US-EU-JPN Workshop on RF Heating Technology of Fusion Plasmas 2009

2 MW, 170 GHz Pre-Prototype Coaxial-Cavity Gyrotron for ITER

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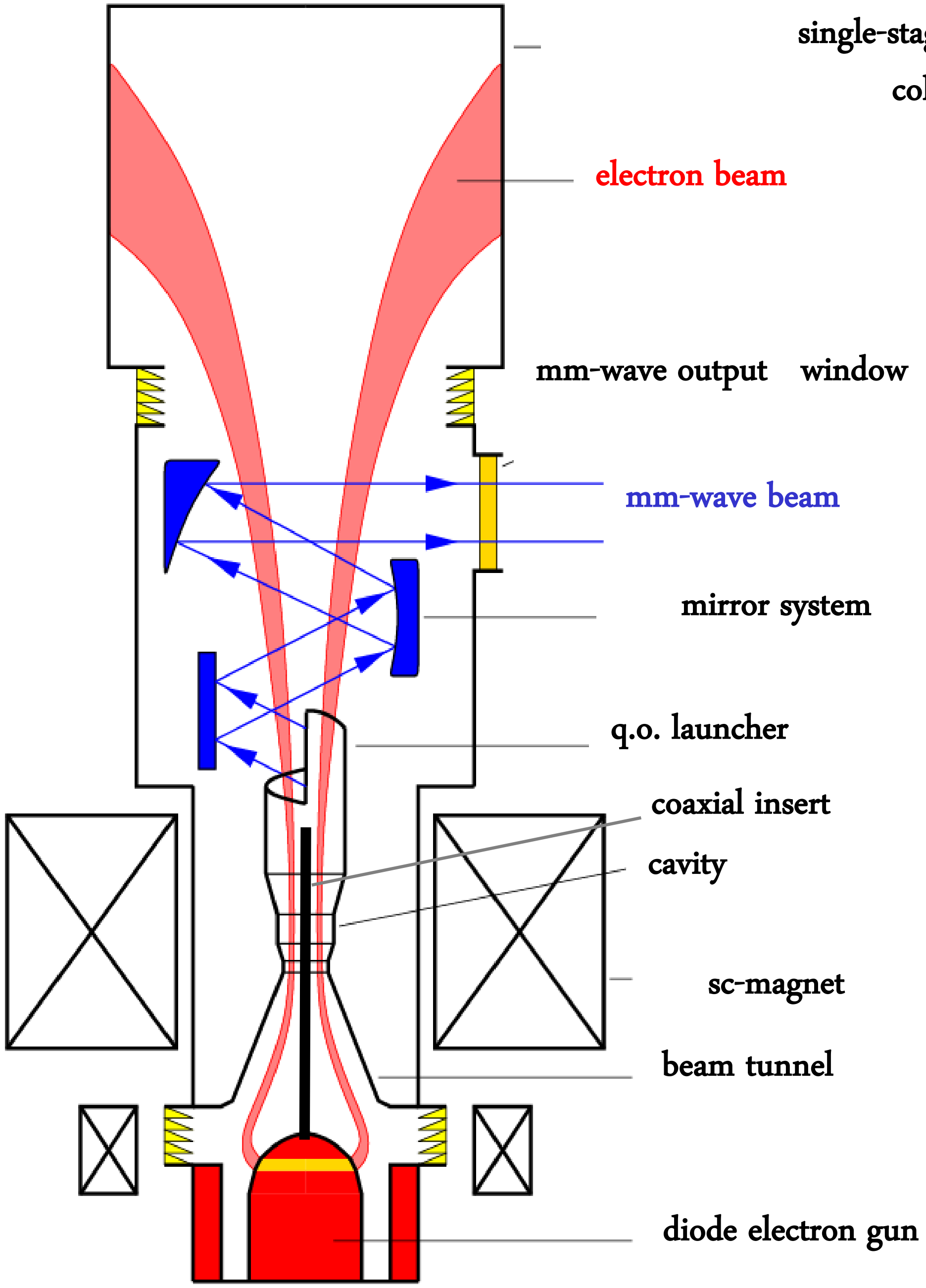
OUTLINE

1. Parameters of coaxial-cavity gyrotron for ITER
2. Experimental results on the pre-prototype tube
3. Improvement of quasi-optical (q.o.) mode converter
4. Verification of the mm-wave output coupling system
5. Summary and conclusions

2 MW, 170 GHz Coaxial-Cavity Gyrotron for ITER (I)



Design Specifications

Cavity mode	$TE_{34,19}$
Output frequency	170 GHz
mm-wave output power	2 MW
Beam current	< 75 A
Accelerating voltage	< 90 kV
Cavity magnetic field	6.86 T
Output efficiency (w/o SDC)	33 %
Output efficiency (SDC)	> 50 %

Short-Pulse Pre-Prototype Tube at FZK

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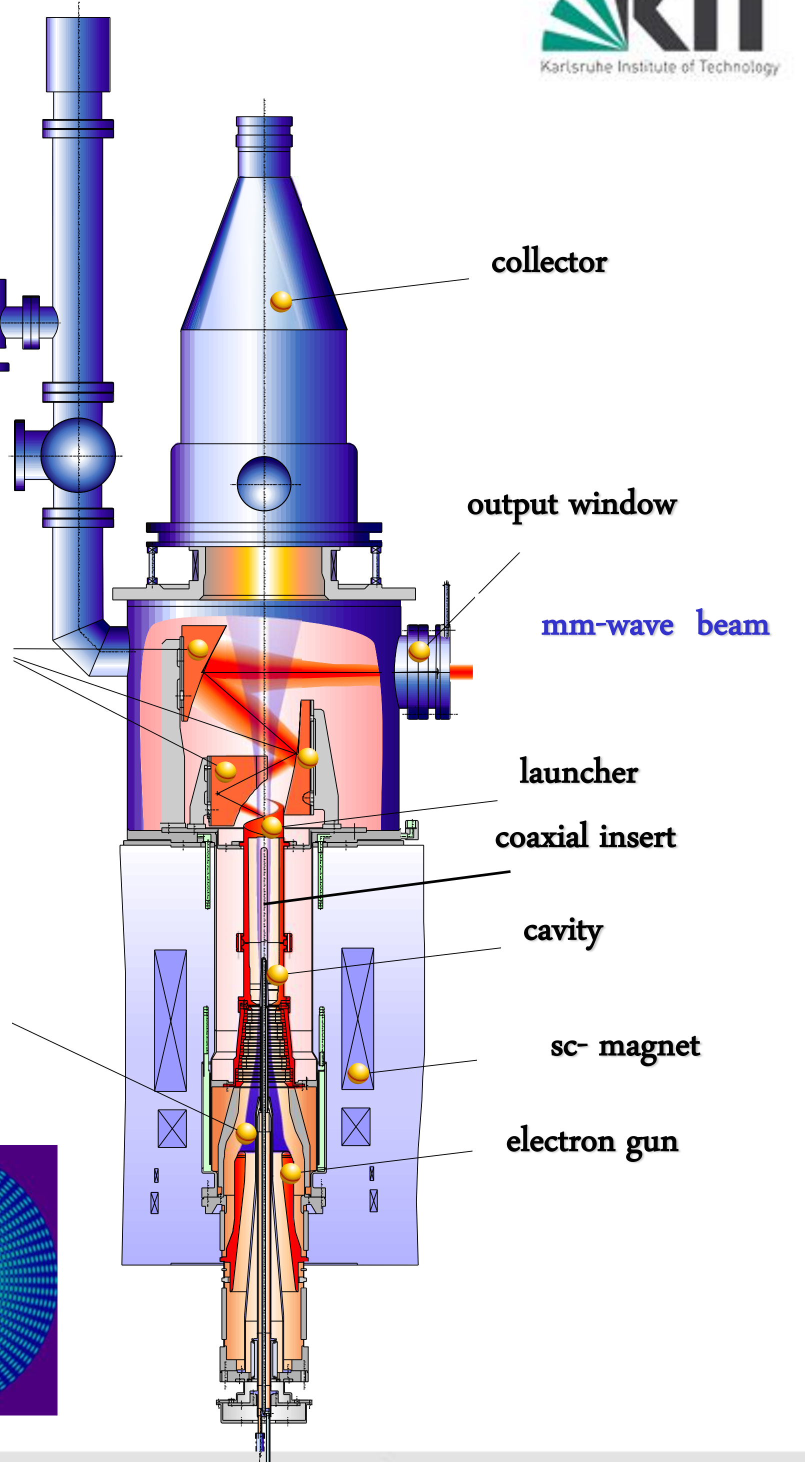
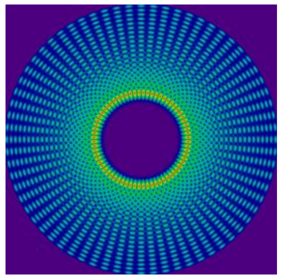
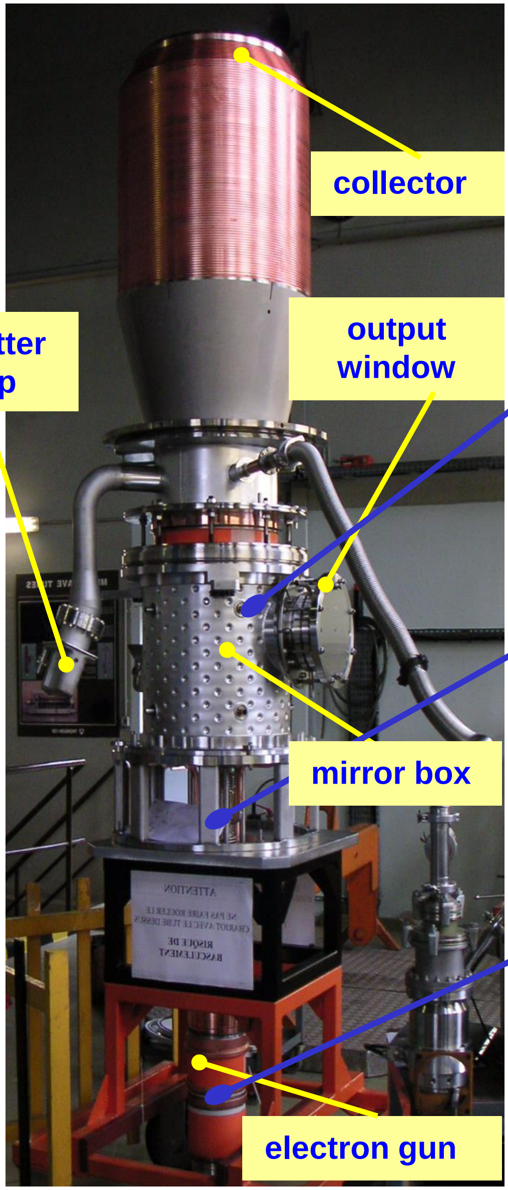


