EXPERIMENTAL ANALYSIS OF ADVANCED COOLING SOLUTIONS FOR CAVITIES OF MULTI-MW CW GYROTRONS

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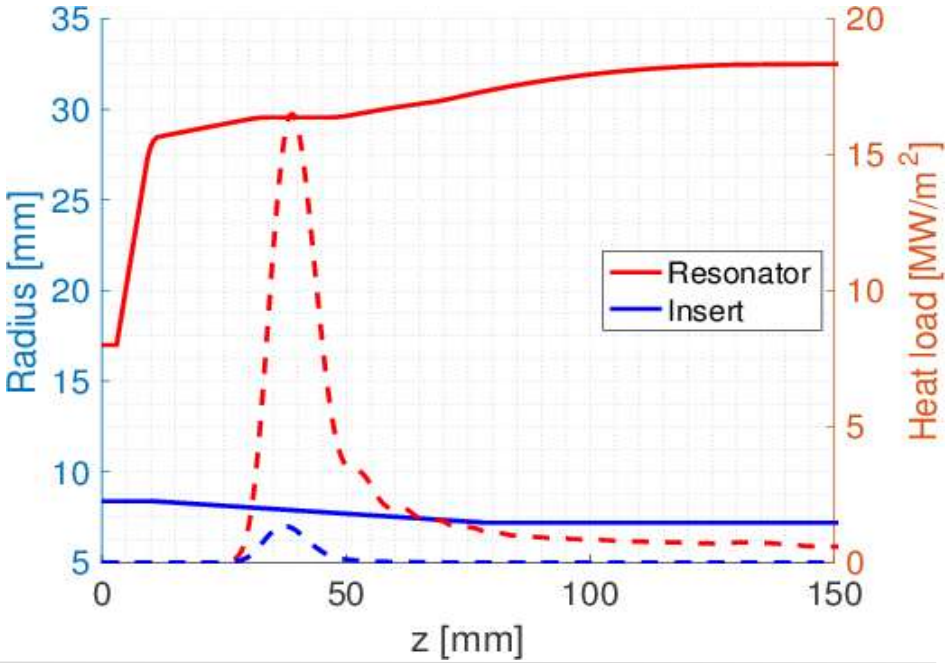
Outline

- High power CW gyrotron cavity cooling – mini-channels (MC) cooling approach
- KIT experimental set-up based on induction heating for examination of cavity cooling techniques
- Tests on MC mock-ups
- Current work - upgrade of the KIT cavity cooling test stand
- Conclusion and outlook

Cavity cooling

- What is this all about?
  - Developing of an advanced cooling for resonators of future 2 MW CW gyrotrons.
- Why we need this?
  - If not sufficiently cooled (e.g. Raschig Rings cooling), the very high thermal load on cavity wall (ca. 2 kW/cm^2), after ca. 0.2 s leeds to a cavity deformation that kills the nominal mode.



K. A. Avramidis et al., "Numerical studies on the influence of cavity thermal expansion on the performance of a high-power gyrotron", IEEE Trans. Electron Devices, January 2018, DOI: 10.1109/TED.2017.2782365.

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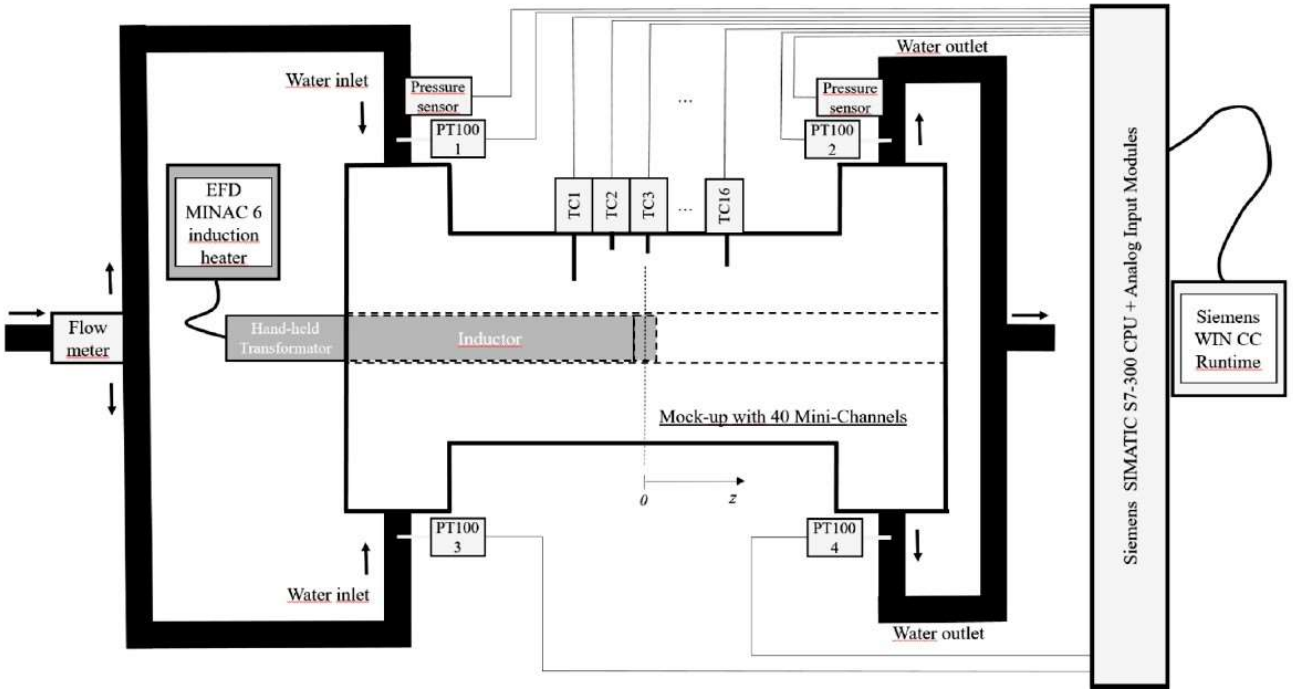
Cavity cooling

