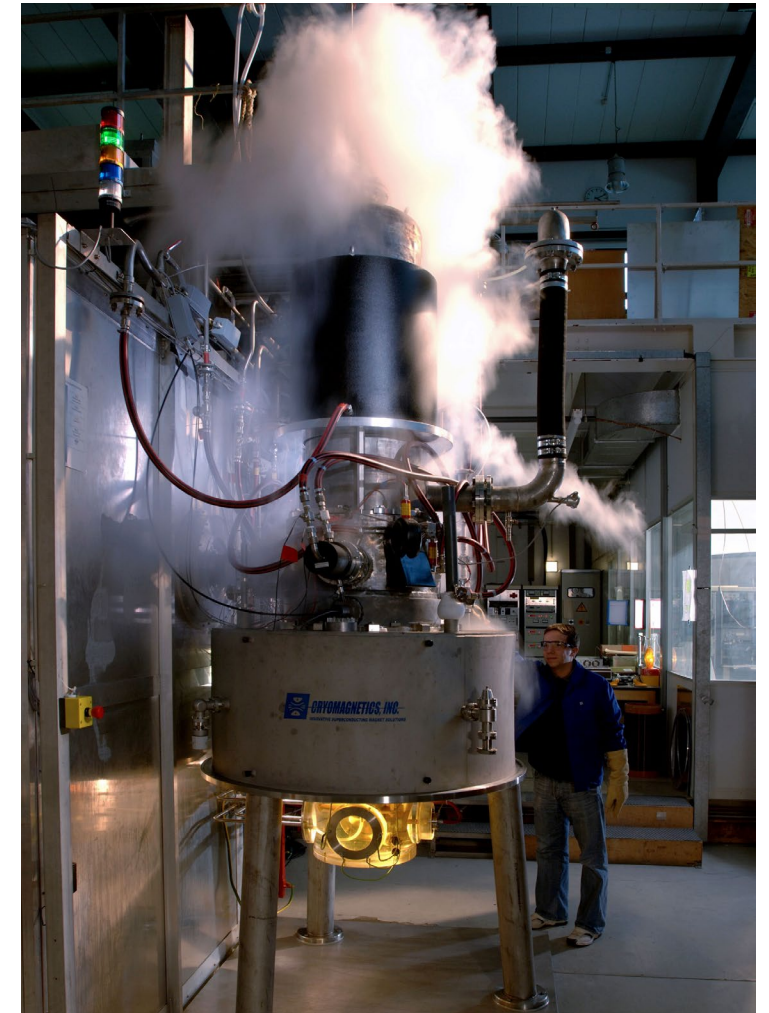
Gyrotron Research and Development at KIT



- **Member of European Gyrotron Consortium (EGYC) for ITER**
- Partner of IPP for 1 MW and **1.5 MW / 2 MW developments for W7-X (BMFTR HiPMiB)**
- **EUROfusion** tasks leader for gyrotron R&D, leading the 2 MW coaxial-cavity gyrotron technology, Multistage Depressed Collector (MDC), operation at 2nd harmonics, electronic stability and frequency control
- Lead in test and validation of megawatt-class gyrotrons (**FULGOR**)
- Partner in gyrotron developments for European and worldwide nuclear fusion experiments such as TCV, CEA/WEST, DTT and GADIII-D
- Project coordinator for BMFTR project HeatQIS together with **PROXIMA Fusion**, **Diamond Materials** and **THALES** towards 238 GHz gyrotrons, EC launchers and windows

140 GHz 1 MW Gyrotron for W7-X (THALES TH1507)

- **140 GHz TE_{28,8} conventional cavity**
- Diode-type electron-optical system
- Nominal beam current 40 A (max. <50 A)
- Specified efficiency $\eta > 45 \%$
- Cavity Magnetic Field 5.6 T
- Internal q. o. mode converter
(HL launcher, 97 % gaussian mode content)
- CVD-diamond window
(d = 106 mm, t = 1.8 mm)
- Single-stage depressed collector
with collector at ground potential
 - cathode - 50 kV (40 A)
 - body +30 kV (10 mA)
- Vertical and transversal collector sweeping



1.5 MW / 2 MW Gyrotron for W7-X

W7-X



Towards
2 MW, smart control
175 GHz CTS



THALES



EPFL



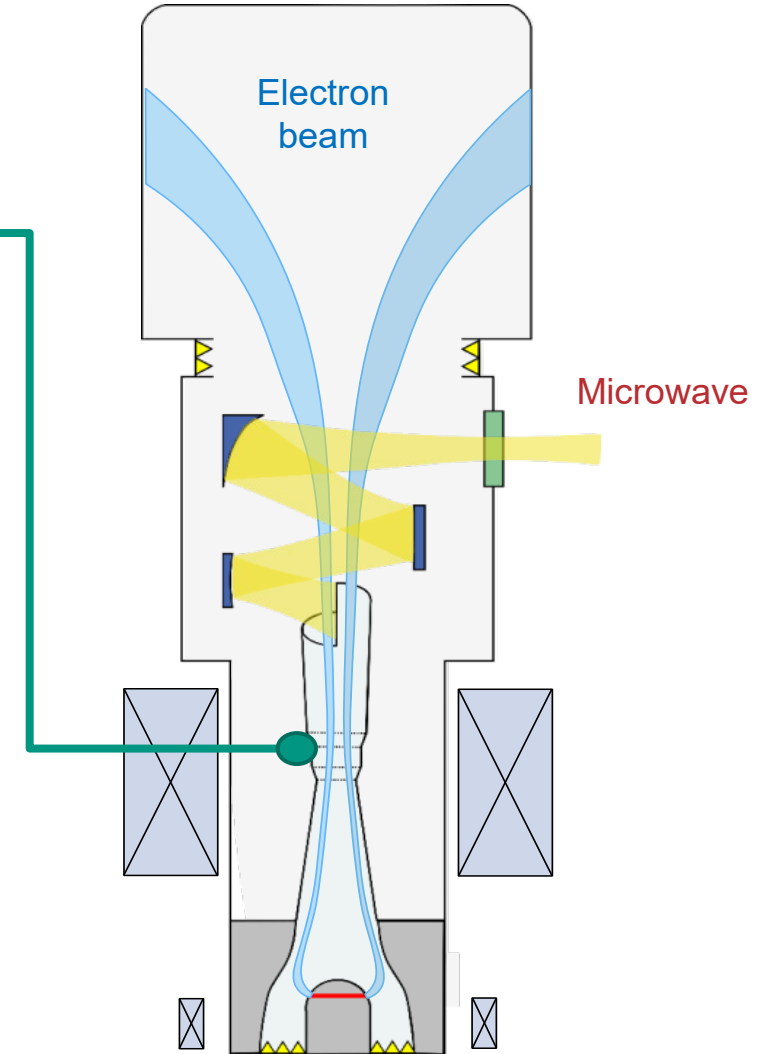
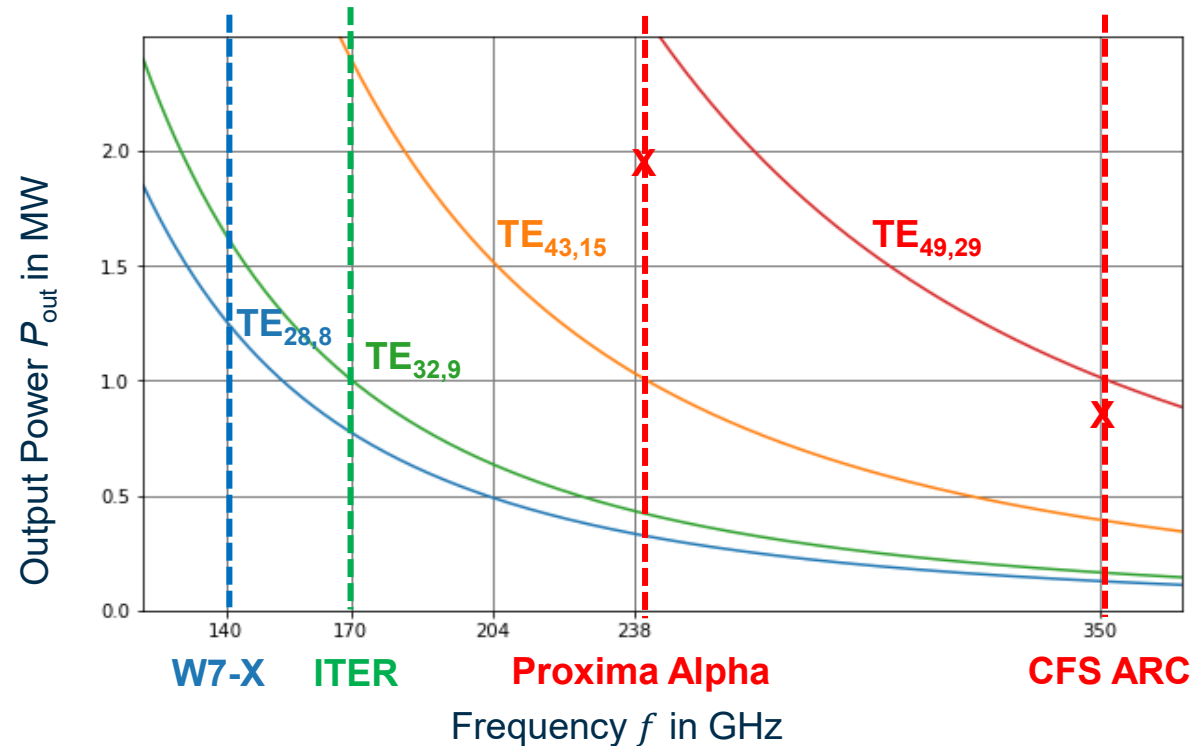
Power vs. Frequency Considering Specific Mode Orders

Cavity

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

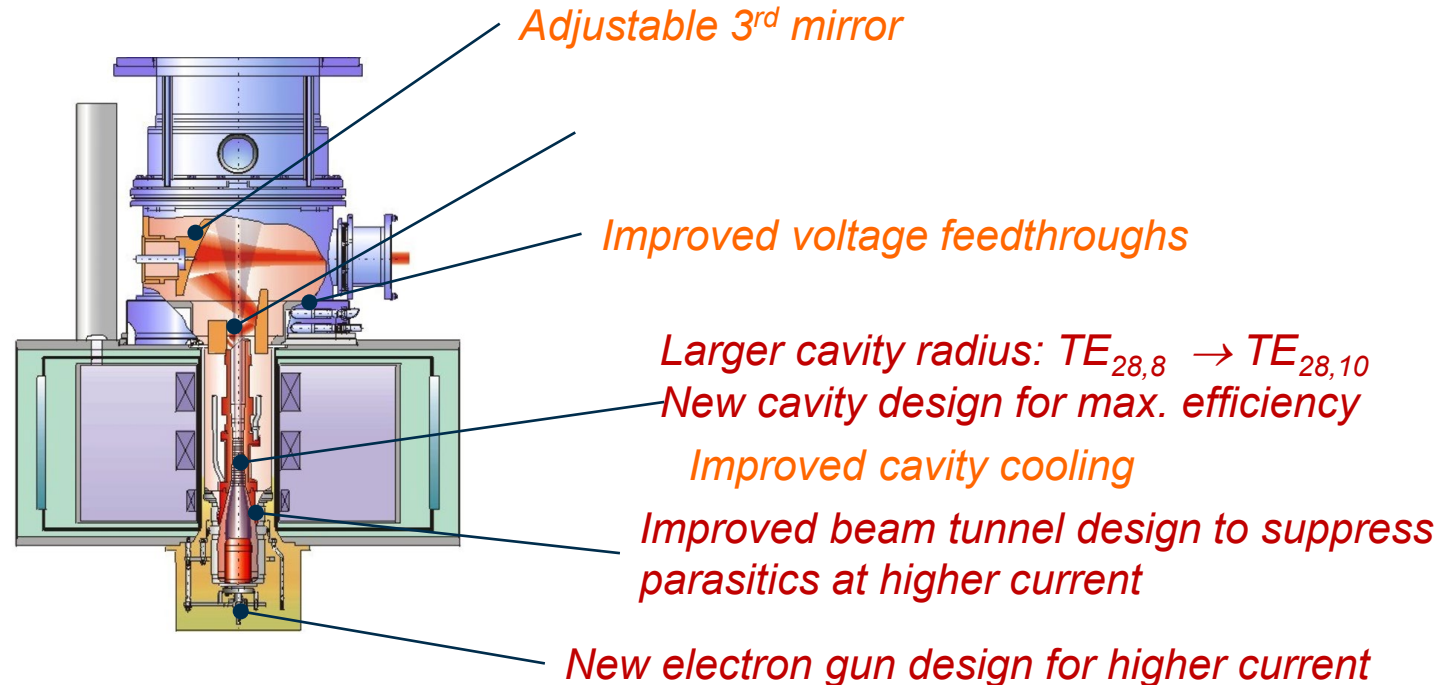
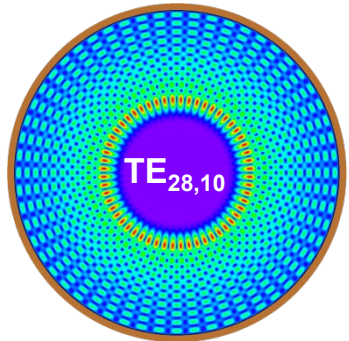
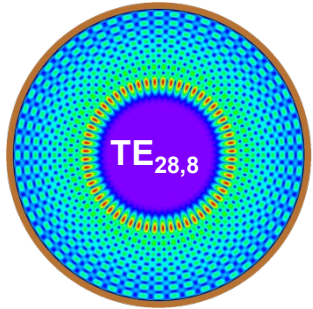
(limited to $\leq 2 \frac{\text{kW}}{\text{cm}^2}$ by cooling system)

→ Need for very high-order TE mode



1.5 MW 140 GHz Gyrotron Upgrade (THALES TH1507U)

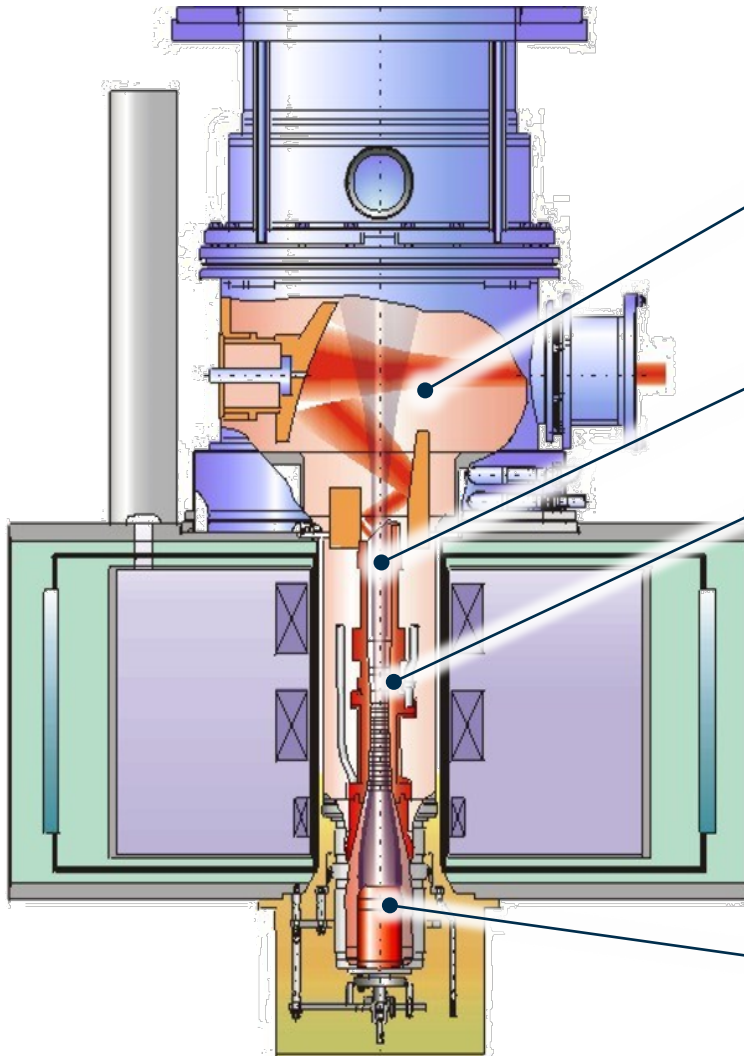
Strategy: Upgrade from $TE_{28,8}$ – mode to $TE_{28,10}$ – mode
*Minimize risk and cost; operate in the same magnetic field profile;
increase current from 40 A to 55 A.*



