Vacuum Electronics 2018
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Ongoing Developments for the KIT 2-MW 170-GHz Coaxial-Cavity Gyrotron Prototype

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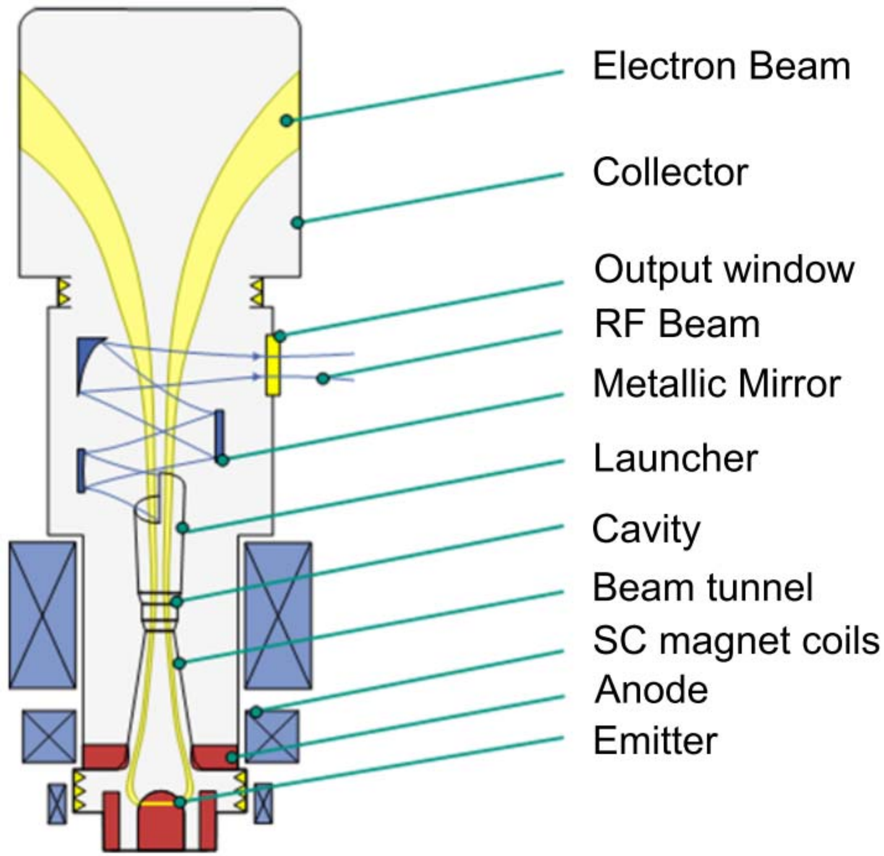
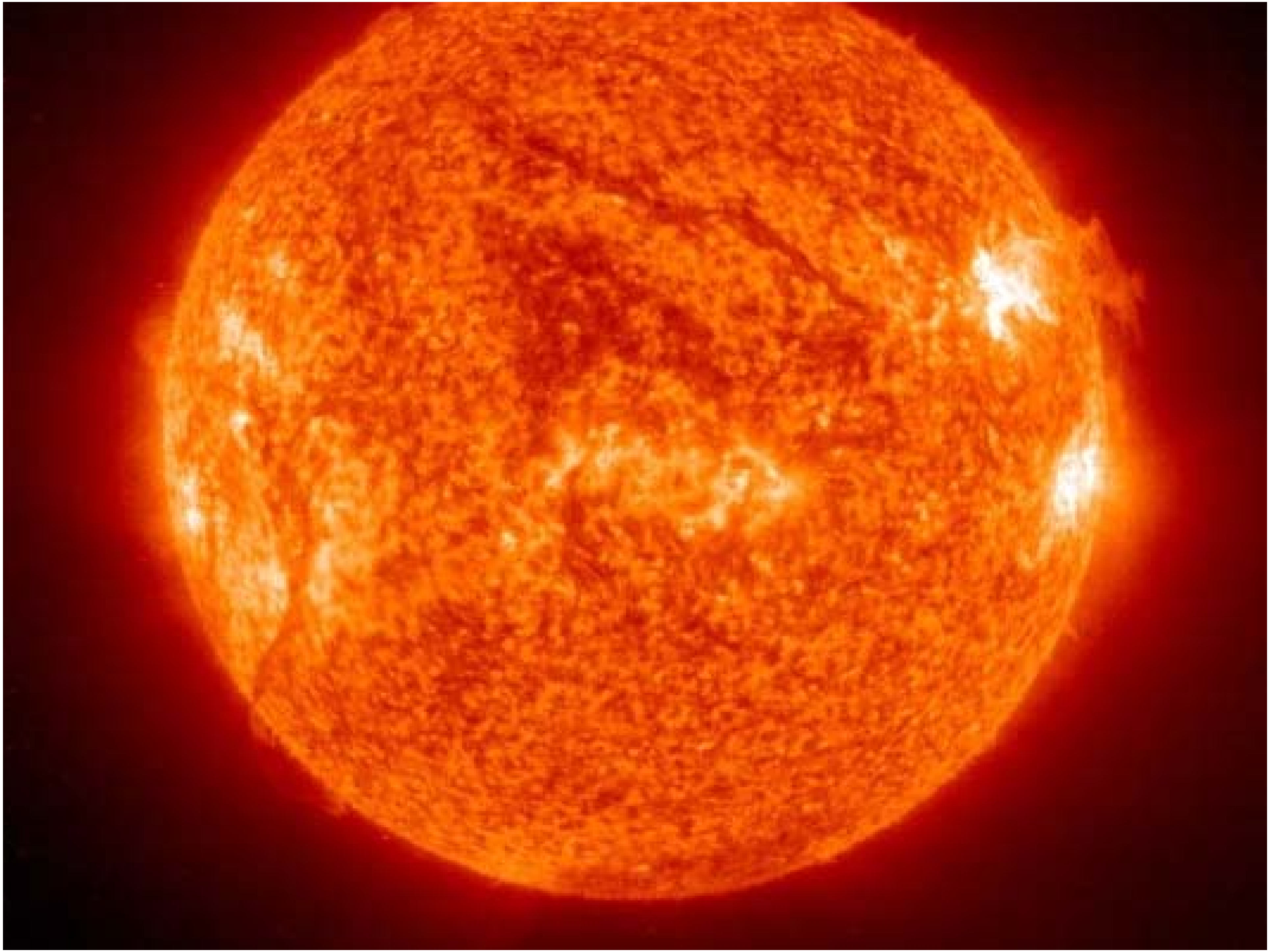
Gyrotrons for Plasma Heating

- **Functional Principle**:
  - Emitter create an hollow electron beam with $W = eU_{acc}$
  - Electrons transit a high magnetic field
    ➔ gyrating movement
    ➔ **Resonance:** $f_C \approx 28 \frac{B/\mathrm{T}}{\gamma} \mathrm{GHz}$
  - TE_{mn}-mode couples with the electron-beam
    ➔ **energy exchange**
  - Quasi-optical system converts waveguide mode in a Gaussian beam



RF power	Pulse length	Efficiency	Frequency
1 – 2 MW	0.001 – 1800 s	50 %	100 – 170 GHz

