Karlsruher Institut für Technologie

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# Numerical Investigation on the Influence of Insert Misalignment on the Insert Loading of a 170 GHz, 2 MW Coaxial-cavity Gyrotron

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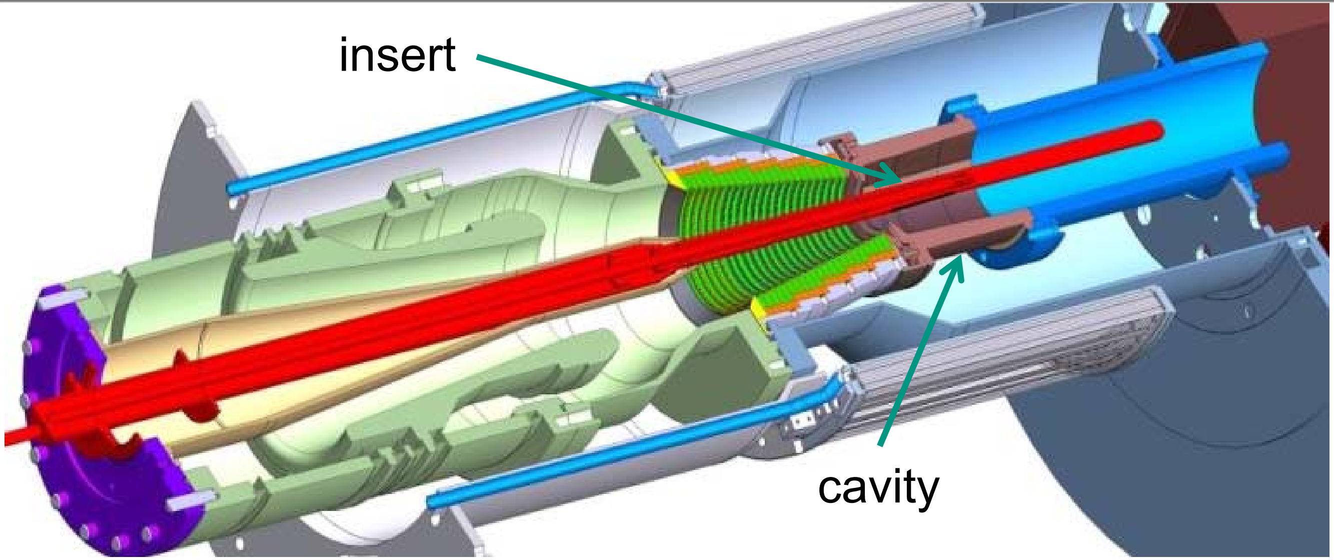


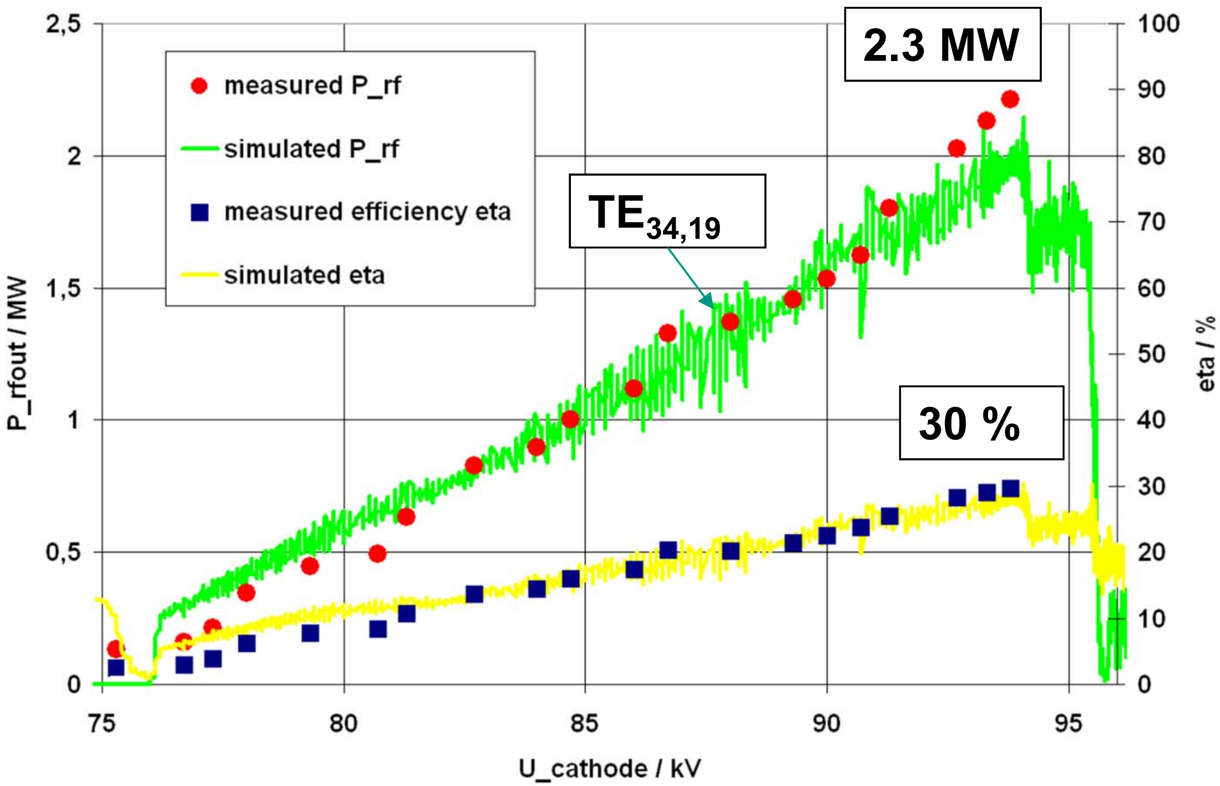
# Contents

- **Background**
  - Towards long-pulse coaxial-cavity gyrotrons
  - Introduction to insert cooling system
  - Motivation and objectives
- **Multi-physics Simulation Approach**
- **Results:**
  - Performance analysis of existing insert cooling system
  - Influence of axial insert misalignment
- **Conclusions and Outlook**