Scientific upgrades (KIT/NKUA/IPP)

Technical upgrades (THALES/PoliTo)

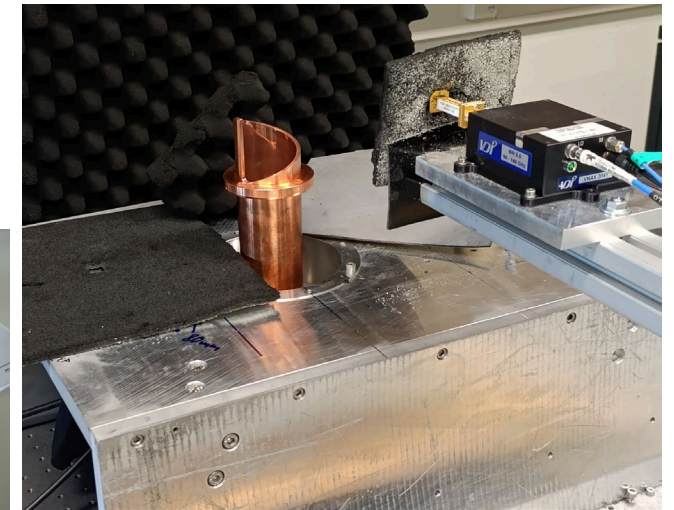
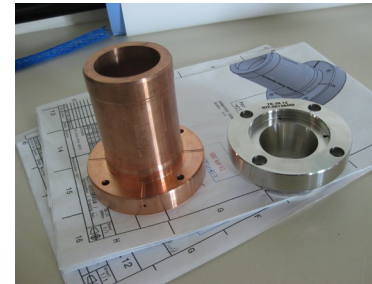
2 MW 140 GHz Gyrotron Upgrade (BMFTR HiPMiB)



*Modified voltage potential concept
+ modified Q.O.-system*

New launcher antenna (mode-converter)

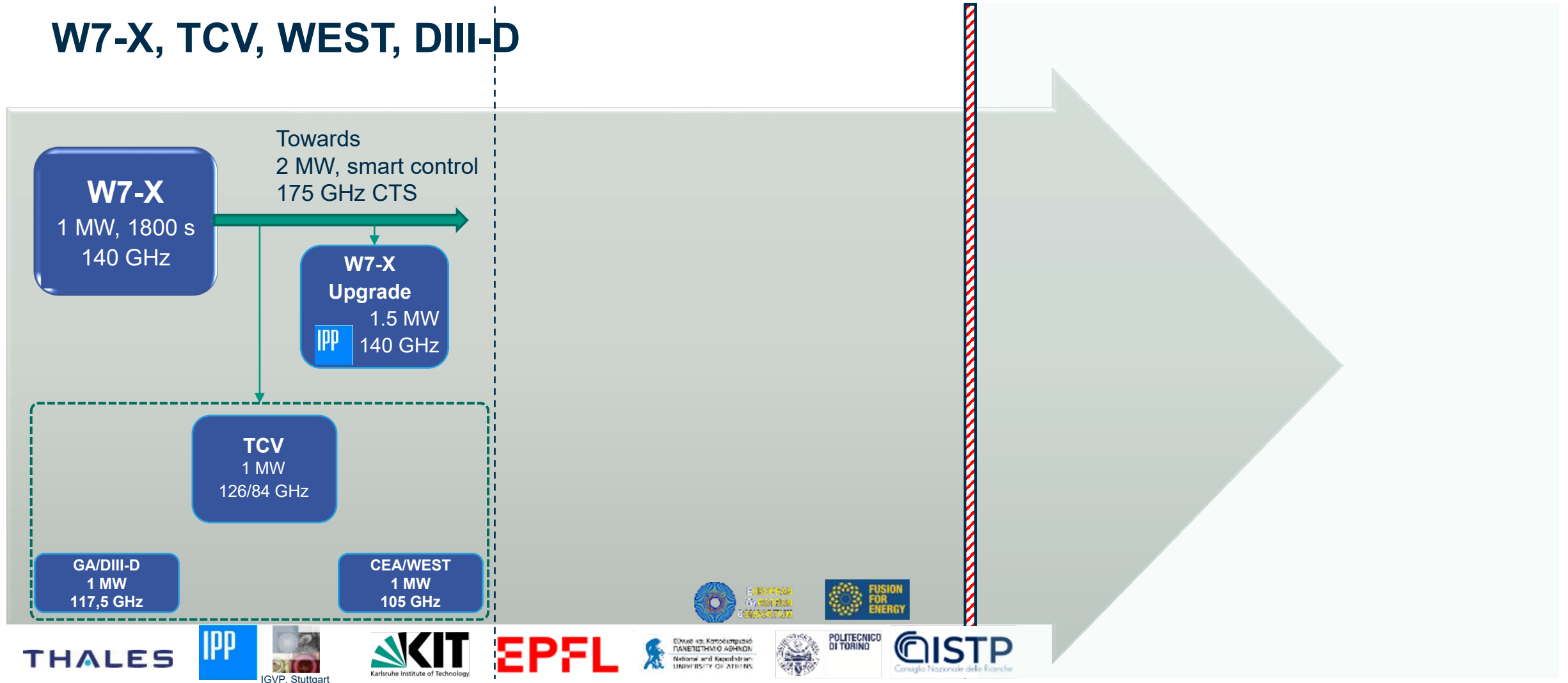
$TE_{28,12}$ -mode



Adaption of MIG

Variants of the W7-X Gyrotron (TH1507)

W7-X, TCV, WEST, DIII-D



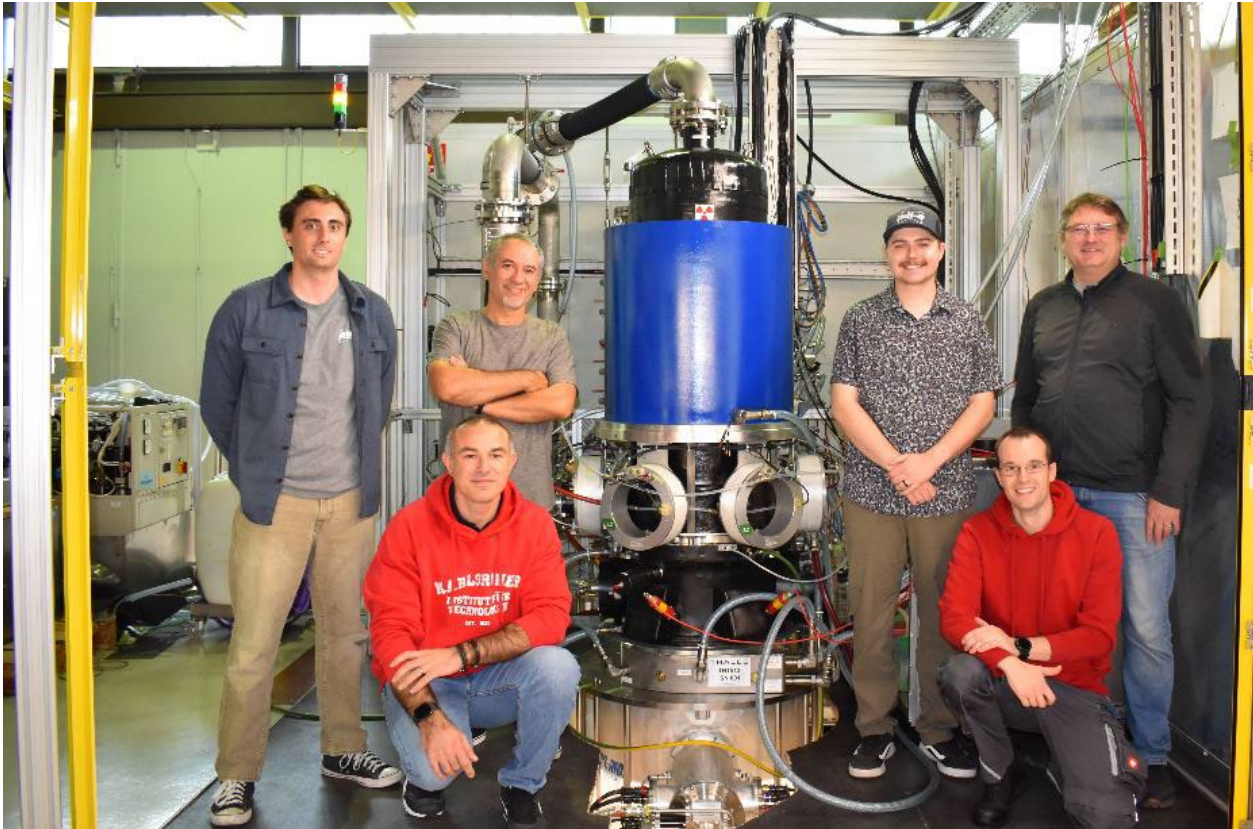
105 GHz 1 MW Gyrotron for CEA/WEST (THALES TH1511)



CEA WEST 105 GHz, 1MW CW	
f	105 GHz
B_c	4.13 T
P_{rf}	1 MW
Mode	TE _{20,8}
Efficiency	40%
Pulse length	60 s
Magnets	Cryogen free SCM - Cryomagnetics
Goal	FAT

A. Leggieri *et al.*, "**THALES TH1511** 105 GHz 1 MW CW Industrial Gyrotron: A New ECRH Power Source for the WEST Fusion Reactor," 2026 IEEE International Vacuum Electronics Conference (IVEC), Monterey, CA, USA, 2026, pp. 11-12, doi: 10.1109/IVEC65405.2026.11555928

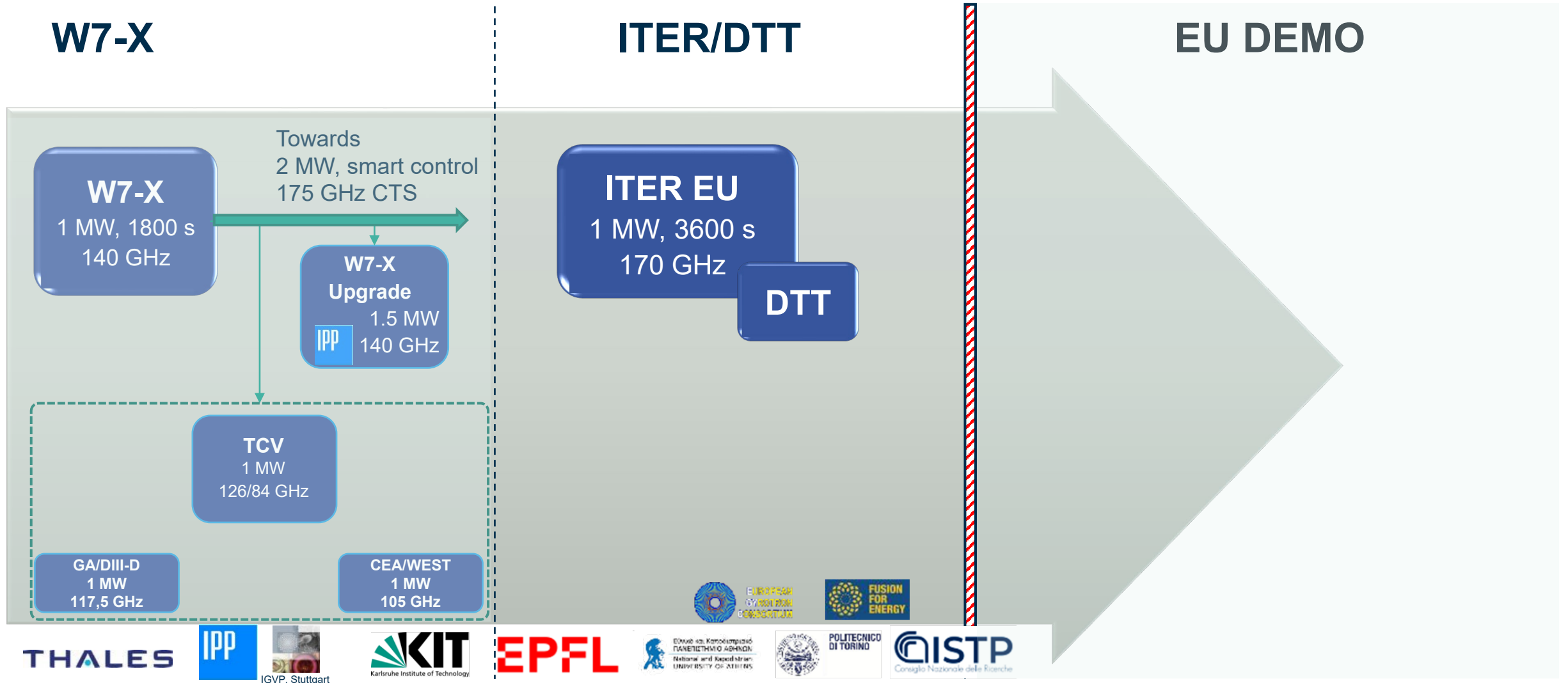
GA DIII-D 117.5 GHz, 1 MW (10 s) Gyrotron (THALES TH1512)



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

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

170 GHz 1 MW Gyrotron for ITER and DTT



170 GHz 1 MW Gyrotron for ITER and DTT



Pre-prototype validation at KIT

- Up to 1.6 MW at short pulses (ms) demonstrated
- Efficiency ~50 % achieved (with singlestage depressed collector and novel potential elevation structure)

Industrial prototype TH1509U

- 1.03/0.96 MW at 300/1000 s and 45/38 % (measured at F4E teststand, Lausanne)
- ➔ Support of ITER in the final optimization, validation and installation
- DTT final design review passed in 2024
 - ITER final design review passed with actions in 2025



