Recent Investigations on Stable Operation of High-Power Gyrotrons

G. Gantenbein[1], G. Dammertz[1], V. Erckmann[2], S. Illy[1], S. Kern[1], T. Rzesnicki[1], W. Kasparek[3], B. Piosczyk[1], A. Samartsev[1], A. Schlaich[4], M. Thumm[1, 4]

[1]Forschungszentrum Karlsruhe, Association EURATOM-FZK, Institut für Hochleistungsimpuls- und Mikrowellentechnik, Hermann-von-Helmholtz-Platz 1, D-76344 Eggenstein-Leopoldshafen, Germany
[2]Max-Planck-Institut für Plasmaphysik, Teilinstitut Greifswald, Association EURATOM, Wendelsteinstr. 1, D-17491 Greifswald, Germany
[3]Institut für Plasmaforschung, Universität Stuttgart, Pfaffenwaldring 31, D-70569 Stuttgart, Germany
[4]Universität Karlsruhe, Institut für Höchstfrequenztechnik und Elektronik, Kaiserstr. 12, D-76131 Karlsruhe, Germany

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Content

Introduction

High Power high-frequency gyrotrons show a increased danger of parasitic oscillations (not necessarily from gyrotron interaction in cavity:

- Shoyama, Sakamoto et al. (Jpn. J. Appl. Phys. **40**, (2001)): > 10 kW RF power (140 – 160 GHz) in gun area of 170 GHz gyrotron, ⇒ degradation of beam quality
- CPI, ICOPS 2008
- Gantenbein et al., ICOPS 2008: parasitic oscillations, 120 – 130 GHz in W7-X gyrotron (140 GHz), estimated power 1 – 5 kW, thermal damages in beam tunnel area after inspection

Theoretical work:

Tigelis et al. (U of Athens, Greece, IEEE Trans Plasma Science 26, 1998): Numerical calculation of fields in beam tunnel, no active media, idealised geometry

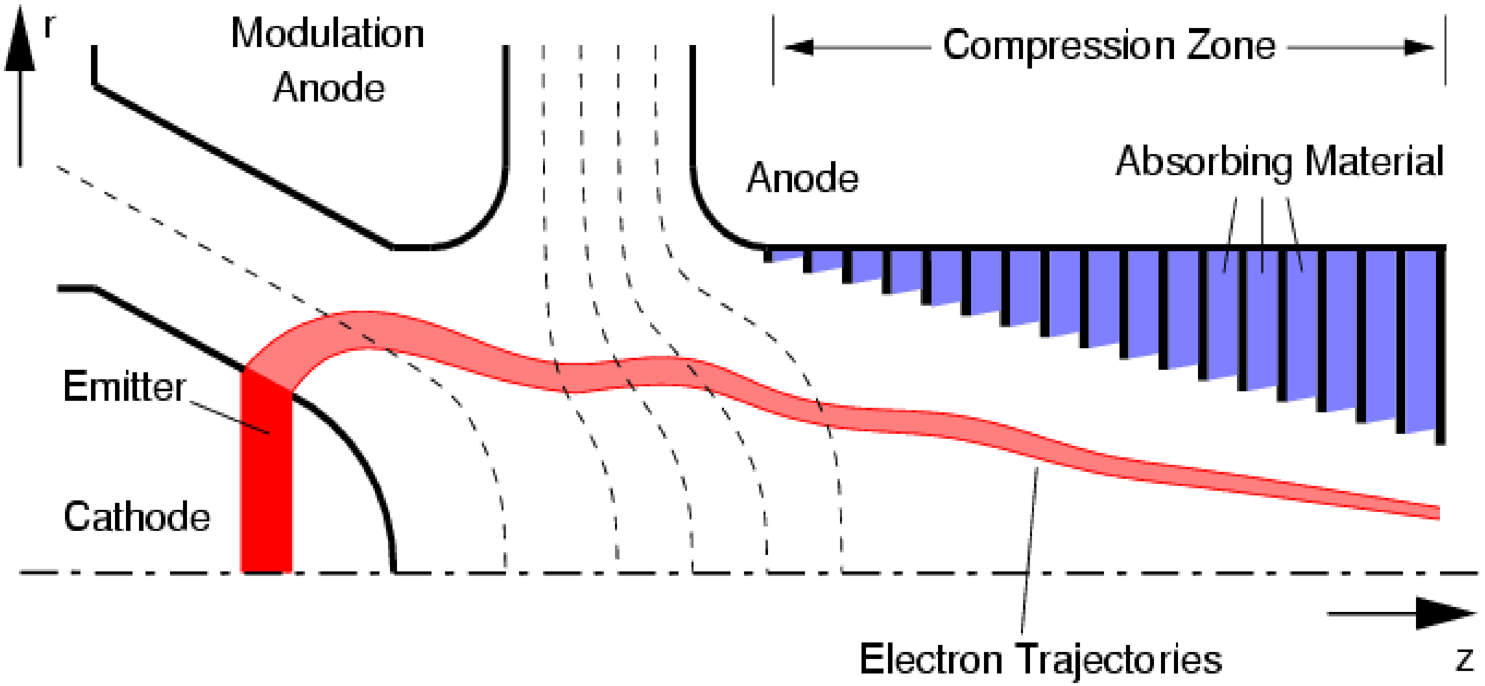
Yu et al. (U of Maryland, USA, ICOPS 2009): Excitation of backward waves in the beam tunnel of a high power gyrotron

Also:

Low-frequency oscillations, experimentally observed (FZK ~ MHz),

Yan, Antonsen and Nusinovich (ICOPS 2009): Analytical theory of low-frequency oscillations in gyrotrons, trapped electrons