- Numerical analysis of cavity cooling
  - Currently used cooling techniques in european gyrotrons, such as Raschig rings cooling and annular gap cooling, are not sufficient for applications in 2 MW CW fusion gyrotrons.
  - New aproach with ***mini-channels cooling*** was systematically investigated and developed using numerical calculations.
  - Work at KIT: K. A. Avramidis, S. Ruess, P. C. Kalaria, P. T. Brücker.
  - Work at Politecnico Torin (PoliTo): L. Savoldi, A. Bertinetti, A. Allio, R. Difonzo.
  - Output – publications of ca. 10 papers, several EUROfusion reports and a bachleor thesis.

Cavity cooling

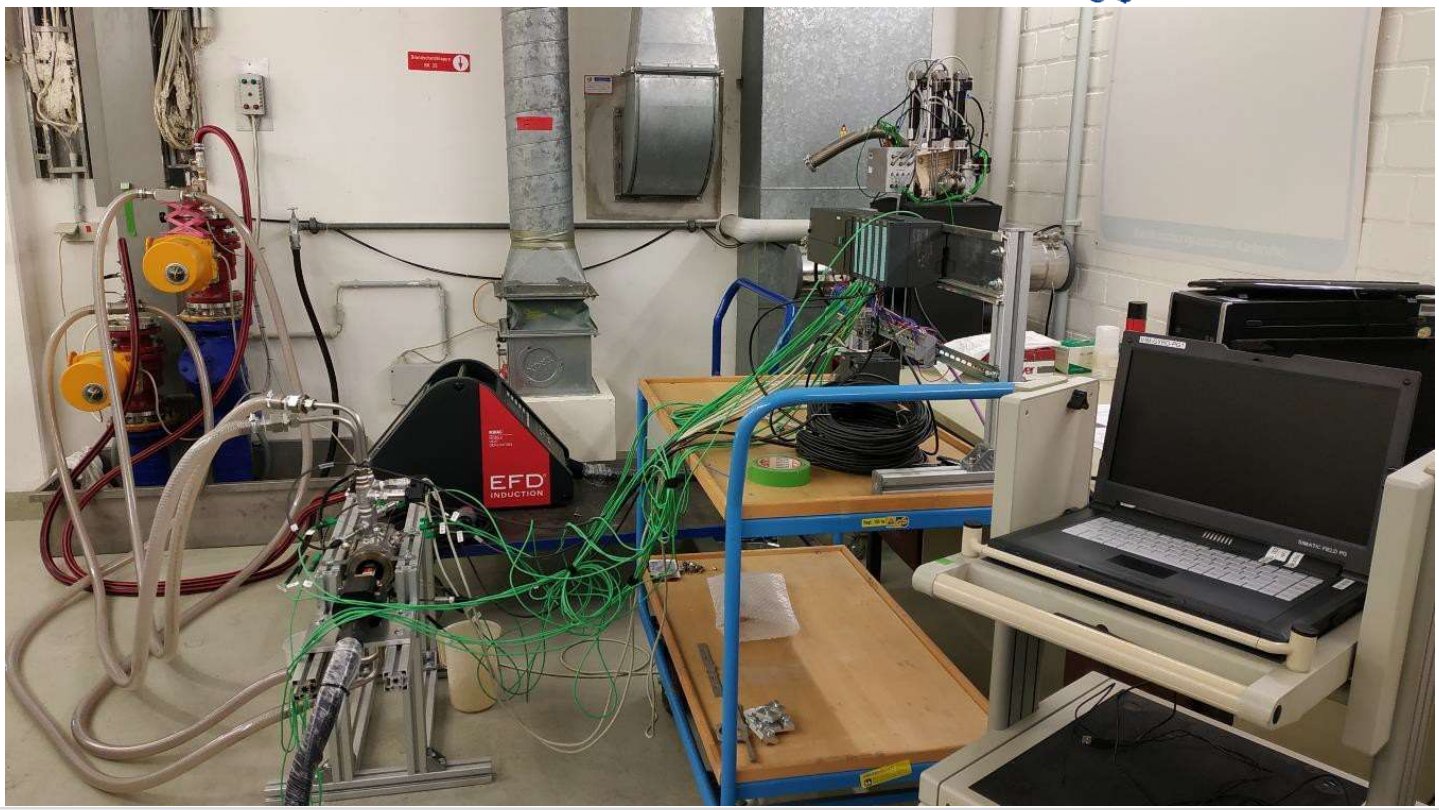
- Previous work
  - Before 2020:
    - Numerical simulations, design and construction of a mini-channel mock-up, installing the experimental set-up (K. A. Avramidis, S. Ruess, J. Weggen).
    - Definition of requirements, ordering and commissioning of the induction heater MINAC, first experiments (P. C. Kalaria, S. Stančulović).
  - Since 2020:
    - Experiments with different mock-ups, validation of the multi-physics simulations (KIT - S. Stančulović, PoliTo – L. Savoldi, R. Difonzo).