# Experimental Results of the 170 GHz, 2 MW Gyrotron

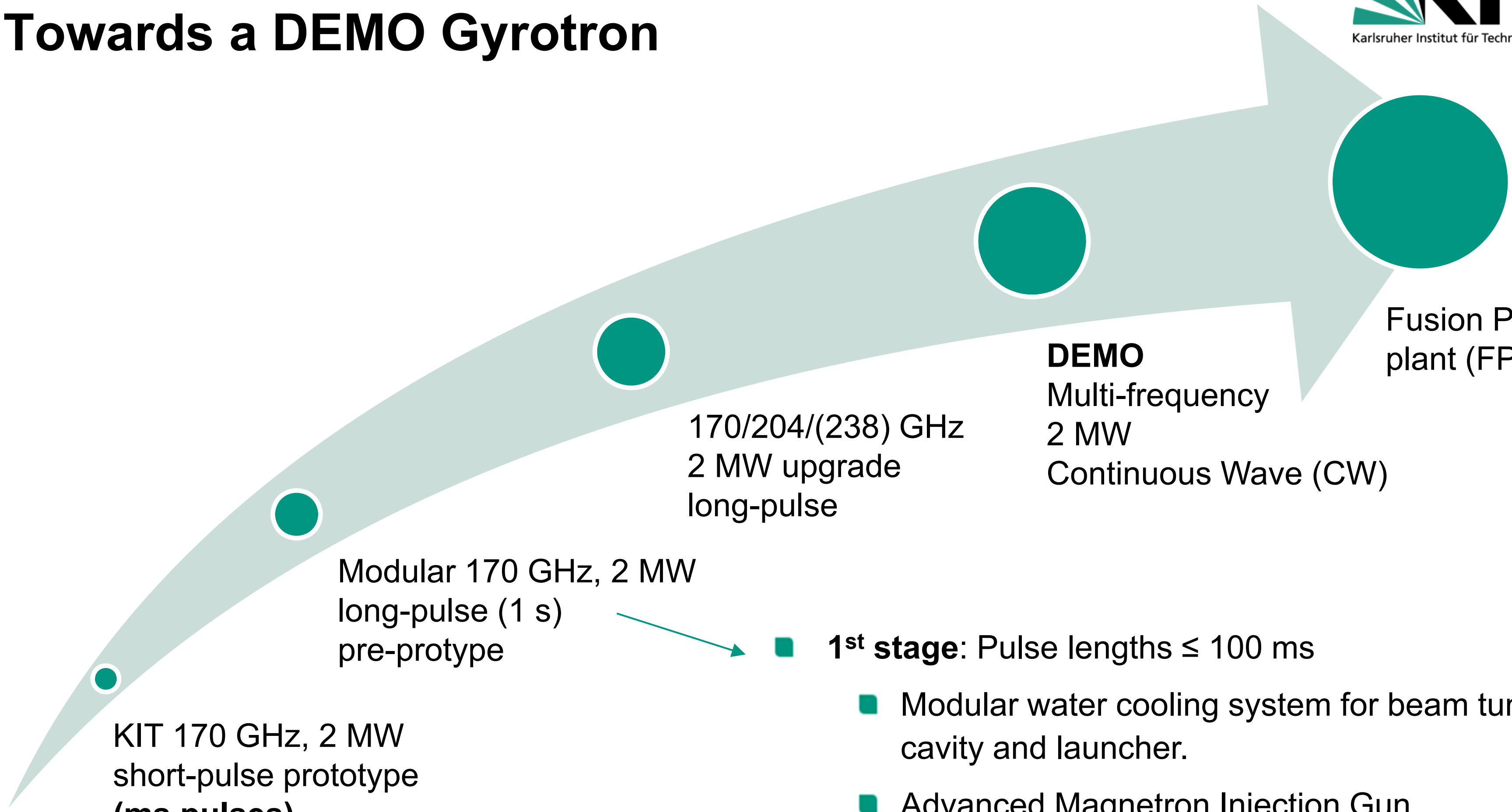
## Short-Pulse Operation

- **2.0 MW,** efficiency: ~28.5 % (non-depressed)
  **pulse length ~1.5 ms**
- **2.3 MW,** efficiency 29.5 % (non-depressed)
  **pulse length ~0.6 ms**
- Efficiency of 48 % (with depression)
- **Pulse length limited by non-cooled components**
- No parasitic oscillations
- Gaussian mode content ~ 96 %



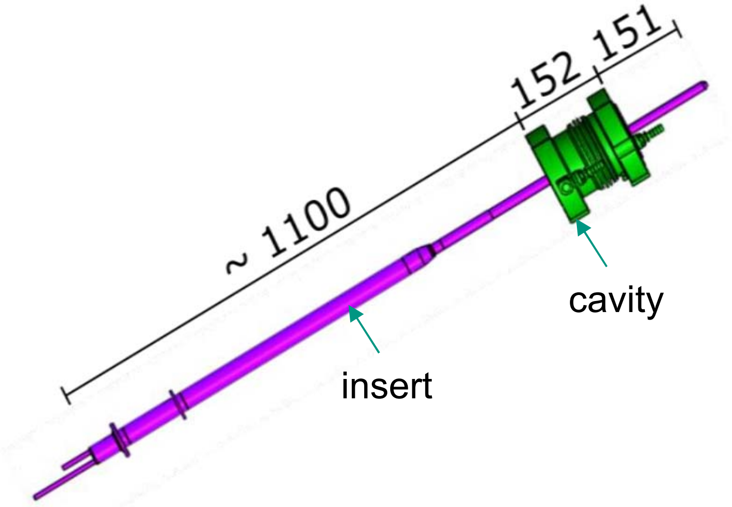

T. Rzesnicki, et al., "2.2-MW Record Power of the 170-GHz European Pre-Prototype Coaxial-Cavity Gyrotron for ITER", IEEE Transactions on Plasma Science, Vol. 38, No. 6, pp. 1141-1149, 2010.

# Towards a DEMO Gyrotron

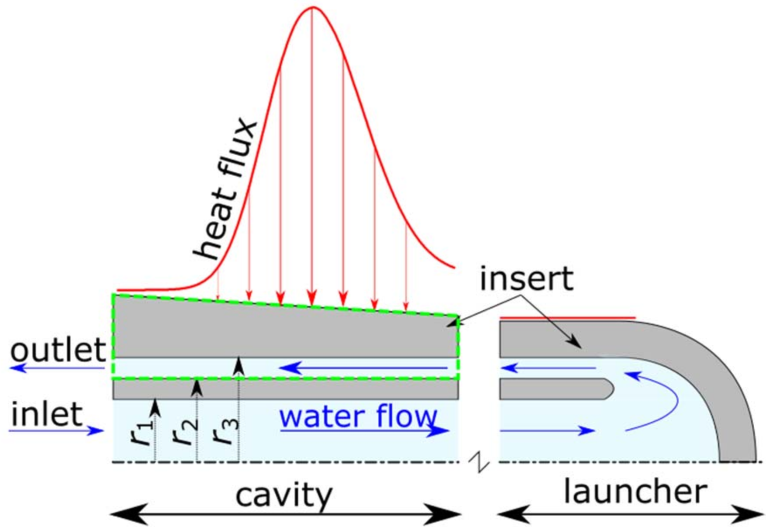



- **1st stage**: Pulse lengths ≤ 100 ms
  - Modular water cooling system for beam tunnel, cavity and launcher.
  - Advanced Magnetron Injection Gun
- **2nd stage**: Pulse lengths ≤ 1 s
  - CW collector
  - Water cooled synthetic diamond output window and mirrors

# Introduction to Insert Cooling System




Insert and cavity of a 170 GHz longer-pulse gyrotron. All the dimensions are in millimeter.




Simple sketch of the existing insert cooling system with the heat flux profile.
($r_1$= 3 mm, $r_2$ = 4 mm and $r_3$ = 5 mm)

RF heat flux → Increase in insert temperature → Deformation of insert geometry → Modify operating frequency

Modify heat flux

# Motivation:
# Performance Analysis of an Insert Cooling System

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- Insert cooling system of a **170 GHz, 2 MW** coaxial-cavity gyrotron

Experimentally verified for short-pulse (~ 1 ms) operation → For long-pulse operation

Experimentally verified for short-pulse (~ 1 ms) operation → not critical

For long-pulse operation → possibly critical, systematic study requested

Major objectives:

- Verify present insert cooling system
- Identify limit for maximum insert-loading
- Study the effects of insert misalignment

# Contents

# Overview of the Selected Simulation Approach

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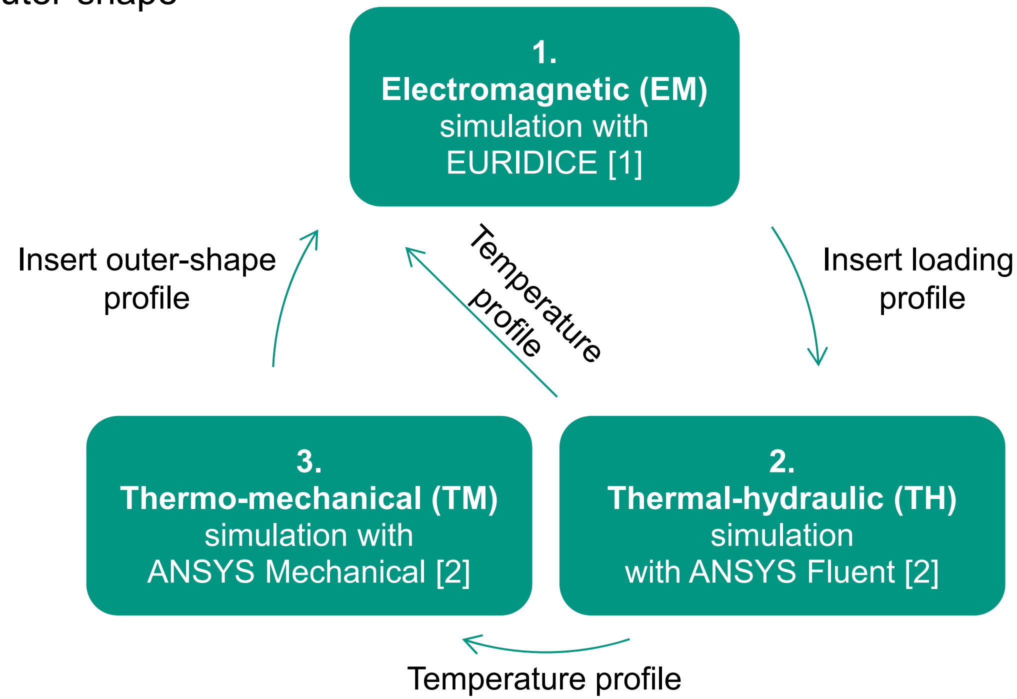
- Iterative procedure until reaching convergence/consistency of the profiles of:
  - Insert loading
  - Temperature
  - Insert outer-shape



