



Demountable Coil Technology for Improved Access and Cost Efficiency in Fusion Power Plants

T. Bagni, A. Herrmann, J. Jankovsky, N. Mitchell – Gauss Fusion Group, Germany

S. Runkel, A. Navitski – RI Research Instrument, Germany

M. Noe, N. Bagrets, D. Garfias Davalos, S. Schlachter, K.-P. Weiss – Karlsruhe Institute of Technology, Germany

M. Bombardieri, G. Celentano, A. Di Zenobio, A. Masi, L. Muzzi – ENEA, Italy

Sat-Mo-Or4-02 MT29 – July 5, 2025 – Boston, MA

CONTENT



- 1 Motivation
- 2 Demountable coils
- 3 Development strategy
- 4 Single joint
- 5 1:1 Mock-up
- 6 SULTAN samples
- 7 HTS conductor and joint development
- 8 Demountable Model Coil

GAUSS FUSION DESIGN

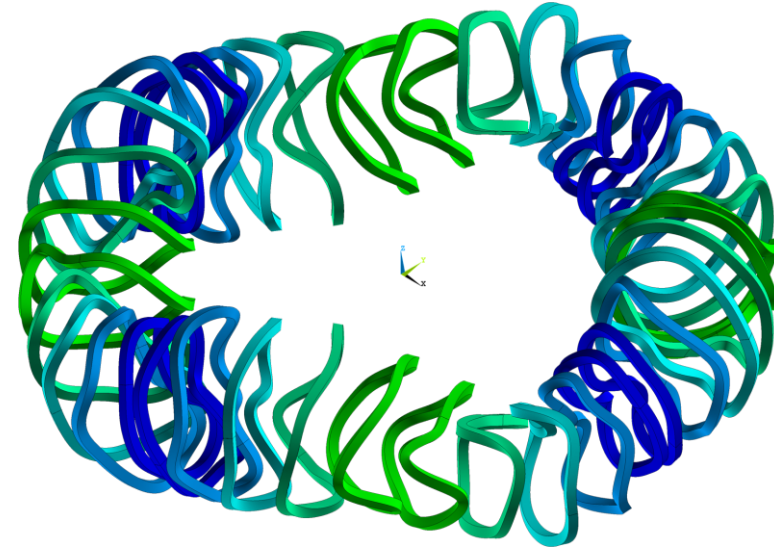
Stellarator GIGA



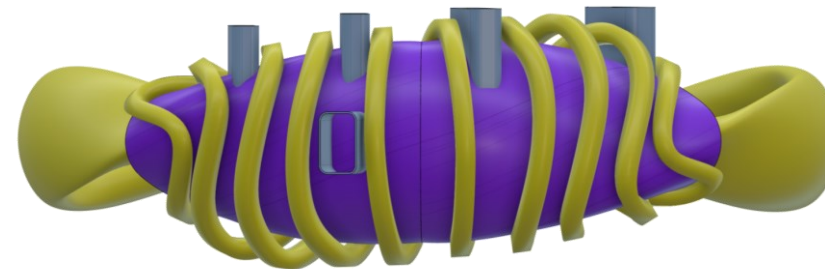
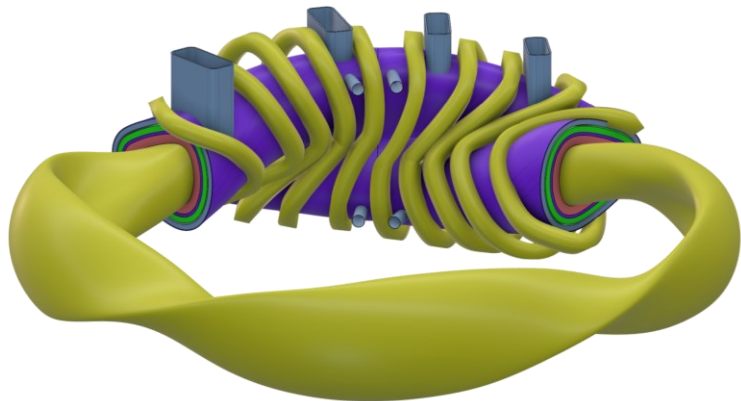
Sizing of GIGA:

- 3GW thermal, 1GW electric
- First wall neutron load 1MW/m² (consistent with FW/blanket life of 5 years)
- Magnet and vacuum vessel life 40years
- Volume: 1500 m³
- Field periodicity: 4
- Coil Current 12.2MAT
- Max B-field on axis: 6 T (170 GHz ECRH), about 11.5T on coils

40 Coils baseline



Conceptual VV and Coil Layout



See N. Mitchell presentation Sat-Mo-Or2-01
for more details on GIGA coils design

MOTIVATION

Fusion Reactor Access Limitations



In-vessel components like blanket and divertor require regular replacement due to neutron-induced material damage.

Remote maintenance (RM) must be integrated early in the design phase.

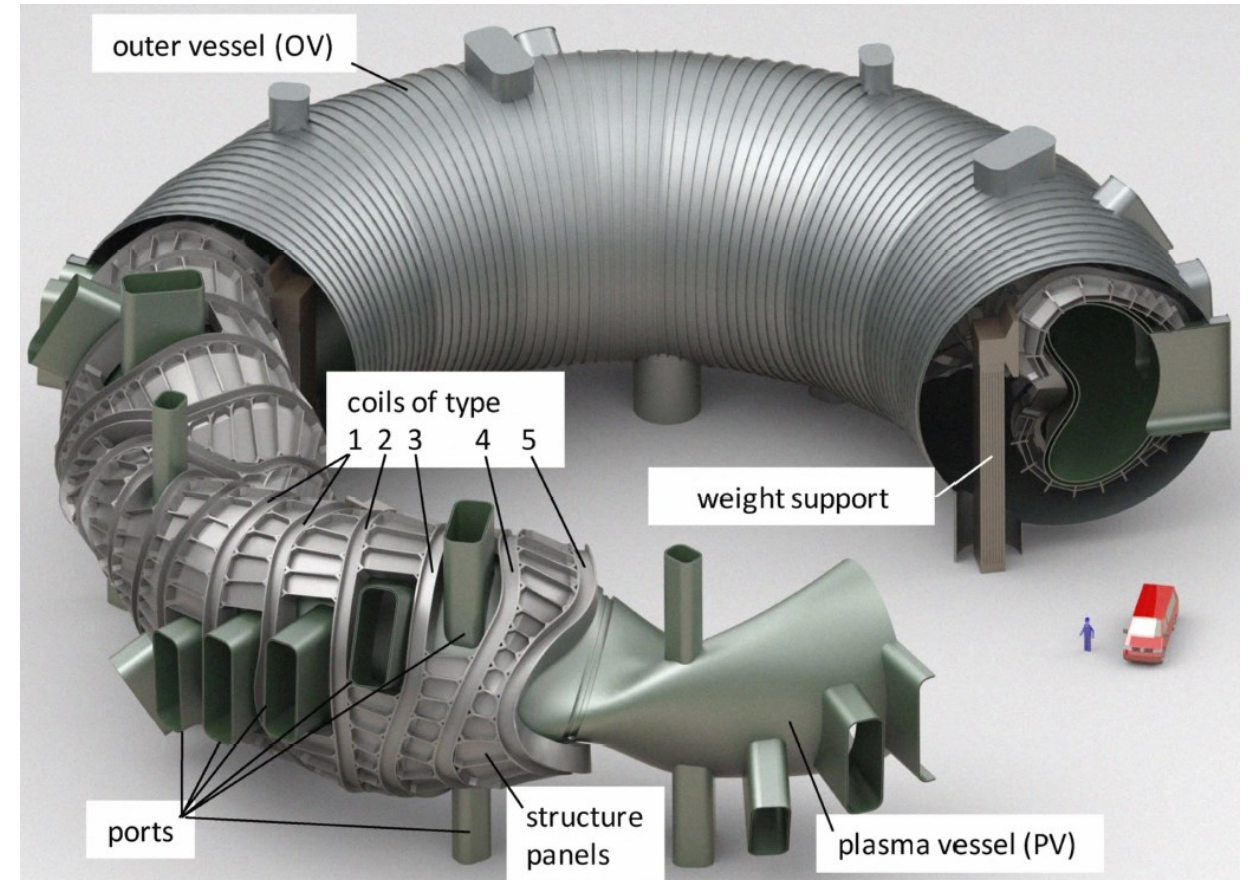
Stellarators pose unique RM challenges due to:

