Design of a MW Level 2nd Harmonic Coaxial Gyrotron Cavity with Variable Corrugation Depth of the Inner Conductor

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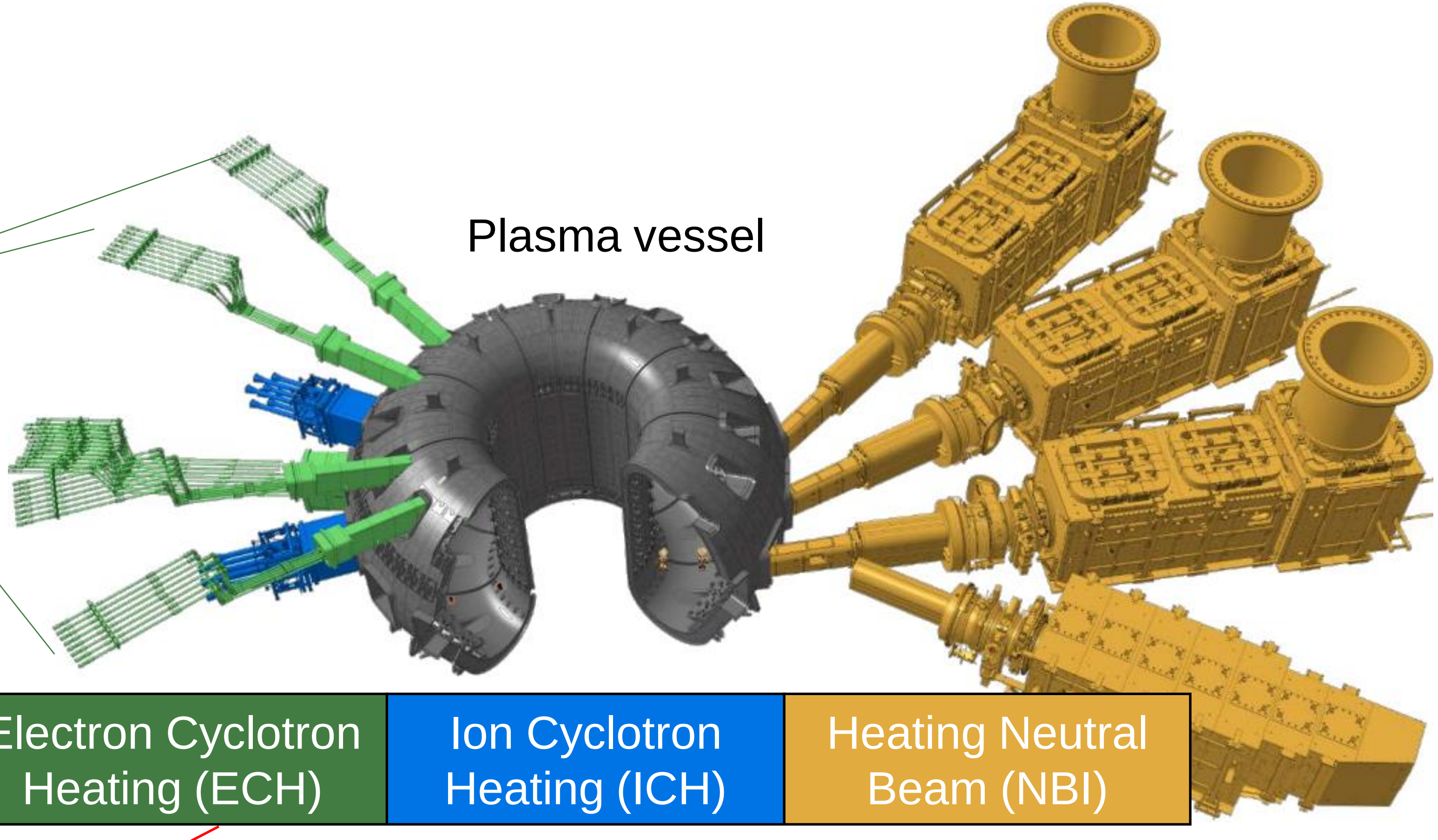
Heating and Current Drive Systems Installed at ITER

Gyrotron

EC wave is used for:

- Heating
- Current drive
- Stabilization
- Diagnostics



~~20 MW~~ DEMO: > 100 MW

20 MW

33 MW

C. Darbos, IRMMW-THz, 2020

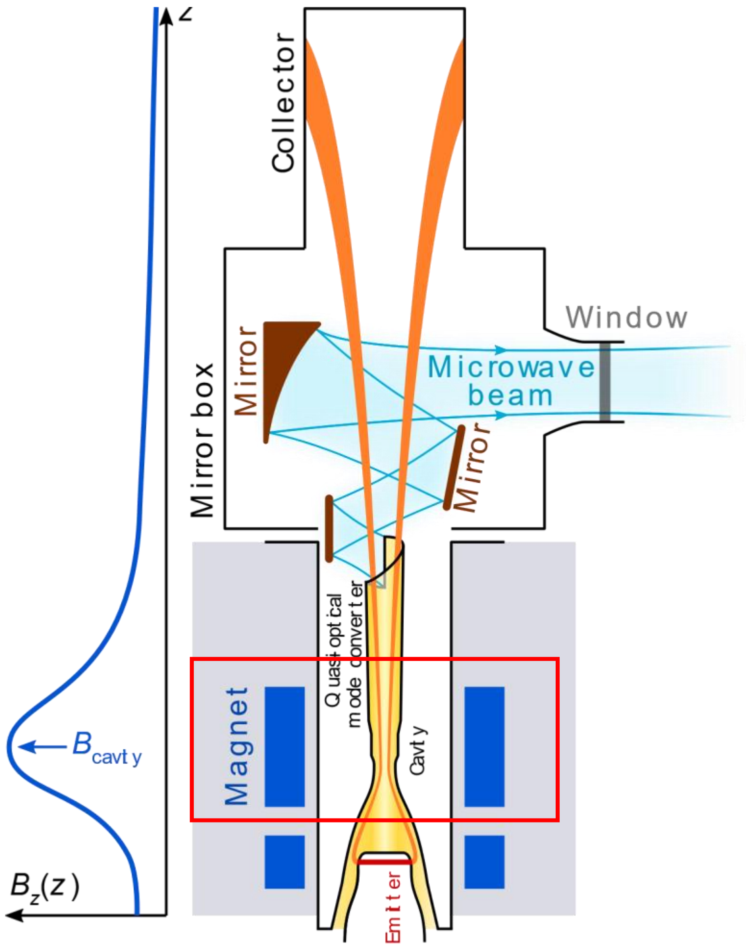
Gyrotron

- Overmoded cavities possible

→High output power

- No structures in size of the wavelength
  - Cyclotron frequency $\Omega_c = \frac{e}{m_e \gamma} B$
  - RF-Frequency $\omega \approx s\,\Omega_c$

→High frequencies



Second Harmonic MW Level Gyrotrons

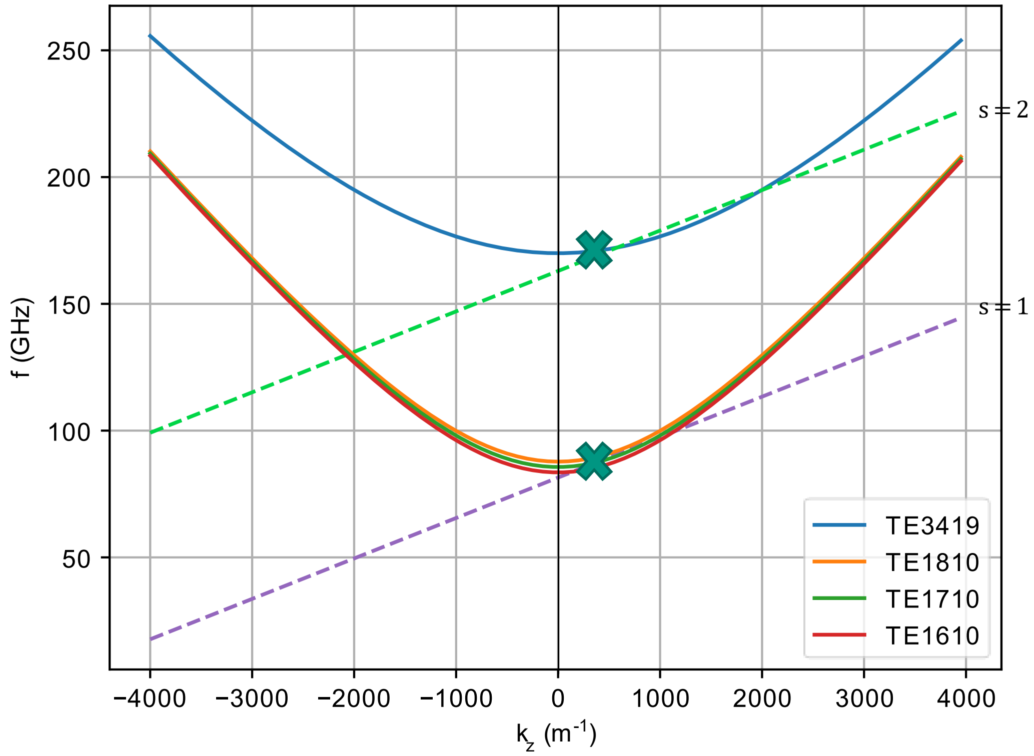
- Demand for high power (> 1 MW) and high frequencies (> 204 GHz)
- Reduction of the required gyrotron magnetic flux density by a factor of two
- Compact and cost-efficient gyrotron systems at DEMO relevant frequencies
- Conceivable applications for switching between fundamental and harmonic operation

