Update on Design and Tests for the Beam-Beam Long-Range Wire Compensation

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WP2/WP13 HL-LHC Satellite Meeting – Long Range Beam-Beam Wire

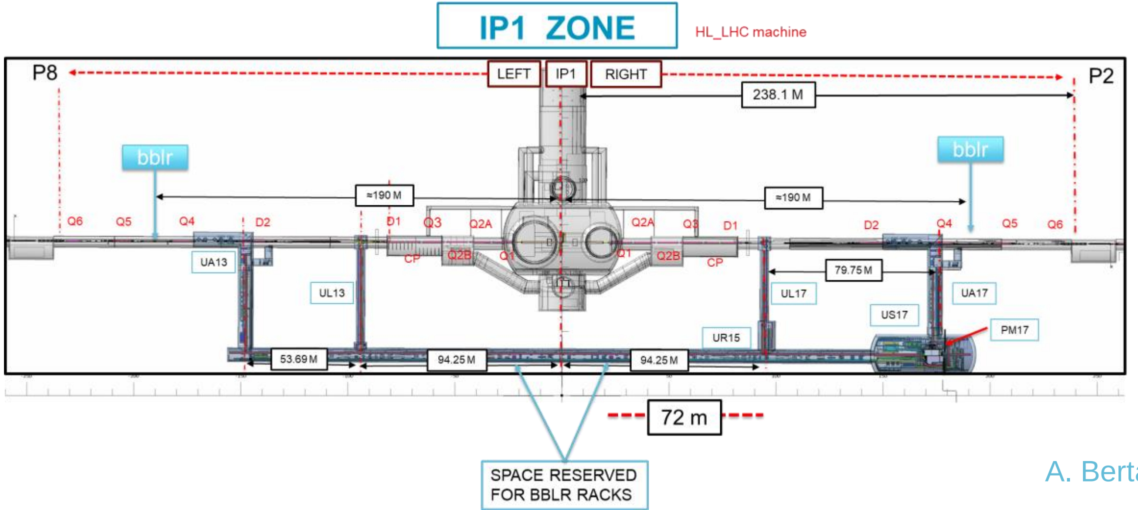
Uppsala 23.09.2022 (remote presentation)

Outline

- Context
- Design Assumptions
- Design Features and Layout
- Simulations
- POC Experimental Results
- Conclusions

Context

- **Beam-Beam Long-Range Compensators** with **physical DC wires** are considered a valuable options for HL-LHC to increase dynamic aperture at small crossing angles
- A space reservation of **4.5 m** on both beams was made on either sides of **IP1** and **IP5**, allowing 1 unit per beam per location



Initial Design Assumptions

- These assumptions are a **preliminary set of requirements** defined for mechanical design purposes:
  - **1 wire per beam and per side** of **IP1** and **IP5** $\rightarrow$ **8 wires**
  - **Single wire** positioned in a vacuum chamber per beam
  - **Round wire** cross-section
  - Wire total **active length 3 m**
  - **450 Am DC** per wire, i.e. **150 Am/m**
  - Wire positioned **in the shadow of Tertiary Collimators** (>10.4 σ)
  - Wire to beam **orientations**: horizontal (IP1) and vertical (IP5)
  - **Beam and RF losses** considered **negligible** vs Joule heating

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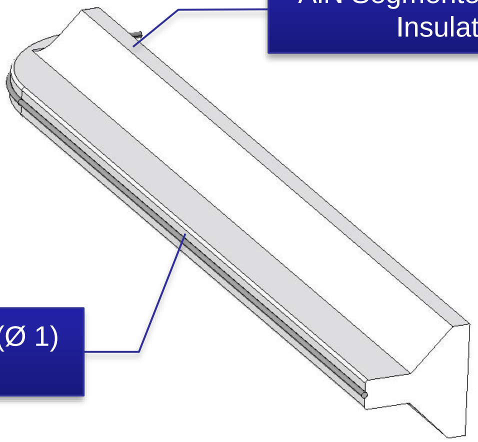
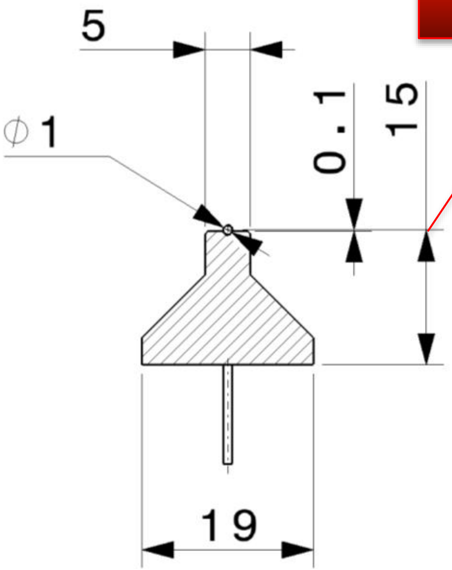
The Concept

- Use a slim, light design with a **thin, bare, metal** wire, allowing to move as close as necessary to the beam, while minimizing interactions with beam particles
- Bond the metal wire onto a support being both an **electrical insulator** and a **thermal conductor** (**ceramic**)
- Keep design simple and affordable, using a **mobile vacuum chamber**, integral with wire, which can be shifted horizontally and vertically. Host **two parallel assemblies**, side by side on Beam 1 and 2
- Ease fabrication, assembling and installation, splitting the **active length** (**3 m**) in **three independent modules**
- Each module mounted and aligned on a **single support** structure, which can be rigidly **actuated in both horizontal and vertical** directions

Main Design Features: Wire and Insulator

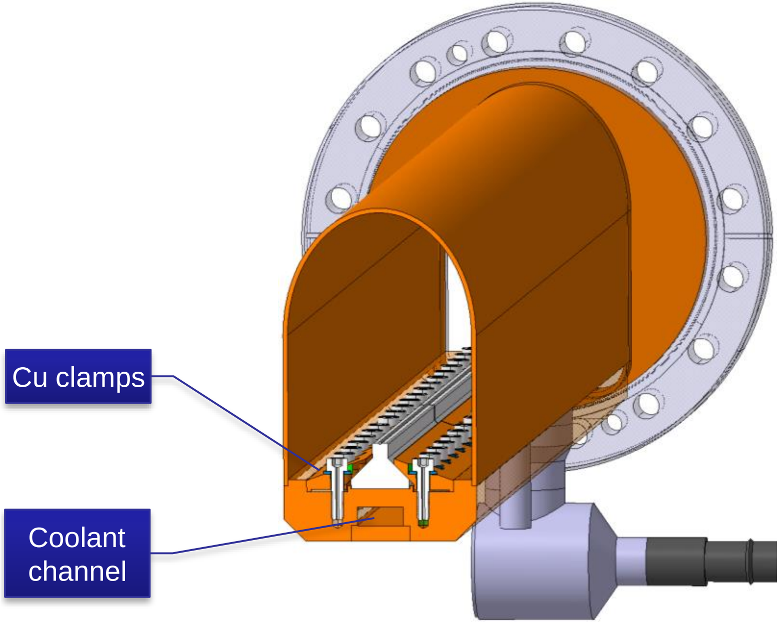
- We assume a **1 m**-long **Mo wire** with **150 A** current bonded to **AlN insulator**
  - **Vacuum brazed** solution
  - Mo wire has higher electrical resistivity compared to Cu, but is better **matching ceramic (AlN) CTE** and is refractory (higher robustness)
  - **Baseline** diameter is **Ø1 mm** for performance reasons (risk of temperature run away …). **Ø0.8 mm also investigated** although riskier …

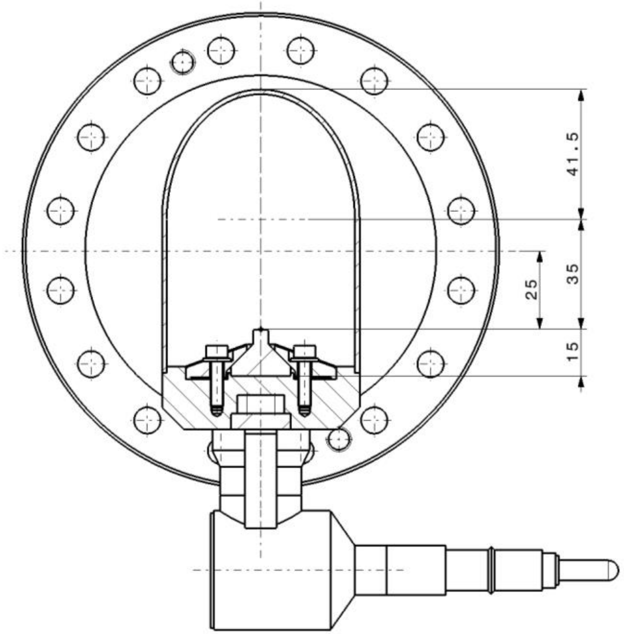




Main Design Features: Housing

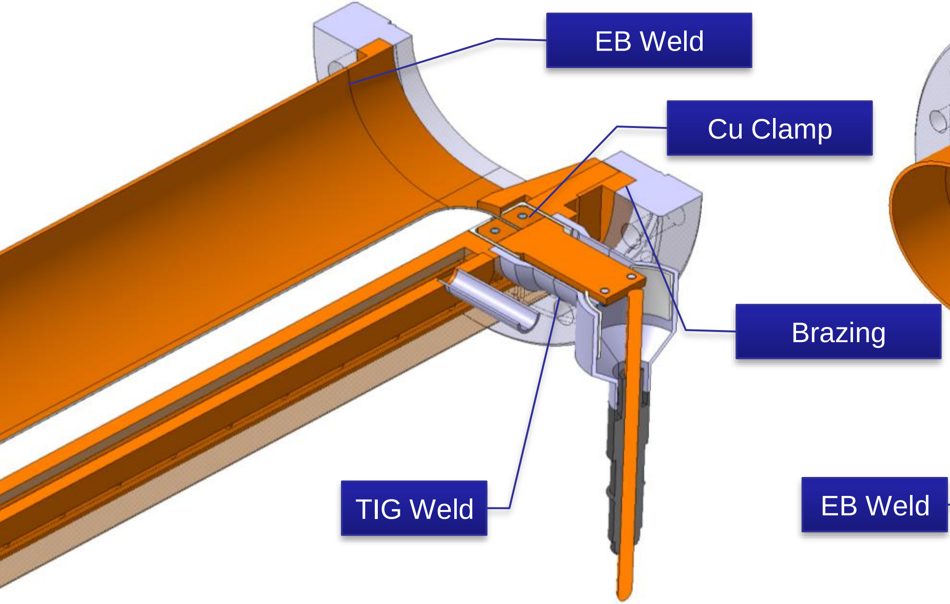
- **Insulator** with wire is **mechanically clamped to a Cu-based housing**, via controlled-torque screws
- Cu clamps to **minimize RF impedance**
- Wire **active length 1 m**. Given AlN fabrication constraints, **several insulator modules** to be assembled (**up too 350 mm long**)

