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From ITER to DEMO: Towards Multi-Purpose Multi-MW Gyrotrons Operating above 200 GHz

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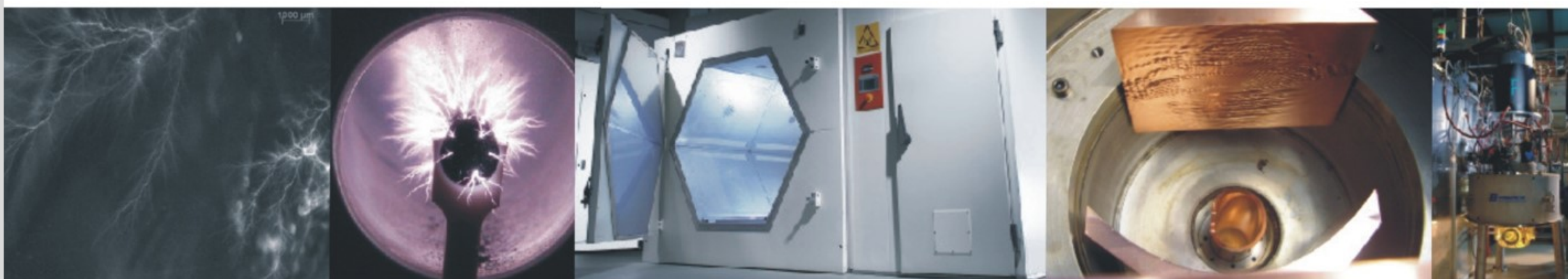
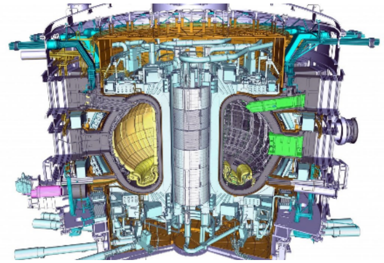
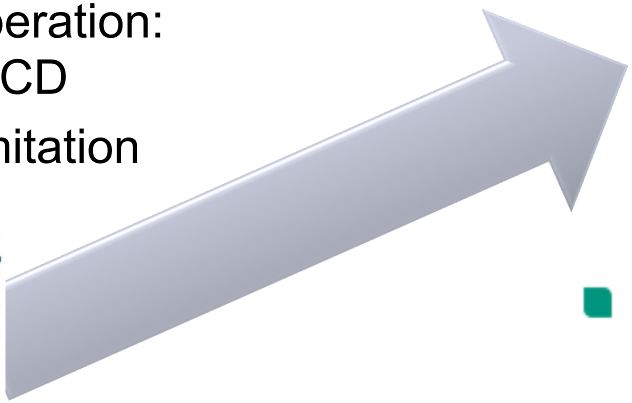


From ITER towards DEMO

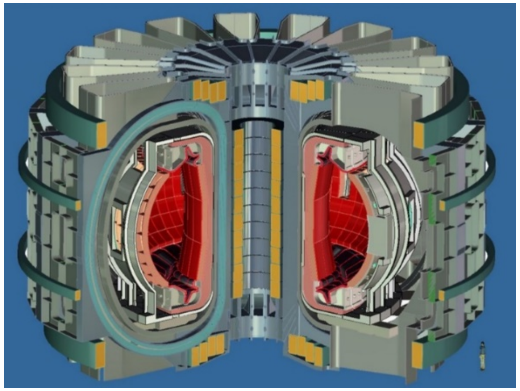
ITER

- Single frequency operation: 170 GHz for EC H&CD
- Single frequency limitation





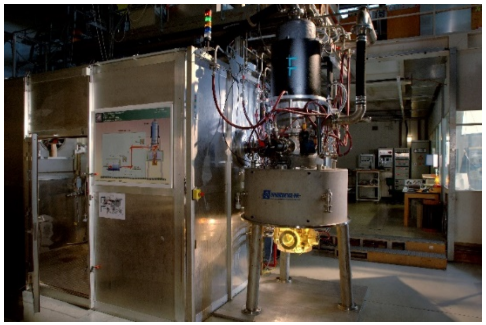
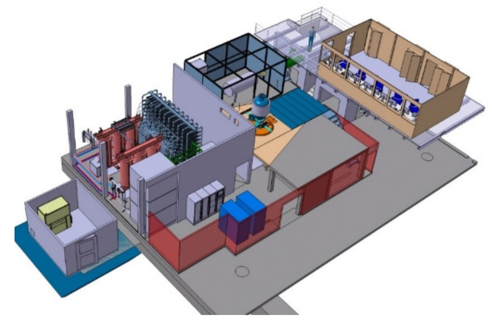
DEMO



- **Multi-frequency operation:** 170/204/(238) GHz for EC H&CD, stabilization
- Multi-purpose gyrotron

	ITER	DEMO
Frequency [GHz]	170	170/204/(238)
RF power [MW]	1	2
Step-tunability	Not required	± 10 GHz

Towards gyrotron operation above 200 GHz

	Recently in operation	Future
Test stand	 ▪ Magnet is limited at ~ 6.9 T (~ 6.9 T → ~ 170 GHz)	 ▪ New magnet is limited at 10.5 T (10.5 T → ~ 260 GHz)
Gyrotron	 ▪ 170 GHz gyrotron ▪ Single frequency ▪ 2 MW RF output power ▪ Coaxial-cavity	Our goal: ▪ 170/204/(238) GHz multi-frequency operation ▪ 2 MW RF output power 1. Which mode at 204 GHz? 2. Which changes are required?