ENR Second Harmonic Gyrotron

- Gyrotron interaction possible when:

$$\omega \approx s \underbrace{\frac{eB}{m_e \gamma}}_{\Omega_c} - k_z v_z$$

- Competition with fundamental competitors most critical
- **So far only fundamental fusion gyrotron**



ω : RF frequency
s : Harmonic number
B : Magnetic flux density
e : Elementary charge
m_e : Electron rest mass
γ : Relativistic factor
k_z : Propagation constant
v_z : Axial electron velocity

ENR Second Harmonic Gyrotron

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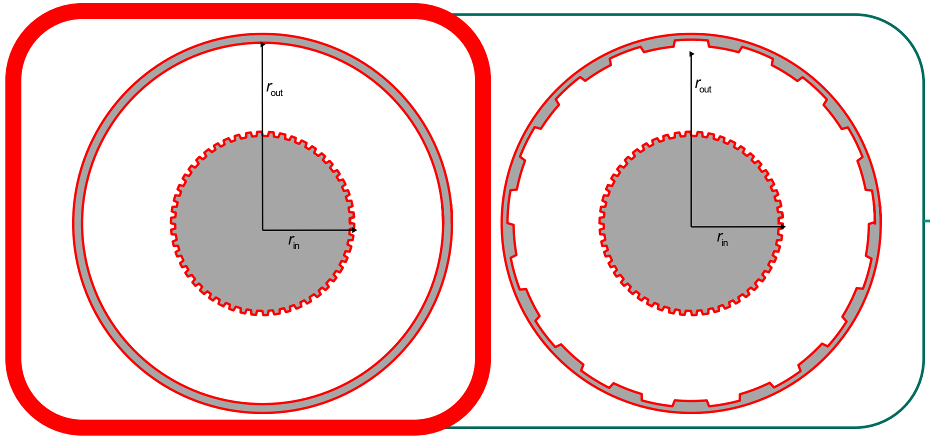
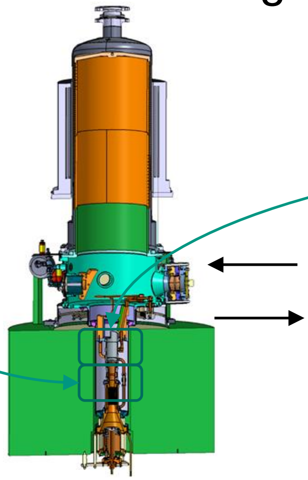
Target: New MW class gyrotrons operating at 2nd harmonic (s = 2)

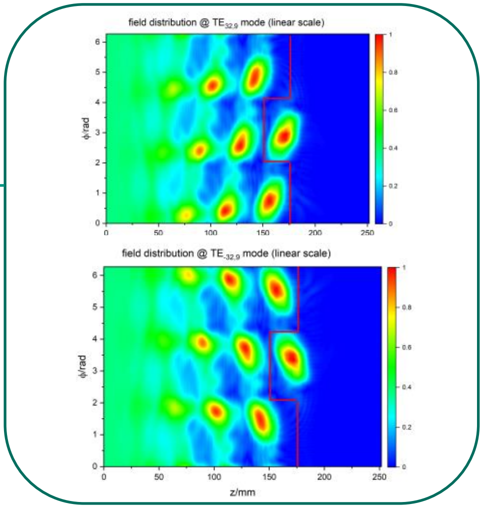
- Requires half the magnetic field compared to fundamental operation
- Higher operating frequencies possible
- Challenge of suppressing fundamental competition
- Main solutions for second harmonic operation:

Coaxial corrugated cavity (inner/outer)



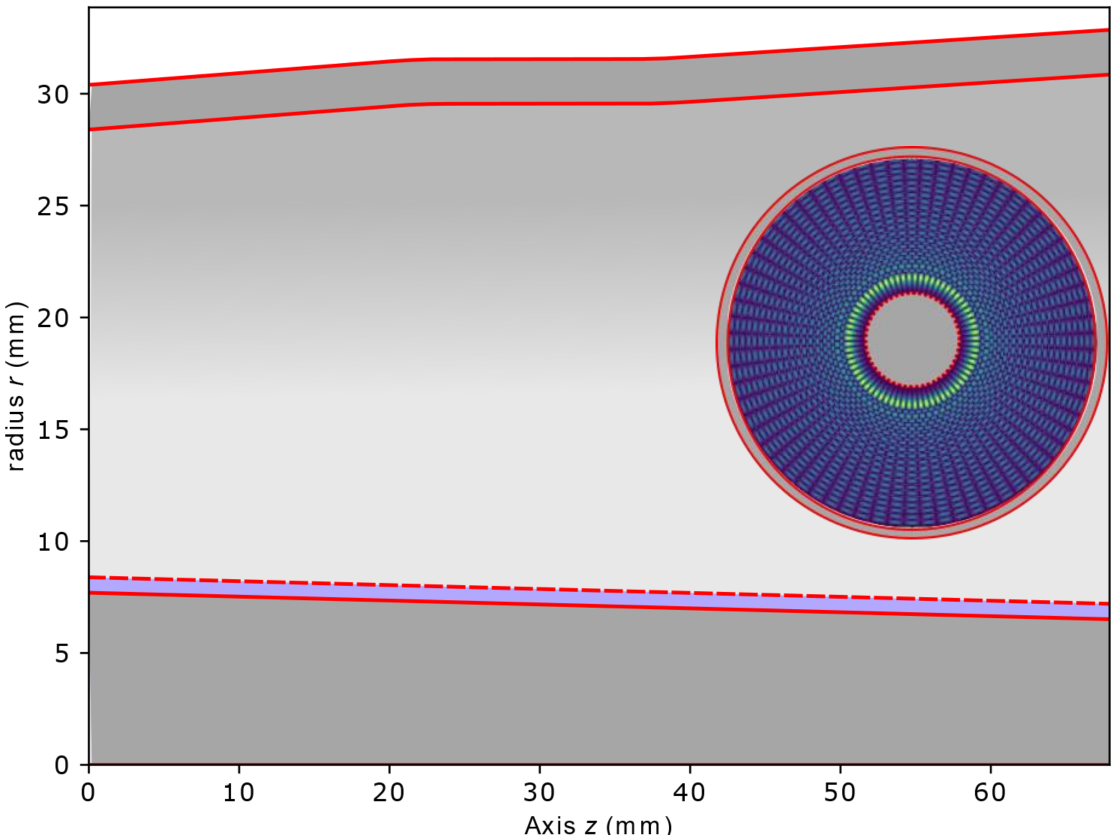
Injection locking by an external signal with co and counter rotating launcher





ENR Second Harmonic Gyrotron

- Suppression of fundamental competing modes due to:
  - Tapered inner and outer conductor
  - Special designed axial corrugations of the coaxial insert
  - Lowered Quality Factor
- Only the fundamental competing modes are influenced
- Operating mode not disturbed by coaxial insert