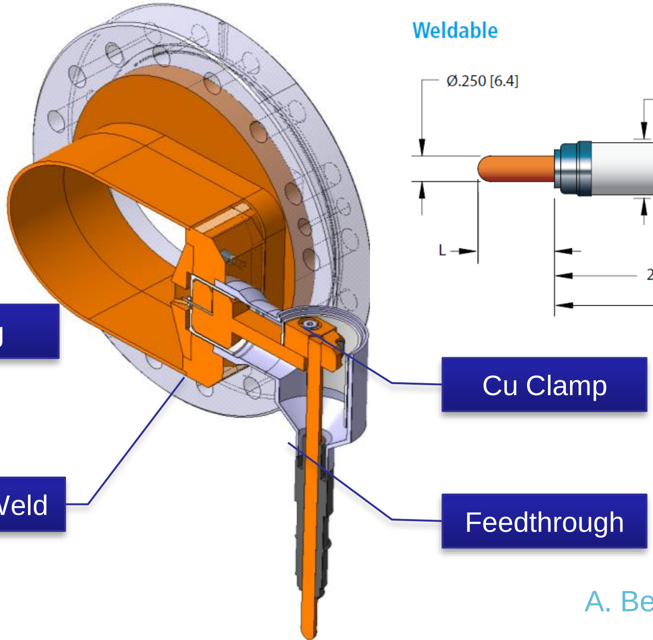


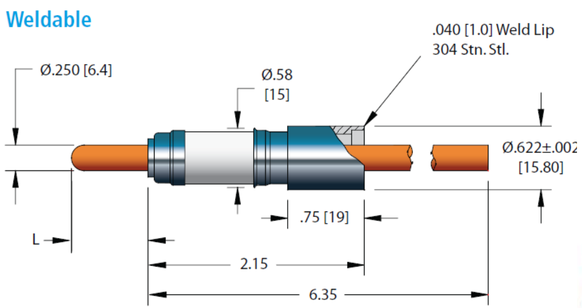


Main Design Features: Vacuum Chamber

- Water **cooling channel** machined in the Cu housing, closed with brazed cover
- **Commercial feedthrough** connection carrying **up to 185 A**. If more current is needed, liquid-cooled feedthroughs should be adopted
- Cu half-shell welded to the housing
- Stainless steel flange brazed to copper and then welded to vacuum chamber

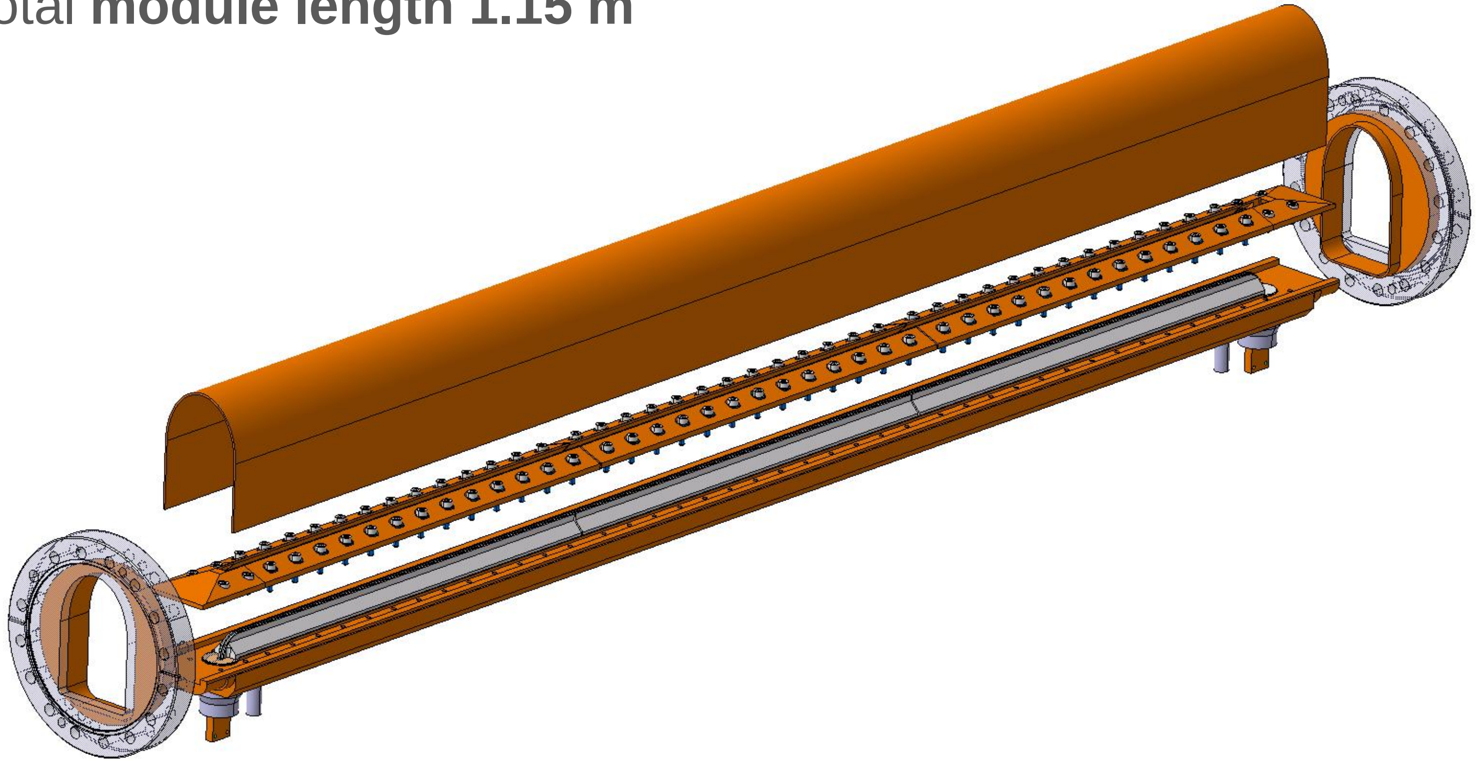






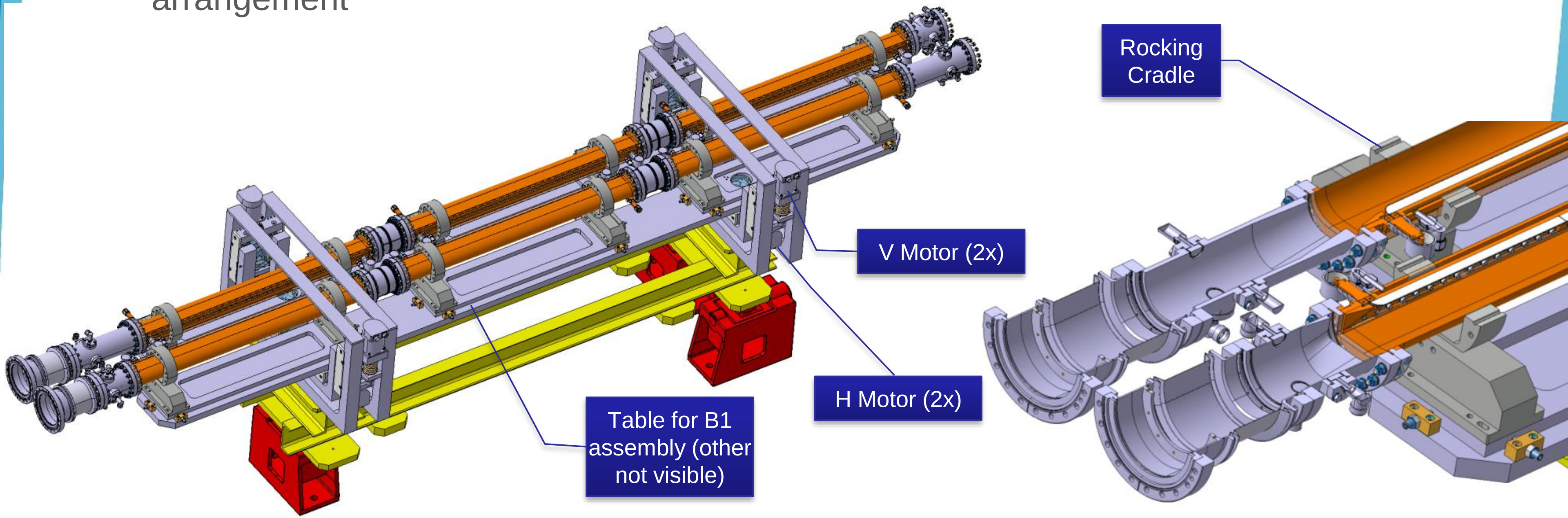
Main Design Features: Individual Module

- Wire **active length** (straight part) **1 m**
- Total **module length 1.15 m**