Block diagram of experimental set-up

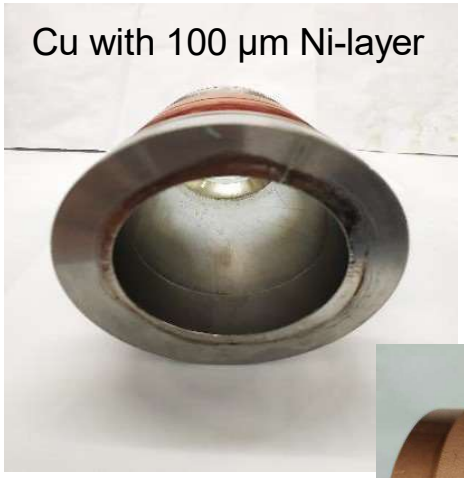


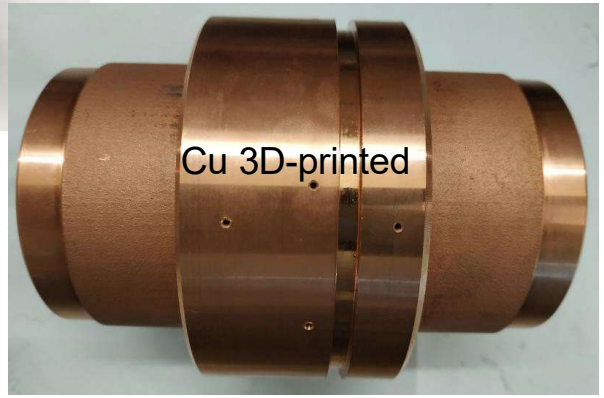
Mini-channel cooling mock-up, thermocouples (TC1… TC16), PT100 thermometers, pressure sensors, flow meter, MINAC 6/10 inductor heater with hand-held transformer and the inductor head, as well as SIMATIC S7-300® hardware and a computer with WIN CC® software.