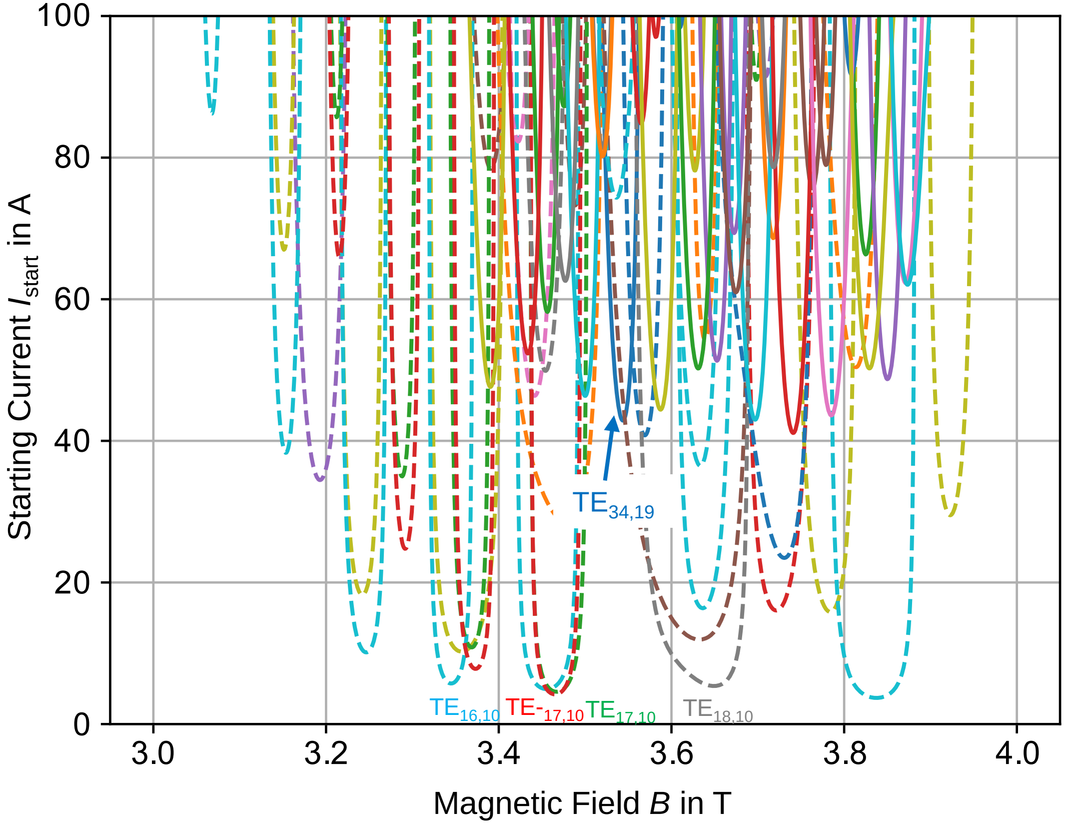
Fundamental KIT Coaxial 2 MW Gyrotron

- Fundamental Coaxial Gyrotron [1]
- Operating mode $TE_{34,19}$
- Frequency 170 GHz
- Magnetic field **6.9 T** ➡ **3.5 T**
- Output power **2 MW** ➡ **> 1 MW**

[1] T. Ruess *et al.*, ‘Performance Expectation and Preparation of the First Experimental Campaign of the KIT 2 MW 170/204 GHz Coaxial-Cavity Gyrotron’, in *2021 22nd International Vacuum Electronics Conference (IVEC)*, Apr. 2021, pp. 1–2. doi: 10.1109/IVEC51707.2021.9722448.

Fundamental KIT Coaxial 2 MW Gyrotron

- Operating mode $TE_{34,19}$
- Frequency 170 GHz
- Magnetic field 6.9 T ➡ **3.5 T**
- No second harmonic operation possible, because of the fundamental competitors
- **New cavity design for second harmonic interaction necessary**



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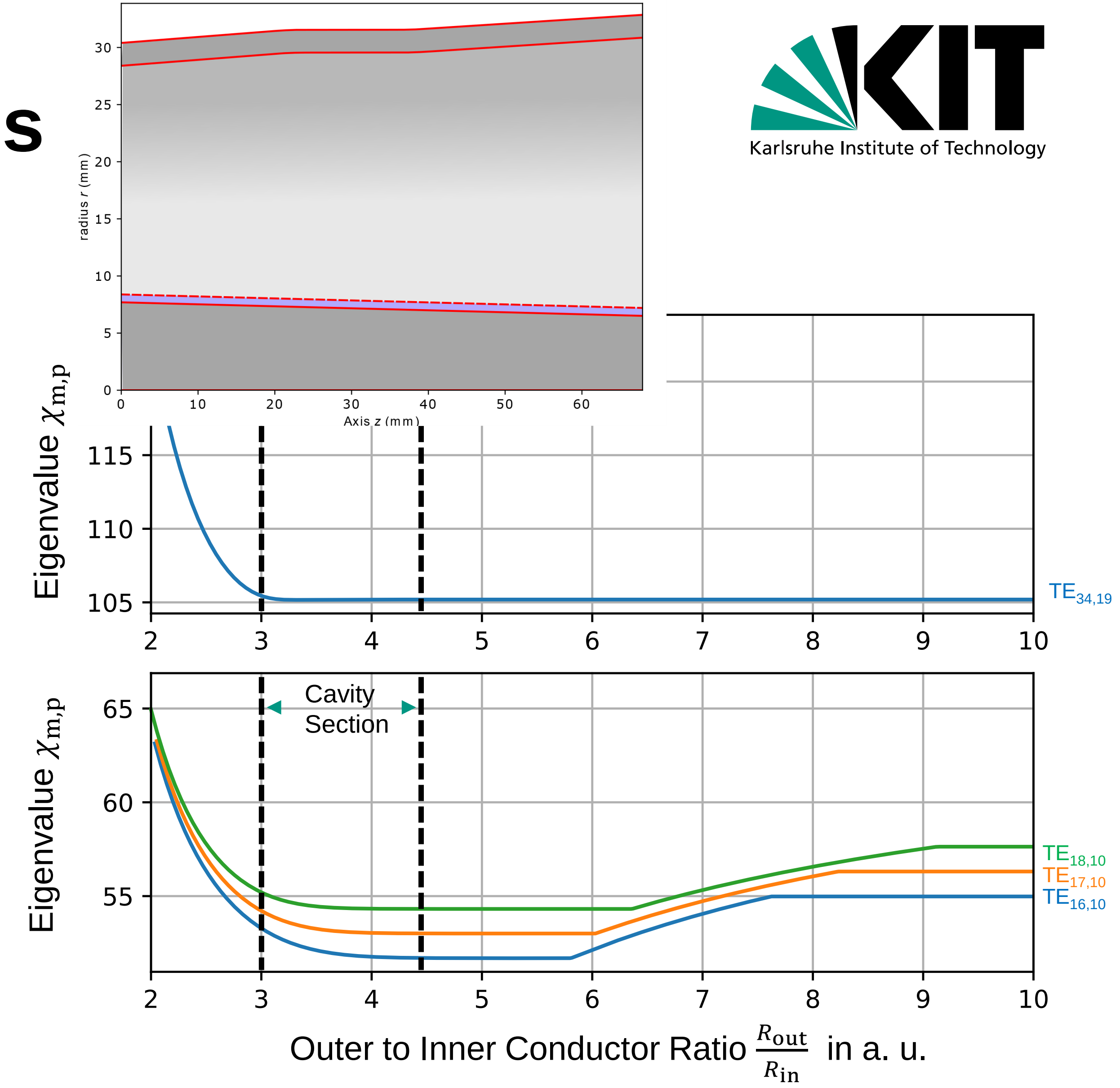
Eigenvalues of Coaxial Modes

- Corrugations are modelled with Surface Impedance Model (SIM)
- Eigenvalue of coaxial modes depends on outer to inner wall ratio and corrugation depth
- Operating mode not disturbed by coaxial insert
- Corrugation depth for second harmonic cavity: $0.4 - 0.6\,\lambda_{c,o}$

