Present Status and Future Prospects of High Power CW Gyrotron Development at KIT

S. Illy, K.A. Avramidis, B. Ell, L. Feuerstein, G. Gantenbein, Z. Ioannidis, J. Jin, L. Krier, A. Marek, S. Stanculovic, T. Ruess, T. Rzesnicki, M. Thumm, M. Vöhringer, C. Wu, J. Jelonnek

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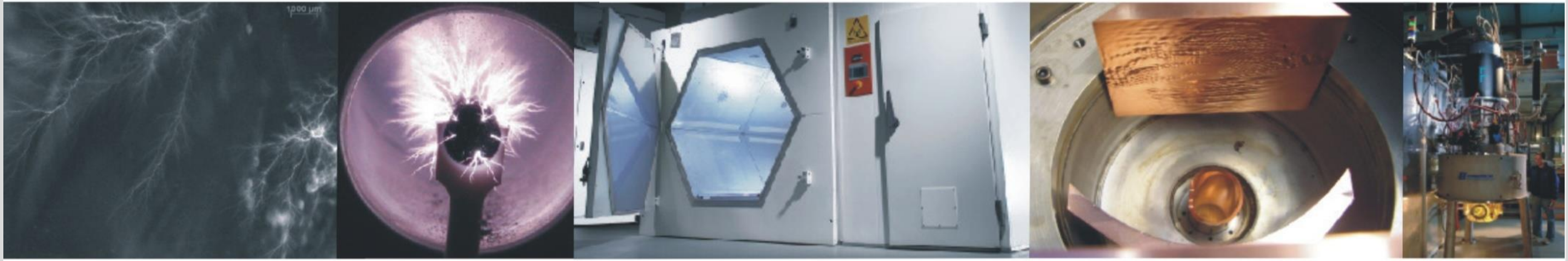
Institute for Pulsed Power and Microwave Technology (IHM), Karlsruhe Institute of Technology, Karlsruhe, Germany



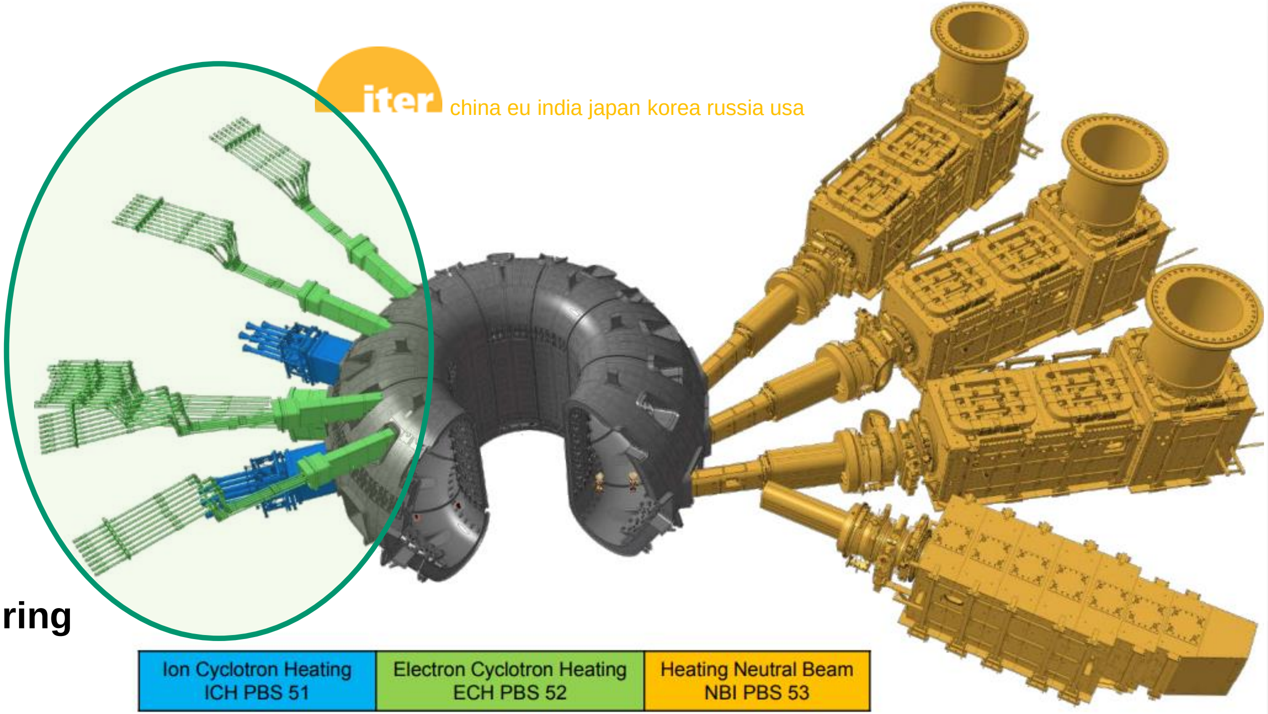
Outline

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

Caroline Darbos @IRMMW-THz Conference, 2020

Heating and Current Drive Systems Installed at ITER

Caroline Darbos, “Achievement and challenges for ITER heating & current drive systems”, IRMMW-THz, 2020



Ion Cyclotron Heating ICH PBS 51	Electron Cyclotron Heating ECH PBS 52	Heating Neutral Beam NBI PBS 53	
20 MW	**20 MW**	**33 MW**	*= 73 MW total installed H&CD power*
+16,5 MW	+20 MW	+20 MW	*= 110 MW for extended burn*

RF Heating systems installed during construction phase:

- IC: 40-55 MHz, 20 MW
- **EC: 170 GHz, 20 MW**

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

Karlsruhe Institute of Technology

- Principles of ECRH:
  - A resonance between the electrons and RF waves is exploited: $\Omega_c = \frac{eB}{m_e \gamma}$
  - 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):**

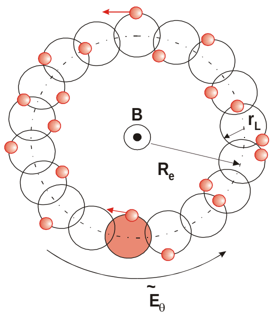
  10+ MW ECRH system of the Wendelstein 7X stellarator at IPP Greifswald
- Microwave sources can be also used for plasma diagnostics