1. Multi-frequency operation

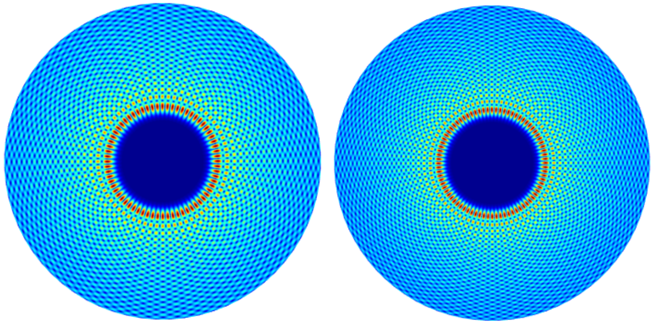
Design Criteria

Frequency Determination

- Frequencies: 170/204/(238) GHz
- Operating frequency is determined by the **window disk thickness**

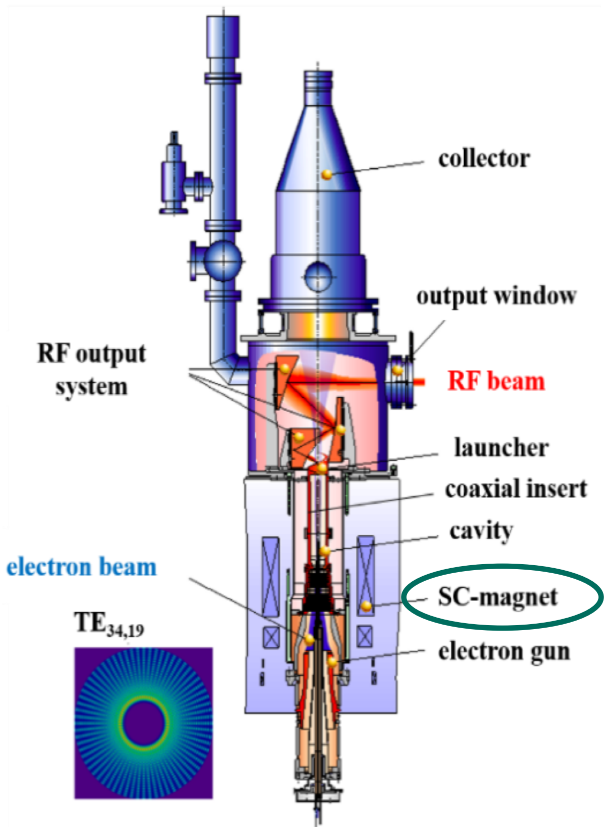
Mode Selection

- Modes with nearly equal caustic radii
- $TE_{34,19}$-mode at 170 GHz
- $TE_{40,23}$-mode at 204 GHz



$TE_{34,19}$-mode $TE_{40,23}$-mode

2. Required changes in gyrotron hardware



- Discussion about changes for a first principle operation and an optimized operation
- Studied key components:
  - Superconducting Magnet
  - Magnetron Injection Gun (MIG)
  - Coaxial-Cavity
  - Quasi-Optical Output System

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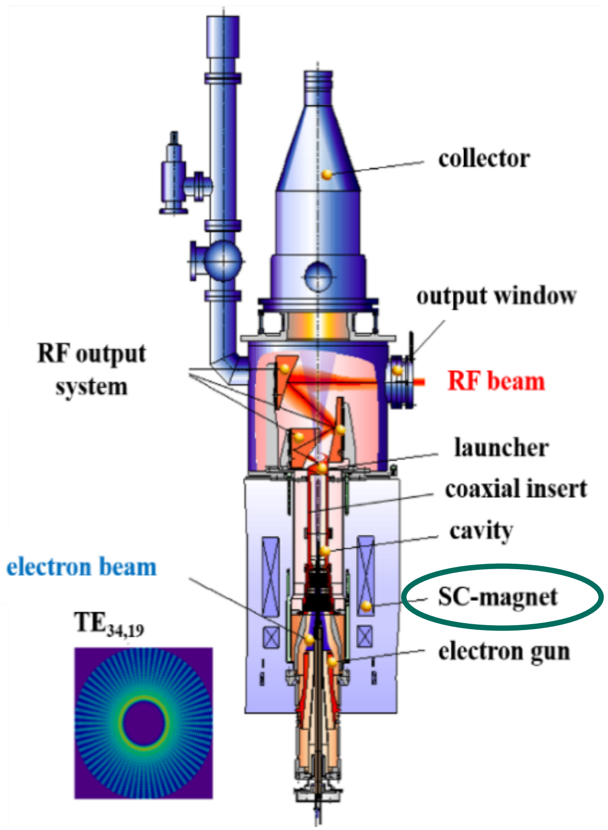
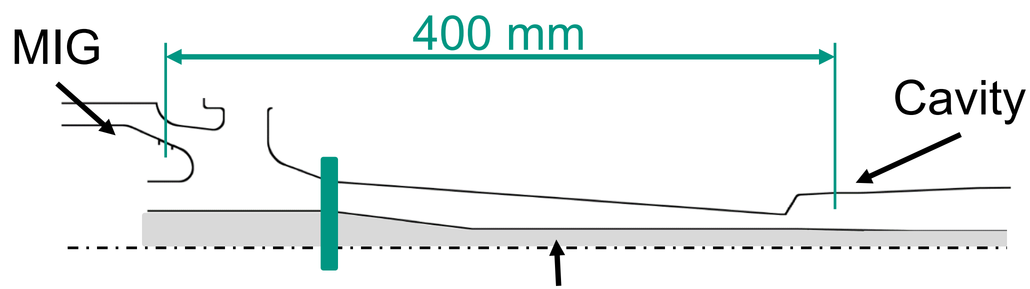
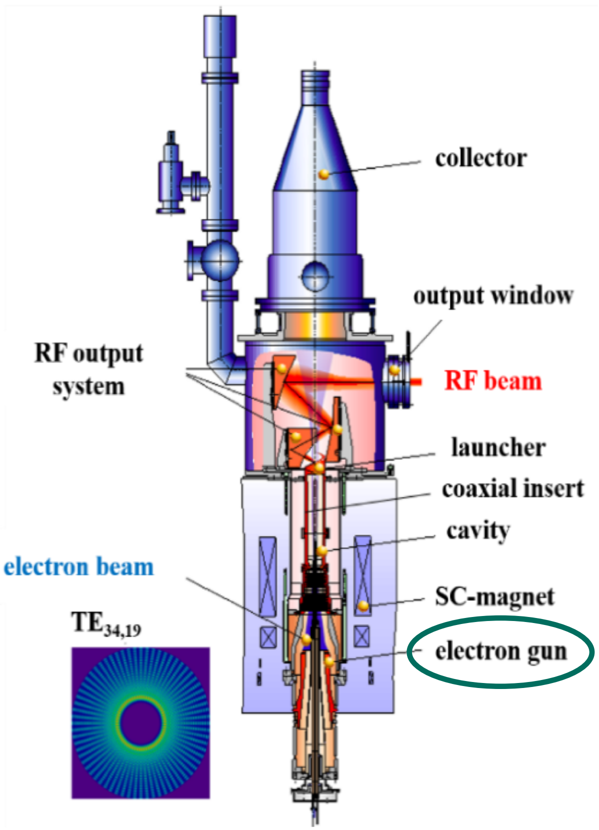
New super-conducting magnet from TESLA