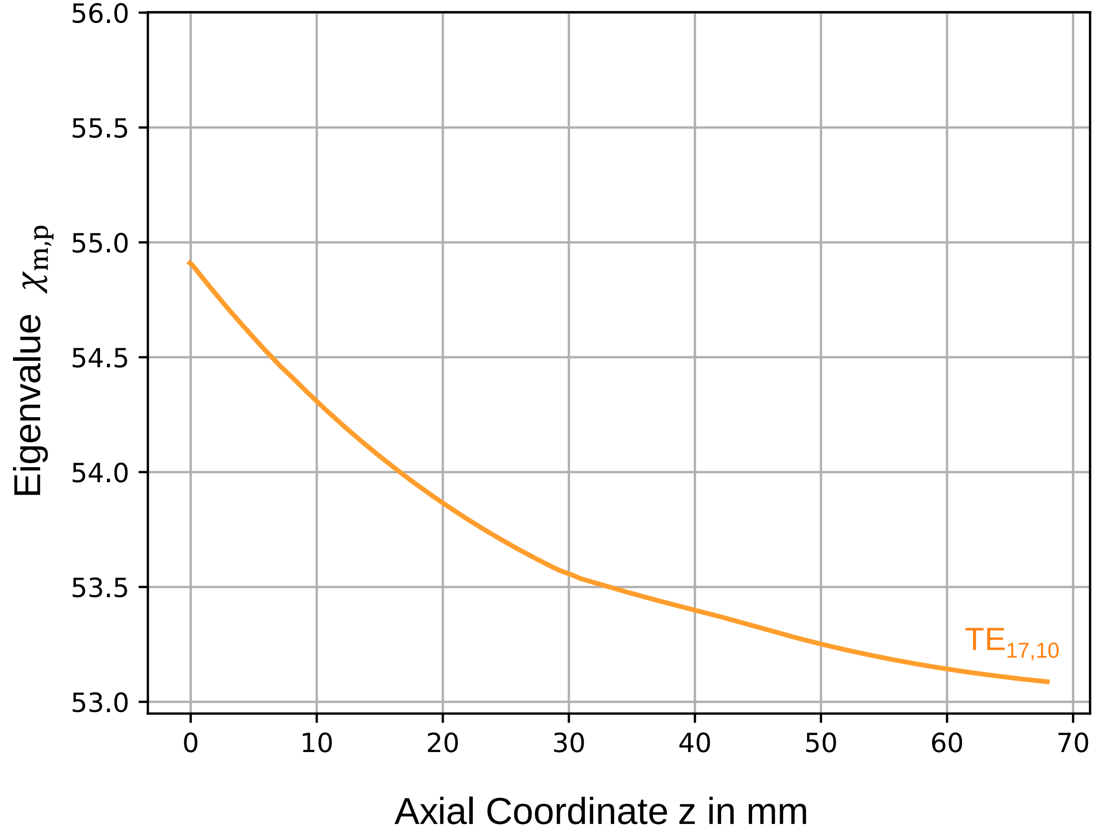


λ_c : Free space wavelength at cutoff frequency

Eigenvalues of Coaxial Modes

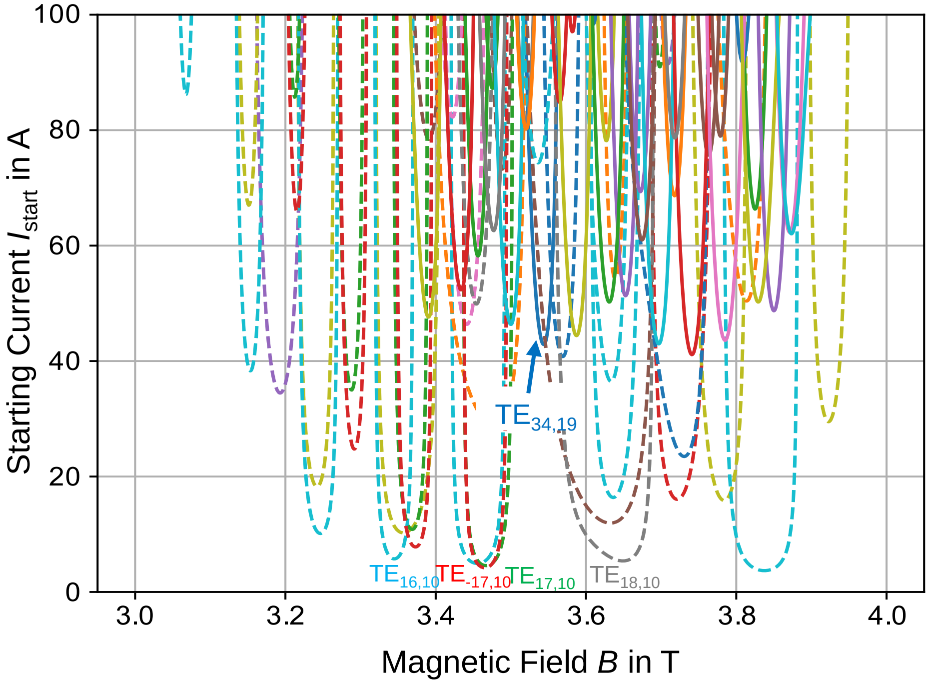
- Corrugated coaxial cavity enabling technology to suppress competition
- Strong decrease of Q- Factor of competing modes
- Diffractive quality factor in the same cavity:

Mode	$d \approx 0.25\,\lambda_c$	$d \approx 0.4\,\lambda_c$
$TE_{34,19}$	Q = 2300	Q = 2800
$TE_{17,10}$	Q = 4000	Q = 460

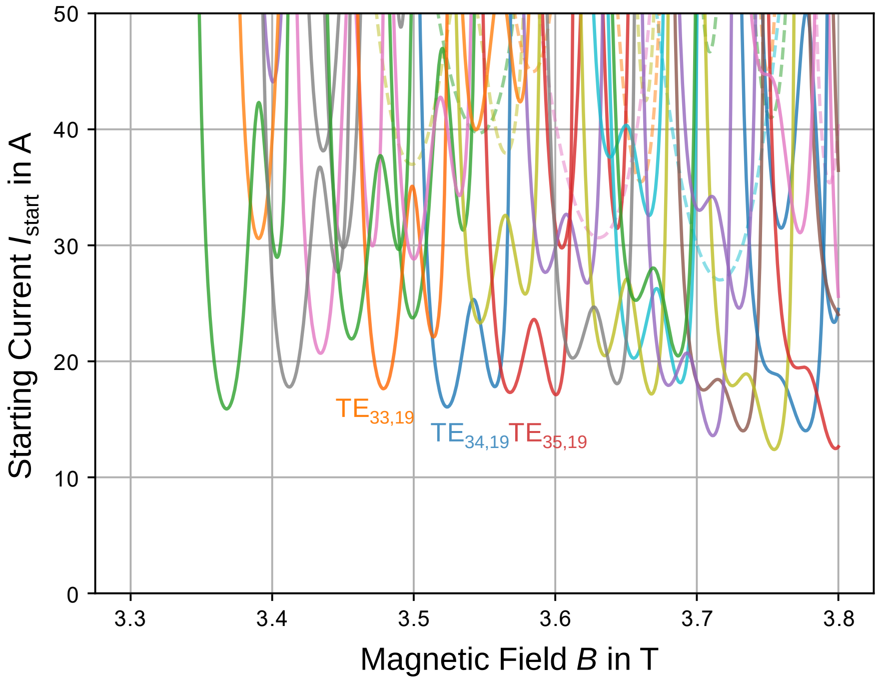


Starting Currents

Fundamental Cavity



Second Harmonic Cavity



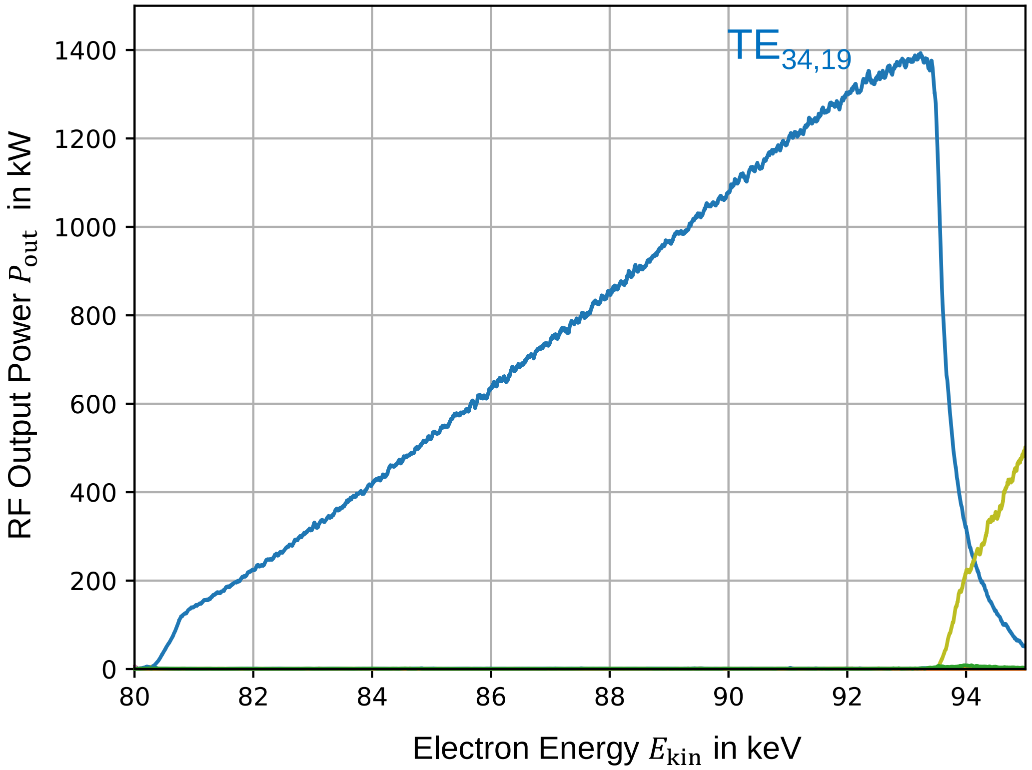
Interaction Modelling

- Electron beam parameters by 2D beam optics code [1]
- Self consistent time-dependent multi-mode simulation
  - Trajectory approach for electrons [2]
  - Particle-in-cell (PIC) modelling with 3D electron beam [3]
- Simulation with the 50 most dangerous fundamental competitors and 49 second harmonic competitors