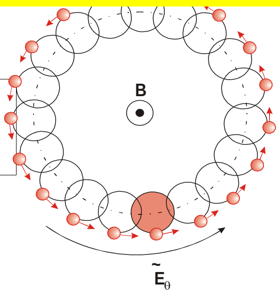
→ Presentation by Laurent Krier

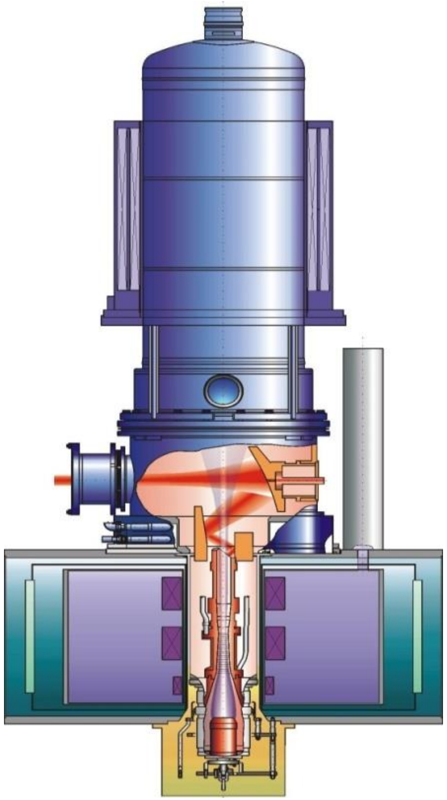
The Gyrotron – a Powerful mm-Wave Source

- Vacuum electron tube in a strong magnet
- Up to 2 MW RF power at frequencies of 70 ~ 200 GHz
- Efficiency: currently ~ 50 %
- „Gyrotron“ = „gyrating electron“
- Operates as oscillator – but amplifiers are also possible

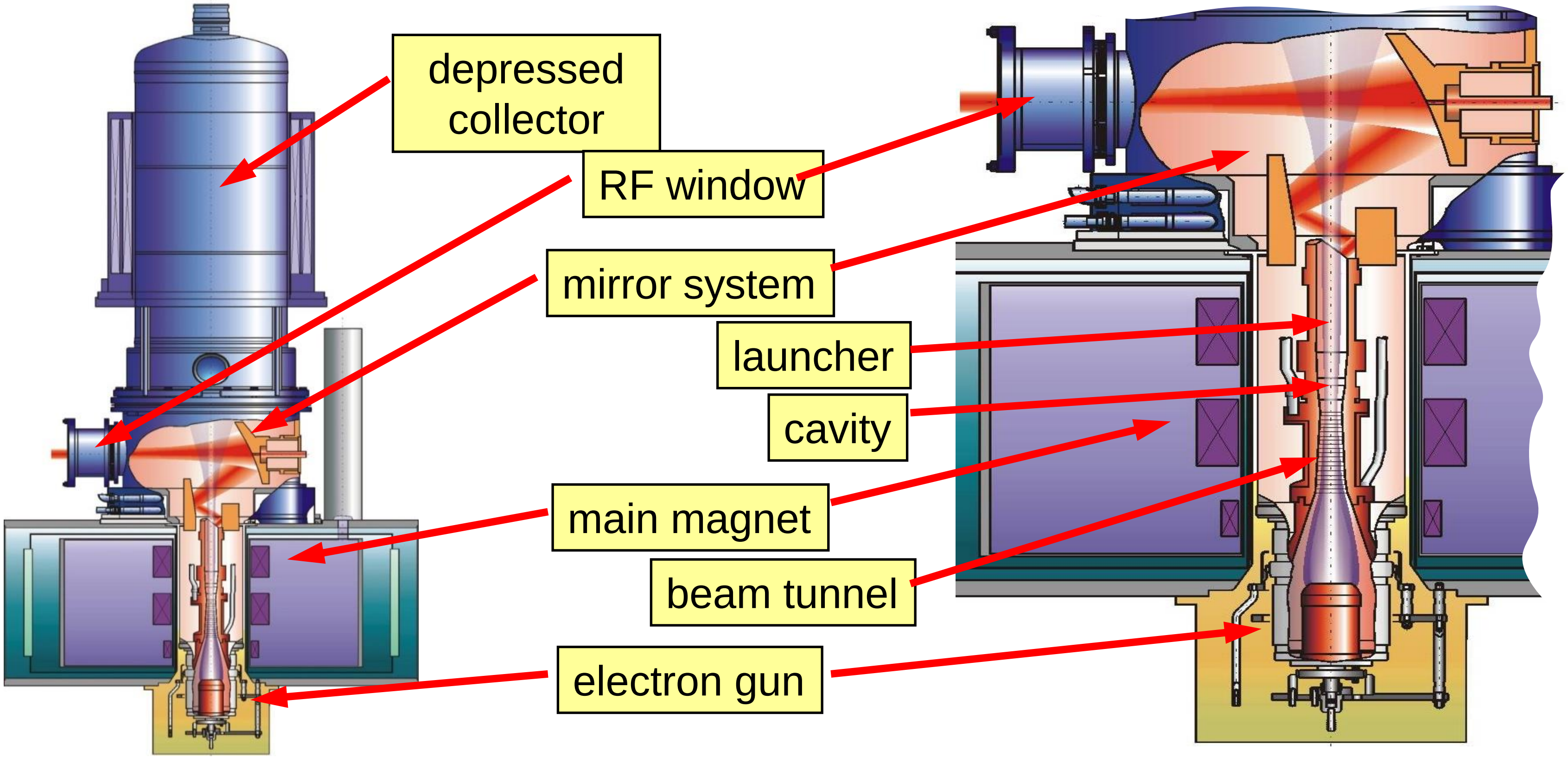
→ Presentations by Alexander Marek & Max Vöhringer