$TE_{34,19}$



2 MW, 170 GHz Coaxial-Cavity Gyrotron for ITER (II)

170 GHz, CW, $TE_{34,19}$ – Mode Prototype and Short Pulse (5 ms) Pre-Prototype



Prototype at CRPP

same q.o. output coupler

same cavity

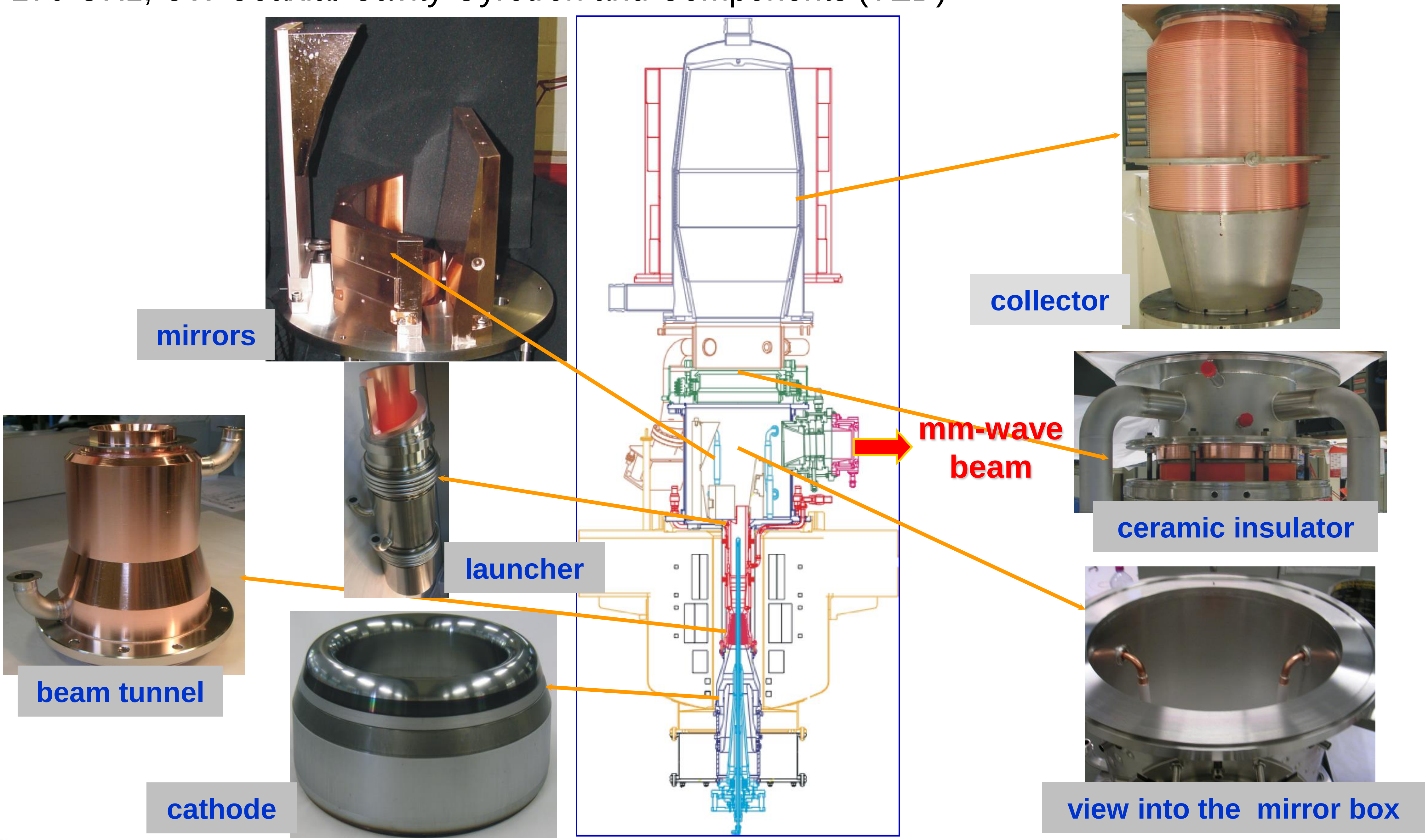
very similar coaxial electron gun

=> Results obtained with the pre- prototype are relevant for industrial tube

Pre-Prototype at FZK

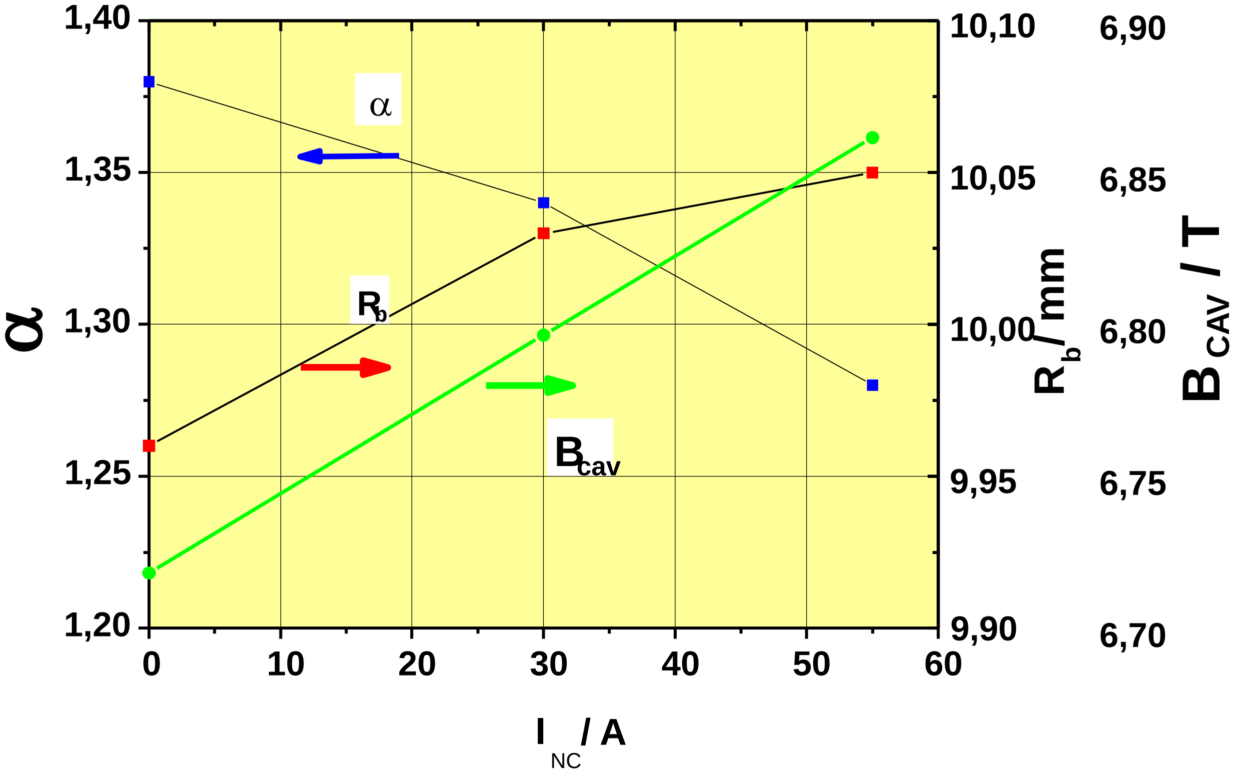
2 MW, 170 GHz Coaxial-Cavity Gyrotron for ITER (III)

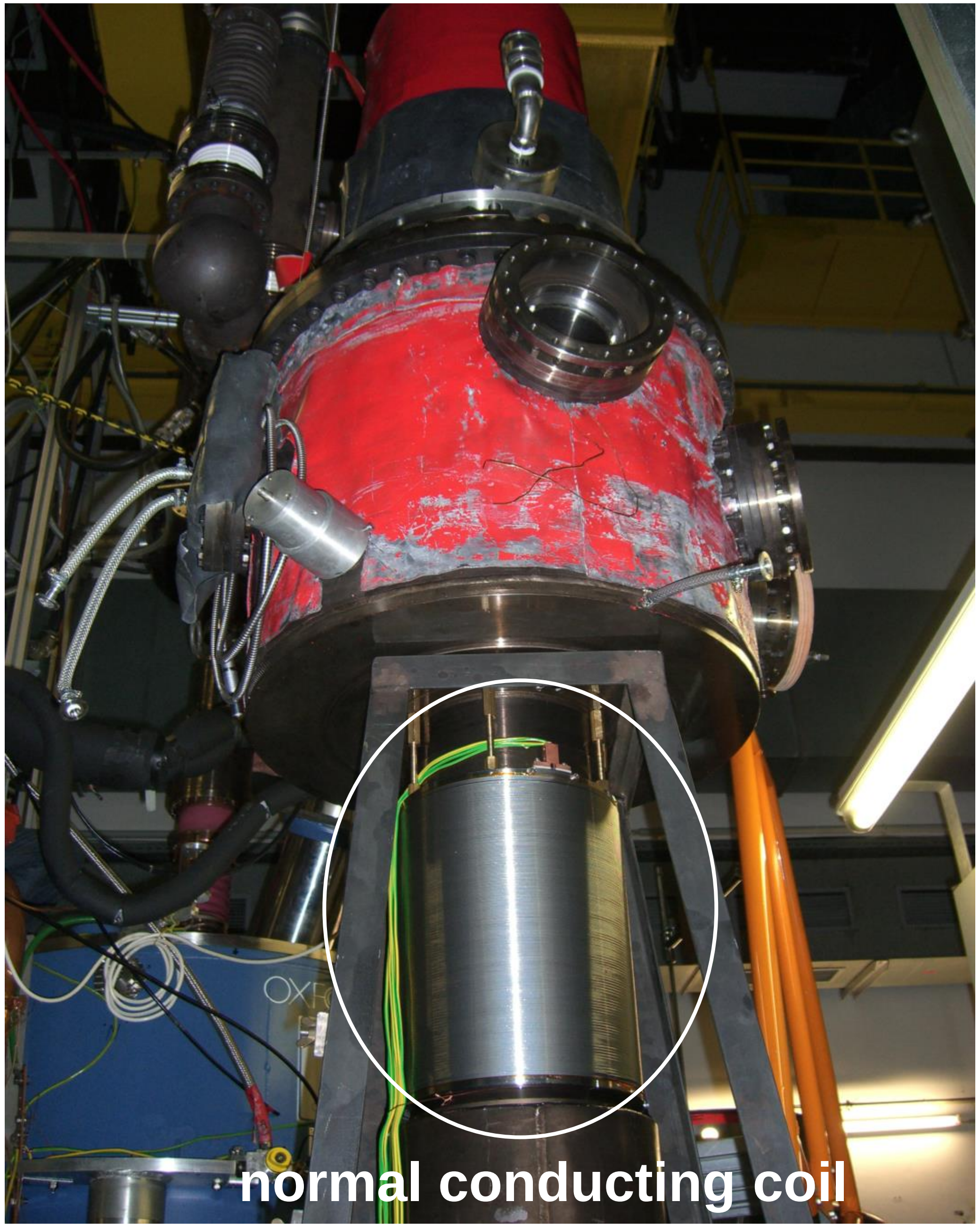
170 GHz, CW Coaxial-Cavity Gyrotron and Components (TED)



Experiments at Nominal Magnetic Field (~ 6.87 T)

- Limitation of the FZK sc-magnet at 6.72 T
- Additional normal conducting coil (55 A) wound directly onto the gyrotron body, close to the cavity
- The MIG anode has been adjusted for:
  6.86 T / 90 kV / 75 A / R_b=10.05 mm / α=1.28





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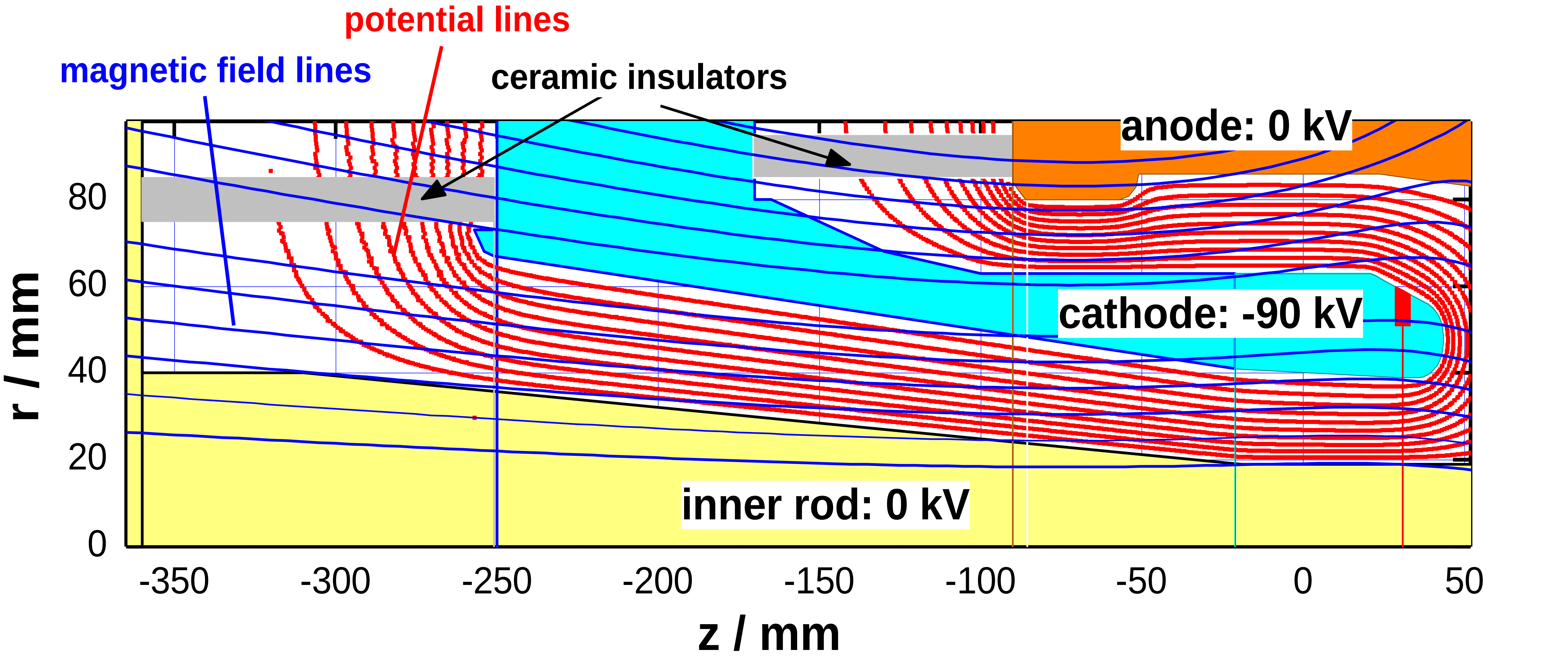
Electron Gun of the Pre-Prototype Gyrotron