- Existing magnet: ~ 6.9 T → ~ 170 GHz
- ⇨ New 10.5 T magnet → ~ 260 GHz
- Height of magnet is enlarged (distance emitter-cavity: 400 mm)
- Body and insert enlargement required



Simulation with existing MIGs



- New magnet
  - Changed magnet dimensions
  - Changed magnetic field profile
- Check if required beam quality is possible
- Three existing guns:
  - Inverse MIG (IMIG)
  - Coaxial MIG with coated emitter rims (cMIG)
  - Coaxial diode MIG

Choice of MIG

Parameter	IMIG	cMIG	Coaxial MIG
Configuration	Triode	Triode	Diode
Additional required hardware	Power supply for modulation anode	Power supply for modulation anode	-
Required Changes	- Anode - Enlargement of body - Tightness (still under development)	- Enlargement of body	- Enlargement of anode

Oldest and most validated gun at KIT

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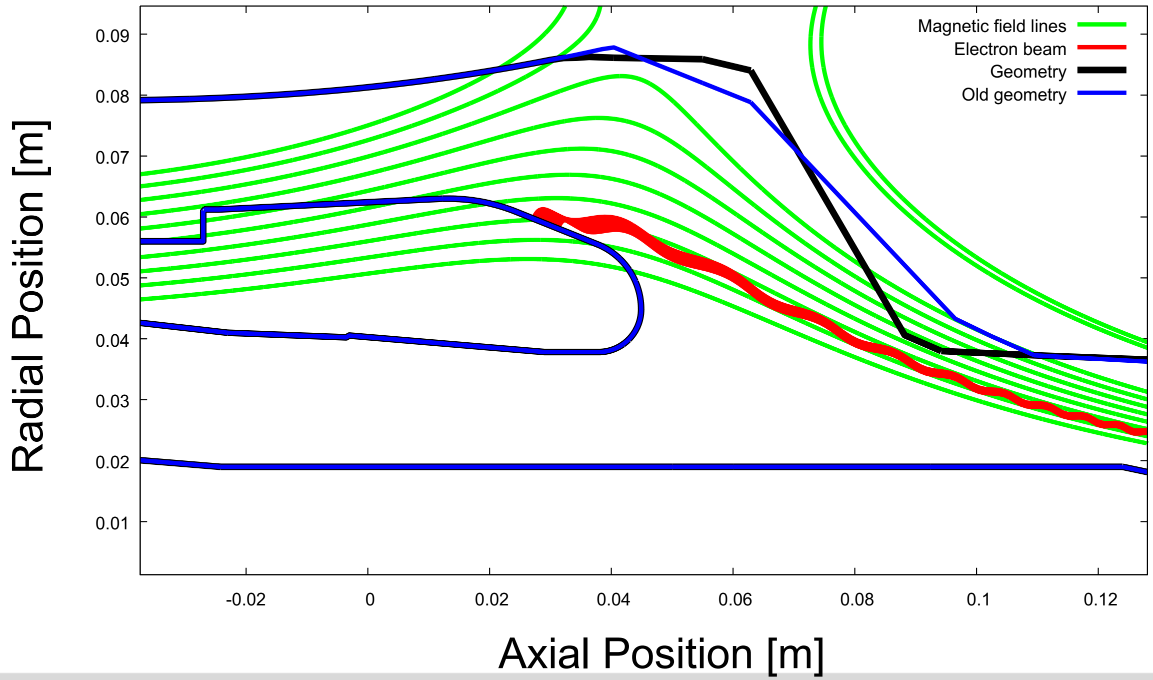
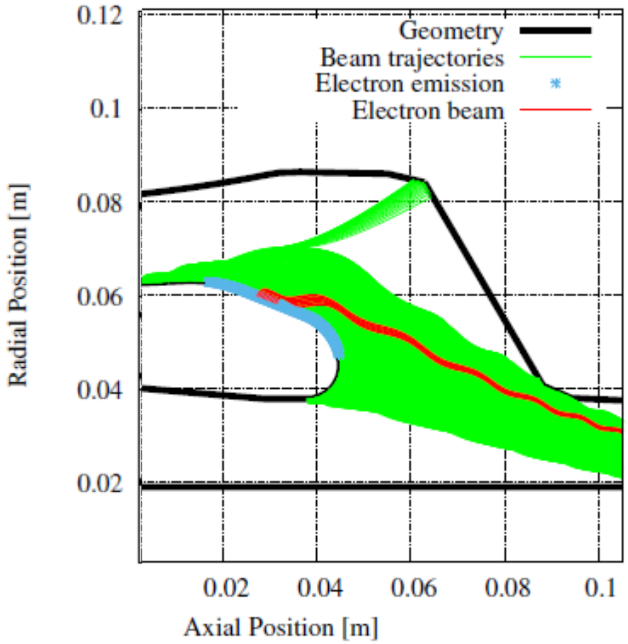
Coaxial diode simulations

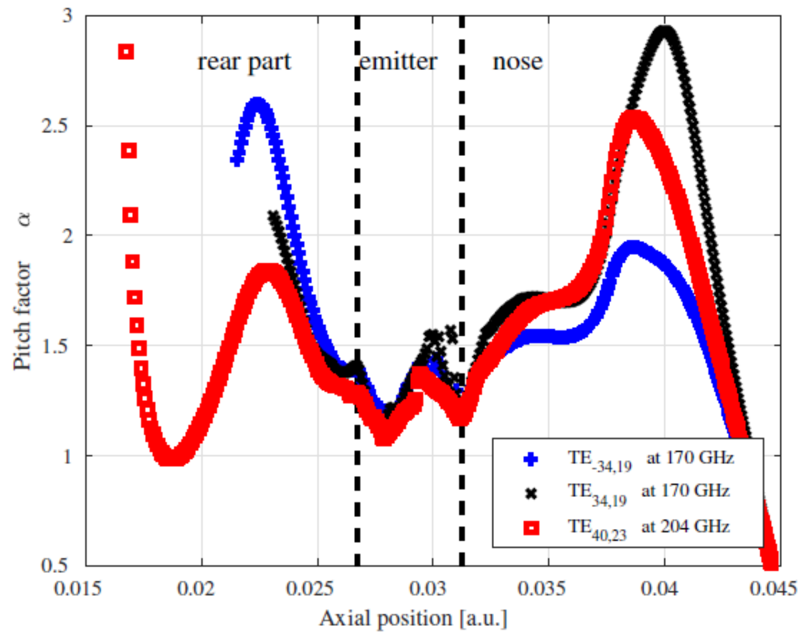
- Optimization parameter: only the anode shape
- Challenge to find an anode configuration for $TE_{34,19}$-/$TE_{40,23}$-mode at 170/204 GHz → $\alpha_{f_{204\,\mathrm{GHz}}} \approx \alpha_{f_{170\,\mathrm{GHz}}}$
- Idea: use counter-rotating $TE_{-34,19}$-mode and change polarity of magnet