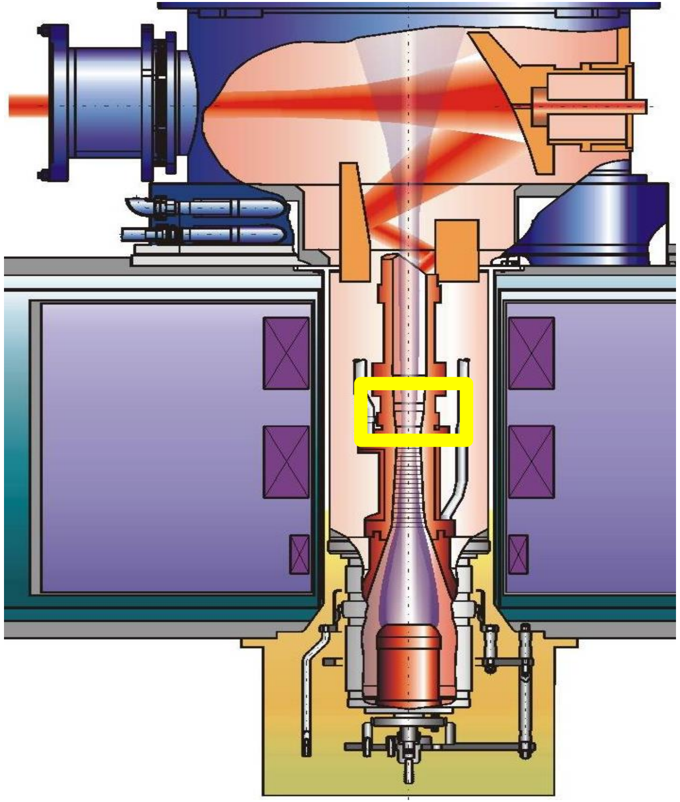




The Gyrotron – Overview of Components



The Gyrotron Cavity



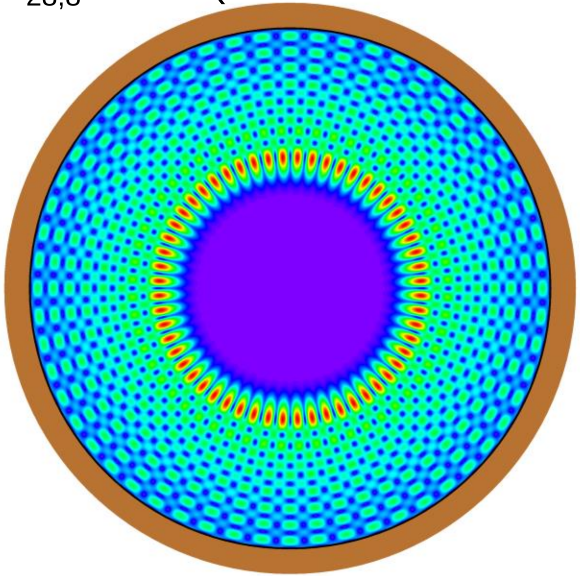
Institute for Pulsed Power and Microwave Technology (IHM)

Electromagnetic wave modes in cylindrical waveguides

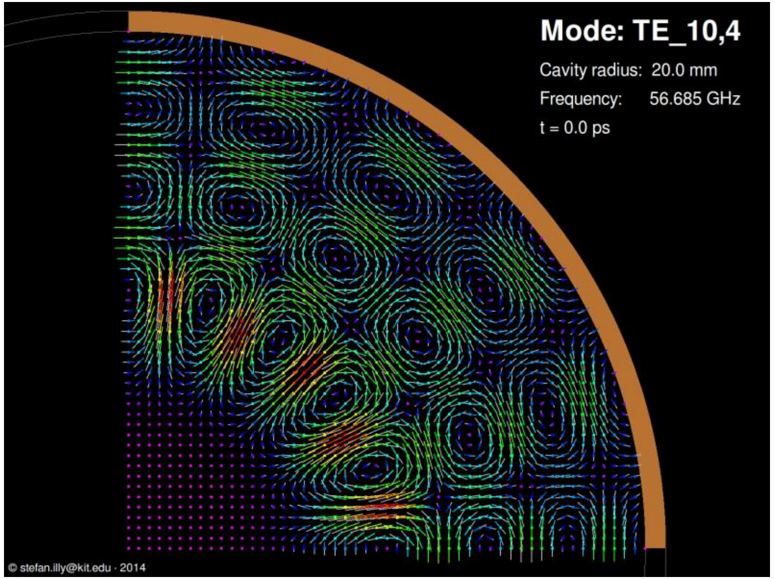
Standing wave, azimuthal: sine function (periodic pattern)

radial: Bessel functions

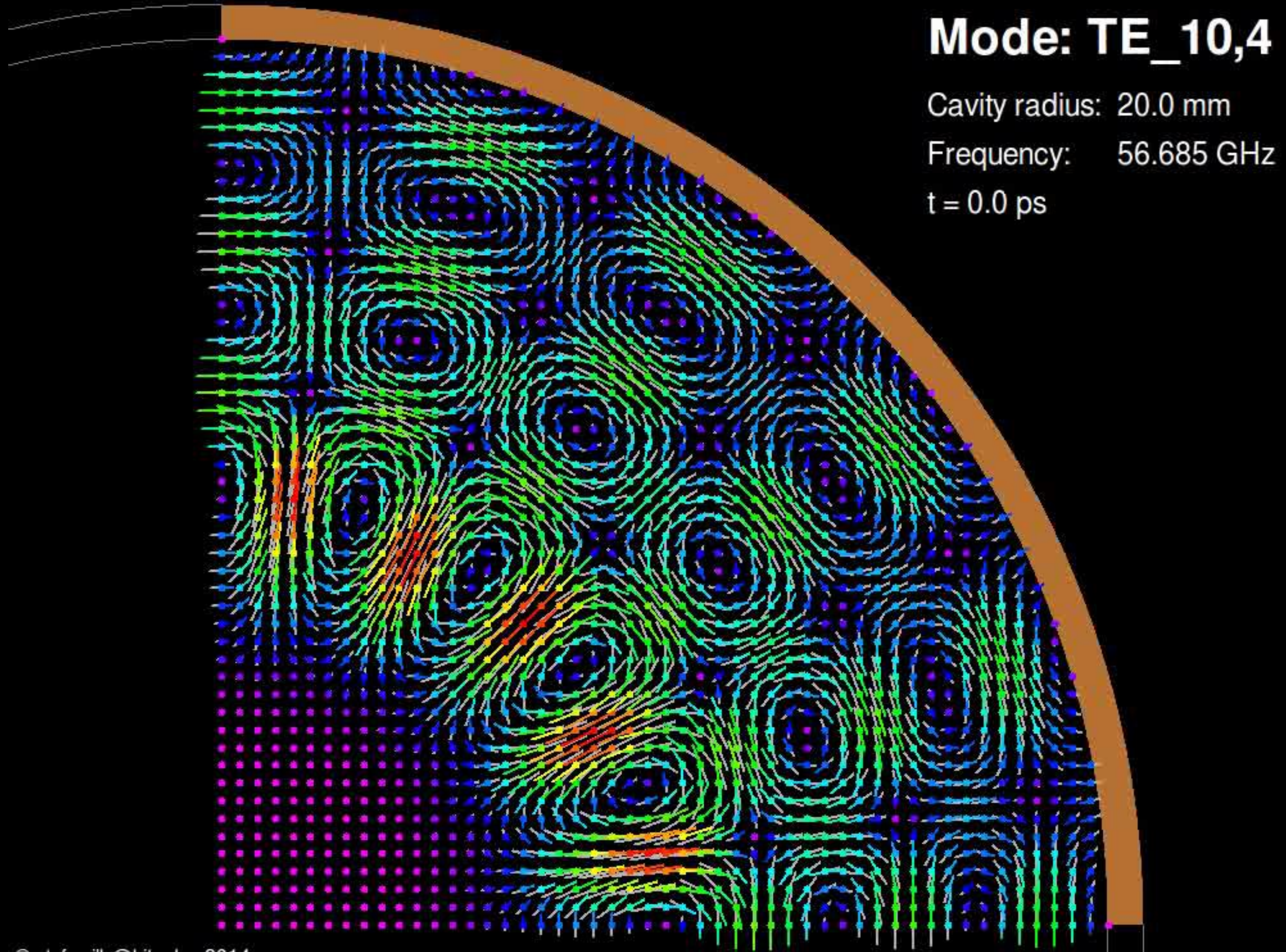
$TE_{28,8}$ Mode (abs. value of E-field)



