Karlsruhe Institute of Technology

Recent Status of Gyrotron Research and Development at KIT as Part of the European Fusion Gyrotron Program

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Institute for Pulsed Power and Microwave Technology (IHM)

Collaborating institutions and industrial partners

THALES · EPFL École Polytechnique Fédérale de Lausanne · Swiss Plasma Center · National Programme of Controlled Thermonuclear Fusion · IFP Istituto di Fisica del Plasma "Piero Caldirola", Consiglio Nazionale delle Ricerche · Universität Stuttgart

This work is partly supported by Fusion for Energy under Grants F4E-GRT-432 and F4E-GRT-553 to the European Gyrotron Consortium (EGYC), F4E-OPE-458 to KIT and F4E-OPE-447 to TED. EGYC is a collaboration among SPC, Switzerland; KIT, Germany; HELLAS, Greece; IFP-CNR, Italy.
Other part of this work has been partly carried out within the framework of the EUROfusion Consortium and has received funding friom the European Union's Horizon 2020 Research and Innovation Programme under grant agreement 633053.
The views and opinions expressed herein do not necessarily reflect those of the European Commission.

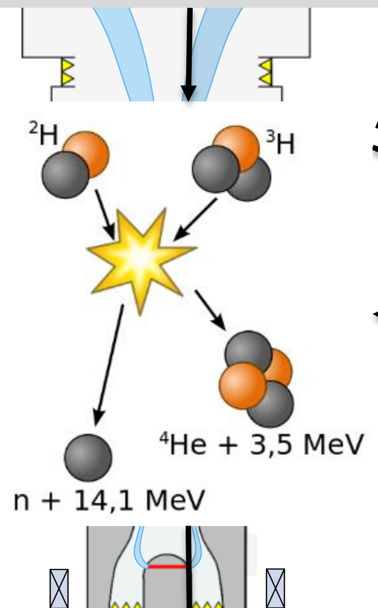
Fusion for Energy · EUROfusion

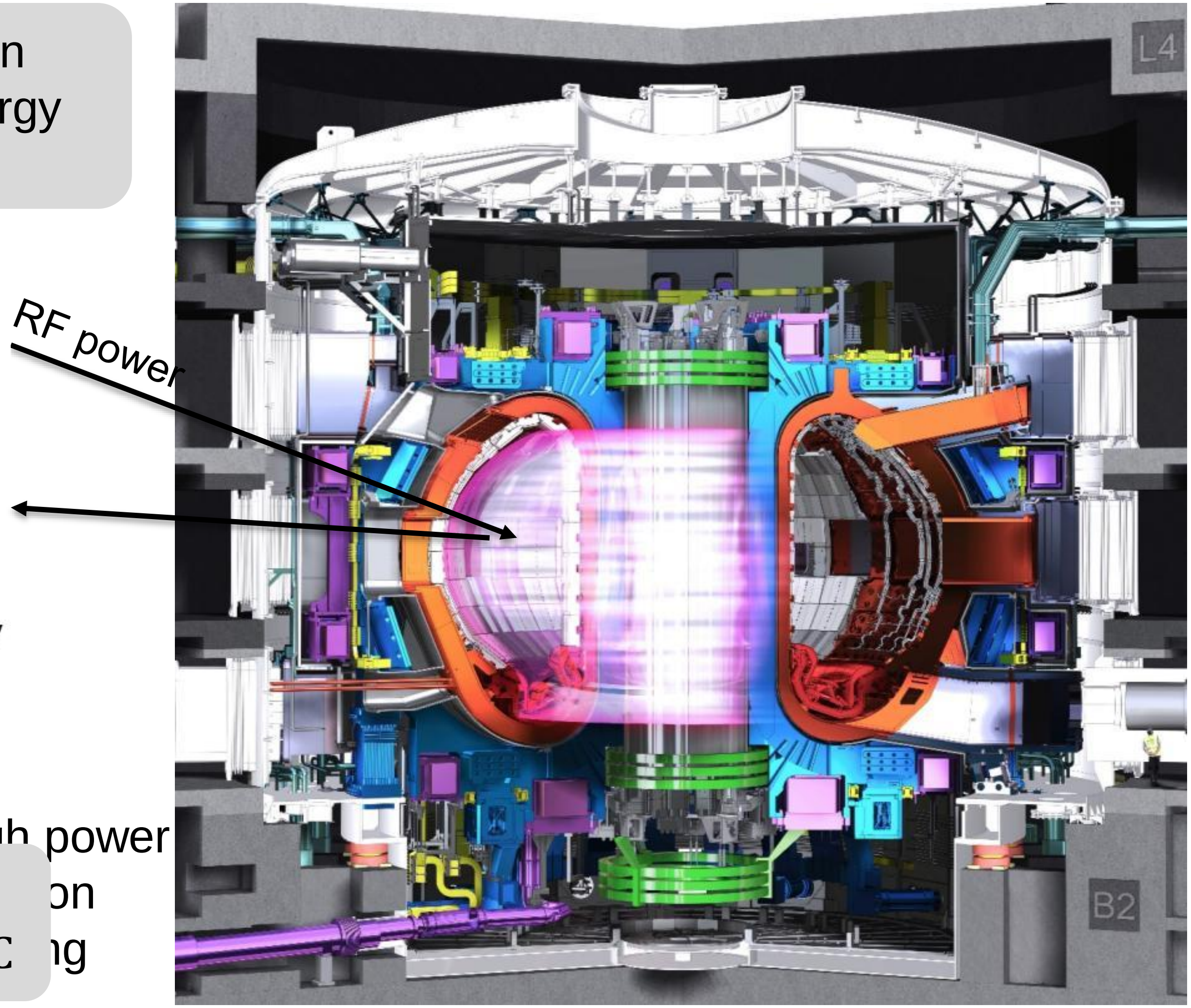
Outline

- Introduction
- Basic Principles of Gyrotron Operation
- In-House Design Tools for Gyrotron Development
- ECRH / Gyrotron Development Projects at IHM
- Project FULGOR: 10 MW Test Stand for Future DEMO Gyrotrons
- Conclusion