[1] S. Illy *et al.*, 'Gyrotron electron gun and collector simulation with the ESRAY beam optics code', *IVEC*, 2015, pp. 1–2. doi: 10.1109/IVEC.2015.7223779.
[2] K. A. Avramides *et al.*, 'EURIDICE: A code-package for gyrotron interaction simulations and cavity design', *EPJ Web of Conferences*, vol. 32, p. 04016, 2012, doi: 10.1051/epjconf/20123204016.
[3] A. Marek *et al.*, 'Time-Domain Simulation of Helical Gyro-TWTs With Coupled Modes Method and 3-D Particle Beam', *IEEE Trans. on Electr. Dev.,* vol. 69, 2022, doi: 10.1109/TED.2022.3182292.

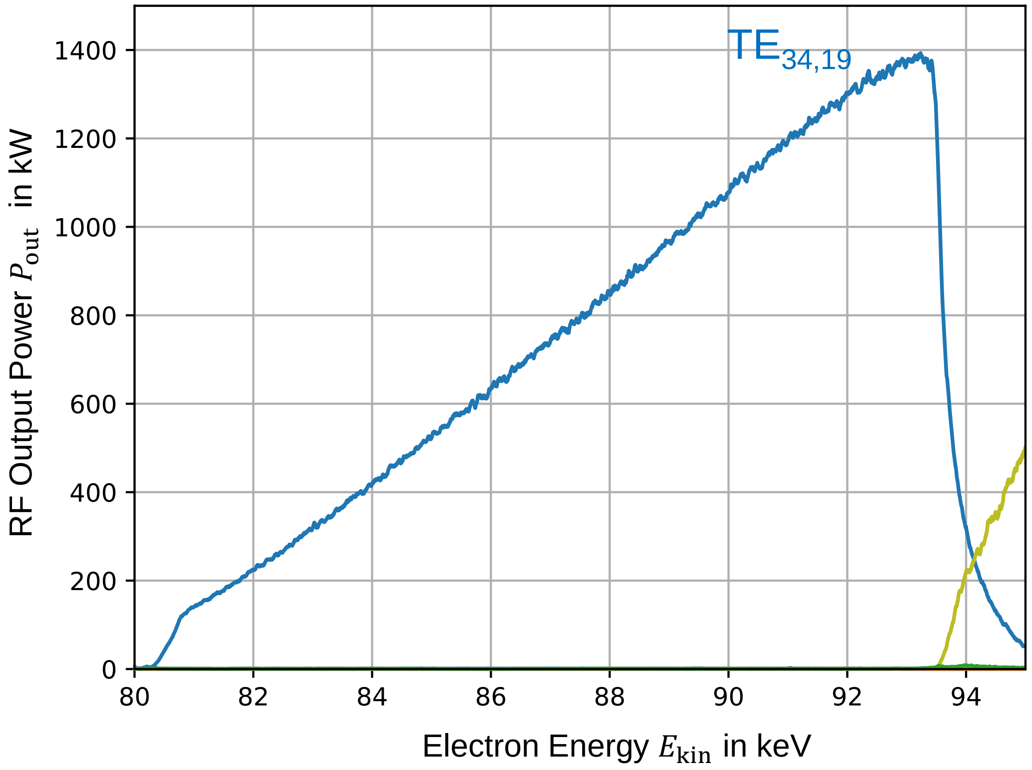
Interaction Simulations

	Operating Point	Spread
Kinetic Electron Energy	E_{kin} = 92 keV	0.19 %
Beam Current	I_{b} = 75 A	
Electron Pitch Factor	α = 1.3	7.56 %
Guiding Center Radius	r_{gc} = 9.62 mm	1.24 %
Magnetic Field	B = 3.5 T	



Interaction Simulations

- Output Power : $P_{\mathrm{out}} = 1.33\ \mathrm{MW}$
- Frequency: $f = 170.01\ \mathrm{GHz}$
- Electronic Efficiency : $\eta_{\mathrm{elec}} \approx 19\ \%$
  (without Collector)
- Total Efficiency: $\eta_{\mathrm{tot}} \gtrsim 50\ \%$
  (with Multi-stage depressed collector [5])



[5] B. Ell *et al.*, 'Coaxial multistage depressed collector design for high power gyrotrons based on E×B concept', *Physics of Plasmas*, vol. 26, no. 11, p. 113107, Nov. 2019, doi: 10.1063/1.5118338.

ENR Second Harmonic Gyrotron

- Maximum output power > 1 MW possible
- Excellent suppression of fundamental competitors with and without injection locking possible

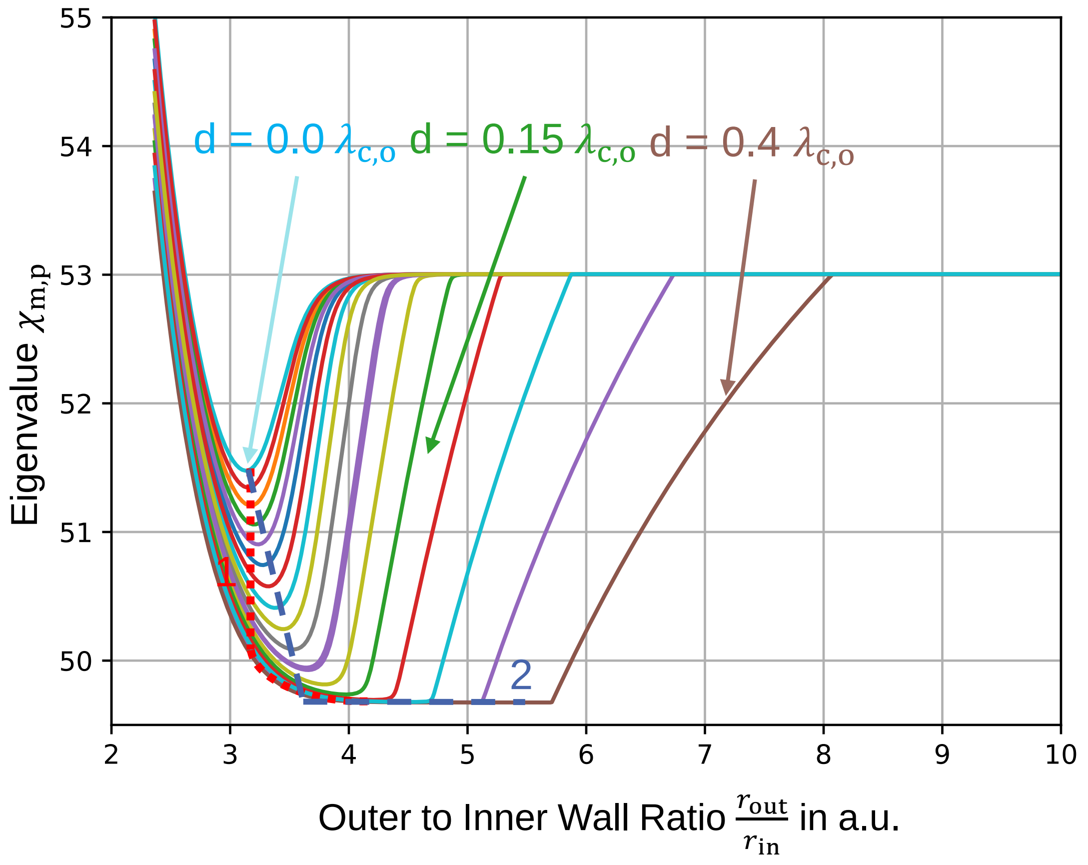
Operating Mode	Frequency	Driving Power	Output Power	Electronic Efficiency η_{elec}
$TE_{34,19}$	170 GHz	-	1.33 MW	19 %
$TE_{40,23}$	204 GHz	-	1.1 MW	20 %
$TE_{36,20}$	280 GHz	-	0.8 MW	15 %
$TE_{34,19}$	170 GHz	200 kW	1.6 MW	

Problems

- Design Limits:
  - Outer cavity wall (~ 2 kW/cm^2)
  - Inner conductor (~ 230 W/cm^2)
  - Beam clearance to inner conductor
- At high beam currents fundamentals start to prevail
  - $I_{b,max}$ = 78 A
  - $P_{out,max}$ = 1.45 MW
- How to increase stability region/ beam clearance?