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



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


Mode: TE_10,4
Cavity radius: 20.0 mm
Frequency: 56.685 GHz
t = 0.0 ps

Electron-Cyclotron-Interaction

relativistic cyclotron frequency

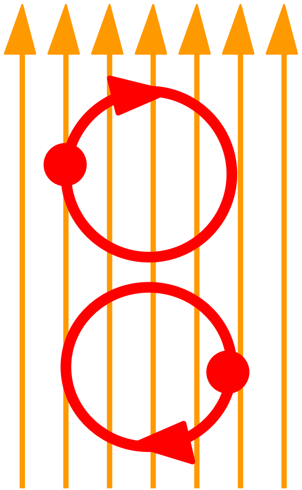
$$\Omega_c = \frac{eB}{m_e \gamma} \approx 2\pi \frac{28\mathrm{GHz} \cdot B/\mathrm{T}}{\gamma}$$

relativistic factor

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

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

magnetic field **B** $\otimes$



Deceleration
electron loses energy
-> γ decreases

Acceleration
electron gains energy
-> γ increases

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

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!

Simulation of the Gyrotron Interaction

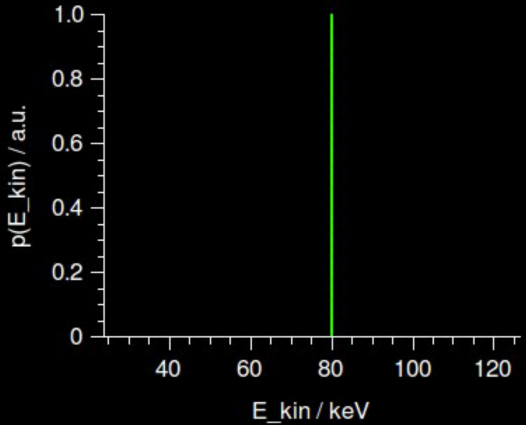
Stefan Illy · Karlsruhe Institute of Technology (KIT) · IHM

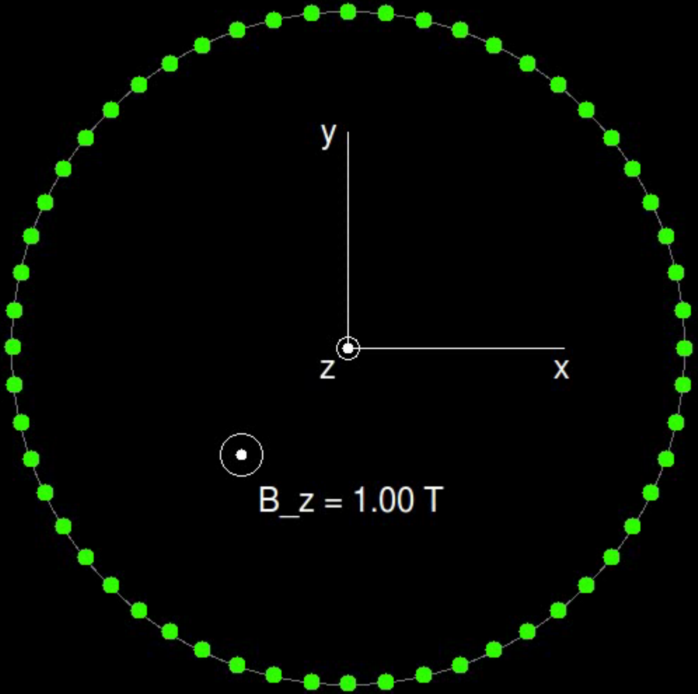
```
t/T_c:
  -2.00

E_x:
  -0.00 MV/m

E_y:
  -0.00 MV/m

E_kin (avg):
  80.00 keV
±  0.00 keV
```



