Operation Limits of a 236 GHz Hollow-Cavity Gyrotron for DEMO

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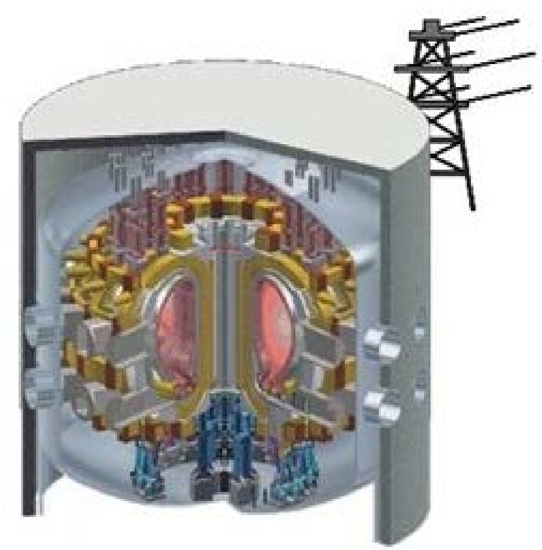
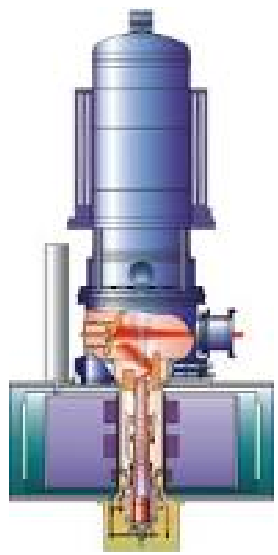
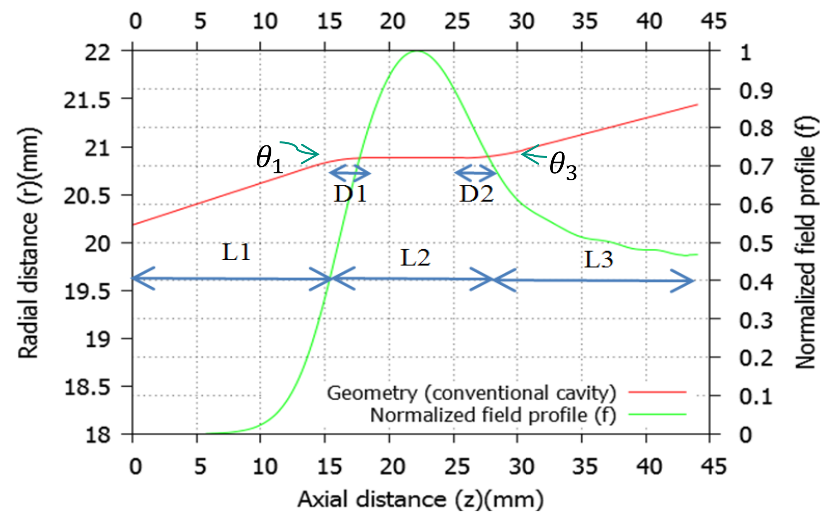
5th ITG International Vacuum Electronics Workshop 2016, 08h – 09th Sept. 2016, Bad Honnef, Germany







Outline of the presentation

Introduction

- Requirements for **DEMO gyrotrons**

Current status of DEMO gyrotron development at KIT

- **Hollow-cavity** and **coaxial-cavity** gyrotron designs
- Quick performance analysis

Operation limits of DEMO gyrotrons

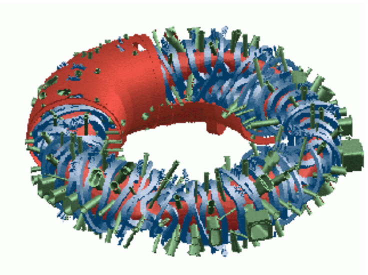
- Motivation for this study
- Methods to find mode **eigenvalue limits**
- New **236 GHz 1.5 MW** design
- **Triode start-up** scenario

Conclusions

- Conclusive remarks

What Is DEMO?

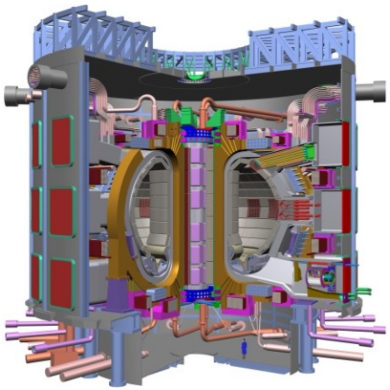
Wendelstein 7-X (W7-X)



(now)

- ❖ Max-Planck-Institut für Plasmaphysik (IPP), Greifswald, Germany
- ❖ Stellarator
- ❖ Long pulse plasma operation (30 min)
- ❖ First plasma test- **Dec 2015**

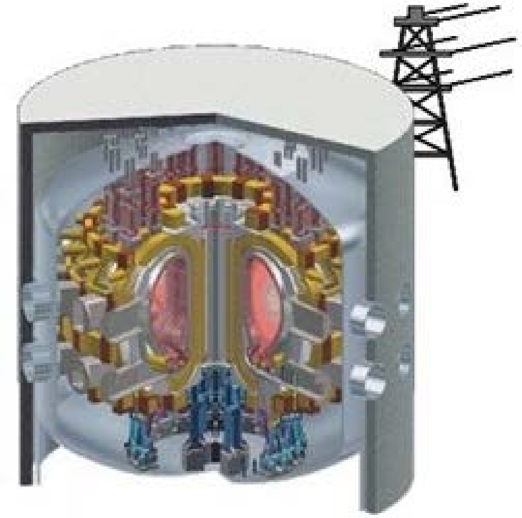
ITER



(next)

- ❖ Cadarache, France
- ❖ EU, India, Japan, China, Russia, South Korea, US
- ❖ Tokamak
- ❖ 500 MW Fusion power
- ❖ Q ≈ 10
- ❖ 400 sec
- ❖ Initial plasma experiments expected in **2025**

DEMOnstration Power Plant (DEMO)



(later)

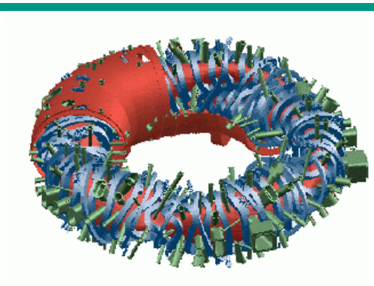
- ❖ **DEMO is the prototype of a fusion power plant which will follow ITER.**
- ❖ first fusion reactor to generate electrical power.
- ❖ Tokamak
- ❖ 3000 MW Fusion power
- ❖ Q ≈ 35-50
- ❖ Long pulse and later steady-state operation
- ❖ **Conceptual design is ongoing**.

Gyrotrons for ECRH&CD

DEMOnstration Power Plant (DEMO)

ITER

Wendelstein 7-X (W7X)



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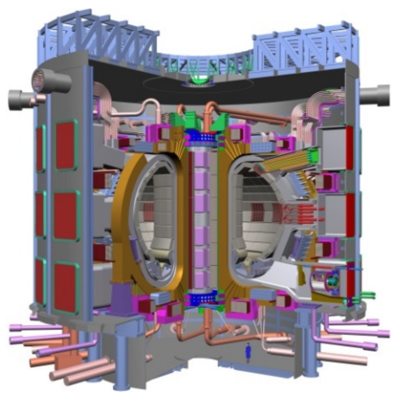

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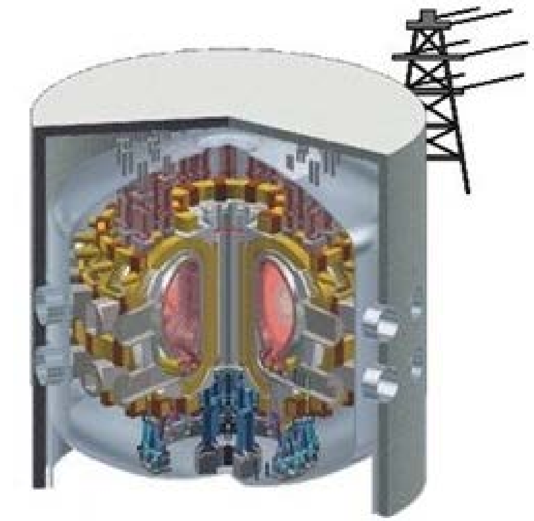

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Gyrotrons are the only high-power (~ 1 MW), high frequency (> 100 GHz) RF sources for Electron Cyclotron Resonance Heating and Current Drive (ECRH&CD) in fusion experiments.