- *More coils* → less space between coils
- *Smaller ports* → limits segment size, increases complexity
- *3D geometry* → more intricate RM tool paths

Effective RM impacts:

- Maintenance time
- Equipment complexity
- Plant layout and costs
- Safety and failure recovery

HELIAS 5



ACCESS CHALLENGES

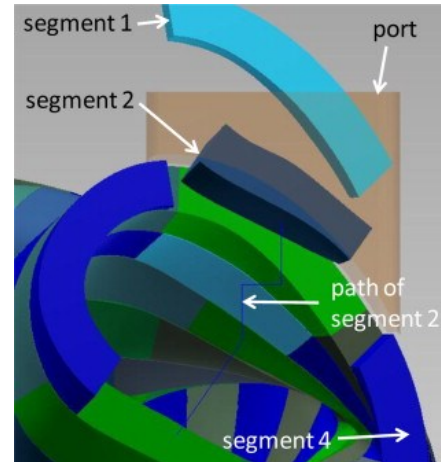
Existing RM Approaches and Limitations



Vertical Ports

Tokamak-inspired vertical maintenance through small ports.

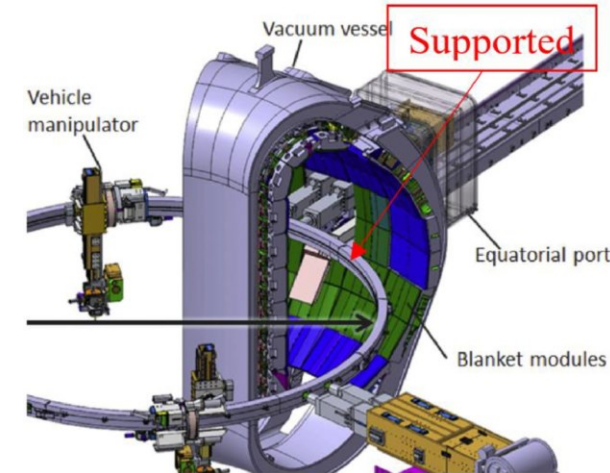
- *Simple concept; well-understood*
- *Limited access; constrained by coil spacing*



Hybrid with Horizontal Ports

Adds horizontal ports between outboard coils for mixed access.

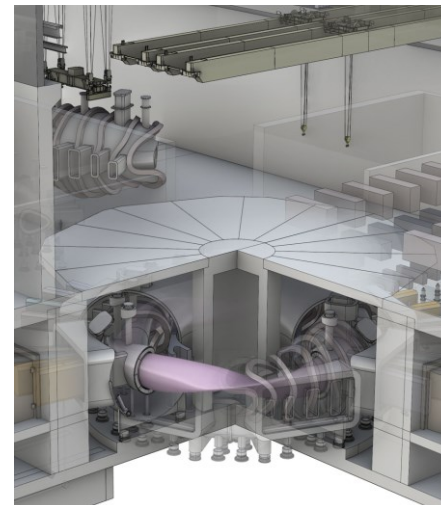
- *Better blanket handling & inspection*
- *Radiation shielding complexity; impacts plant layout*



Radial Module Removal

Entire stellarator module splits radially for full side access.

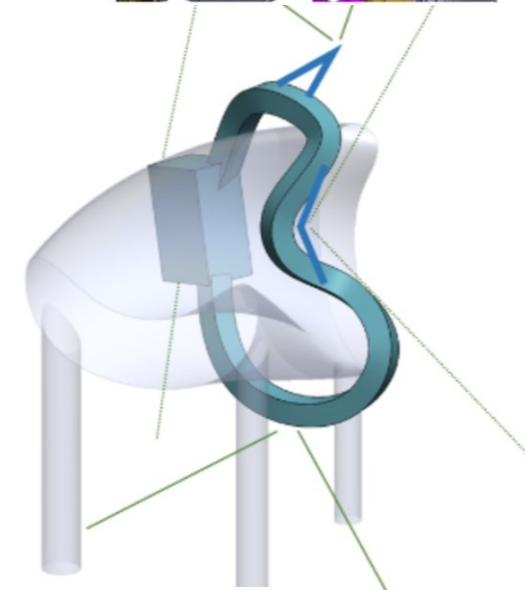
- *Maximum space for handling & inspection*
- *Expensive hardware; requires major plant design adaptations*



Movable Large Coil

One enlarged coil can shift toroidally to create a large port.

- *Greatly improves vertical access & maintainability*
- *Coil disconnection is complex; affects cryogenics and structure*