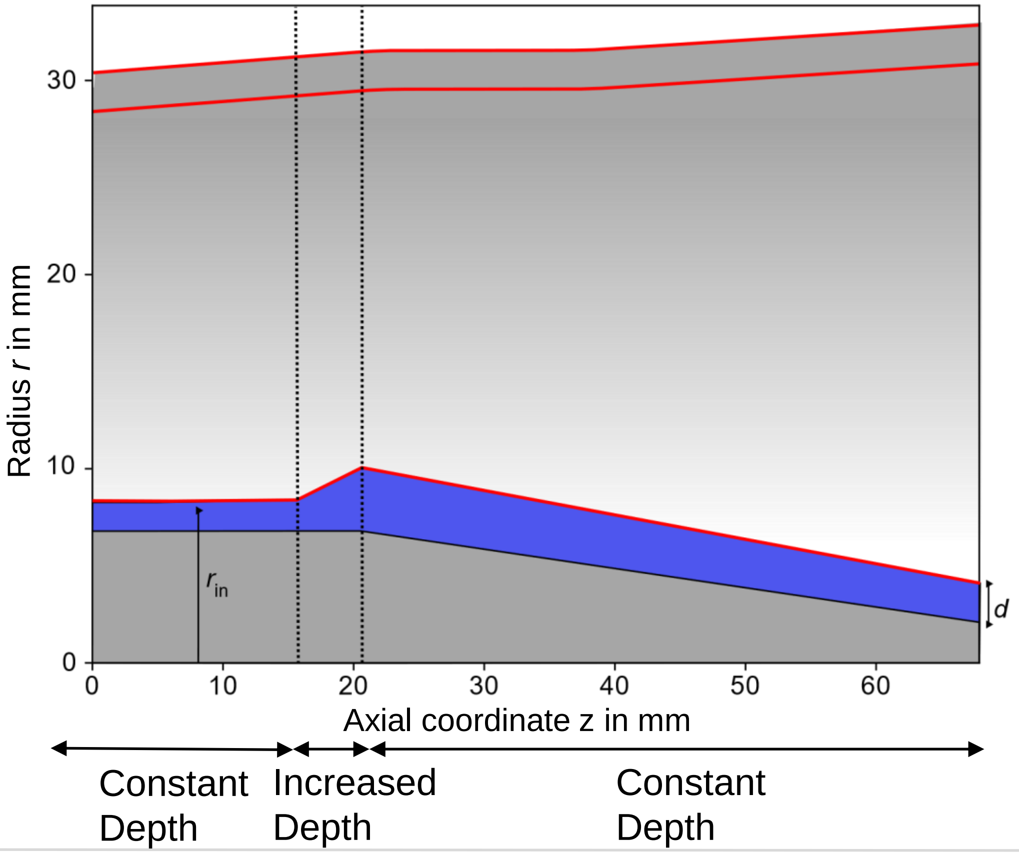
Eigenvalues of Coaxial Modes

- Eigenvalue of coaxial modes depends on outer to inner wall ratio and corrugation depth
- Idea: Increase corrugation depth along the cavity
- Increased drop in competing mode eigenvalues along the cavity axis