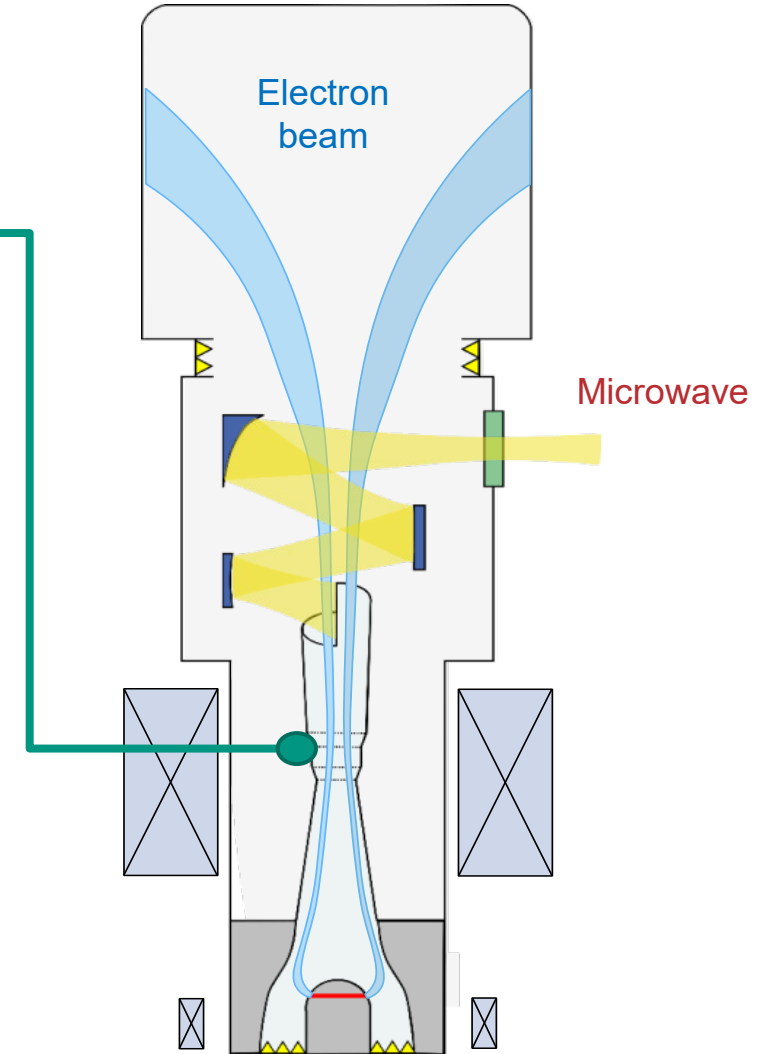
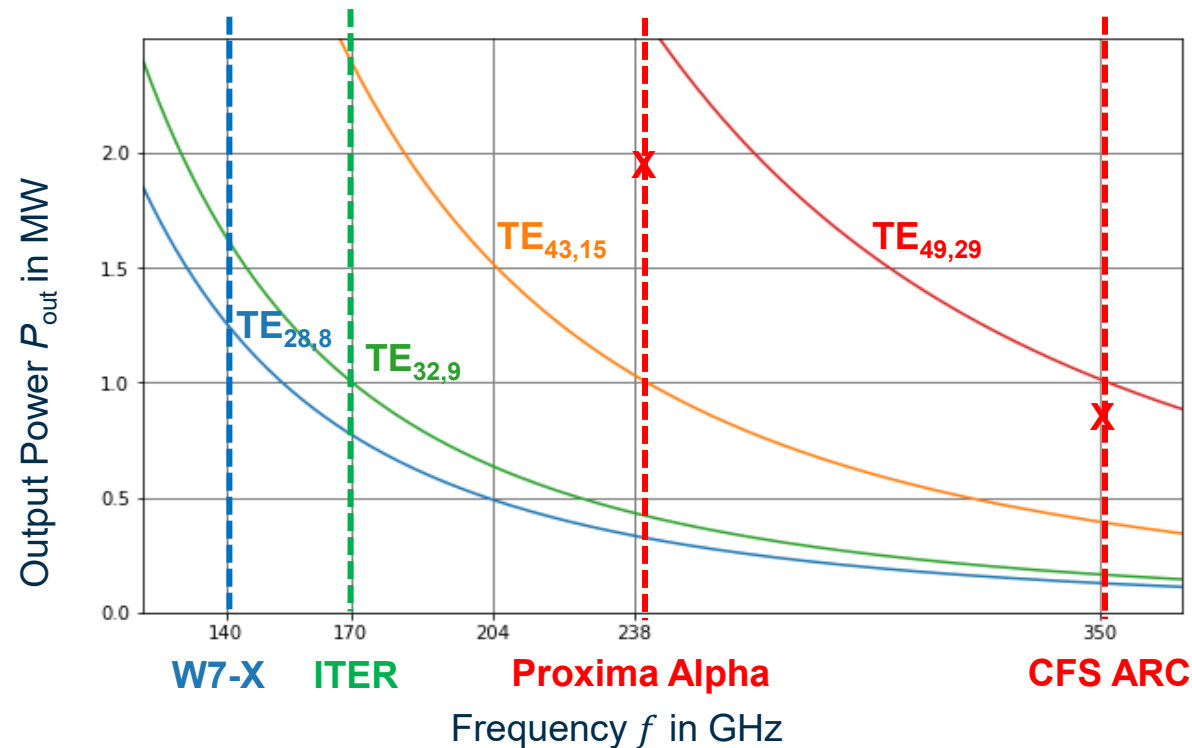
Power vs. Frequency Considering Specific Mode Orders

Cavity

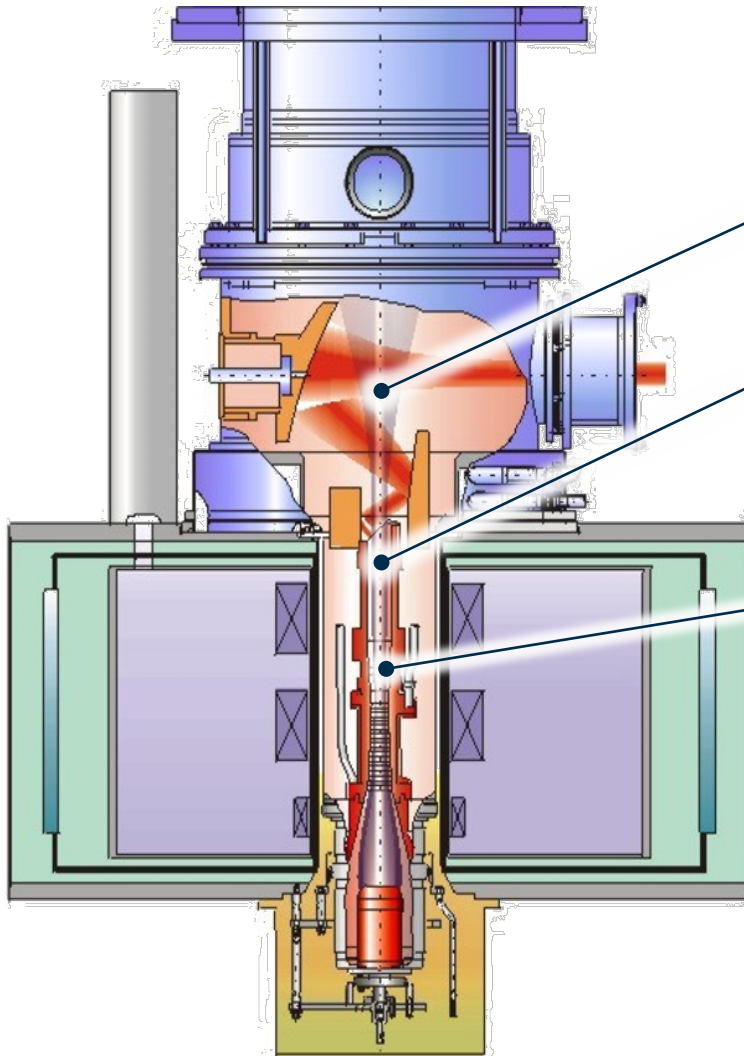
Thermal wall loading $\sim f^{2.5}$

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

→ Need for very high-order TE mode



EU Gyrotron Upgrade for ITER (**ITER upgrade** / ITER néo)



*Modified voltage potential concept
+ modified Q.O.-system*

New launcher antenna (mode-converter)

A. Schmidt *et al.*, „Design and Operational Strategies for Mitigating Static After Cavity Interaction Based on the European ITER Gyrotron.,” J Infrared Milli Terahz Waves 47, 35 (2026). <https://doi.org/10.1007/s10762-026-01141-4>

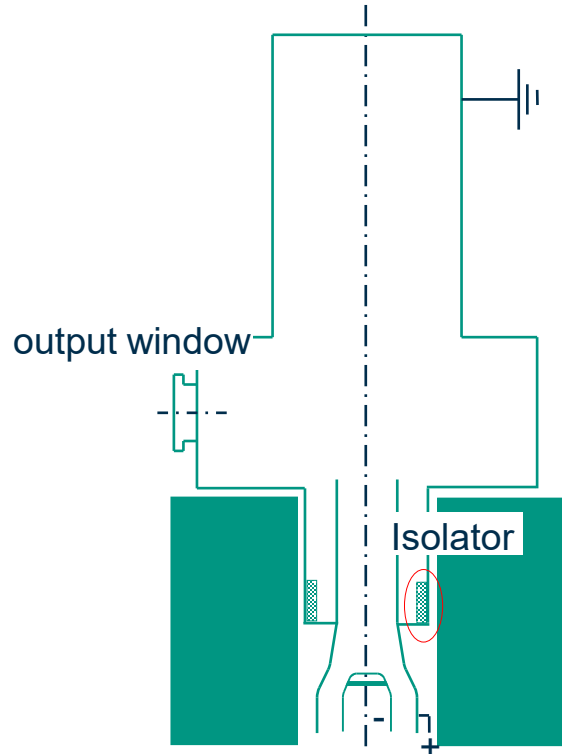
***New cavity mode $TE_{32,11}$ -mode
+ improved cooling capabilities***

R. Bertazzoni *et al.*, „Predictive Capabilities of an Automated Non-Linear Multi-Physics Framework for High-Power CW Gyrotron Cavities,” EC 23, Barcelona, 2026

Towards a Unified Architecture with Improved Efficiency

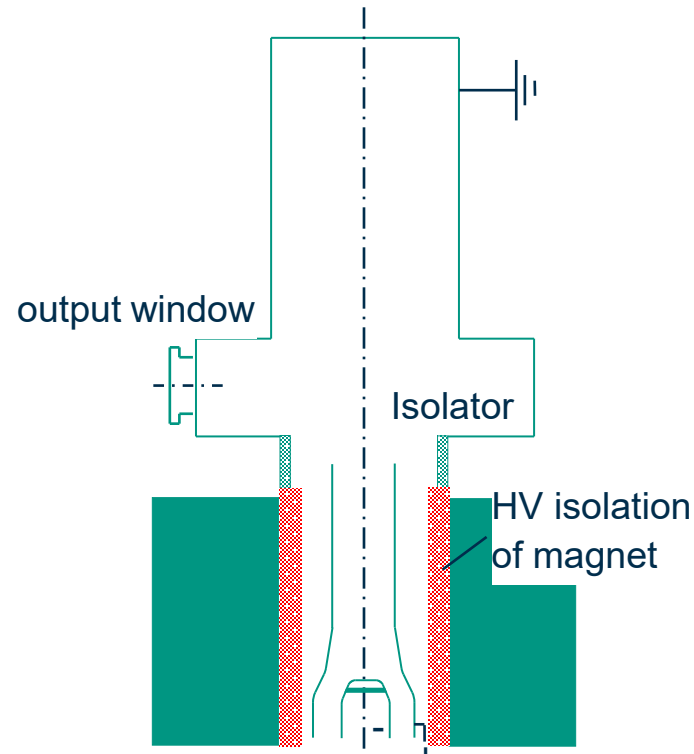
TH1507

- EU (Thales) State-of-the-Art
- Very compact design 🍀
- Poor efficiency 🚩



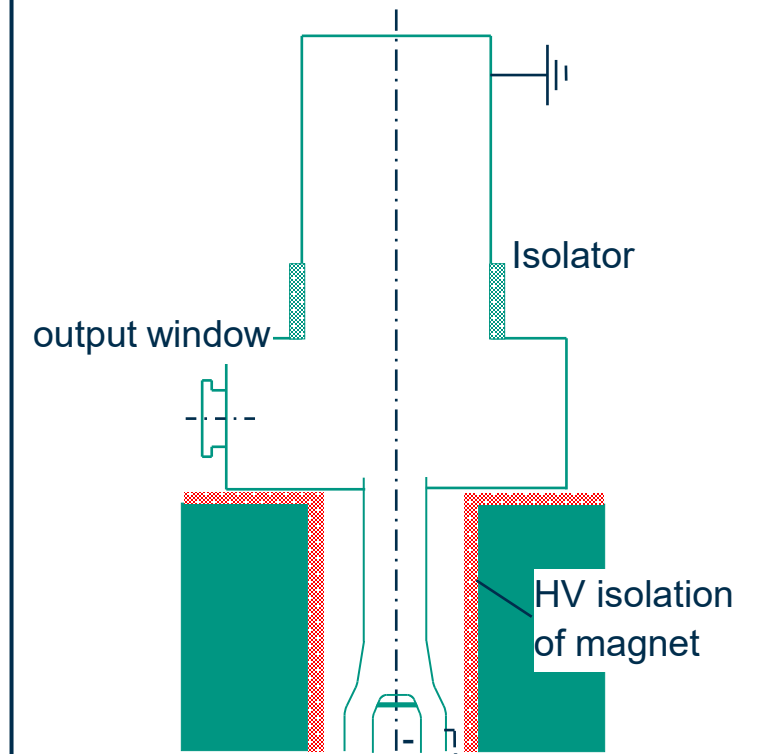
Intermediate

- Competitor State-of-the-Art
- Window grounded 🍀
- Increased efficiency 🍀

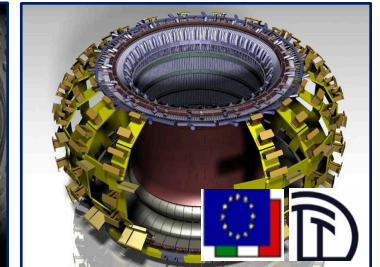
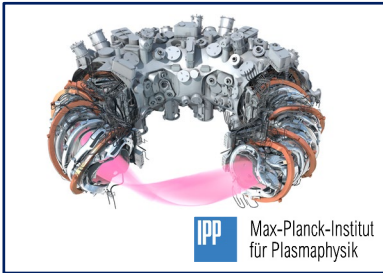
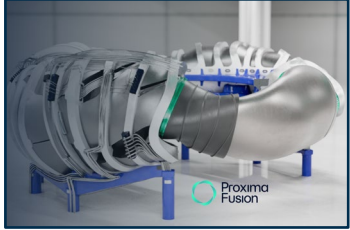


TH1508

- Coaxial tube
- Best concept in terms of efficiency 🍀
- Big technological challenges 🚩



Gyrotron Research and Development at KIT



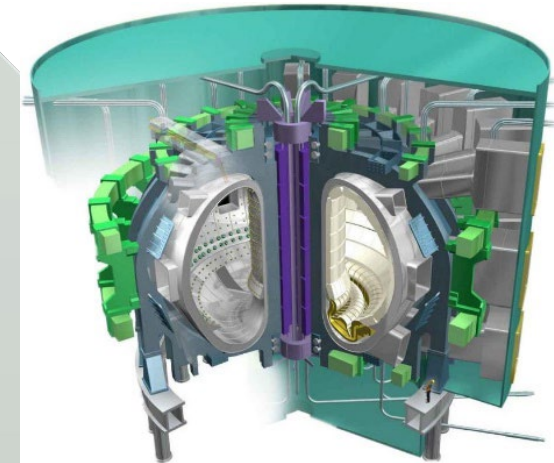
- Member of European Gyrotron Consortium (EGYC) for ITER
- Partner of IPP for 1 MW and 1.5 MW / 2 MW developments for W7-X (BMFTR HiPMiB)
- **EUROfusion tasks leader for gyrotron R&D, leading the 2 MW coaxial-cavity gyrotron technology, Multistage Depressed Collector (MDC), operation at 2nd harmonics, electronic stability and frequency control**
- Lead in test and validation of megawatt-class gyrotrons (FULGOR)
- Partner in gyrotron developments for European and worldwide nuclear fusion experiments such as TCV, CEA/WEST, DTT and GA/DIII-D
- Project coordinator for BMFTR project HeatQIS together with PROXIMA Fusion, Diamond Materials and THALES towards 238 GHz gyrotrons, EC launchers and windows

Towards DEMO Relevant Gyrotrons

W7-X

ITER/DTT

EU DEMO



136 / 170 / 204 / 240 GHz
2 MW CW

- + multi-purpose operation
- + frequency steering into the plasma
- + operation at long pulses
- + sufficiently high plug-in efficiency