[1] Schauer et al., Fusion Eng. Des., 2013, 88, pp. 1619–1622

[2] Warmer et al., Fusion Eng. Des., 2024, 202, 114386

[3] Izard et al., Fusion Eng. Des., 2015, 98-99, pp. 1505-1508

GAUSS FUSION DESIGN



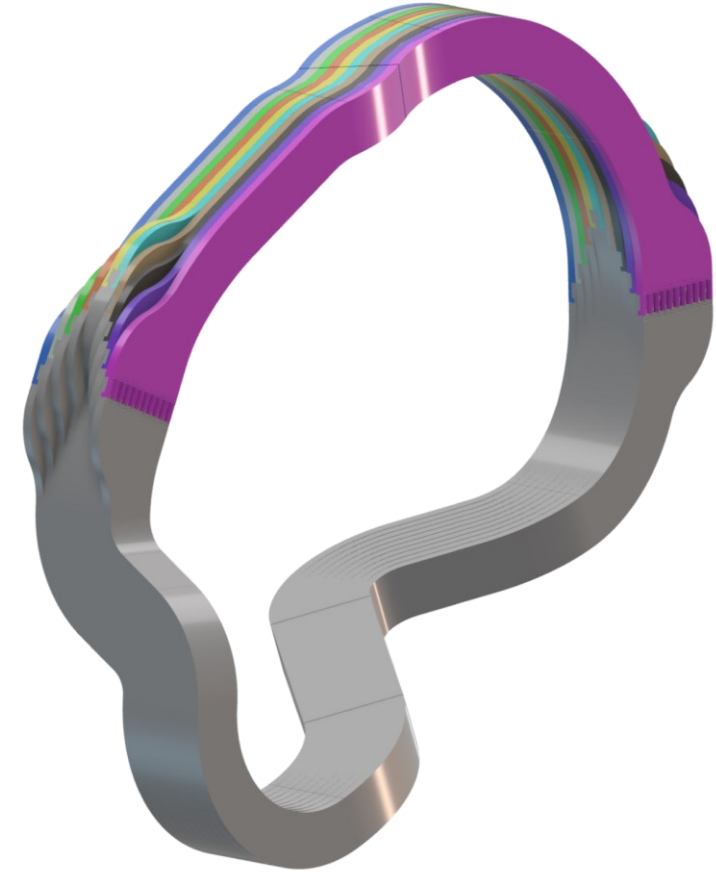
Gauss Fusion's Demountable Coil Concept

- Much easier maintenance/repair both coils and in-vessel components
- Vacuum vessel assembly largely simplified (no access problems)
- Coils can be made off site and more easily transported
- Coil manufacturing changed from a winding process to a lay-up process
- Conductor grading possibilities greatly extended
- Advantage is larger for stellarators (which have more coils) than tokamaks
- **Assembly, maintenance and repair options are substantially improved**

Key problems to be addressed

- **Individual joint resistance** (target $<1\text{n}\Omega$)
- Coolant (He) containment
- Coil load transmission
- Compact design
- Remote handling compatible

Equivalent coil diameter 14m



This work was supported by the German Federal Ministry of Education and Research (BMBF) as part of the funding program *Fusion 2040 – Research on the Path to a Fusion Power Plant*, contract number: 13F1001D.

GAUSS FUSION DESIGN

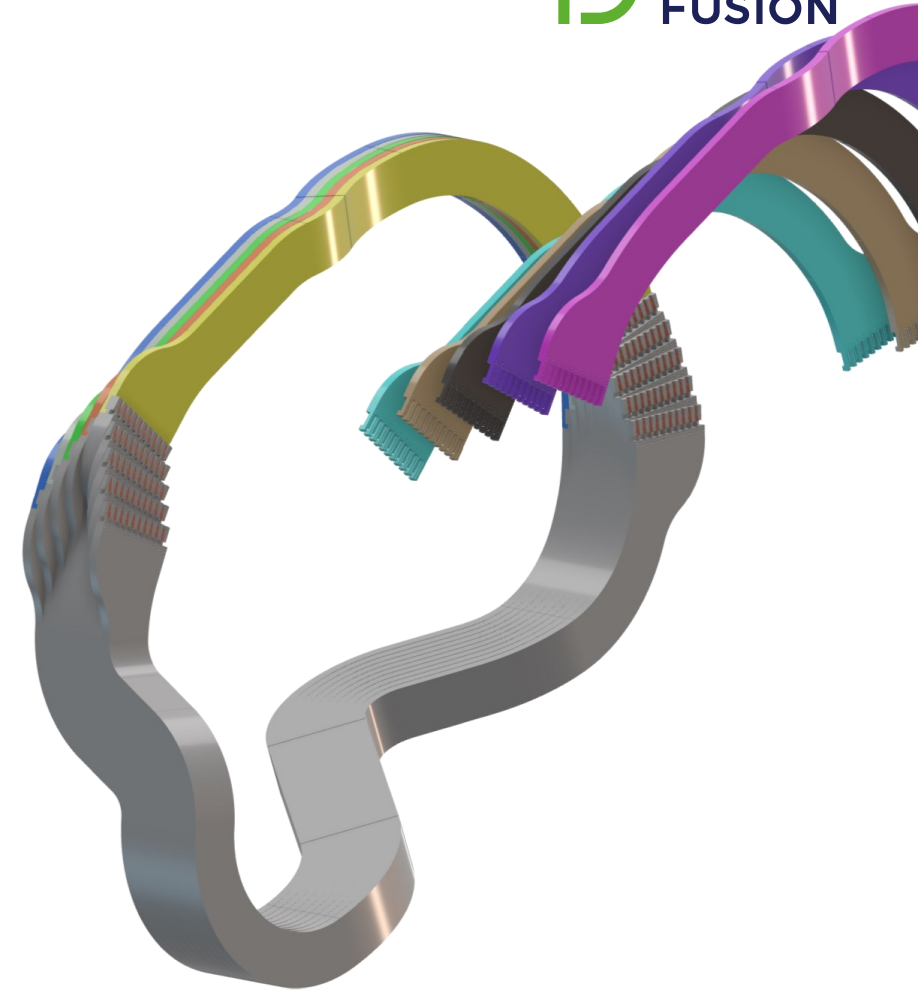


Gauss Fusion's Demountable Coil Concept

- Much easier maintenance/repair both coils and in-vessel components
- Vacuum vessel assembly largely simplified (no access problems)
- Coils can be made off site and more easily transported
- Coil manufacturing changed from a winding process to a lay-up process
- Conductor grading possibilities greatly extended
- Advantage is larger for stellarators (which have more coils) than tokamaks
- **Assembly, maintenance and repair options are substantially improved**

Key problems to be addressed

- **Individual joint resistance** (target $<1\text{n}\Omega$)
- Coolant (He) containment
- Coil load transmission
- Compact design
- Remote handling compatible



This work was supported by the German Federal Ministry of Education and Research (BMBF) as part of the funding program *Fusion 2040 – Research on the Path to a Fusion Power Plant*, contract number: 13F1001D.

JOINT TECHNOLOGY

Ultra-Low Resistance Target



One GIGA coil has ~12 MAT

The GIGA conductor is designed to operate at 100 kA

1 nΩ at 100 kA = 10 W per joint

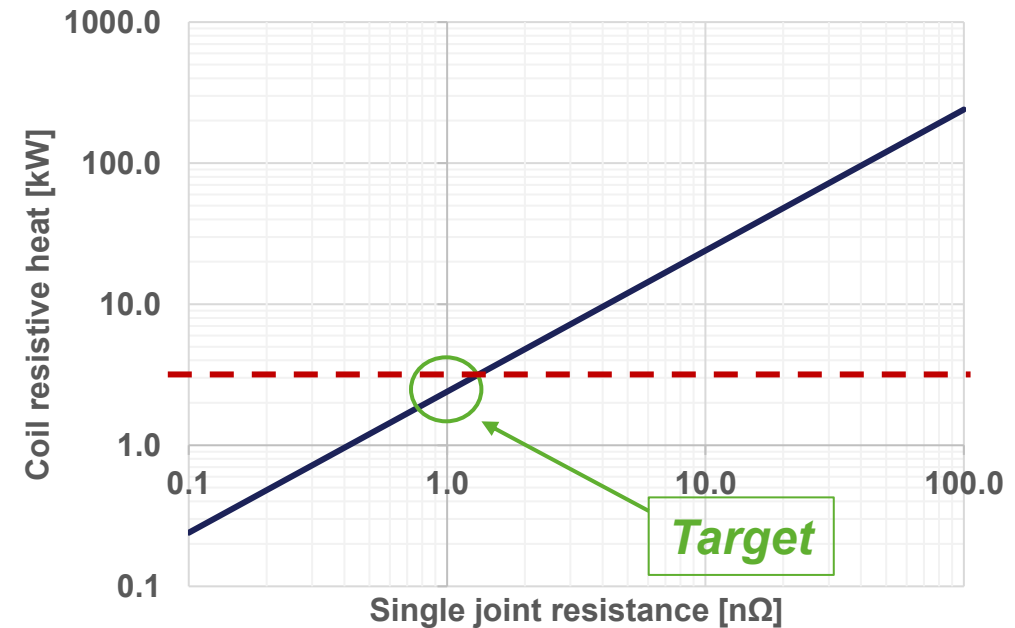
240 joints → 2.4 kW of resistive heating at cryogenic temperatures