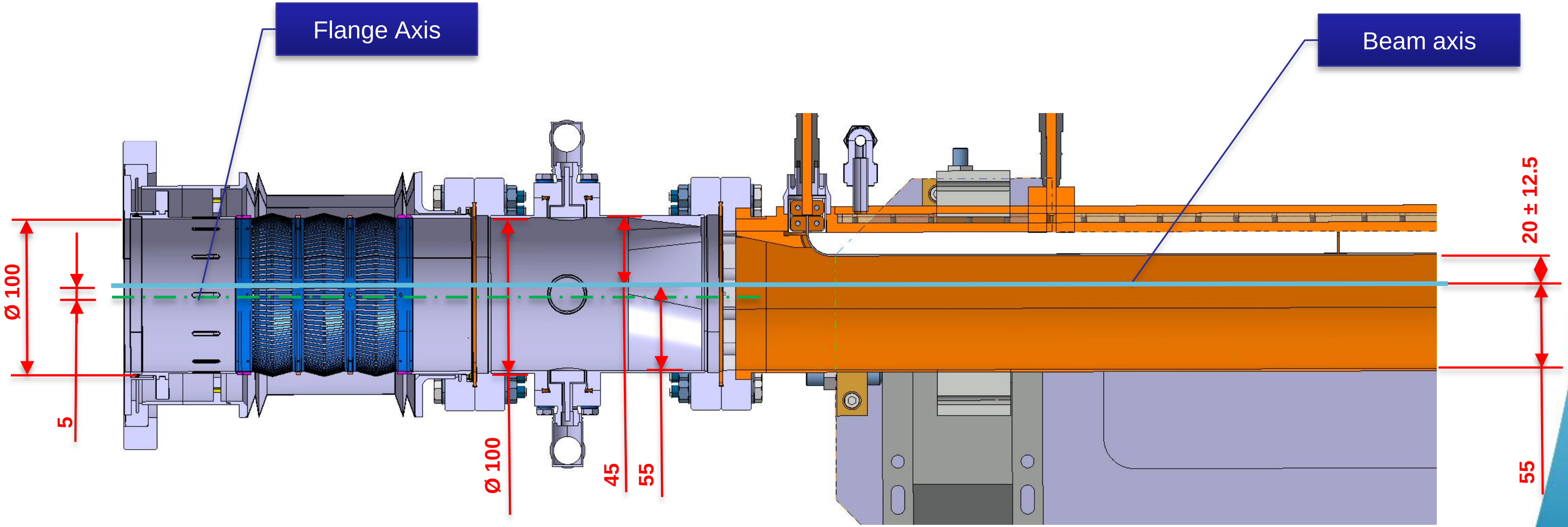
Main Design Features: Assembly Layout

- **Two parallel assemblies** on a **single support** with **independent actuation** tables
- **4 motors** per table. **~ 30 mm total stroke** in both **H** and **V** directions
- Each assembly on **rocking cradles** allowing **360º manual rotation** of the wire modules
- Risks of interference addressed by shifting B1/B2 assemblies and 90º feedthrough arrangement



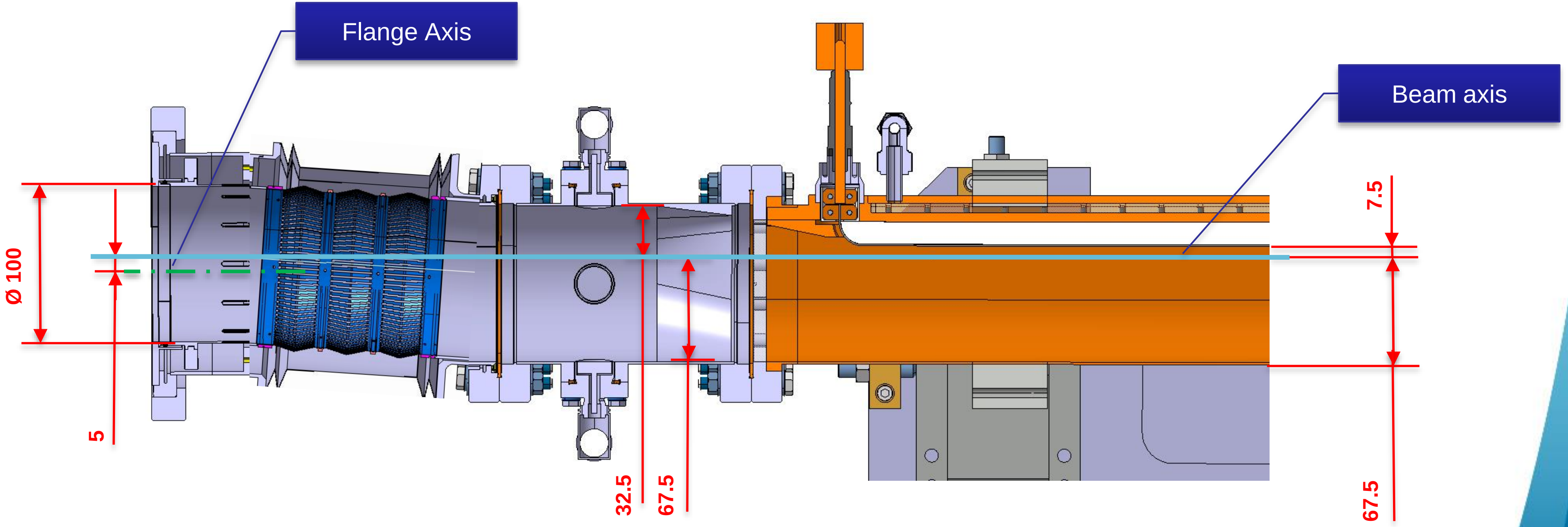
Main Design Features: Lateral Stroke

- Neutral **Position** (straight bellows – wire 20 mm from Beam)
- Actual **useful stroke ± 12.5 mm**



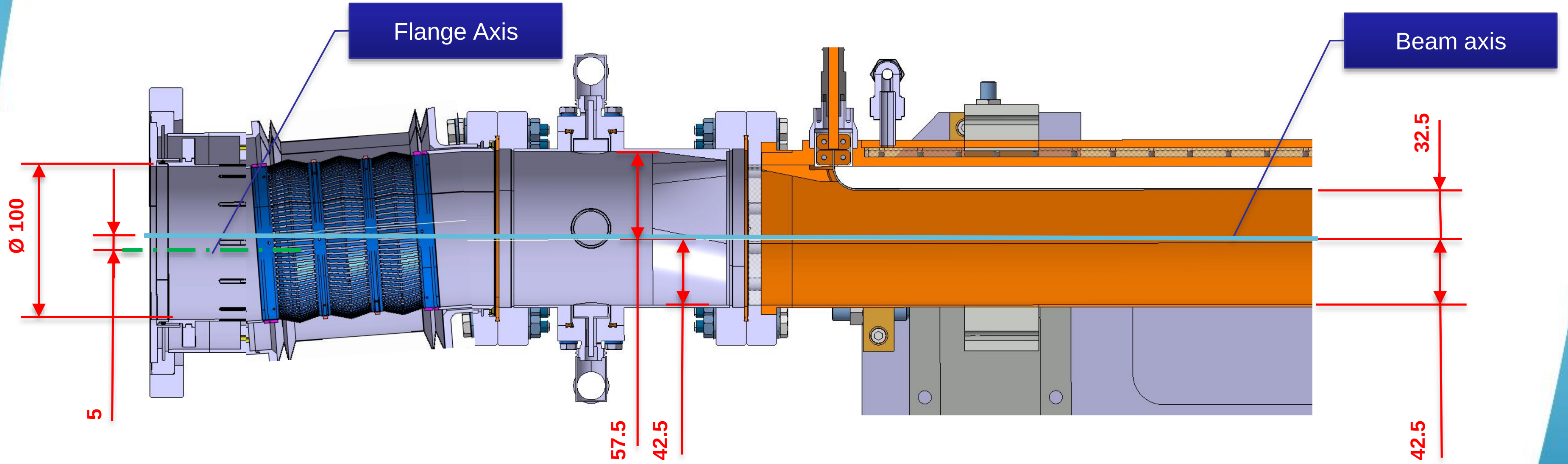
Main Design Features: Lateral Stroke

- Wire **Full-In Position** (7.5 mm from Beam – 12.5 mm stroke from neutral)