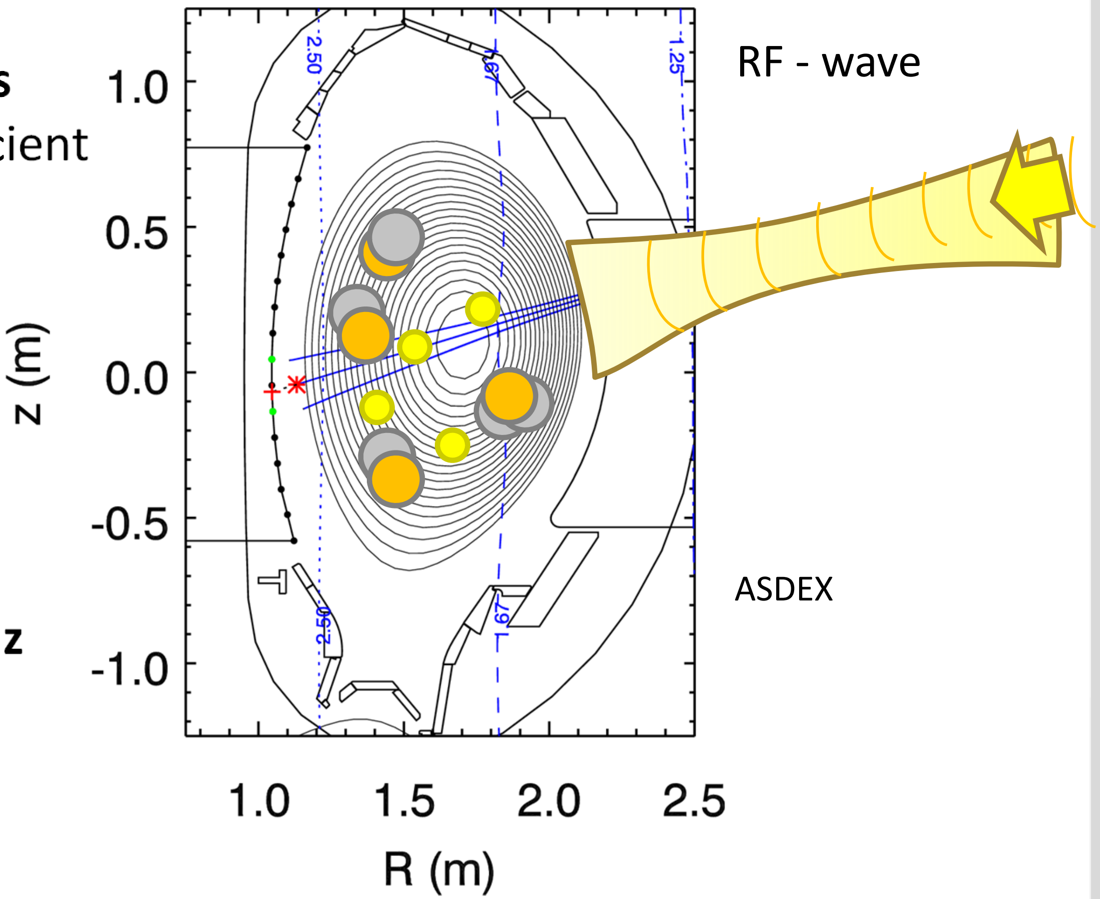


RF Heating Principle

- Question: How do we reach the temperature?

- Plasma **electrically conducts**
  → ohmic heating is not efficient

- Plasma has **resonances**
  → RF wave will be
  absorbed at suitable
  frequency



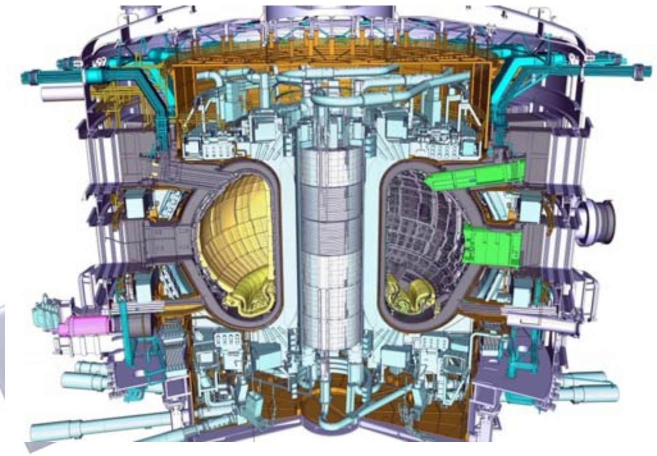
- Resonance at W7-X: **140 GHz**
  Necessary power: **10 MW**

Requirements of ECRH in Power Plants

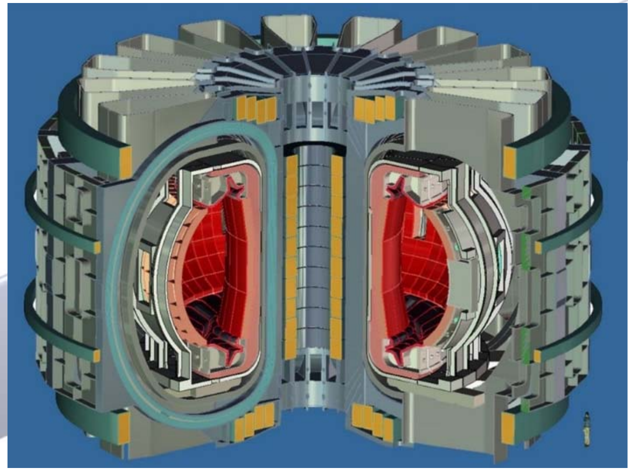
ITER

- Operating Frequency 170 GHz
- 24 MW RF Power for ECRH

→ 24 x 1 MW Gyrotron



EU DEMO

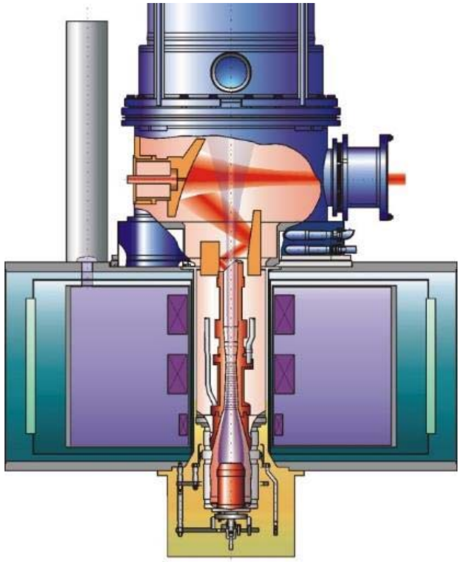


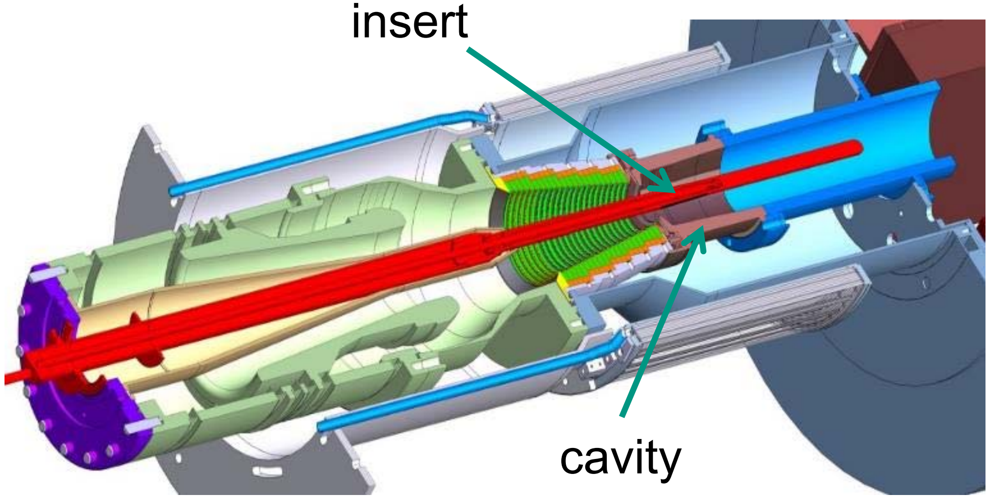
- Operating Frequency >200 GHz
- ~50 MW RF Power for ECRH