We have two possible scenarios:

- 5 K operation → ~ 300 W of input power for removing 1 W → ~ 720 kW per demountable coil
- 20 K operation → ~ 60 W of input power for removing 1 W → ~ 144 kW per demountable coil

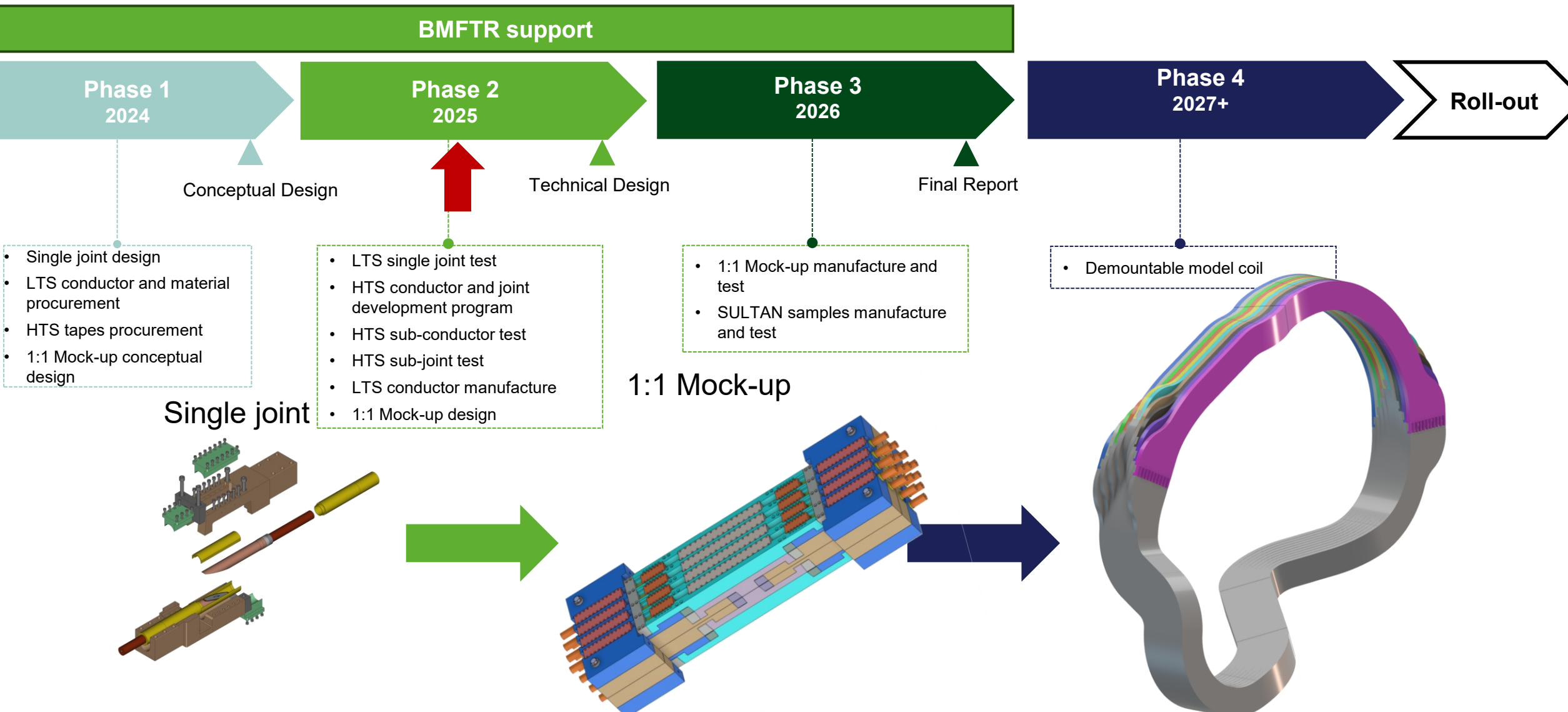
In large-scale superconducting systems, cryo-power from joint resistance scales linearly with joint count and quadratically with current.

At 100 kA and 240 joints, **1 nΩ is not just a target — it is a system-level constraint.**