W7-X
1 MW, 1800 s
140 GHz

Towards
2 MW, smart control
175 GHz CTS

W7-X Upgrade
1.5 MW
140 GHz
IPP

TCV
1 MW
126/84 GHz

GA/DIII-D
1 MW
117,5 GHz

IPP Prague
1 MW
105/140 GHz

CEA/WEST
1 MW
105 GHz

ITER EU
1 MW, 3600 s
170 GHz

DTT

THALES



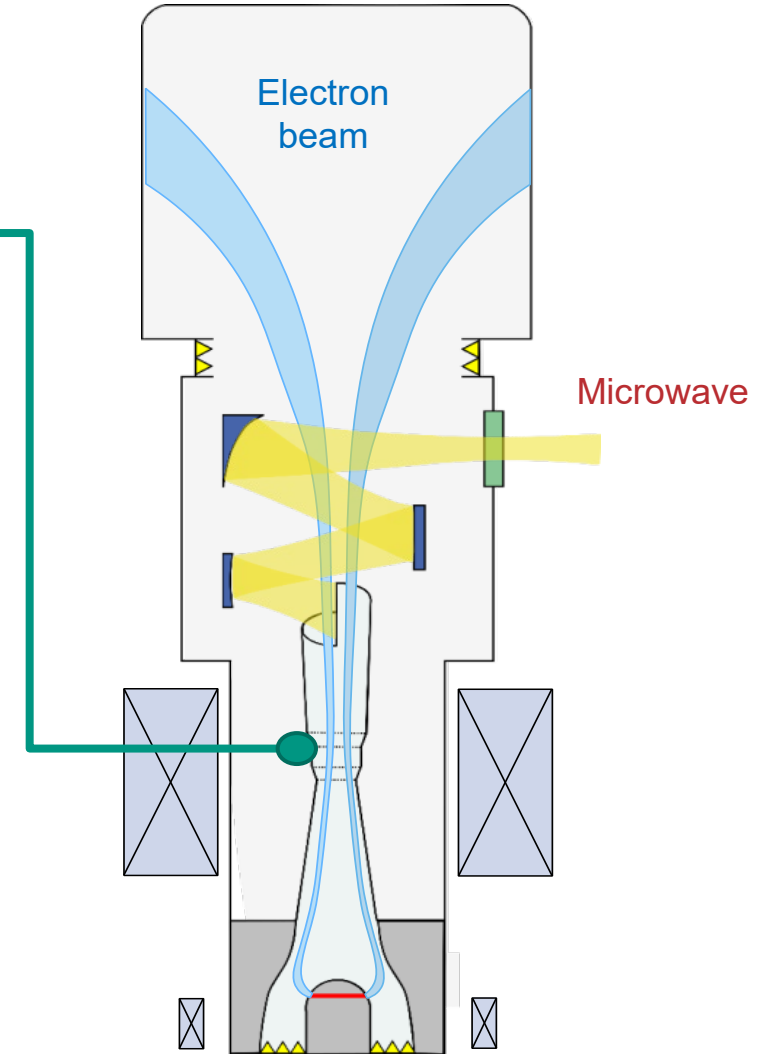
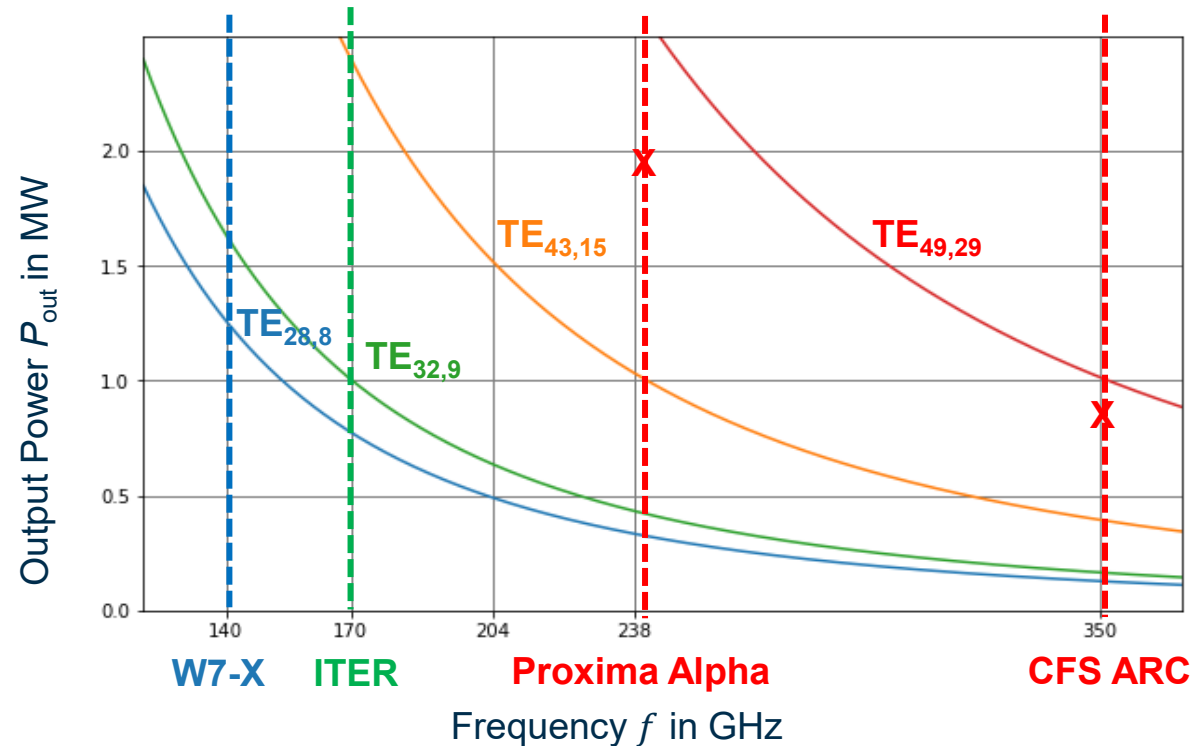
Power vs. Frequency Considering Specific Mode Orders

Cavity

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

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

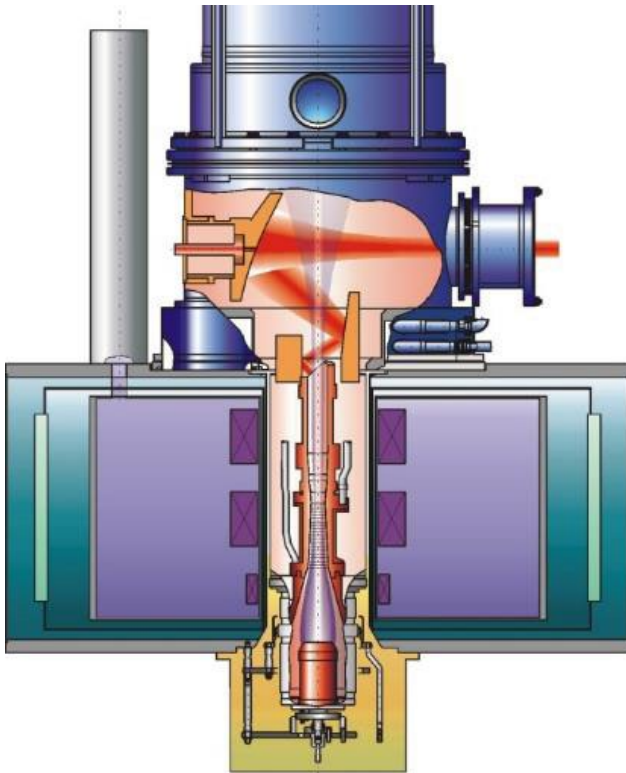
→ Need for very high-order TE mode



Towards 2 MW Gyrotrons: Conventional vs. Coaxial-cavity Gyrotron

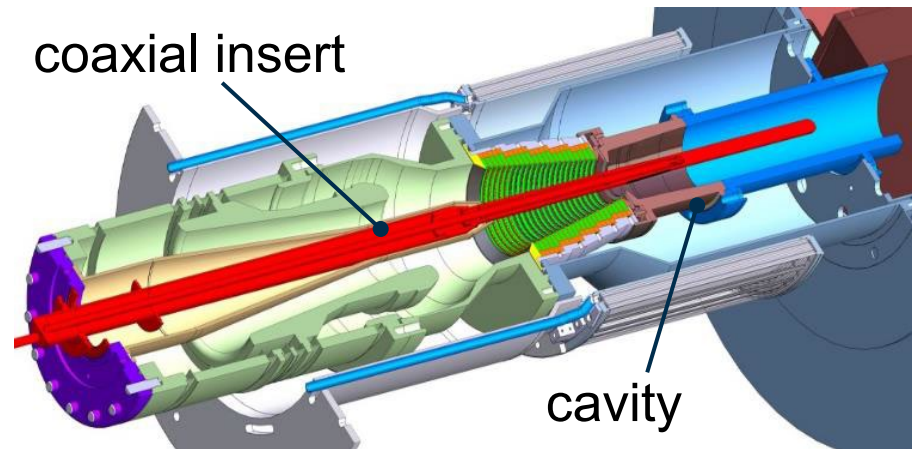
Conventional

- + Simpler design
- + Verified technology



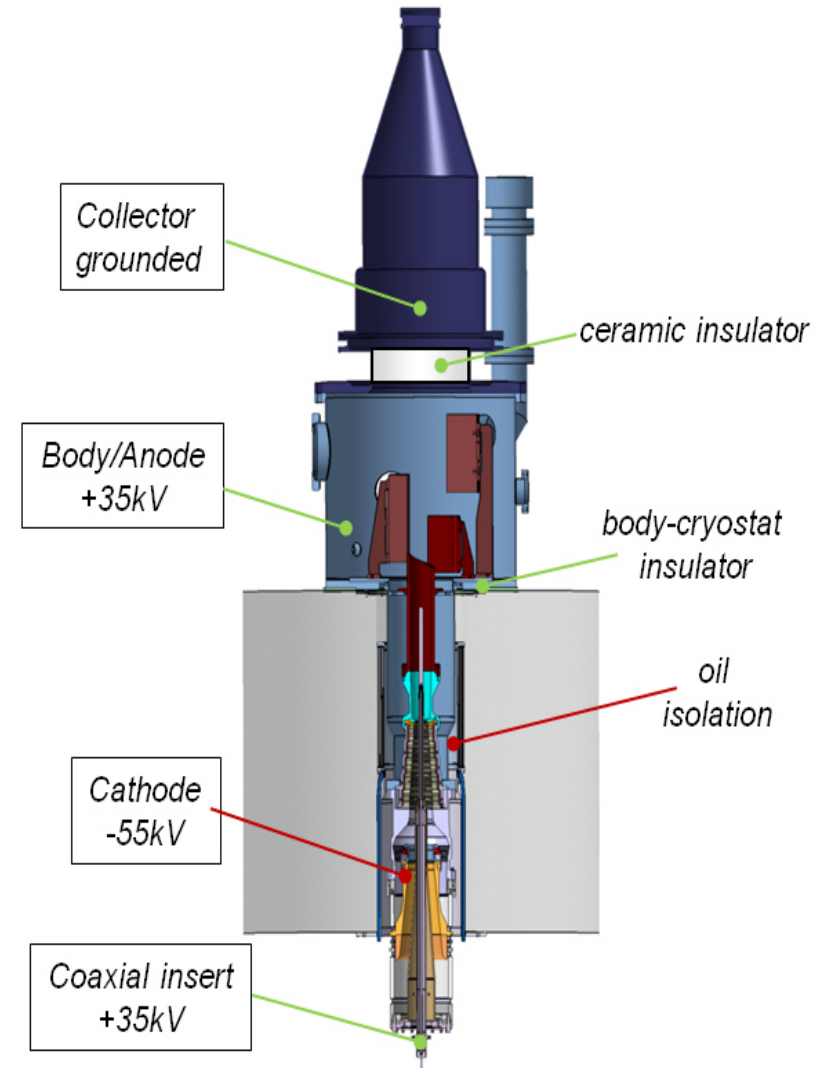
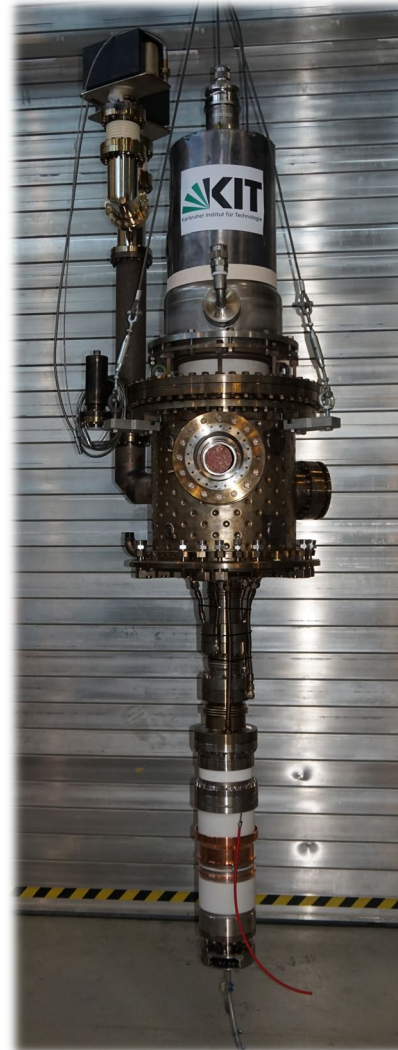
Coaxial

- + Reduced mode competition
→ operation at very high-order mode
 - + Reduced voltage depression
- ➡ **higher output power** ⬅
- coaxial insert:
additional risk of misalignment and thermal loading

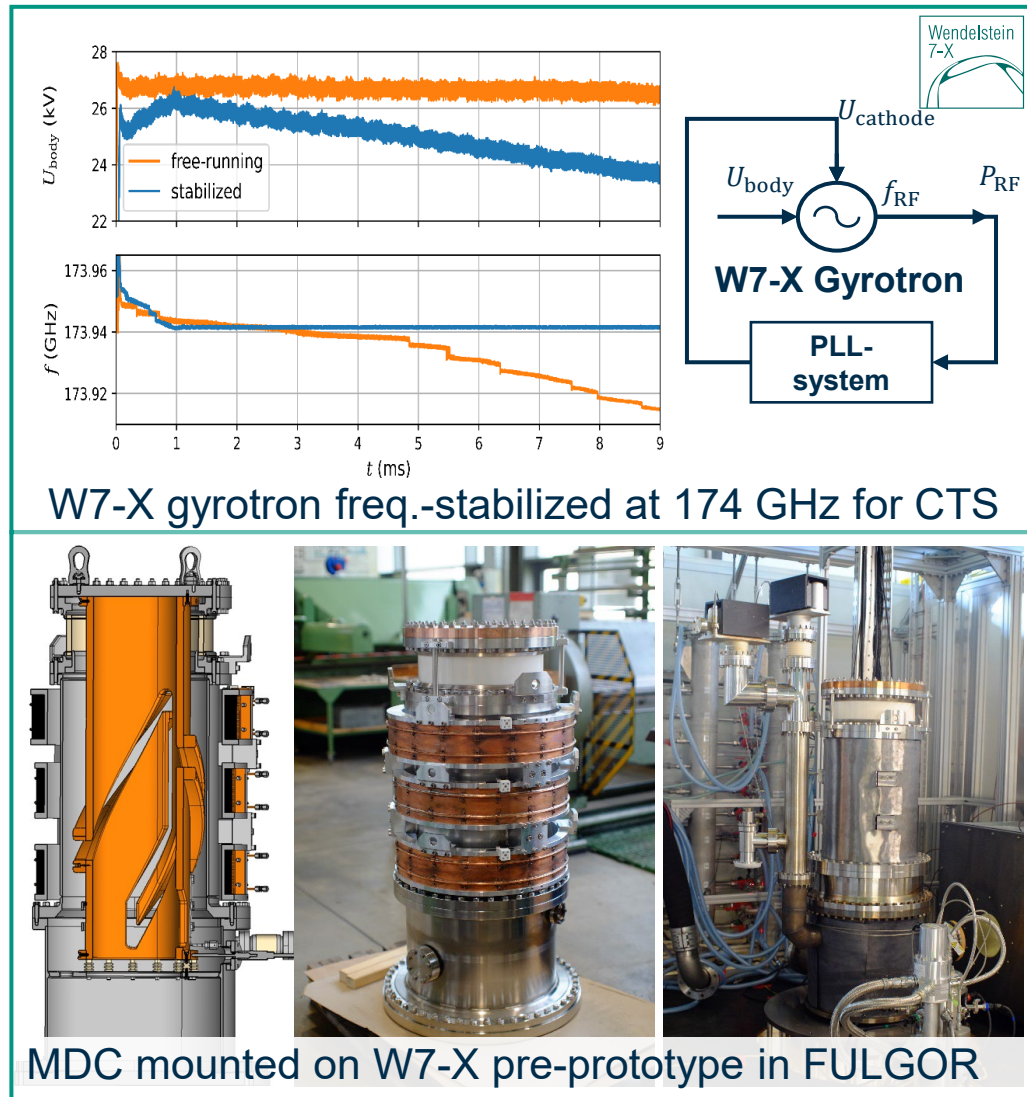


2 MW, 170 GHz Coaxial-Cavity Gyrotron

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 %



EUROfusion Developments



- 2 MW (< 1 s) modular coaxial pre-prototype prepared for test at longer pulses ≥ 50 ms
- FULGOR gyrotron test stand prepared for 240 GHz operation, 10.5 T gyrotron magnet ready for operation at KIT
- Multistage Depressed Collector (MDC) for short-pulse operation manufactured and first test done with W7-X SP pre-prototype in CEA magnet(bottom)
- Collaboration with IPP on Engineering Grant on PLL-controlled gyrotrons led to world-first 174 GHz diagnostics tool for W7-X (top)
- Enabling research (ENR) on gyrotrons operating at 2nd harmonics of electron cyclotron frequency in collaboration with NKUA

Total Gyrotron Efficiency

Velocity ratio (pitch factor)

$$\alpha = \frac{v_{\perp}}{v_{\parallel}} \approx 1.0 \dots 1.5$$

→ **50% - 70%**

of the electrons' kinetic energy is
in the perpendicular velocity $v_{\perp}$

Theoretically up to **72%**
of this energy can be
extracted by the rf field:

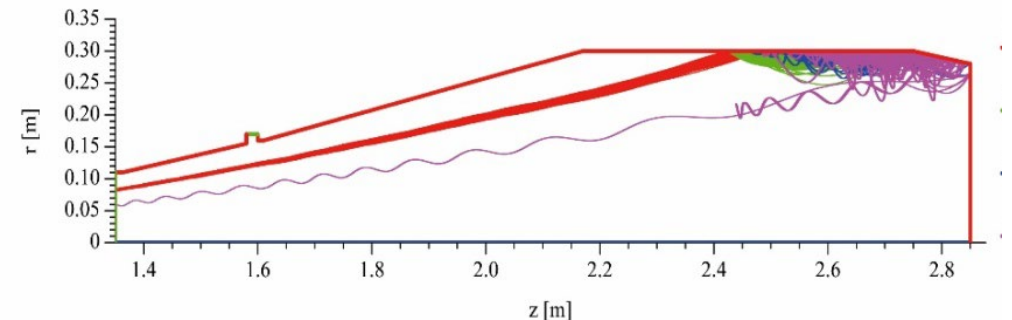
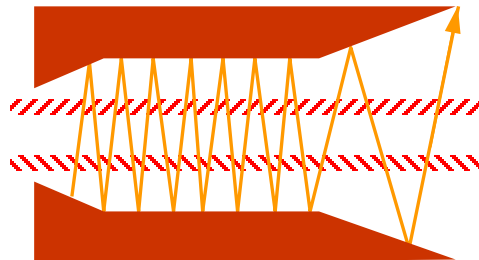
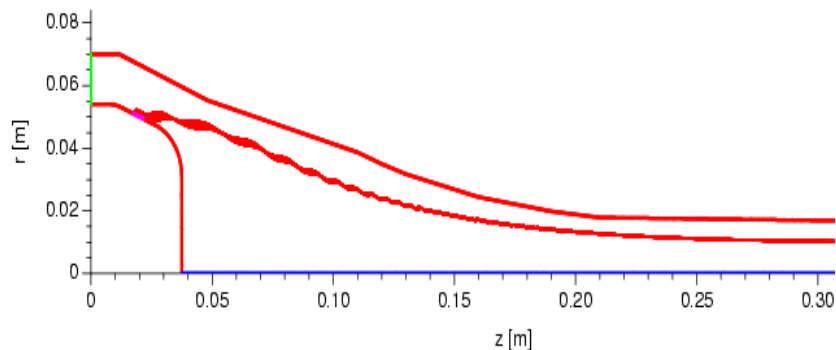
→ **Interaction
efficiency**

~25% - 40%

„Recycling“ by applying a retarding
potential at the collector
→ „depressed collector“

→ **Total gyrotron
efficiency**

40% - 70%



Multi-Stage Depressed Collectors (MDCs) – Mandatory to Increase the Total Gyrotron Efficiency η_{total}

Interaction efficiency: $\eta_{\text{int}} \approx 35 \%$

- Limited by pitch factor
- Optimization limited

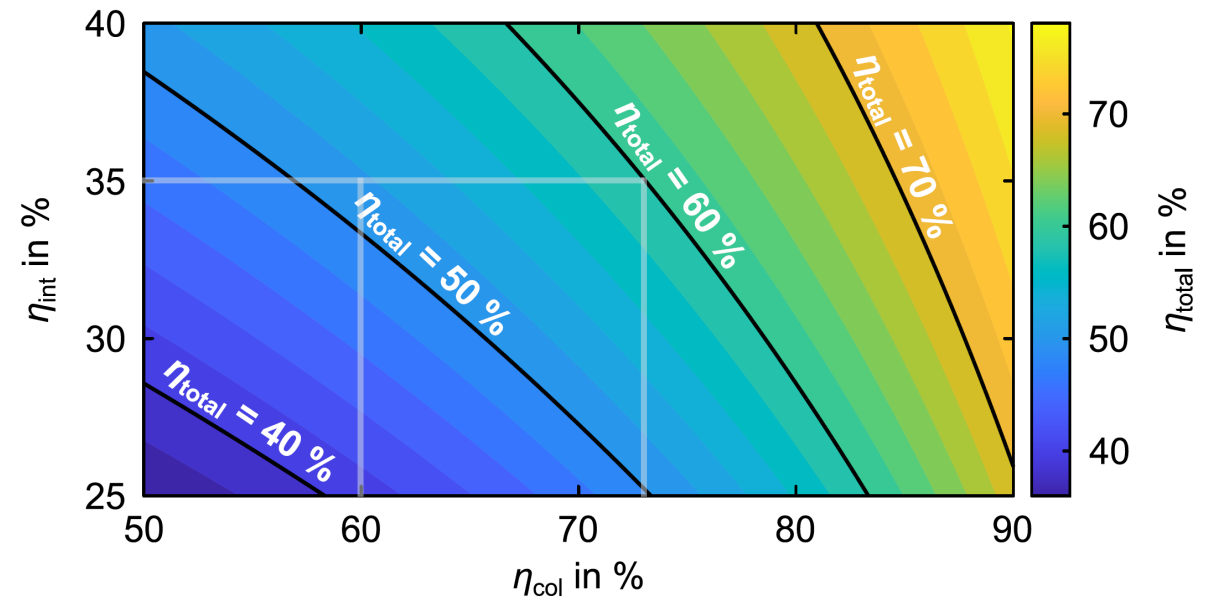
Transmission efficiency: $\eta_{\text{RF}} \approx 90 \%$ (estimated)

- After cavity interaction
- Ohmic losses
- Stray radiation

Collector efficiency: $\eta_{\text{col}} \approx 60 \%$

- State-of-the-Art SDC
- Recovered power / spent beam power

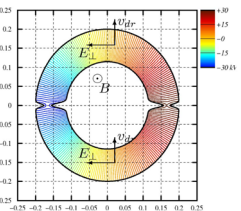
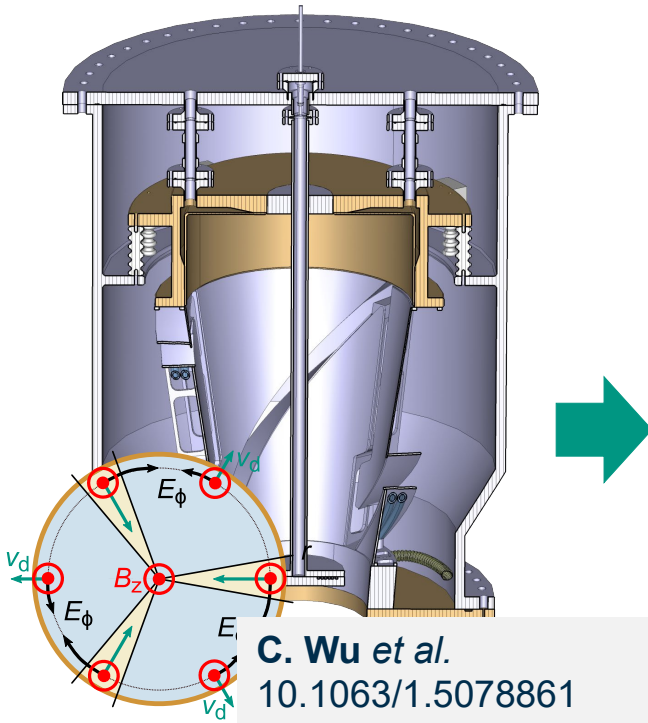
$$\eta_{\text{total}} = \frac{\eta_{\text{int}} \cdot \eta_{\text{RF}}}{1 - (1 - \eta_{\text{int}}) \cdot \eta_{\text{col}}}$$



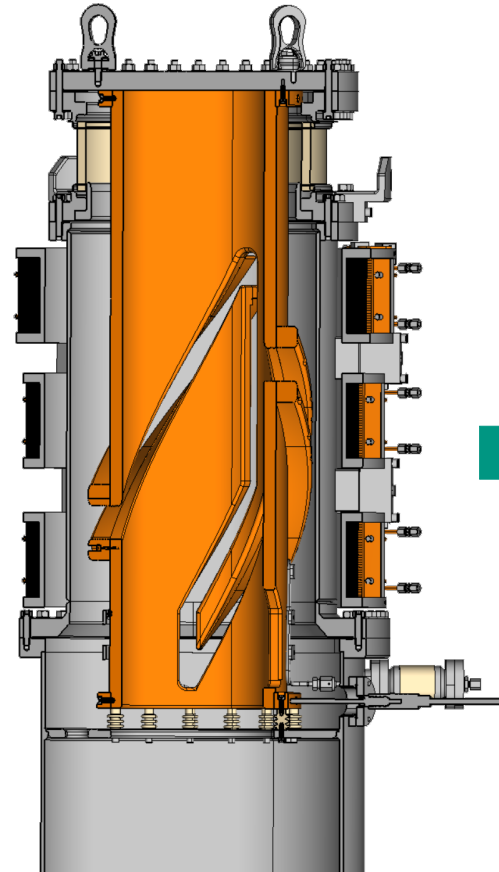
➡ **Multistage Depressed Collector (MDC)**

From Short-Pulse MDC to a CW Compatible Design

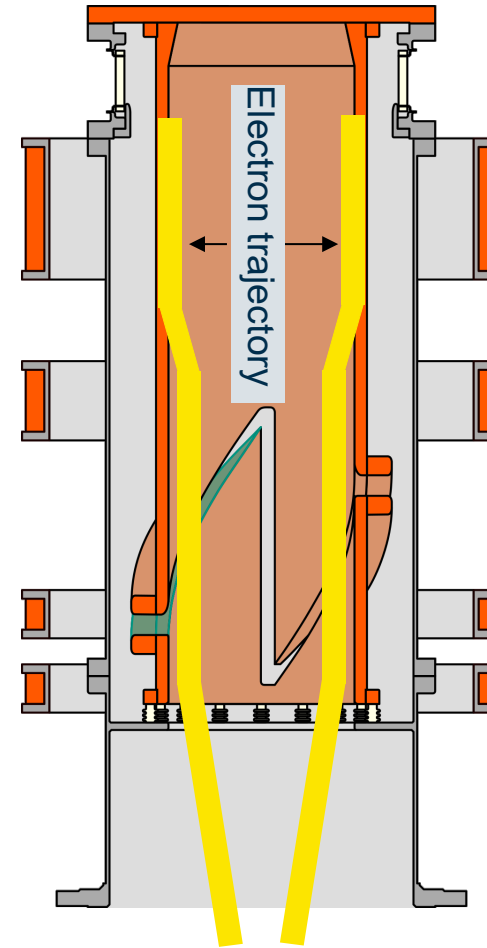
- Triple helix for reduced length
- Helical extensions for reduced reflected current



Pagonakis et al.
10.1109/TPS.2008.917943



B. Eil et al.
10.1051/epjconf/202431304006

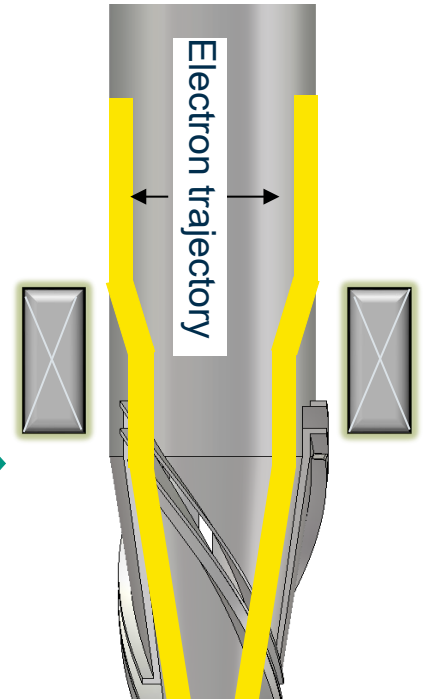


Upscaled CW MDC

B. Eil et al.
10.1109/TED.2023.3234885



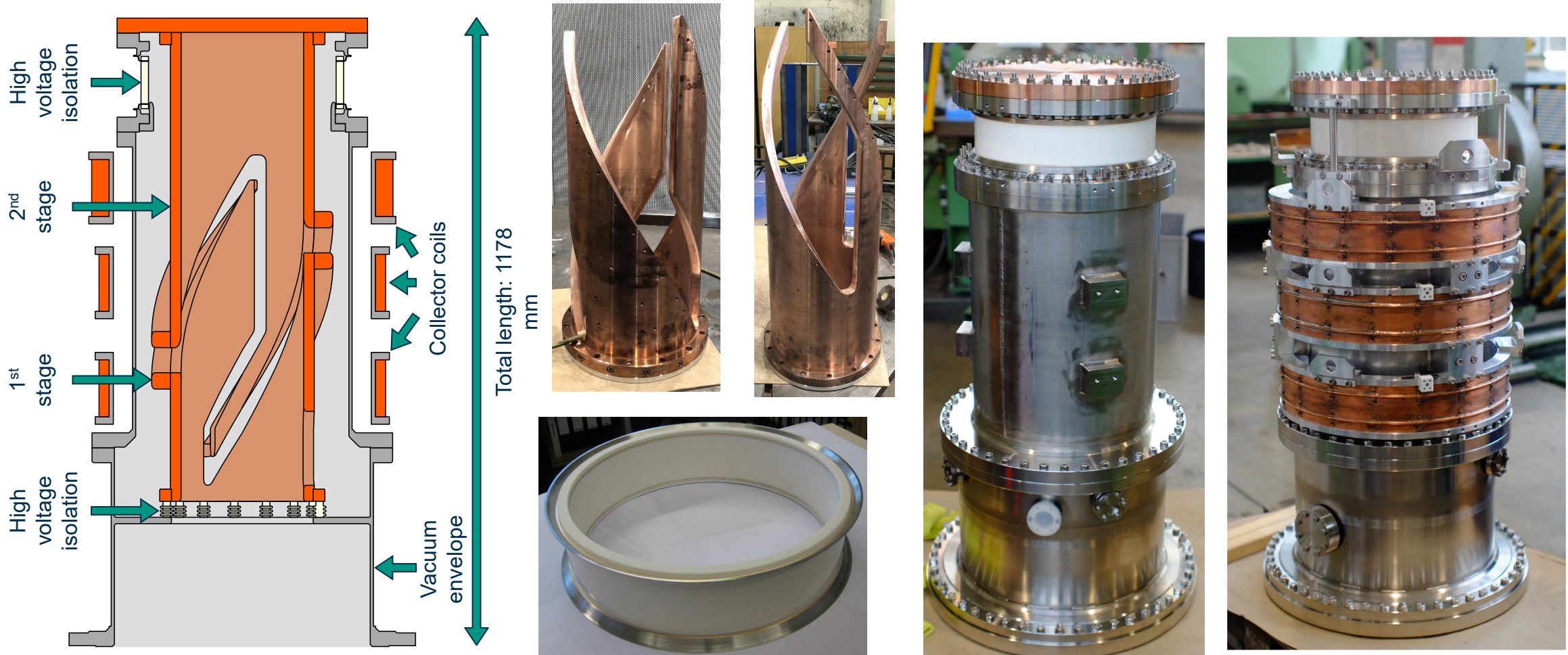
Optimized CW MDC



B. Eil et al.: Design Improvements of the Continuous Wave Gyrotron Multistage Depressed Collector at KIT, EC 23, Barcelona, 2026