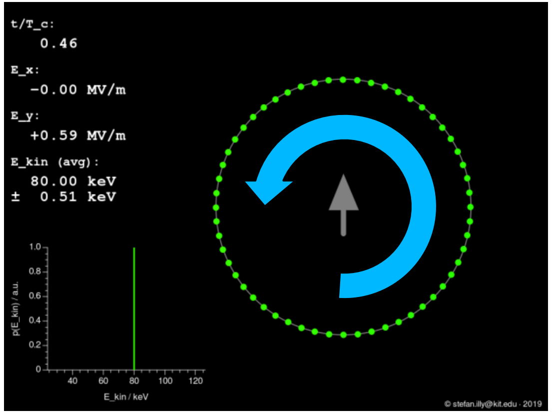


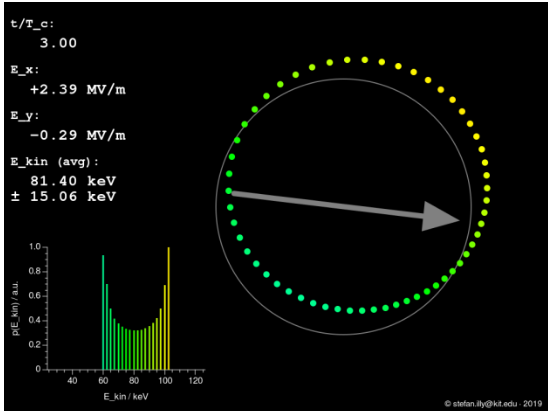
alpha = 1.50, gamma = 1.157

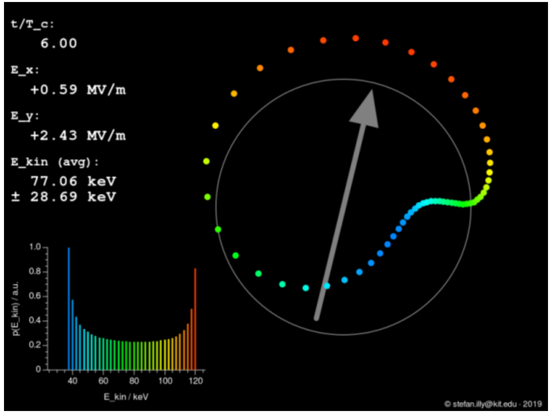
r_L = 0.824 mm, f_c = 24.203 GHz

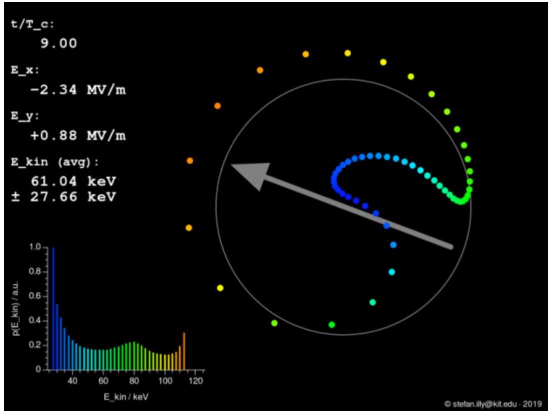
f_rf = 1.077 × f_c = 26.067 GHz

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



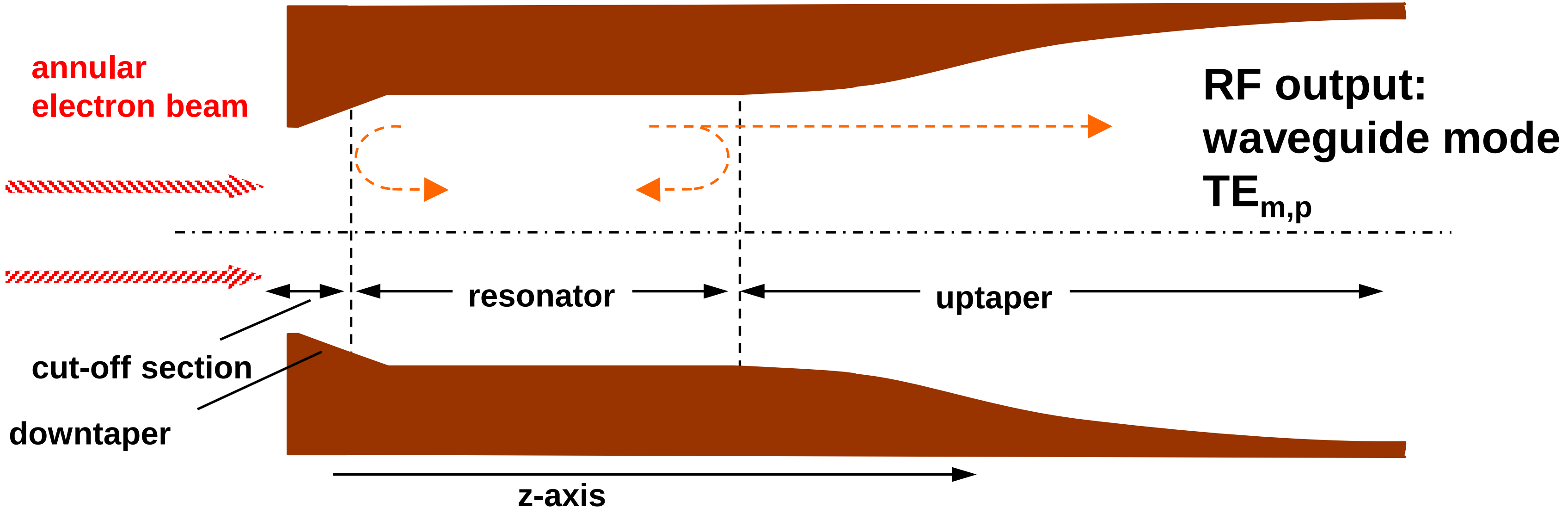


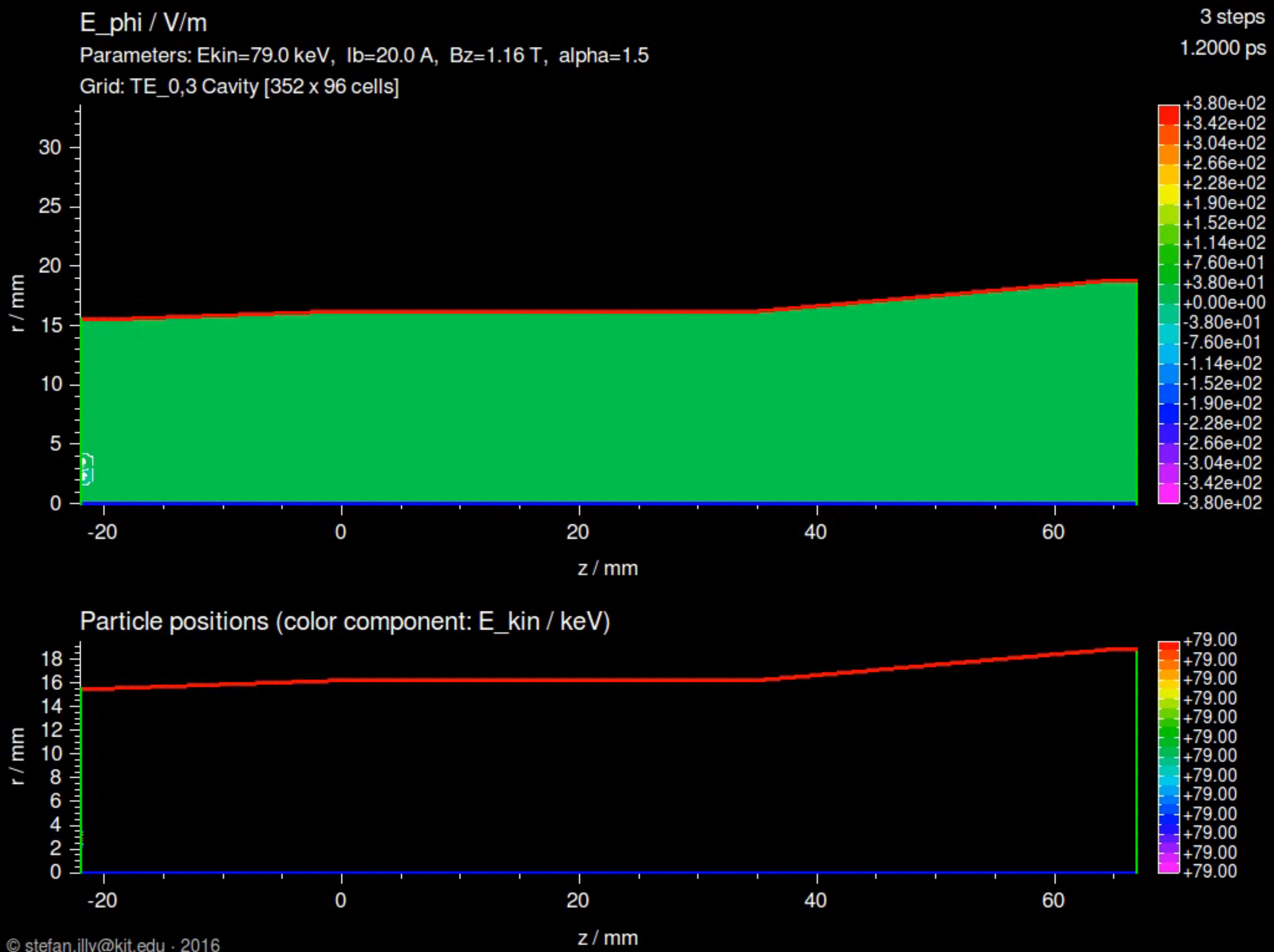




Resonator (Cavity)

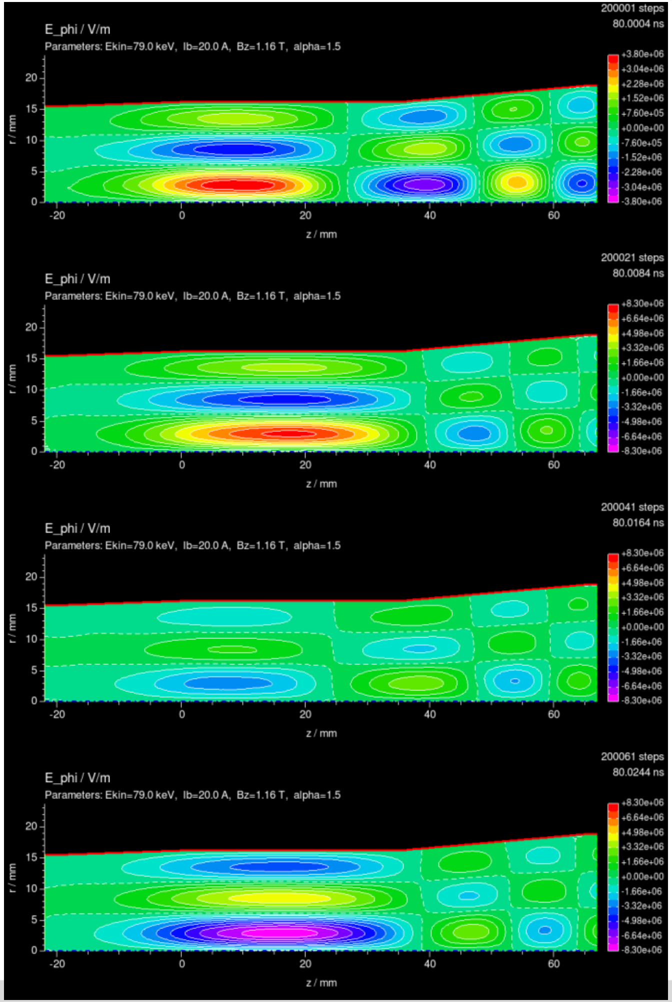
- Open waveguide resonator (hollow waveguide or coaxial)
- Downtaper at the electron entrance to minimize RF power traveling towards the gun: The operating mode is reflected.
- Non-linear uptaper at the exit to increase the diameter.