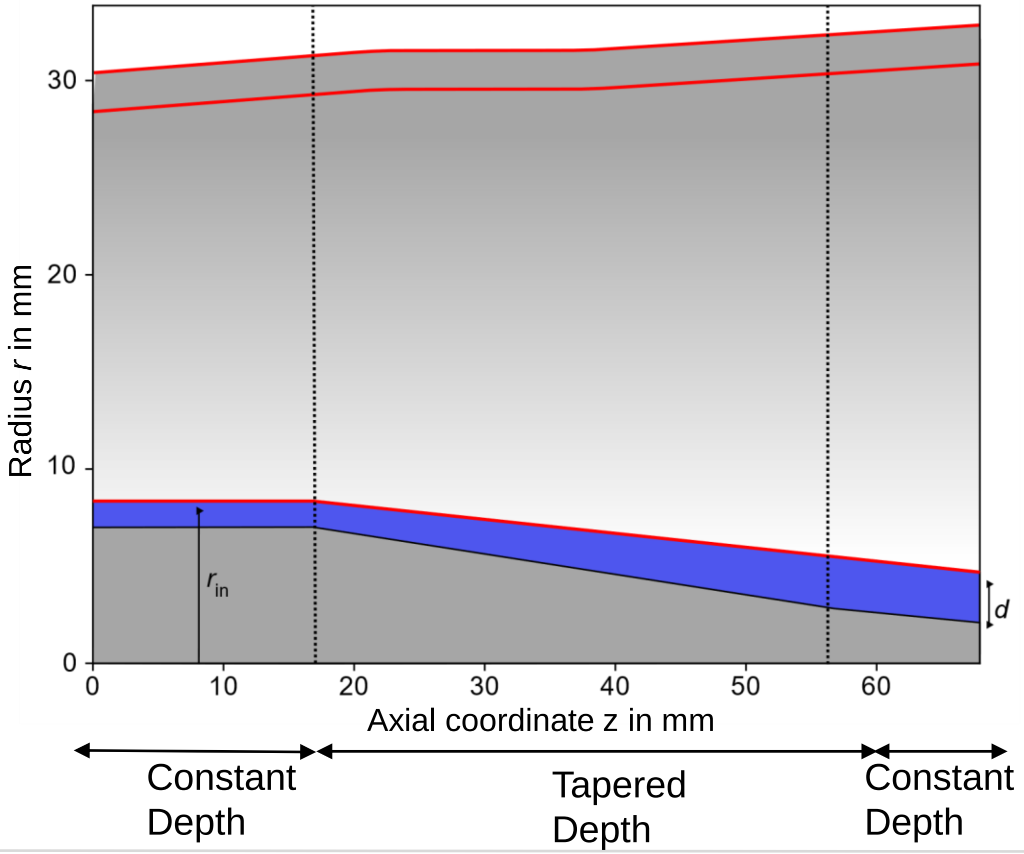


Possible Corrugation Profiles

Profile 1



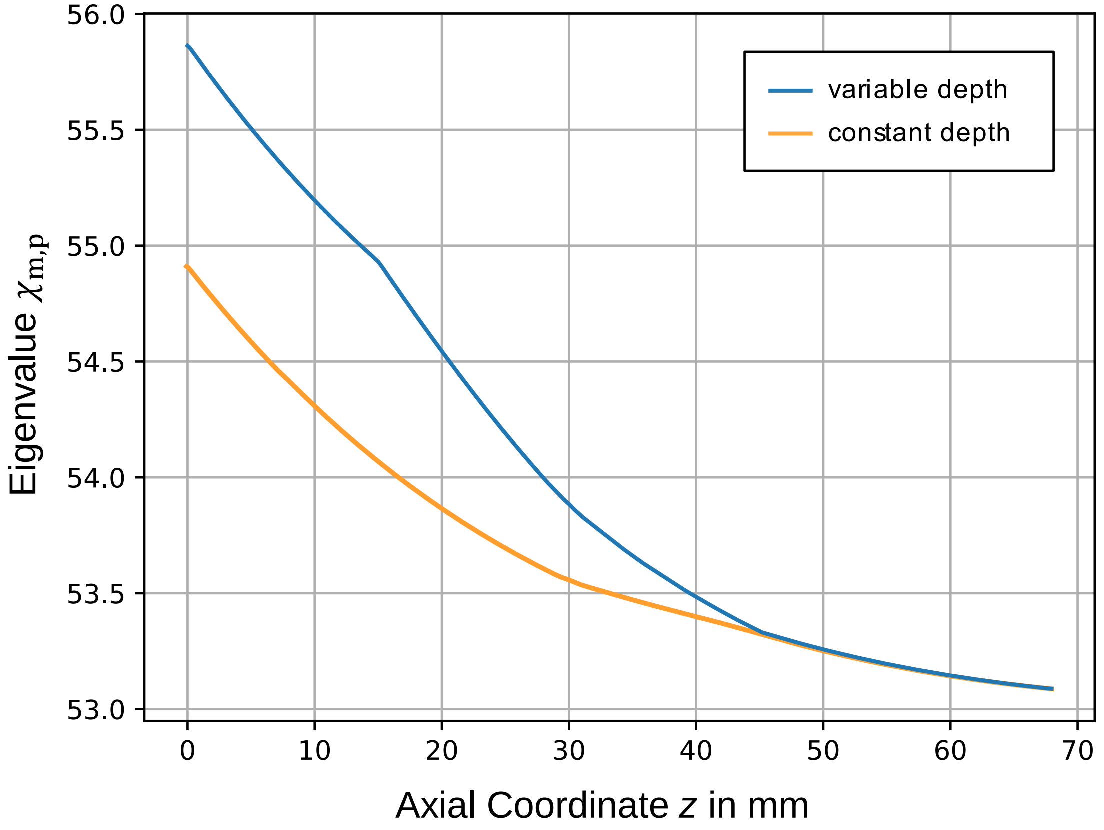
Profile 2



TE34,19 Variable Corrugation Depth

- Change of the effective surface impedance
- Increased drop in competing mode eigenvalues along the cavity axis
- Reduction of the diffractive quality factor of the competing mode
- Diffractive quality factor in the same cavity:

Mode	Constant Corrugation Depth	Tapered Corrugation Depth
$TE_{34,19}$	Q = 2800	Q = 2550
$TE_{17,10}$	Q = 460	Q = 232



Variable Corrugation Depth: Pitch Factor Tolerance Studies

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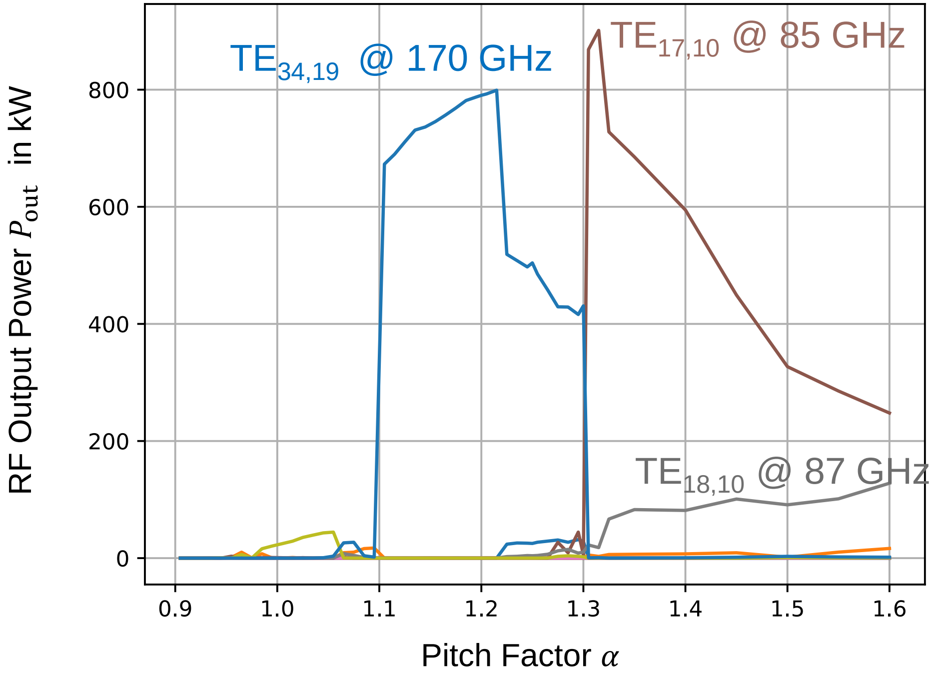
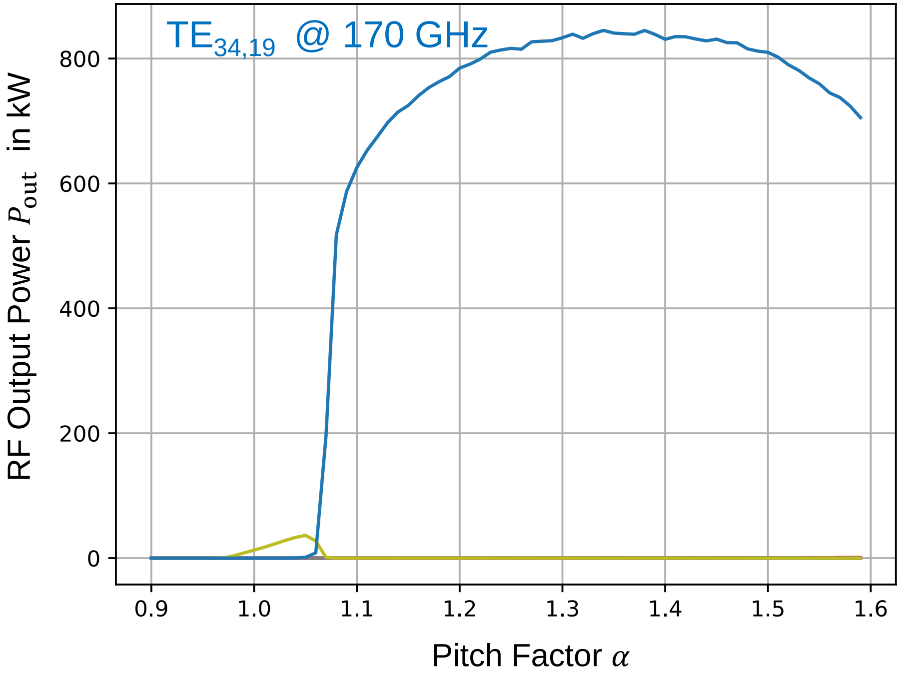
Const Corrugation Depth