Requirements for DEMO gyrotrons

- **Frequency: 230 – 240 GHz** (high power, high frequency → higher order mode)
- Output Power P_{out} **≈ 1 MW** (hollow cavity), **≈ 2 MW** (coaxial cavity)
- Interaction efficiency η **> 35 %**
- Total efficiency η **> 60 %** (with multi-stage depressed collector)
- **Fast frequency step-tunability** (in a few seconds) in steps of **2 – 3 GHz.**
- **Slow frequency tunability** (in a few minutes) in leaps of **30 – 40 GHz** for multi-purpose use (**multi-frequency gyrotron**).

Goal	Value
Peak ohmic wall loading at cavity ρ_{R}	≤ 2 kW/cm^2
Emitter current density j_{E}	< 4 A/cm^2
Electric field at emitter E_{E}	< 7 kV/mm
Width of electron guiding centers	$\leq \lambda/5$
Parameter	**Value**
Magnetic field (cavity)	~ 9 – 10 T
Maximum emitter radius $R_{\text{E,max}}$	$50 - 65$ mm

* as per the EUROfusion baseline for DEMO, 2012. DEMO aspect ration = 4.0

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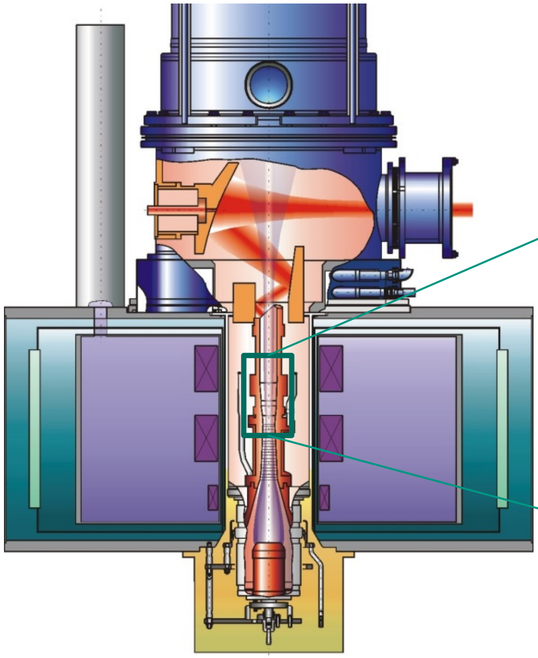
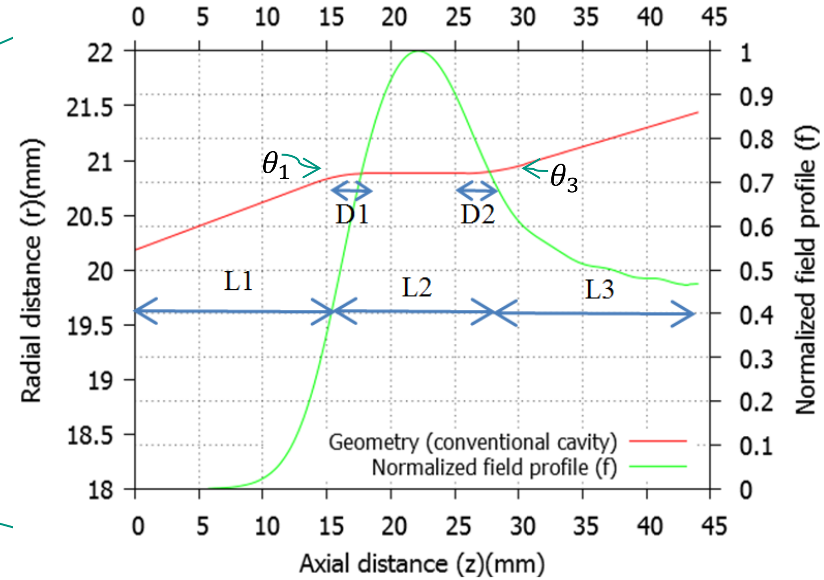
Current status of DEMO gyrotron development at KIT

Hollow cavity vs Coaxial cavity gyrotron

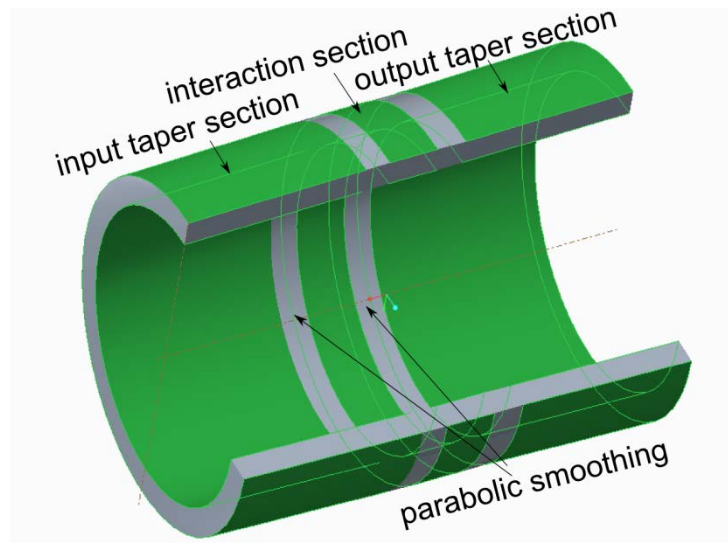




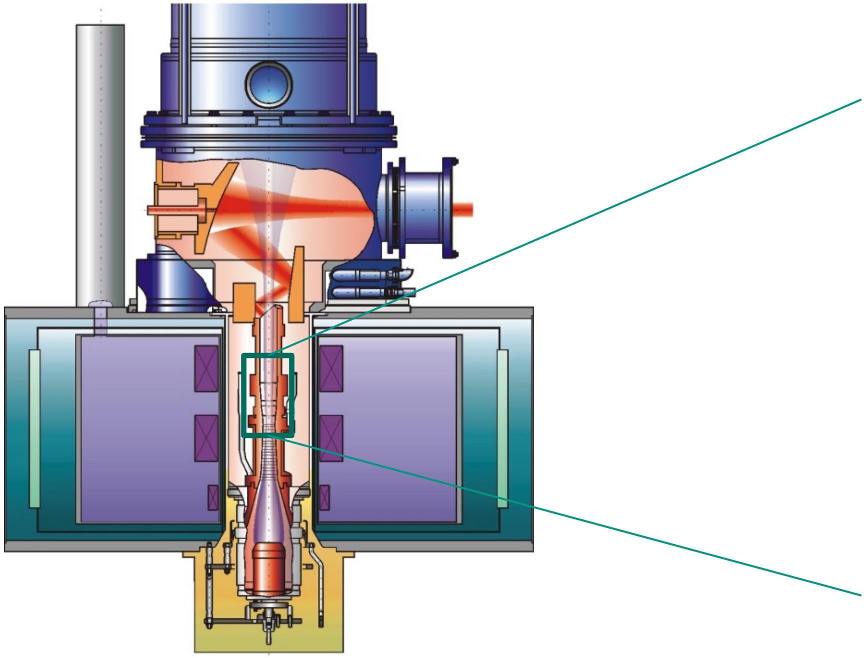
Hollow cavity

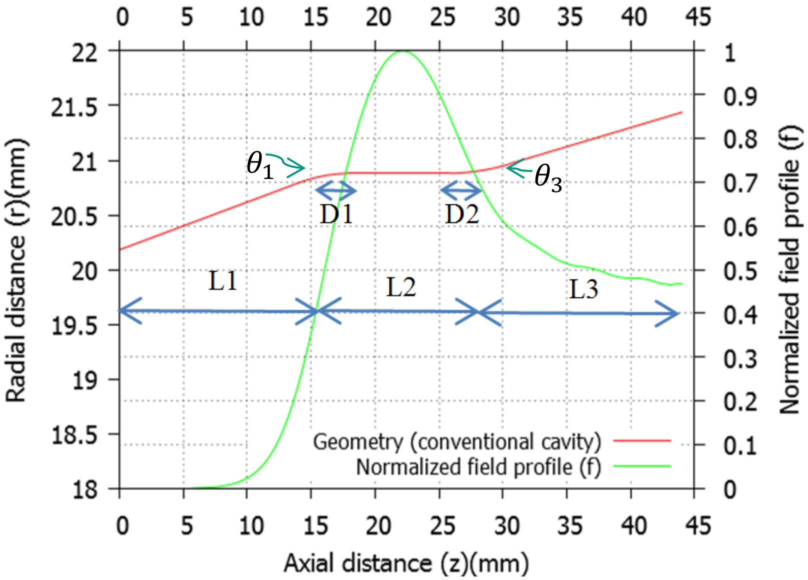
- Simple and robust design
- Suitable for long-pulse operation