→ 50 x 1 MW Gyrotron

Alternative: 25 x 2 MW Gyrotron

Conventional-Cavity vs. Coaxial-Cavity Design





Conventional Cavity

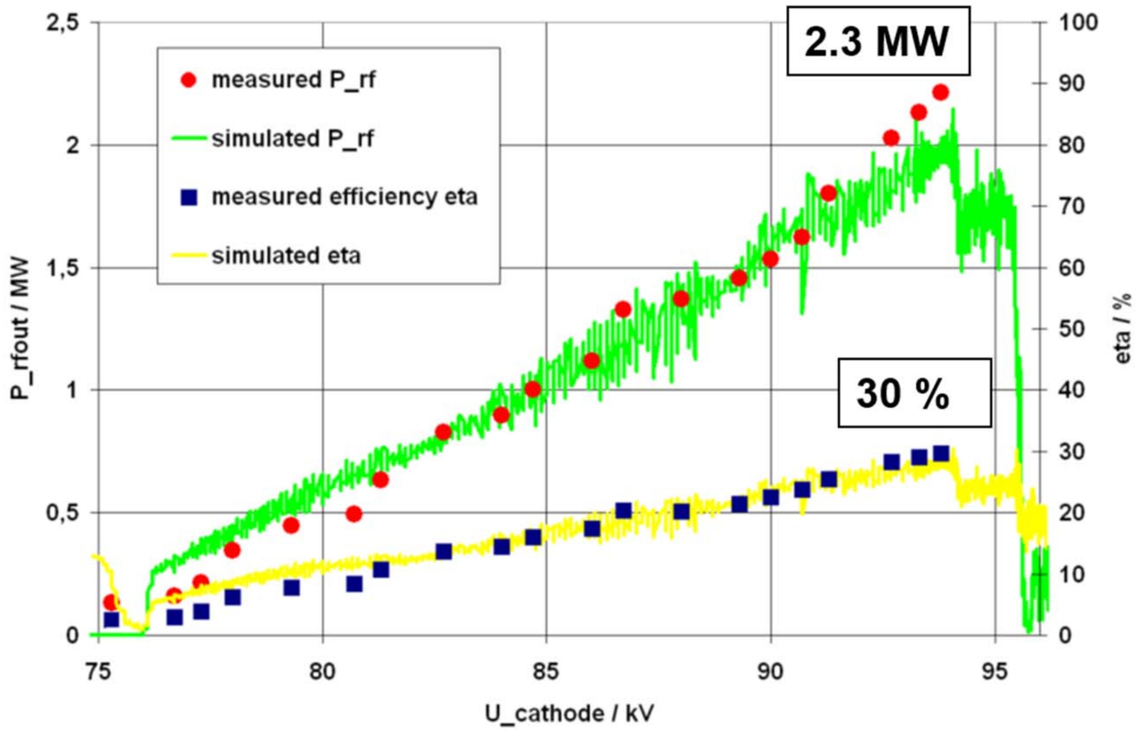
+ Simple and robust design
– Dense TE_{mn} mode spectrum
  → stable operation limited to a specific maximum angular and radial mode number

Coaxial Cavity

+ Reduced mode competition
  → operation at very high-order mode
  → **higher output power**
+ Reduced voltage depression
– Inner conductor:
  Risk of misalignment + thermal loading

Experimental Results of the 2 MW Gyrotron

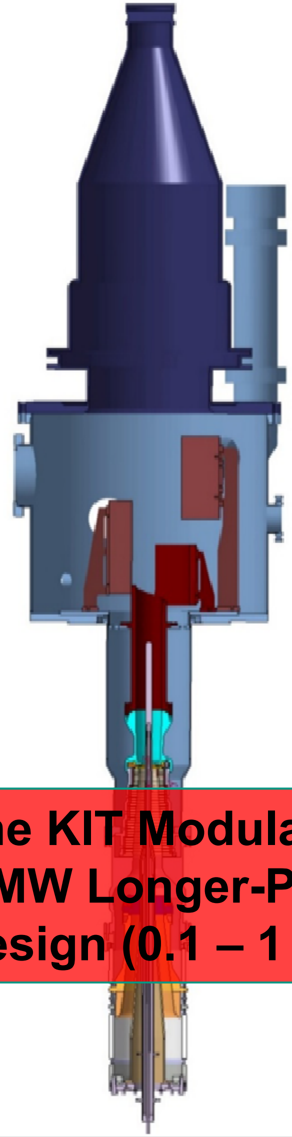
Short-Pulse Operation



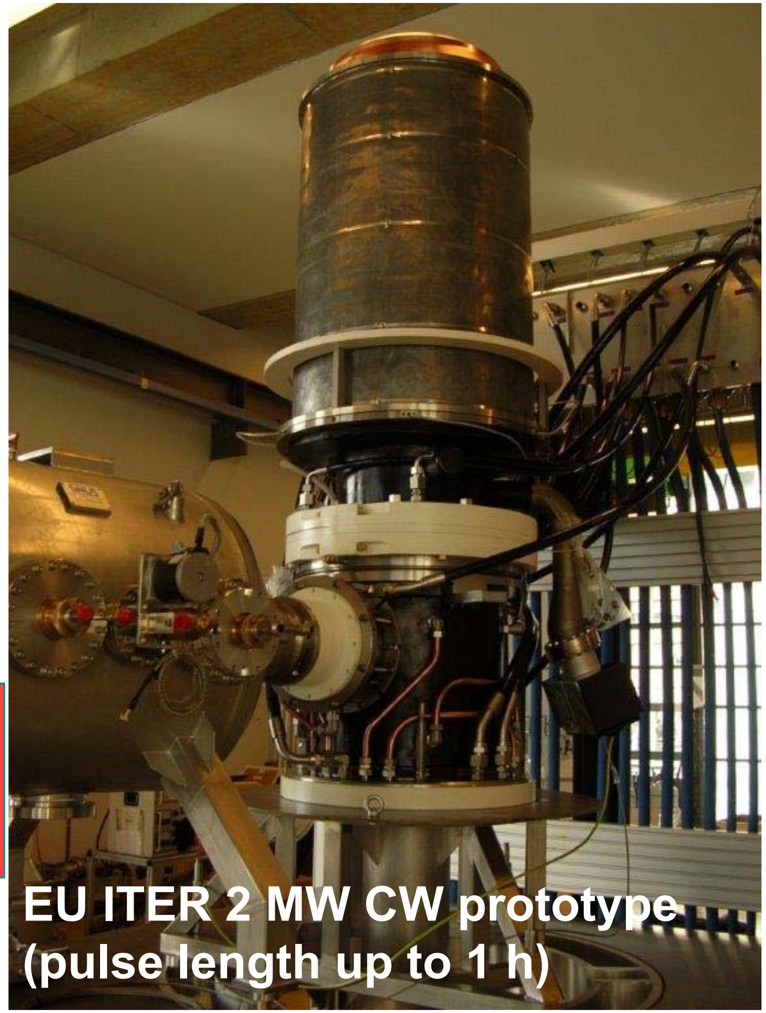
- **2.0 MW, 91 kV, 77 A, efficiency ~28.5% (non-depressed) ~1.5ms**
  (pulse length limited by non-cooled components)
- **2.3 MW, 92 kV, 84.7 A, efficiency 29.5% (non-depressed), pulse length ~0.6ms**
- No parasitic oscillations has been observed
- Measured stray radiation level ~4%, Gaussian mode content of the RF beam ~95%

From Short Pulses to Steady State Operation

KIT 2 MW short-pulse prototype (ms pulses)



The KIT Modular 2 MW Longer-Pulse Design (0.1 – 1 s)



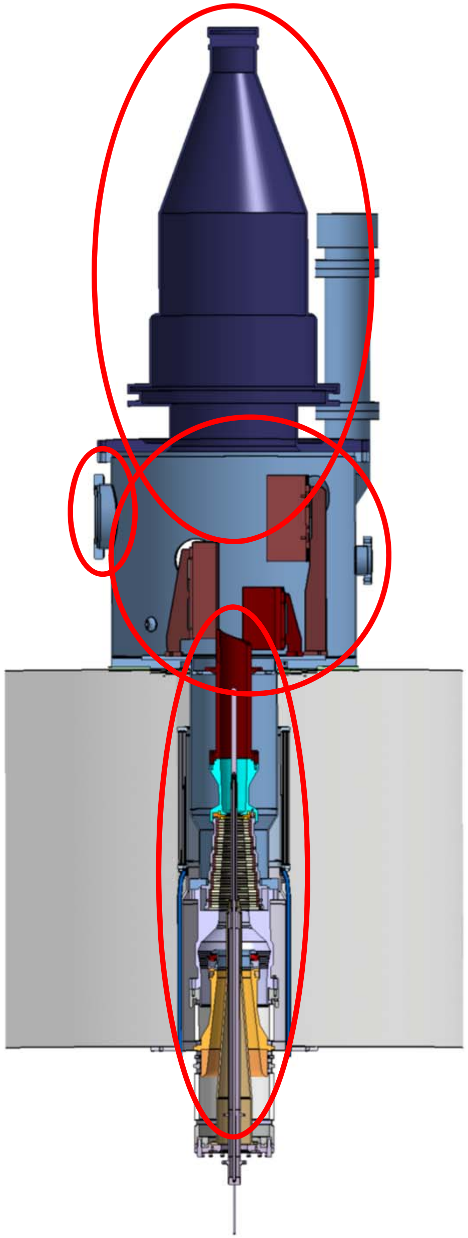
EU ITER 2 MW CW prototype (pulse length up to 1 h)