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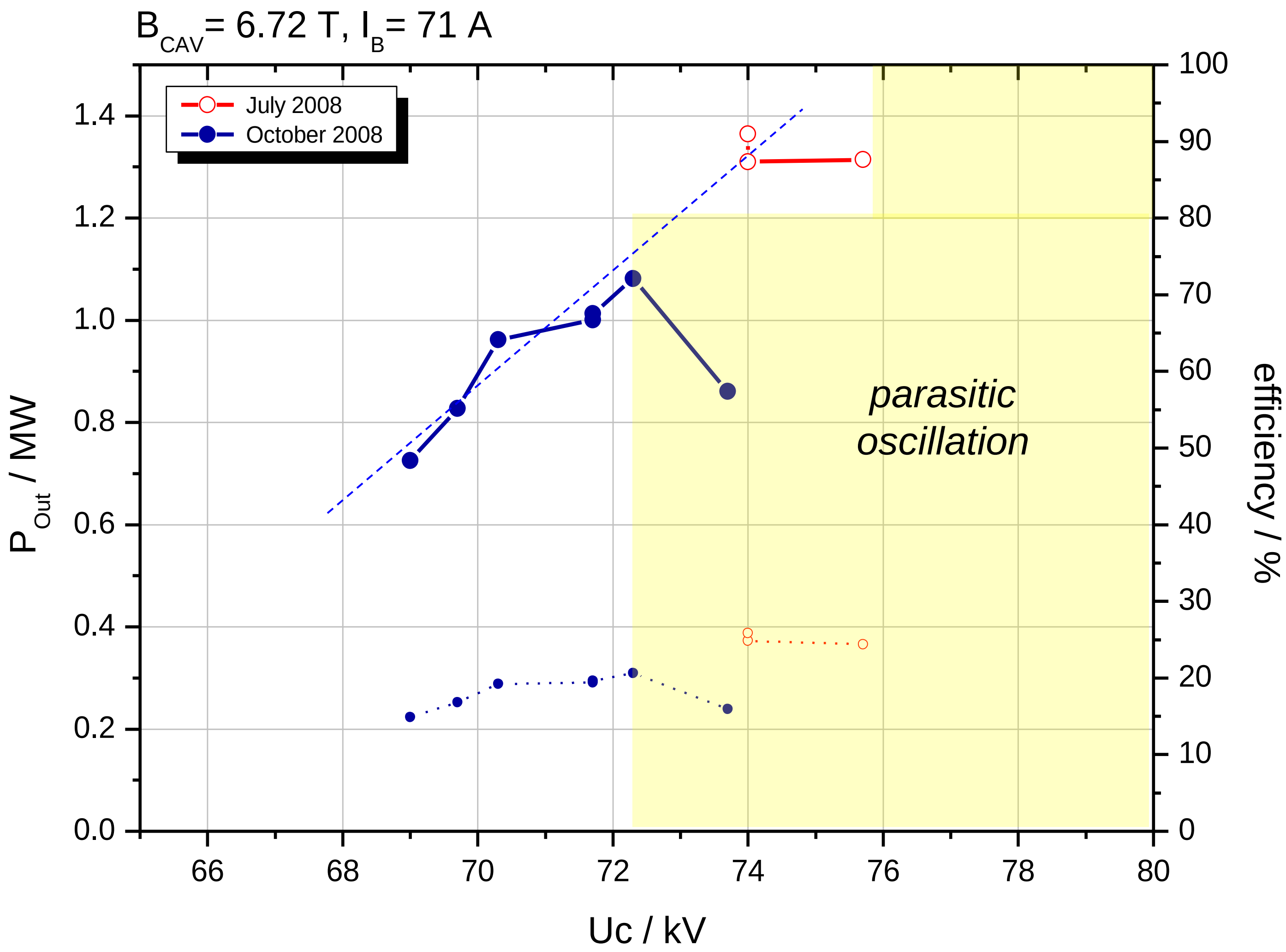
Parasitic Oscillations

- Experiments at reduced magnetic field (~ 6.72 T) and reduced voltage (80 kV) performed in 2008



- Max. output power: ~ 1.4 MW
- Parasitic oscillation ~ 160 GHz and significant power reduction at U_C > 73 kV

Problem of beam tunnel?

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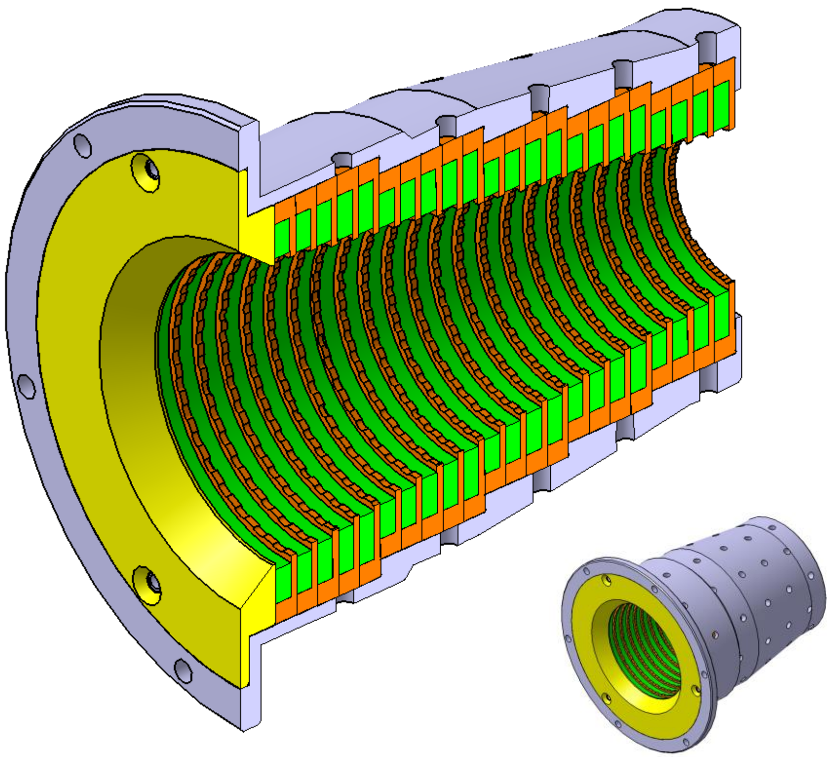
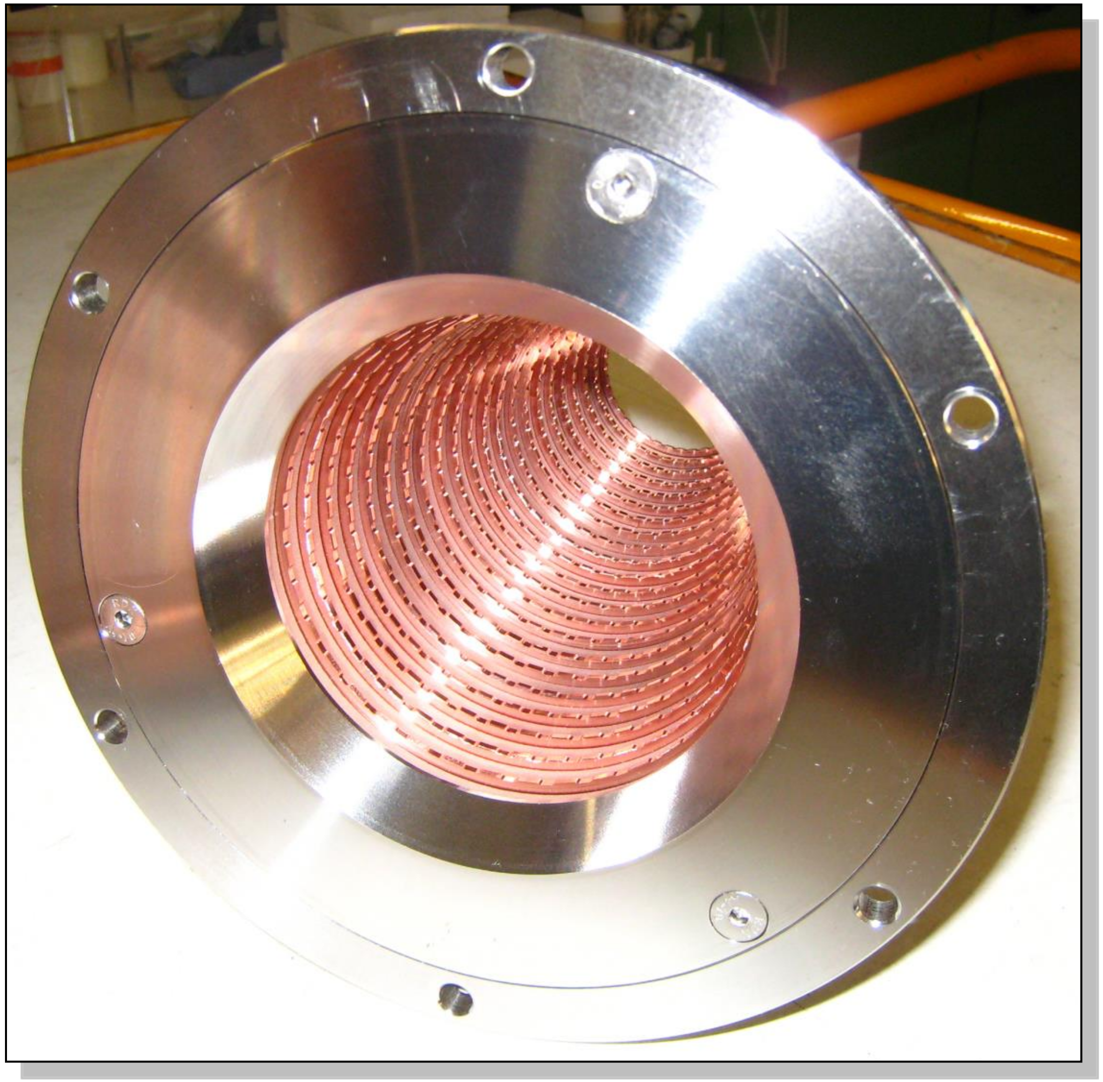
Suppression of the Parasitic Oscillations

<u>New beam tunnel design:</u>
Breaking of cylindrical symmetry to suppress azimuthal currents