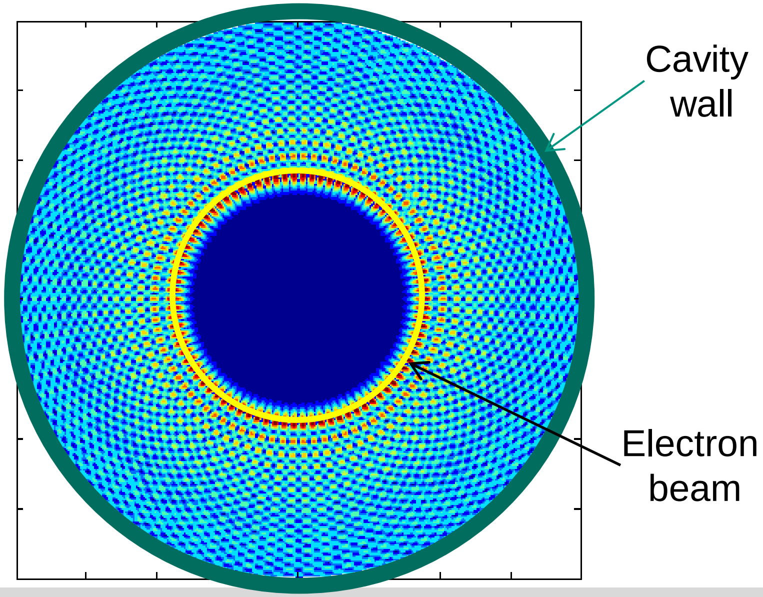
- Compared to coaxial design, less **output power** and **power handling capacity** for a particular frequency



Hollow cavity vs Coaxial cavity gyrotron







<u>Hollow cavity</u>

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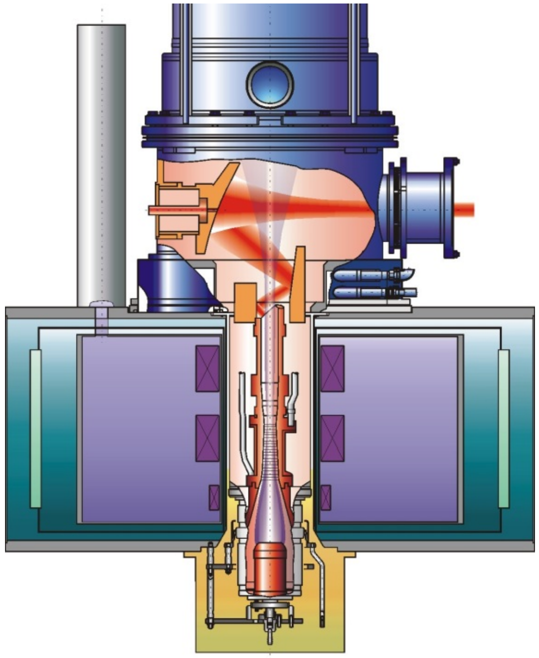
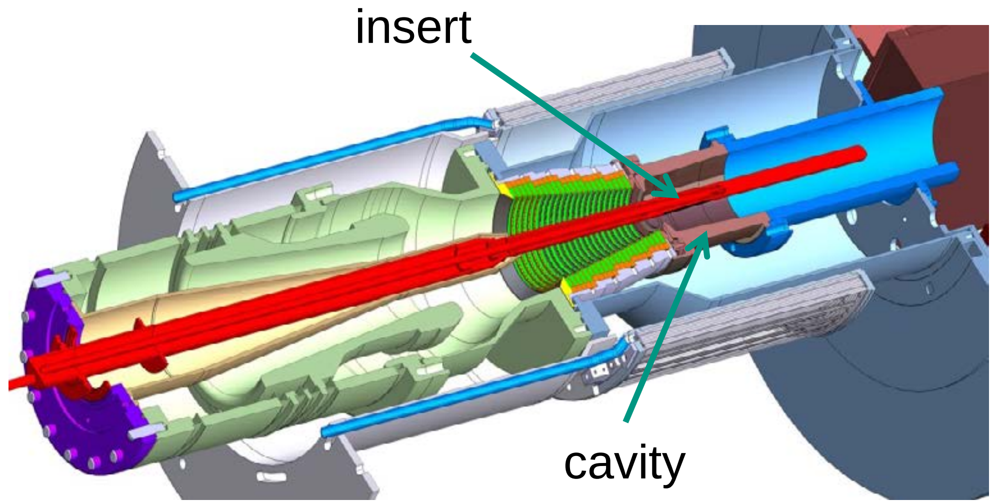
Hollow cavity vs Coaxial cavity gyrotron





Hollow cavity

- Simple and robust design
- Suitable for long-pulse operation

- Compared to coaxial design, less **output power** and **power handling capacity** for particular frequency

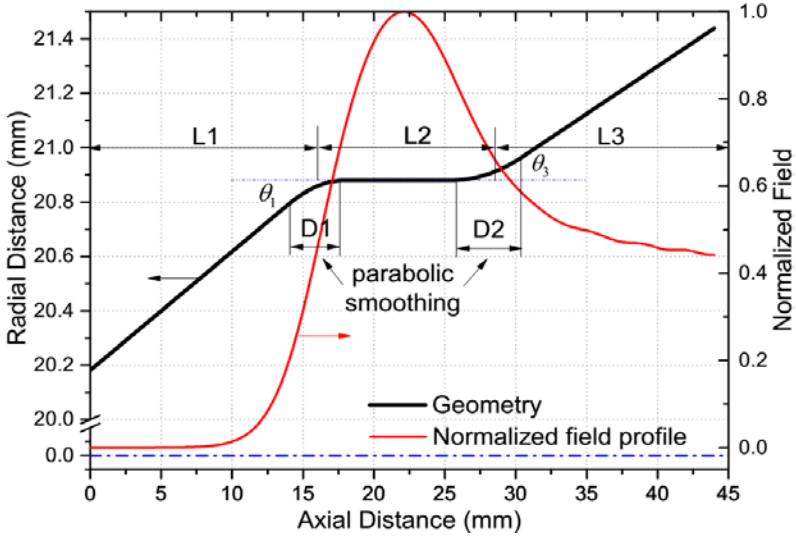
Coaxial cavity

- Reduced mode competition due to insert → Allow operation of very high order mode → higher output power
- Significantly reduced voltage depression

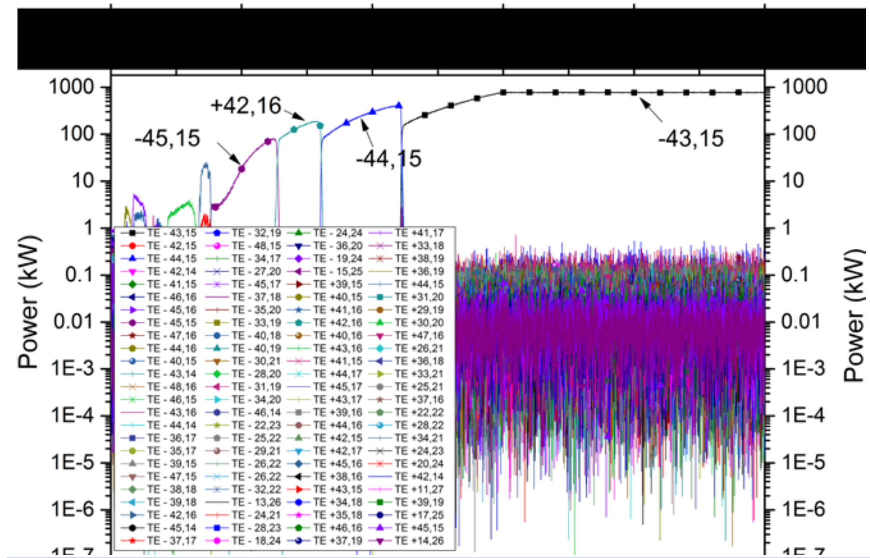
Session 1.4, L1.4-1, 15:40 – 16:05, J. Franck et al., "Insert Misalignment in Coaxial Gyrotrons: Physical Effects and Numerical Treatment"