Project Setup

Use a KIT in-house solution

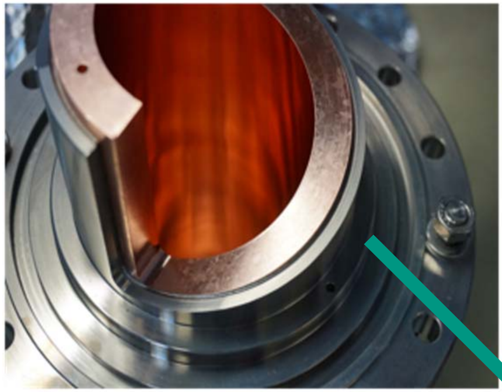
- Keep the modular approach
- Reuse as much existing parts as possible

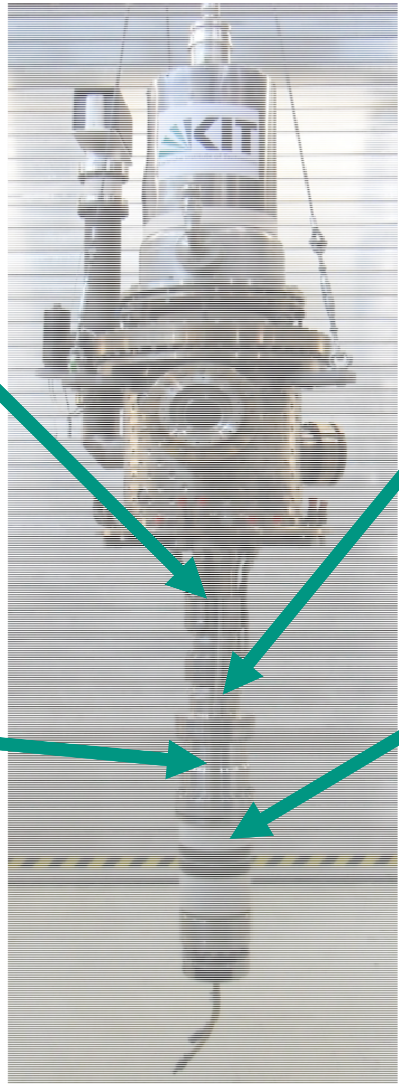
- **Decide for a two-step approach:**
  - **1st step**: Pulse lengths <100 ms
    - Modular water cooling system for beam tunnel, cavity and launcher.
    - Advanced Magnetron Injection Gun
  - **2nd step**: Pulse lengths <1 s
    - CW collector
    - Water cooled diamond output window
    - Water cooled mirrors



Longer-Pulse Components

Launcher



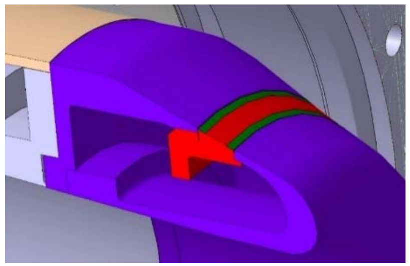


Beam Tunnel

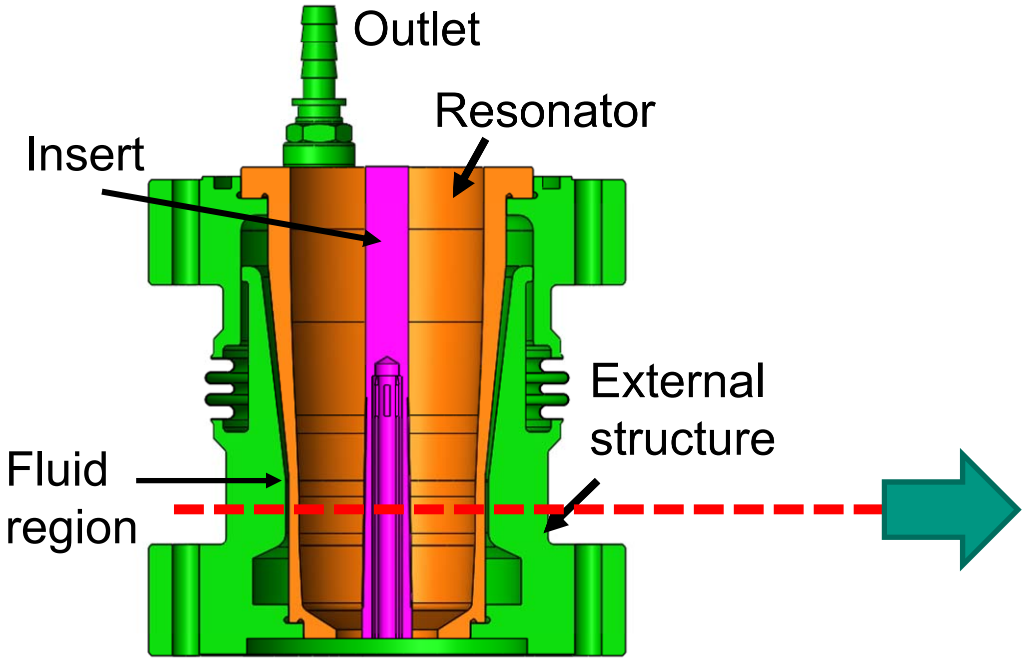
Cavity

Inverse MIG

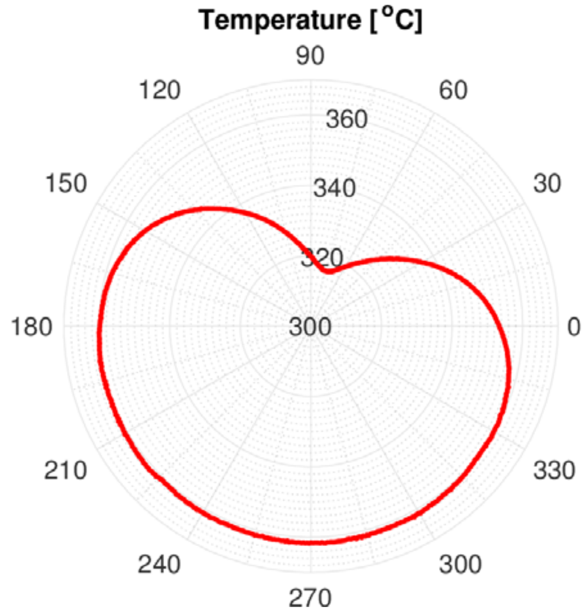
MIG with anti-emissive coated emitter edge rims



Current Short Pulse Cooling System



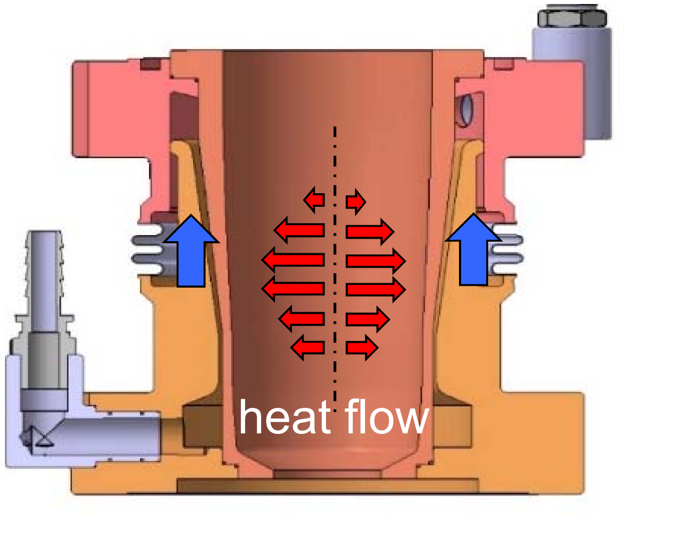
Polar temperature distribution

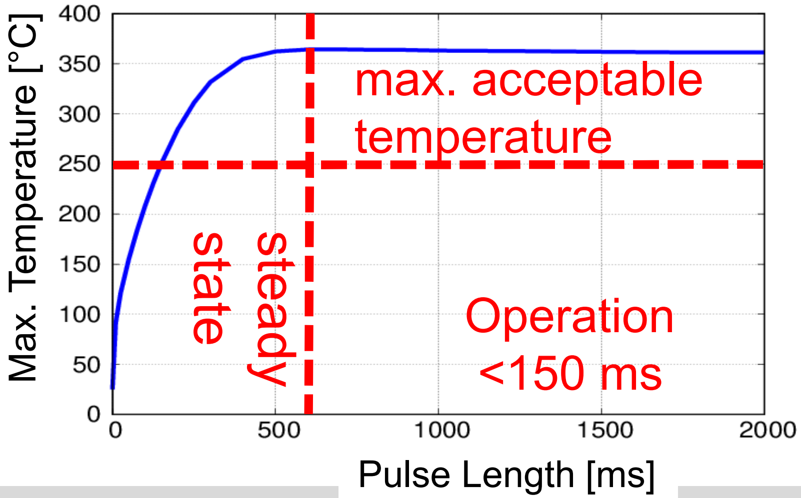


- No homogenous azimuthal temperature distribution.
- Maximum surface temperature of 360 °C at CW operation
  → optimization potential