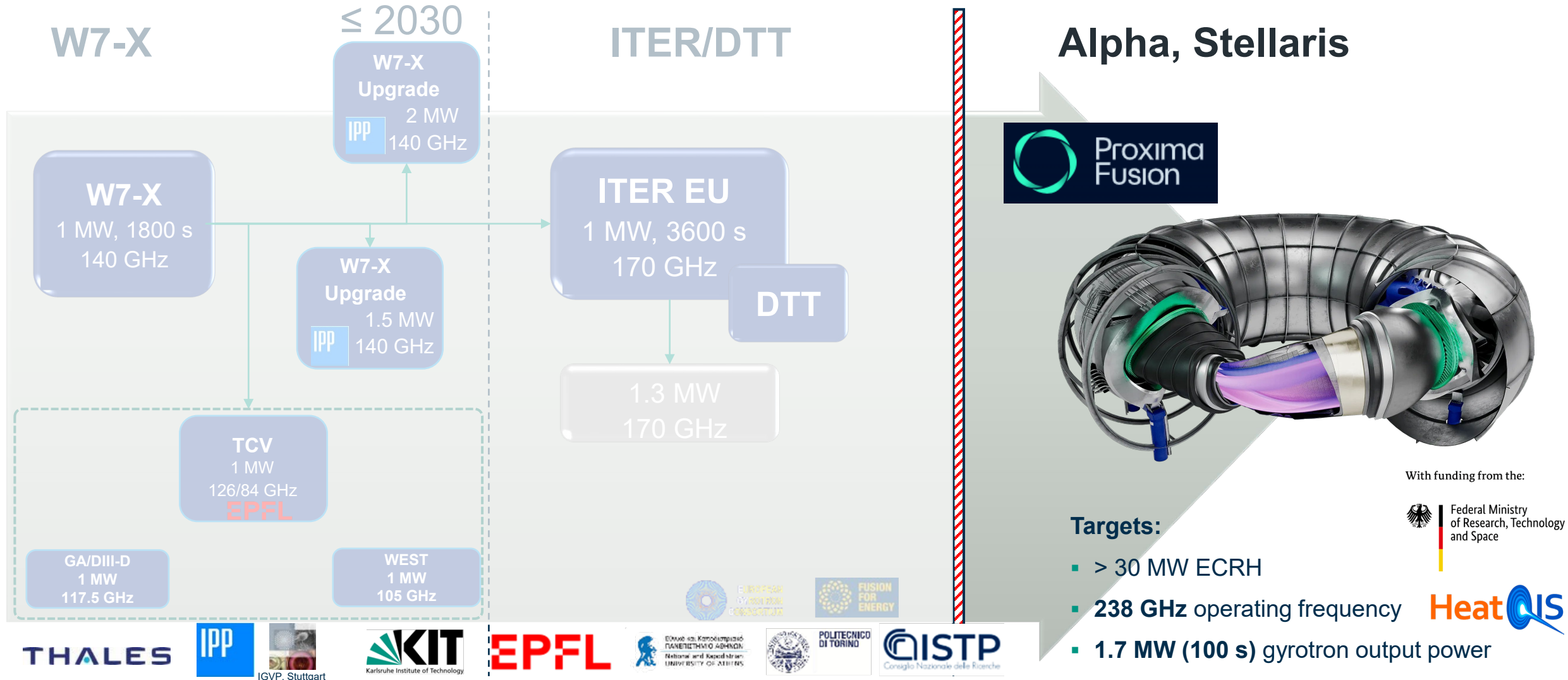
First Short-Pulse Multi-Stage Depressed Collector (MSDC)

Short-pulse prototype, electron beam sorting based on $E \times B$ drift



B. Ell et al., IVEC, 2021, DOI: 10.1109/IVEC51707.2021.9722425

Towards One of Germany's Next Fusion Devices



BMFTR Project HeatQIS: Development of EC Components for Proxima Alpha

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)

HeatQIS AP 2:

Diamond disks for gyrotron microwave power extraction and safety-critical torus windows

Steering options:

- Mechanical steering
- Electronic frequency steering

Plasma

HeatQIS AP 3:

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

HeatQIS AP 1(a):

238 GHz / 1,7 MW (100 s) gyrotron demonstrator

Diamond Windows

HeatQIS AP 1(b):

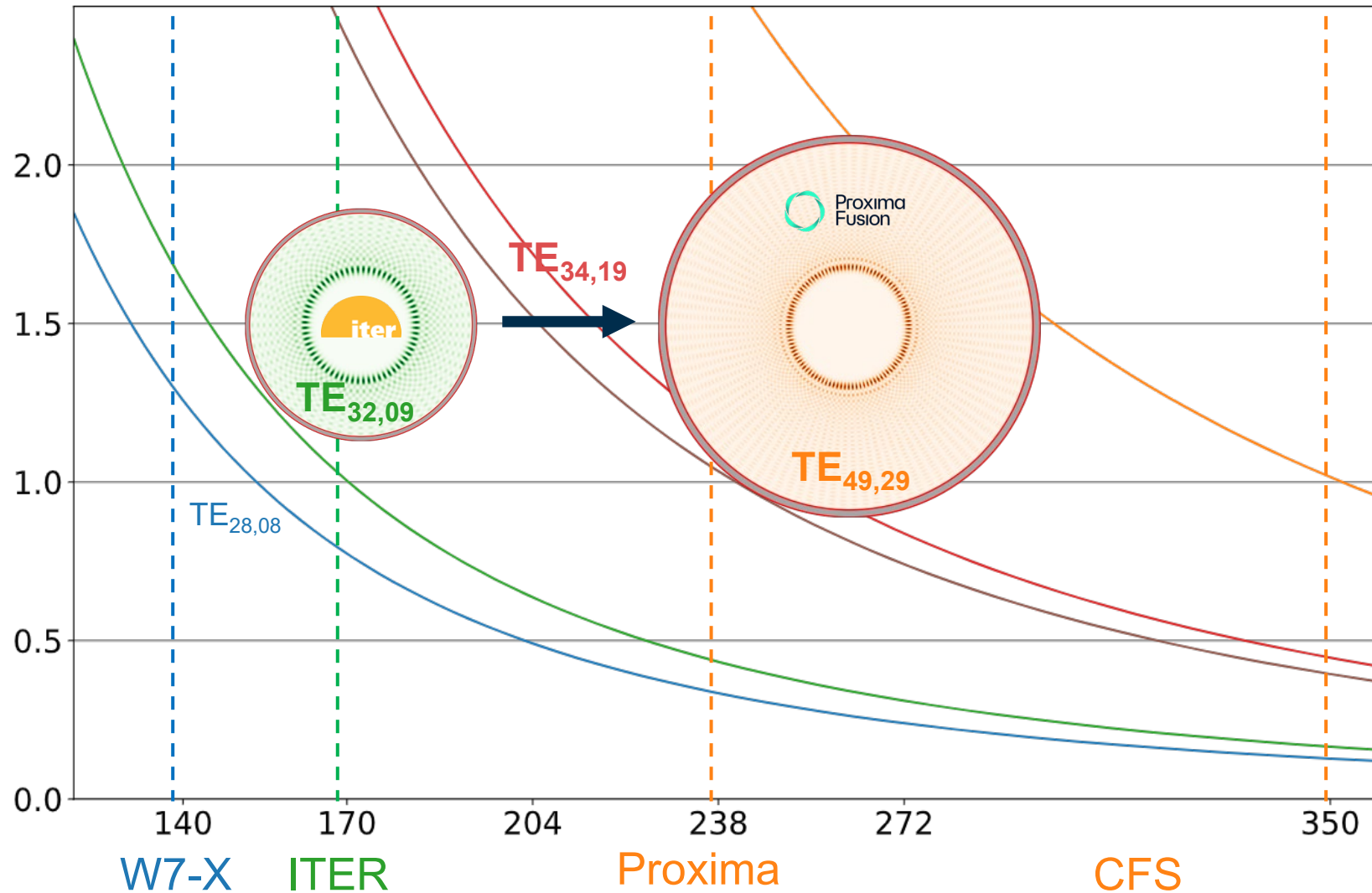
Conceptual design of a HTS gyrotron magnet

cher Design 2024



Gyrotron

From „170 GHz“ to „238 GHz“ and from „1 MW“ to „2 MW“

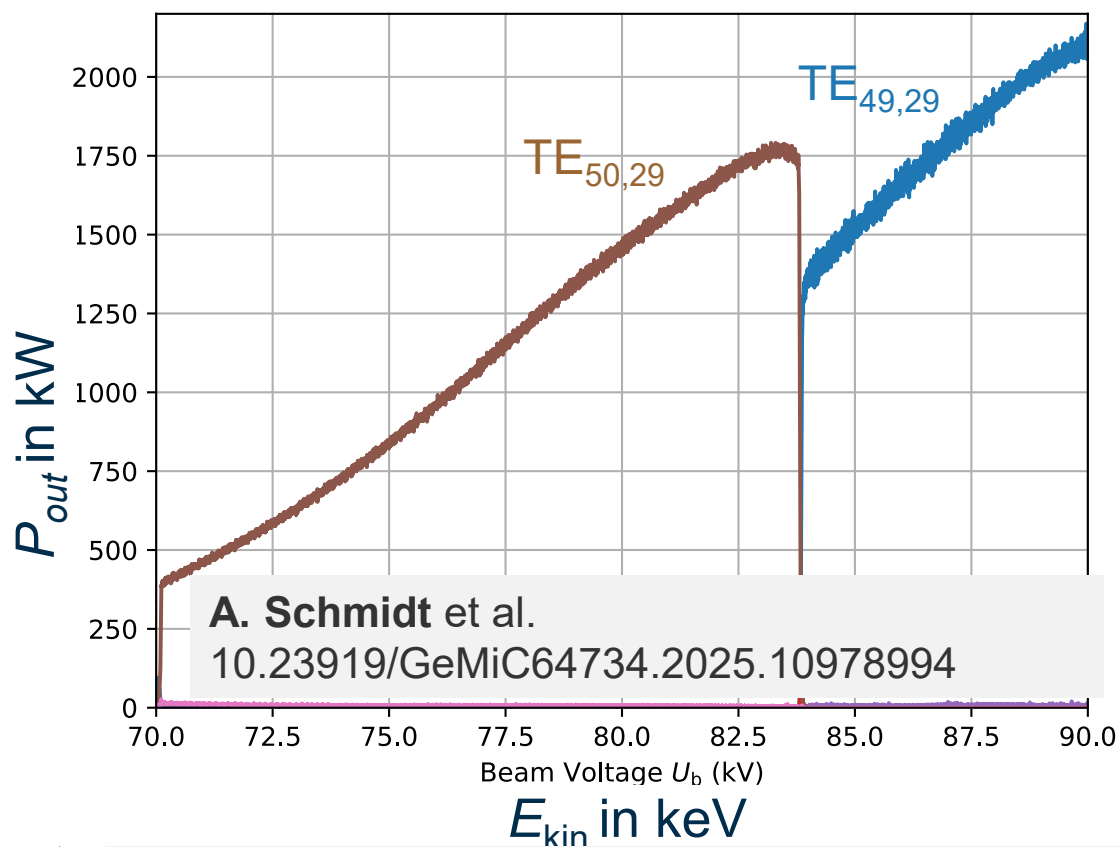


$$\rho \sim f^{\frac{5}{2}} \cdot \left[\chi_{m,p}^2 \cdot \left(1 - \frac{R_{\text{caustic}}}{R_{\text{cavity}}} \right)^2 \right]^{-1}$$

Q	1400
L/λ	9
ρ	$2 \frac{\text{kW}}{\text{cm}^2}$
σ	$1.73 \cdot 10^7 \frac{\text{S}}{\text{m}}$

Interaction Simulation of a TE_{49,29} –Mode Cavity at 238 GHz

- Self consistent time-dependent multi-mode simulation: ROCK^[1]
- Using electron beam parameters from ESRAY^[2]
- Considering over 40 competing modes



Parameter	Value
B	9.62 T
U	90 kV
I	63 A
α	1.3
P	2.1 MW
$\eta_{\text{interaction}}$	37 %
ρ	2.1 kW/cm ²

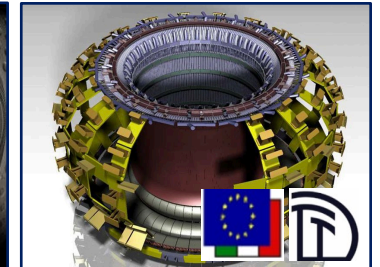
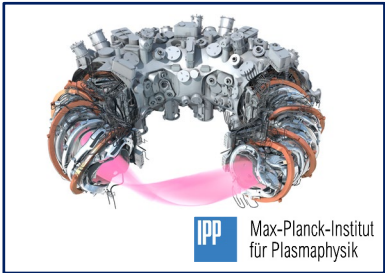
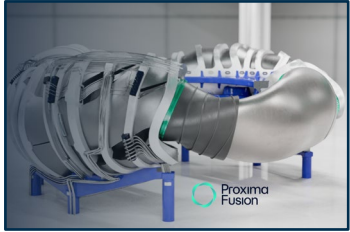
C. Wu et al., „ROCK: a flexible gyrotron cavity simulation toolkit using an accuracy-improved time-dependent self-consistent multimode interaction model,“ J Infrared Milli Terahz Waves 46, 50 (2025). <https://doi.org/10.1007/s10762-025-01065-5>

S. Illy et al., Gyrotron electron gun and collector simulation with the ESRAY beam optics code. 1-2. 10.1109/IVEC.2015.7223779



Chuanren Wu et al., "Accuracy-enhanced Model and Flexible Design of the New KIT Gyrotron Interaction Code ROCK", **Session 1A6**

Gyrotron Research and Development at KIT



- Member of European Gyrotron Consortium (EGYC) for ITER
- Partner of IPP for 1 MW and 1.5 MW / 2 MW developments for W7-X (BMFTR HiPMiB)
- EUROfusion tasks leader for gyrotron R&D, leading the 2 MW coaxial-cavity gyrotron technology, Multistage Depressed Collector (MDC), operation at 2nd harmonics, electronic stability and frequency control
- **Lead in test and validation of megawatt-class gyrotrons (FULGOR)**
- Partner in gyrotron developments for European and worldwide nuclear fusion experiments such as TCV, CEA/WEST, DTT and GA/DIII-D
- Project coordinator for BMFTR project HeatQIS together with PROXIMA Fusion, Diamond Materials and THALES towards 238 GHz gyrotrons, EC launchers and windows

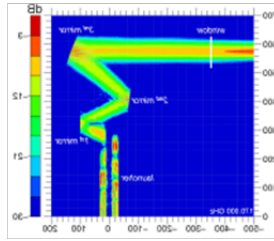
KIT Tools for Gyrotron Simulation and Design

KARLESSS

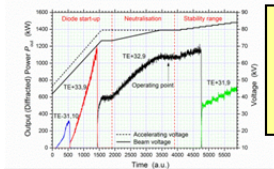
SIMPLERICK

ROCK

Collector: Simulation with **ESRAY**



Launcher / quasi-optical System: **TWL_DO, Surf3D**



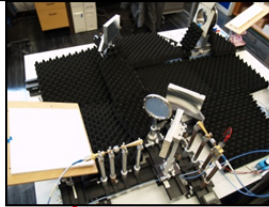
Interaction: **SELFTEURIDICE, CAVITY**



Magnet: **MAGGEN**

Electron gun: **ARIADNE, ESRAY**

RF window
scalar Network analyzer



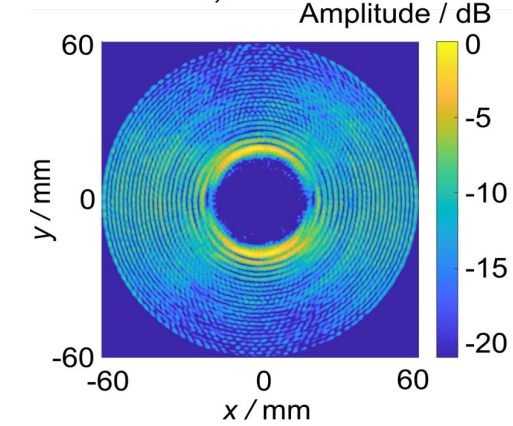
Spectrum, frequency

Launcher / quasi-optical System: Low-power measurements with 3D-Scanner

Mode generator, 3D-Scanner, vector network analyzer



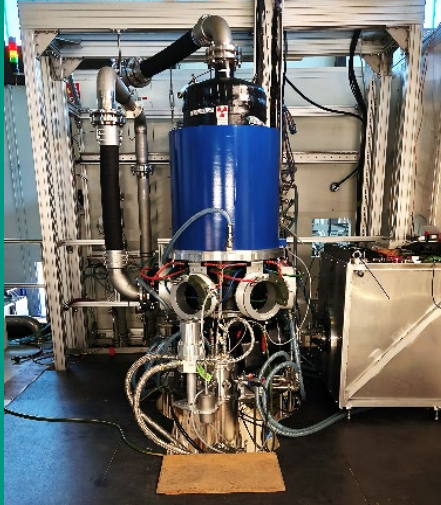
TE_{40,23}-mode



A. Marek et al., *EPJ Web of Conferences* (Vol. 149, p. 04016). EDP Sciences (2017)
A. Marek et al., *IEEE Transactions on Electron Devices* 69, no. 8 (2022)