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]
3 steps
1.2000 ps
r / mm
z / mm
+3.80e+02
+3.42e+02
+3.04e+02
+2.66e+02
+2.28e+02
+1.90e+02
+1.52e+02
+1.14e+02
+7.60e+01
+3.80e+01
+0.00e+00
-3.80e+01
-7.60e+01
-1.14e+02
-1.52e+02
-1.90e+02
-2.28e+02
-2.66e+02
-3.04e+02
-3.42e+02
-3.80e+02
Particle positions (color component: E_kin / keV)
r / mm
z / mm
+79.00

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*
  - Instabilities of different kinds are always challenging (in beam tunnel / cavity / after cavity)

    → Presentation by Lukas Feuerstein

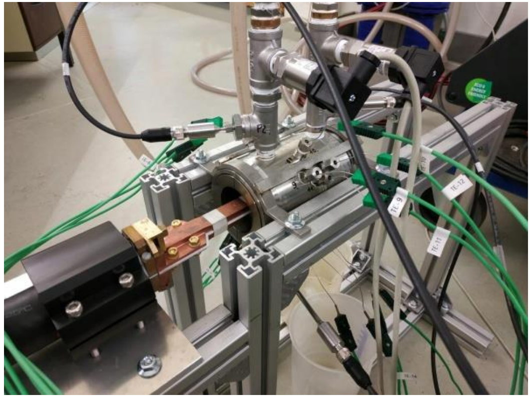
  - Superconducting magnets get expensive (Nb_3Sn):
    → *second harmonic operation (possibly combined with injection locking)*