DEMOUNTABLE COILS

Development Strategy Overview



SINGLE JOINT

FBI Experimental Setup

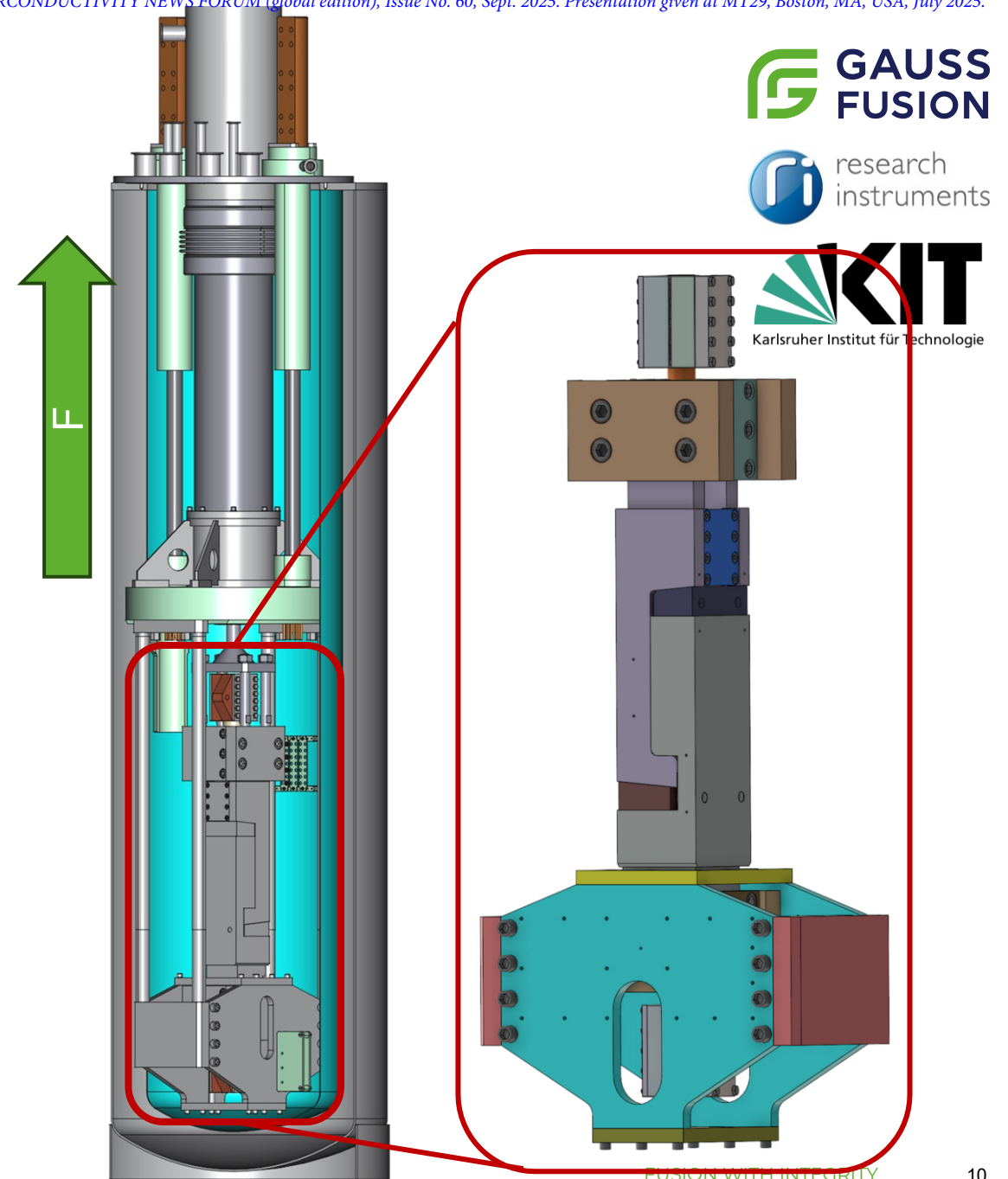
Combines mechanical loading and cryogenic electrical testing

Test Capabilities

- **Mechanical load application**
 - Simulates axial stresses during operation **up to 100 kN**
 - **5 extensometers** will measure the sample deformation
- **Electrical resistance measurement**
 - Performed in liquid helium bath at **4.2 K**
- **Current up to 10 kA**
 - Sufficient for the contact resistance initial assessment
 - **16 voltage taps** will monitor the voltage distribution across the conductor and joint

Outcome

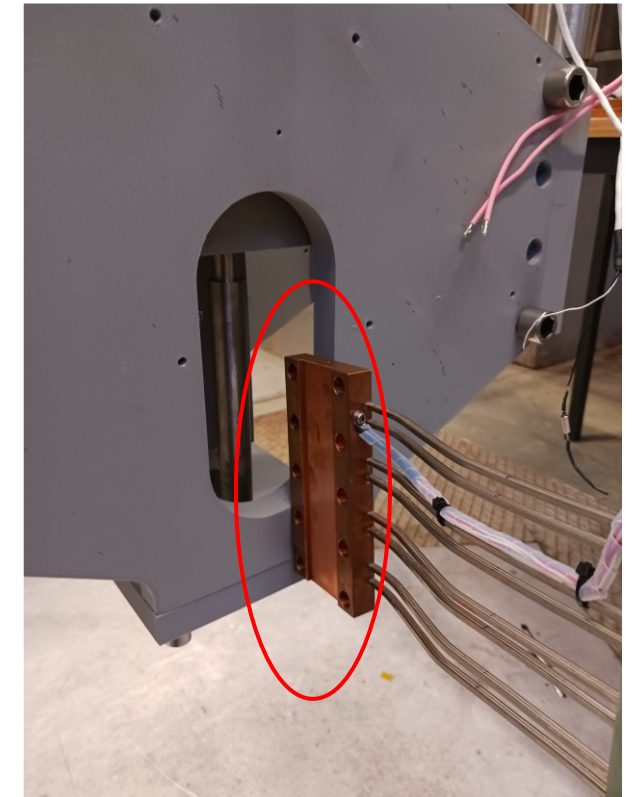
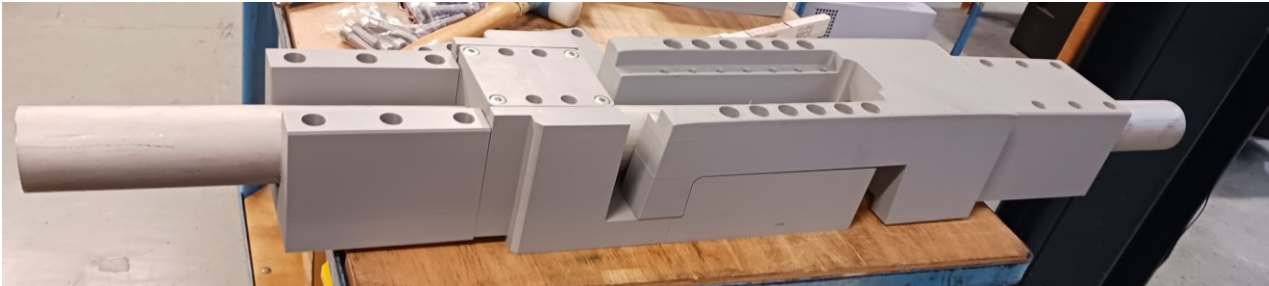
- **Characterize joint behavior** under relevant cryogenic and mechanical conditions
- Validate **contact pressure control, insulation integrity, and electrical performance**



SINGLE JOINT

FBI sample 3D printed fitting test

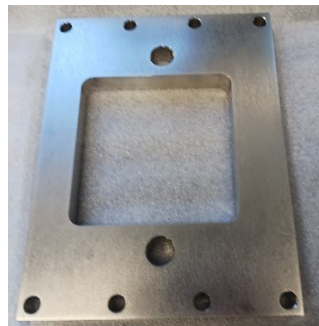
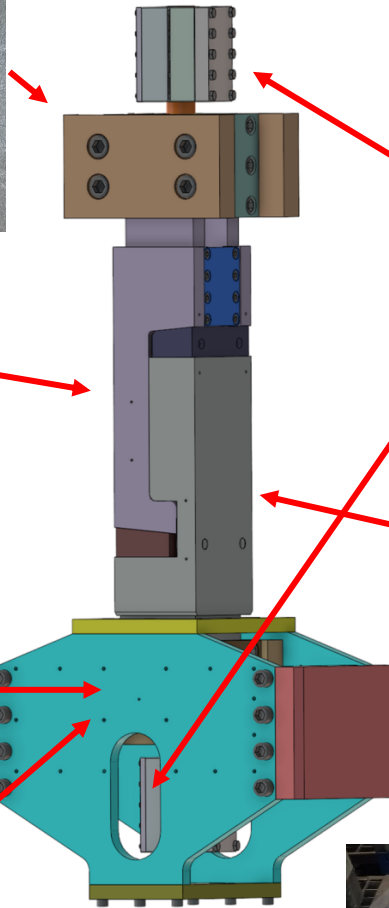
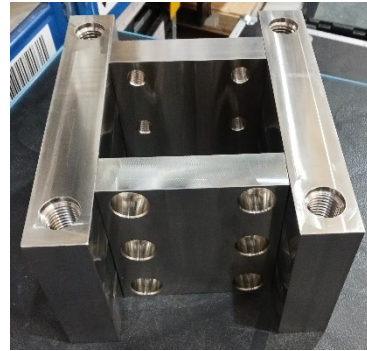
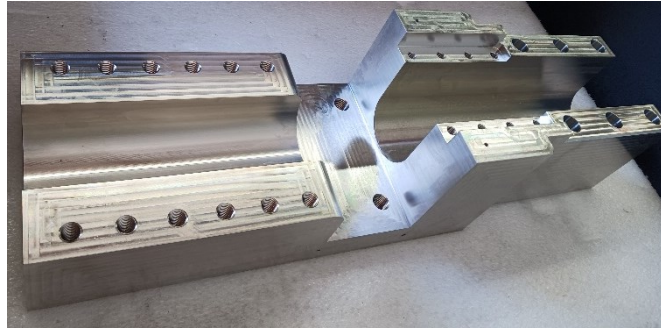
To validate the design and the tolerances of the sample holder a 3D printed version was produced and assembled in the FBI facility.