- Long-pulse operation has not been demonstrated yet
- **More complicated manufacturing**

Hollow cavity 236 GHz, $TE_{43,15}$ mode gyrotron



selected hollow cavity design with its field profile
(from systematic cavity design approach)
(L1/L2/L3 = 16/12/16 mm, D1/D2 = 4/5 mm, θ_1 / θ_3 = 2.5°/2°)



RF behavior of cavity with realistic electron beam parameters
("–": mode co-rotating with beam, "+": counter-rotating mode)

- Systematic cavity design approch, wall loading < 2 kW/cm^2
- Multi-mode self-consistent time dependent calculation using EURIDICE
  (Main mode: $\mathrm{TE}_{43,15}$ and 99 neighboring modes)
- Realistic electron beam parameter:
  Perpendicular rms velocity spread 6 %, radial width = $\lambda/4$)
- Stability margin considered, no spurious mode generation at steady state, Glidcop conductivity
- Output **power** = **920 kW**, interaction **efficiency = 36%**

Comparison of hollow- and coaxial-cavity gyrotrons for DEMO

Parameters	Hollow Cavity Design		Coaxial Cavity Design	
Frequency [GHz]	236.04		237.5	
Operating Mode	$TE_{43,15}$ (Eigenvalue ~ **103**)		$TE_{49,29}$ (Eigenvalue ~ **158**)	
Magnetic Field [T]	9.13	9.175	9.58	9.58
Beam Current [A]	39	43	69.3	69.3
Beam Energy [keV]	58	61	85.6	85.6
Pitch Factor (α)	1.25	1.25	1.22	1.22
Ohmic Wall Loss [kW/cm^2]	2.00	2.00	2.00	2.00
Output Power [kW]	828	**920**	2000	**1900**
Interaction Efficiency[%]	38	**36**	35	**33**
Considerations	• Ideal beam • Copper cavity ($\sigma = 1.4{\cdot}10^7$ S/m)	• Realistic beam (velocity spread = 6%, radial width = λ/4) • Glidcop cavity ($\sigma = 1.91{\cdot}10^7$ S/m) • Stability margin = 2 keV	• Ideal beam • Copper cavity ($\sigma = 1.4{\cdot}10^7$ S/m)	• Realistic beam (velocity spread = 6%, radial width = λ/4.4) • Copper cavity ($\sigma = 1.4{\cdot}10^7$ S/m)

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Limits of a 236 GHz hollow cavity gyrotron

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Motivation: output power limit analysis

W7X
ECRH: **10 MW**
→**10** Gyrotrons
(140 GHz, 1 MW)
Hollow-cavity design

ITER
ECRH: **24 MW**
→**24** Gyrotrons
(170 GHz, 1 MW)
Hollow-cavity design

DEMO
Estimated ECRH power: **50 MW**
→ **25 – 50** Gyrotrons
(200 GHz – 240 GHz)
Hollow- or coaxial-cavity design

Goal: Maximize output power per tube with sufficient mode stability

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Motivation: output power limit analysis

Present design: output power **~ 920 kW per tube**
(mode: $TE_{43,15}$: eigenvalue (Bessel root) = 103.2)

Smaller number of tubes desired for particular power requirements

Operation at **higher output power**

Large cavity radius required

High-order operating mode is necessary

$$\left(R_{cav} \approx \frac{c \cdot \chi_{m,n}}{2 \cdot \pi \cdot f}\right)$$

Dense mode spectra and high mode competition, **difficult to excite** operating **mode**

For relevant frequencies, the **maximum mode eigenvalue** for stable operation is essential to estimate the **maximum possible output power**(diode start-up condition)

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Towards higher modes for higher power

- Modes with eigenvalues between 104 and 145
- All modes have nearly the same relative caustic radius ($R_{caustic}$ / R_{cavity}).
- Particular cavity design is optimized in each case.

High-order modes considered for this analysis

Case identifier	**DM1**	**DM2**	**DM3**	**DM4**	**DM5**	**DM6**	**DM7**	**DM8**	**DM9**
Mode	$TE_{-44,15}$	$TE_{-45,16}$	$TE_{-48,17}$	$TE_{-50,17}$	$TE_{-52,18}$	$TE_{-53,19}$	$TE_{-56,20}$	$TE_{-58,20}$	$TE_{-59,21}$
Eigenvalue	104.46	109.17	116.4	118.91	124.87	129.58	136.8	139.32	144.02
Cavity radius (mm)	21.14	22.09	23.55	24.06	25.26	26.22	27.68	28.19	29.14
Beam radius (mm)	9.28	9.49	10.10	10.51	10.93	11.13	11.75	12.16	12.37
Rel. caustic radius	0.42	0.41	0.41	0.42	0.42	0.41	0.41	0.42	0.41
Output Power (kW)*	**1120**	**1211**	**1360**	**1409**	**1520**	**1641**	**1804**	**1873**	**1980**

(*single mode analysis, realistic electron beam parameters, straight interaction section length: $9 \cdot \lambda$ = 11.5 mm)

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Methods to find limits of 236 GHz DEMO gyrotron (Eigenvalue, output power)

1. Using the **linear theory** for gyrotron interaction

- 1.1 Starting current plot analysis
- 1.2 Study of mode spectra

2. Using the **non-linear theory** for gyrotron interaction

- 2.1 Multi-mode start-up analysis
- 2.2 Stability check

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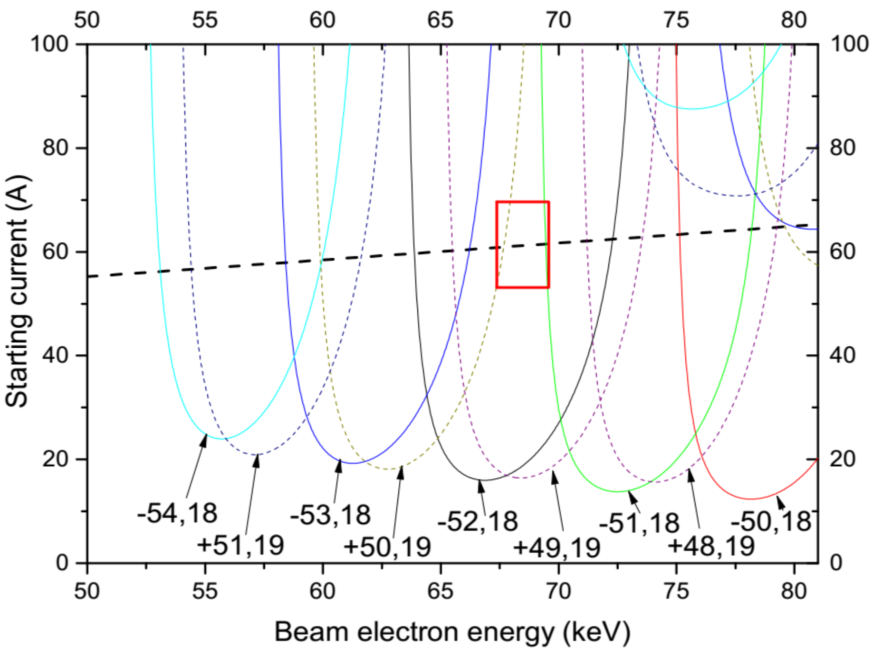
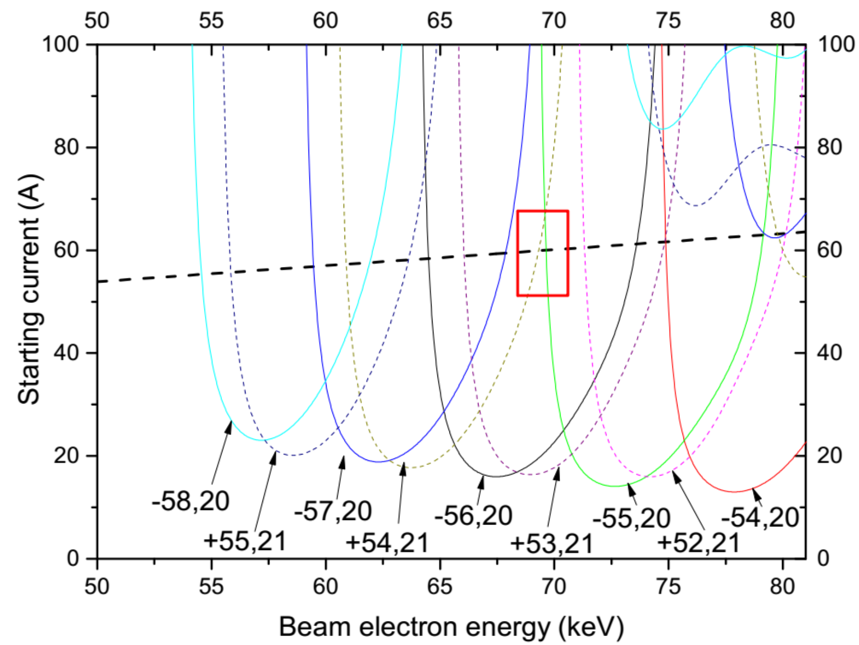
Starting current plot analysis