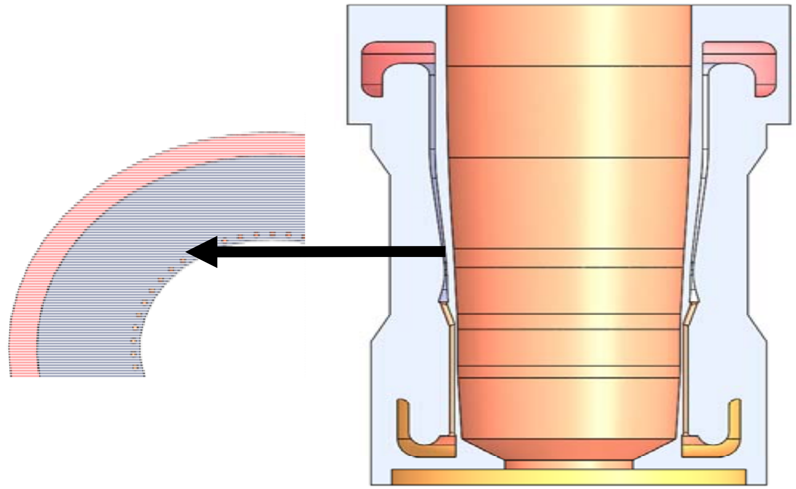
Improved Water Cooling System

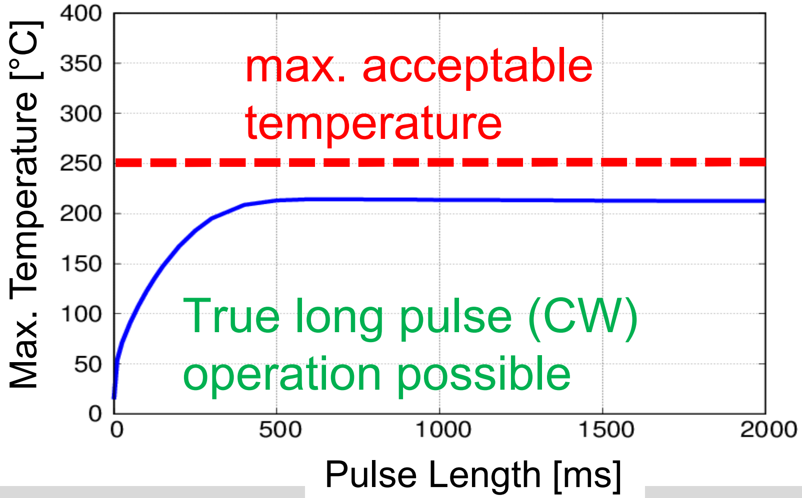
Cooling in short-pulse





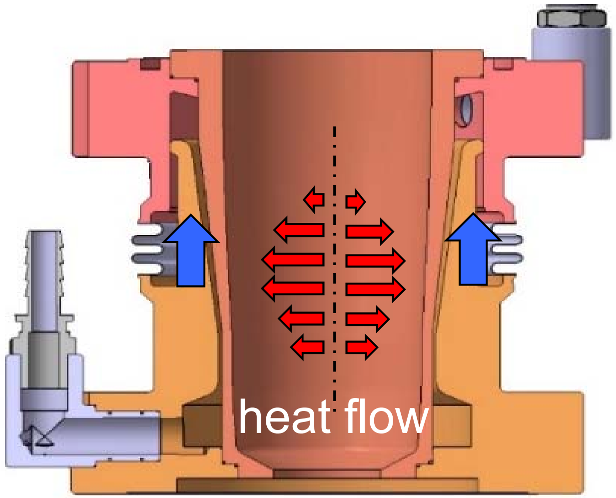
Advanced microchannel cooling

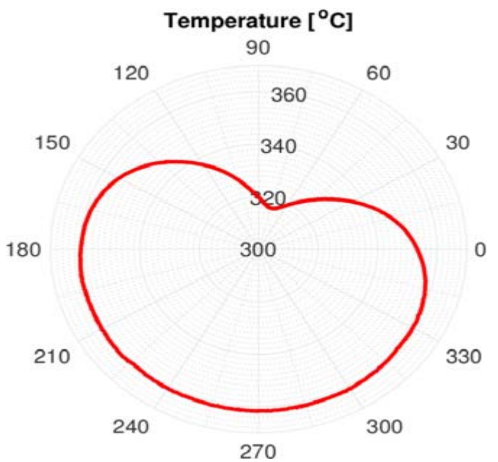




Improved Water Cooling System

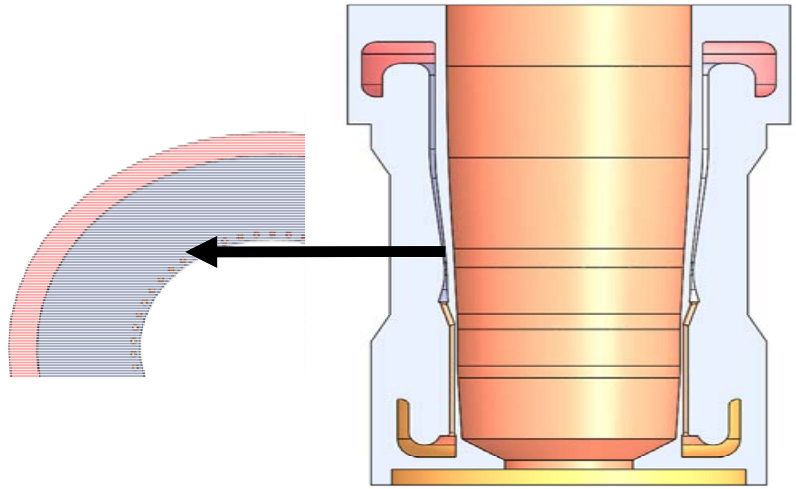
Cooling in short-pulse

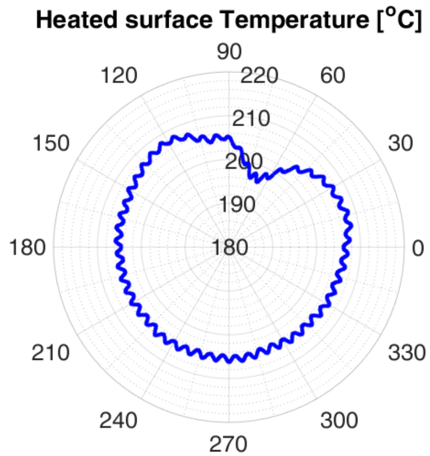




Temperature Inhomogenity **ΔT = 44 °C**

Advanced microchannel cooling

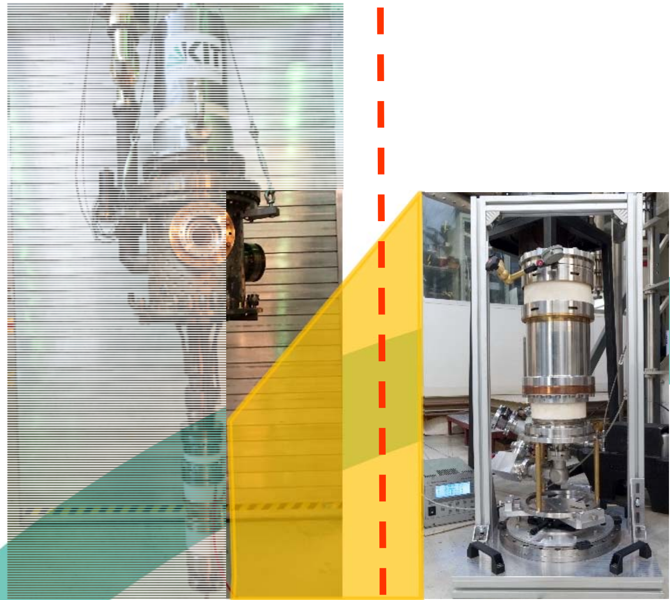


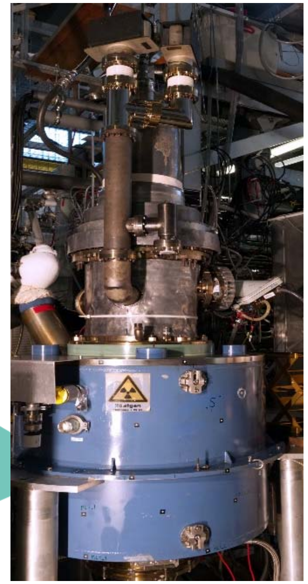


Temperature Inhomogenity **ΔT = 10 °C**

Road Map 2018 of the Coaxial-Cavity Long-Pulse Gyrotron