Set-up with induction heater

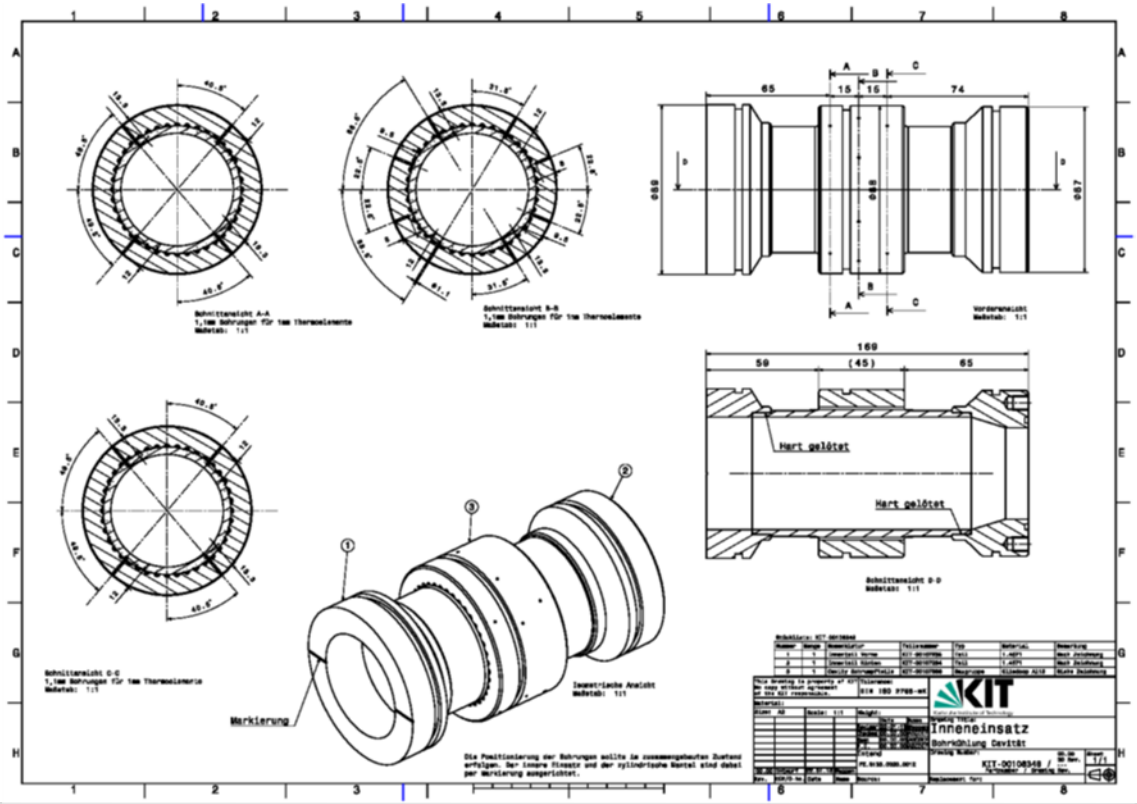


Components and mock-ups



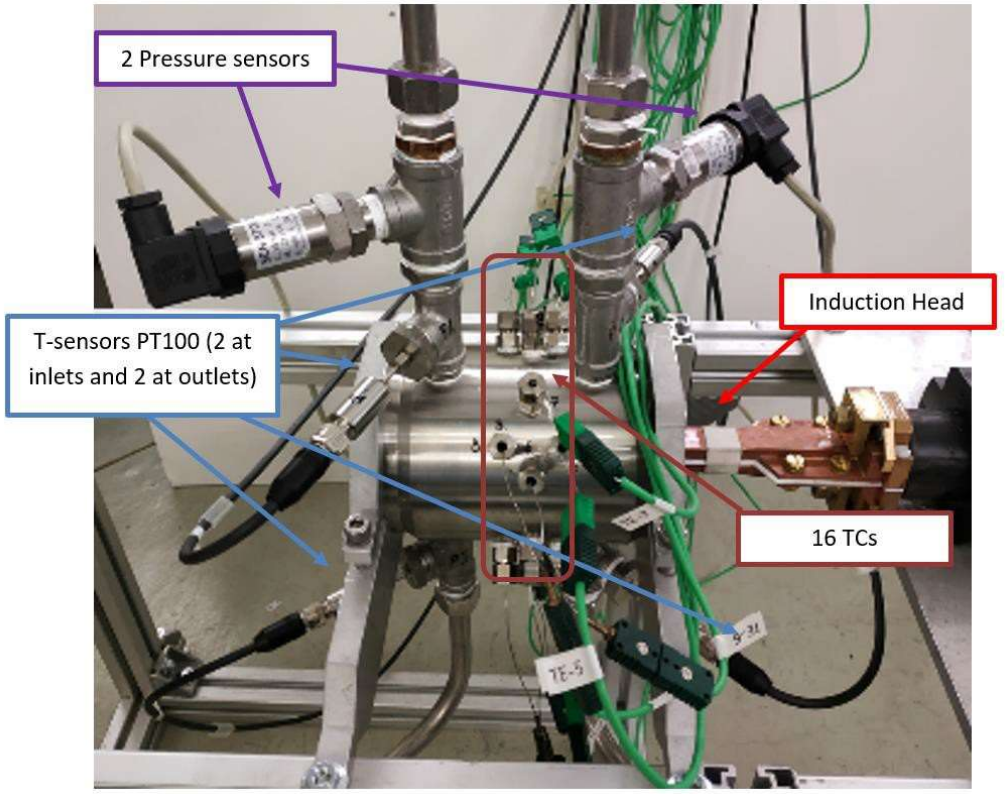


Drawings of the KIT mock-up



KIT MC mock-up

- Cavity geometry
  - 170 GHz, 2 MW, coaxial longer pulse gyrotron
  - $Ø_i$ = 59 mm
  - 40 MCs, semicircular cross section, r_{MC} = 1,4 mm