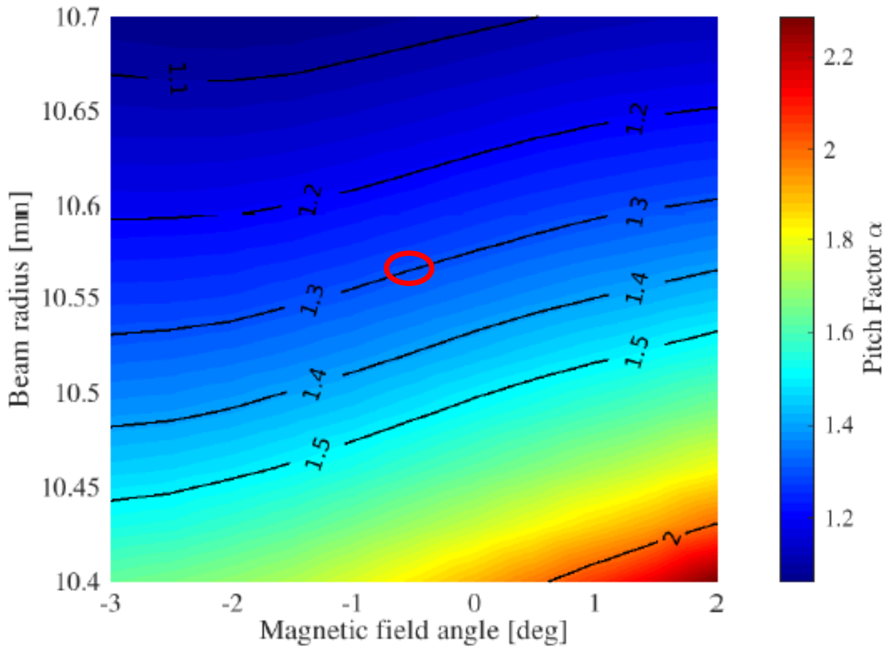
Secondary electrons

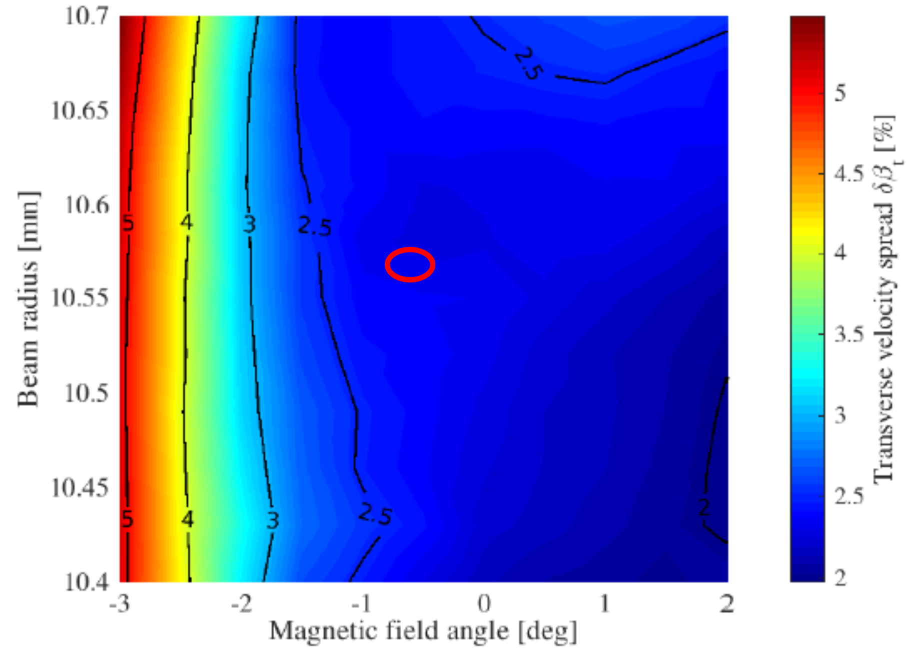
- Test for adiabatically trapped electrons which are emitted from the cathode surface
- Pitch factor of $\alpha \leq 3$ for a safe operation





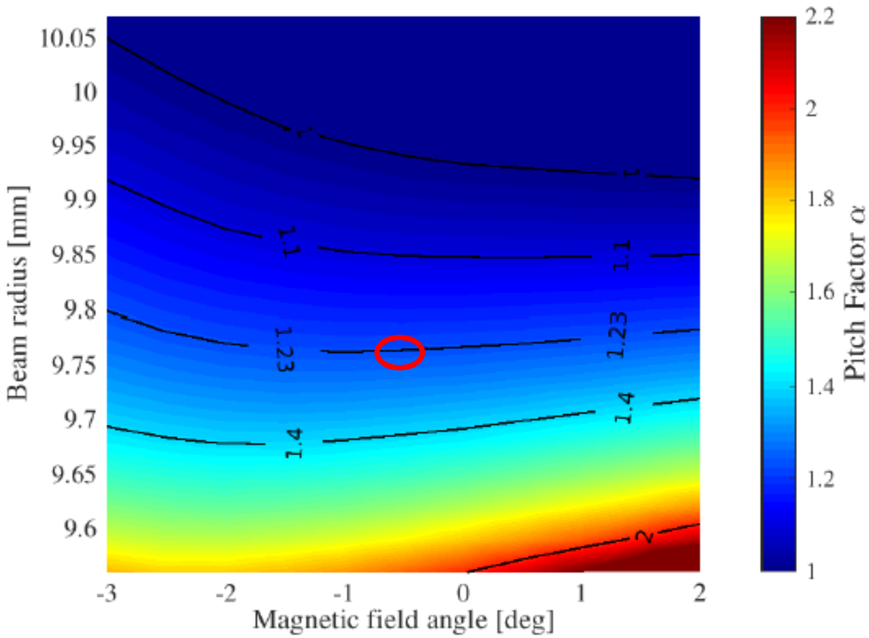
Operation parameters 170 GHz, $TE_{-34,19}$-mode