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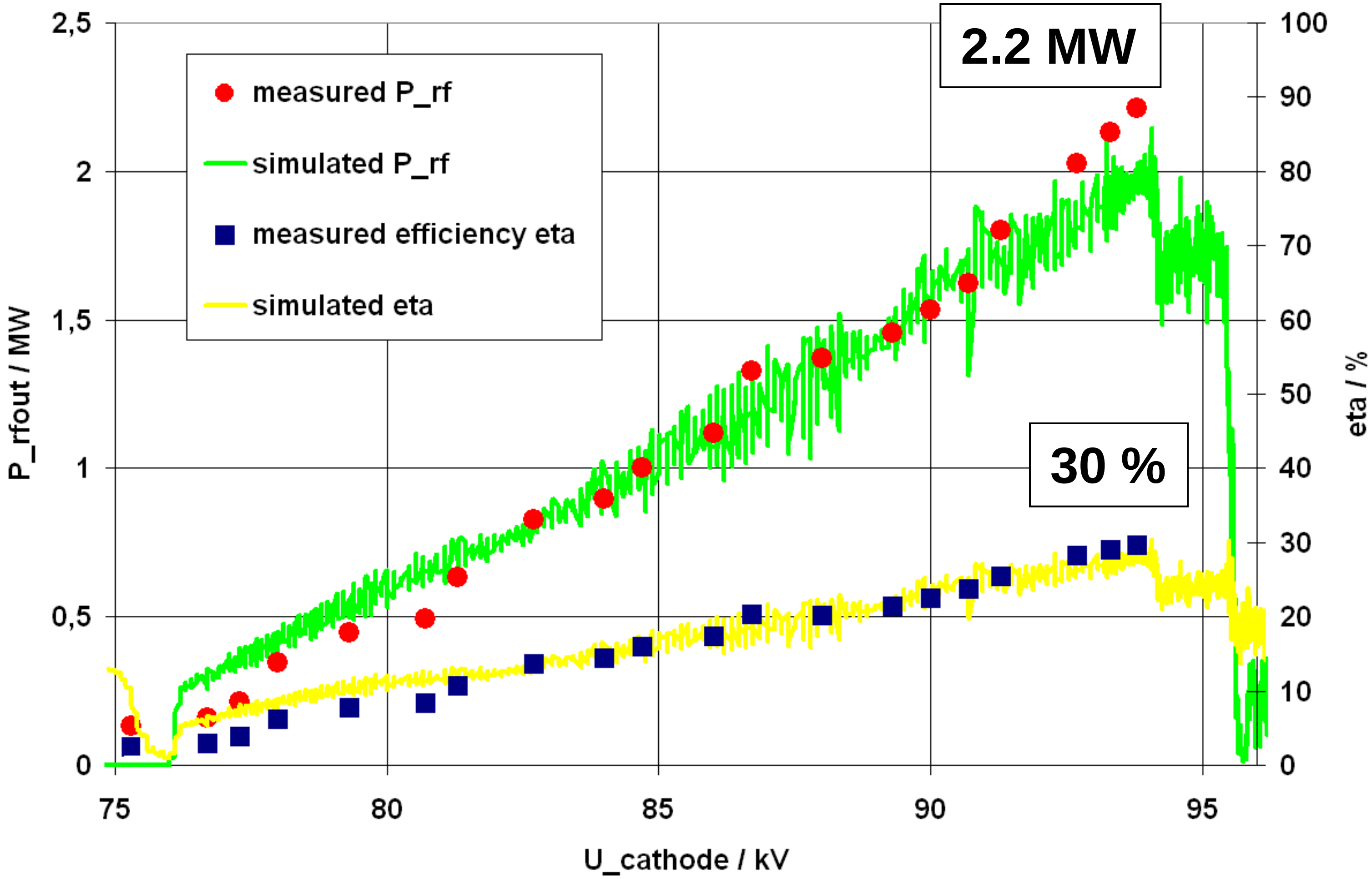
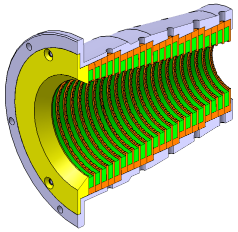
Recent Experimental Results (at Nominal Magnetic Field)

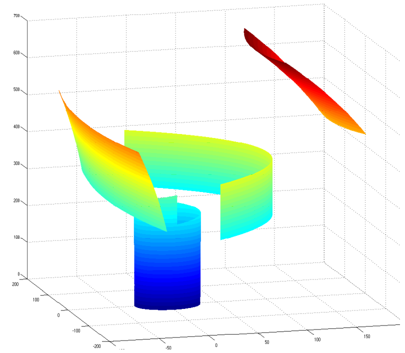


Gyrotron operated with:

- New beam tunnel



- Improved q.o. output system

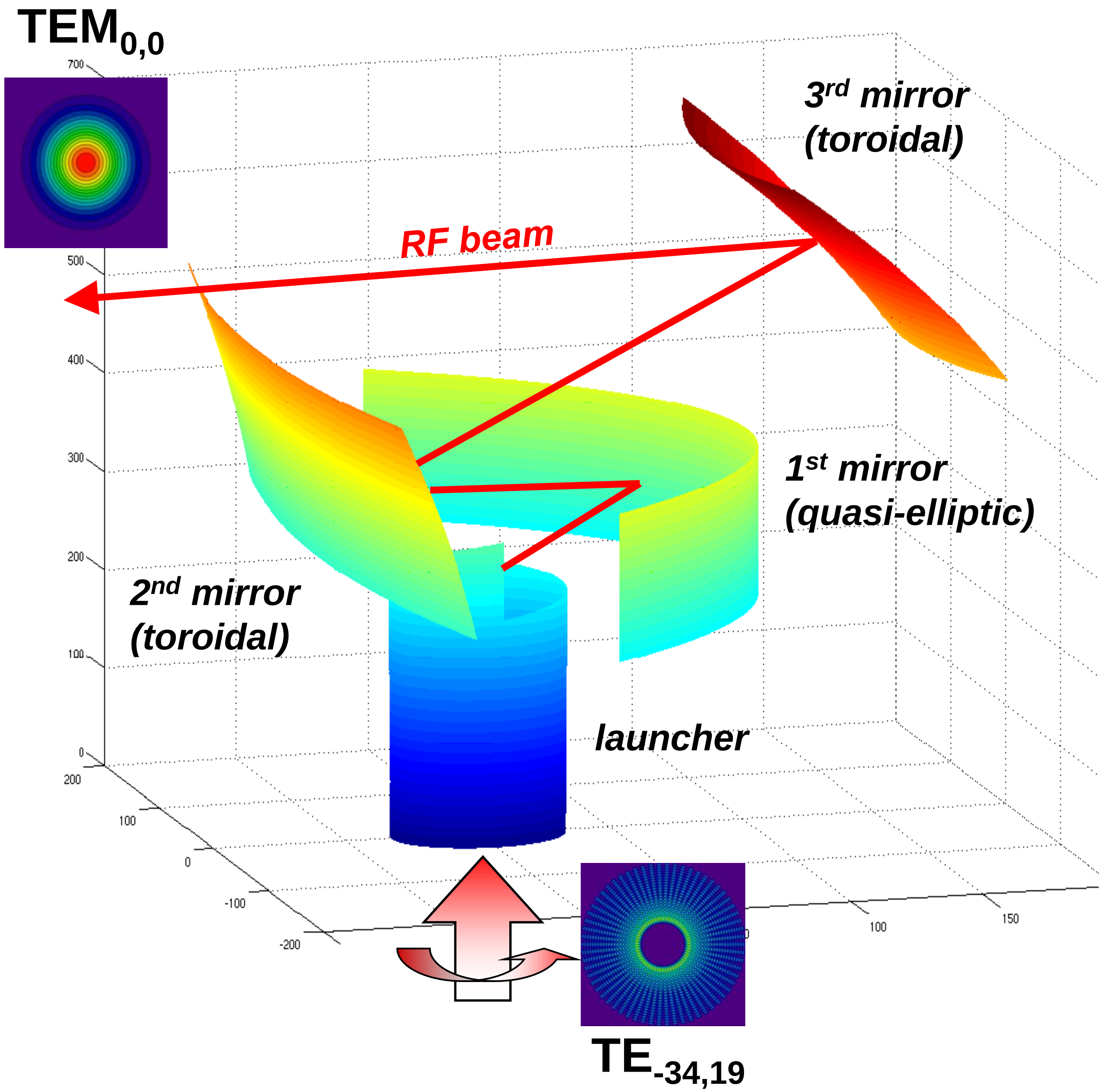


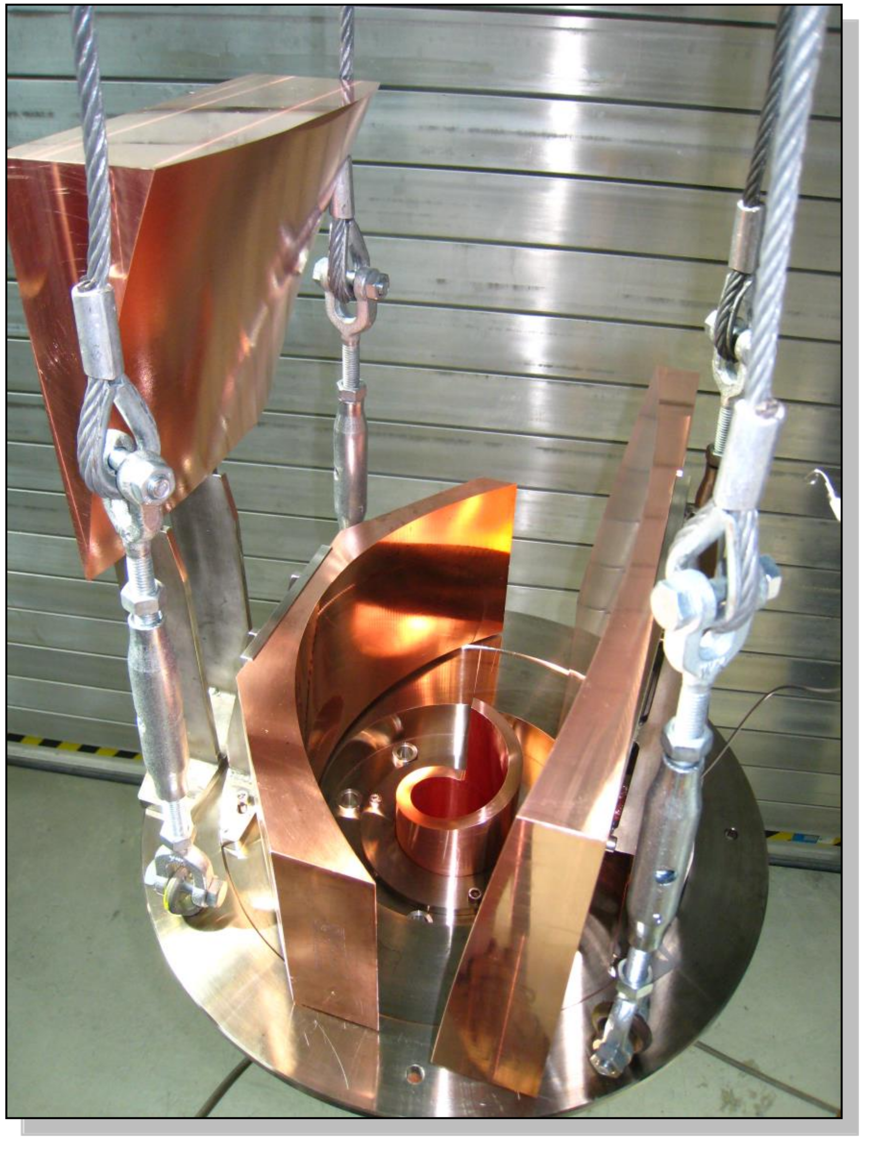
- **Stable operation up to 93 kV / 80 A at 6.88 T**
- **Strongly reduced intensity of the parasitic oscillations**
- **Maximum mm-wave output power ~2.2 MW at 30 % efficiency (without SDC) at ~1 ms pulse length**
- **Good agreement with selfconsistent multimode calculations incl. 10 % losses and 5 % vel. spread**
- **Measured internal stray radiation 7 ± 2 %**

Theoretical Losses and Internal Stray Radiation

	Losses	Stray radiation
Spurious cavity modes ($TE_{m,19}$; m = 36,35,33,32)	---	3 %
Ohmic losses of cavity and uptaper	2.2 %	---
Mode conversion losses of uptaper	0.2 %	0.2 %
Ohmic losses of launcher	1.8 %	---
Reflection of launcher	0.3 %	0.3 %
Stray radiation of launcher	0.7 %	0.7 %
Ohmic losses of 3 mirrors	0.5 %	---
Diffraction losses of 3 mirrors and window aperture	1.1 %	1.1 %
Absorption losses of quartz window	3.3 %	---
Reflection of window	0.4 %	0.4 %
Total Losses/Stray Radiation	**10.5 %**	**5.7 %**