Introduction: Nuclear Fusion & ECRH

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

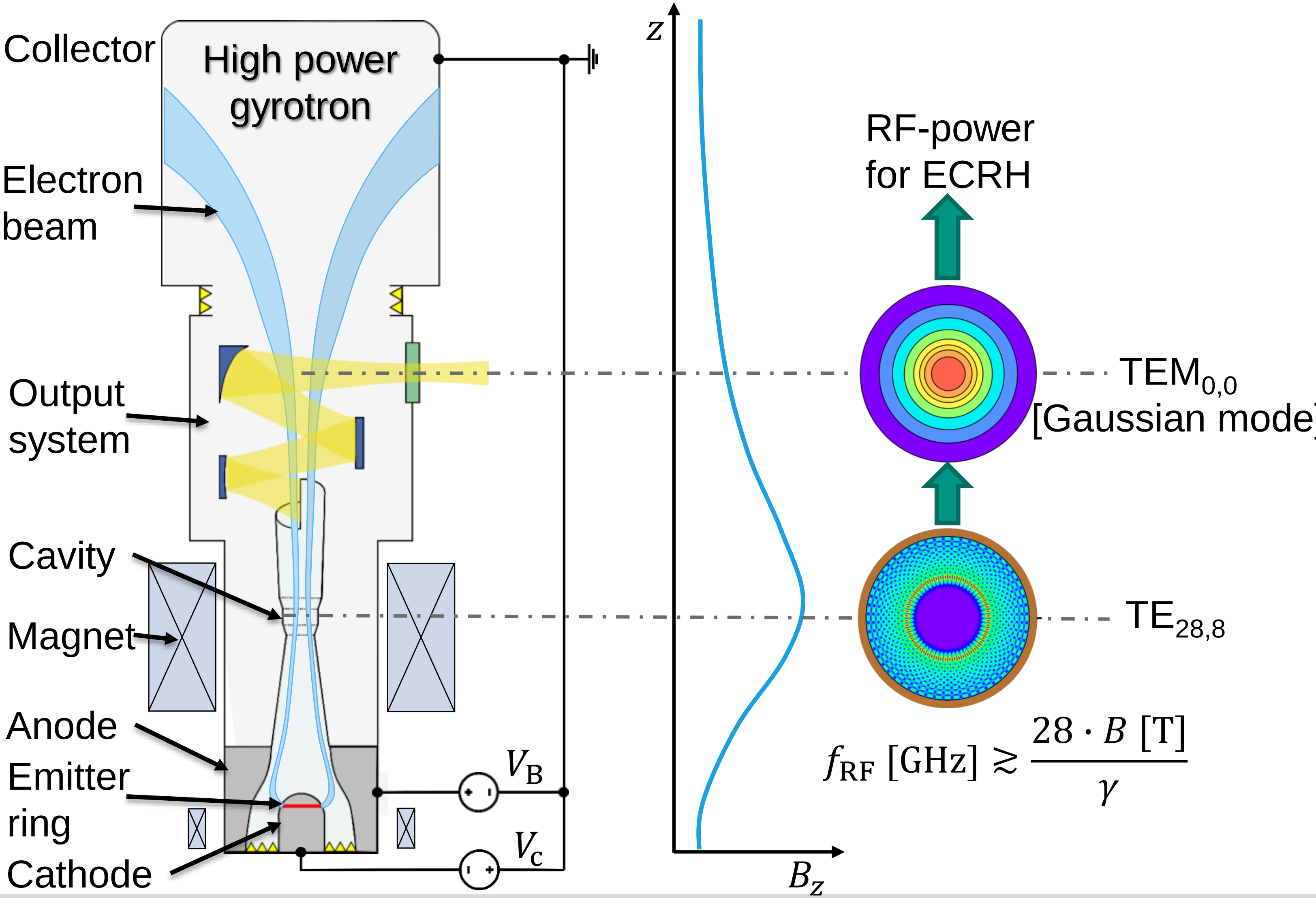




Gyrotrons are used as high power microw... on Cyclotr... ng (ECRH).

Temperature: 100-200 million ℃

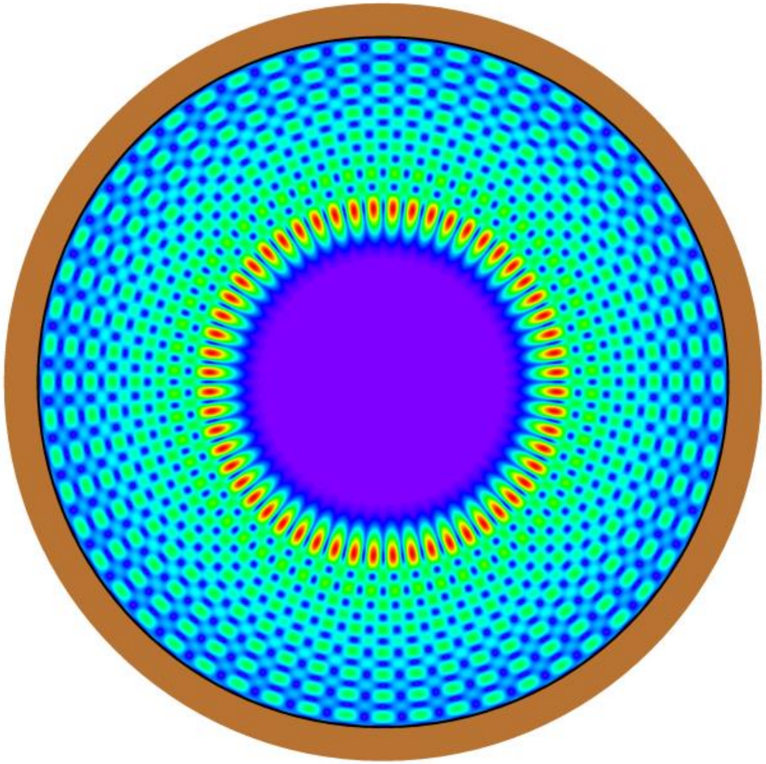
Introduction: High Power Gyrotrons



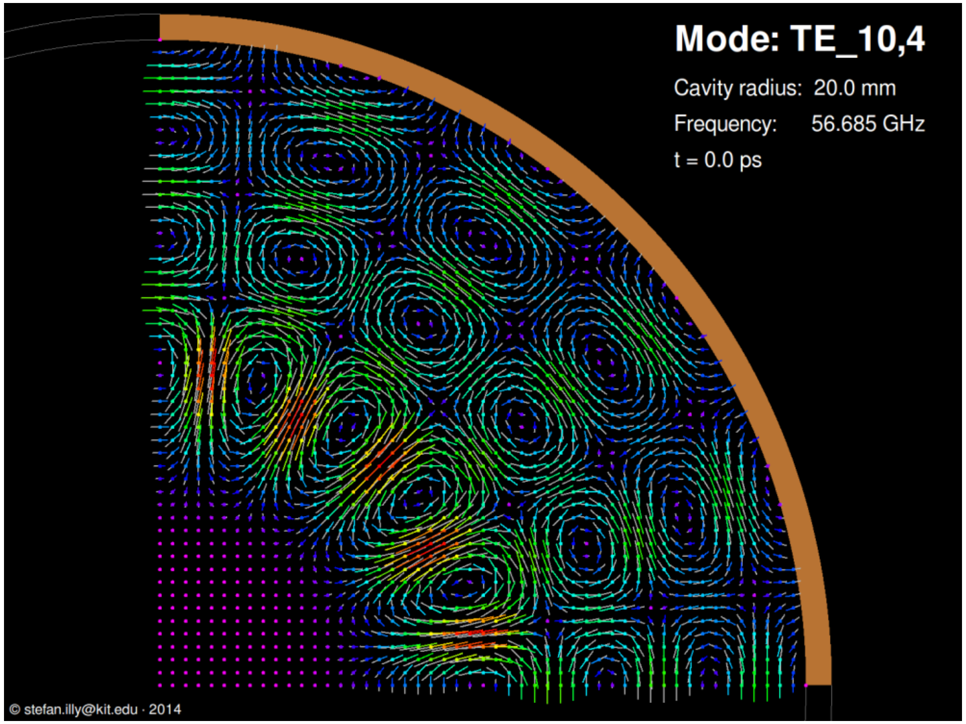
$$f_{RF}\,[\mathrm{GHz}] \gtrsim \frac{28 \cdot B\,[\mathrm{T}]}{\gamma}$$