Gyrotron Test Stand(s) at IHM

FULGOR



LEGACY west



LEGACY east



Simultaneous
operation

CRYOGENIC 10.5 Tesla gyrotron magnet



S. Stanculovic et al., Expansion of MW-Class ECRH Gyrotron Testing Capabilities at KIT: From Industrial Validation to Next-Generation Concepts, EC 23, Barcelona, 2026

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

Fusion Long-Pulse Gyrotron Laboratory – **FULGOR**

Gyrotron output power

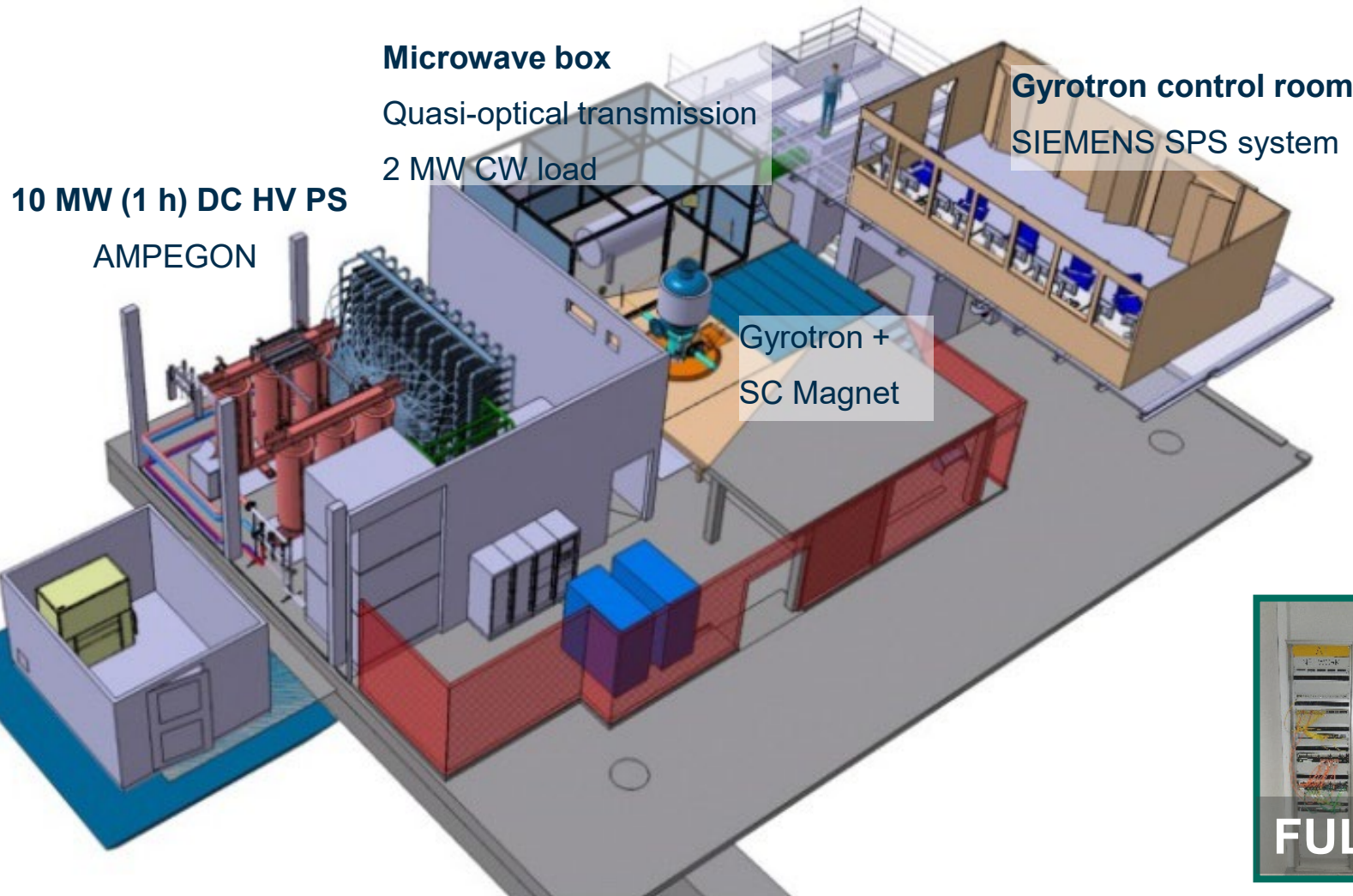
- 2 MW (CW)
- 4 MW (3600 s) in dual-output configuration (*additional cooler + test box*)

Gyrotron operating frequency

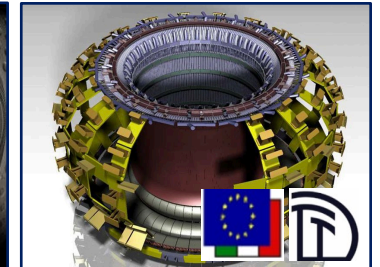
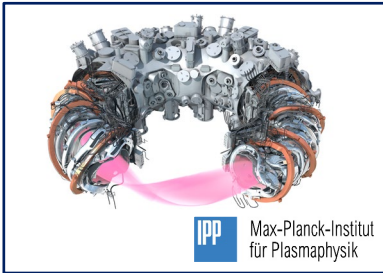
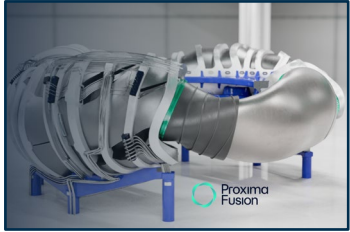
- up to 240 GHz (with 10.5 T SC magnet)

Gyrotron total efficiency

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



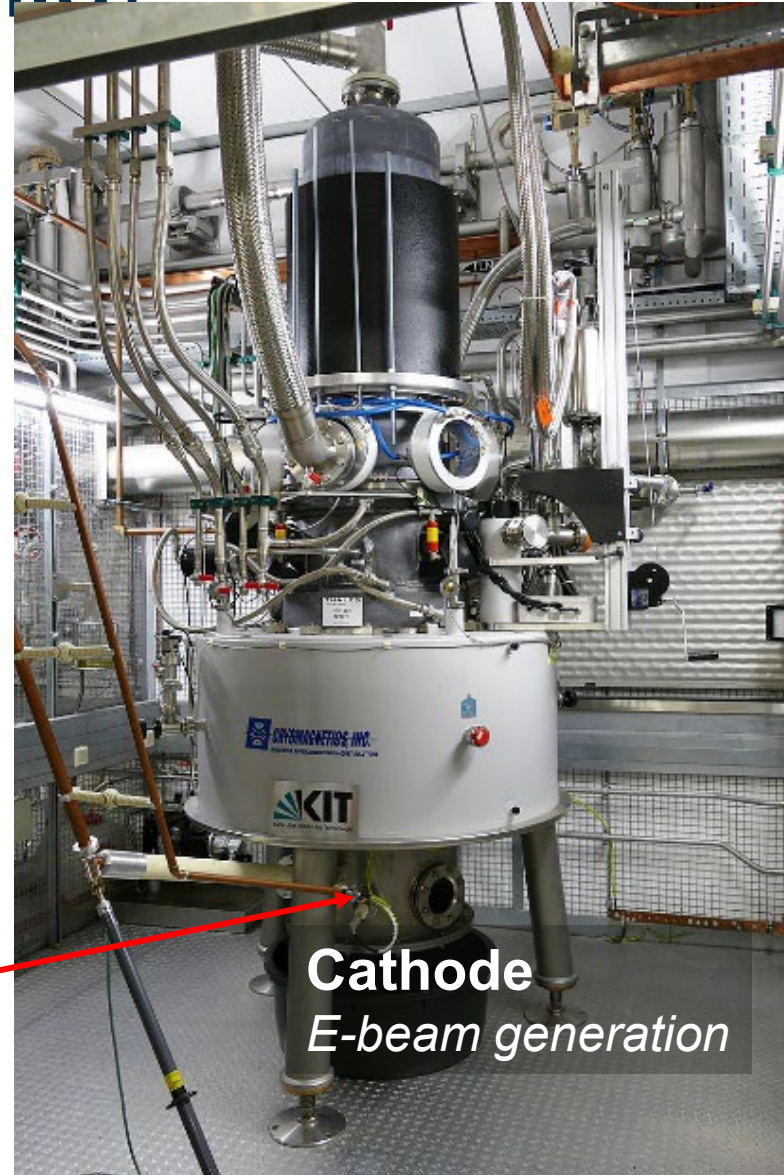
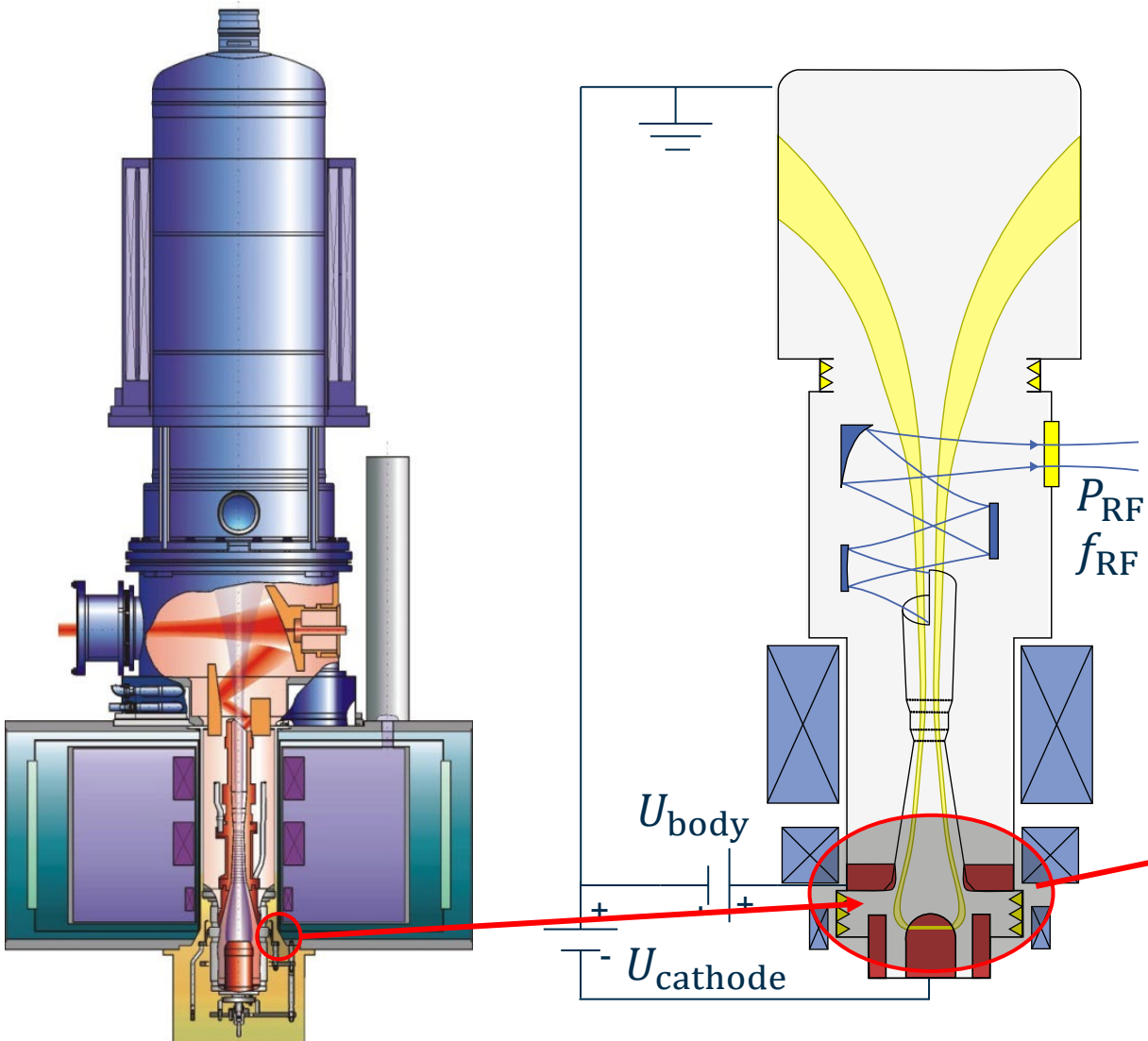
Gyrotron Research and Development at KIT



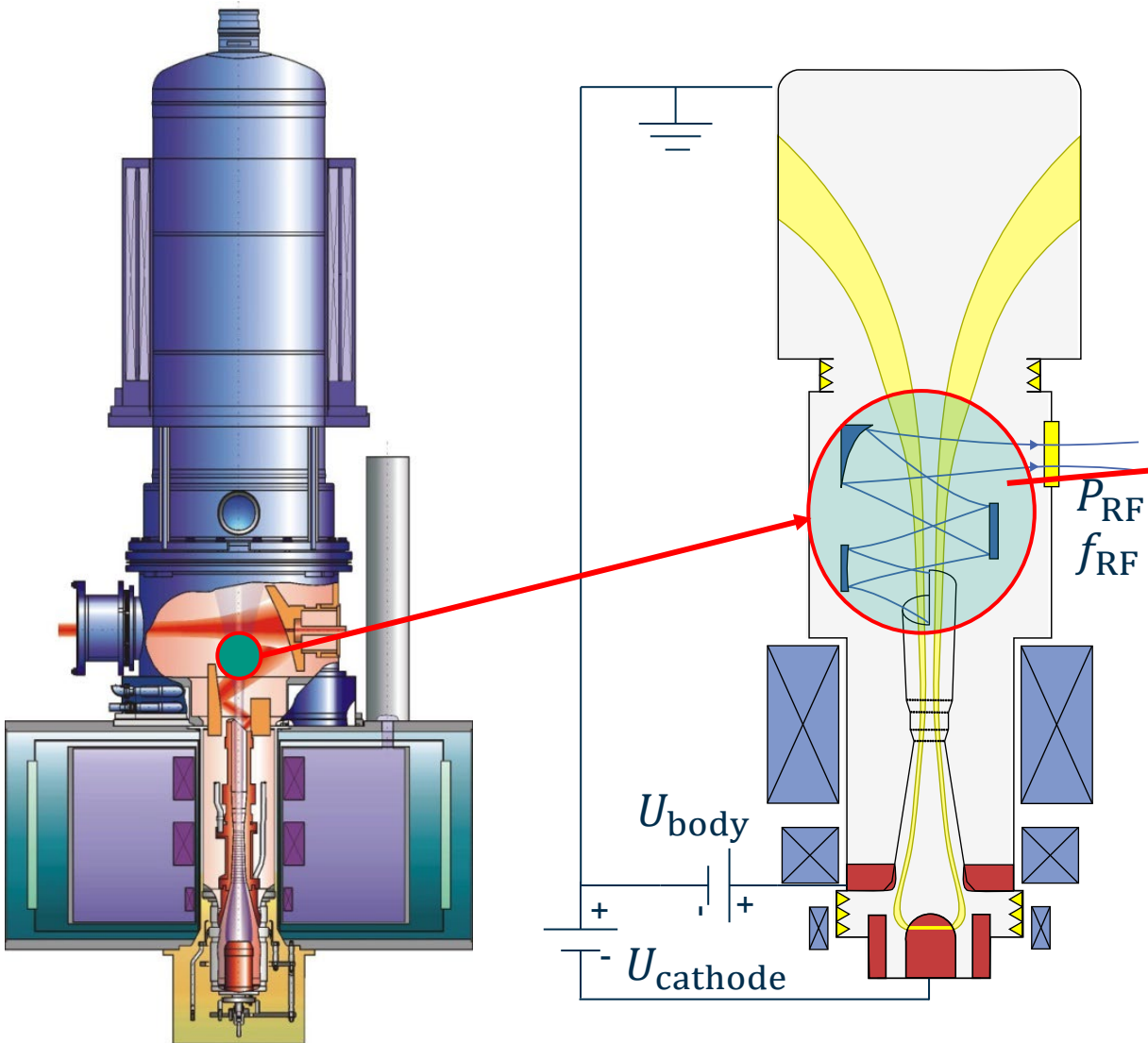
- **Member of European Gyrotron Consortium (EGYC) for ITER**
- Partner of IPP for 1 MW and **1.5 MW / 2 MW developments for W7-X (BMFTR HiPMiB)**
- **EUROfusion tasks leader for gyrotron R&D**, leading the 2 MW coaxial-cavity gyrotron technology, Multistage Depressed Collector (MDC), operation at 2nd harmonics, electronic stability and frequency control
- Lead in test and validation of megawatt-class gyrotrons (**FULGOR**)
- Partner in gyrotron developments for European and worldwide nuclear fusion experiments such as **TCV, CEA/WEST, DTT** and **GA/DIII-D**
- **Project coordinator for BMFTR project HeatQIS** together with **PROXIMA Fusion, Diamond Materials** and **THALES** towards 238 GHz gyrotrons, EC launchers and windows