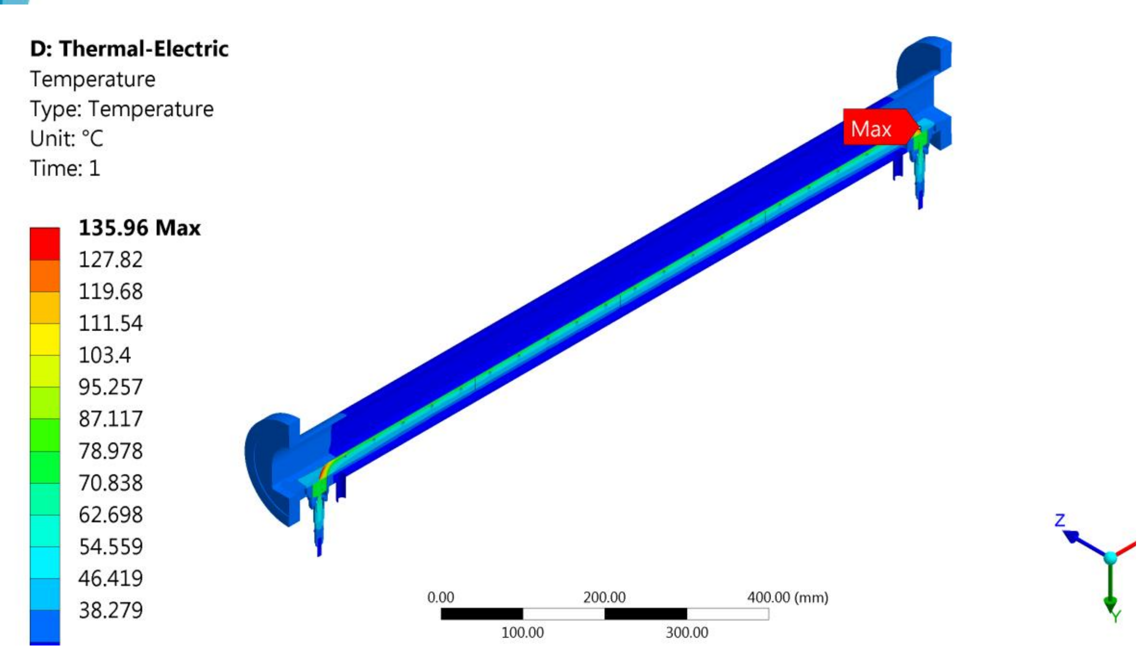
Main Design Features: Lateral Stroke

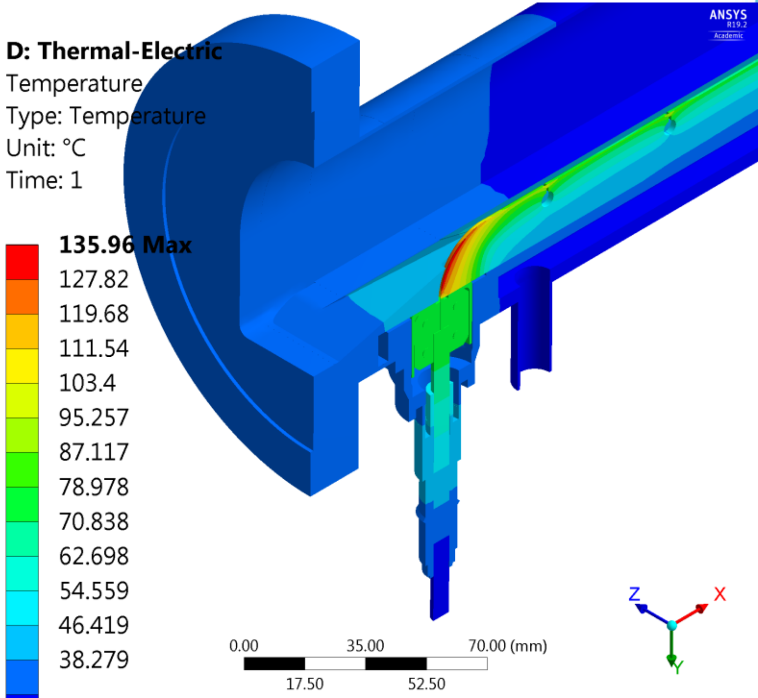
- Wire **Full-Out Position** (32.5 mm from Beam – 12.5 mm stroke from neutral)



Preliminary Numerical Simulations

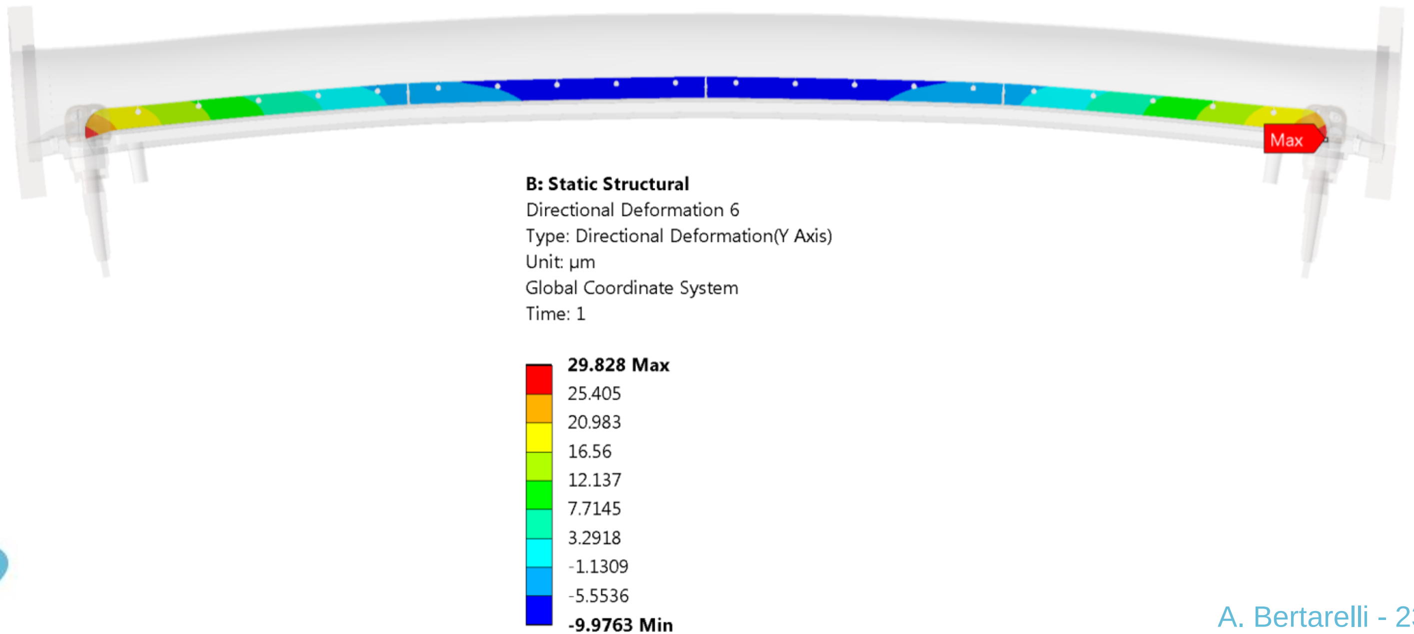
- With a ∅ 1 mm **Mo** wire and **150 A per module**, Joule-effect power to be dissipated is **~ 2.1 kW** corresponding to **~ 14 V** (~ 90 mΩ)
- Maximum temperature **~ 90 °C** in straight wire (up to **~ 140 °C** in the end transitions)
- Water coolant circulating at **~ 1.5 m/s**, **~ 12 L/min**





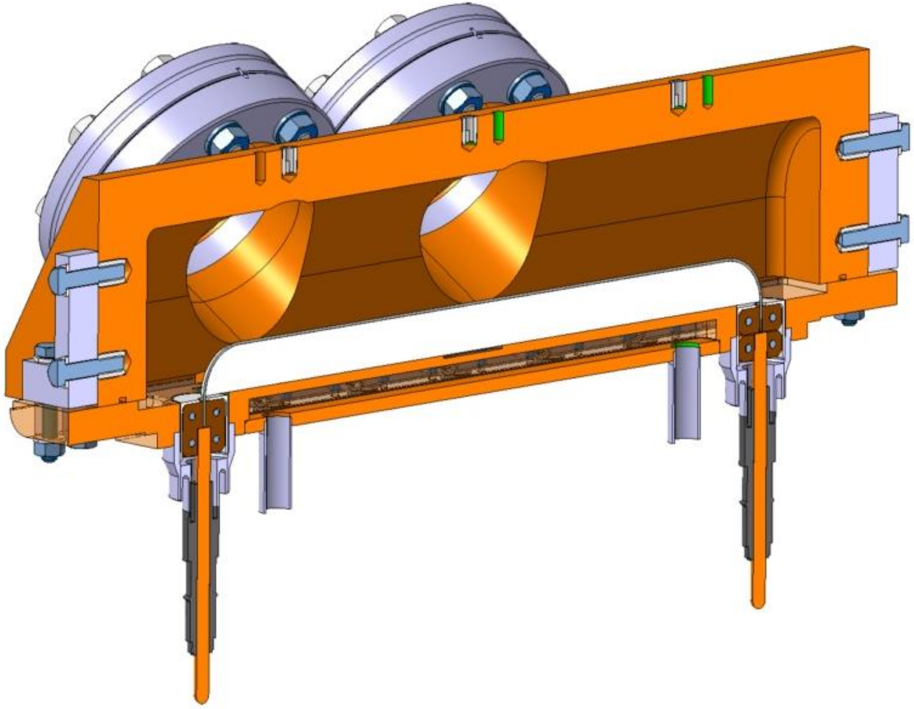
Preliminary Numerical simulations

- Estimated deflection of the vacuum chamber in operating conditions is ~ 30 μm
- Simulation to be updated and refined to take more realistic boundary conditions into account.