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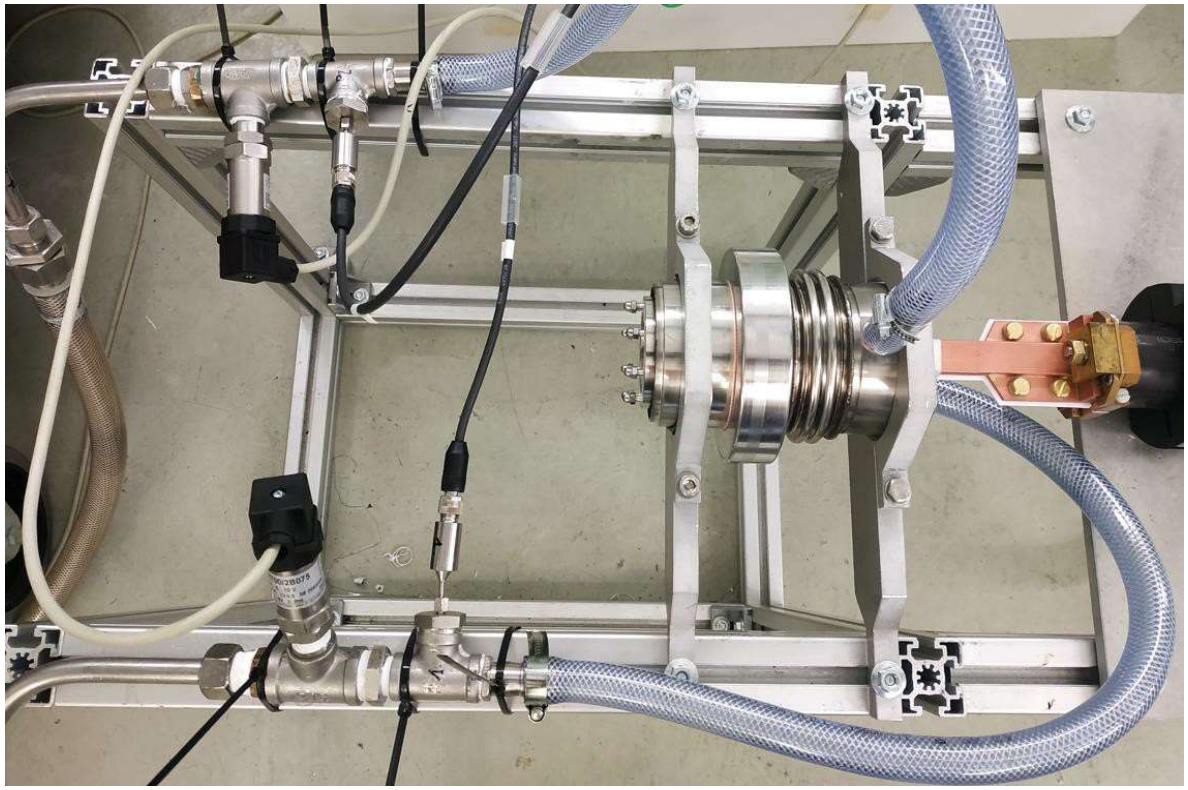
Thales MC mock-up



- Cavity geometry
  - TH1507U (W7-X)
  - $\varnothing_i$ = 46 mm
- TCs issue

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Cooling tests

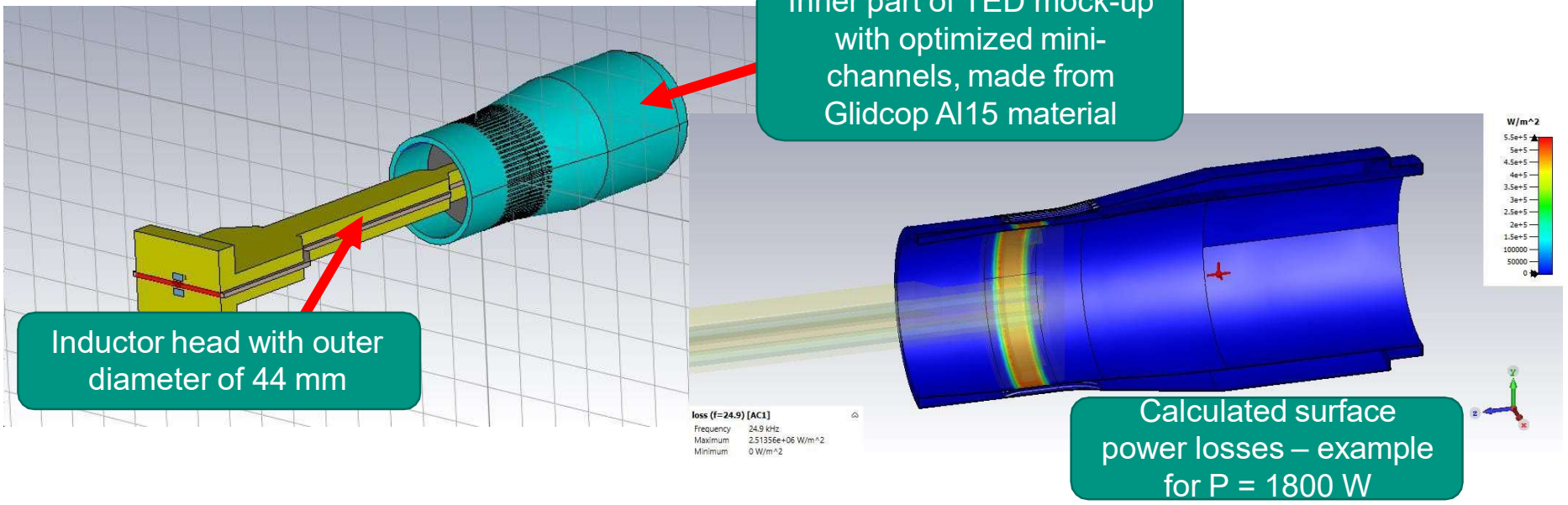
- Different power levels: from 1800 W up to 3600 W with MINAC 6/10 and up to 17000 W with MINAC 25/40 (max heating power level defined with device internal interlock).

- Different flow rates: from 3 l/min up to 20 l/min.
  - Low flow rates (up to 5 l/min) – higher temperature rise and higher accuracy of calorimetric measurements
  - High flow rates – more accurate pressure drop measurements, turbulent flow

- Different mock-ups:
  - MC KIT mock-ups: with Glidcop, Cu (3D-printed) and Cu with 100 µm Ni-layer cavities.
  - Thales mock-ups with MC and Raschig Rings (RR) cooling (Glidcop material).