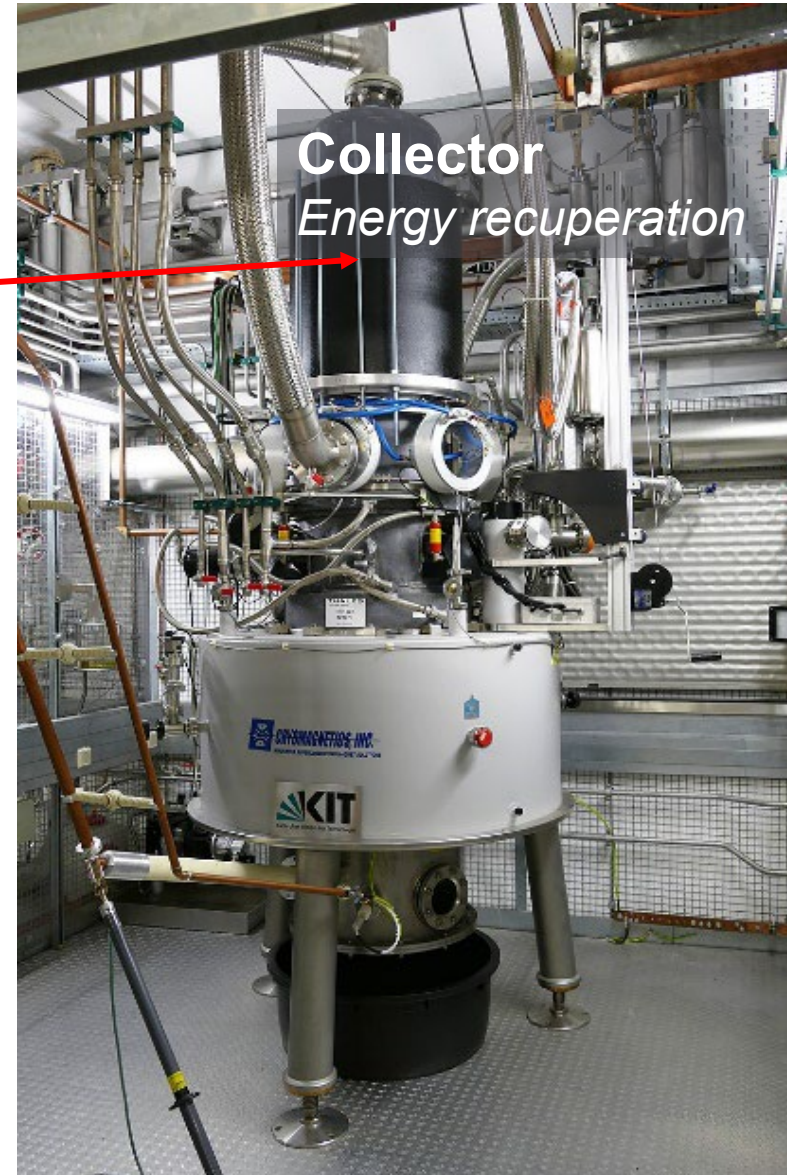
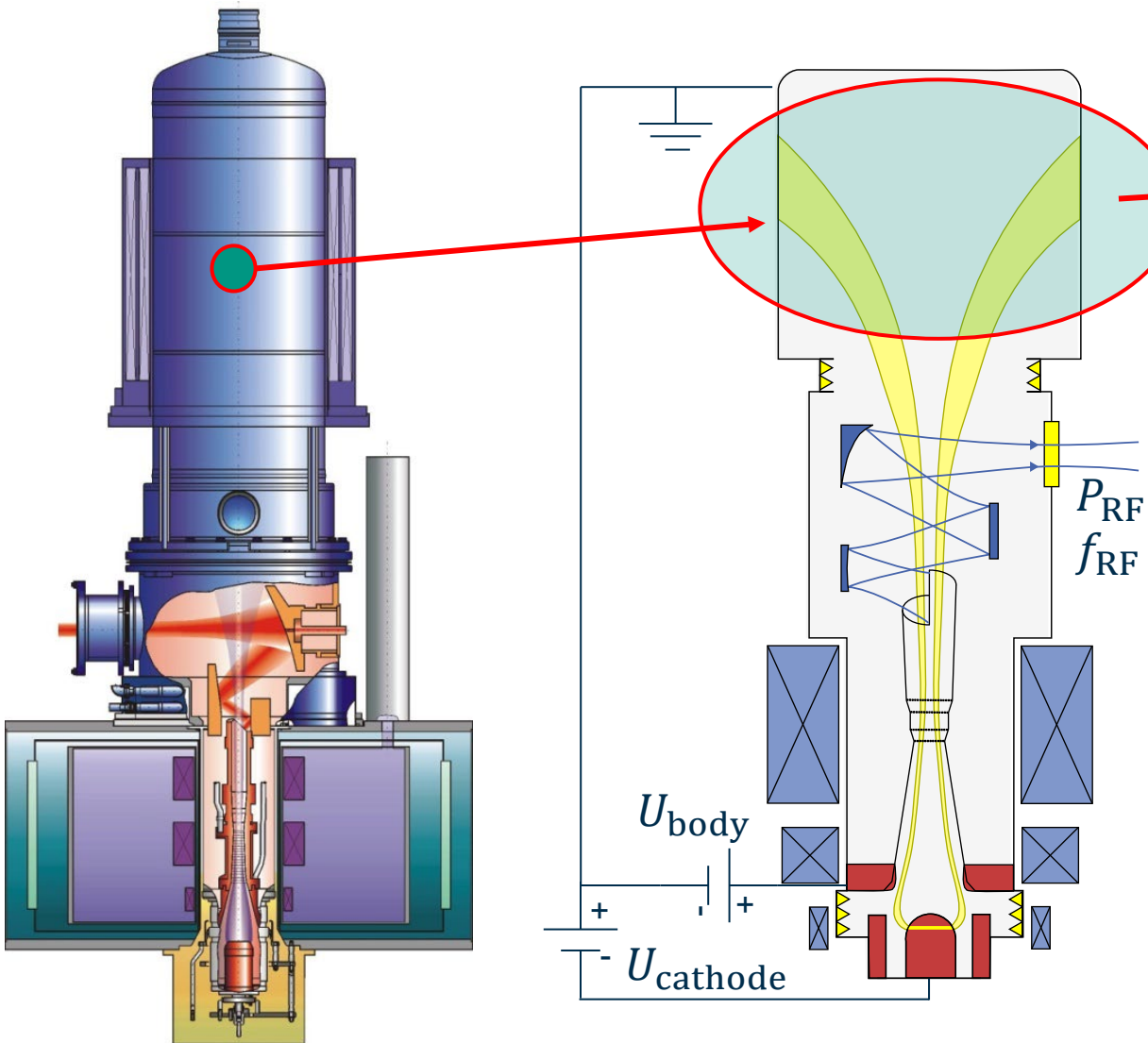
The Magnetron Injection Gun (MIG)



The Launcher and Quasi-Optical System



The Collector



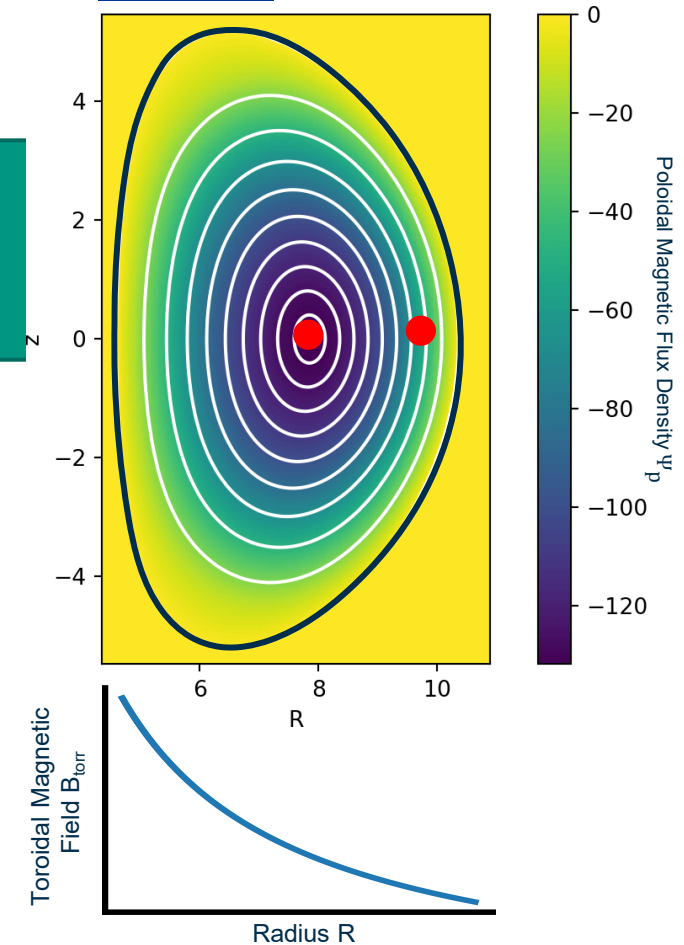
Technologies Considered within EUROfusion AWP-24

AWP-24 (2024-2026): Novel dual-harmonic gyrotrons for DEMO featuring fast switching between distant frequencies: concept elaboration and experimental demonstration of key elements

Target: A MW class gyrotron operating at 1st harmonic ($s = 1$) and at 2nd harmonic ($s = 2$) of the electron cyclotron frequency
→ **Fast (sub-second) switching between distant frequencies**

Following two enabling technologies are included:

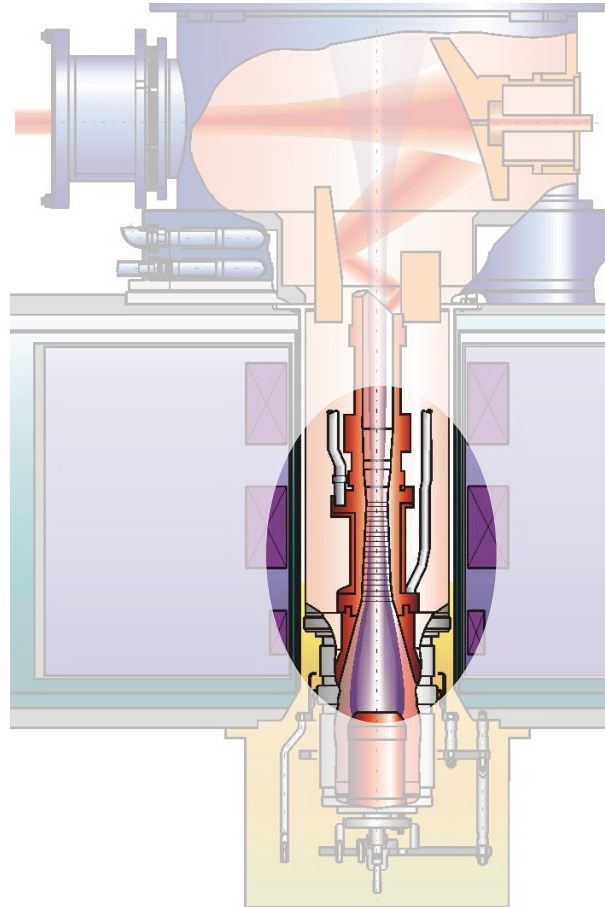
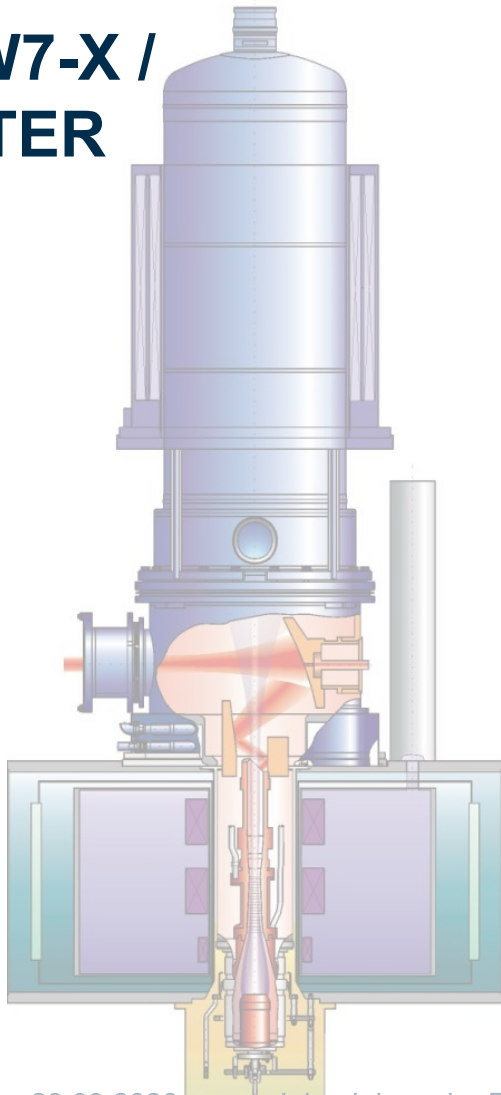
1. The **coaxial-type cavity technology** that is specifically adapted to the operation at 2nd harmonics in combination with advanced inner and outer corrugations
2. The **Multistage Depressed Collector (MDC) technology** based on $E \times B$ drift concept



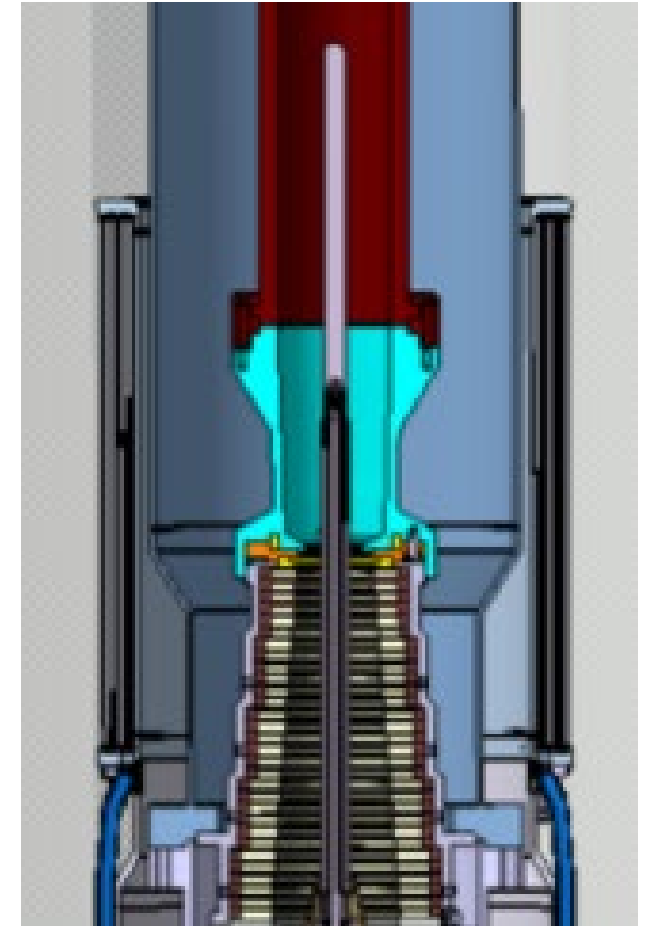
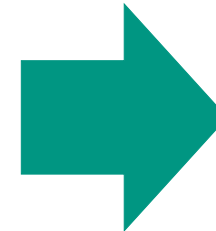
S. Illy et al., "Dual Harmonic Gyrotron Operation for Enhanced Plasma Heating and Stabilization, EC 23, Barcelona, 2026

Towards 1.7 MW 238 GHz Gyrotron for Proxima Fusion

W7-X /
ITER



Hollow cavity



Coaxial cavity