Proof of Concept - Demonstrator

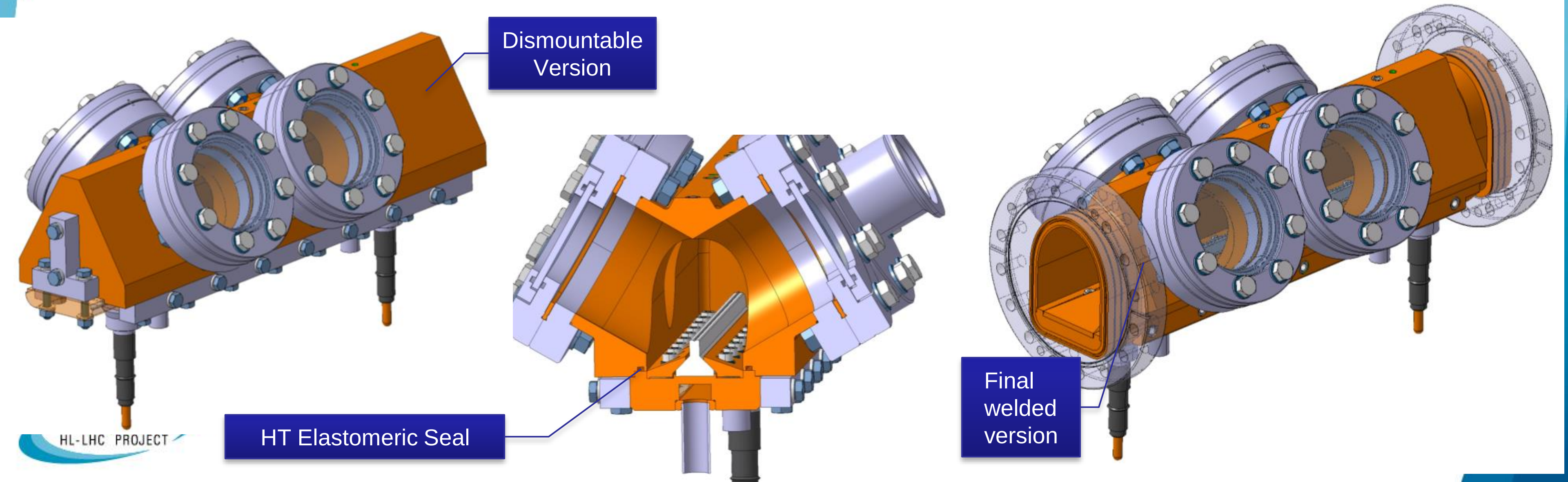
- Vacuum Brazing is the most critical step in the process (few mm gap between wire and cooler may induce a thermal runaway of hundreds degrees …)
  $\rightarrow$ **Proof of concept proposed**
- On this basis a **low-cost short demonstrator** (290 mm long) was built and tested to validate the concept and perform online measurements
- **Optical viewports** were foreseen to measure wire and insulator temperatures (IR camera) and wire deflection while varying current …



Proof of Concept - Demonstrator

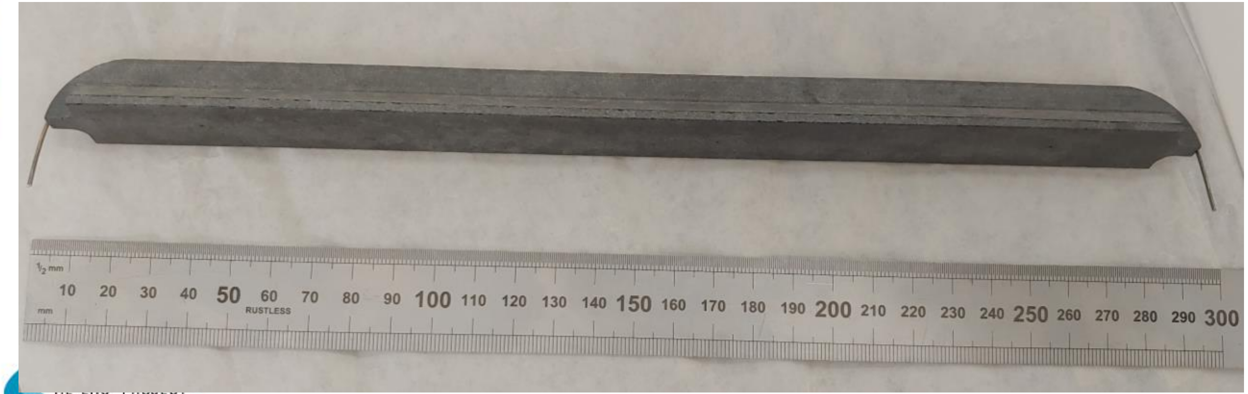
- The demonstrator was designed to allow testing **two variants**:
  - A first **openable version** allows mounting and dismounting the insulated wire and perform all thermal measurements under primary vacuum → **tested end of 2021**
  - A second **welded version,** to be executed if required, with limited modifications to the chamber to test UHV performances and materials outgassing → **not built yet**

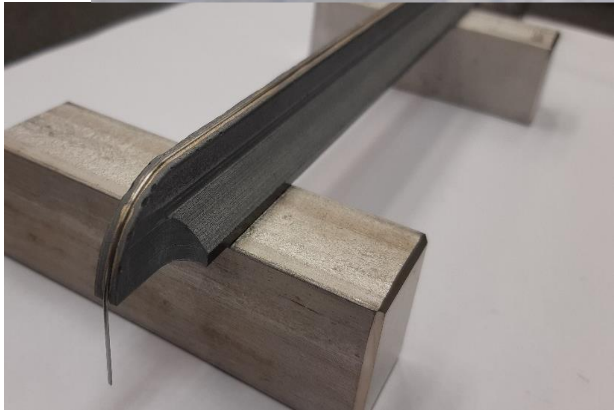
  ...



Proof of Concept (POC) - Demonstrator

- **Two wire diameters** (Ø0.8 and Ø1 mm) **successfully brazed** on AlN housings at EN-MME main workshop
- Good adhesion throughout the length, only minor braze lacks at the ends
- AlN also thermo-physically characterized to ascertain its thermal properties as a function of temperature
- Mechanical components procured or fabricated by EN-MME