Outcome

- We were able to detect two nonconformities in the current lead connections before manufacturing the components

SINGLE JOINT FBI sample holder fabrication



SINGLE JOINT

1st LTS Joint Preparation



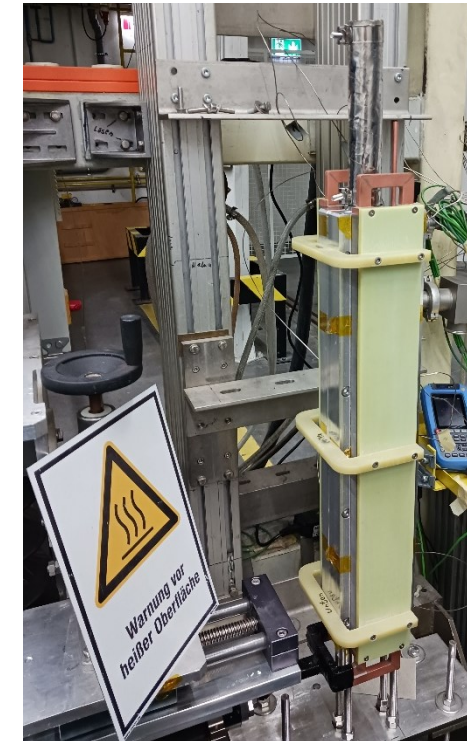
Crome etching and crimping of the Cu tube on the CiCC



4 conductor sections heat treated at PSI



Inductive solder impregnation of the samples



Scarf joint 15-degree pre-cut



DEVELOPMENT STRATEGY

1:1 Coil Section Mock-up

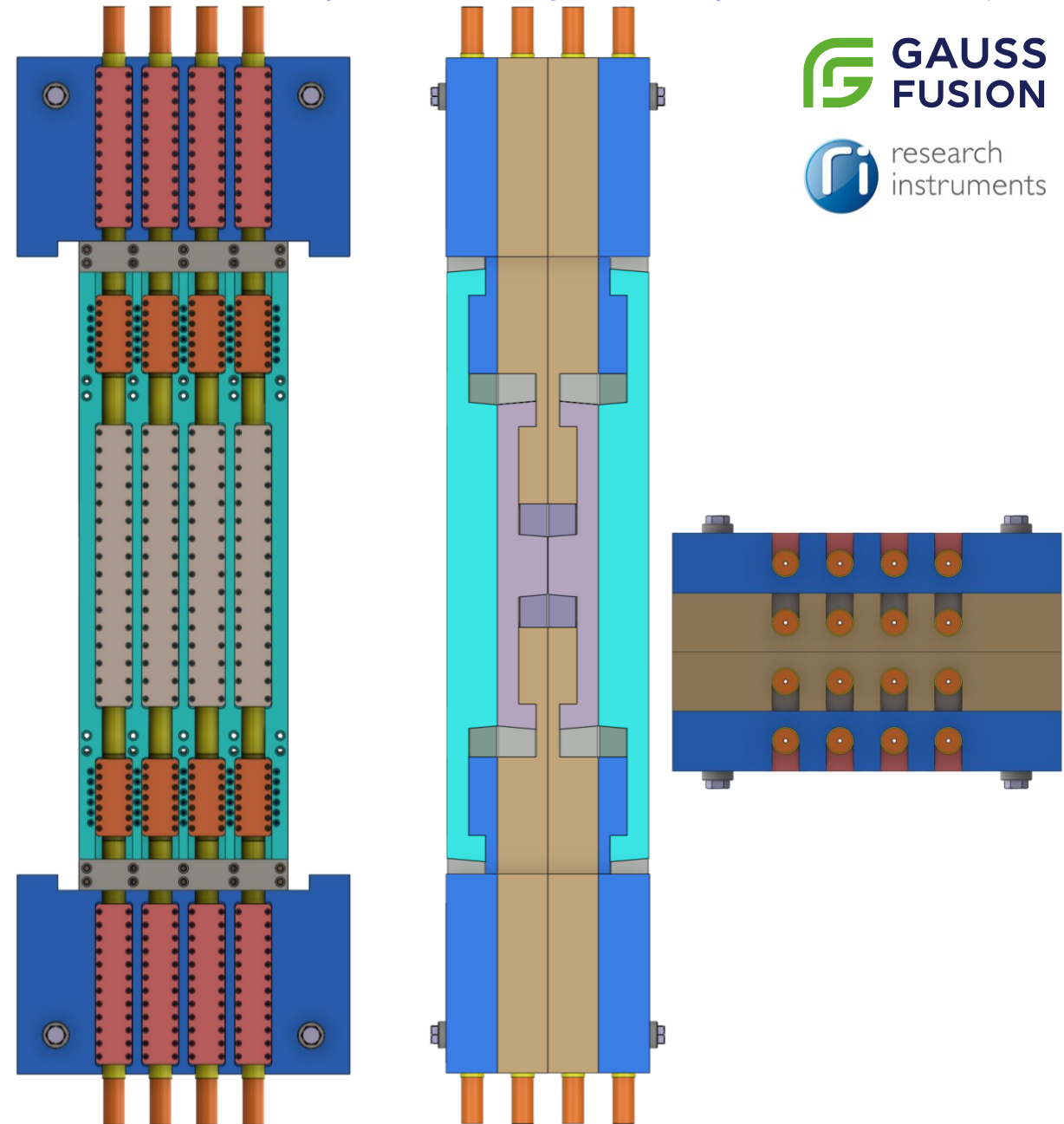
- Bridge between **small-scale joint prototypes** and **full coil systems**
- **Full-size coil segment** (~3 m length)
- Represents realistic **engineering scale and complexity**

Conductor & Joint Configuration:

- **16 conductors**
- **32 demountable joints:**
 - **1 layer** fully instrumented with **LTS joints**
 - **2 layers** dedicated to **HTS joint design testing**
 - ≥ 2 joints per layer for representative layout and stress conditions
 - **1 spare layer** reserved for future modifications or backup