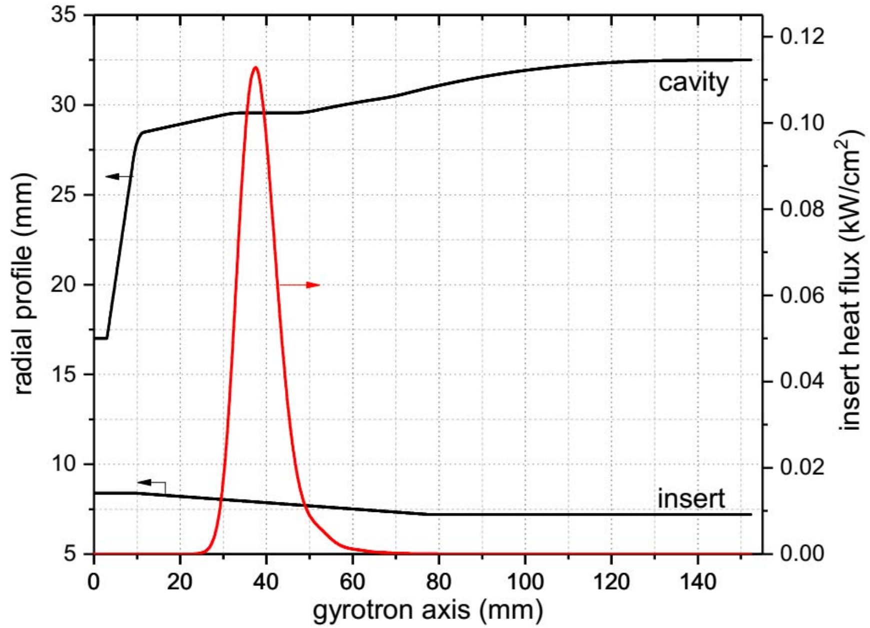


[1] *K. A. Avramides et al.,"EURIDICE: A code-package for gyrotron interaction simulations and cavity design", EC-17, Deurne, The Netherlands, May 7-11, 2012, EPJ Web of Conf. 32, 04016 (2012).*
[2] *Ansys (v18.2) User's Manual 2018*

# Beam-wave Interaction Simulations with EURIDICE

- Cavity and insert design of 170 GHz, 2 MW gyrotron
- Realistic magnetic field profile ($B_{max}$ = 6.89 T)
- Temp. dependent Glidcop conductivity
- 75 corrugations with depth of 0.44 mm
- Beam parameters: beam energy = 90 keV, beam current = 75 A, velocity ratio = 1.3
- Output power: 2.3 MW,
  Efficiency: 33 % (non-depressed)

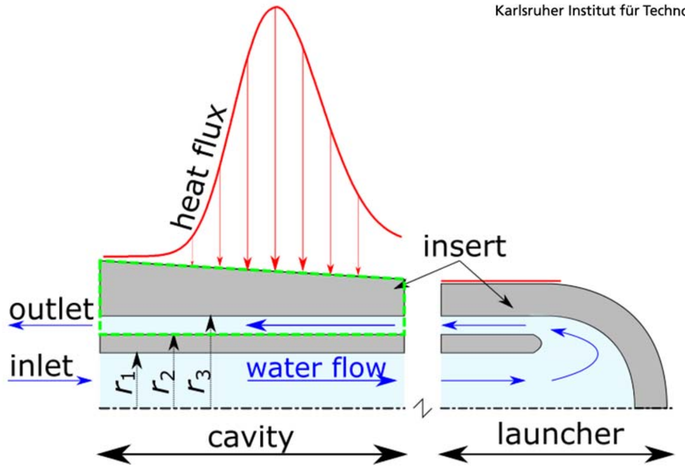
Time-dependent, self-consistent interaction simulations to determine gyrotron behavior and insert heat-load profile



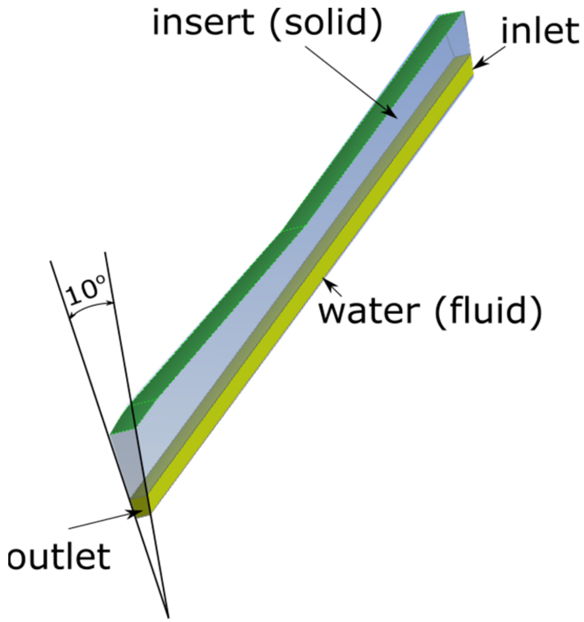

| Parameter at cavity center | Values |
|---|---|
| $r_{cav}$ | 29.55 mm |
| $r_{insert}$ | 7.86 mm |
| $r_{beam}$ | 10 mm |

# Thermal-Hydraulic (TH) Simulations - I

- Software: Ansys Fluent V18.2
- Initial analysis:
  10° section, rotational periodic BC
  20° section, rotational periodic BC
  90° section, two symmetric planes
  } same results within 1 °C
- **10° section with rotational periodic BC** is selected for the further analysis
- Initial water temp. : **27 °C**
- Water flow rate: 10 L/min
- Water speed at inlet: **5.89 m/s**
- Highly turbulent flow → turbulence model required
- Selected turbulence model:
  **Shear-Stress Transport (SST) k - ω model**




($r_1$= 3 mm, $r_2$ = 4 mm and $r_3$ = 5 mm)