Electromagnetic wave modes in cylindrical waveguides

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



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

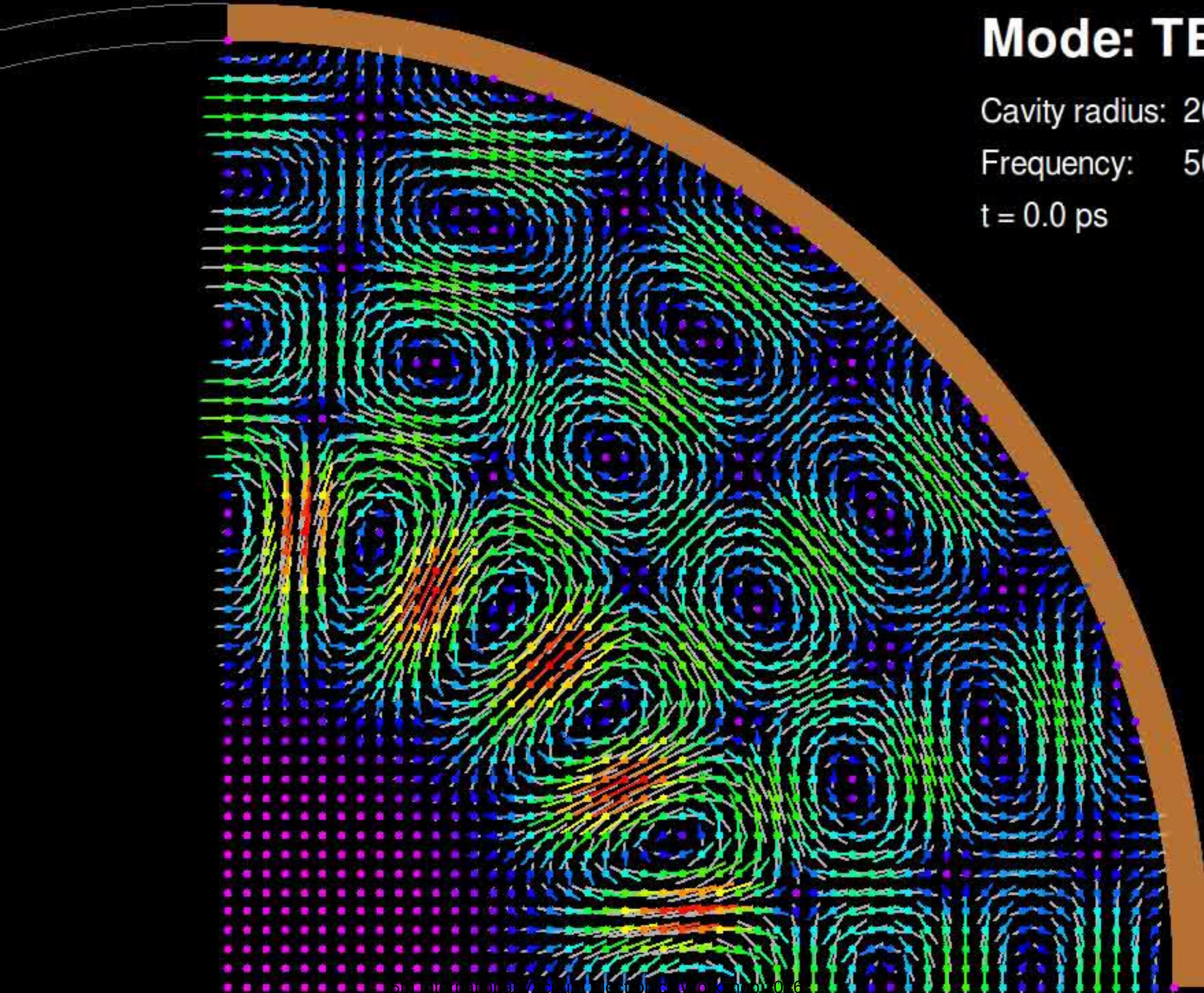


Mode: TE_10,4

Cavity radius: 20.0 mm

Frequency: 56.685 GHz

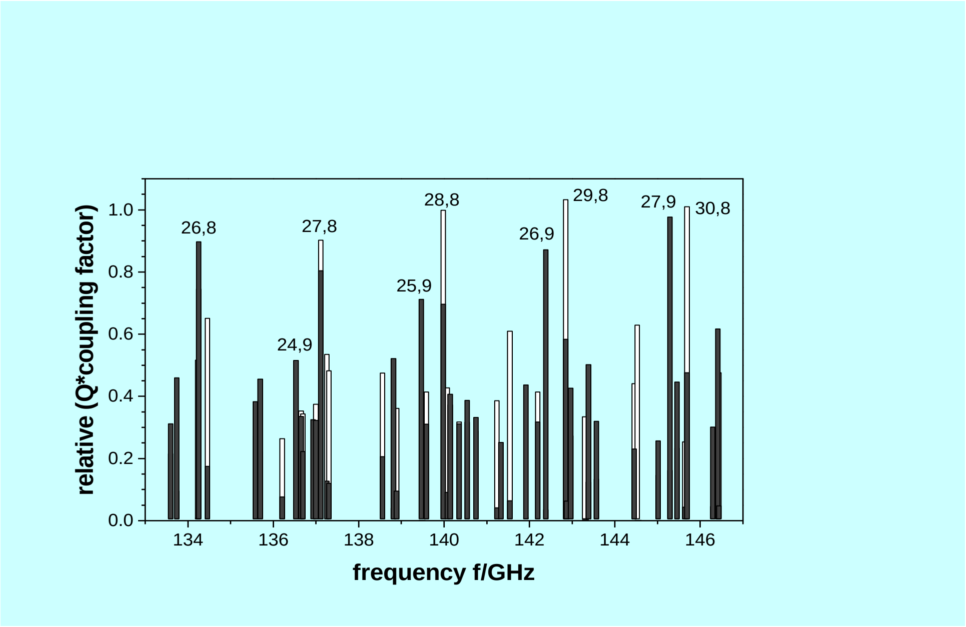
t = 0.0 ps

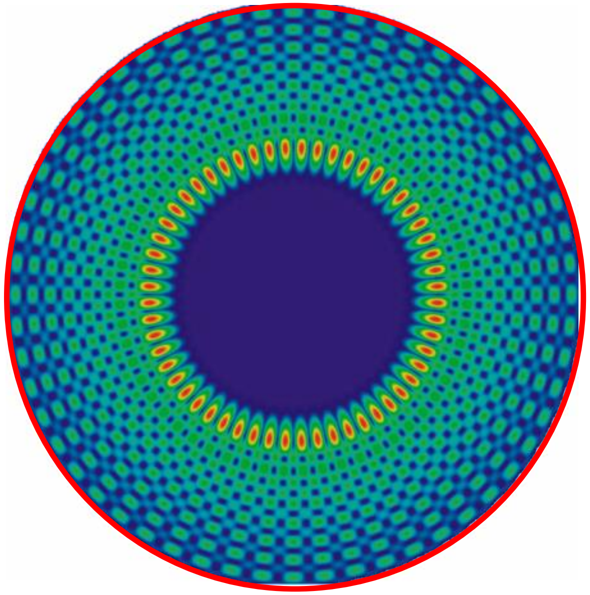


Cavity Mode Spectrum

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

wall losses @ 1 MW: ~ 2 kW/cm²





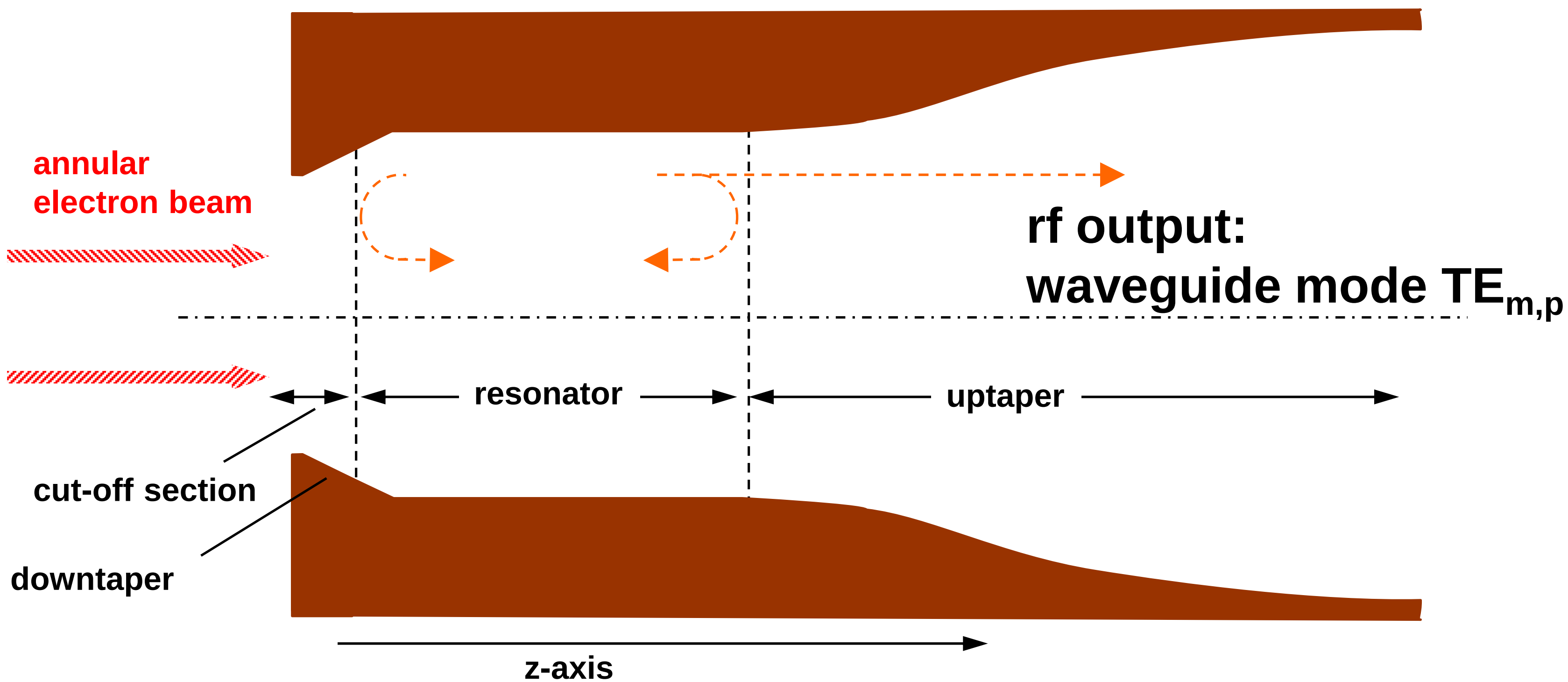
$TE_{28,8}$ mode

Stefan Illy

Institut für Hochleistungsimpuls- und Mikrowellentechnik (IHM)