    → EUROfusion ENR project together with Greek institutions

Main Conceptual & Technical Challenges (II)

- Most critical thermomechanical challenges:
  - Resonator (≈ 2 kW/cm² peak loading,
    risk of deformation / damage)
    → studies are ongoing to enhance the cooling capabilities

    → KIT developed a test stand based on induction heating to test cooling concepts



  - Collector (≥ 5 kW/cm² instantaneous peak loading)
    → “magnetic” sweeping of the electron beam is required
    but: fatigue problems at low sweeping frequencies!
    → Possible solution: “electric” sweeping at much higher frequencies

    → Presentation by Benjamin Ell

Main Conceptual & Technical Challenges (III)

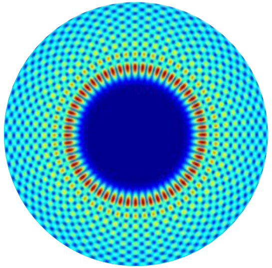
- Multi-Frequency Operation:
  - Needs compatible operation modes
  - Quasi-optical output system must be capable to convert different modes
  - Diamond output window must match the different frequencies (→ Brewster window, demonstrated at KIT)
- Enhancing overall efficiency (to values above 60%)
  -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

Short pulse MDC prototype

KIT Fusion Gyrotron Family

Past – Present – Future

W7-X, Greifswald



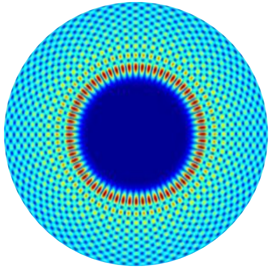
$TE_{28,8}$

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

In Operation

Upgrade to 1.5 MW
1st CW series tube under test!

ITER, Cadarache

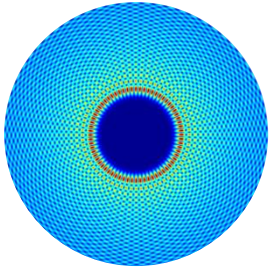


$TE_{32,9}$

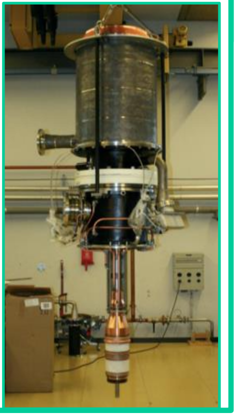
170 GHz
1 MW (3600 s)
50 %

Final development phase

DEMO (EUROfusion)



$TE_{34,19}$



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

Research phase

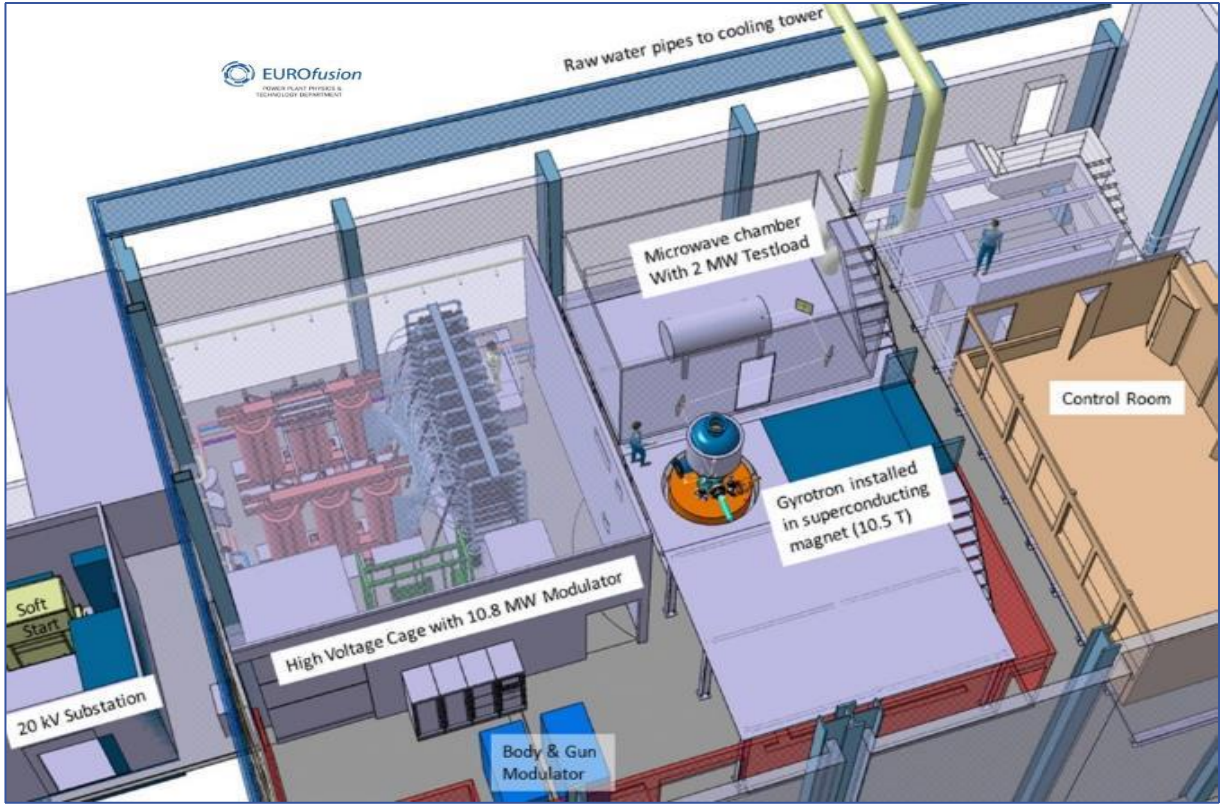
New Gyrotron Test Stand FULGOR

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 Power Supply
  → installed / tested / **operational**
- 10 T cryofree SC magnet
  → procurement running