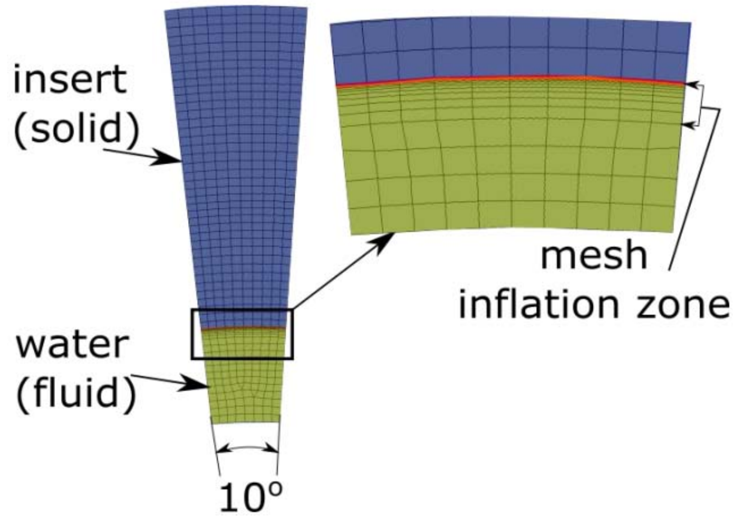


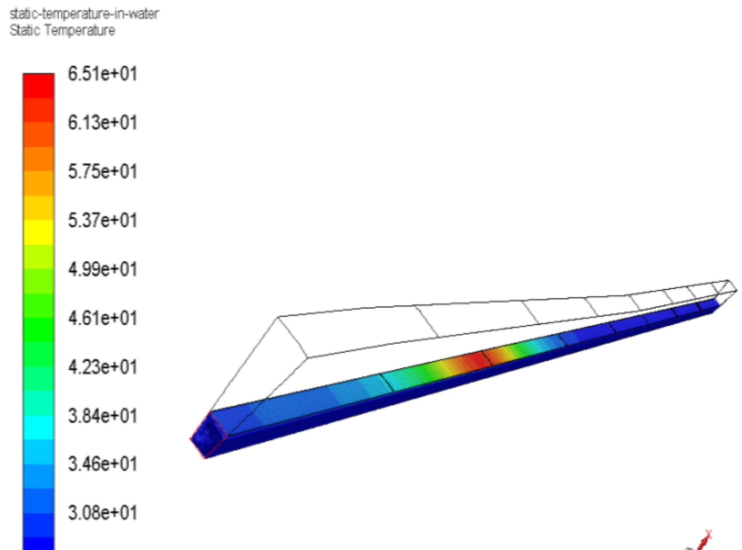
# Thermal-Hydraulic (TH) Simulations - II

- Highest temp. gradient at interface → mesh refinement needed
- Mesh inflation zone at interface
- Criteria:
  - 1st layer: $y^{+} \leq 1$
  - 10th layer: $y^{+} \leq 200$

| First layer height | No. of inflation layer | Growth rate |
|---|---|---|
| 1.5e-3 mm | 10 | 1.4 |

Thermal-Hydraulic (TH) simulations to determine temperature profiles.

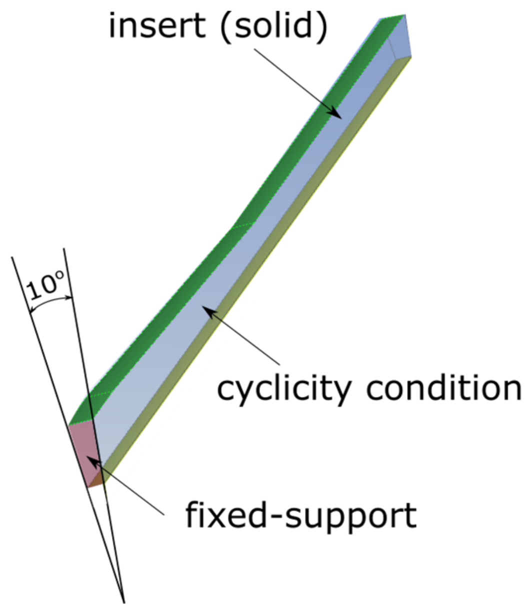



Temperature profile of water

# Thermo-Mechanical (TM) Simulations

- Software: Ansys Mechanical
- Only solid part of insert is considered for simulation
- Heat-load imported from thermal-hydraulic (TH) simulation
- Fixed-support condition on the lower face of the selected insert domain
- Cyclicity boundary condition
  (equivalent to the rotational periodicity condition used in TH simulation)




Thermo-Mechanical (TM) simulations to determine insert deformation due to thermal load.

Glidcope Al-15 material properties

| Parameters | Values |
| --- | --- |
| Density | 8830 kg/m$^3$ |
| Coefficient of thermal expansion | $1.7 \times 10^{-5}$ /°C |
| Young's modulus | 117 GPa |
| Poisson‘s ratio | 0.33 |

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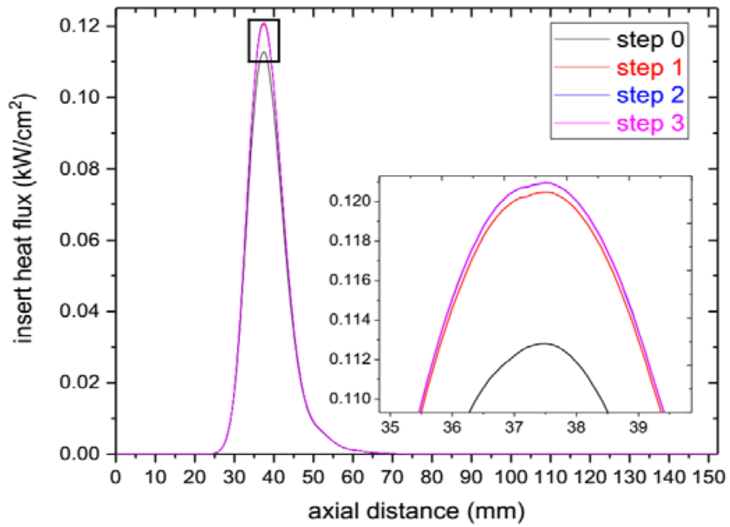
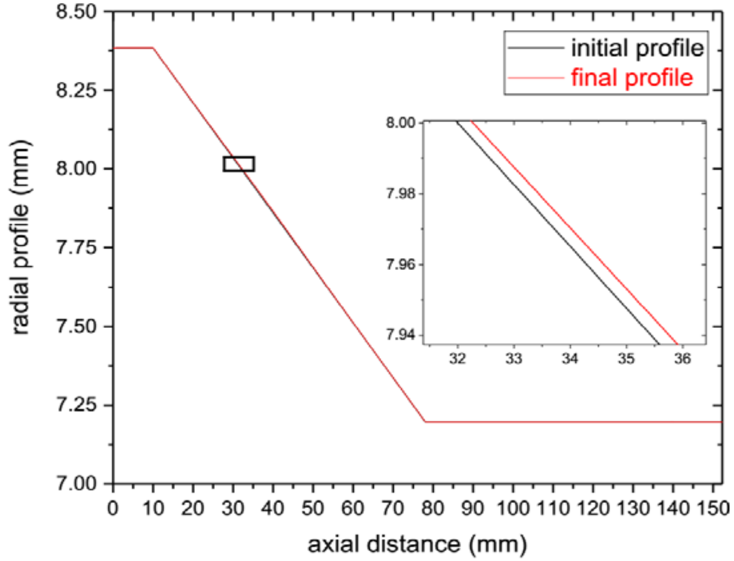
# Performance Analysis of Existing Insert Cooling System

- Process convergence in 3 iterations
- Max. insert loading: **0.122 kW/cm²**
- Max. surface temp.: 74 °C
- Max. water temp.: **65 °C**
- Max. radial deformation: **5.6 µm**
- Max. axial deformation: **18.4 µm**

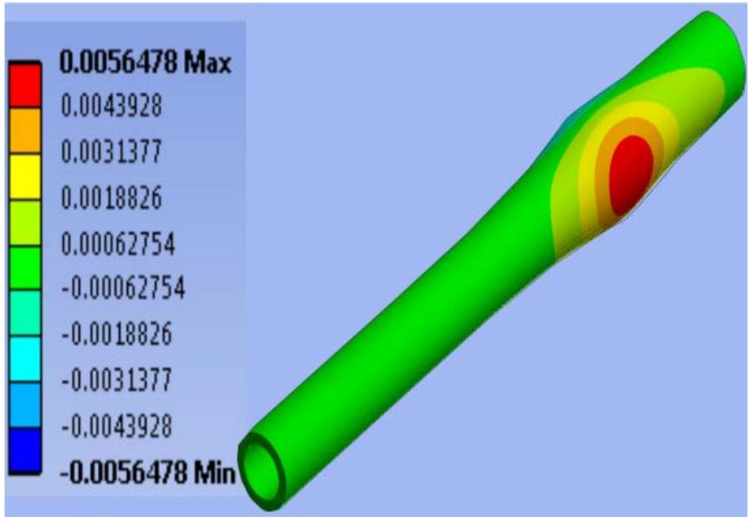


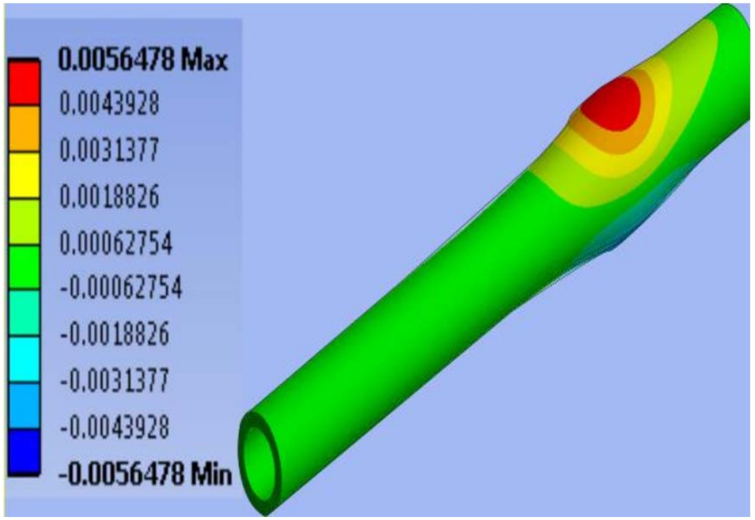

- Maximum water temperature is well below the boiling temperature.
- Very small deformations of the insert geometry.