Traditional Beam Tunnel

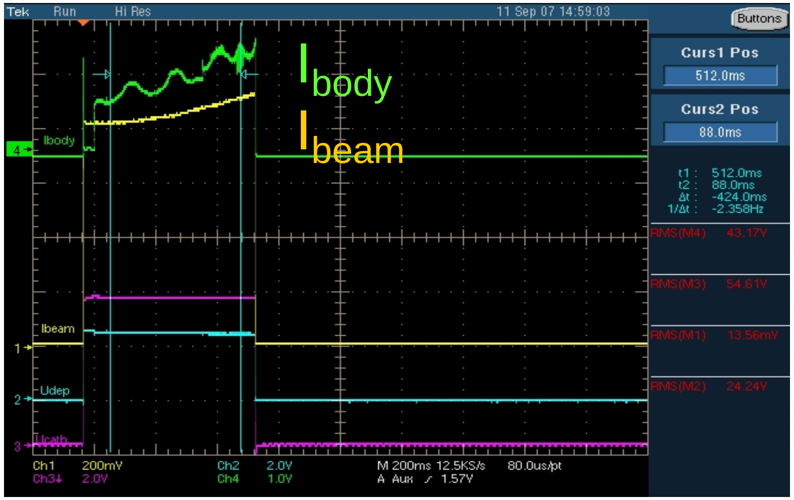


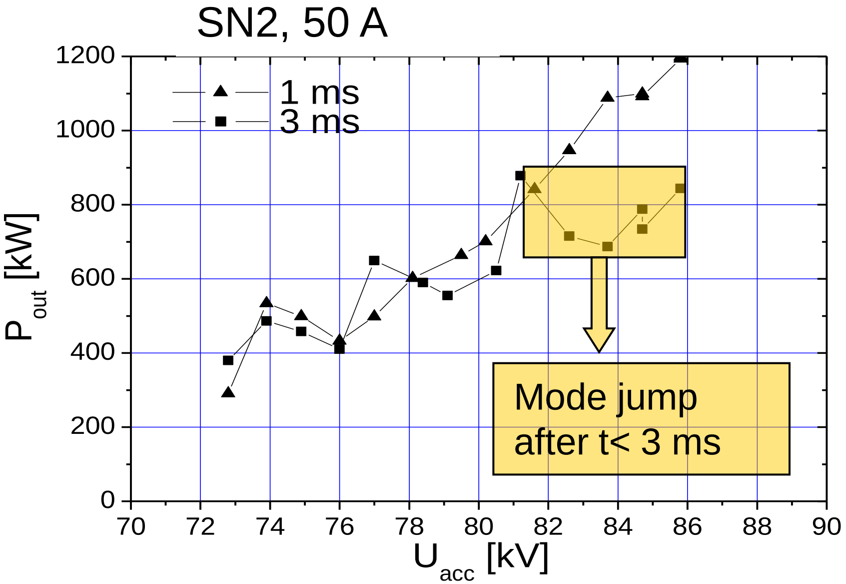
- Highly overmoded: Possible excitation of a large number of modes
- Cu rings and ceramics material (e.g. BeO/SiC, AlN/SiC): no surface charging and absorption of RF power
- Good experience in the past, simple technology, but
- Performance is strongly influenced by dielectric properties of ceramics material

Parasitic Oscillations in W7-X Gyrotron

- Occurrence of parasitic oscillations in the frequency range 120 – 130 GHz (plus possible mode competition with azimuthal neighbour of cavity mode)
- Frequency difficult to measure precisely, simultaneous occurrence with design mode
- Possible consequence: Increase of internal currents

$\Rightarrow$ vacuum interlock





Mode jump after t< 3 ms

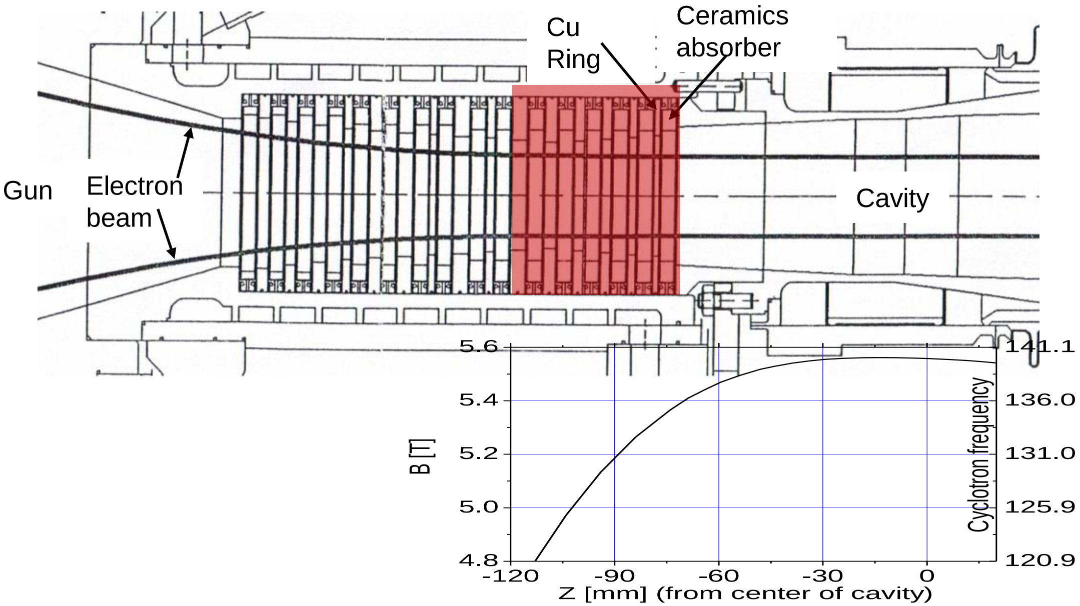
Parasitic Oscillations in W7-X Gyrotron

- During long-pulse operation temperature increase in gun/beam tunnel area is observed

 ⇒ estimated power of parasitics 1 – 5 kW

- Inspection of beam tunnel after tests showed:

Damages of brazing structure, cracks of absorbing ceramics, probably caused by thermal overload



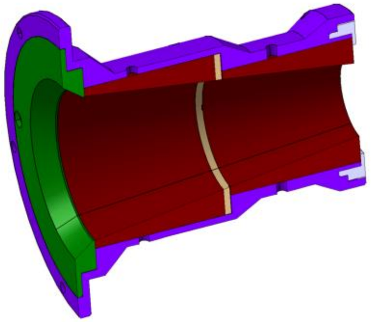
Possible origin: excitation of spurious oscillations correlates with cyclotron frequency of electrons

Avoidance of parasitic oscillations:

- Conical contour
- Breaking of symmetry
- High absorption of ceramics

Improved Beam Tunnel (1)

- Pure ceramics beam tunnel: SiC (Cerasic-B, Toshiba Ceramic Co.)
- Works well, but
- According to gyrotron manufacturer: new brazing technology
- Dielectric properties??



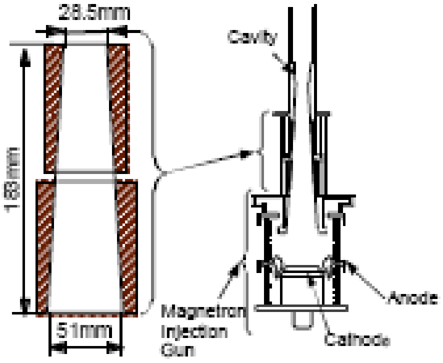


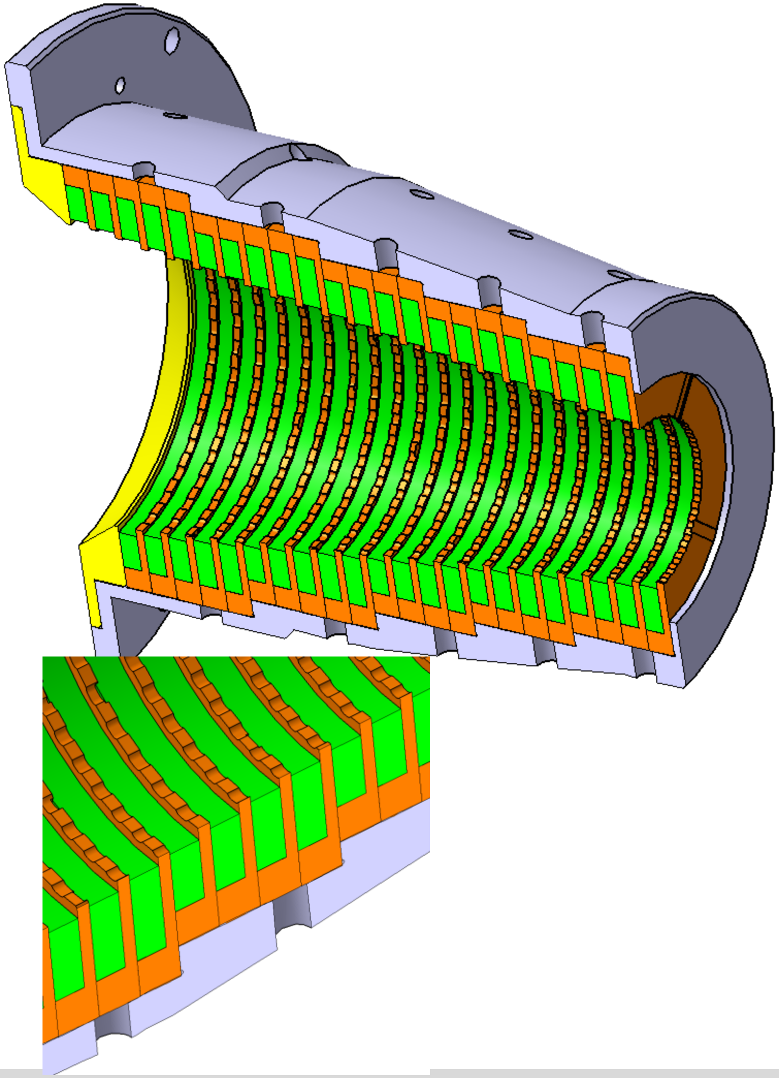
Fig.4: SiC cylinder at beam tunnel for suppression of parasitic oscillation.