DM5 : $TE_{-52,18}$: eigenvalue ~ 125



DM7 : $TE_{-56,20}$: eigenvalue ~ 135



DM5: Starting current plots of next neighbors ($TE_{+50,19}$ and $TE_{-51,18}$) are well separated
DM7: immediate jump between $TE_{+54,21}$ and $TE_{-55,20}$; this suppresses excitation of $TE_{-56,20}$

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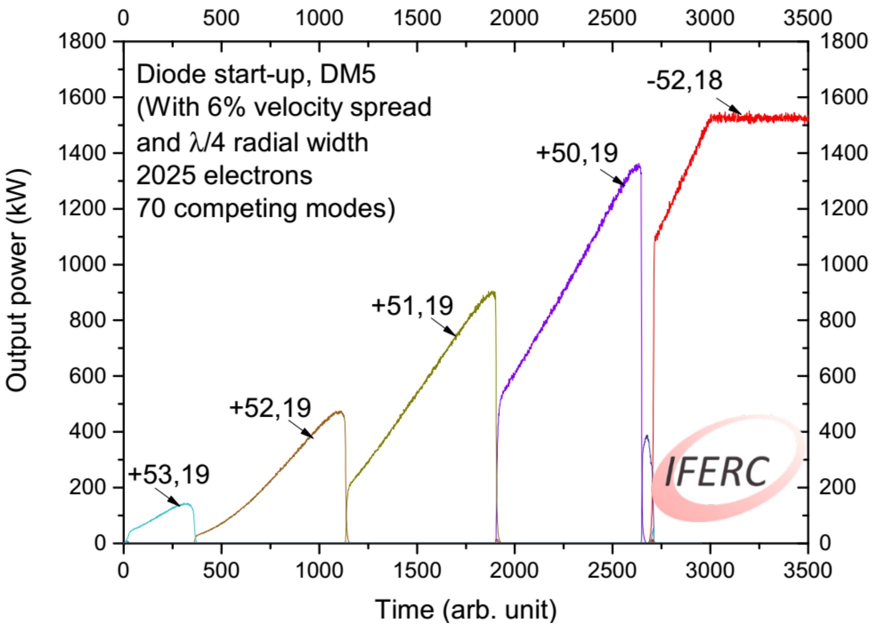
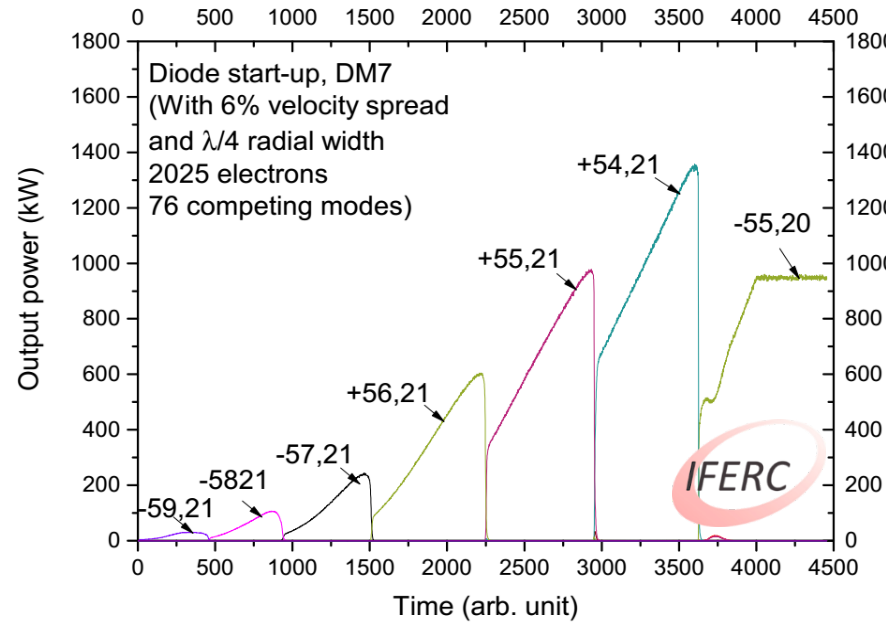
Multi-mode start-up analysis

DM5 : $TE_{-52,18}$: eigenvalue ~ 125

DM7 : $TE_{-56,20}$: eigenvalue ~ 135





DM5: Stable operation of $TE_{-52,18}$ mode

DM7: Due to high mode competition, $TE_{-56,20}$ can not be excited in typical diode start-up

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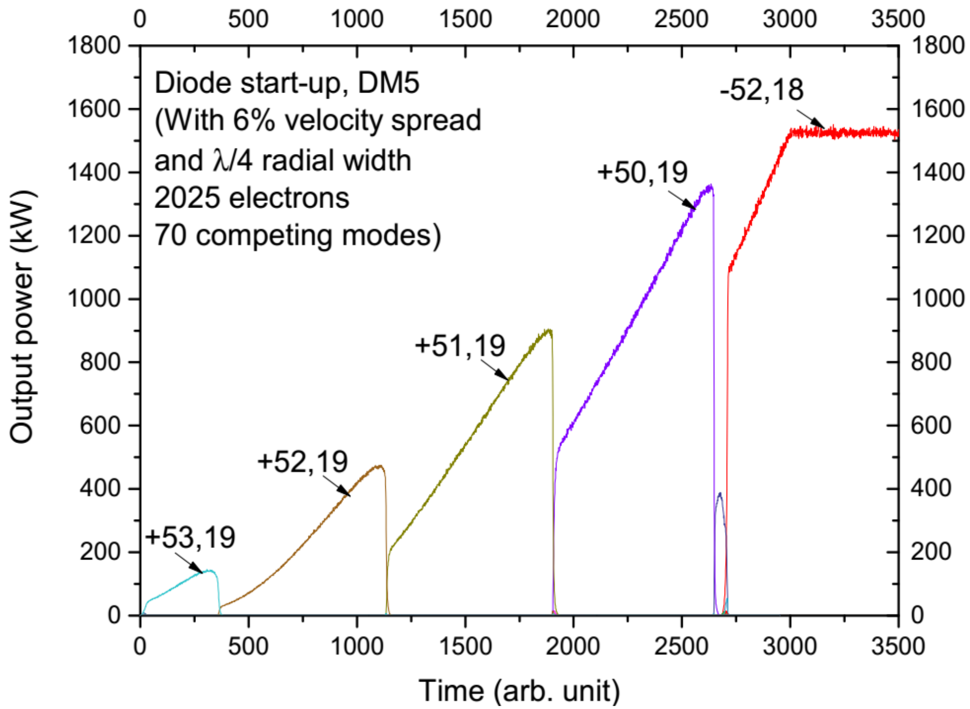
New 236 GHz 1.5 MW design