➢ **Insert cooling is compatible with CW operation!**

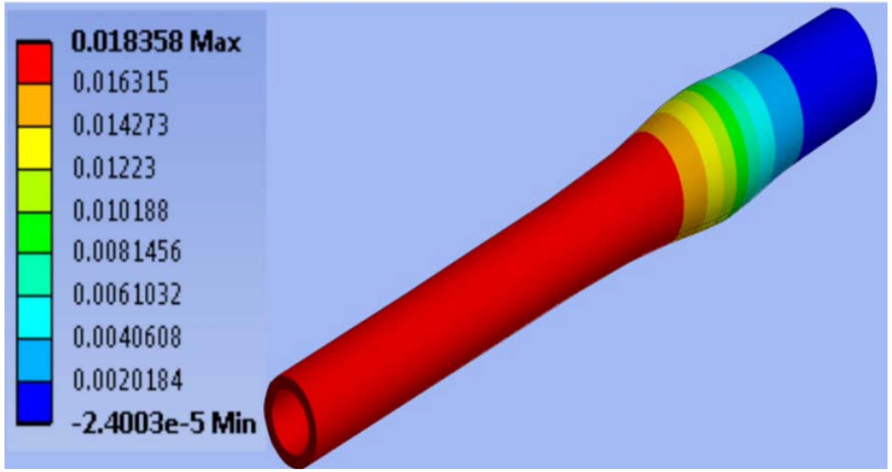
# Insert Deformation: Perfectly Aligned Case




deformations in x-direction: **-5.6 – 5.6 µm**




deformations in y-direction: **-5.6 – 5.6 µm**




deformations in z-direction: 0 – 18.4 µm

(*not to scale)

# Identify the Limit of Insert Heat Flux

| | (a) by increasing beam current | (b) by increasing insert radius | |
|---|---|---|---|
| | | $\Delta r$ = 0.175 mm | $\Delta r$ = 0.275 mm |
| Max. initial heat flux at wall ($kW/cm^2$) | 0.21156 | 0.22293 | 0.31816 |
| against the initial conditions (0.11282 $kW/cm^2$) | 187.5 % | 197.6 % | 282.0 % |
| Max. final heat flux at wall ($kW/cm^2$) | 0.24259 | 0.25523 | 0.38935 |
| **Max. final temperature in water (°C)** | **101.1** | **105.9** | **148.4** |
| Max. final equivalent stress (MPa) | 92 | 96 | 145 |

(boiling temp. of water at 6.2 bar = 160 °C , limit of elasticity = 338 MPa)

- Limiting phenomenon: water boiling
- Tolerable maximum heat flux of **0.39 $kW/cm^2$** for water boiling at 160 °C
- Design limit of insert heat flux (0.2 $kW/cm^2$) can be increased up to two times.

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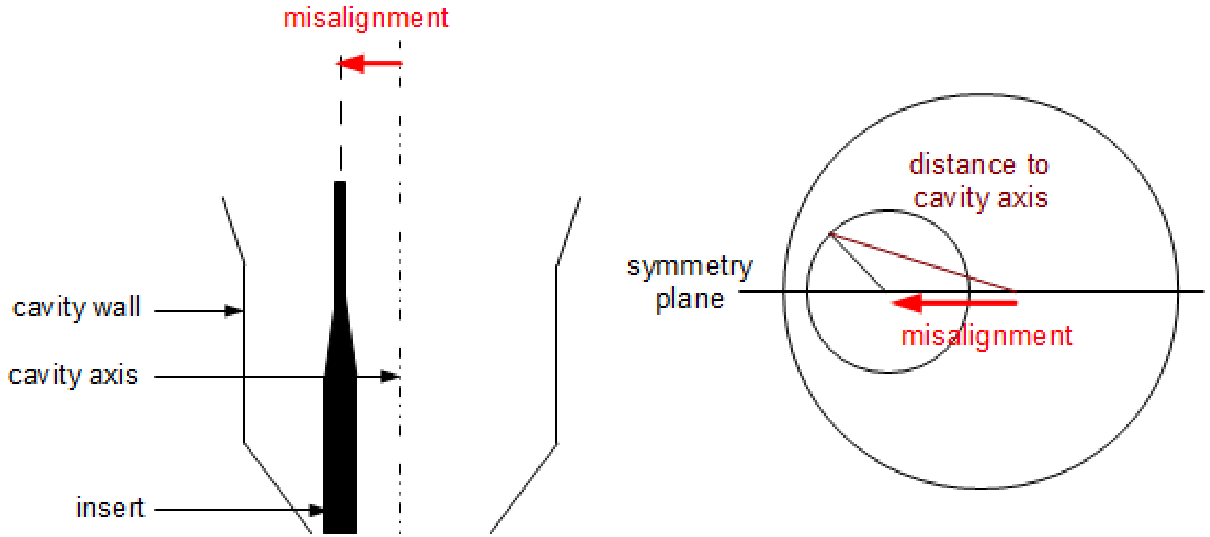
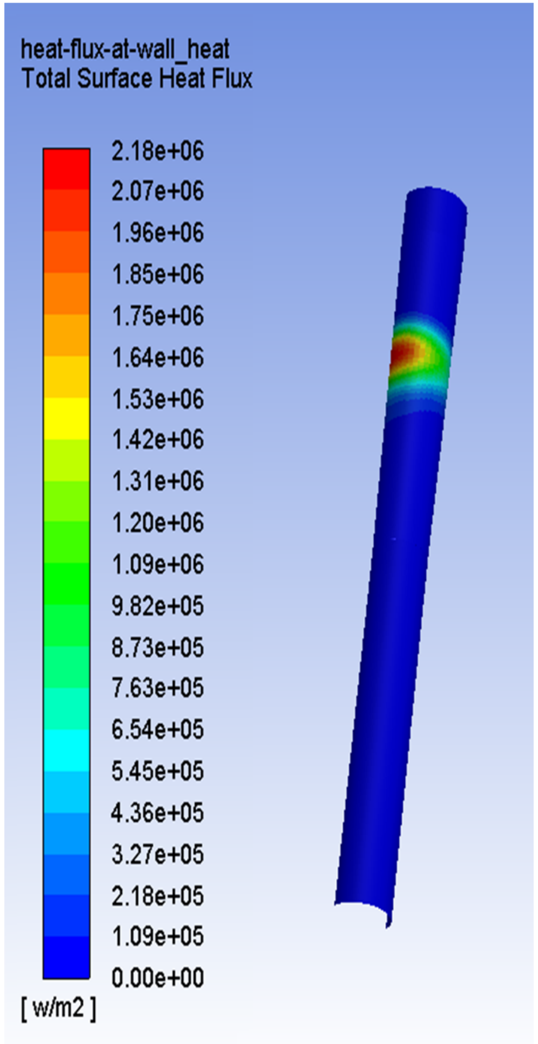
# Influence of Insert Misalignment on Thermal-loading




- Heat flux is no longer axisymmetric
- 180° section of insert has been considered for the simulation using planner symmetry boundary condition
- Eighteen 10° angular sectors for EURIDICE calculation