Cooling tests

- Evaluation of the thermal-hydraulic (TH) numerical simulations
  - EM simulation (CST software) of the heat load as input for TH calculations – spatial distribution and power level calibration



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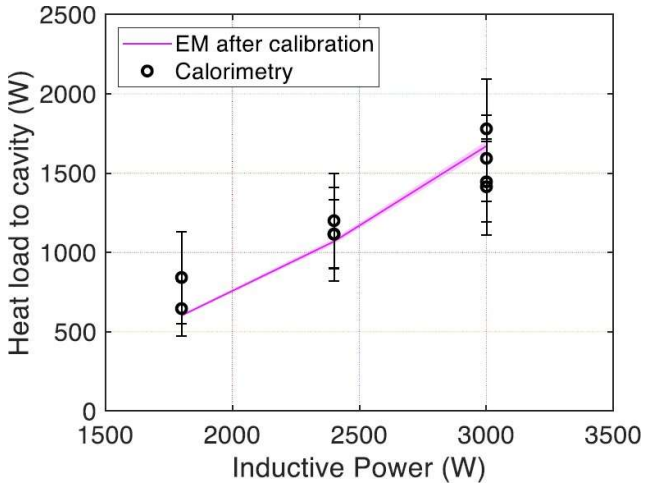
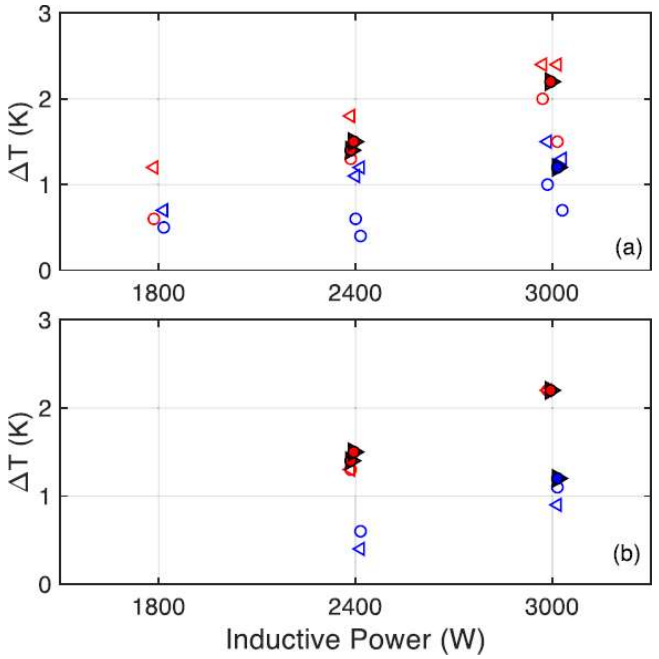
Cooling tests

- Evaluation of the thermal-hydraulic (TH) numerical simulations
  - Validation of the predictions of the TH simulation (PoliTo)