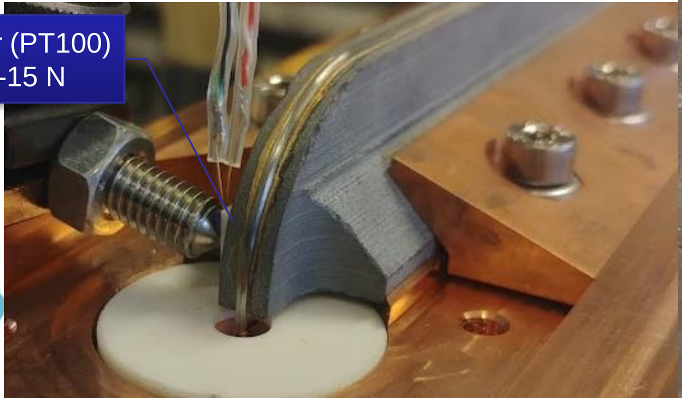


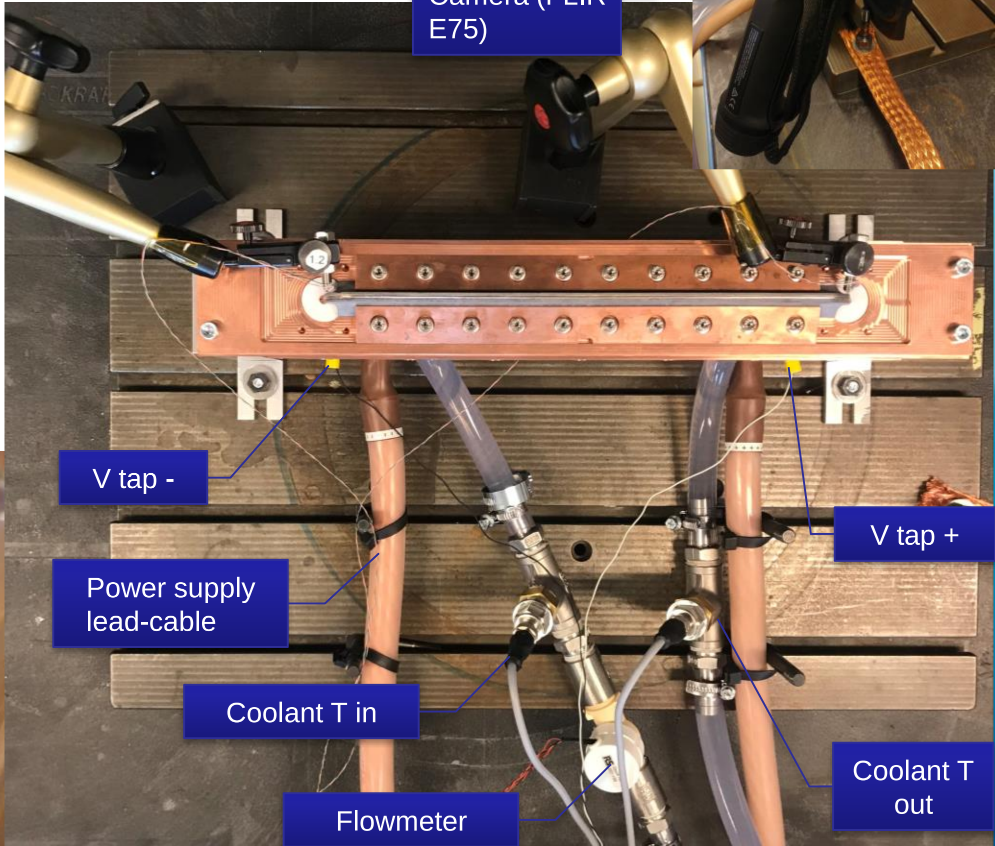


Proof of Concept - Demonstrator

Demonstrator Testing

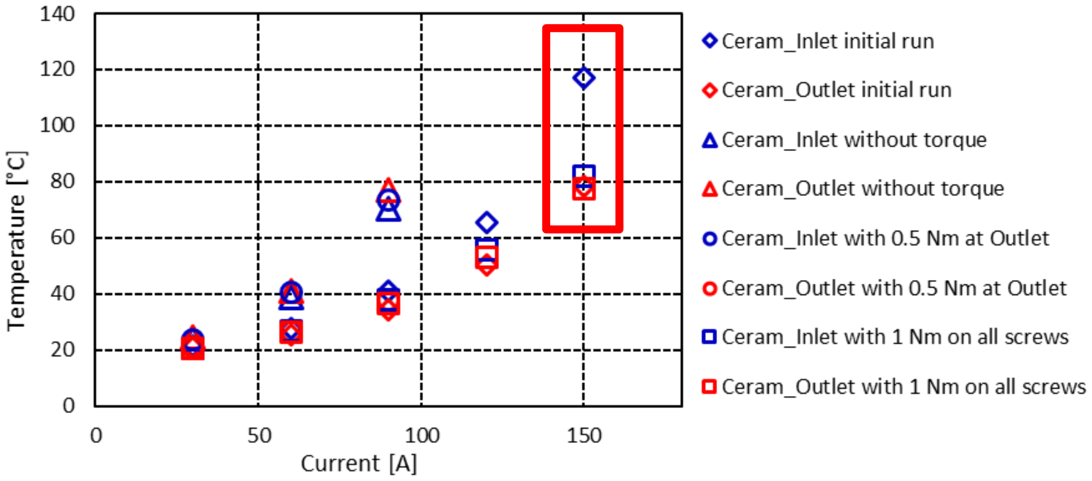
- POC tested Oct-Dec ’21 in EN-MME Mech Lab. Initially without chamber (wire exposed to air)
- DC Power supply up to 400 A and 15 V
- Water cooling with flow rate ~ 11 L/min
- Instrumentation including
  - IR Thermal Camera
  - Voltage taps
  - Temperature sensors close to hot spots
  - T sensors at inlet and outlet
  - Flowmeter



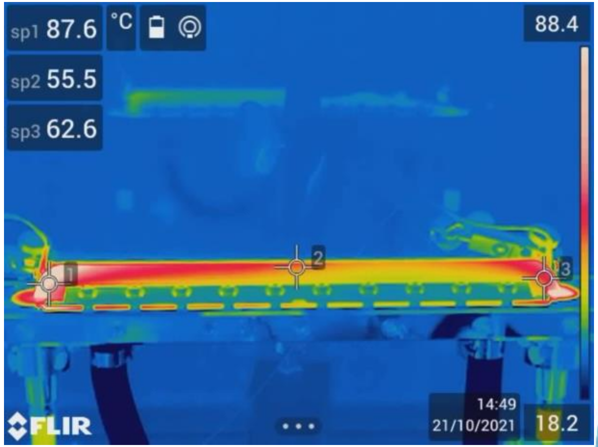


1 mm Wire – In-Air Results

- In-air tests were performed both with stepwise and single bursts up to 150 A
- Initial unbalance between two ends was corrected once higher, uniform screw tightening torque was applied
- Temperature at control points slightly below numerical predictions (at 150 A ~ 80°C vs. ~ 100°C)
- T in straight part in line with simulations



150 A; 1-mm wire; Uneven screw torque

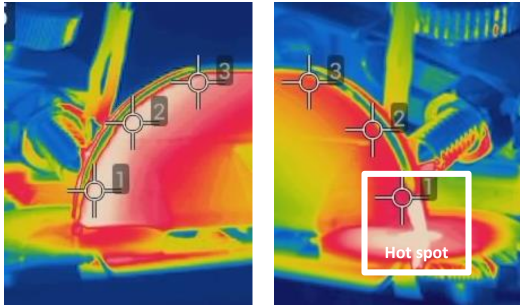


150 A; 1-mm wire; 1 Nm on all screws

1 mm Wire – Oxidation at 180 A in air

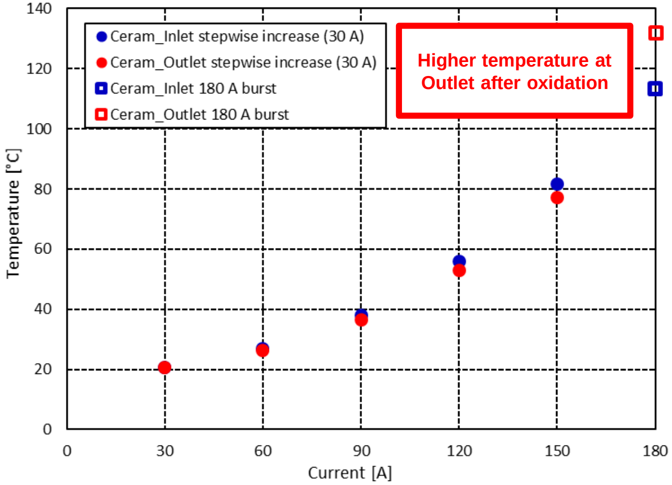
- Clear indications of oxidation were found after test at 180 A in air, mostly at the outlet-side transition between insulator and wire clamp where a hotspot is created for local lack of brazing …
- Mo oxide tends to peel off reducing the effective wire cross section
- This phenomenon is absent in under vacuum testing

Inlet **Outlet**



Oxidation at Outlet side

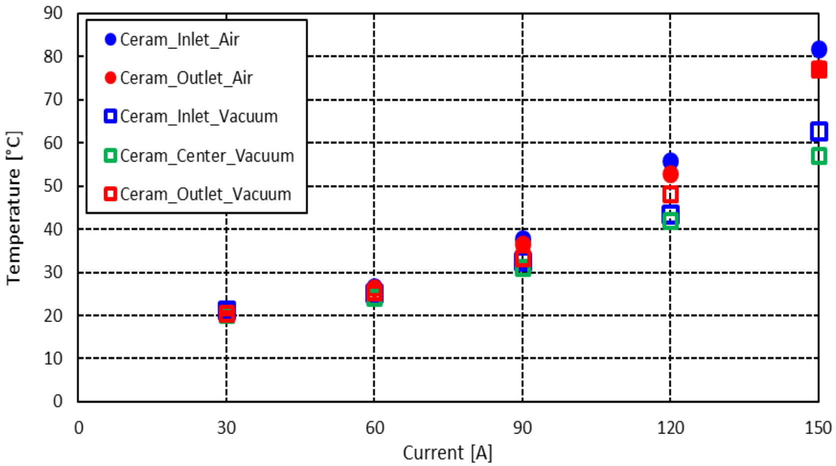
Outlet side after cleaning



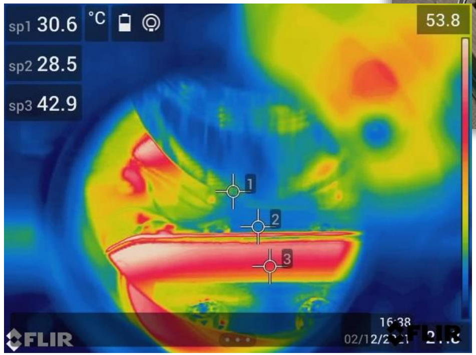
1 mm Wire – Under Vacuum Tests

- Similar tests were carried out under primary vacuum
- One additional T sensor was added at the centre of the insulator
- Results showed even lower temperatures compared to in-air tests, despite the lack of natural convection, thanks to thermal diffusion in the chamber dome

Stationary temperatures in air and in vacuum
(Comparability limited due to oxidized wire in vacuum tests)

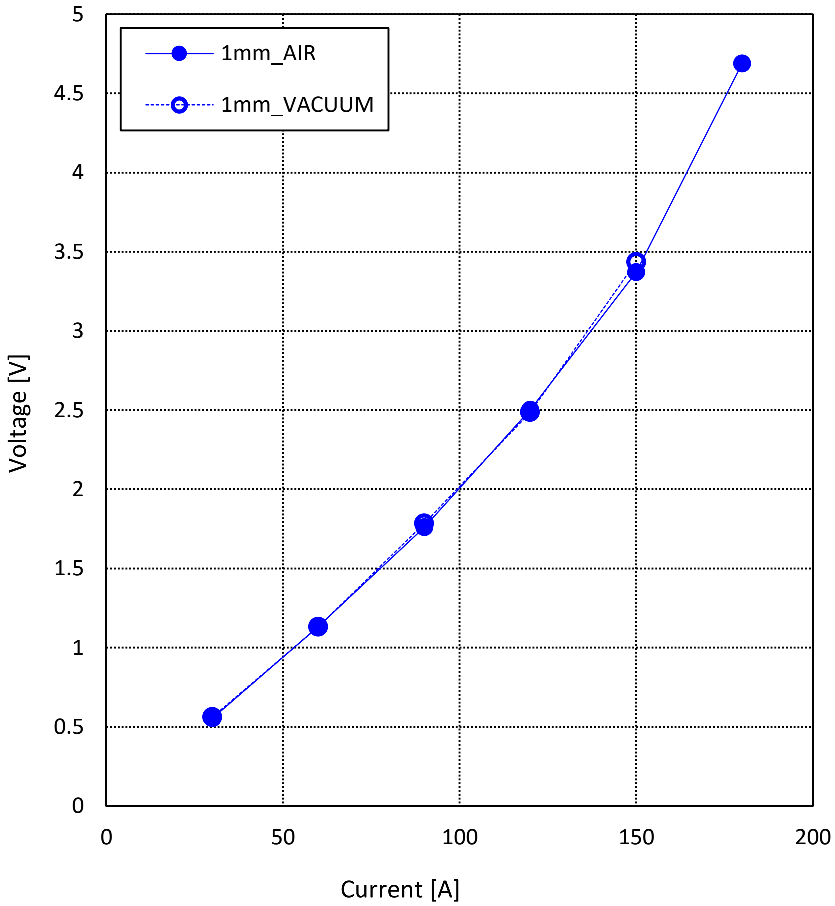


View on Inlet side at 150 A stationary



1 mm Wire – Voltage Drop

- Voltage drop is around 3.5 V at 150 A, corresponding to ~ 12 V for a 1 m long wire (rough extrapolation)
- This is slightly lower than predictions and might be related to the contribution of the conductive brazing alloy … any effect on electrical field?