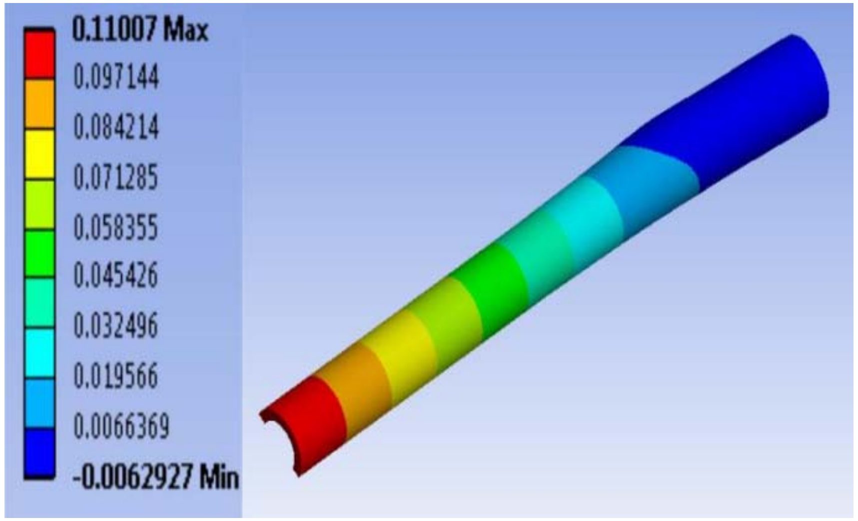
# Influence of Insert Misalignment on Thermal-loading

| | Initial misalignment (µm) | 150 | 200 |
|---|---|---|---|
| electromagnetic | maximum heat flux at wall (kW/cm²) | 0.2183 | 0.2688 |
| thermal-hydraulic | **maximum temperature in water (°C)** | **81.0** | **89.0** |
| thermo-mechanical | maximum deformation in the x-direction (µm) | **80.1** | **110.1** |
| | maximum deformation in the y-direction (µm) | 6.4 | 7.0 |
| | maximum axial deformation (µm) | 24.6 | 27.8 |

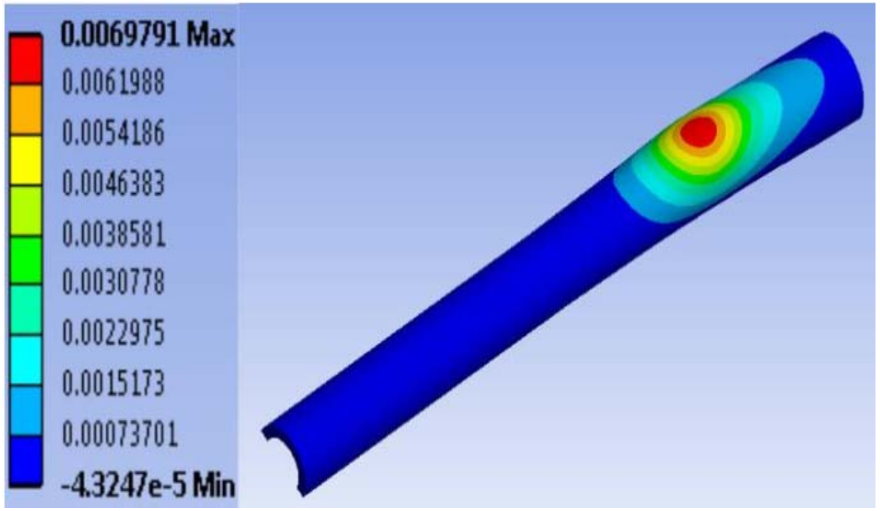
→ Beyond 200 µm, electromagnetic limit

- Temperature of water remains far from its boiling temperature
- Transversal deformations compensate the initial insert misalignment

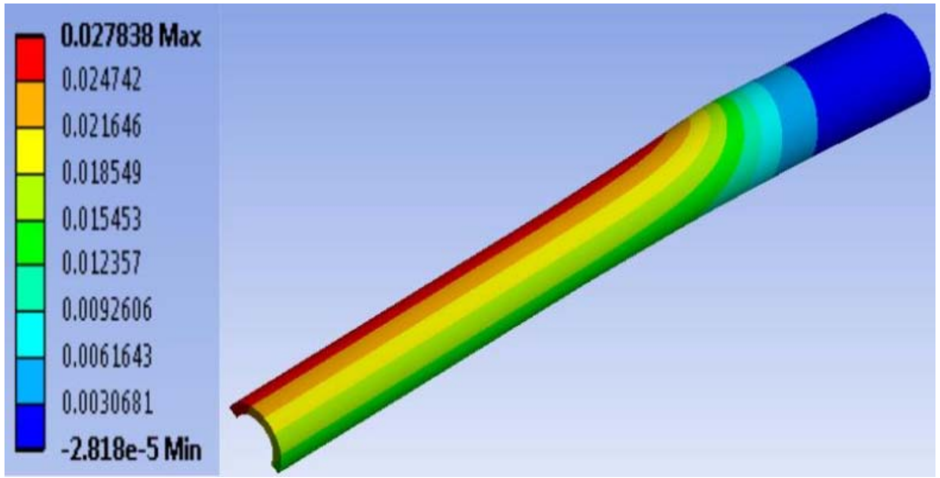
# Insert Deformation: Considering Axial Misalignment of 200 µm (in negative X-direction)




Max. deformations in x-direction: 110 µm




Max. deformations in y-direction: 7 µm




Max. deformations in z-direction: 28 µm

(*not to scale)

# Conclusions

- Development of **a 170 GHz, 2 MW coaxial-cavity long-pulse gyrotron** is ongoing at KIT-IHM.
- To study the performance of the insert cooling system, **a multi-physics simulation model** has been developed with the **relevant turbulence model and mesh parameters**.
- Considering the nominal gyrotron operating parameters, the **results suggest stable operation** of the insert with the existing design.
- Reliable insert operation up to insert loading of **0.39 kW/cm$^2$**, which is almost **double** to the considered insert loading limit of **0.20 kW/cm$^2$** during gyrotron design.
- With **axial misalignment up to 200 µm**, the insert is far from resulting in water boiling or plastic deformations.

# Outlook

- Combined multi-physics simulations with cavity and insert
- Experimental validation of the simulation results
- Investigate performance of a coaxial-cavity gyrotron operating with the modes having higher radial index

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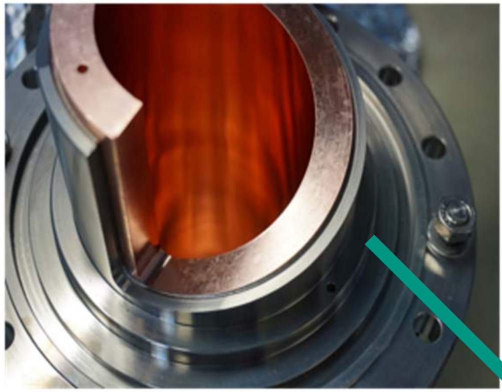
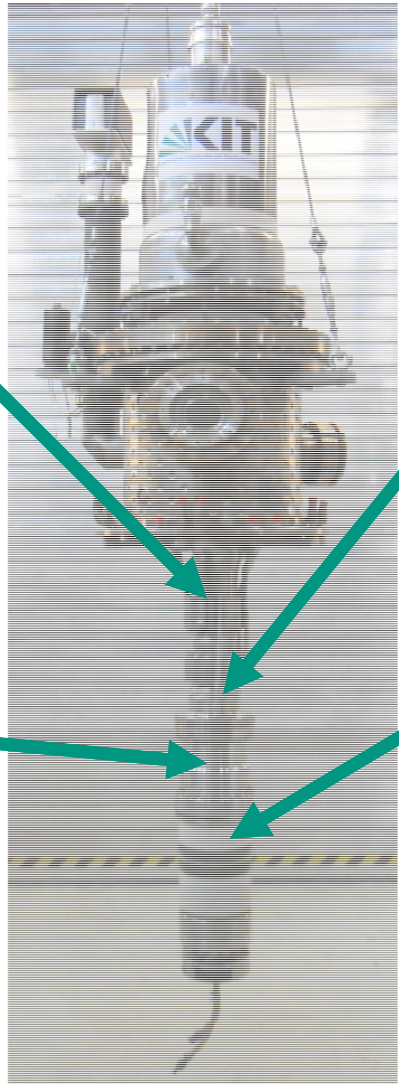
EUROfusion