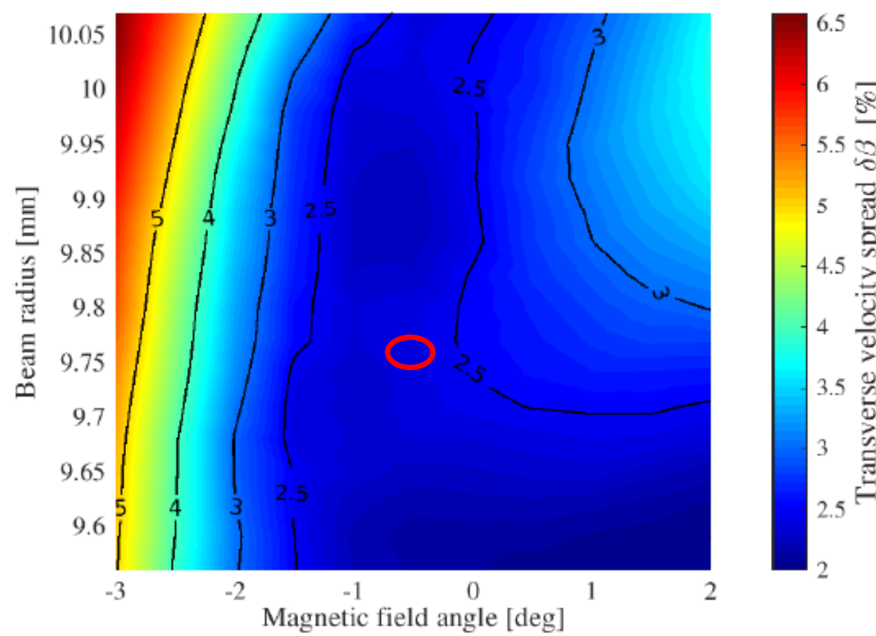




Parameter	Value
Pitch factor	1.3
Transverse velocity spread [%]	2.3
Electron energy spread [%]	0.17
Radial beam width	λ/6.7

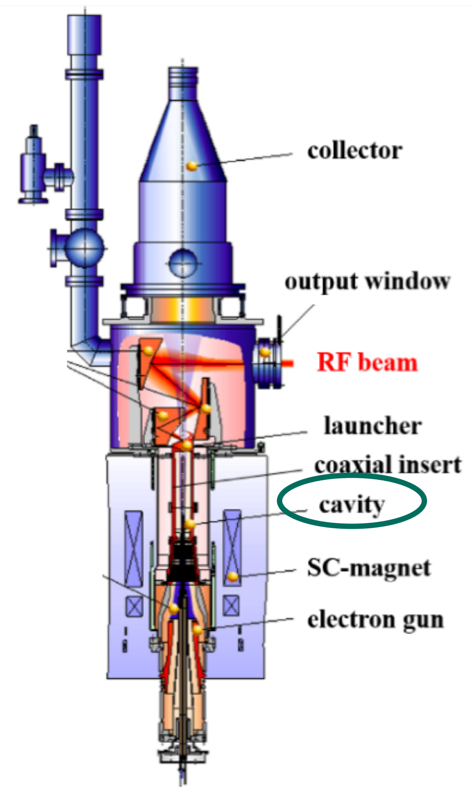
Operation parameters 204 GHz, $TE_{40,23}$-mode





Parameter	Value
Pitch factor	1.23
Transverse velocity spread [%]	2.4
Electron energy spread [%]	0.2
Beam thickness	$\lambda/6$

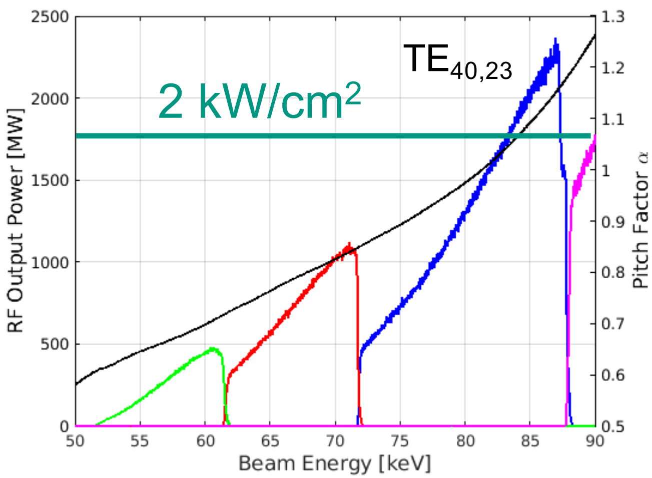
Interaction region – coaxial cavity



- Results with existing cavity and diode MIG

Modes	$TE_{34,19}$	$TE_{40,23}$
Frequency [GHz]	170.0	204.1
RF output power [MW]	2.2	1.72