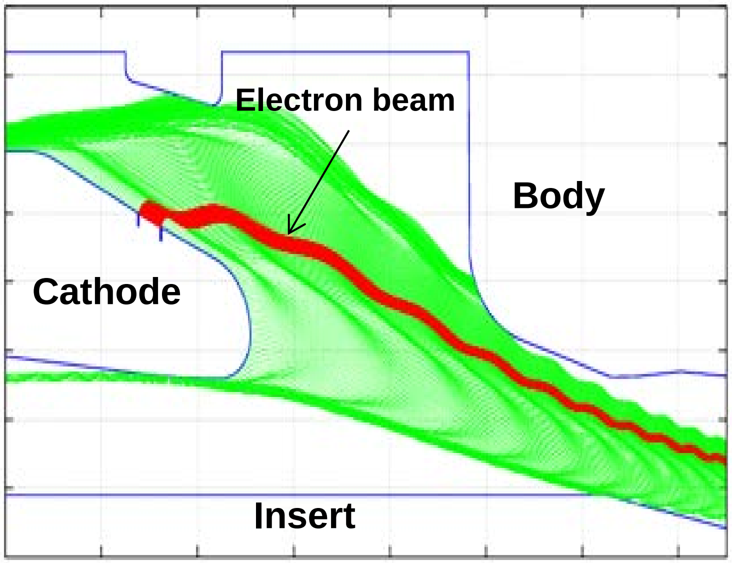
- Operating mode: $TE_{-52,18}$
- Diode start-up scenario
- Cavity mid-section length = 11.5 mm
- Space-charge neutralization effects are also analyzed
- Electron beam misalignment study: stable operation till 0.25 mm of beam misalignment



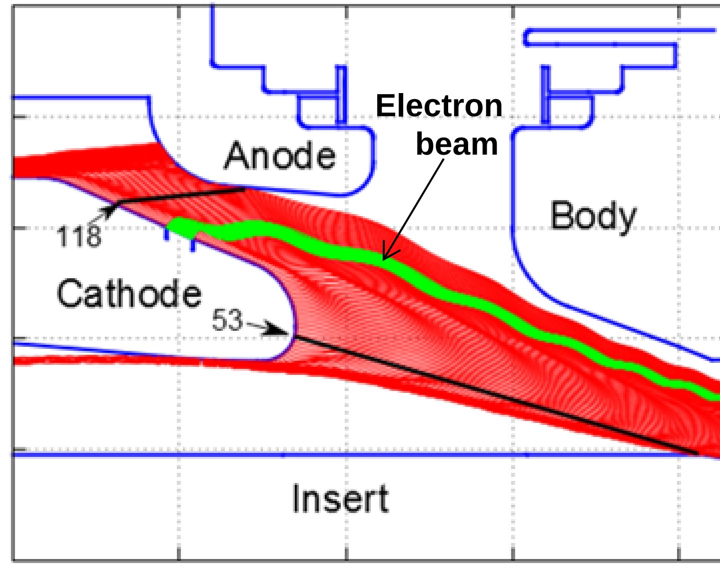
RF behavior of cavity with realistic electron beam parameters

Mode	Eigenvalue	Cavity radius (mm)	Output Power (P_{out})(kW)	Efficiency (η)(%)
$TE_{43,15}$	103	20.88	**920**	**36**
$TE_{52,18}$	125	25.26	**1530**	**34**

Diode-type and triode-type gun design



Diode-type coaxial gun

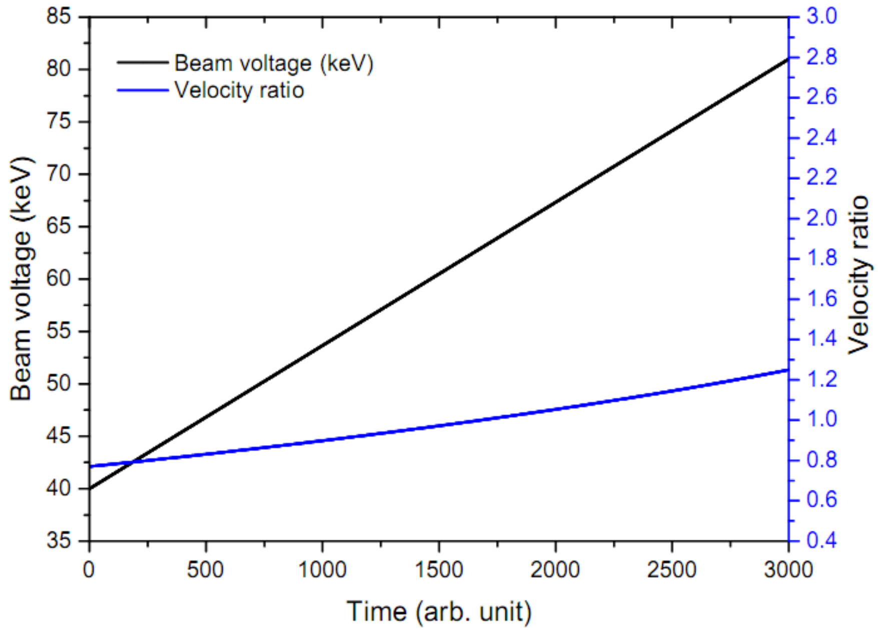


Triode-type coaxial gun

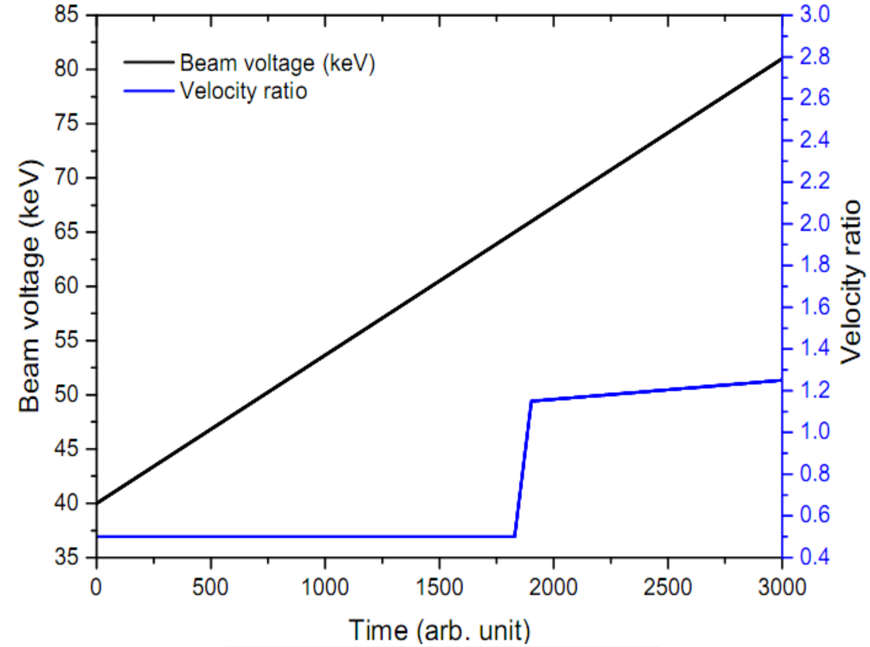
In triode-type guns, the pitch factor of the beam electrons can be controlled using the modulating anode

(Image courtesy: Sebastian Ruess, IHM-KIT)