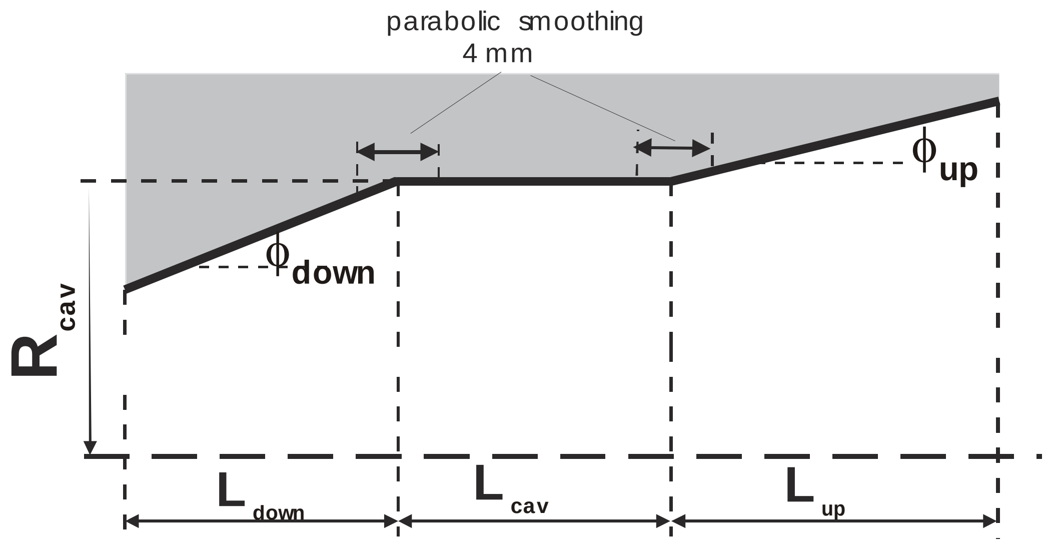
Resonator (Cavity)

- 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



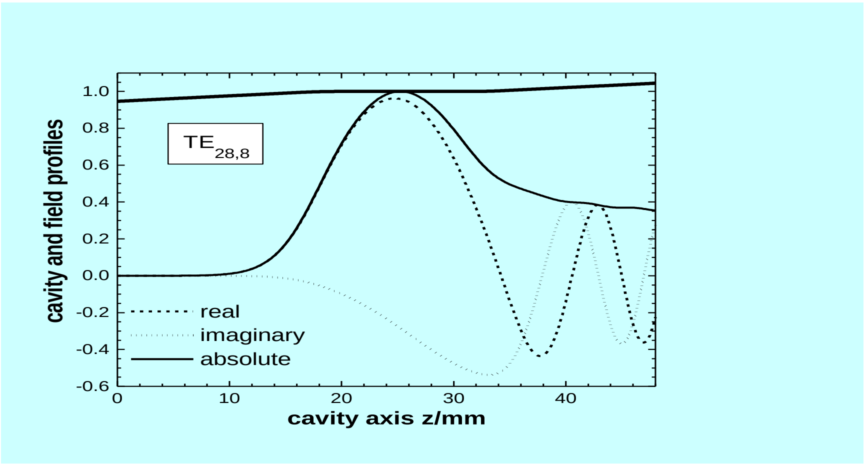
Institut für Hochleistungsimpuls- und Mikrowellentechnik (IHM)

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

Electron-Cyclotron-Interaction

Karlsruhe Institute of Technology

relativistic cyclotron frequency

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

relativistic factor

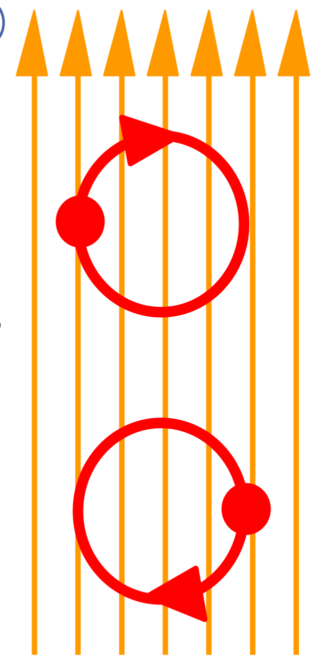
$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}} \approx 1 + \frac{W_{kin}}{511keV}$$

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

magnetic field **B** $\otimes$

Deceleration
electron loses energy
-> γ decreases

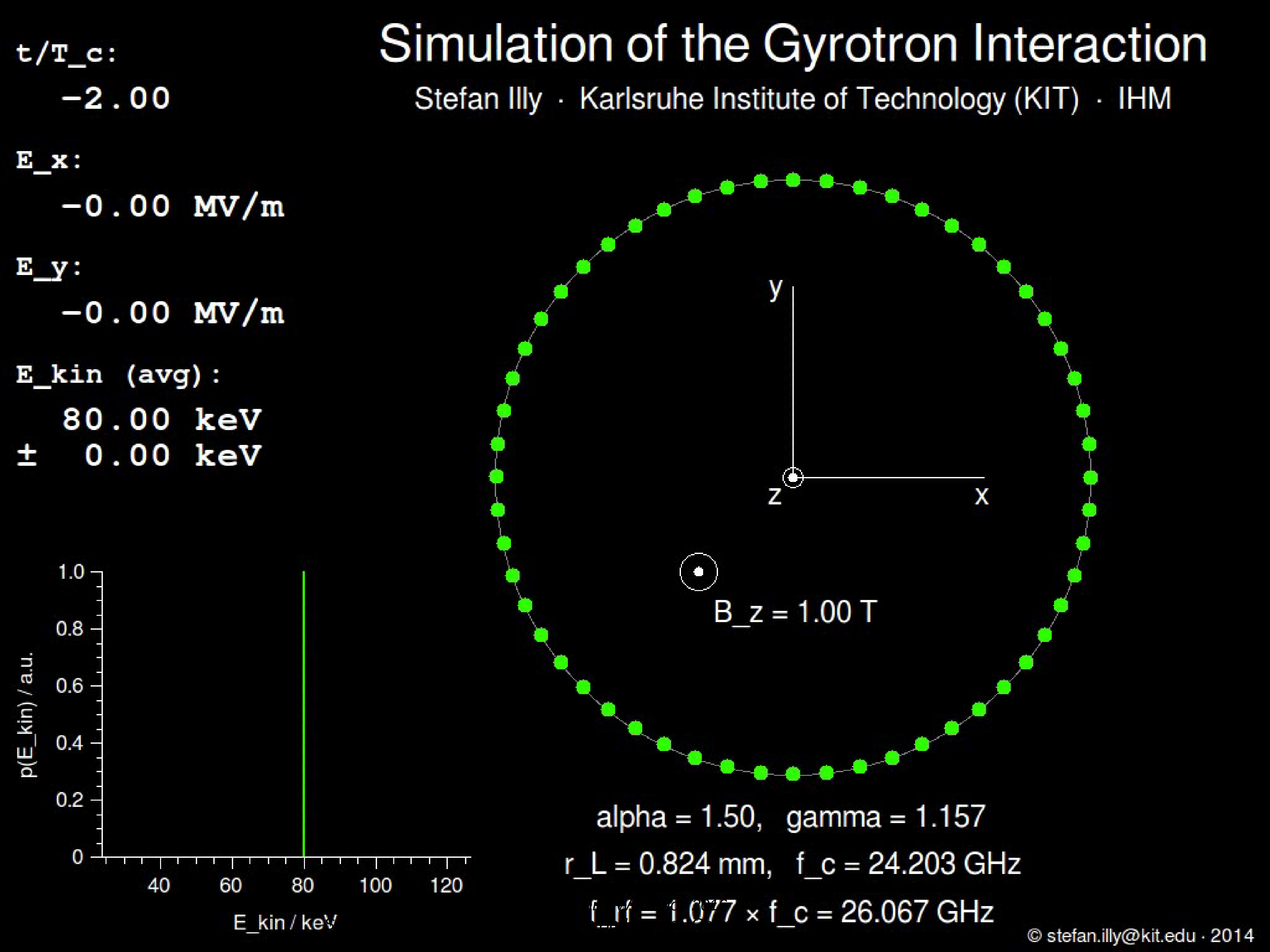
Acceleration
electron gains energy
-> γ increases