today





1 s Operation

- Long pulse operation (1 s)
- Implementation of optimized cooling concepts

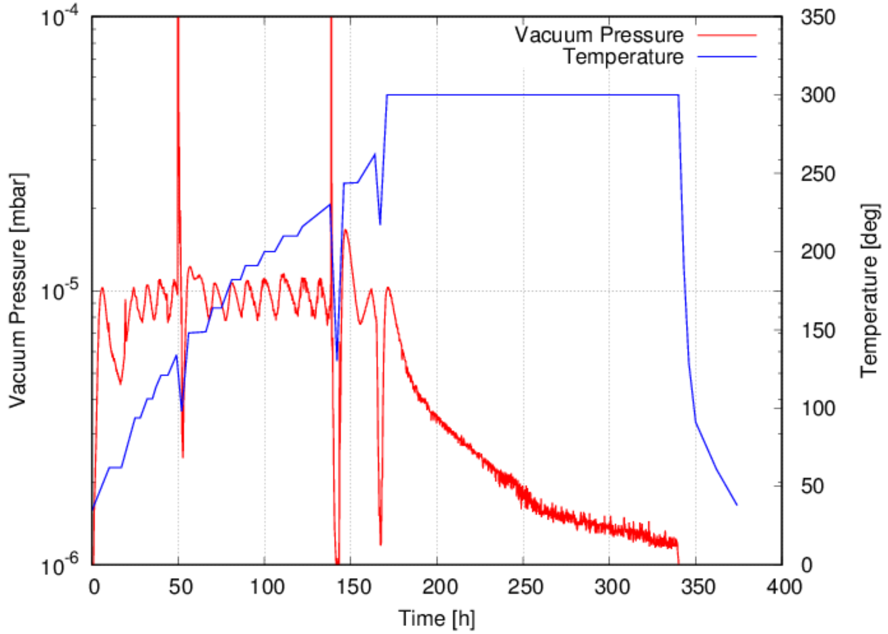
Upgrade with advanced MIGs

- Long pulse operation (100 ms)
- Use of MIG with coated emitter and in-house manufactured IMIG

Verification

- Short pulse operation
- Using old coaxial short pulse MIG

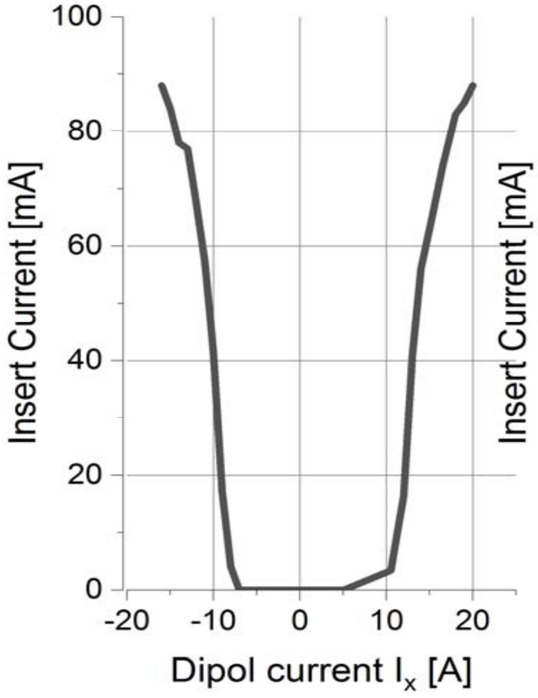
Bake-Out Procedure

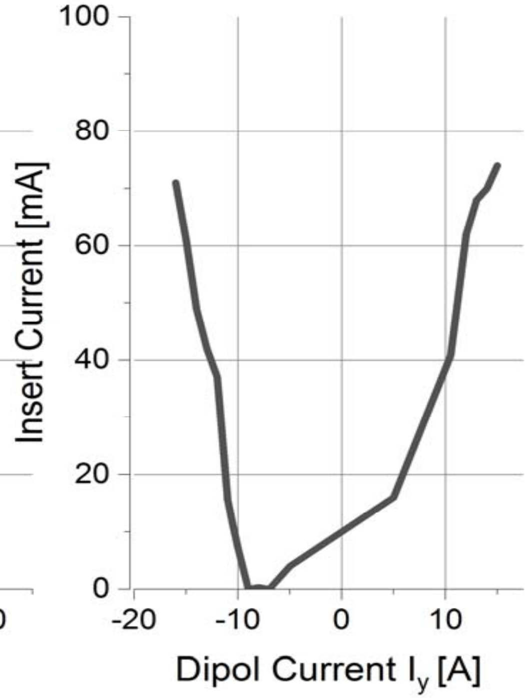


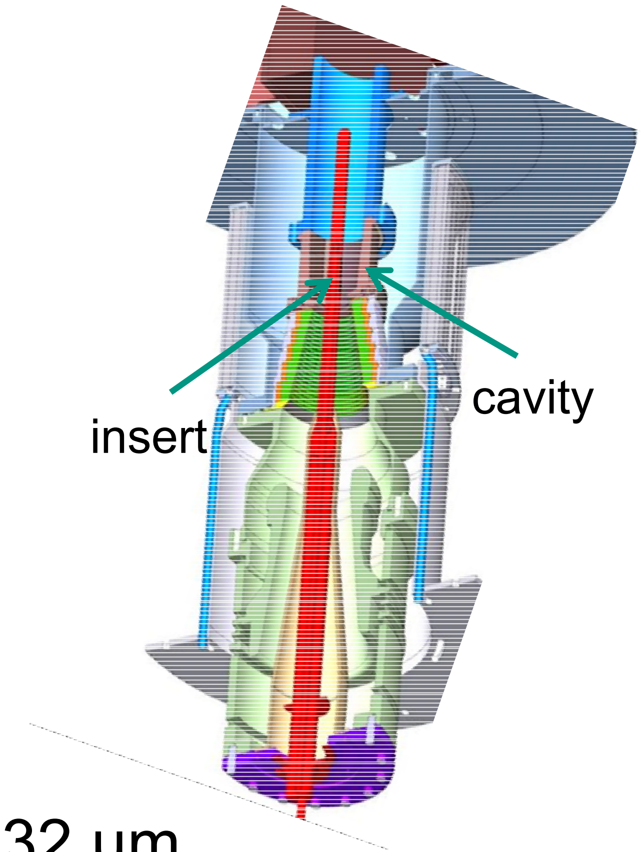
- Outgassing of oxygen, oil, water and other impurities
- Maximum operating temperature 250 °C
  → Bake-out at 300 °C
- Significantly better vacuum conditions