From: Sakamoto et al., IAEA 2002

Improved Beam Tunnel (2)

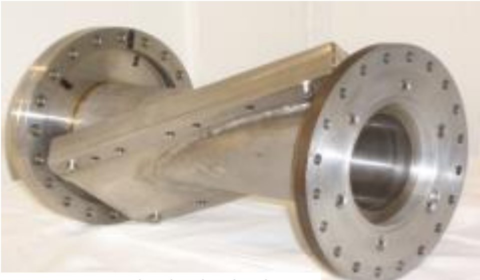
- Keep traditional technology
- Avoid cylindrical section
- Disturb azimuthal symmetry and longitudinal periodicity
- Corrugations in Cu rings, different numbers in adjacent rings
- Damping of TEmn modes (m=0), Surface currents
- Corrugated structure acts as a grating with many grating constants
- Q-value of a resonant structure is strongly decreased

⇒ Increased starting current of mode excitation

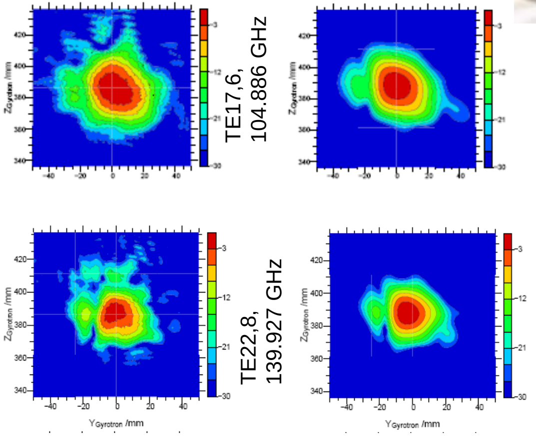


Experiments with Step-Frequency Tunable Gyrotron (1)

- Frequency range: 105 – 143 GHz
- Design mode: TE22,8 (140 GHz)
- 1 MW, short pulse (~ ms)
- Broadband optimisation of components



Mode	Frequency [GHz]	Gaussian Content (Measure-ment)	Gaussian Content (Simulation)
TE$_{18,6}$	108.398	0.896	0.929
TE$_{20,7}$	124.185	0.894	0.934
TE$_{21,7}$	127.680	0.877	0.917
TE$_{21,8}$	136.305	0.894	0.930
TE$_{22,8}$	139.927	0.875	0.933
TE$_{23,8}$	143.342	0.852	0.915

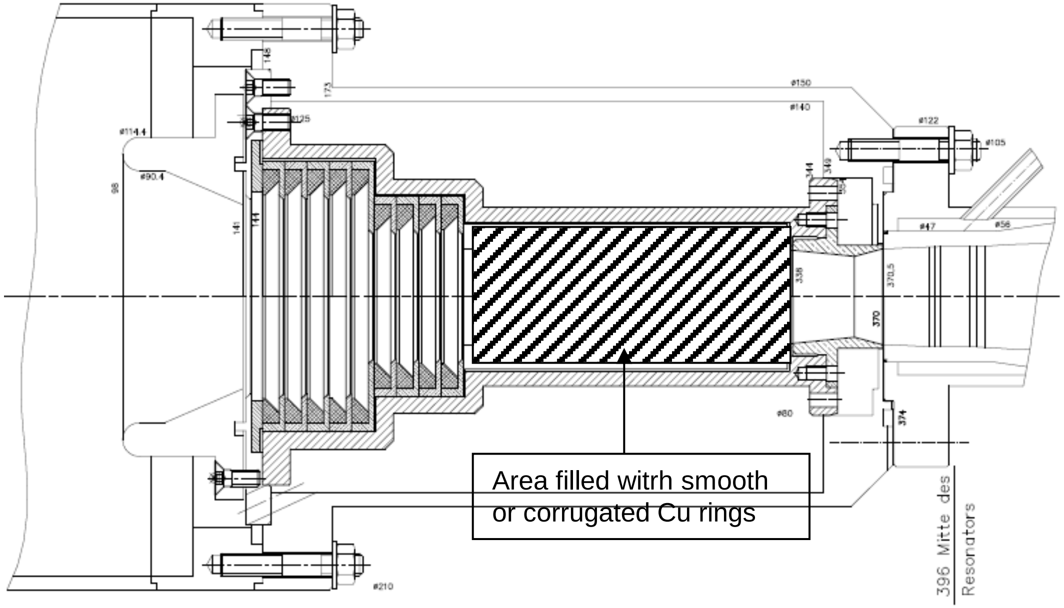


Near term goal:

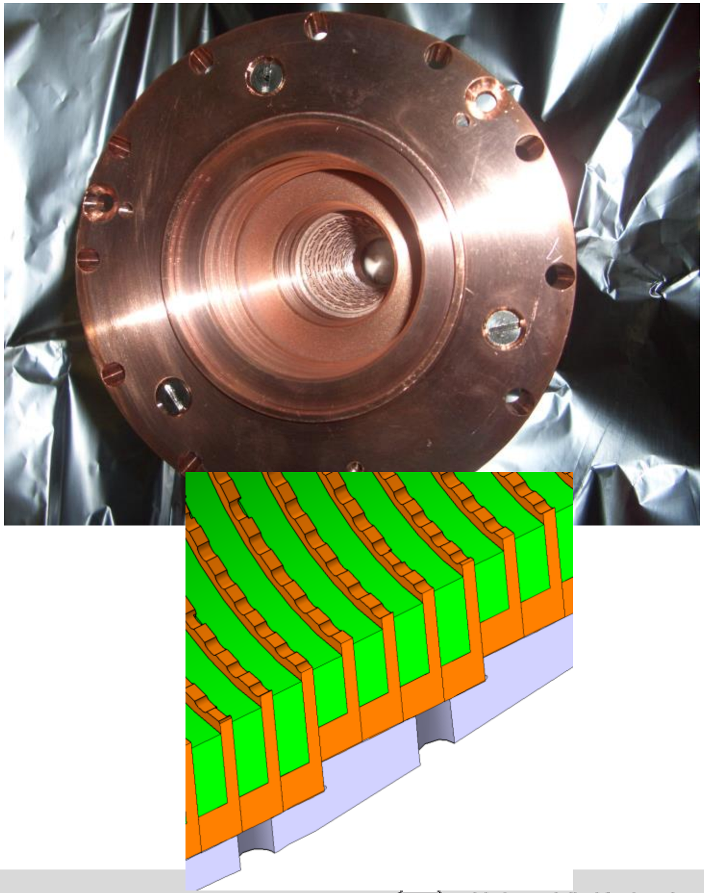
Fast frequency tuning (~ 3 GHz in 0.5 s) and CVD Diamond Brewster angle window