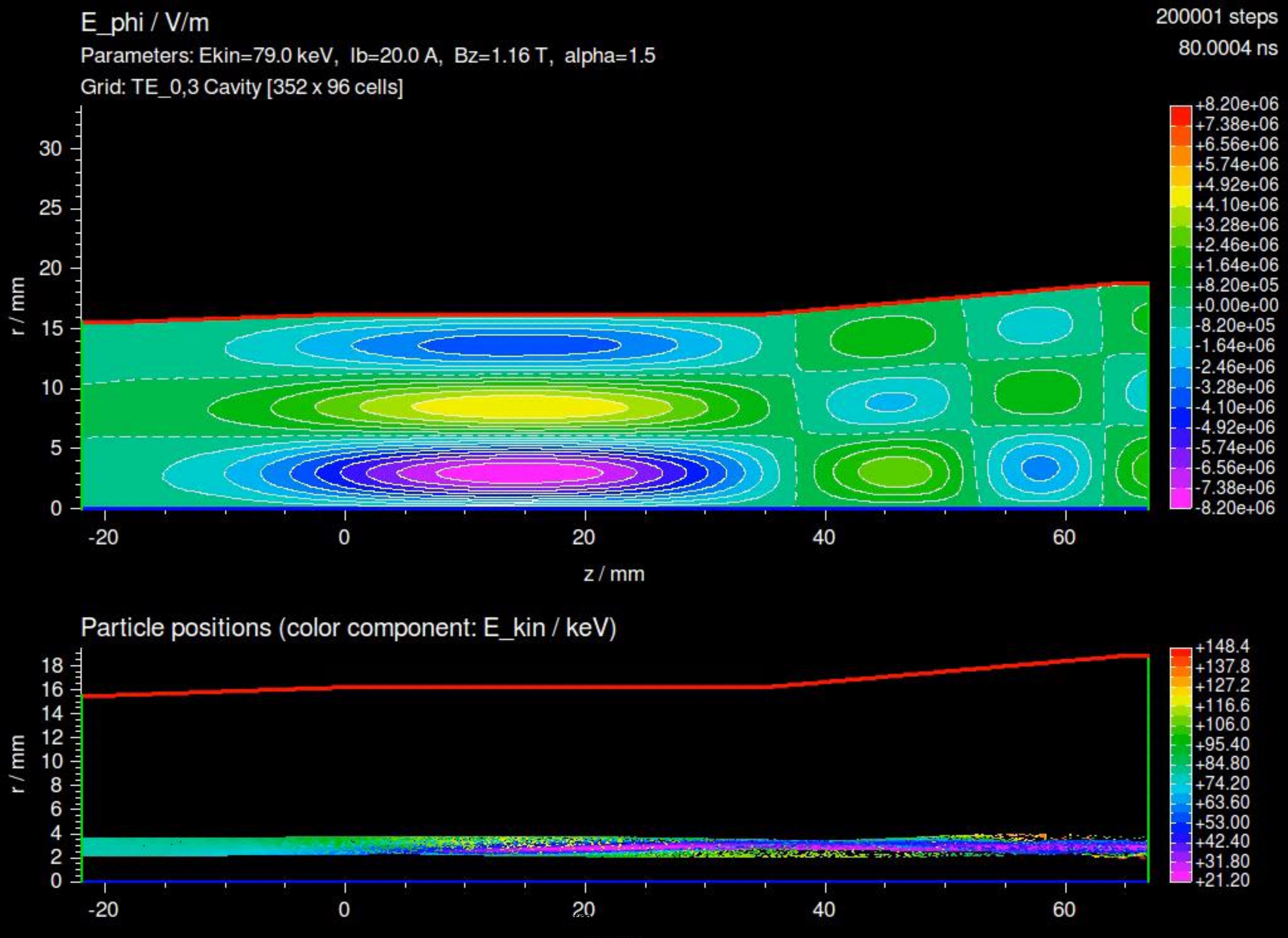
$\omega_{rf} > \Omega_c$	$\omega_{rf} < \Omega_c$
$\Omega_c \uparrow \quad \Delta\Lambda \downarrow$	$\Omega_c \uparrow \quad \Delta\Lambda \uparrow$
$\Omega_c \downarrow \quad \Delta\Lambda \uparrow$	$\Omega_c \downarrow \quad \Delta\Lambda \downarrow$

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 !



Simulation of the Gyrotron Interaction
Stefan Illy · Karlsruhe Institute of Technology (KIT) · IHM
t/T_c:
-2.00
E_x:
-0.00 MV/m
E_y:
-0.00 MV/m
E_kin (avg):
80.00 keV
± 0.00 keV
y
z
x
B_z = 1.00 T
p(E_kin) / a.u.
1.0
0.8
0.6
0.4
0.2
0
40
60
80
100
120
E_kin / keV
alpha = 1.50, gamma = 1.157
r_L = 0.824 mm, f_c = 24.203 GHz
f_rf = 1.077 × f_c = 26.067 GHz
© stefan.illy@kit.edu · 2014


E_phi / V/m
Parameters: Ekin=79.0 keV, Ib=20.0 A, Bz=1.16 T, alpha=1.5
Grid: TE_0,3 Cavity [352 x 96 cells]
200001 steps
80.0004 ns
r / mm
z / mm
0
5
10
15
20
25
30
-20
0
20
40
60
+8.20e+06
+7.38e+06
+6.56e+06
+5.74e+06
+4.92e+06
+4.10e+06
+3.28e+06
+2.46e+06
+1.64e+06
+8.20e+05
+0.00e+00
-8.20e+05
-1.64e+06
-2.46e+06
-3.28e+06
-4.10e+06
-4.92e+06
-5.74e+06
-6.56e+06
-7.38e+06
-8.20e+06
Particle positions (color component: E_kin / keV)
r / mm
z / mm
0
2
4
6
8
10
12
14
16
18
-20
0
20
40
60
+148.4
+137.8
+127.2
+116.6
+106.0
+95.40
+84.80
+74.20
+63.60
+53.00
+42.40
+31.80
+21.20

Current In-House Design Tools for Gyrotron Development

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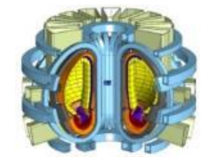
Short wavelengths / rel. large structures request specialiced numerical tools!