  Start: 10^{-7} mbar   End: 10^{-9} mbar

Alignment Procedure of the Coaxial Insert

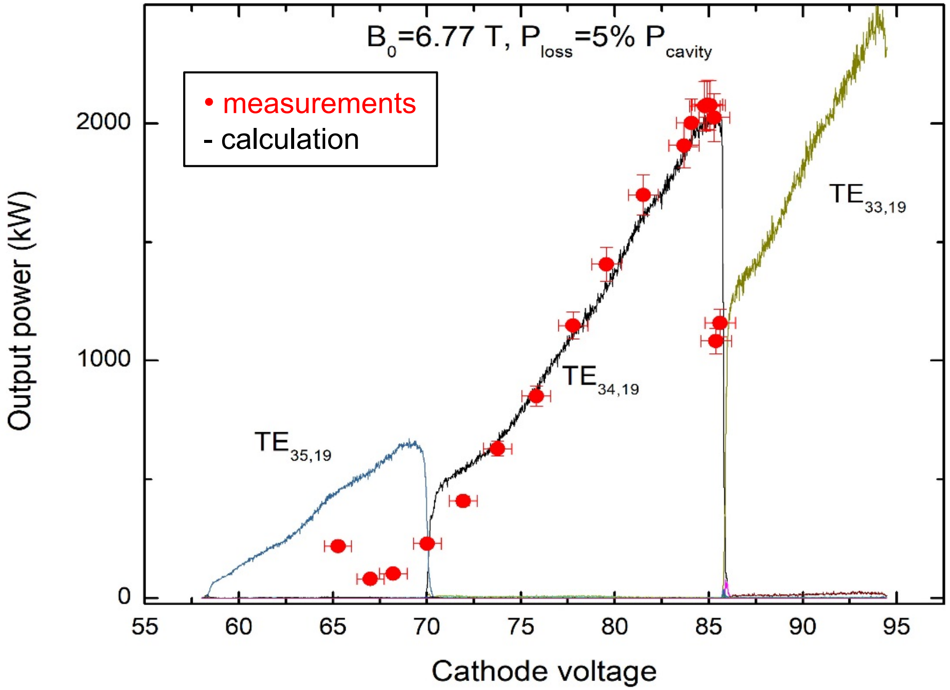






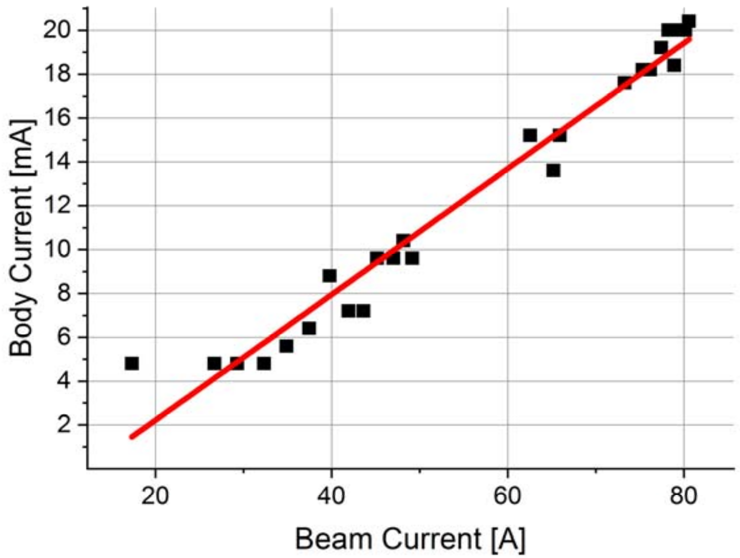
- Insert misalignment $\Delta x = 36\ \mu m$, $\Delta y = 32\ \mu m$
- Inhomogenous electron beam

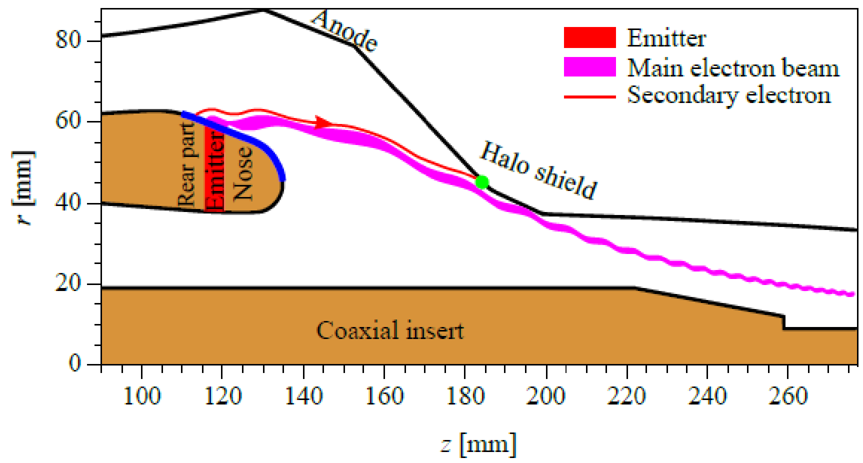
Verification of the Coaxial-Cavity Long-Pulse Gyrotron



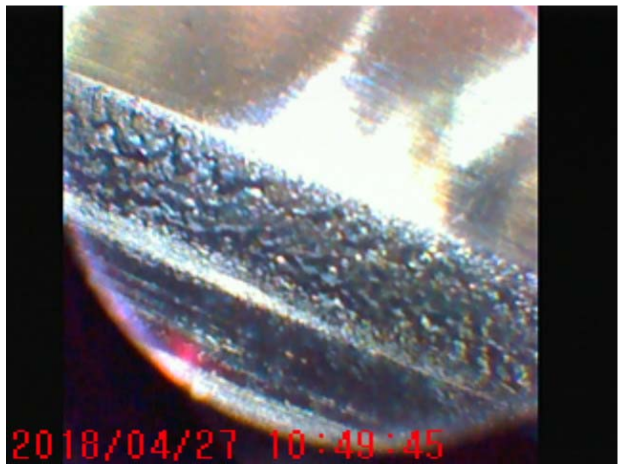
- **2.2 MW, 84 kV, 80 A, efficiency ~33 % (non-depressed) ~1.5 ms** (power limited by the HV power supply)
- Pulse length limited by body current → New MIG is already delivered

Limiations of the Old MIG





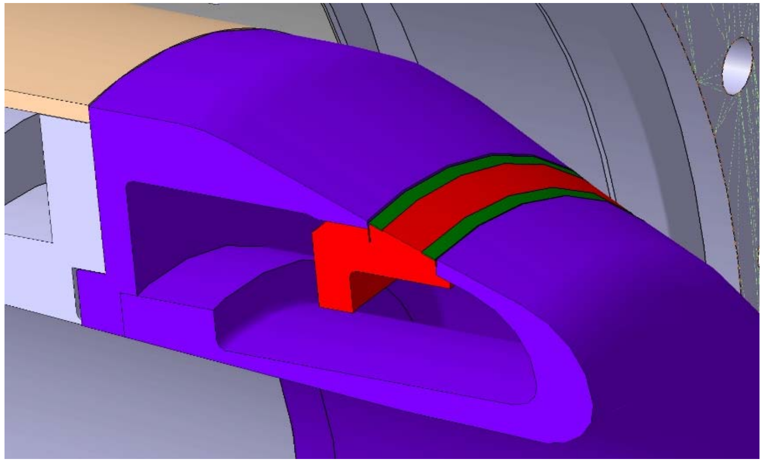
- Significant body current
- Damages at the halo shield
- Finally instable gyrotron behaviour
- Difficulties to increase the pulse length

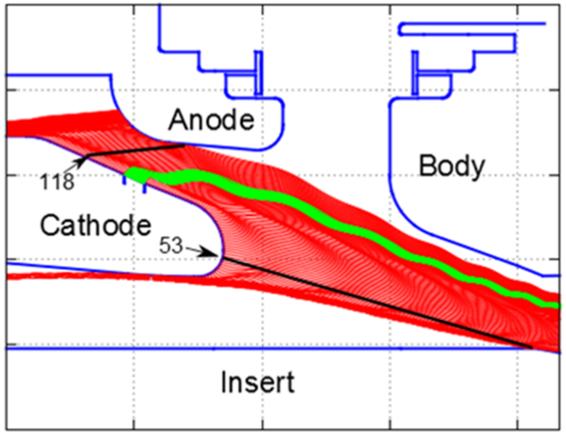


Damaged Halo shield

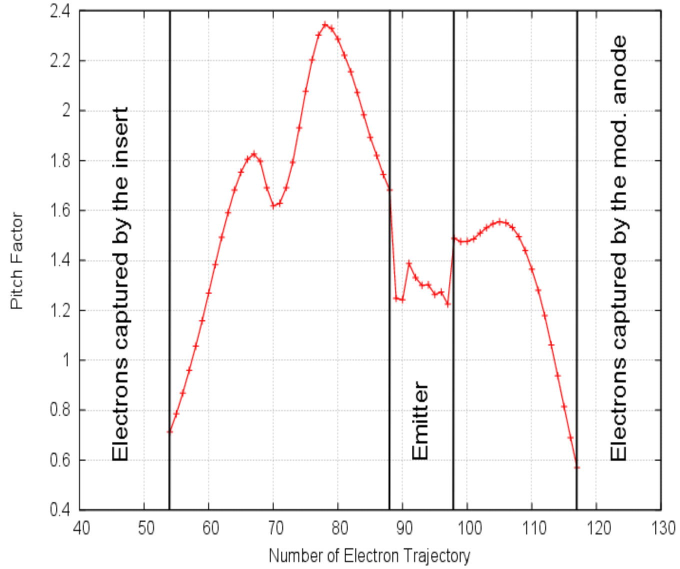
→ IMIG and advanced CMIG will solve this issue