Results

- Validate design robustness for joint reusability
- Evaluate cryogenic operation in LN before (leak test)
- Definition of tolerances for simultaneous joint alignment and automated assembly protocols
- Confirms mechanical design before scaling to full coil



1:1 MOCK-UP

Mechanical and Assembly Testing

Test Objectives

- Validate the **mechanical integrity** of demountable joint and coil segment designs
- Assess **assembly repeatability and maintenance procedures** under realistic handling conditions

Test Setup

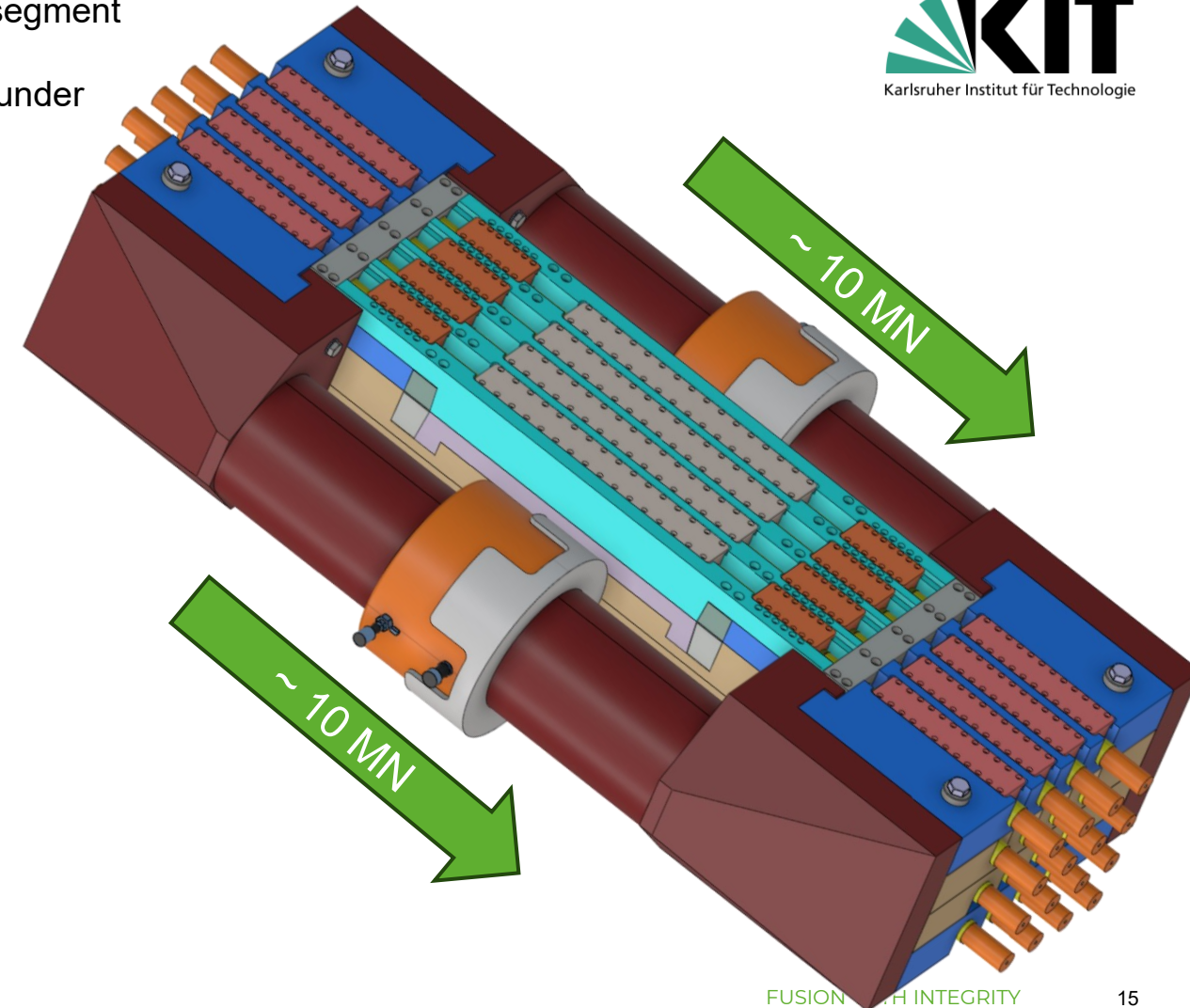
- **Hydraulic platform** for applying **dynamic mechanical loads**
- Simulates:
 - Axial stresses due to Lorentz forces during operation
 - Assembly/disassembly stress
 - Thermal contraction/expansion effects

Testing Procedures

- **Repeated load and unload cycles**
 - Monitors wear and resistance stability
- Mechanical validation of:
 - **Clamping systems**
 - **Alignment features**

Outcome

- Confirms mechanical design
- Provides feedback for design optimization and scaling to full coils



1:1 MOCK-UP

Cryogenic Testing

Test Conditions

- **Cooldown at 77 K** in liquid nitrogen bath
- Simulates thermal environment with thermal contraction
- Enables safe and cost-effective HTS joint evaluation