Name	Purpose	Features & Methods
ARIADNE *(I. Pagonakis)*	Electron gun and collector design	Electrostatic 2D & 3D particle tracing based on a FE potential solver (with curvilinear elements)
ESRAY *(S. Illy)*	Electron gun and collector design; Investigation of transient (low freq.) phenomena	Electrostatic 2D particle tracing based on FD on a non-orthogonal boundary-fitted mesh; Electrostatic and Electromagnetic 2D PIC Versions are available.
EURIDICE *(K. Avramidis)*	Simulation of gyrotron interaction; cavity design and optimization	Self-consistent and time-dependent, multi-mode approaches based on slow-time-scale approximation
TWLDO *(J. Jin)*	Synthesis of quasi-optical launchers and mirrors	Based on an iterative solution of the scalar diffraction eq. (Helmholtz & Kirchhoff)
? *(A. Marek, J. Jin)*	Analysis of quasi-optical launchers and mirrors („under construction“)	Boundary element method based on electric field integral equation (comparable to Surf3D)

Utilized commercial codes: Surf3D, CST Microwave Studio, COMSOL, ANSYS

ECRH/Gyrotron Development at IHM



Additional tube at 2016

W7-X upgrade

W7-X

140 GHz,
0.92 MW,
45 % eff., 1800 s

TCV 126/84 GHz,
1 MW, 2 s

SWISS PLASMA CENTER

ITER

170 GHz,
1.0 MW,
50 % eff., 3600 s

Beyond ITER (DEMO)

240 GHz (EU DEMO 2012)

>1 MW, CW
>60 % eff., CW

advanced (coaxial cavity) gyrotron design,
fast frequency step-tunability,
enhanced energy efficiency and recovery,
+ *enhanced life time and reliability*

IGVP, Stuttgart

THALES

EUROPEAN GYROTRON CONSORTIUM

EUROfusion

PROJECT PMW
1 MW GYROTRONS FOR W7-X

Status Project PMW

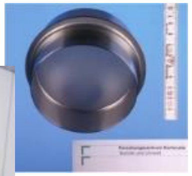
IGVP, Stuttgart

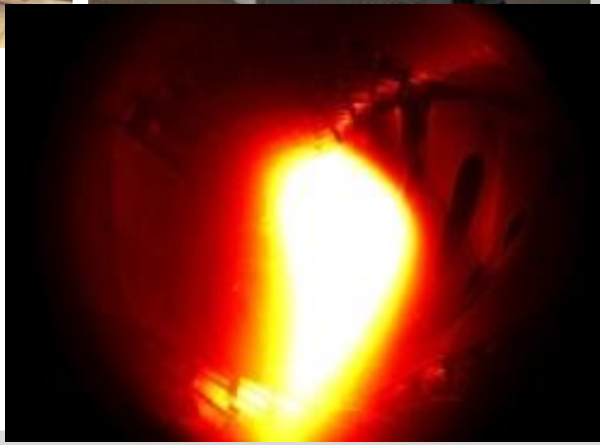
10 MW – 140 GHz – CW Operation
Responsibility of KIT/IPP

- Delivery of all TED series gyrotrons completed.
- Final gyrotron (SN5i) is operating at long pulses with expected output power and efficiency.
- IPP is reporting excellent operability and reliability of the gyrotrons.
- Additional tube (SN8) is under final construction, delivery expected by autumn 2016.

→ **ECRH at W7-X is up and running**

First fusion relevant plasma parameters have been achieved: 1 – 4 MW ECRH, ca. 1 s He- and H-Plasma (fully remote controlled operation)



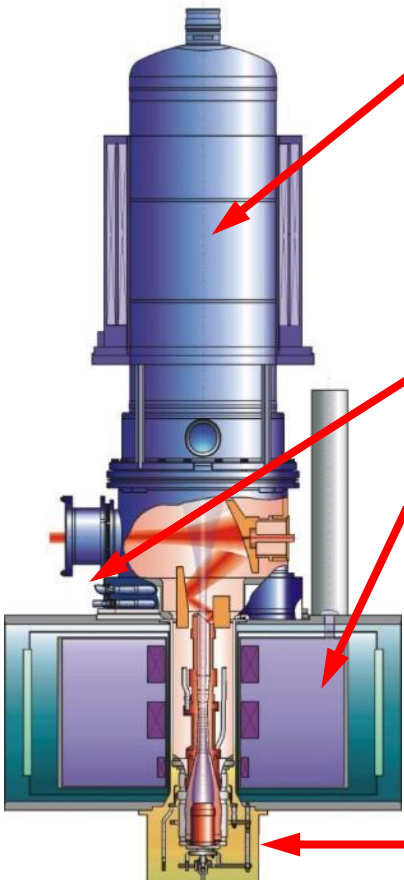


W7-X 140 GHz 1 MW CW Gyrotron

<u>W7-X Gyrotron</u> **operating mode: $TE_{28,8}$**

140 GHz, 1 MW CW, 50% efficiency

U_{acc} = 81 kV, I_b = 40 A, B_r = 5.67 T, α = 1.4

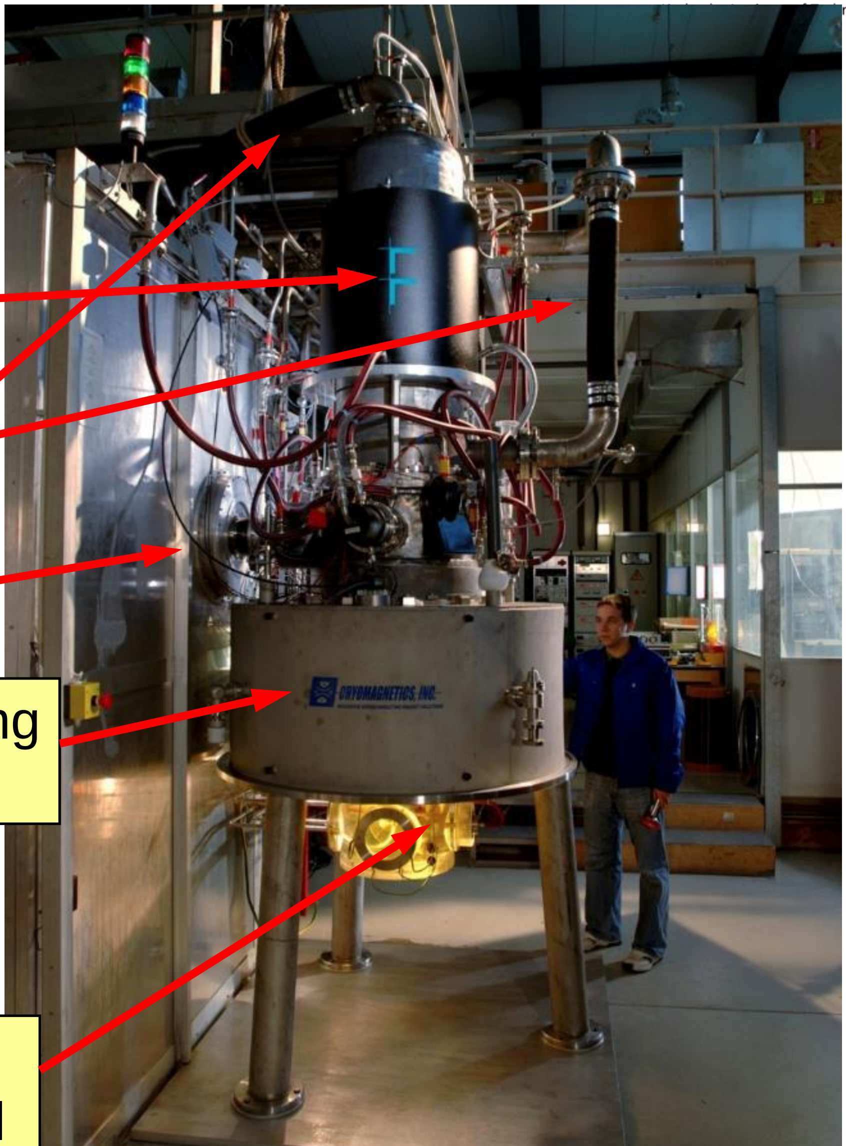


depressed collector

main cooling water pipes

superconducting magnet

electron gun in isolating oil



PROJECT
1 MW GYROTRON FOR ITER

Project Plan

- Development of the EU-1 MW, 170 GHz conventional-cavity gyrotron for ITER
- **A short pulse prototype** *to validate and improve the design of the components and the basic performance at short pulses (~ms).*
- **A industrial CW prototype** *to verify the ITER requirements in terms of output power, efficiency, RF beam quality and pulse length.*

Scientific and technological design:

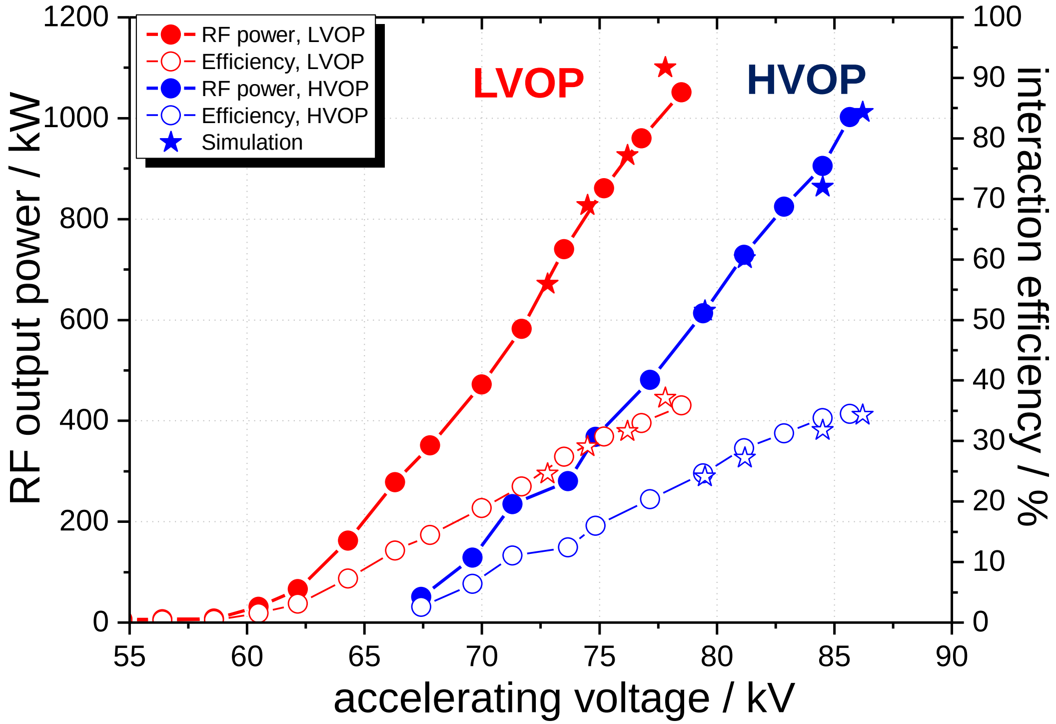
- Maximum possible similarity with the 140 GHz 1 MW CW W7-X gyrotron
- Apply proven and tested technology
- Take into account the experience gained during the development of the 2 MW coaxial gyrotron for ITER

Prototypes

- **Short pulse prototype:**
  - Modular gyrotron with flanges to facilitate the replacement of subcomponents
  - Start of operation at KIT: End of 2014
  - Additional experiments planned in 2016
- **Industrial CW prototype:**
  - Phase 1: RF tests at KIT with existing SC magnet (OI), pulse length limited to 3 min by HVPS
  - Delivered in November 2015
  - Phase 2: Tests at SPC Lausanne, with new He-free SCM (under manufacturing), CW conditions

Power and efficiency (SP w/o SDC)

- Short-pulse gyrotron tested at two operating points:
  - low-voltage operating point (**LVOP**): U_a~78kV, I_b~45 A
    - 1051kW @ 35% of the interaction efficiency
  - high-voltage operating point (**HVOP**): U_a~87kV, I_b~40 A
    - 1002kW @ 34% of the interaction efficiency



The CW Prototype

Identical design with regard to physical performance of major components!

- Electron gun
- Beam tunnel
- Resonator
- Quasi optical system

Improved vacuum pumping

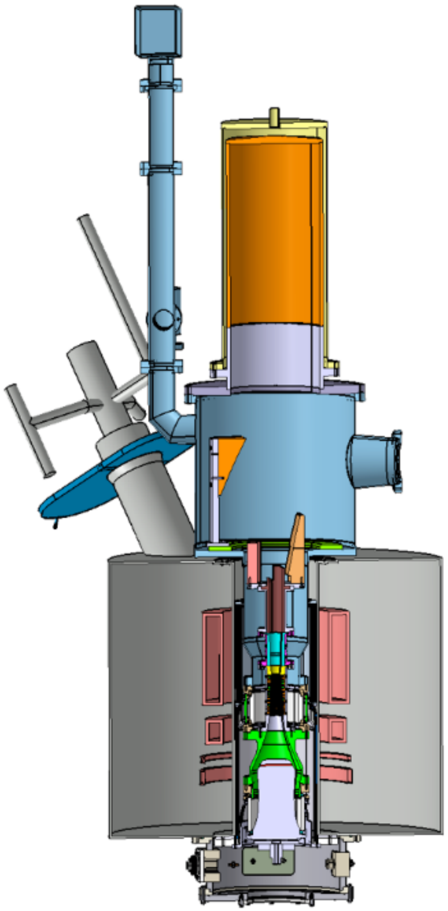
- 1 Storage IGP with permanent magnet
- 4 IPG operating in stray field of SC magnet

CW compatible cooling

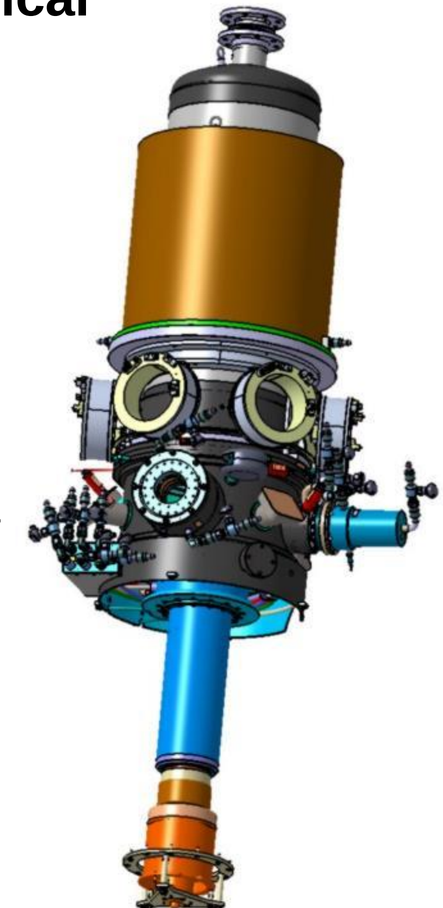
- Water cooling: collector and internal (HV) components
- Oil cooling: MIG, diamond window, relief window