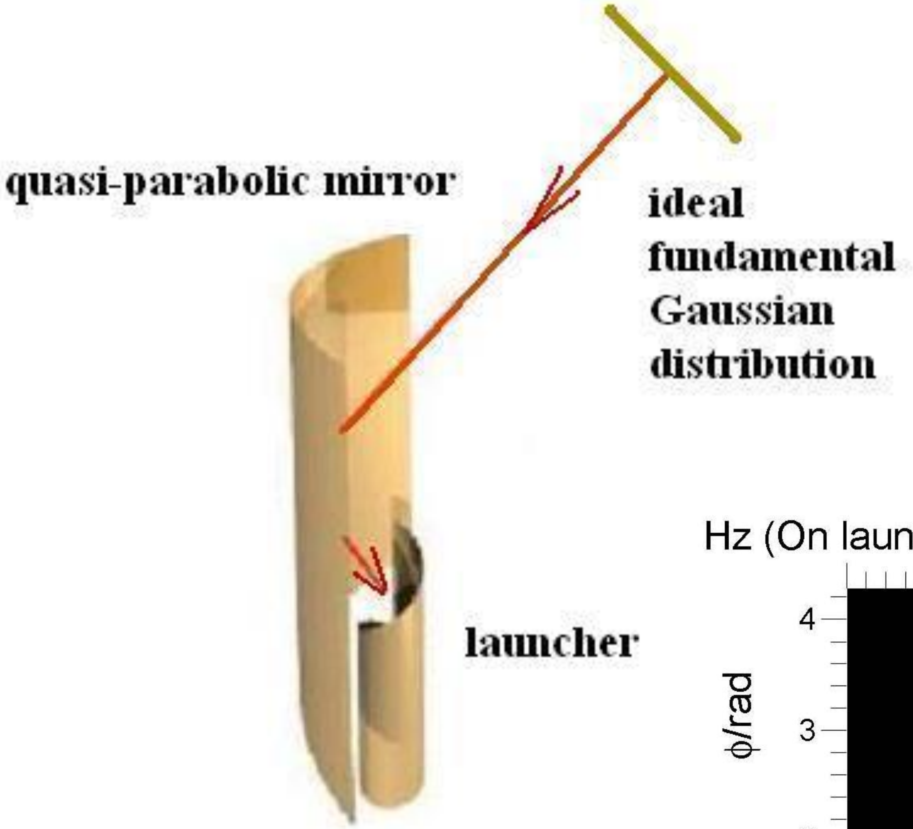
Quasi-Optical mm-Wave Output Coupler

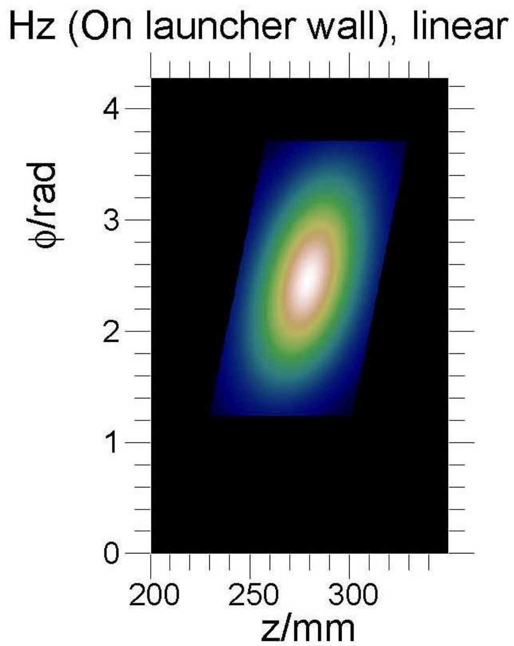


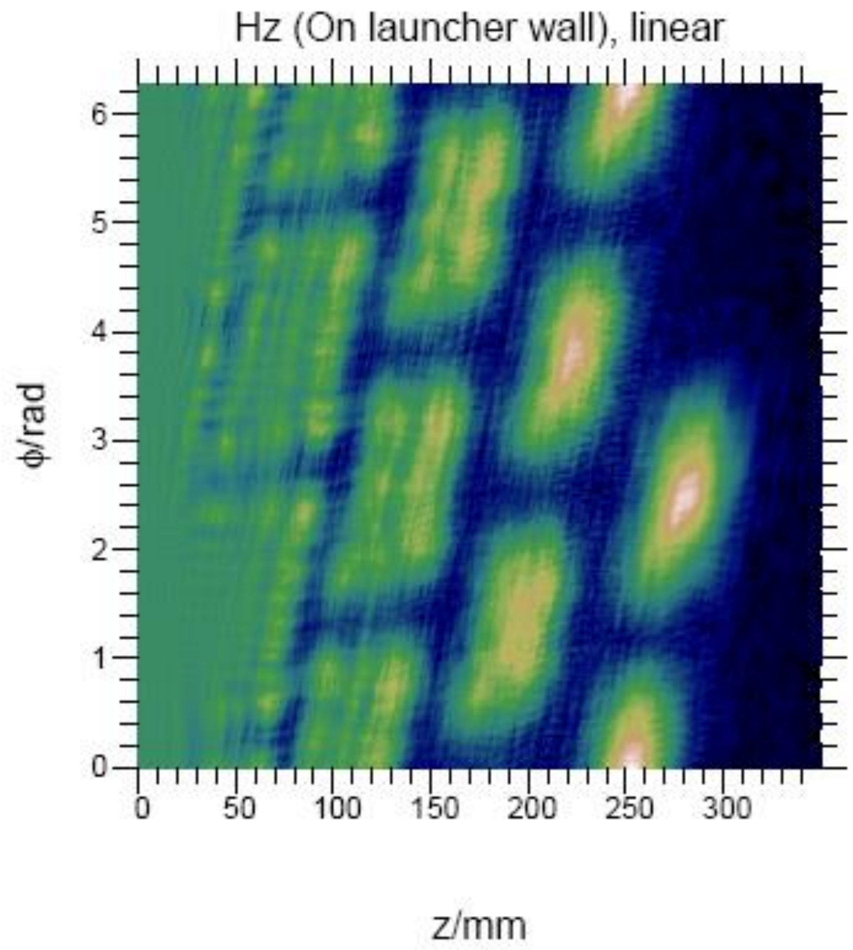


Launcher with Arbitrary Deformations (I)

- Optimization by solving the scalar diffraction integral equation



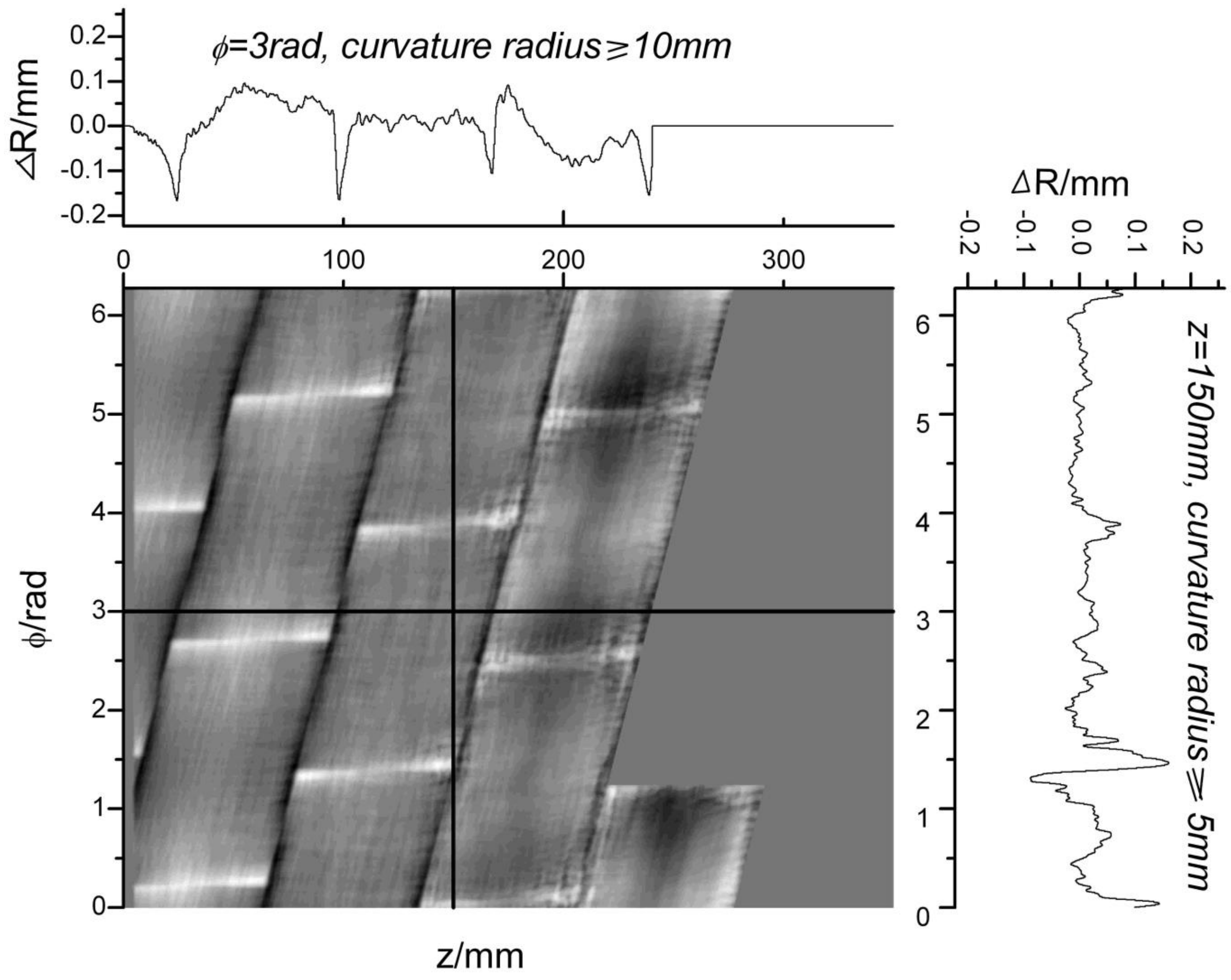


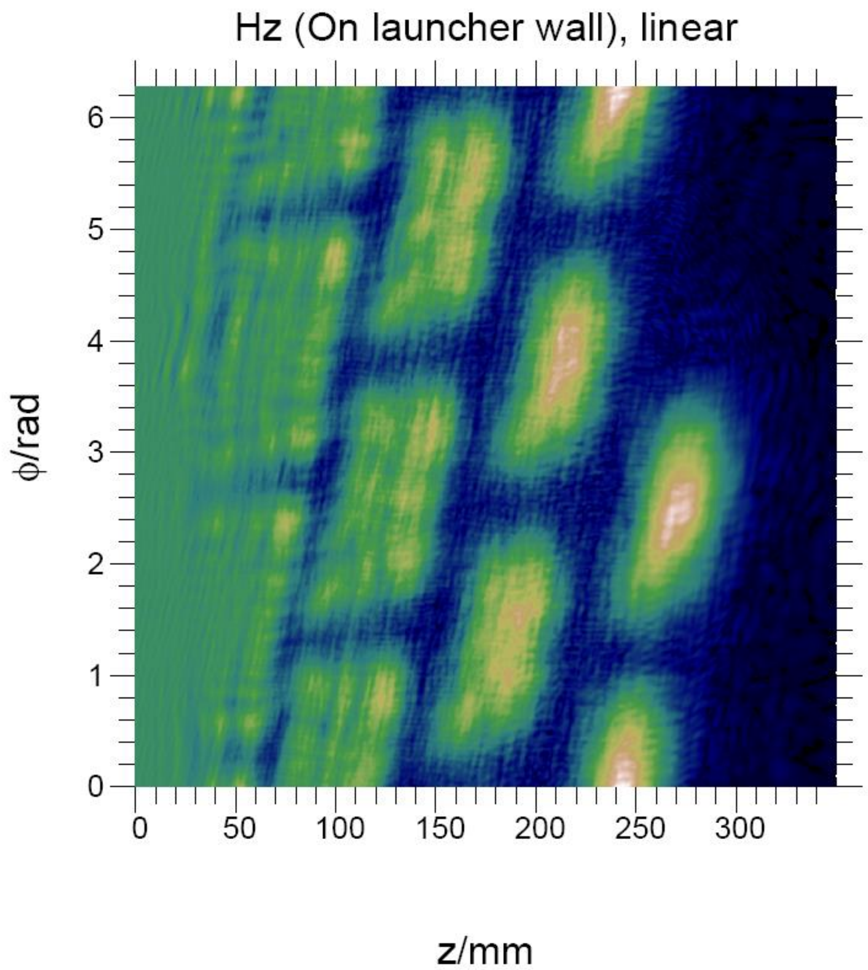


Vector correlation coeff. 96.3 %

Launcher with Arbitrary Deformations (II)