FULGOR


HV Power Supply

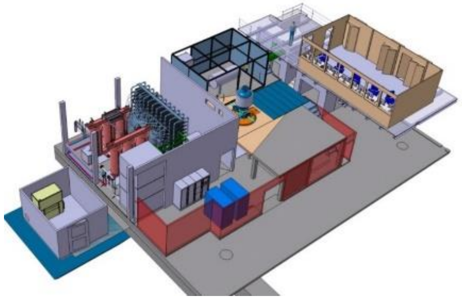

HV Pulsed PS


Measurements System


Data Acquisition & Control


Body Power Supply
AMPEGON


Cooling System




Soft Start System

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

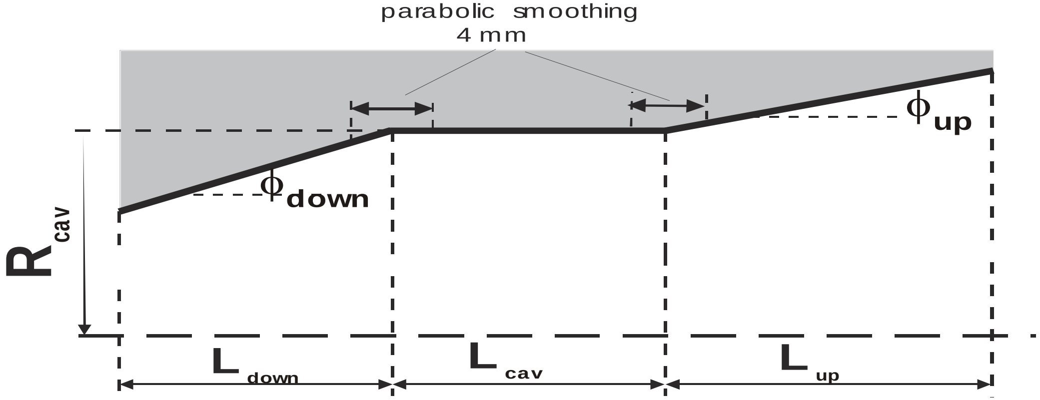
Major Future Challenges

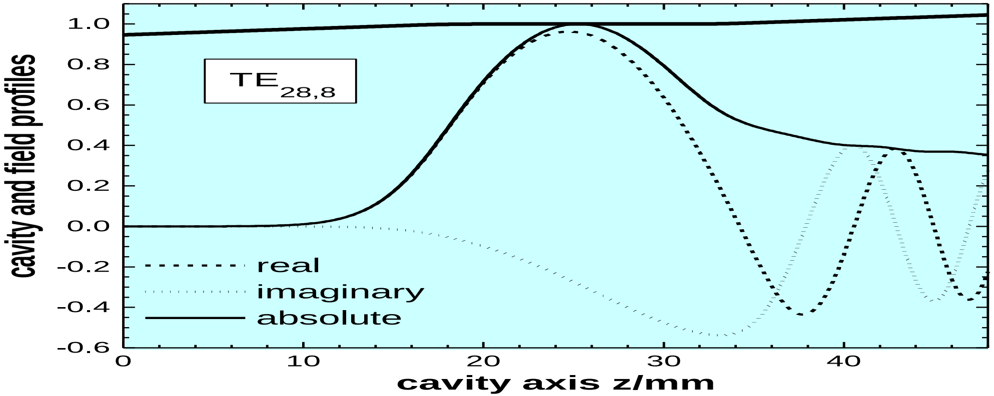
- Reliability and versatility of the sources must be increased
- Even higher power per unit (at even higher frequency) and higher efficiency is desirable: requires developments like the coaxial cavity gyrotron & multi-stage depressed collectors

Thank you for your attention!

Backup Slides

Gyrotron Cavity Example



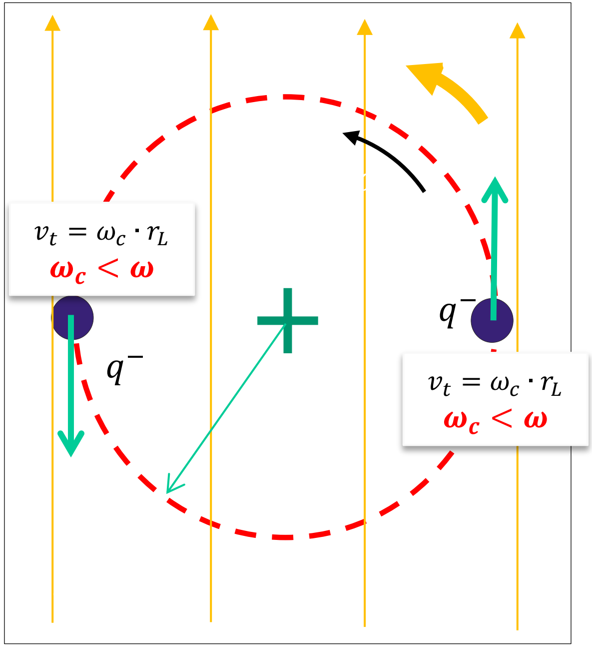


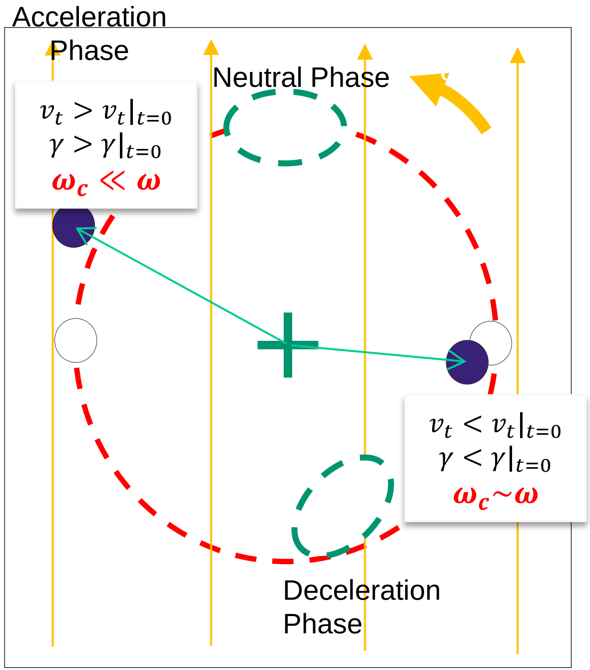
example for 1 MW, 140 GHz (λ_0= 2.14 mm) gyrotron:

- **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

Phenomenological Description of Gyro-Interaction





Phase Focusing in Decelerating Field Region
→ **Netto Energy Extraction**