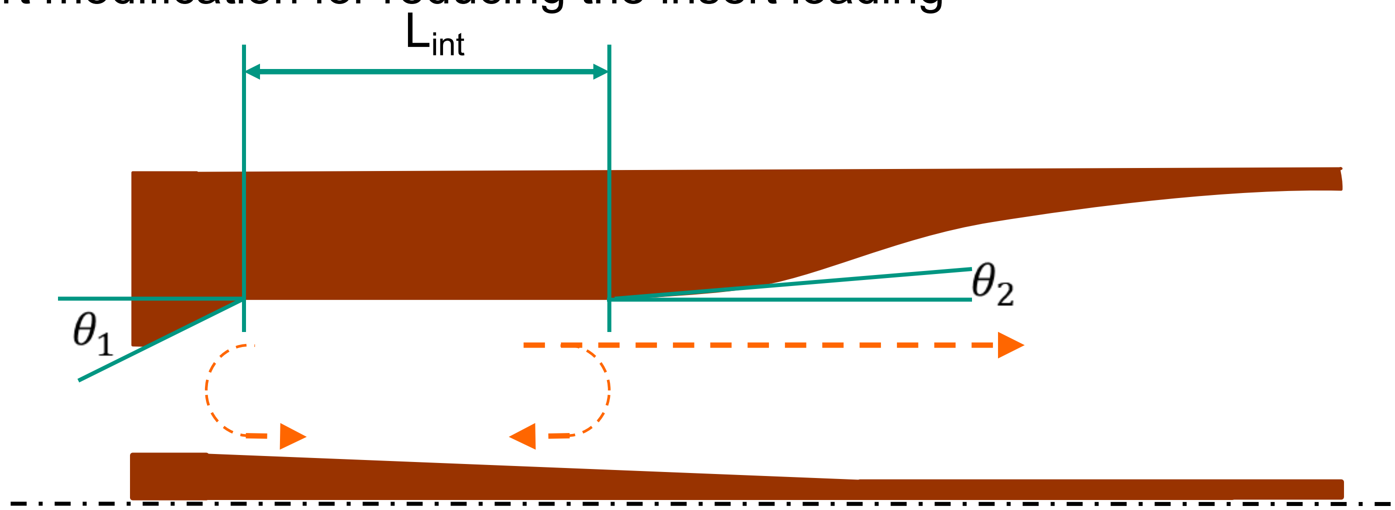
< 2 MW



- **Modifications are required to achieve a RF output power above 2 MW**

Cavity modification

- Cavity was optimized for operation at 170 GHz
- Maximum wall loading constraint: 2 kW/cm^2 ($\rho_\Omega \sim f^{5/2}$)
- L_{int} ↓ → quality factor ↓ → wall loading ↓ → nominal parameters ↑ → power ↑
- Interaction length is reduced: L_{int} = 13.6 mm ≈ 9λ_0 @ 204 GHz
- Insert modification for reducing the insert loading



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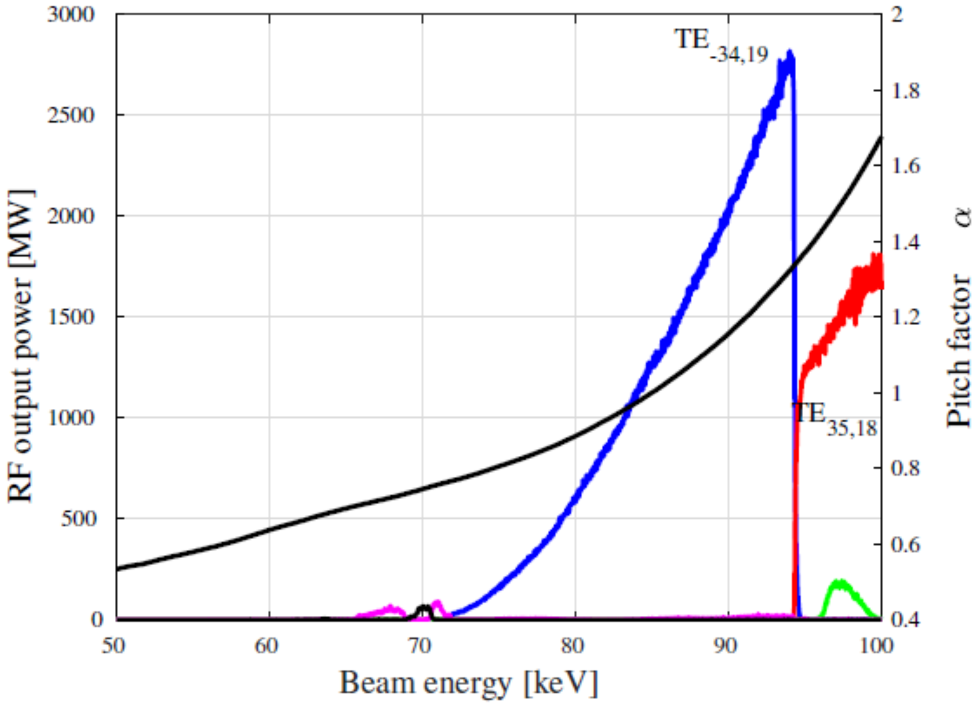
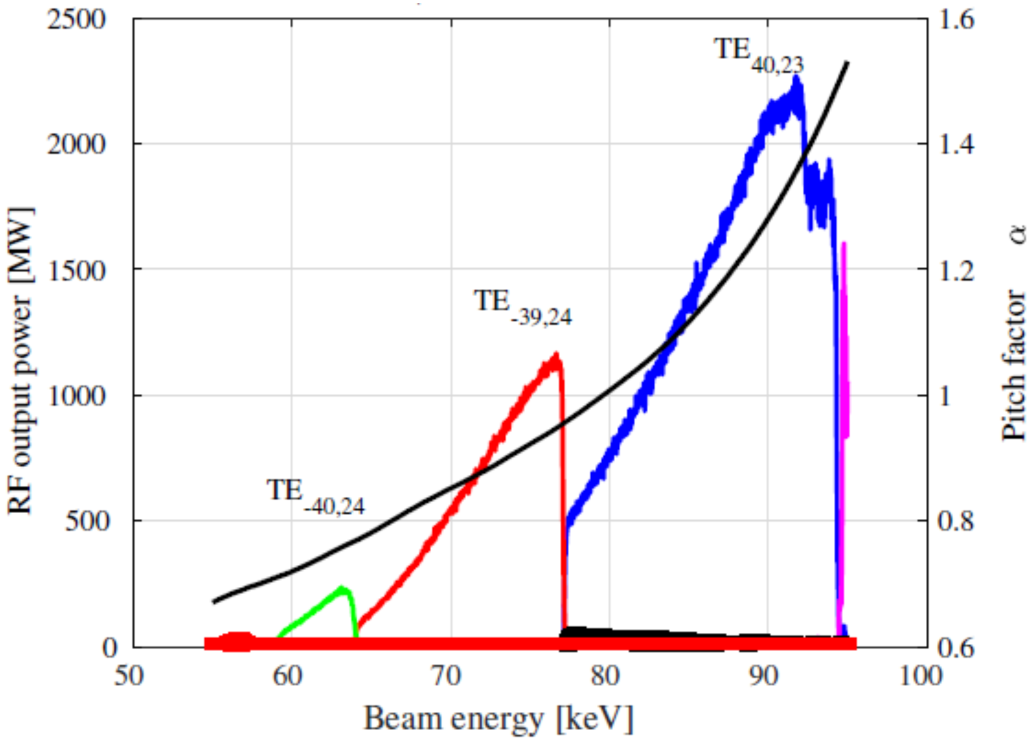
Start-up simulations for $TE_{-34,19}$-mode