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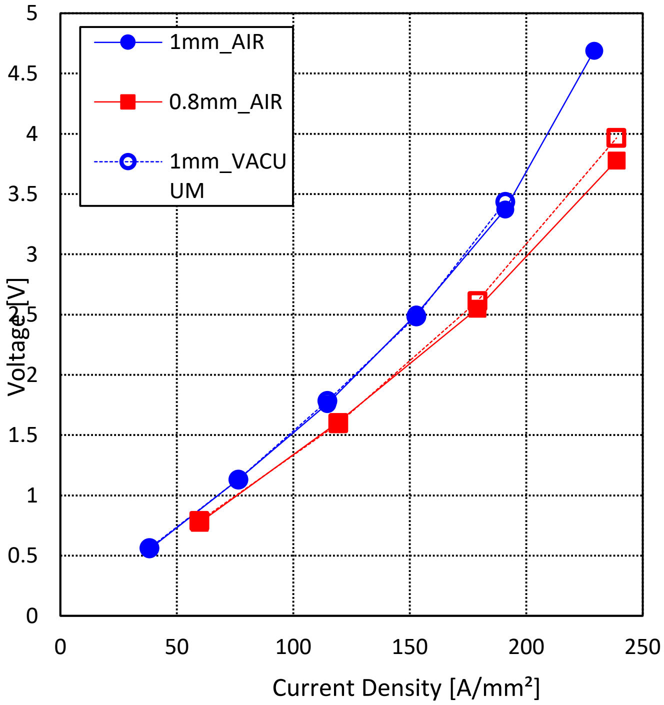
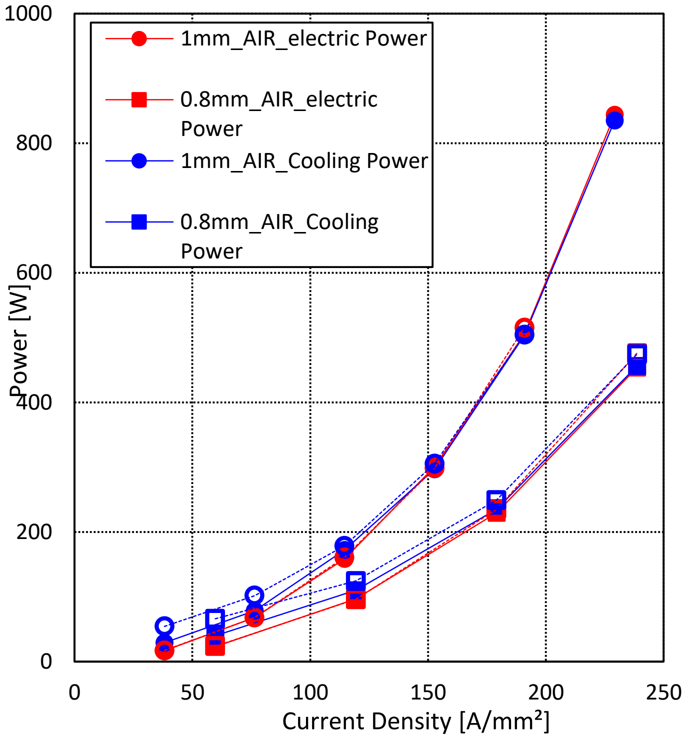
Demonstrator Testing – 0.8 mm Wire

Demonstrator Testing – 0.8 mm Wire

- Initially the wire performed well with performances scalable to 1 mm wire …
- However, eventually a thermal runaway developed during in-air tests due to an accelerated oxidation at one end, leading to wire breakage …



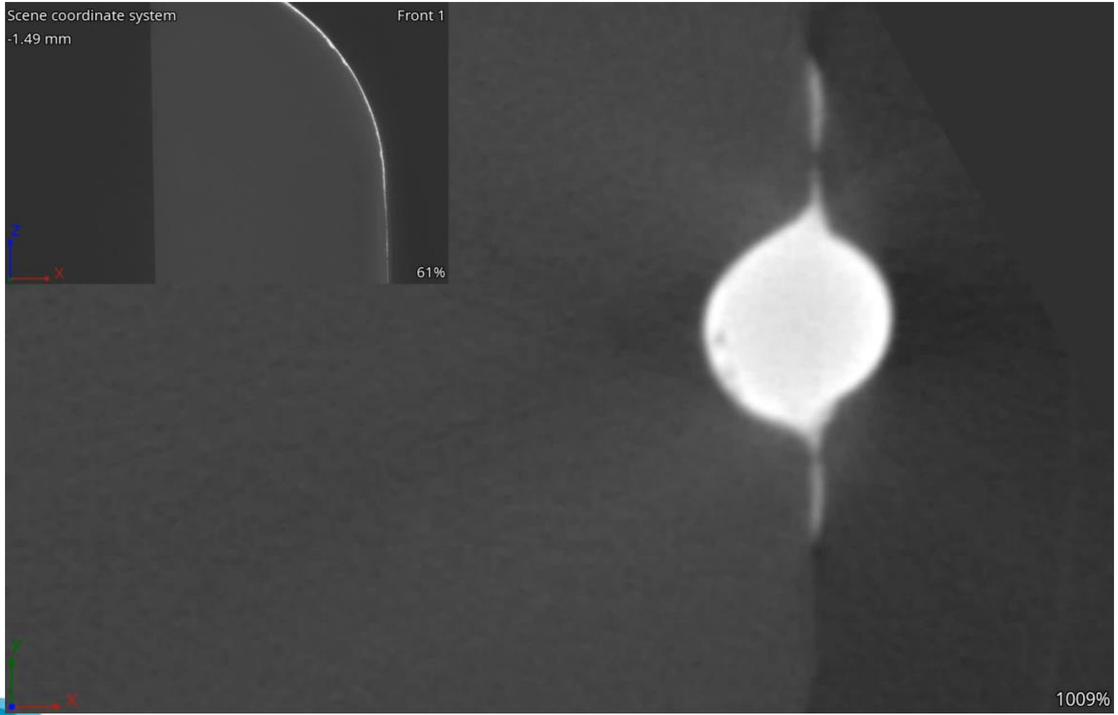


Outlook

- A simple, low-cost, modular design was explored, allowing a certain scalability as to number of modules, current and dimensions
- No showstoppers identified for thin Mo naked wire (Ø ~ 1 mm) brazed onto a ceramic insulator
- Preliminary design ignored several key aspects (e.g. beam and RF losses, fabrication tolerances, etc.) which should be the object of a proper design study
- A demonstrator was manufactured and tested to validate the concept, in particular the delicate wire brazing
- Results showed the viability of the concept for the Ø1 mm wire, with measured temperatures and voltage in line with or better than expectations. However, special attention should be paid to effective brazing, specially in transitions to limit hotspots …
- The effect of brazing alloy benefits thermal response, but its impact on electromagnetic performance should be investigated
- Ø0.8 mm wire failed during tests. Even if the main root cause (oxidation) is absent under vacuum, this indicates that too small cross sections are risky
- Ready for a full-fledged design (interfaces, motorization, integration, RF and EM optimization …) to fully validate the concept

Thanks for your attention

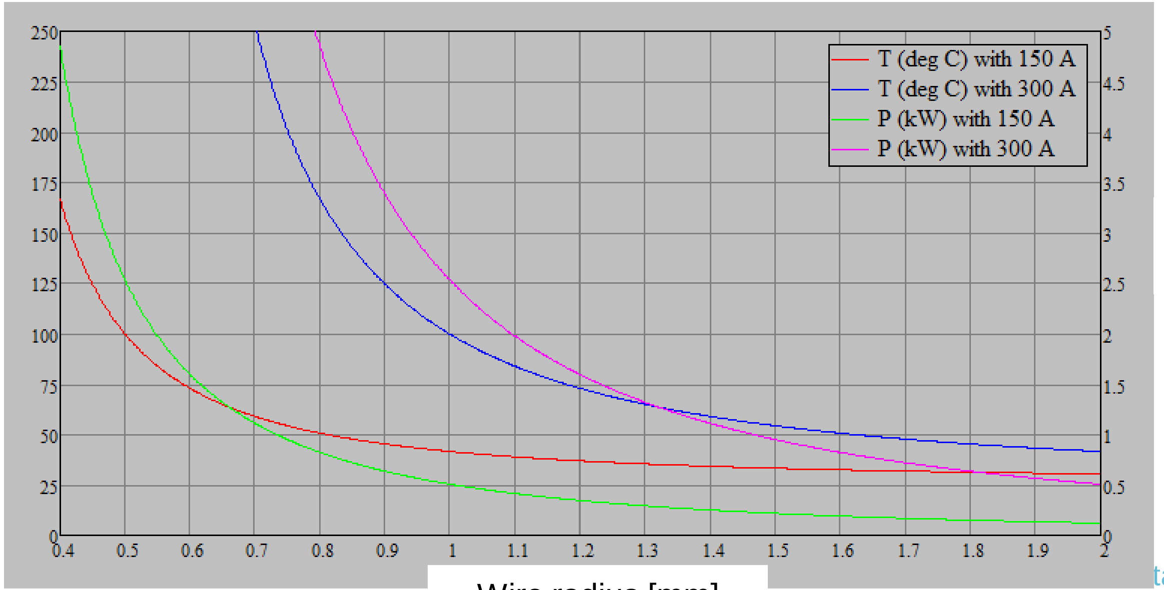
Proof of Concept - Demonstrator



The Idea

- How much current can the wire carry? It depends on its cross section …
  - A linear relationship exists between Current and Power (or max temperature) allowing a simple scaling of the design, if needed.
  - Mo wire used in the example below …