*This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission*

# Status of the Longer-Pulse Tube

Launcher



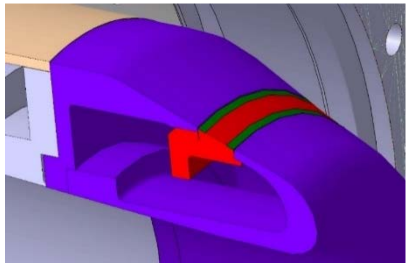


Cavity

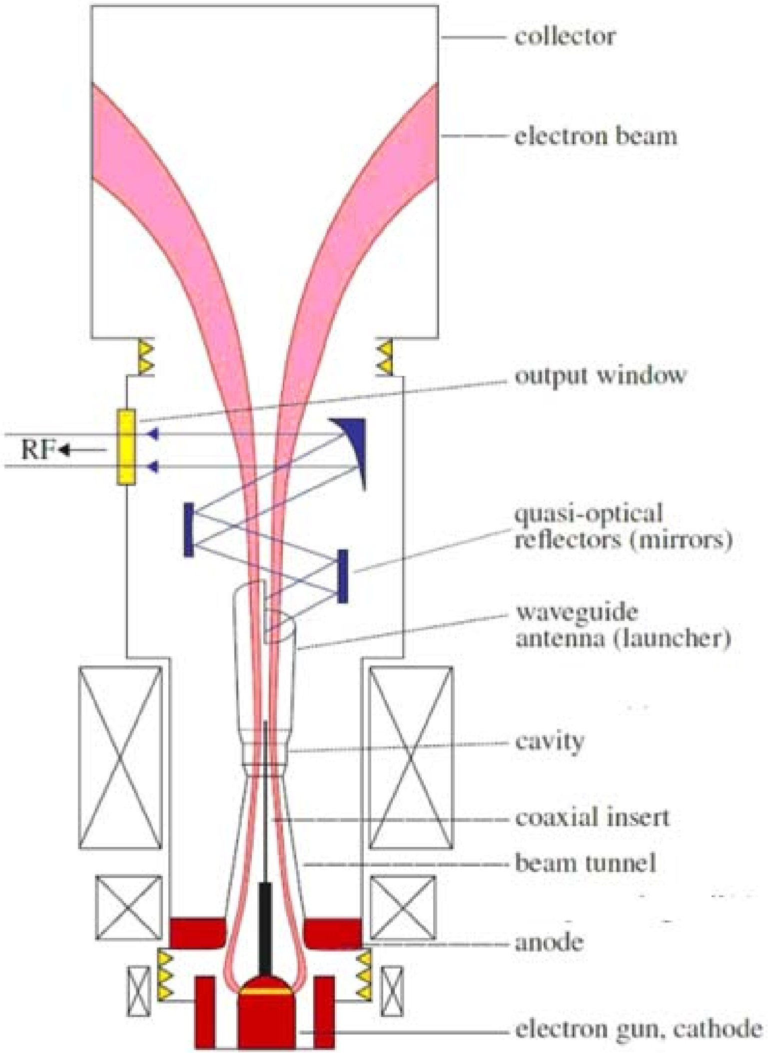
Inverse MIG

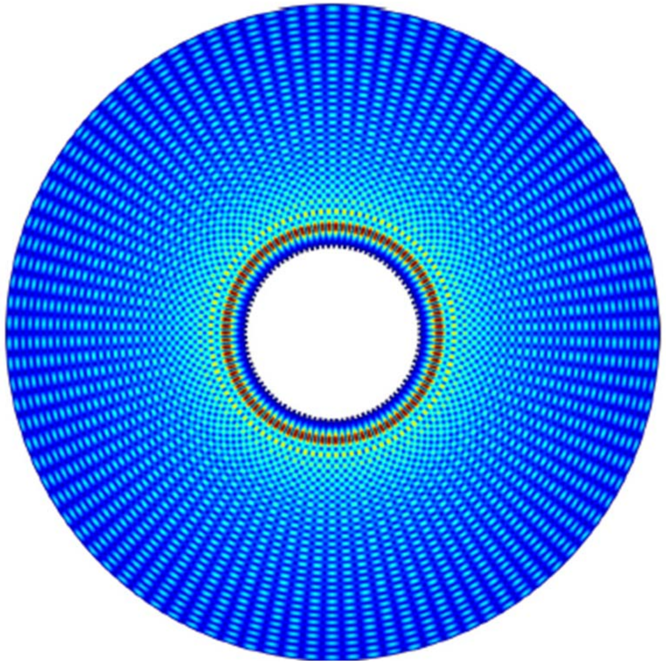
Beam Tunnel

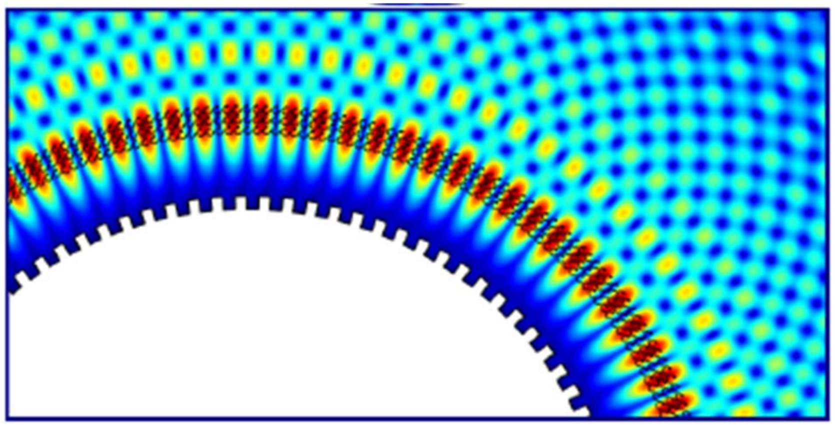
MIG with Coated Emitter Rims



# Parametric Study of perfectly Aligned Insert

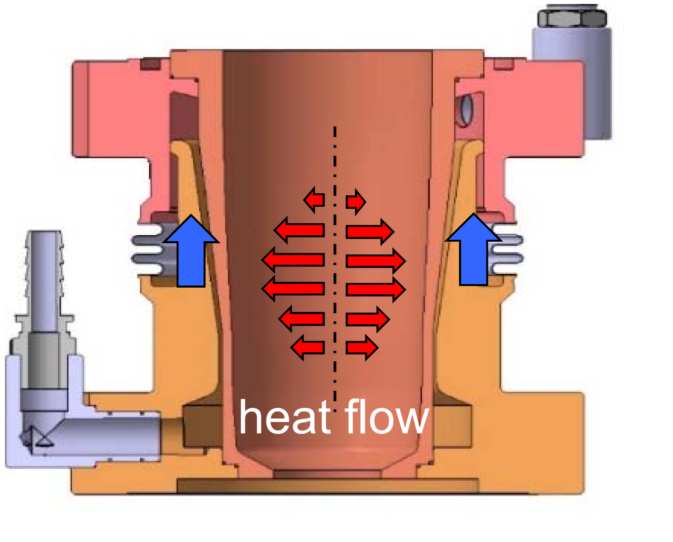


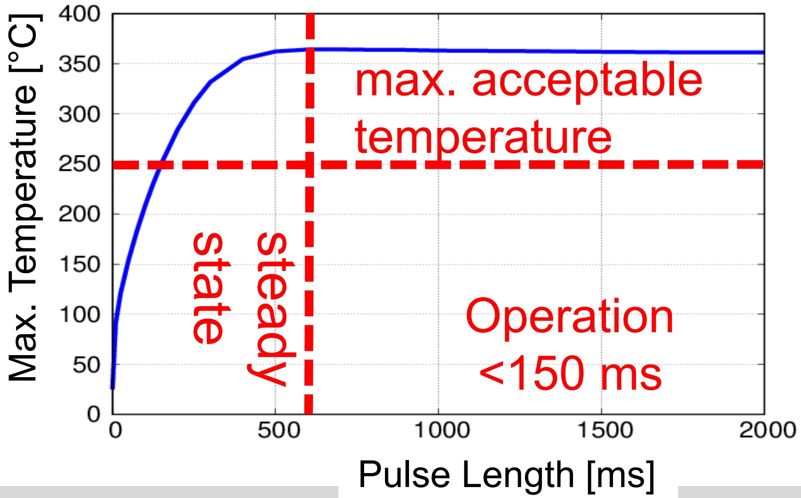





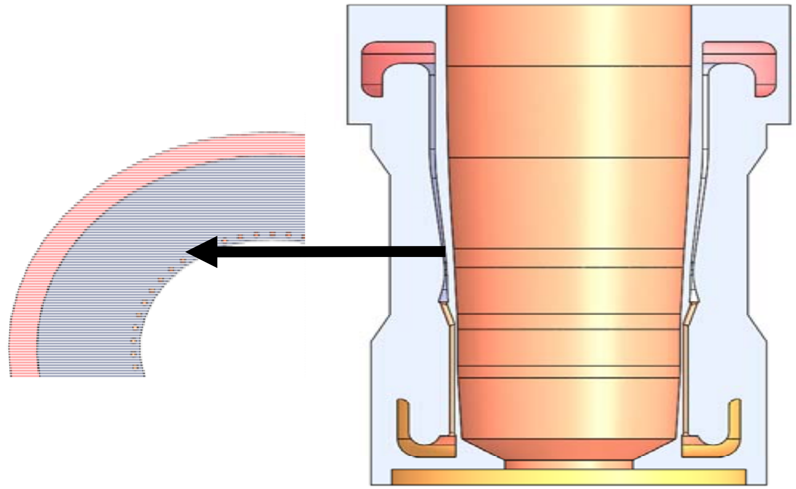
# Improved Water Cooling System

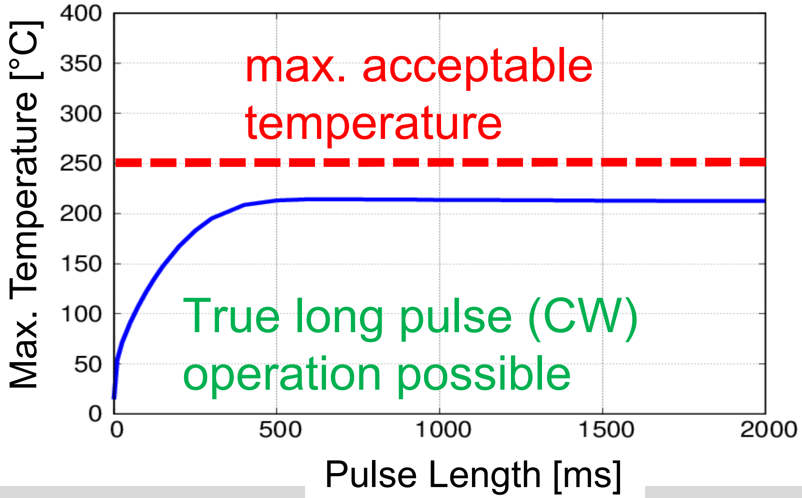
## Cooling in short-pulse




## Advanced microchannel cooling





# Towards Steady State Operation of a 170 GHz Coaxial-cavity Gyrotron

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KIT 2 MW short-pulse prototype
**(ms pulses)**

The KIT Modular 2 MW Longer-Pulse Design
**(pulse length: 0.1 – 1 s)**

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

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


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# Elaboration of the Model: Modelling Turbulence

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$Re = \frac{\rho u d}{\mu}$ → highly turbulent flow → turbulence model needed

k-ε:
most used
+ fit for a large number of problems
- boundary layer resolution

standard k-ω:
+ boundary layer resolution
- strongly sensitive to boundary conditions
→ inaccuracies in far field

Shear-Stress Transport (SST) k-ω:
→ k-ω model in boundary layer
→ k-ω formulation of k-ε model in far field

| **model** | **k-ε** | | **SST k-ω** |
|---|---|---|---|
| mesh | mesh 1 | mesh 2 | 5 different meshes |
| number of elements in copper | 1015980 | 577710 | 37740 to 293760 |
| number of elements in water | 181896 | 207242 | 15198 to 121584 |
| maximum temperature in copper | 66° C | 68° C | 67° C |
| **maximum temperature in water** | 58° C | 60° C | 58 to 59° C |
| **minimum speed of water** | 3.54 $m.s^{-1}$ | 2.79 $m.s^{-1}$ | 1.40 $m.s^{-1}$ |
| maximum speed of water | 6.60 $m.s^{-1}$ | 6.60 $m.s^{-1}$ | 6.96 to 7.00 $m.s^{-1}$ |

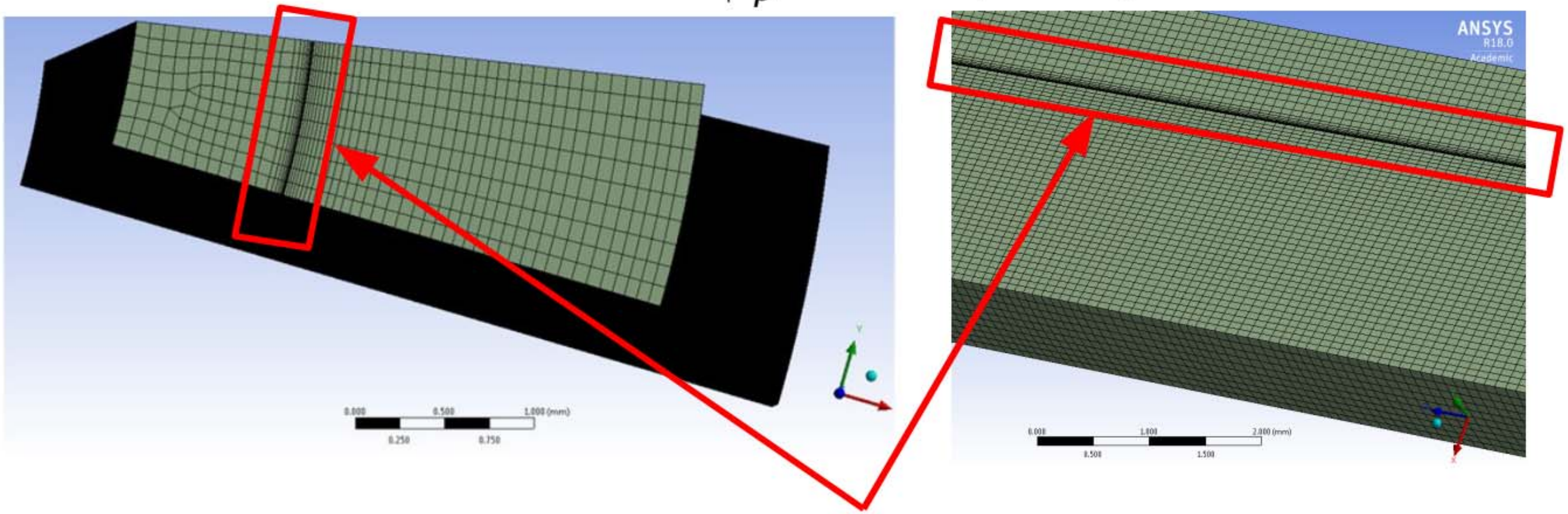
# Elaboration of the Model: Mesh for CFD

Criteria:
- 1st layer: $y^+ \leq 1$
- 10th layer: $y^+ \leq 200$

$$y^+ = \frac{y\,u_\tau}{\nu}$$

$$u_\tau = \sqrt{\frac{\tau_w}{\rho}}$$

y: distance from wall
ν: kinematic viscosity
$\tau_W$: wall shear stress
ρ: density




| size function | inflation water | | | sweep method and edge sizing functions |
|---|---|---|---|---|
| uniform | first layer height | No. of layers | growth rate | so as to impose parallelepipedic elements about 1-mm-long in the axial direction |
| | 1.5e-3 mm | 10 | 1.4 | |