Mode	$TE_{-34,19}$
Beam energy [keV]	92.8
Beam current [A]	72
Magnetic field [T]	6.88
RF output power [MW]	**2.5**
Int. efficiency [%]	**38.5**

- Start-up of co-rotating $TE_{34,19}$-mode is almost similar
- Increase of the nominal operation parameters
- Increase of the RF output power

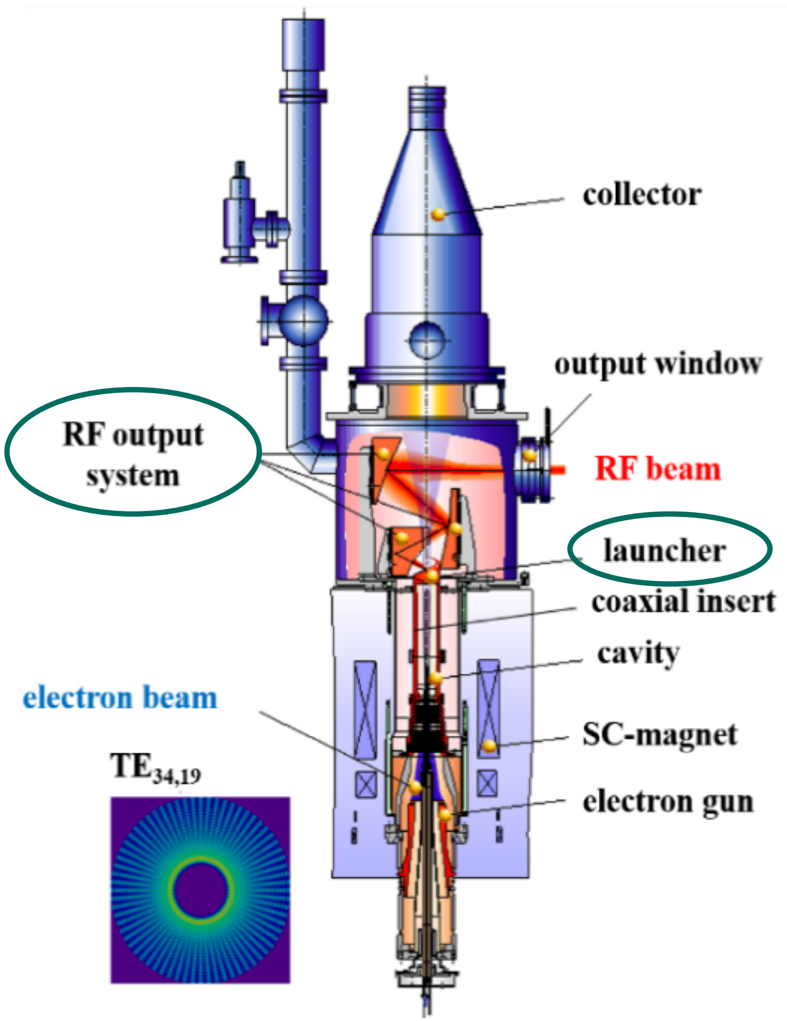
Start-up simulations for $TE_{40,23}$-mode

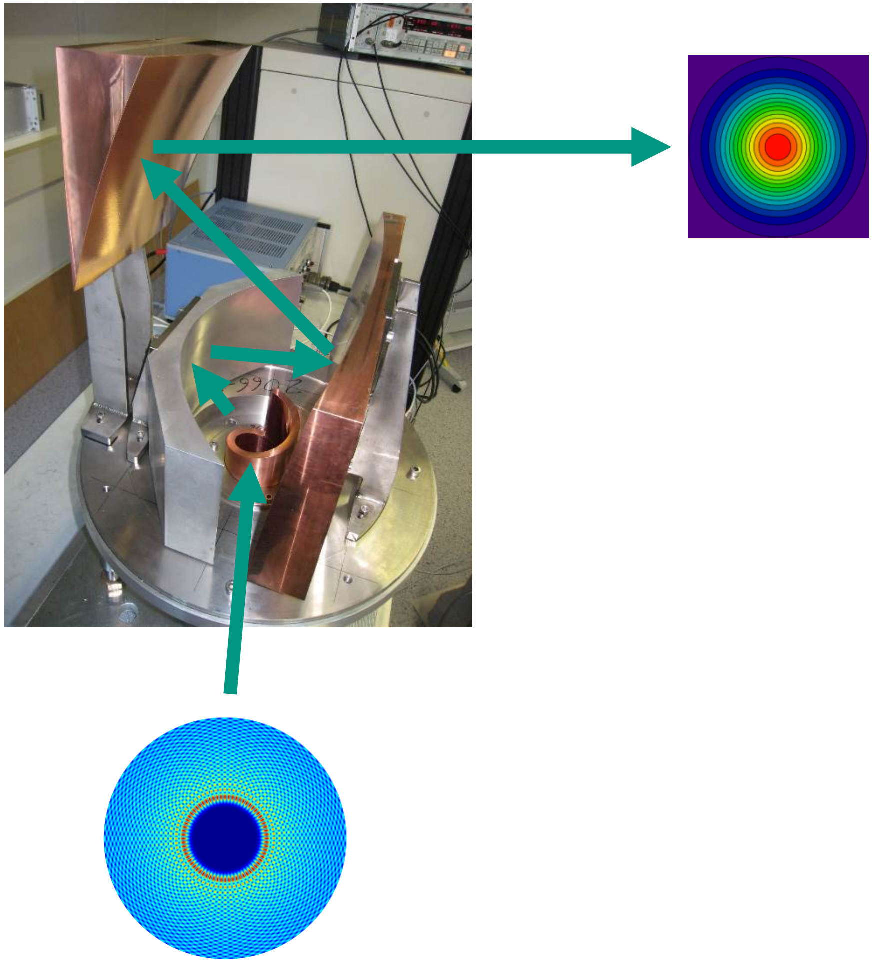


Mode	$TE_{40,23}$
Beam energy [keV]	89.8
Beam current [A]	68
Magnetic field [T]	8.30
RF output power [MW]	**2.04**
Int. efficiency [%]	**34.5**