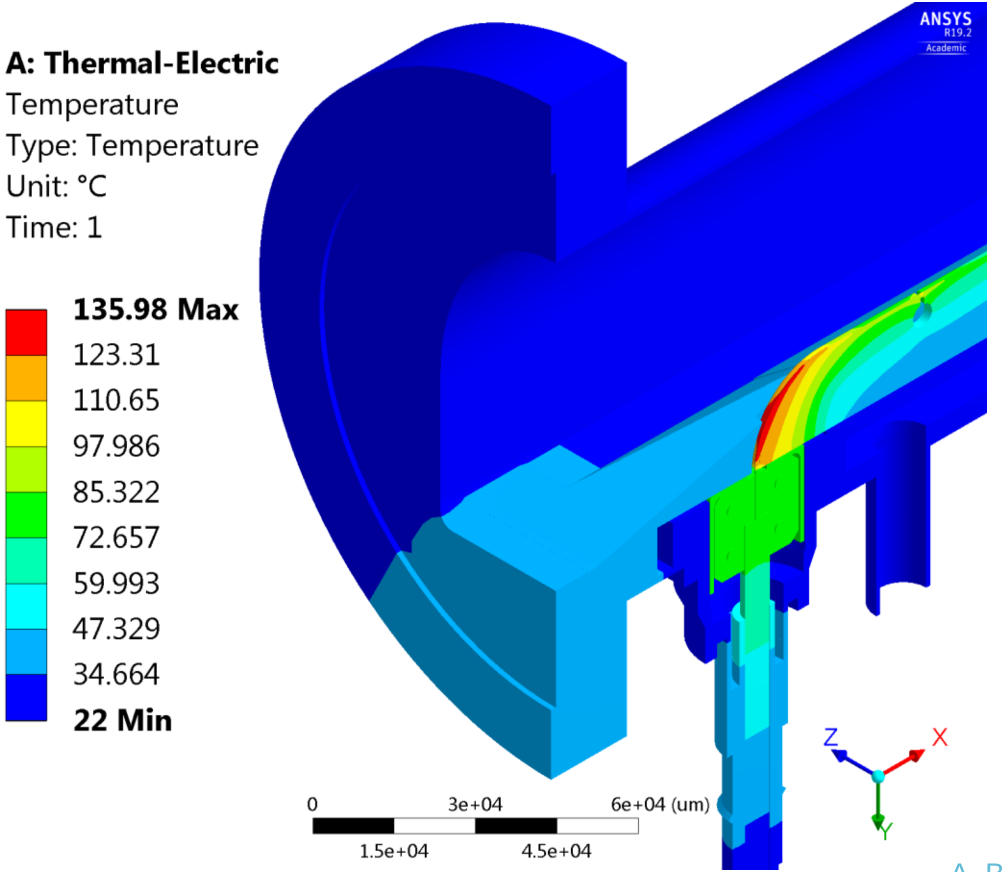
Wire Temp. [°C]



Power [kW]

Wire radius [mm]

Numerical Simulations



Vacuum Tests

- Mounting of vacuum chamber with connected vacuum pump

- Sensors:
  - Analogous to tests in air, 2 PT100 were installed at Inlet and Outlet side
  - One additional PT100 on the ceramic at the center between Inlet and Outlet
  - Usage of thermal camera limited due to the geometries of the windows

Vacuum test results with 1 mm wire

- Temperatures in vacuum are lower compared to the ones in air

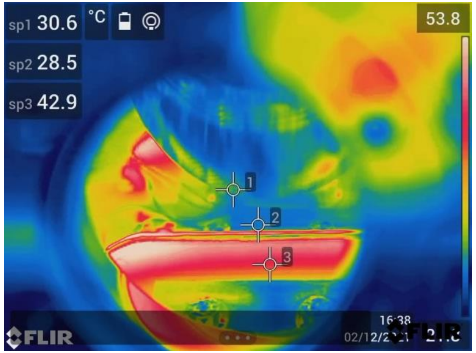
→ Copper chamber increases the heat dissipation surface and thus, reduces the temperatures

→ Influence of convection in air on heat dissipation is negligible

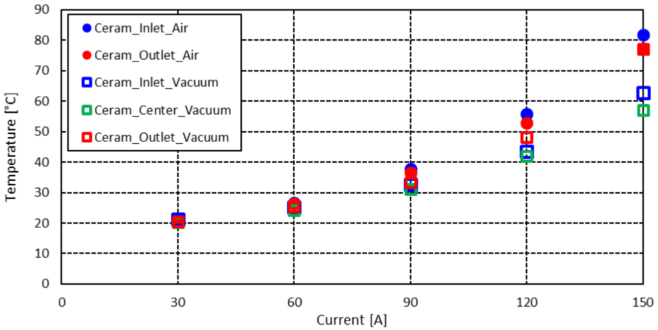
- Air: $T_{Inlet} > T_{Outlet}$
- Vacuum: $T_{Inlet} < T_{Outlet}$

→ Caused by previously occurred oxidation at Outlet side

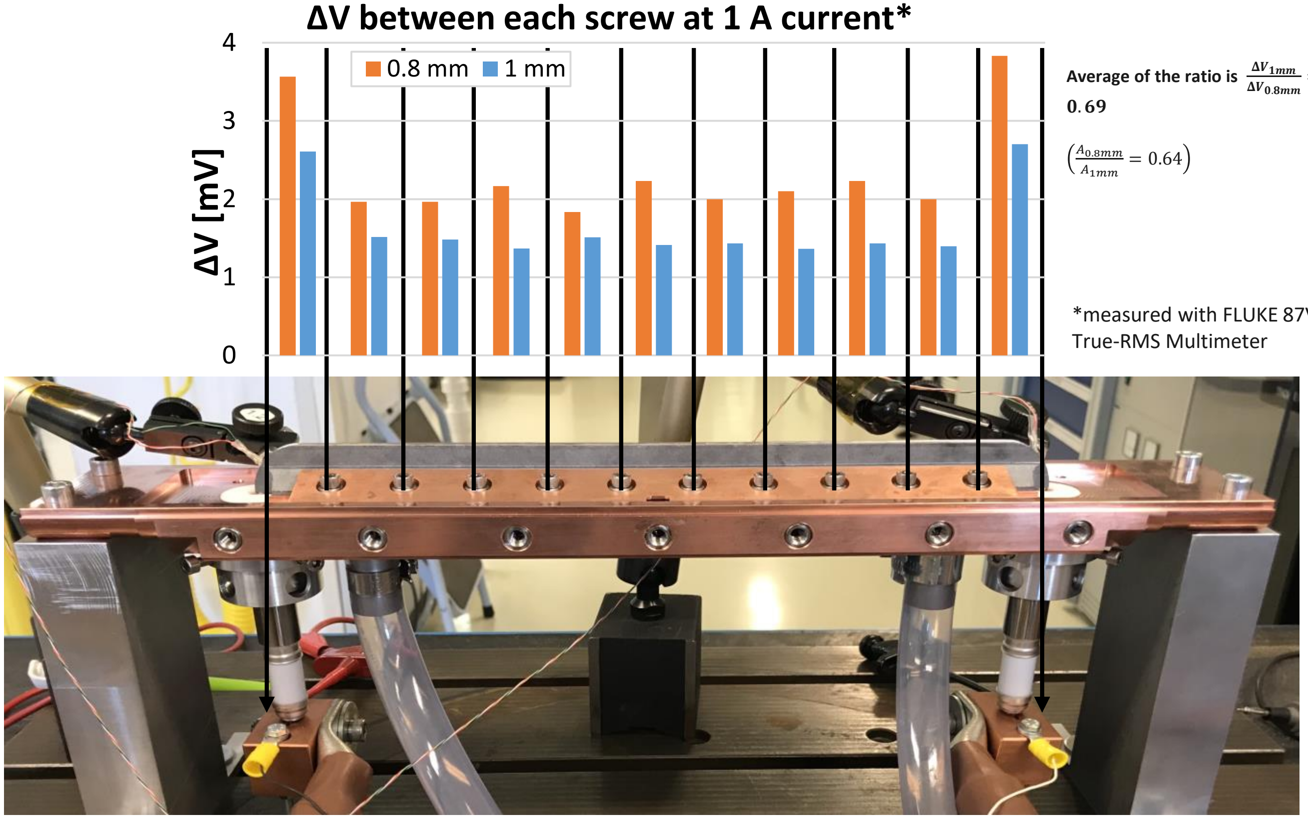
View on Inlet side at 150 A stationary



Stationary temperatures in air and in vacuum (Comparability limited due to oxidized wire in vacuum tests)



Comparison of Resistance in both wires



Average of the ratio is $\frac{\Delta V_{1mm}}{\Delta V_{0.8mm}} = 0.69$

$\left(\frac{A_{0.8mm}}{A_{1mm}} = 0.64\right)$

*measured with FLUKE 87V True-RMS Multimeter