Experiments with Step-Frequency Tunable Gyrotron (2)

- Dedicated experiments to verify the advantage of a corrugated beam tunnel
- Beam tunnel as similar as possible to W7-X gyrotron: comparison of corrugated/non-corrugated design

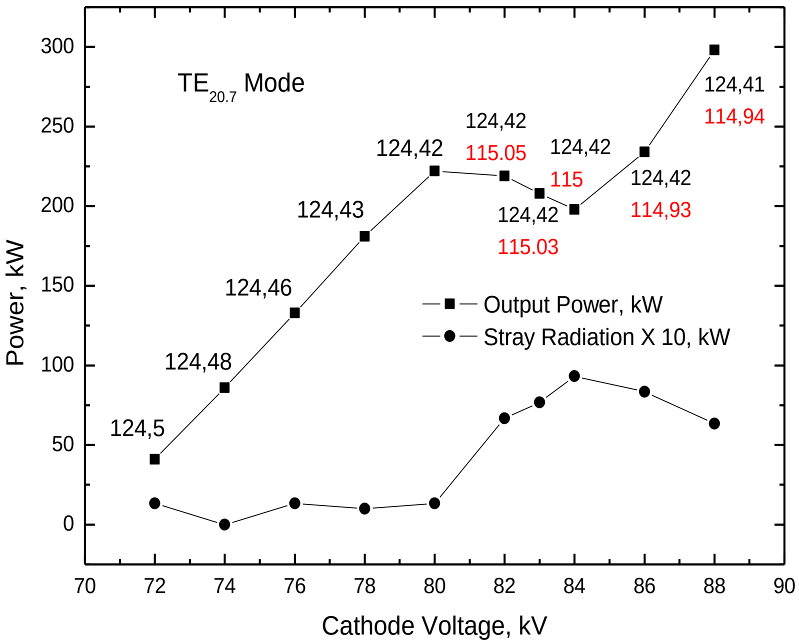


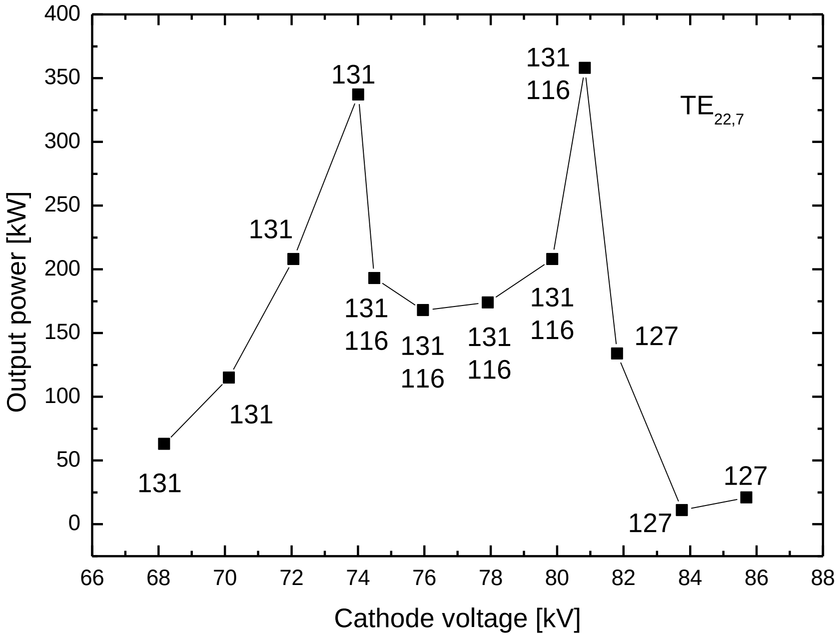
Area filled witrh smooth or corrugated Cu rings



Experiments with Step-Frequency Tunable Gyrotron (3)

Operation of gyrotron with non-corrugated W7-X beam tunnel
Behaviour of output power in the presence of parasitic oscillations



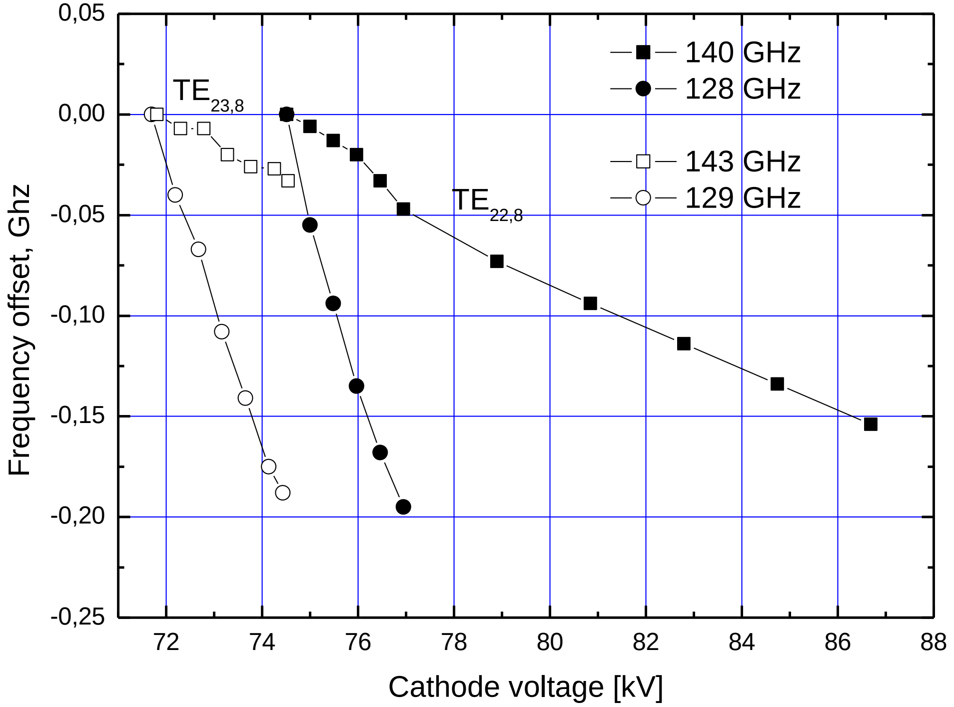


⇒ **Collapse of output power**
⇒ **Strong increase of stray radiation**

Experiments with Step-Frequency Tunable Gyrotron (4)