- Surface contour and field distribution on the inner launcher wall





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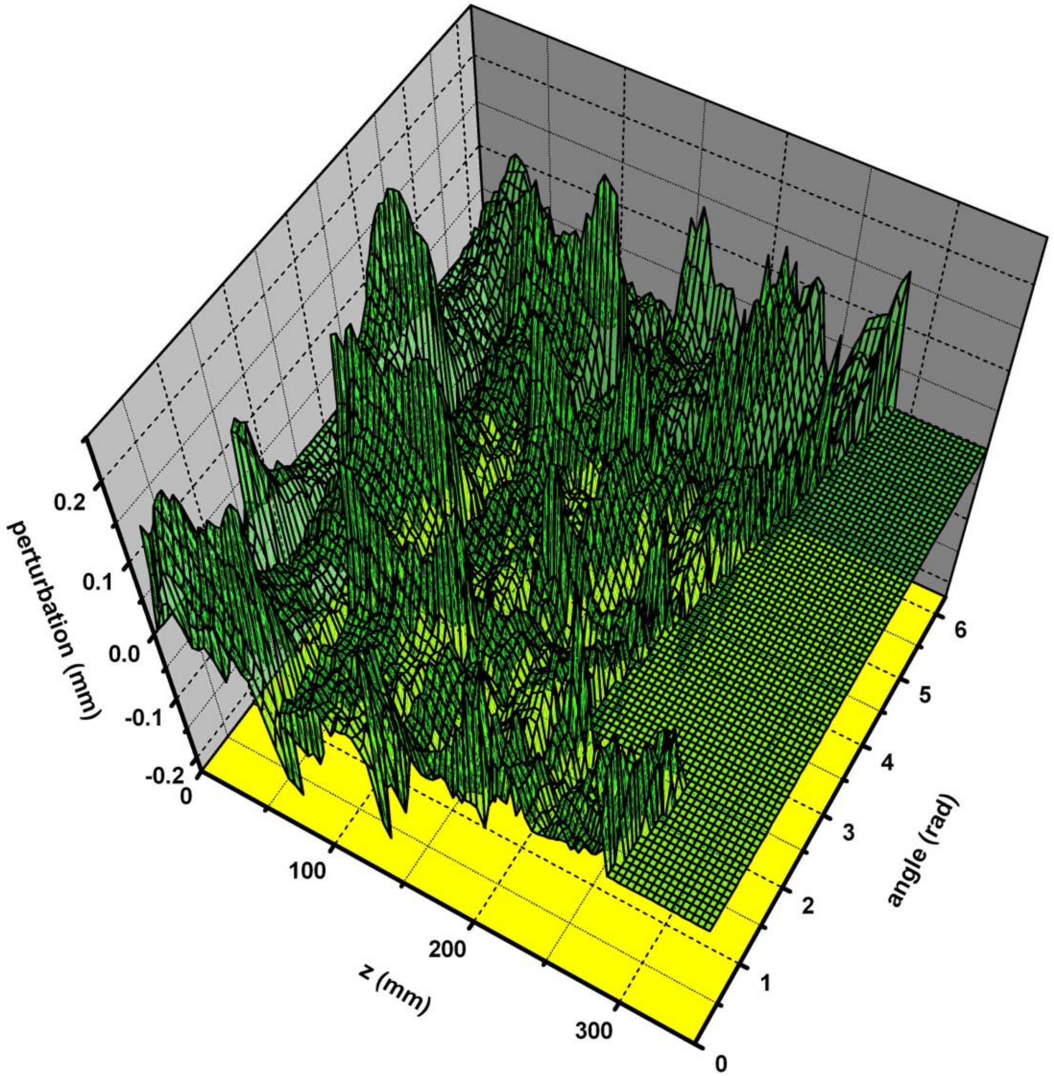
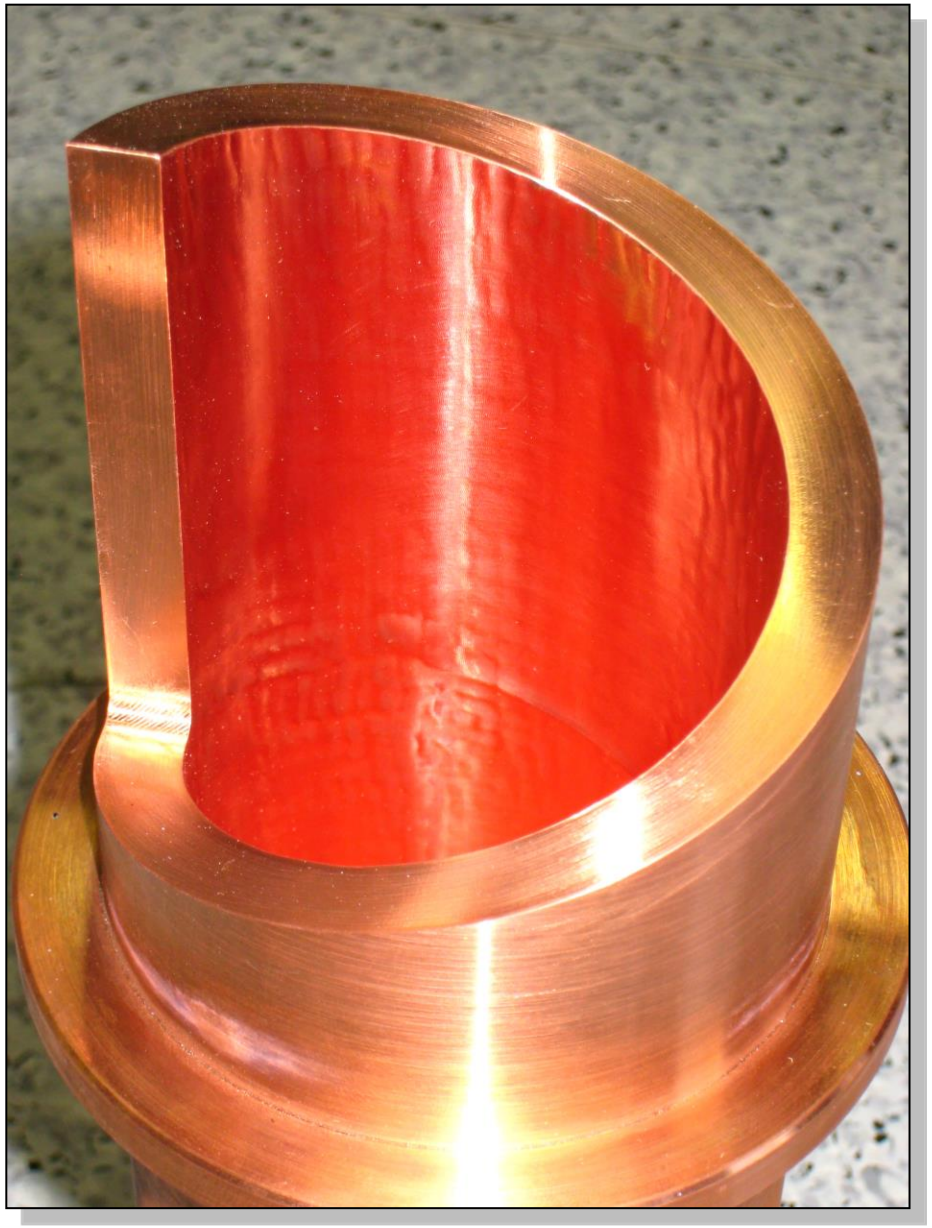
Launcher with Arbitrary Deformations (III)

- Surface contour of the inner launcher wall



Top view



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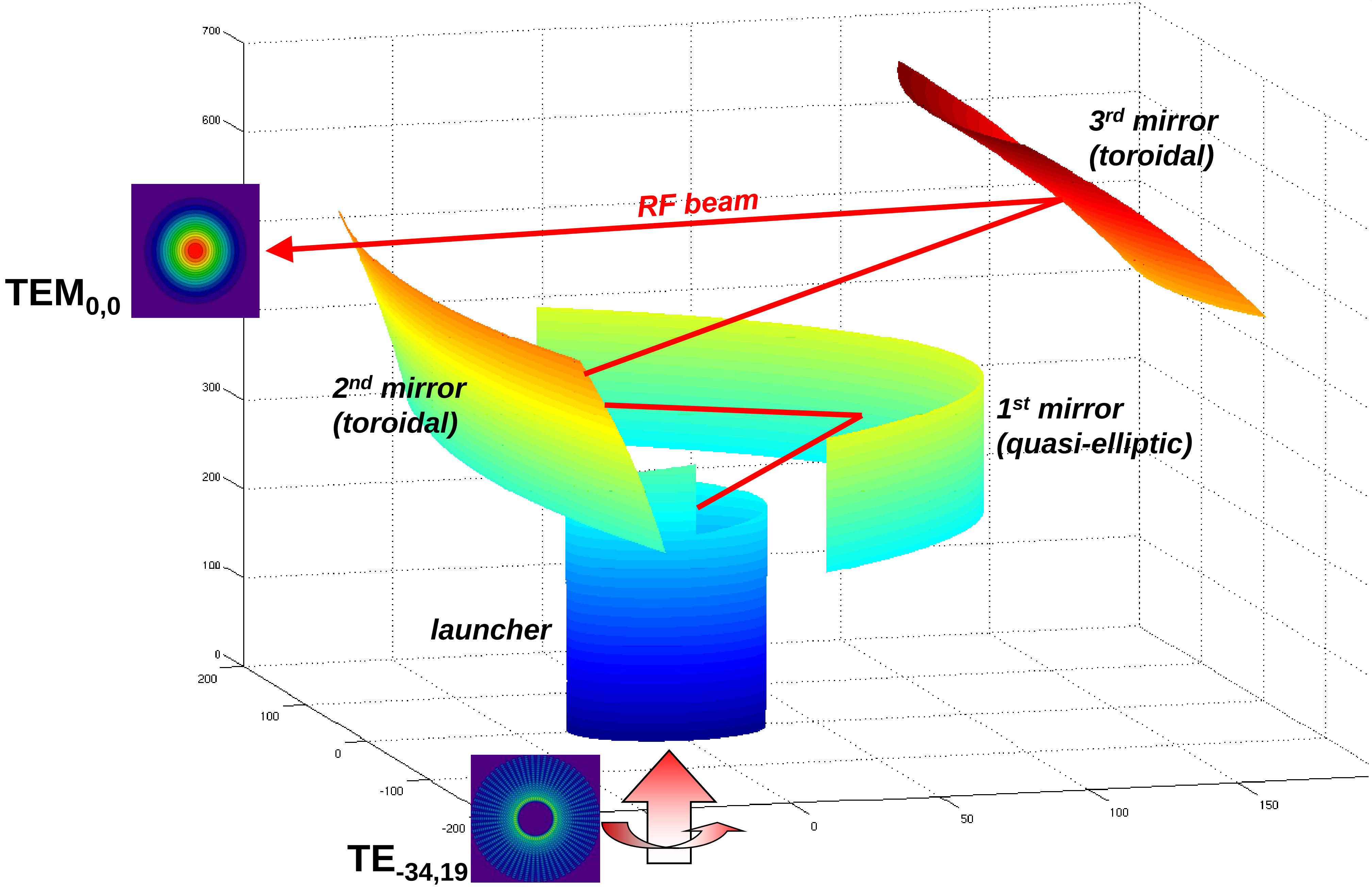
Mirror System Design