- Increase of the nominal operation parameters (previous 82 keV)
- Increase of the RF output power
- Insert wall loading is far below the limit (< 0.39 kW/cm²)

Quasi-optical output system





$TE_{34,19}$-mode

Design of quasi-optical output system

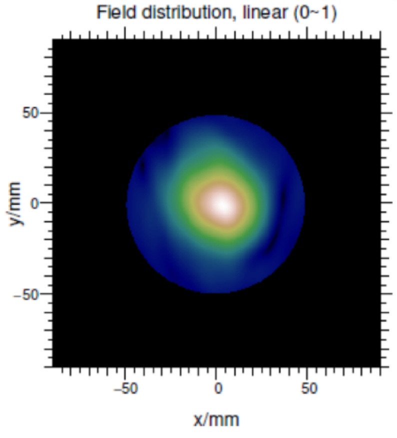
Karlsruhe Institute of Technology

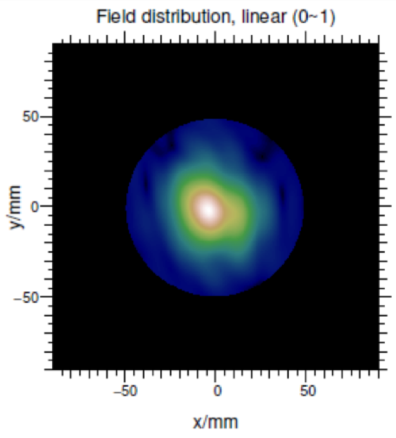
- Mirror line launcher

Gaussian mode Content	$TE_{34,19}$ @ 170 GHz	$TE_{40,23}$ @ 204 GHz
Existing design	96.6 %	91.6 %
New design	97.2 %	96.6 %

- Max. heat loading: 560 W/cm^2

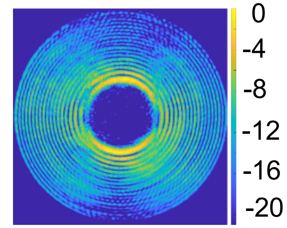
- Quasi-optical output system contains a launcher and 3 mirrors
- 1.5 % stray radiation
- Next step: fabrication and verification



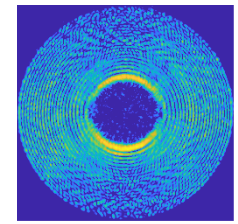


Verification of the quasi-optical components

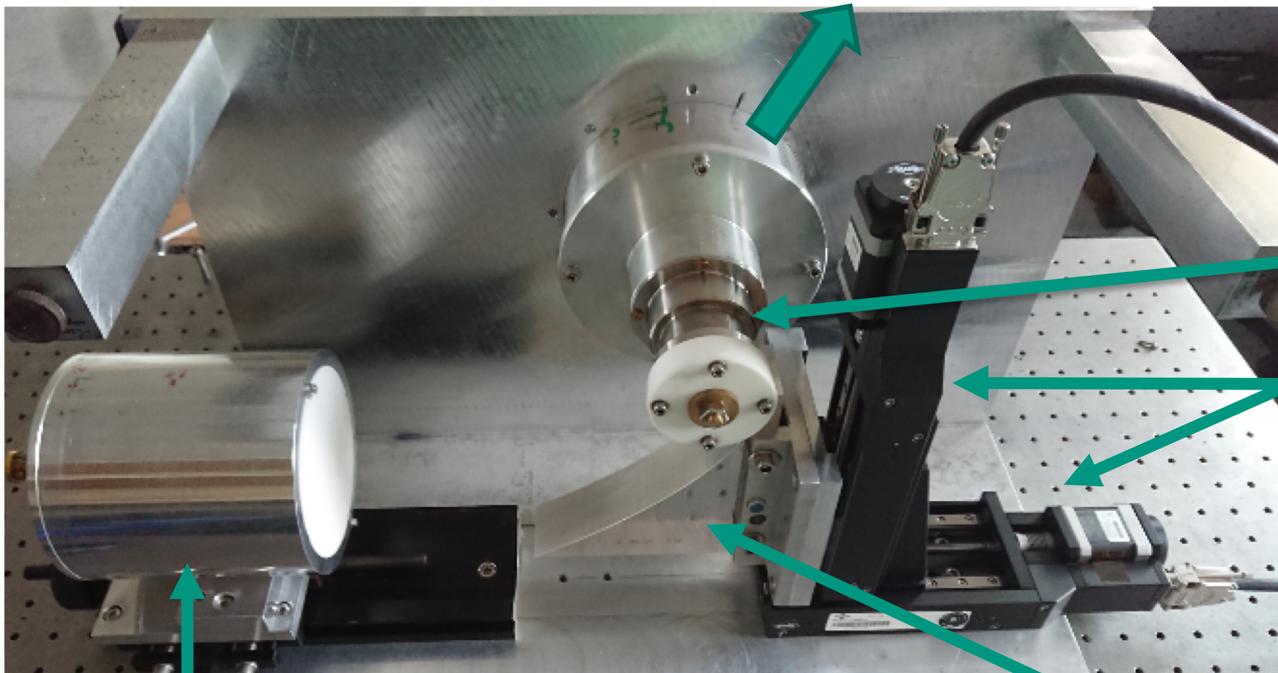
- Mode generator
  - Low power test setup
  - Cold measurements (without electron gun)



TE$_{34,19}$-mode @ 170.325 GHz



TE$_{40,23}$-mode @ 203.95 GHz



Alexandrov et al., Int. J. Infrared and Millimeter Waves, 13 (1992), pp.1369

Conclusion

- Required Hardware for first operation of a 170/204 GHz coaxial cavoty gyrotron
  - Anode
  - Insert elongation
  - Oil box
  - XY-table for adjustment

- Optimized operation at 170/204 GHz
  - Corrugations of insert
  - New shape of coaxial-cavity and non-linear up-taper (achieve 2 MW)
  - Launcher / Mirrors (reduce stray radiation losses)

Outlook

- First experimental tests are planned in Q1 of 2020

- First studies about 238 GHz operation show:
  - Principle operation with the modified cavity is possible
  - New anode for operation at 238 GHz is required
  - Design with new anode delivers a simulated RF output power of 1.7 MW

Acknowledgement

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