Temperature increase across mock-up

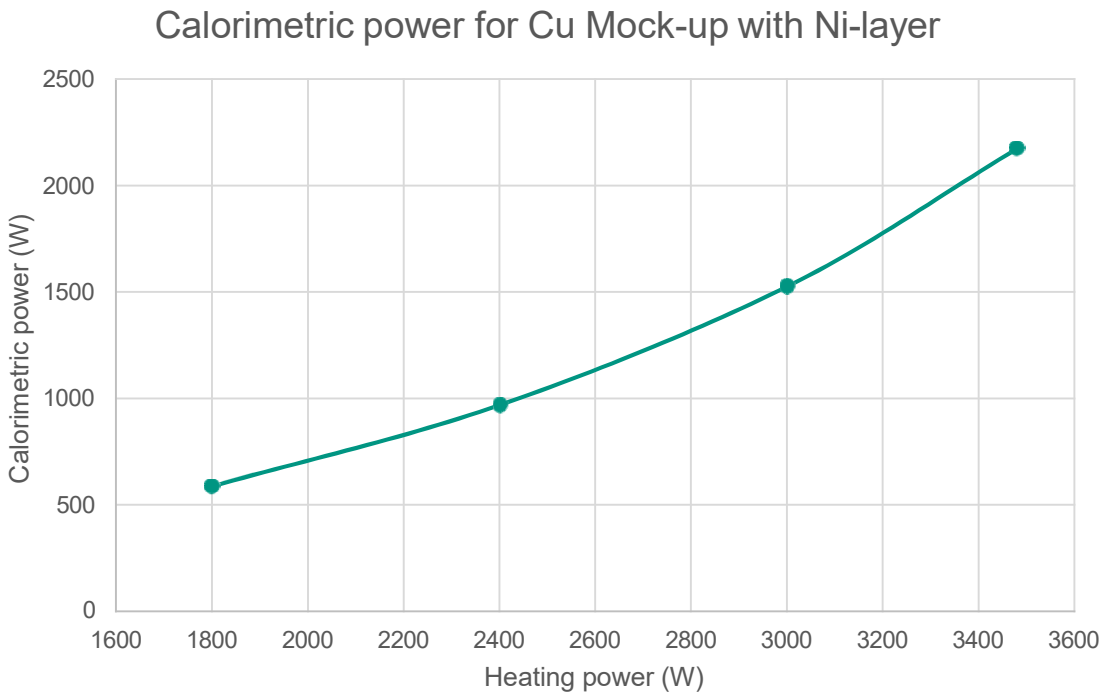


S. Stanculovic, et al., "Calibration of the KIT test setup for the cooling tests of a gyrotron cavity full-size mock-up equipped with mini-channels", Fusion Engineering and Design, vol. 172, June 2021, available online, doi: 10.1016/j.fusengdes.2021.112744.

Cooling tests

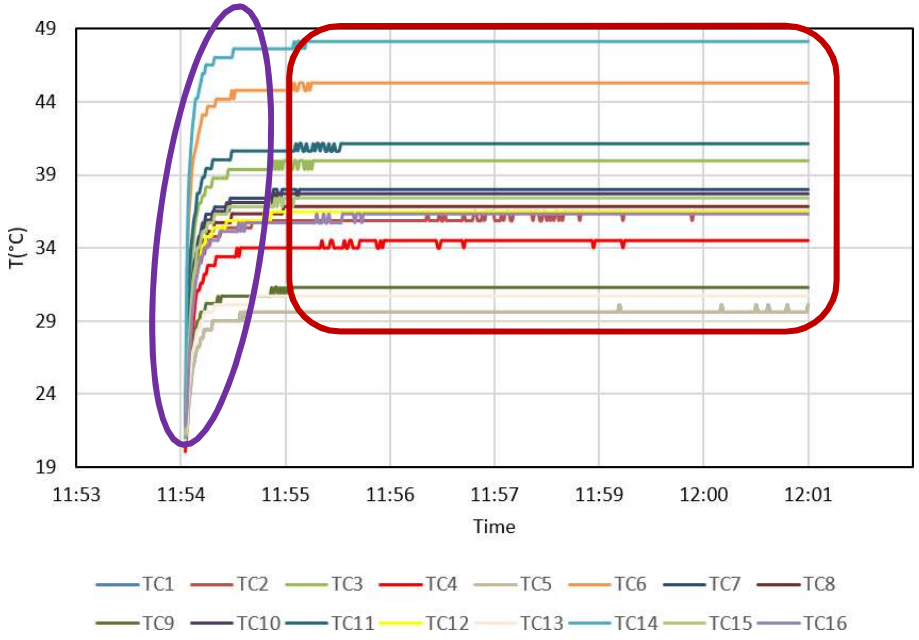
- Investigation of the cooling performances
  - Calorimetric measurements

- ❑ Max. heat load on the inner cavity wall ca. 220 W/cm² (10% of expected value in 2 MW CW gyrotron) → **MAIN CHALLENGE!**
- ❑ In comparison with Cu mock-up the mock-up with 100 µm Nickel layer has an increase of ca. 20% of the induced heat load.



Cooling tests

- Investigation of the cooling performances
  - Measurements of the temperature increase at different flow rates and heating power levels (transient and steady-state case)



Measured temperatures of KIT mock-up after 6 min heating with 3300 W and the total flowrate of 10 l/min

Upgrade of the test stand

- Increasing the measurement accuracy
  - New flow meter – 5 X higher accuracy up to 10 l/min (lower flow rate range).
  - New thermocouples – with reaction times < 0.1 s.
  - Increase of the sampling rate for factor 2.
- Improvements in EM simulations
  - Increase of mesh elements.
  - Increase of results spatial resolution.
  - Direct power calibration in EM simulations – calculated integral losses = measured calorimetric losses

Increasing of the heat flux

- **Rental device for comparisson tests**
  - **Installation of the induction heater with 4 x higher nominal heating power – MINAC 25/40 (25 kW CW power)**
  - **Perfoming the calorimetric measurements (estimation of the increase in the heat flux)**

- Insertion of the thin ferromagnetic rings into the cavity (increase of the losses)
- Coating of the inner cavity wall with > 300 µm Ni-layer