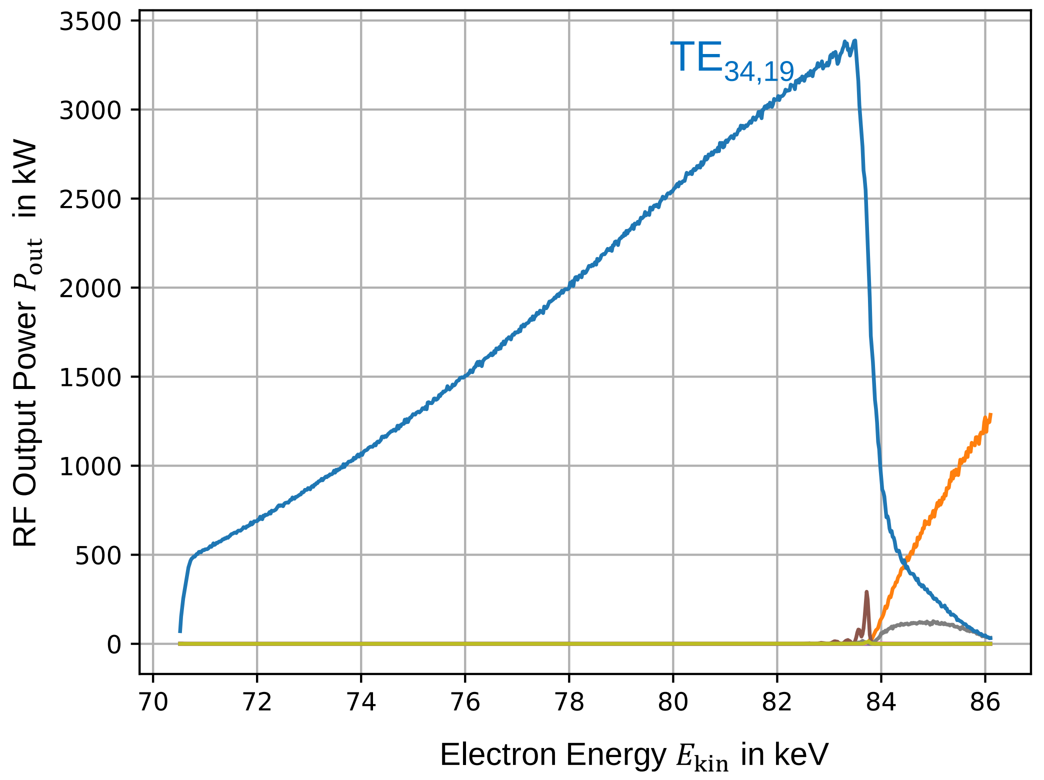


Variable Corrugation Depth



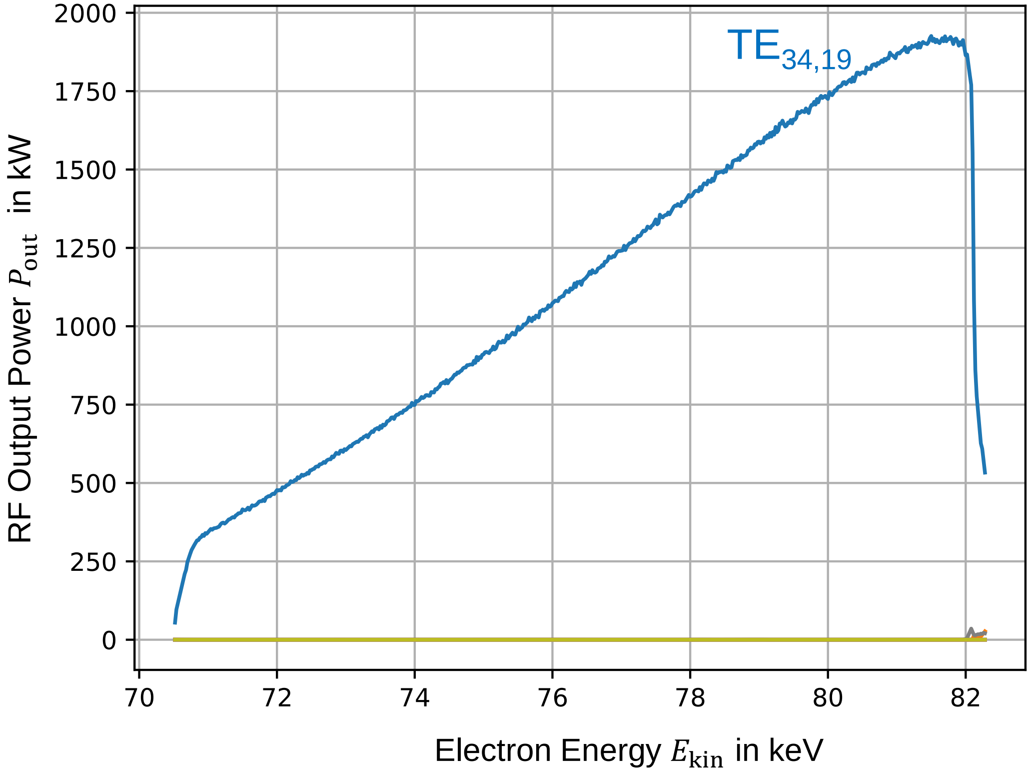
Variable Corrugation Depth: Increased Operating Current

- Constant corrugation depth
  - $I_{b,max}$ = 78 A
  - $P_{out,max}$ = 1.45 MW
  - $\eta_{elec} \approx 20\ \%$
- Tapered corrugation depth
  - $I_{b,max}$ = 140 A
  - $P_{out,max}$ = 3.4 MW
  - $\eta_{elec} \approx 27\ \%$



Variable Corrugation Depth: Decreased Inner Conductor

- Idea: Enhanced suppression of fundamental competitors
- Decrease inner conductor radius by 0.5 mm
  - Decrease of ohmic loading on the inner conductor
  - Increase of clearance between beam and inner conductor
- $I_{b,max}$ = 100 A
- $P_{out,max}$ = 1.8 MW
- Ohmic wall loading ρ_{out} = 2.5 kW/cm²
  ρ_{in} = 0.15 kW/cm²



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Conclusion

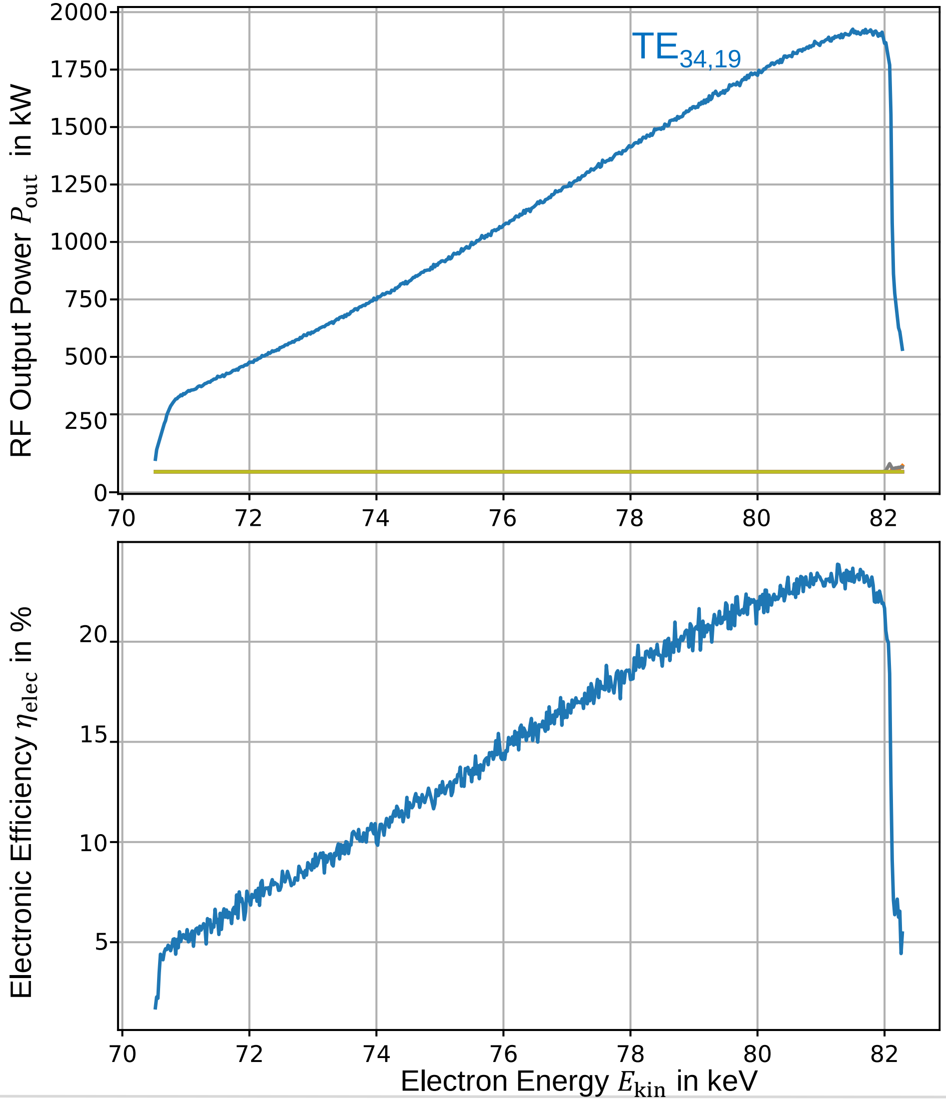
- Corrugated coaxial cavity enabling technology to suppress fundamental competition
- Over 1 MW output power in second harmonic operation of a high order mode possible
- No complex injection locking system required
- The suppression of the fundamentals can be enhanced due to profiled corrugations

Challenges for a Second Harmonic Gyrotron

Design Goals	Challenges
Second Harmonic Interaction in an over moded cavity	Suppression of fundamental competitors
Continuous wave capability	Strong ohmic loading requirements
Operation with current electron gun possible	Lower $\boldsymbol{B}$ field $\rightarrow$ Lower compression
Cavity fits mechanically into the existing short-pulse gyrotron	Fixed overall cavity length
Keep existing quasi optical output system	Fixed operation mode
	Fixed frequency
	Fixed cavity output radius

TE34,19 Variable Corrugation Depth

- Decrease of 0.5 mm
  - $I_{b,max}$ = 100 A
  - $P_{out,max}$ = 1.8 MW



Output Power TE36,20 280 GHz

- Design of a $TE_{36,20}$ Gyrotron Cavity

Kinetic Electron Energy	E_{kin} = 97 keV
Beam Current	I_{b} = 50 A
Electron Pitch Factor	α = 1.2
Magnetic Field	B = 5.82 T

- Increased Beam Clearance

Guiding Center Radius	r_{gc} = 6.25 mm
Maximum Insert Radius without tapered corrugations	r_{in} = 5.8 mm
Maximum Insert Radius with tapered corrugations	**r_{in} = 5.5 mm**