Diode start-up vs. triode start-up



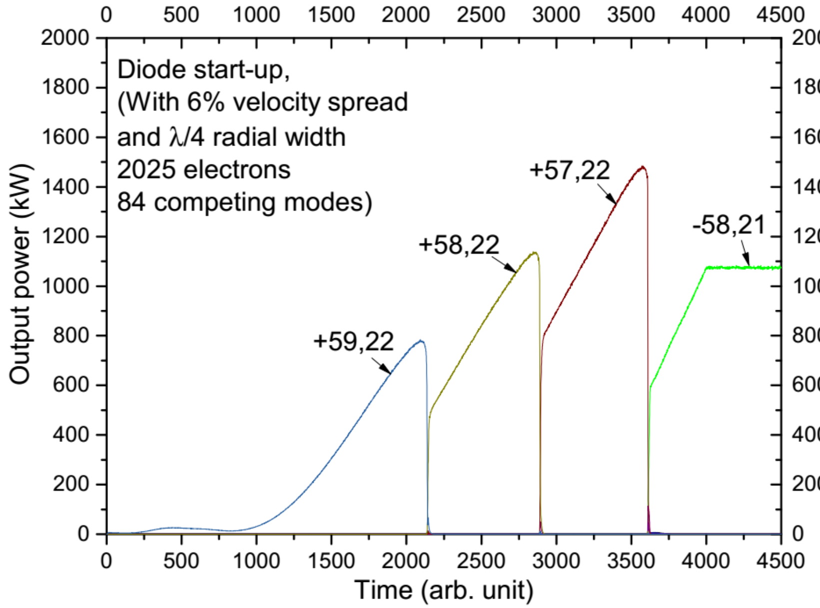
Diode start-up scenario



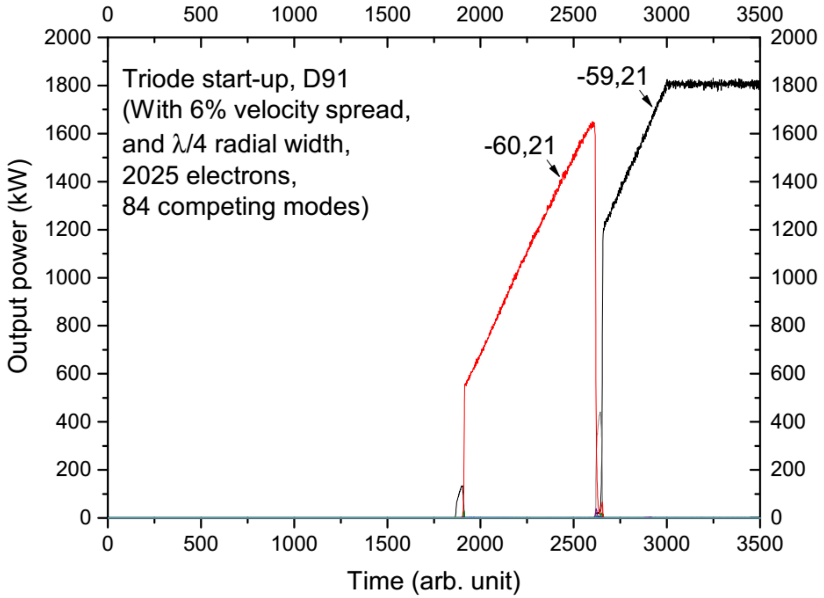
Triode start-up scenario

- **Diode start-up**: Beam voltage: **linear rise**, velocity ratio: **adiabatic change**
- **Triode start-up**: Beam voltage: **linear rise**, velocity ratio: **controlled change**

Diode start-up vs. triode start-up



diode start-up scenario



triode start-up scenario

- Operating mode: $TE_{-59,21}$, eigenvalue ~ 145
- Parameters: beam energy = 81 keV, beam current = 70 A, magnetic field = 9.450 T
- Realistic electron beam parameters

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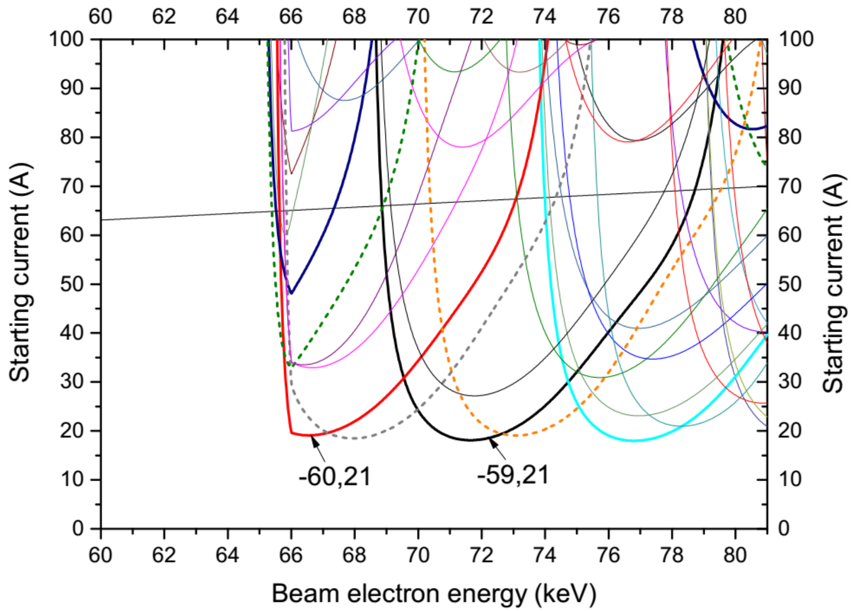
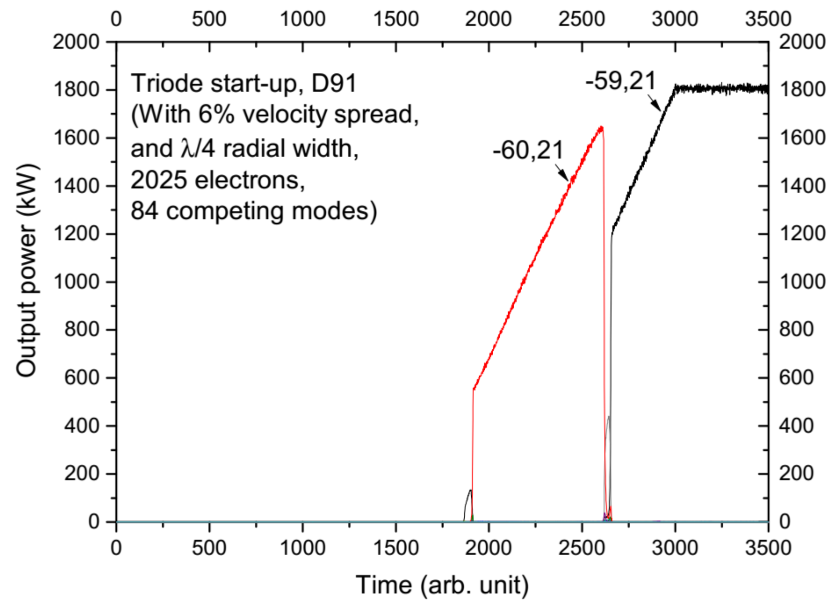
Diode start-up vs. triode start-up



starting-current plots
(triode start-up)



Triode start-up scenario

- Operating mode: $TE_{-59,21}$, eigenvalue ~ 145
- Parameters: beam energy = 81 keV, beam current = 70 A, magnetic field = 9.450 T
- Realistic electron beam parameters

Mode competition can be controlled using triode start-up

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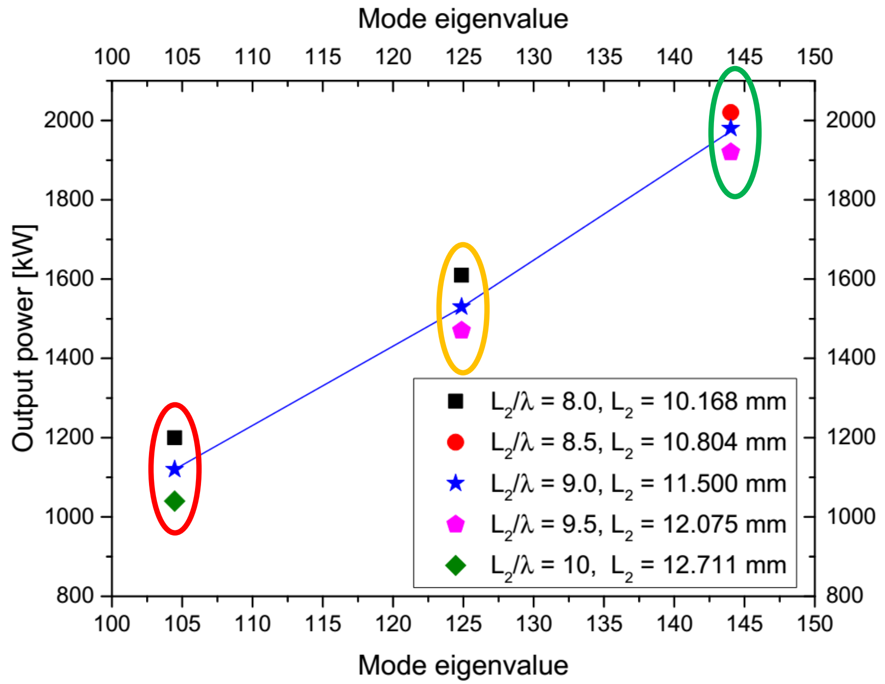
Limits of output power



- Standered design: mode eigenvalue ~ 105: output power **~ 1 – 1.2 MW**
- Mode eigenvalue limit (diode start-up) : eigenvalue ~ 125 : output power **~ 1.4 – 1.6 MW**
- Triode start-up: eigenvalue ~ 145: output power ~ **1.8 – 2 MW**

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Conclusions

- Hollow-cavity DEMO-compatible gyrotrons are under investigation at IHM, KIT, along with coaxial-cavity designs.