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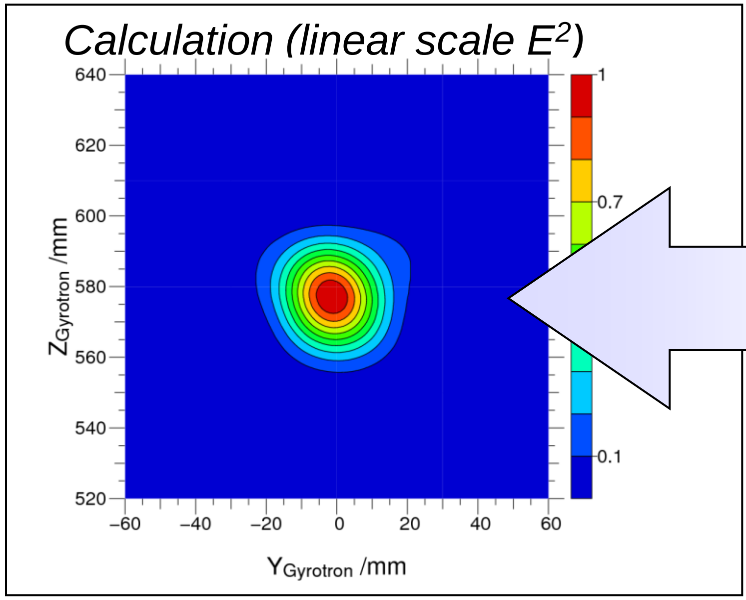
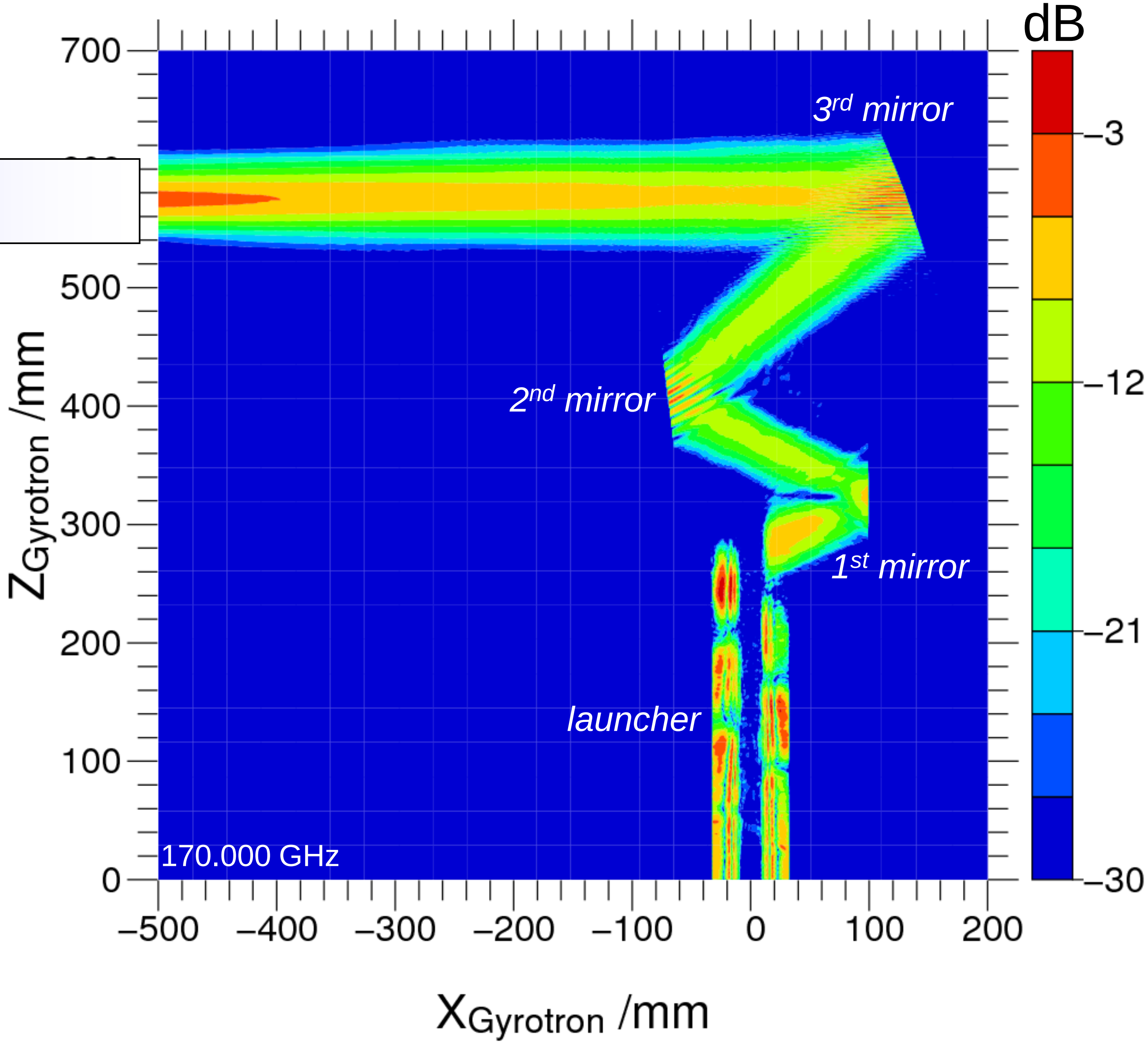
Quasi-Optical mm-Wave Output Coupler (SURF3D)



- Calculated output beam profile (SURF3D)



- Calculated value of the Gaussian mode content at the window position: **~97 %**
- Stray radiation losses: **~ 2 %**

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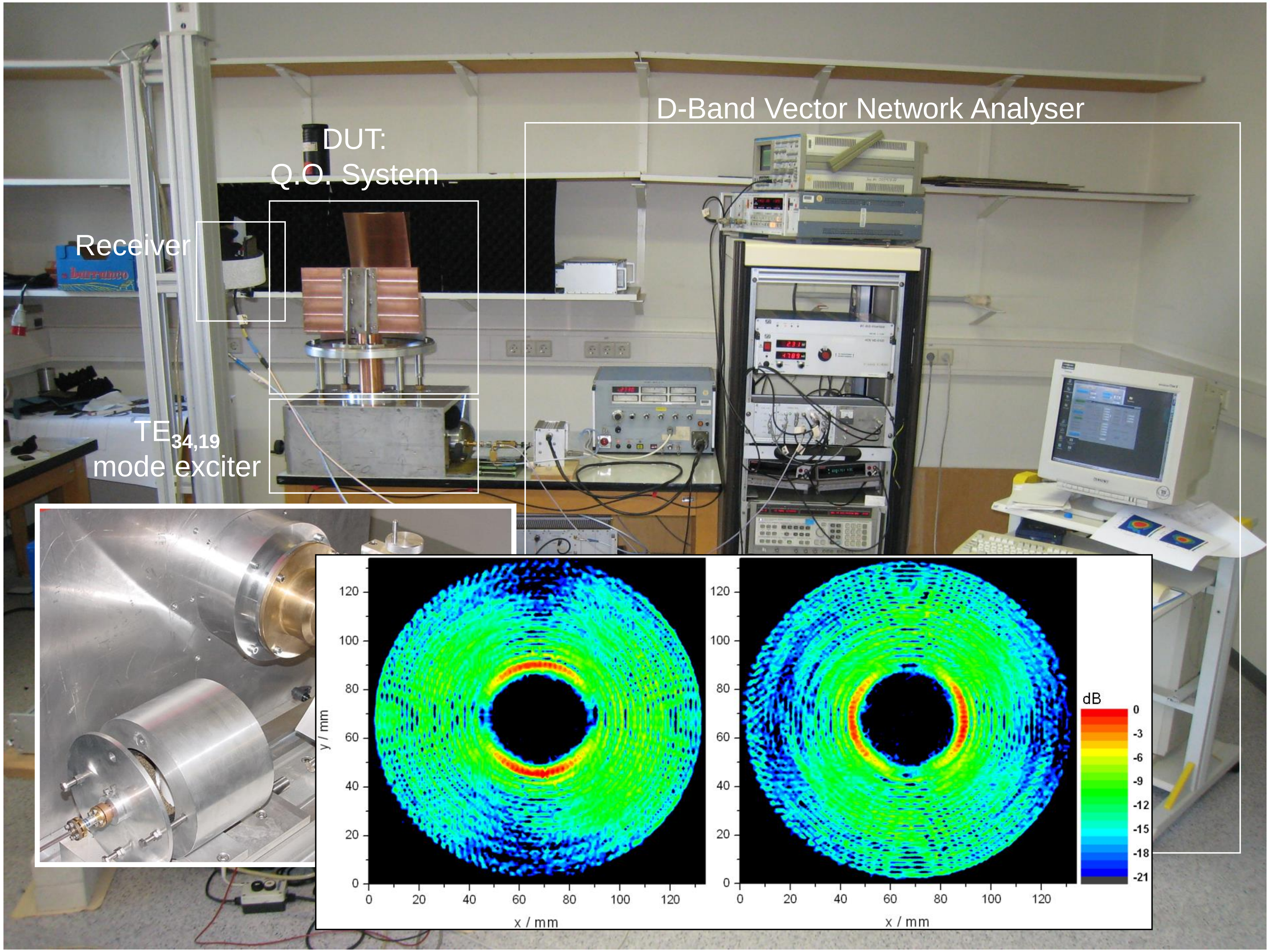
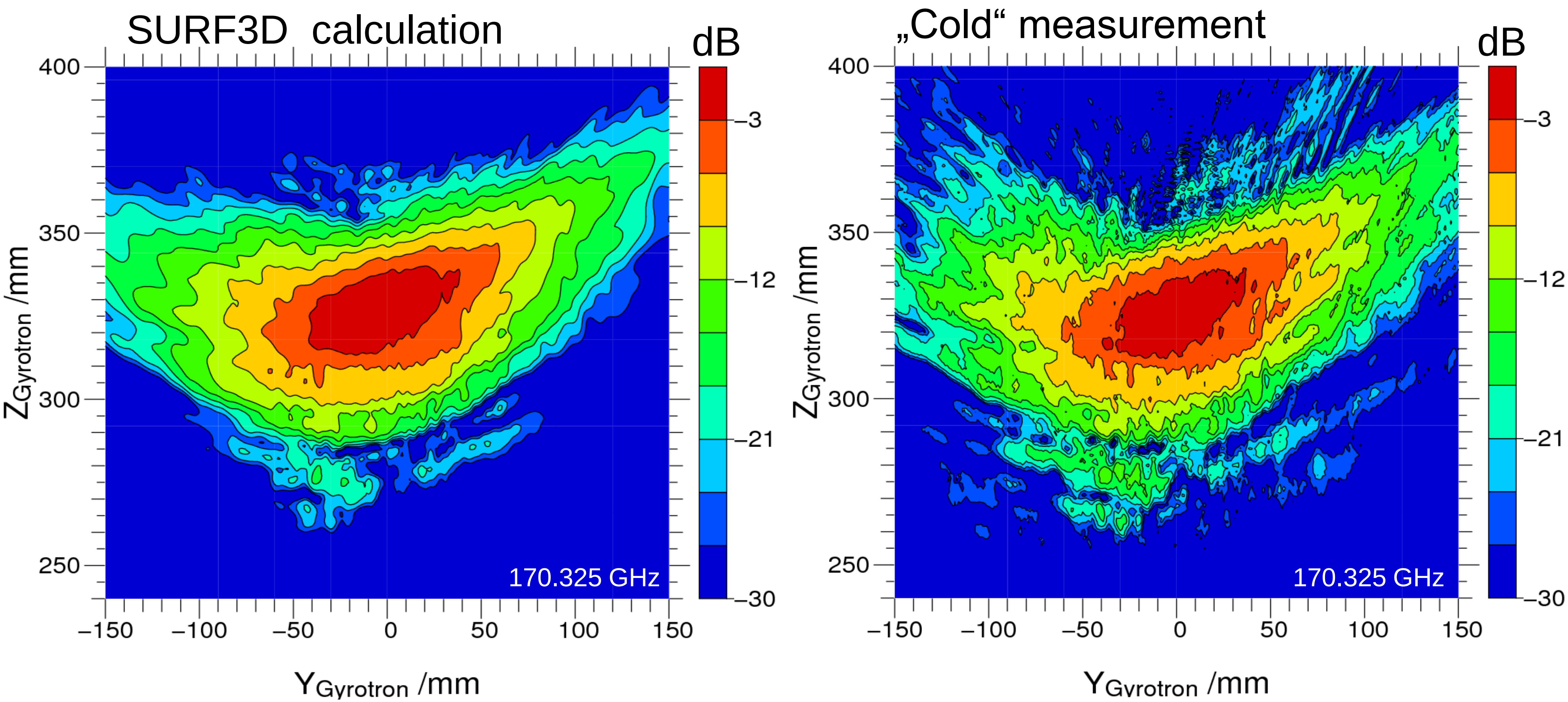
„Cold“ Measurements at Low Power



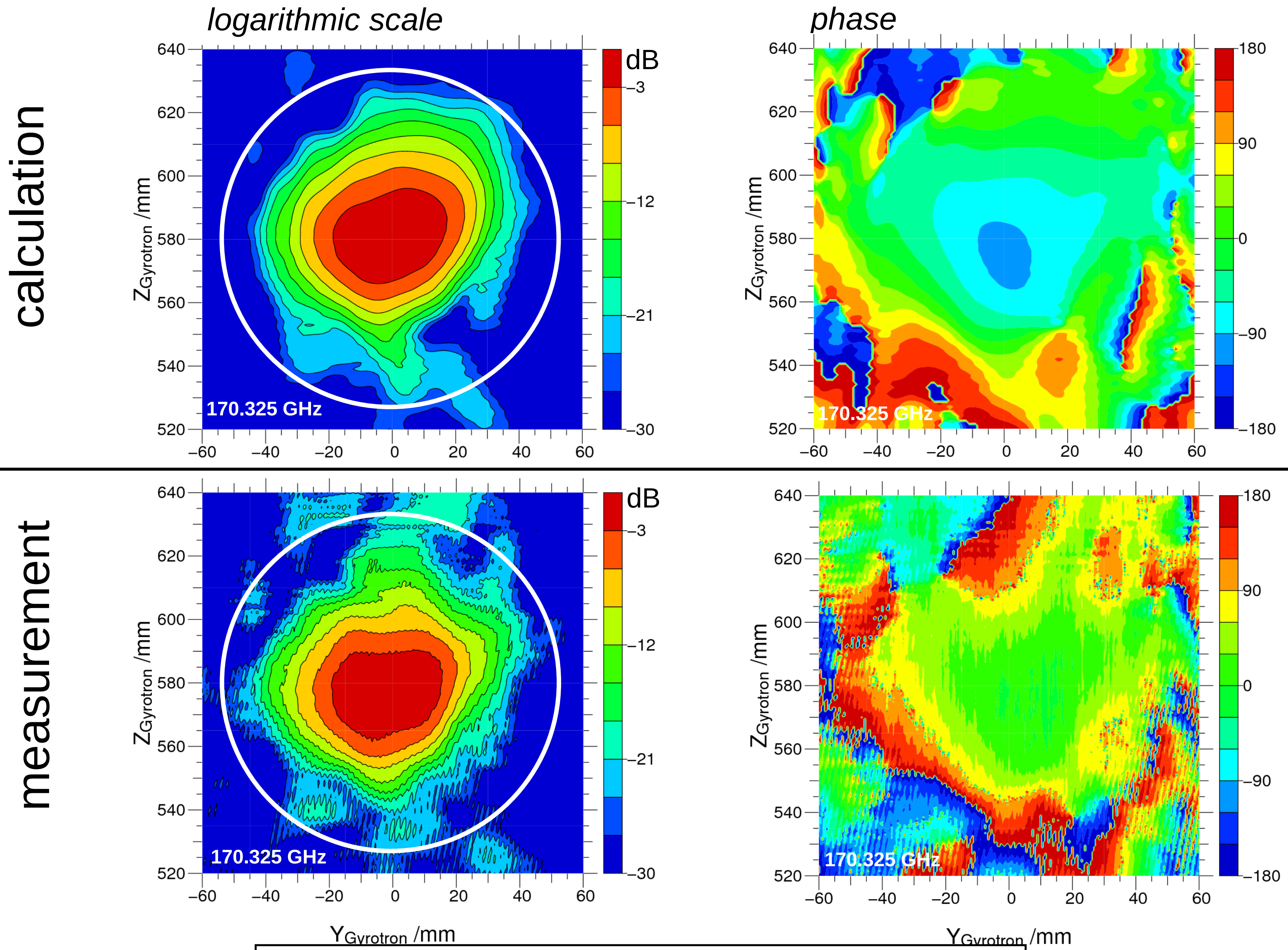
Results of Low Power Measurements - Launcher