Suppression of the Electron Beam Halo: Advanced MIG Designs





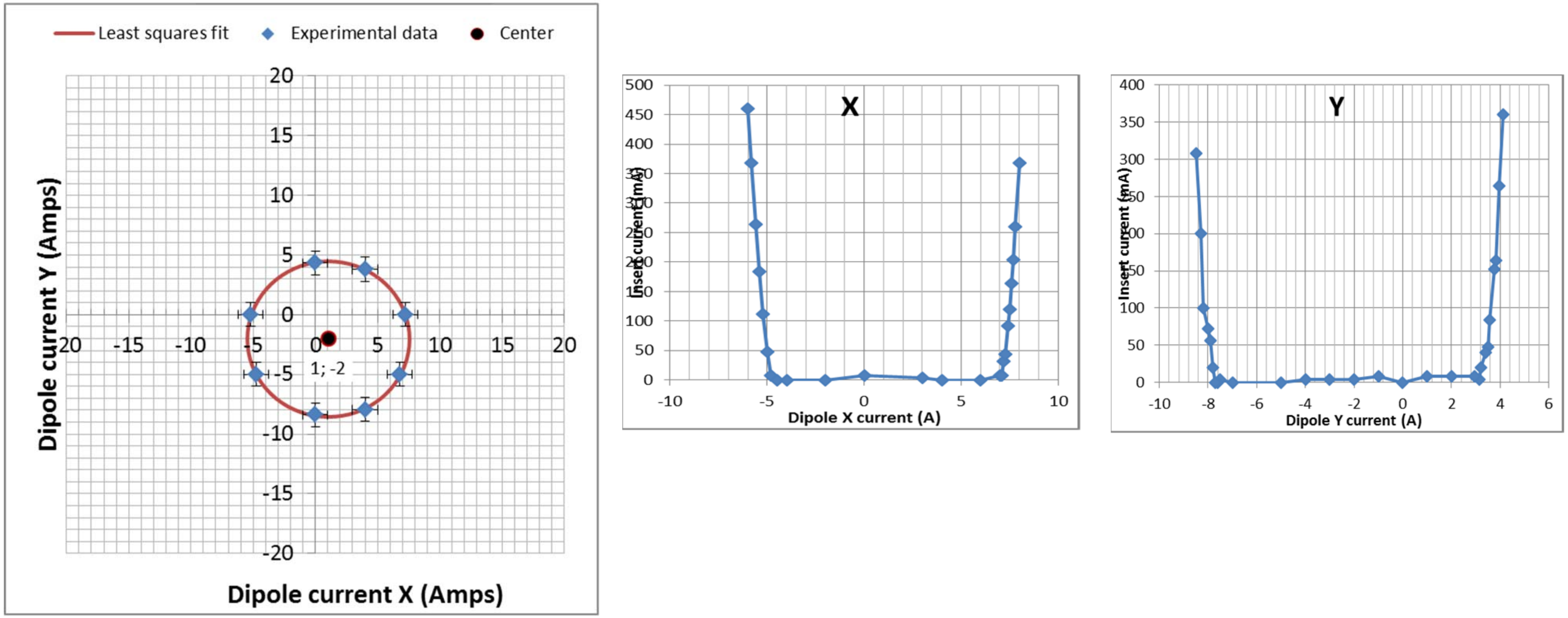
- CMIG satisfies the gun design criteria
- Coated edges of the emitter
- Less sensitive regarding misalignment
- Already installed at the gyrotron
- First promising results achieved



Electron Gun Alternatives: C-(coated)-MIG

First experimental check of the emission uniformity:

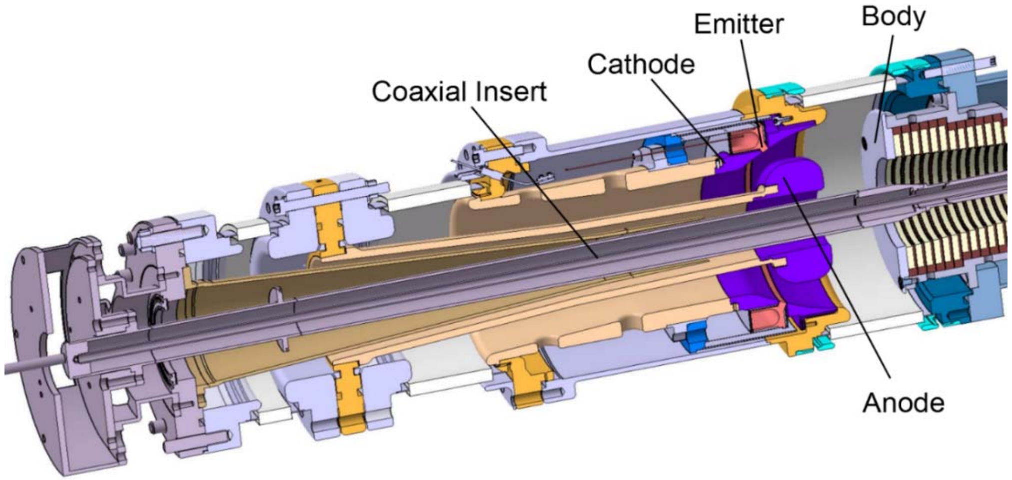
- Analysis of the insert current value with respect to the dipole coils current
- The curves **have much sharper edges** compared to the old gun, indicating a well defined electron beam
- **Symmetric current distribution** to the coaxial insert indicates a good performance of the edge-coated emitter



The Inverse MIG: Design and Manufacturing at KIT

Achievements:

- Possible **operation at 170 / 204 GHz**
- Applicable also to **conventional gyrotrons**
- **Optimized cooling** concept
- **KIT in-house manufacturing**

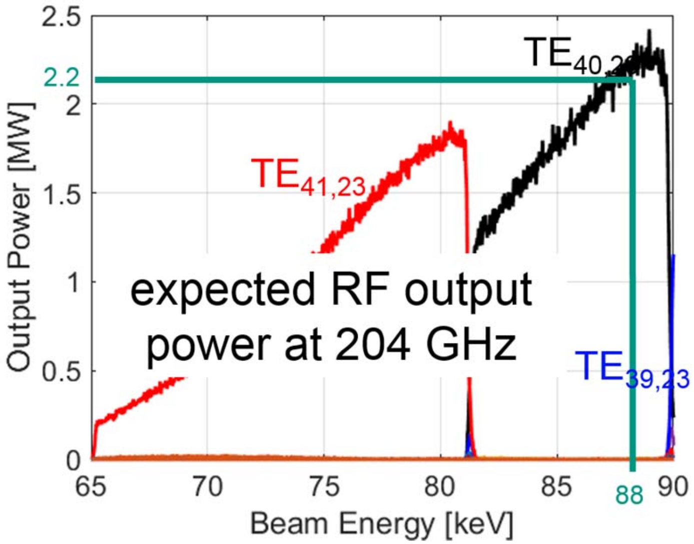


Conclusion

- KIT in-house manufacturing and assembly is successful finalized
- Key components (e.g. launcher) are verified
- MIG using advanced emitter technology shows promising results
- Advanced cooling concepts are developed
- **Coaxial-cavity gyrotron is successfully operating at 2.2 MW with an efficiency of 33 %**

Outlook

- 2018: Verification up to 100 ms
- 2019: Verification up to 1 s
- 2018/2019: Implementation of advanced key components and cooling techniques
- 2019: Upgrade to 170 / 204 GHz operation



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