Operation of gyrotron with non-corrugated W7-X beam tunnel

Frequency variation of cavity mode and parasitics



⇒ Slow variation of cavity mode

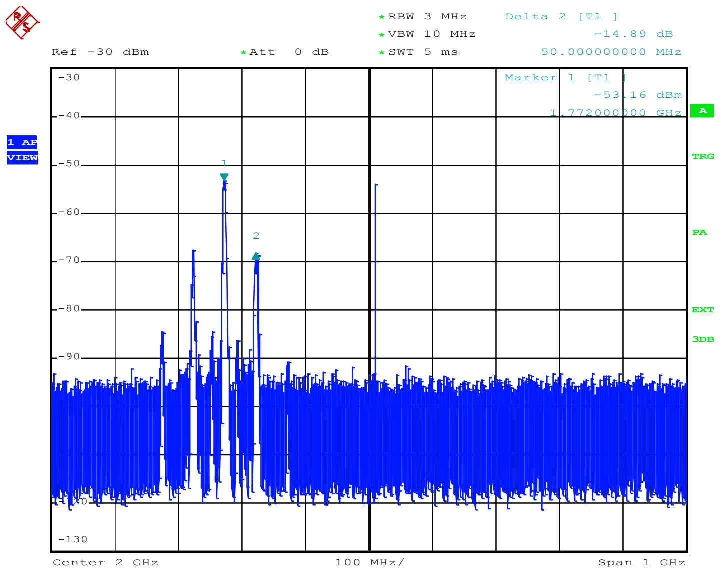
⇒Strong variation of parasitics

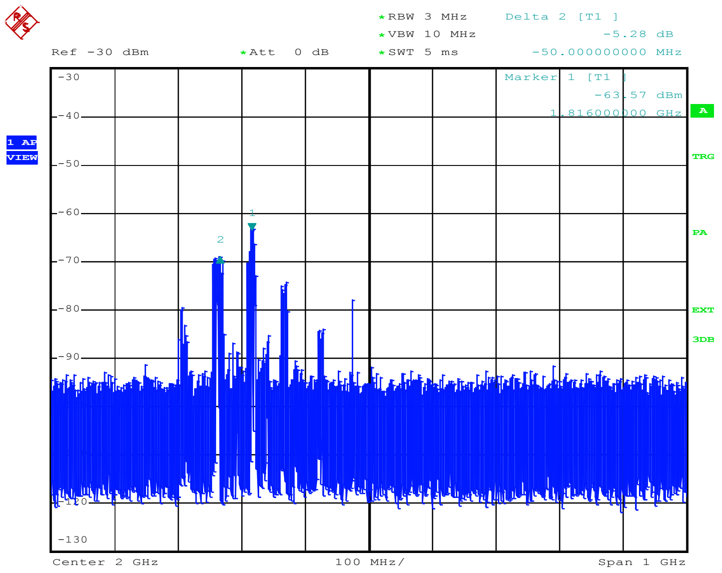
⇒ Indicates gyro-backward mechanism

Experiments with Step-Frequency Tunable Gyrotron (5)

Operation of gyrotron with non-corrugated W7-X beam tunnel

Frequency spectrum



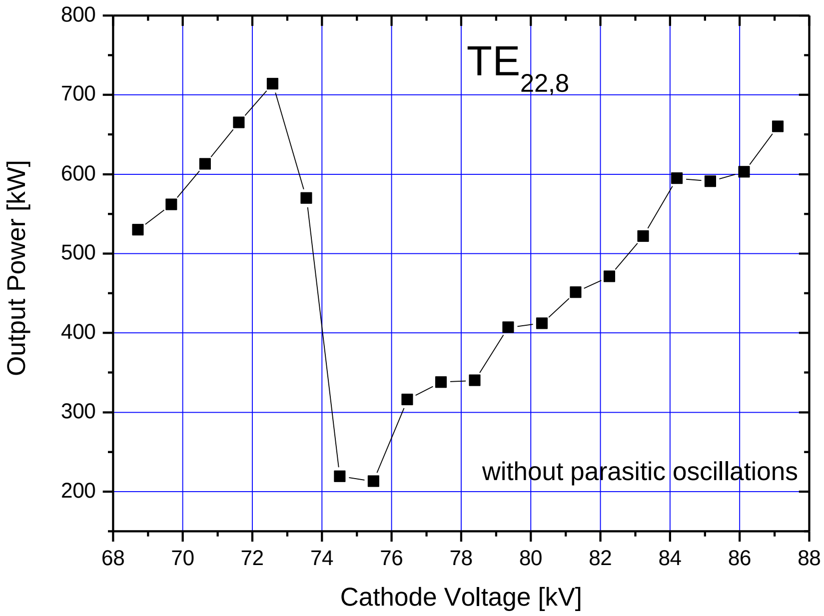


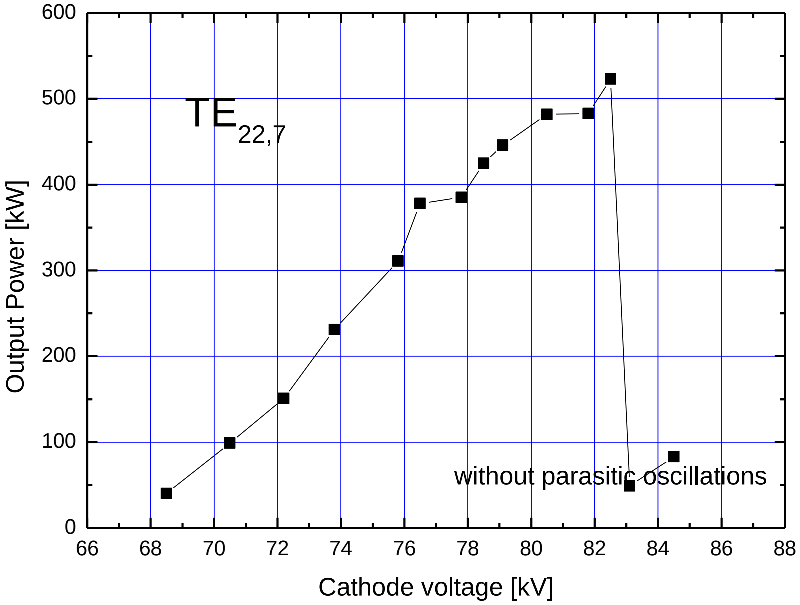
Spectrum of a main mode ($TE_{22,8}$, 140.21 GHz), modulated by a 50 MHz LF oscillation

Parasitic oscillation (135.60 GHz), modulated by a 50 MHz LF oscillation, high phase noise

Experiments with Step-Frequency Tunable Gyrotron (5)

Operation of gyrotron with improved (corrugated) W7-X beam tunnel





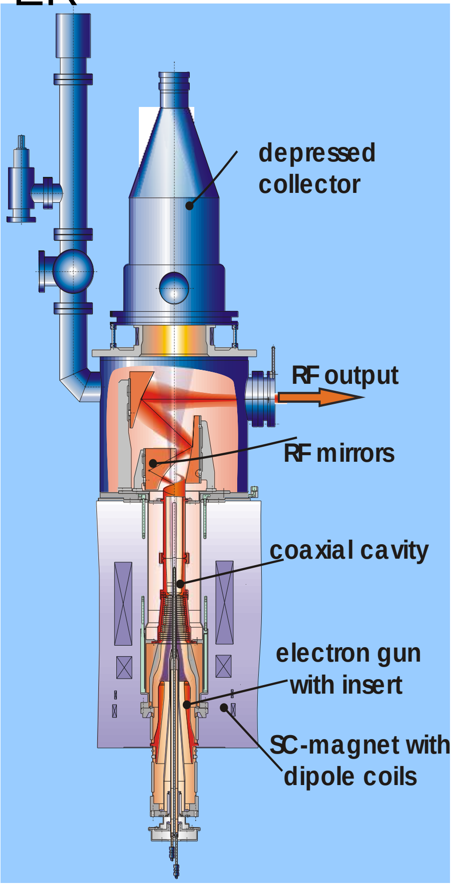
⇒ No collapse of output power

⇒ No parasitic frequency detectable

Coaxial Cavity Gyrotron (1)