- Radiated field in a plane at a distance of 100 mm from the launcher axis



Results of Low Power Measurements - Window

- Field pattern at the window position



Measured Gaussian mode content about 97 %

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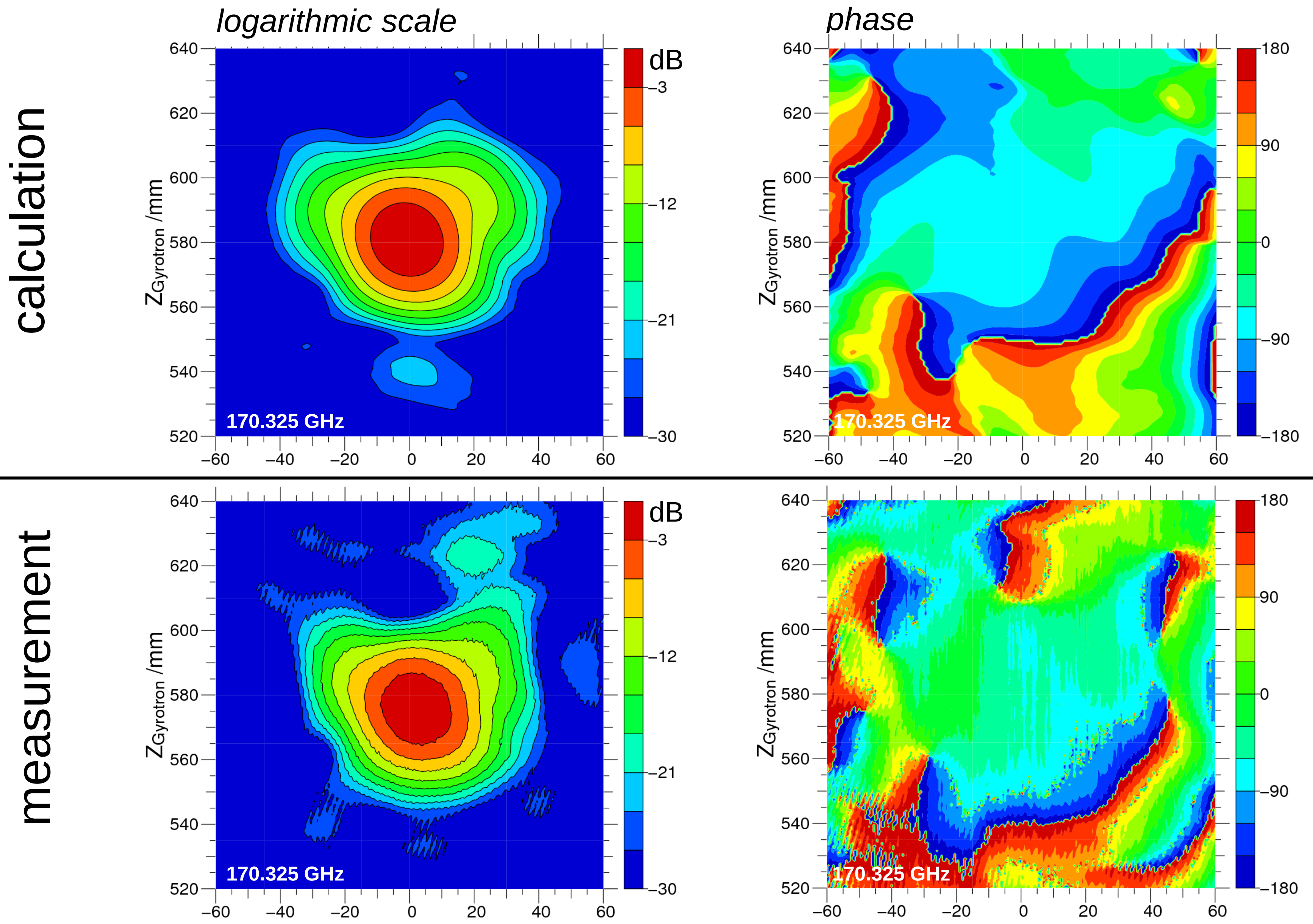
Results of Low Power Measurement – 500 mm

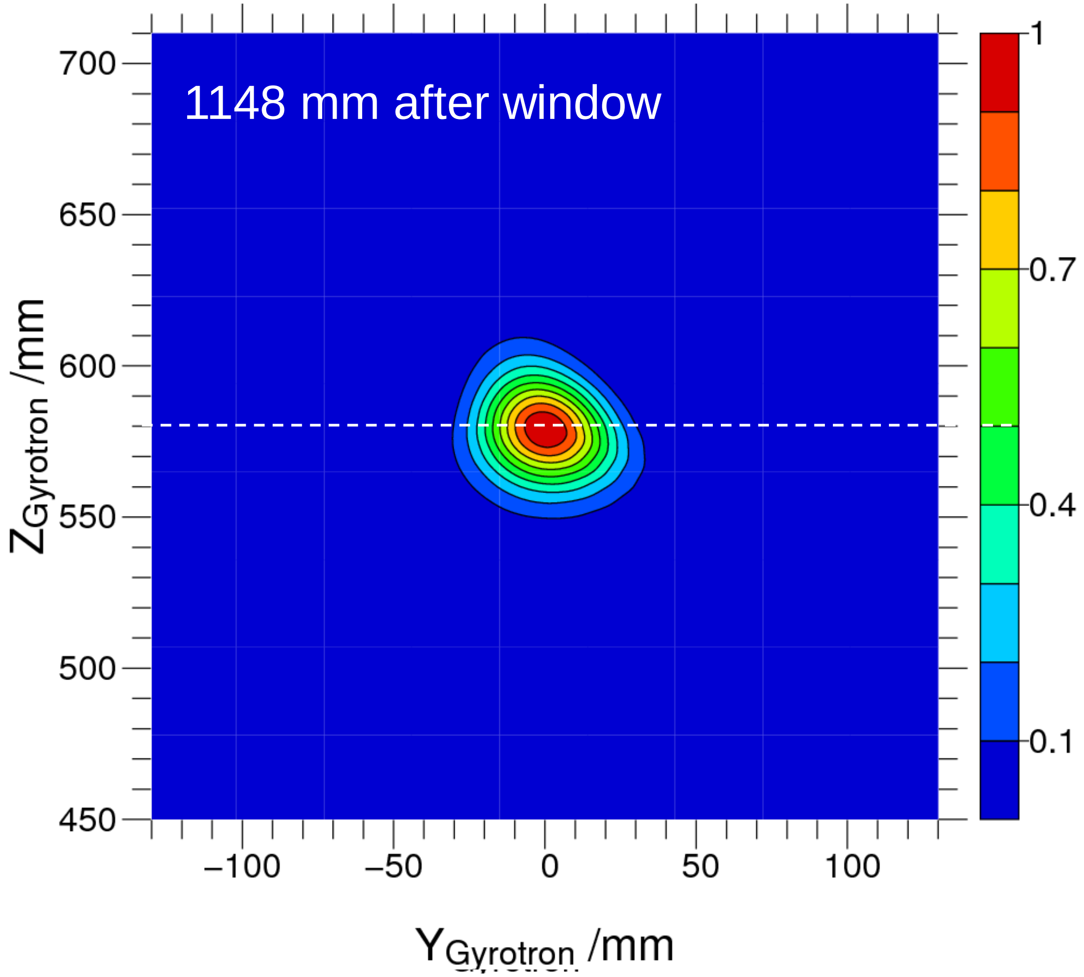
- Field pattern 500mm outside the window



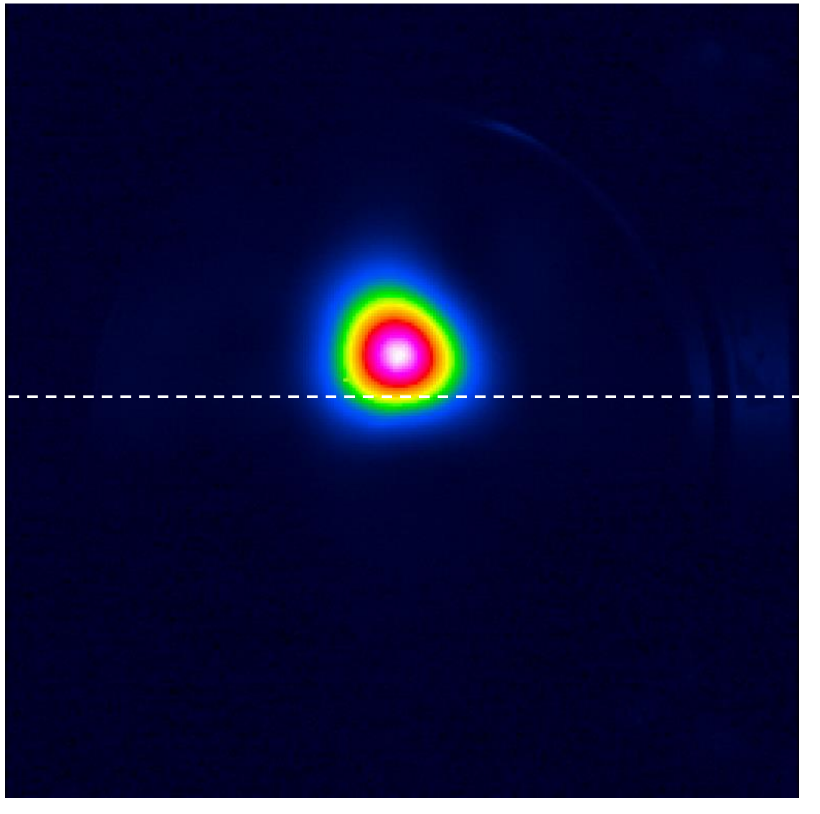
Measured Gaussian mode content about 98.5 %

- mm-wave beam profile at different distances from the gyrotron window (linear scale)

Calculation



„Hot“ measurement



Very first analysis of the measured “hot” mm-wave beam profile has shown at least 95.5 % of the Gaussian mode content

Summary & Conclusions

Experimental results

- At reduced magnetic field ~1.4 MW of mm-wave output power at ~27 % efficiency has been measured
  - parasitic oscillations ~160 GHz and "multi-frequency" scenarios were observed
- New design of the beam tunnel has been investigated experimentally
  - much more stable gyrotron operation and significant reduction of the intensity of parasitic oscillations has been observed
- Using an additional normal conducting coil the nominal magnetic field value (6.88 T) has been achieved
  - in the experiment: **~2.2 MW of mm-wave output power at ~30 % efficiency (quartz window!)**
- Amount of internal stray radiation was measured to be ~7 ± 2% (compared to 8 ± 2% with the previous q.o. output coupler) – where 3% are probably resulting from spurious cavity modes.

Q.O. output coupler

- New q.o. output coupler has been designed based on a new launcher optimized by solving the scalar diffraction integral equation – efficiency: **~97 % Gaussian mode content and ~2 % stray rad. losses**
- The improved q.o. mode converter has been fabricated and experimentally verified
- Very good agreement between calculation and measurements at low power has been found
- Very high value of Gaussian mode content has been confirmed experimentally ("cold" and "hot" tests)