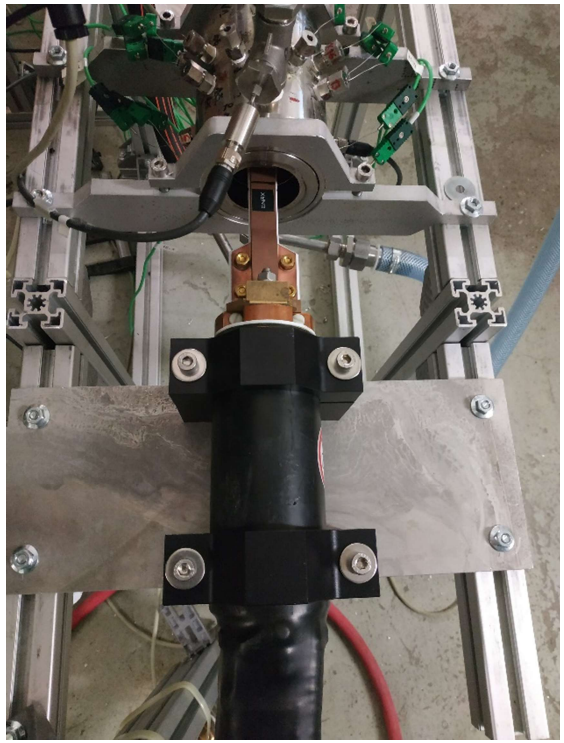
Increasing of the heat flux

- **Rental device for comparisson tests**
  - **Preliminary results**

Device	MINAC 6/10	MINAC 25/40
Nominal/**achieved** heating power	6/**3.6** kW	25/**17.2** kW
max. heat flux (under same conditions)	180 W/cm^2	730 W/cm^2
max. cavity ΔT @ 10 l/min	28.1°C	104.7°C
max. cavity ΔT @ 3 l/min	40.0°C	134.3°C

x 4

Upgrade with MINAC 50/80!!!



Compatibility

- Other proposals for cavity cooling
  - Micro-Channels cooling (IPP, H. Laqua)
  - Triply Periodic Minimal Surfaces cooling (PoliTo, L. Savoldi)
  - Spray cooling (KIT)

- KIT test set-up is compatible with all these alternative cooling techniques

Conclusion and outlook

- Experimental set-up at KIT for investigation of the cavity cooling techniques based on induction heating.
- Tests on mock-ups and results.
- Upgrade of the test set-up in order to increase the heat loads.
- Future steps: Tests with MINAC 50/80 and use of ferromagnetic inserts/layers in the cavity

Acknowledgements

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☺ Thank you for your attention ☺

Additional slides

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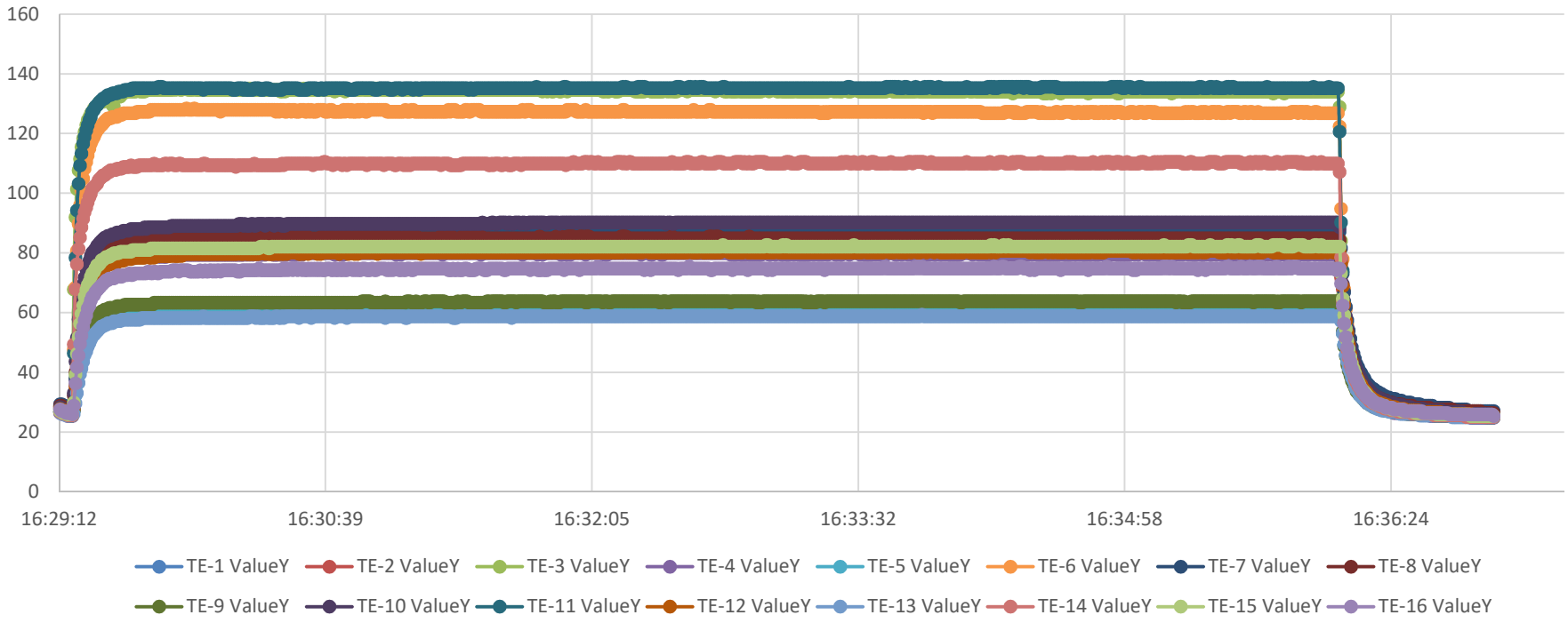
Measrued temperatures @ 10 l/min and 17 kW



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