- Time domain self-consistent simulations were carried out with realistic electron beam parameters (With velocity spread and radial width of electron beam).

  Result: Pout = **920 kW** at interaction efficiency **35%**

- Using **two different methods**, the effect of mode competition is investigated for 236 GHz hollow cavity gyrotron design for DEMO.

- An eigenvalue limit of 125, corresponding to a maximum output power of around **1.5 MW**, for operating mode ($TE_{52,18}$) was determined for stable gyrotron operation using diode start-up.

- Mode competition can be controlled using triode start-up, which might further increase output power up to 1.8 - 2 MW per tube.

Acknowledgements

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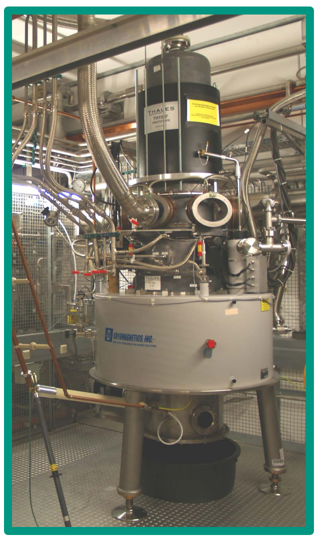
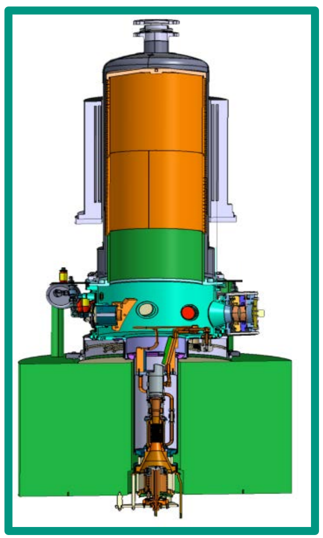
Thank You

Fusion gyrotron development at IHM-KIT

	W7X	ITER EU 1 MW	ITER EU 2 MW (possible upgrade)
gyrotron type operating mode	hollow cavity $TE_{28,8}$ (χ = 60)	hollow cavity $TE_{32,9}$ (χ = 69)	coaxial cavity $TE_{34,19}$ (χ = 105)
single frequency	140 GHz	170 GHz	170 GHz
RF output power	0.92 MW (1800 s)	1.0 MW (3600 s)	2.0 MW (3600 s)
overall efficiency	45 %	50 %	50 %





DEMO Gyrotron

hollow cavity

coaxial cavity

Next steps towards high power DEMO gyrotron design

Triode start-up

- **Diode start-up condition**: Beam voltage: **linear rise**, velocity ratio: **adiabatic**
- **Triode start-up condition**: Beam voltage: **linear rise**, velocity ratio: **controlled**
- Promising initial results: Output power up to **1.8 MW @ 236 GHz**
- Detailed analysis for triode start-up is ongoing

New start-up scenario

- **First step:** generate neutralize electron beam
- **Second step:** triode start-up
- Initial results: Output power up to **2 MW @ 236 GHz**
- Further investigations and validations are ongoing

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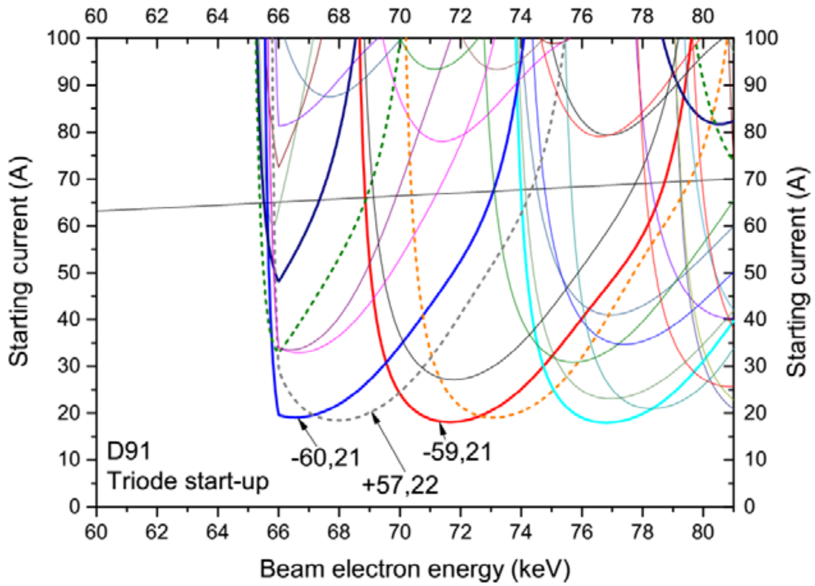
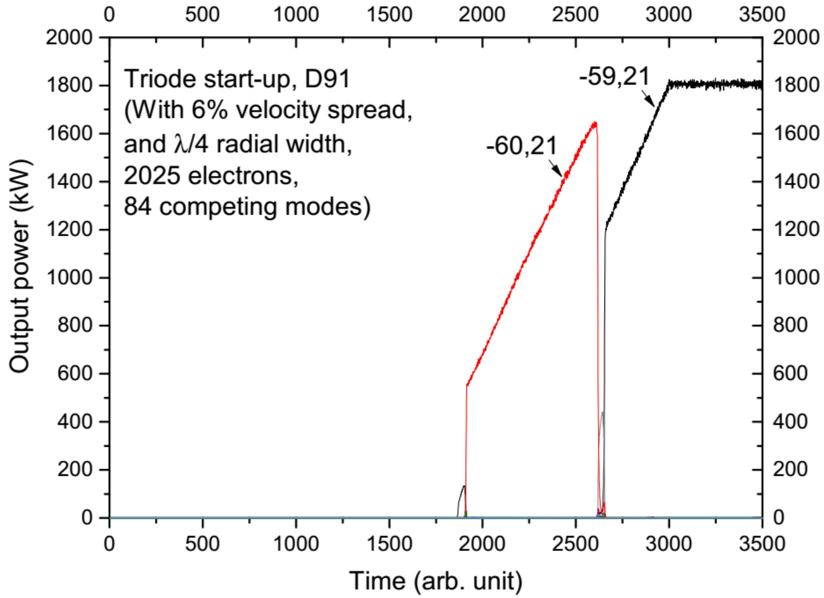
Triode start-up (two mode case)





RF behavior of cavity with realistic electron beam parameters

- Simulation: using external input parameters file in EURIDICE
- Parameters: beam energy = 81 keV, beam current = 70 A, magnetic field = 9.450 T.

Beam energy (keV)	40 – 65	65 – 66	66 – 81
Velocity ratio	0.5	0.5 –1.15	1.15 –1.25

DEM : $TE_{-43,15}$: eigenvalue ~ 103 : $P_{out} \approx 0.9$ MW

DM5 : $TE_{-52,18}$: eigenvalue ~ 125 : $P_{out} \approx 1.5$ MW

D91 : $TE_{-59,21}$: eigenvalue ~ 145 : $P_{out} \approx 1.8$ MW

D11 : $TE_{-65,23}$: eigenvalue ~ 158 : $P_{out} \approx 2$ MW