Short pulse pre-prototype 170 GHz coaxial cavity gyrotron for ITER
Cooperation of:

CRPP *(Switzerland)*
*Fusion for Energy (**F4E**, Spain)*
***NTUA**, (Greece)*
*Thales Electron Devices (**TED**), France*
***CNR**, (Italy)*
***TEKES**, (Finland)*
***FZK**, (Germany)*
***Universität Karlsruhe**, (Germany)*

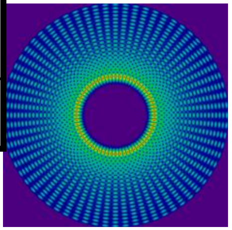


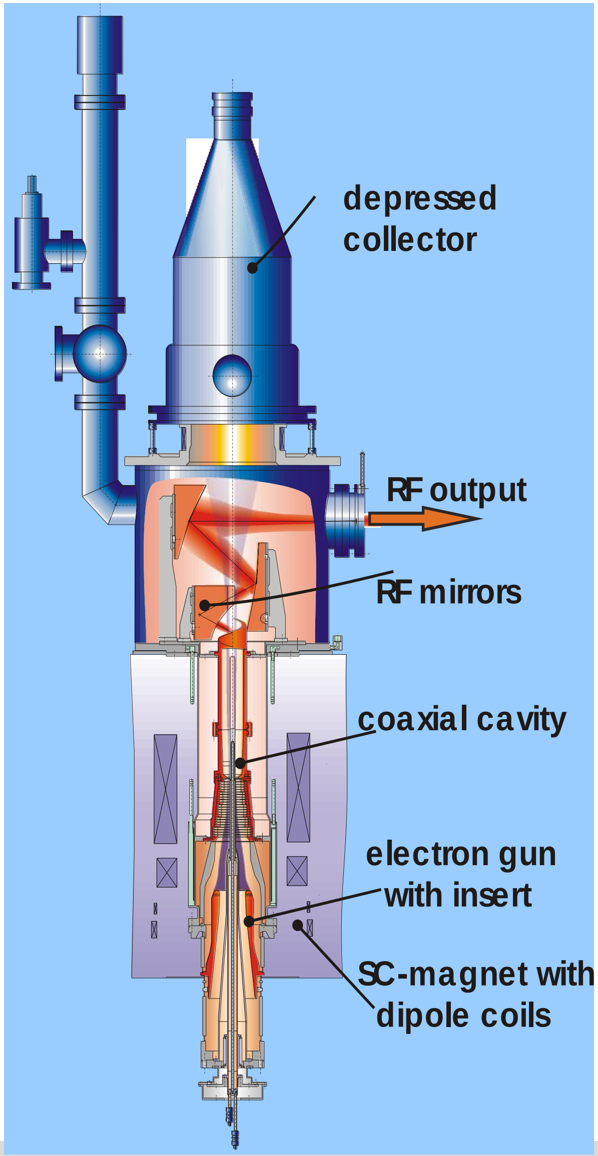
Coaxial Cavity Gyrotron (2)

Short pulse pre-prototype 170 GHz coaxial cavity gyrotron for ITER

	Prototype (CRPP)	**Pre-prototype** (FZK)
Design mode	$TE_{34,19}$	
Output frequency	170 GHz	
RF output power	2 MW	1.5 MW
Beam current	75 A	
Accelerating voltage	90 kV	80 kV
Cavity magnetic field	**6.87 T**	**6.7 T**
Output efficiency (w/o SDC)	30 %	
Output efficiency (SDC)	> 45 %	