Electron beam sweeping on collector

- Combined transversal and longitudinal

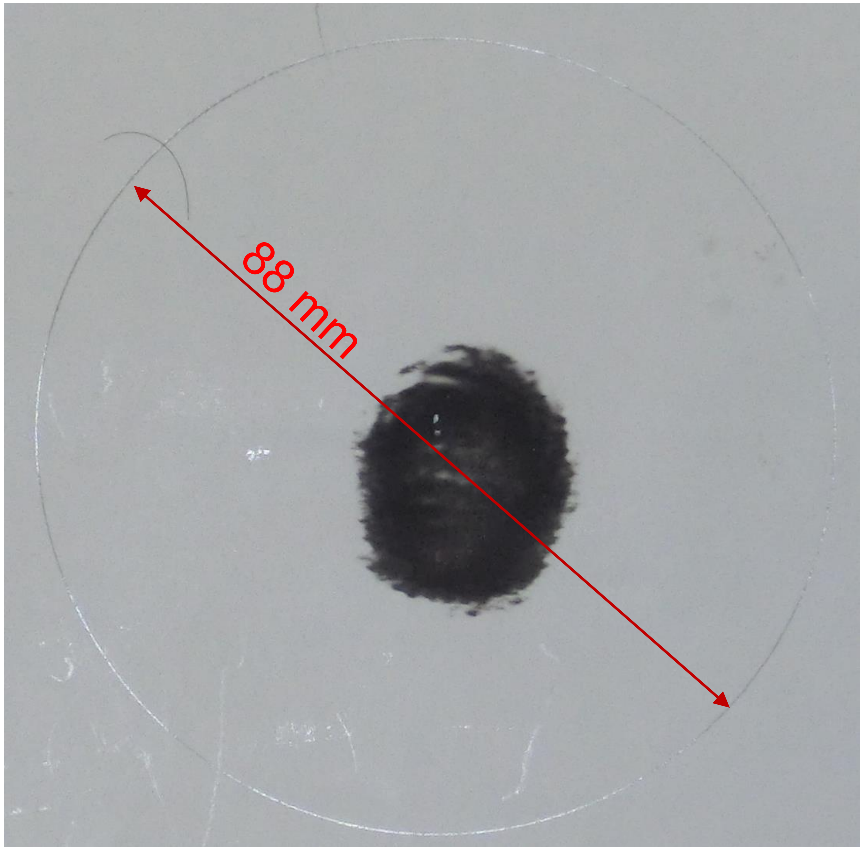


Short-pulse prototype



Experiments with the CW Prototype Gyrotron

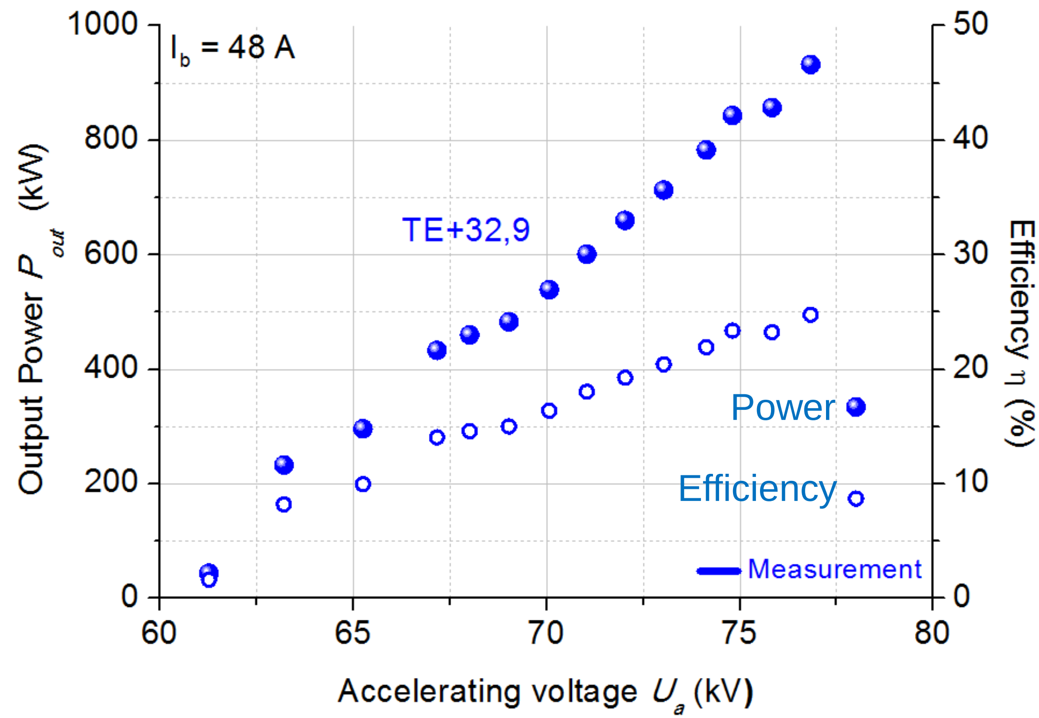
Early verification of output beam



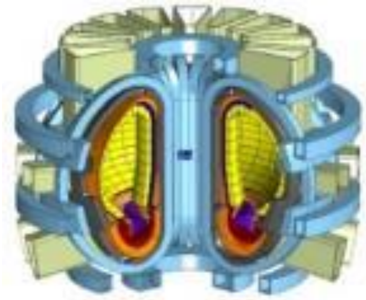
- Thermal paper placed in front of the window (20 cm)
- Basic beam position and shape is confirmed
- Estimated shift of beam within usual tolerance center (@ 20 cm): ~ 5 mm

Experiments with the CW prototype gyrotron

- The experiments with the CW tube started in early 2016:
  - Stable operation with $TE_{32,9}$ mode at 170.22 GHz is achieved for a wide range of operating parameters.
  - RF power in the 1MW level has been achieved with beam current ~48 A.
  - The efficiency (in non-depressed collector operation) is ~26%.



Dependence of the RF power and the efficiency for the LVOP (non-depressed voltage operation)



TOWARDS DEMO PROJECT EUROFUSION / KIT DEVELOPMENTS

POWER PLANT PHYSICS & TECHNOLOGY DEPARTMENT

DEMO relevant Gyrotron R&D in the Frame of EUROfusion

Main Tasks:

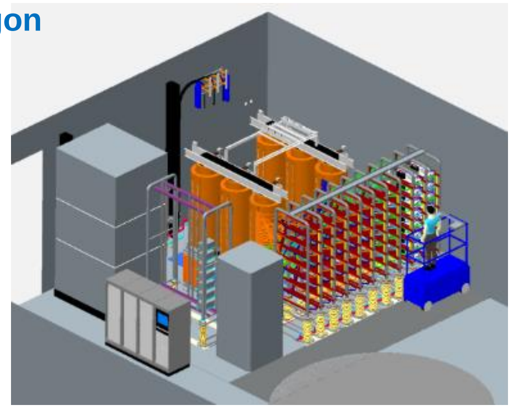
- Verification of a coaxial-cavity gyrotron pre-prototype at longer pulses *(presentation of S. Ruess)*
- Conceptual design and advanced tool developments for future frequency step-tunable 240 GHz gyrotrons *(presentations of J. Franck and P. Kalaria)*
- Advances in multistage depressed collector technologies *(presentation of C. Wu)*

PROJECT FULGOR GYROTRON TESTSTAND FOR FUTURE DEMO GYROTRON

Project FULGOR
(Fusion Long Pulse Gyrotron Laboratory)

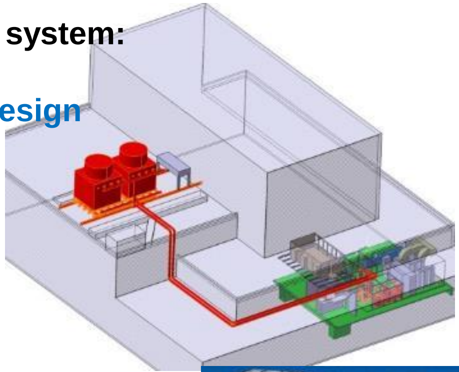
HVDCPS:
- EPSM Modules
- Allows use of MSDC
- Excellent low noise operation

-> Ampegon



Cooling system:
- 10 MW, CW

-> Eproplan design



Control system and data acquisition:
- Siemens S7

-> KIT development

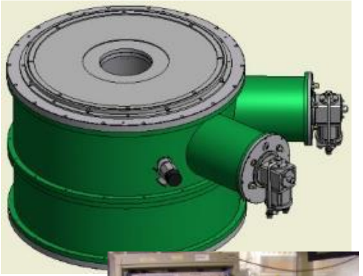
Gyrotron:
- Up to 4 MW RF
- CW (1 hour)
- Up to 240 GHz

EUROfusion

SC Magnet:

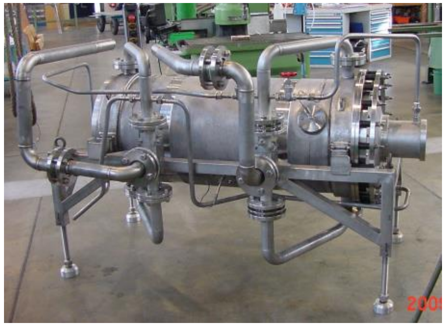
-> negotiations with several suppliers running

EUROfusion



RF diagnostics:
- KIT development
- > 200 GHz

-> KIT development



RF calorimeter:
- 2 MW, CW

-> KIT development

Summary

- Gyrotrons – as RF-sources of the ECRH system – are an essential component of present & future fusion experiments and reactors.
- IHM together with EGYC is one of the main contributors in gyrotron R&D worldwide.
- The project PMW (ECRH system for Wendelstein 7-X) has been successfully finalized.
- The 170 GHz long-pulse prototype gyrotron for ITER is in the testing phase at KIT.
- Conceptual design and advanced tool developments for future frequency step-tunable 240 GHz gyrotrons for DEMO are ongoing.
- The FULGOR project is progressing according to plan.