$TE_{34,19}$

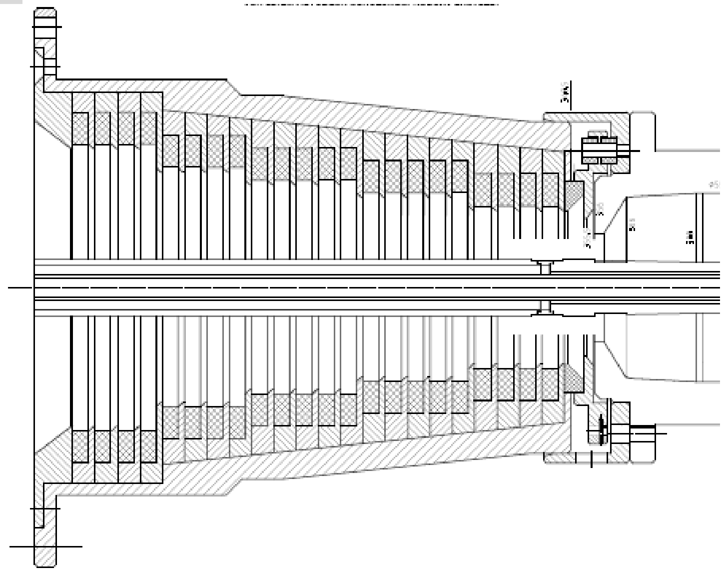


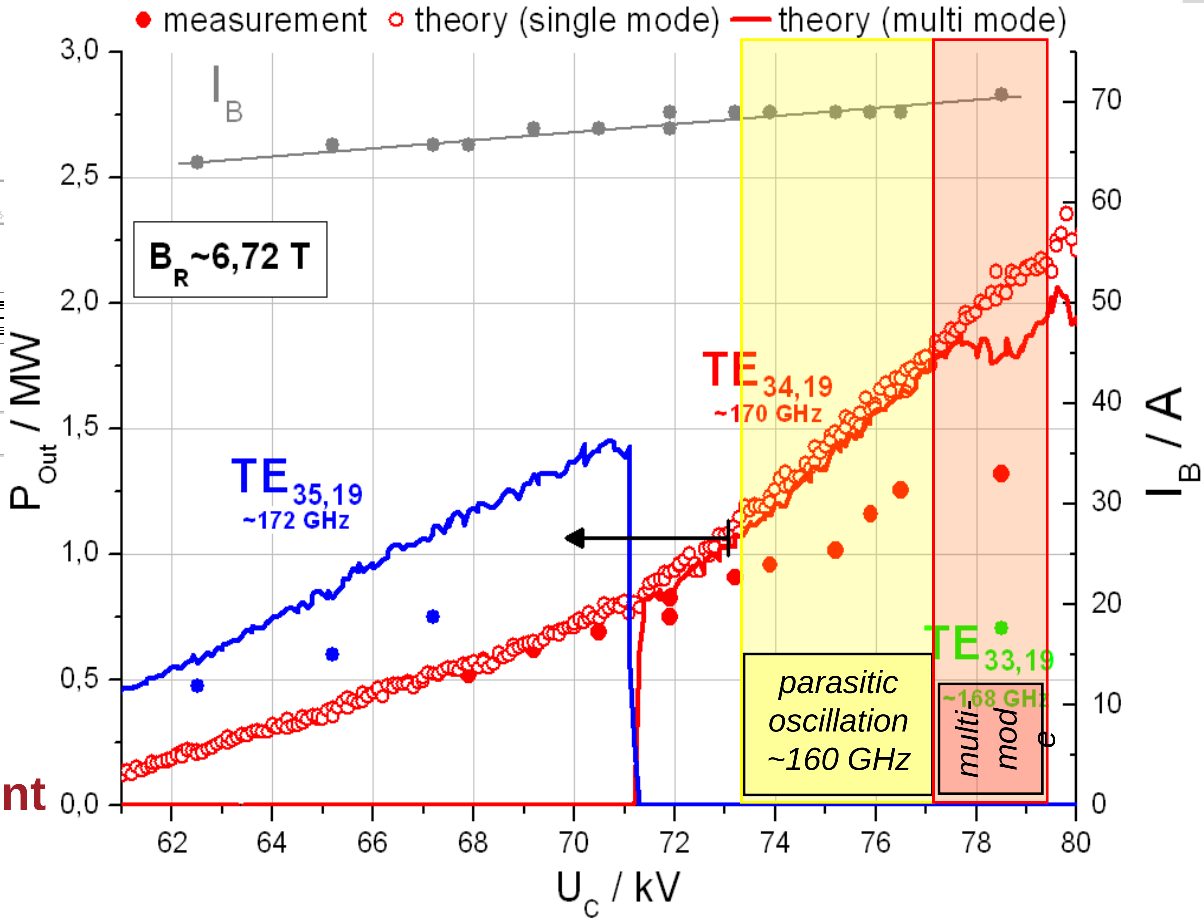


Coaxial Cavity Gyrotron (3)

Karlsruhe Institute of Technology

Operation of gyrotron with traditional beam tunnel





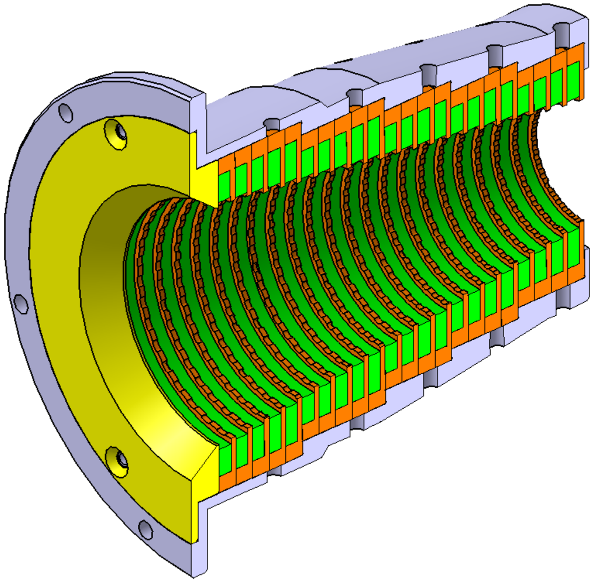
⇒ Parasitic oscillations limit the output power

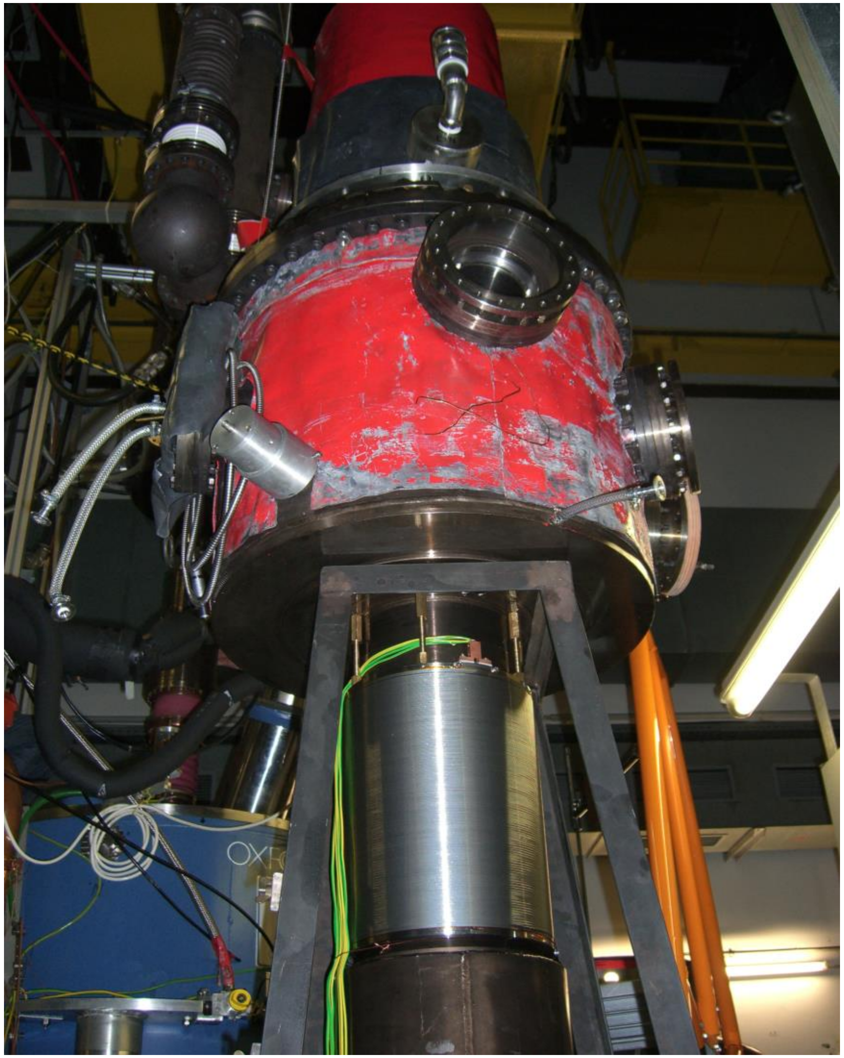
⇒ Disagreement of experiment and simulation with parasitic oscillations

Coaxial Cavity Gyrotron (4)

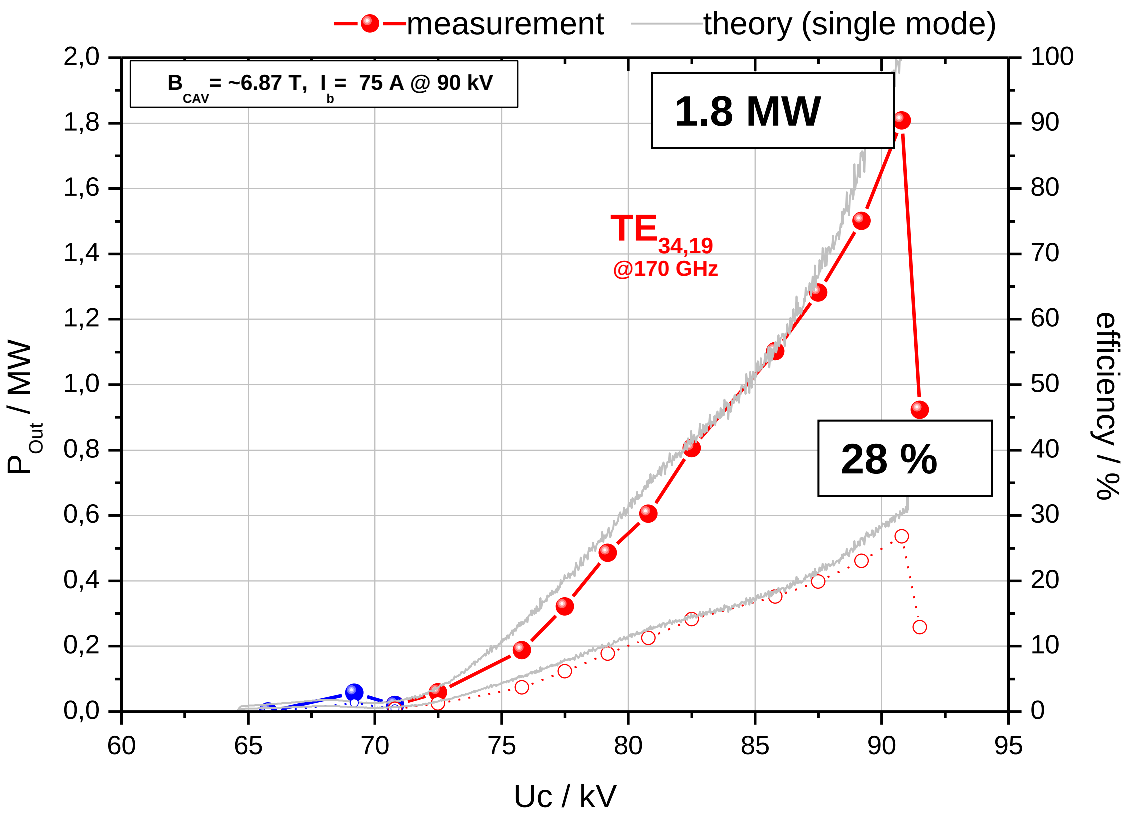
Modification of gyrotron:

- Additional normal conducting coil wounded directly onto the gyrotron body, close to the cavity
- Adjustment of anode for full field operation: 6.86 T / 90 kV / 75 A / R_b=10.0 mm / α=1.3
- **Installation of corrugated beam tunnel**





Coaxial Cavity Gyrotron (5)

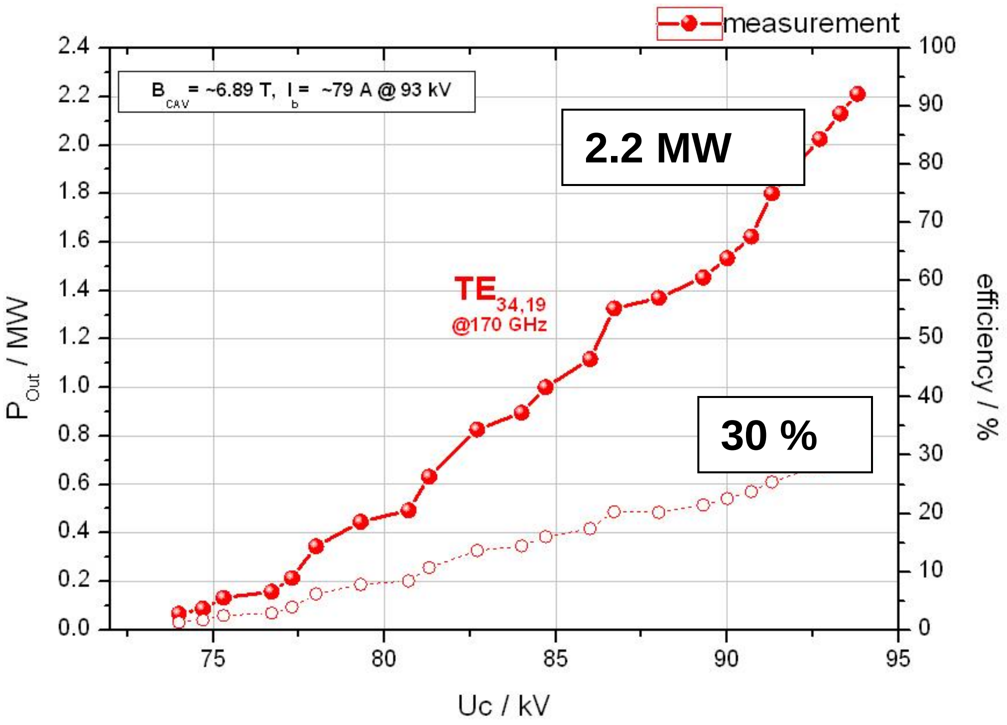


- **stabile operation up to 90 kV / 75 A**
- **maximal RF output power ~1.8 MW with 28 % (non-depressed operation)**
- **good agreement with calculations**
- **strongly reduced parasitic oscillations and multi-frequency operation**

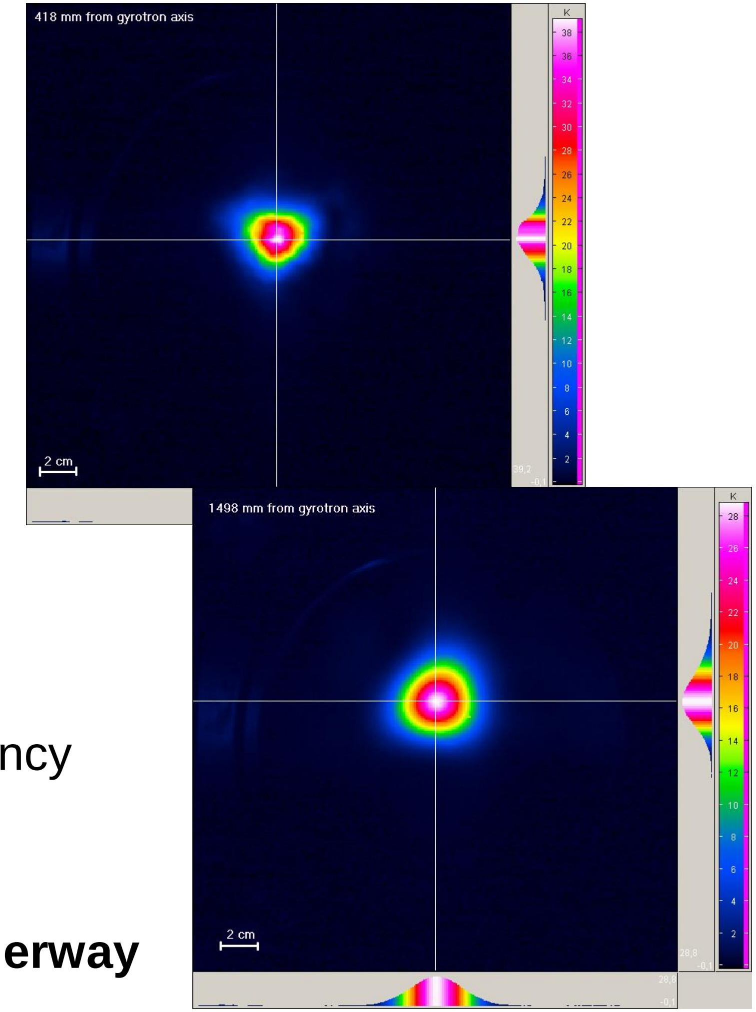
Coaxial Cavity Gyrotron (6)

-Very recent results-

RF power generation



RF beam profile measurement



Maximal RF output power **~2.2MW** at **30%** efficiency

(non-depressed operation)

minor instabilities (~155GHz) observed

⇒ **RF beam profile analysis underway**

Conclusions

- Parasitic oscillations are a serious limitation of performance of high-power gyrotrons
- Parasitic oscillations in beam tunnel area may result in
  - Unstabe operation conditions
  - Reduction of efficiency
  - Thermal overload of components
- Frequency spectrum of cavity mode and parasitic oscillations has been investigated ⇒ BWO interaction
- Stable operation of two gyrotron types has been demonstrated successfully with a corrugated beam tunnel
- Experiments with a full ceramics beam tunnel are in preparation