Key Measurements

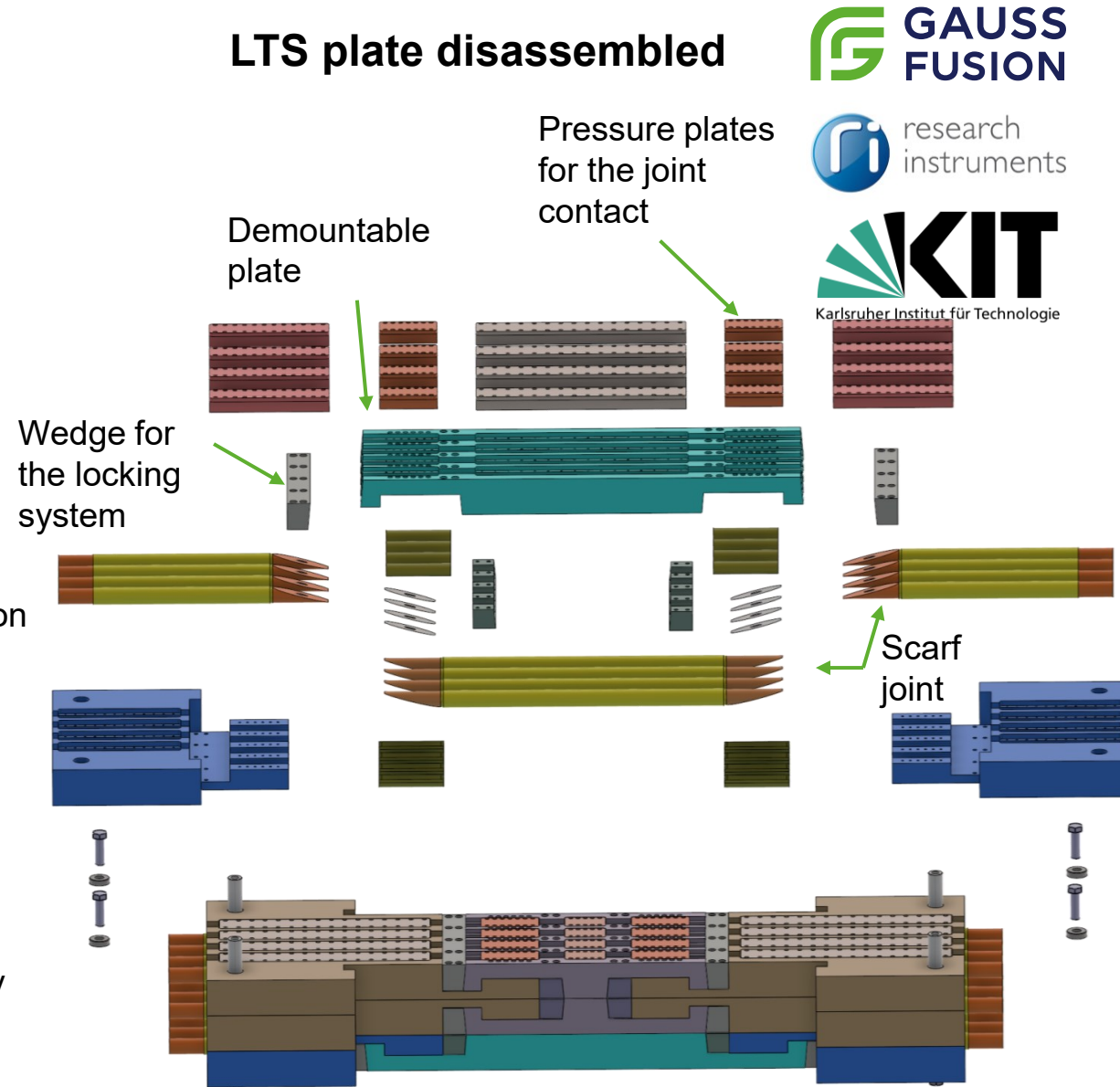
- **Joint resistance**
 - Benchmark electrical performance at cryogenic temperatures
 - Detect degradation after mechanical or thermal cycling
- **Leak test**
 - Verify vacuum tightness and seal performance under contraction

Thermal Cycling Tests

- Multiple **cooldown/warmup cycles** to:
 - Evaluate **durability** and **mechanical stability**
 - Track changes in electrical and sealing performance over time

Outcome

- Validate design robustness for thermal transients and joint reusability
- Evaluate cryogenic operation in LN before testing at lower temperatures (e.g., 4.5 K)



1:1 MOCK-UP

Remote Handling and Maintenance Studies

Objectives

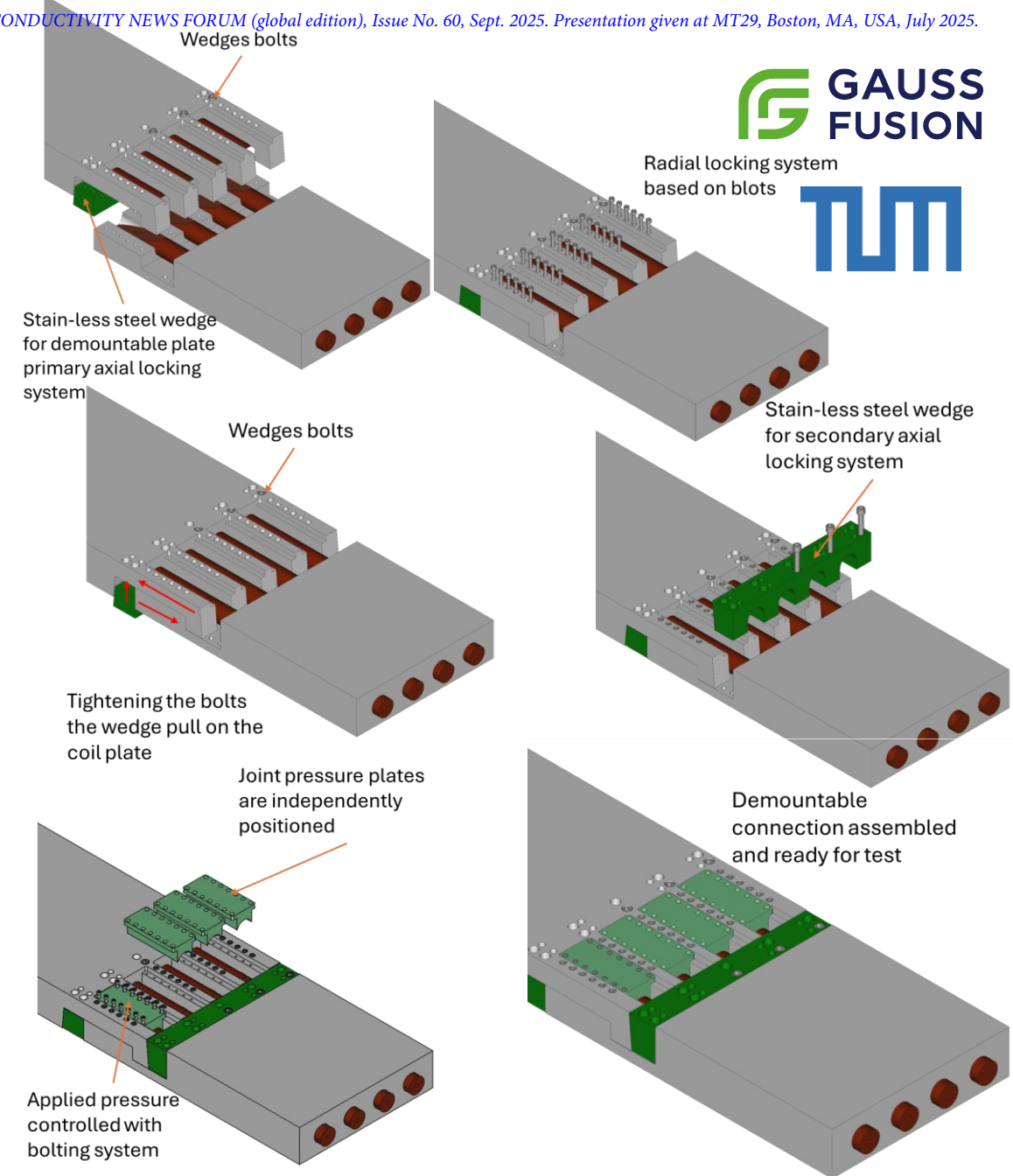
- Explore **automation of joint assembly/disassembly**
- Test **tool accessibility, alignment strategies, and repeatability**
- Develop procedures for **remote maintenance operations** in constrained environments

How the Mock-Up Helps

- Full-scale geometry allows:
 - Testing of **robotic tools** and **end-effectors**
 - Evaluation of **tolerances and connector alignment in blind assembly**

Outcome

- Support development of **automated maintenance protocols** for large superconducting systems



DEVELOPMENT STRATEGY

SULTAN sample

Objectives

- **High-current and high-field validation** of joint design
- Critical step toward qualifying the technology for integration in full-size superconducting systems

Test Configuration

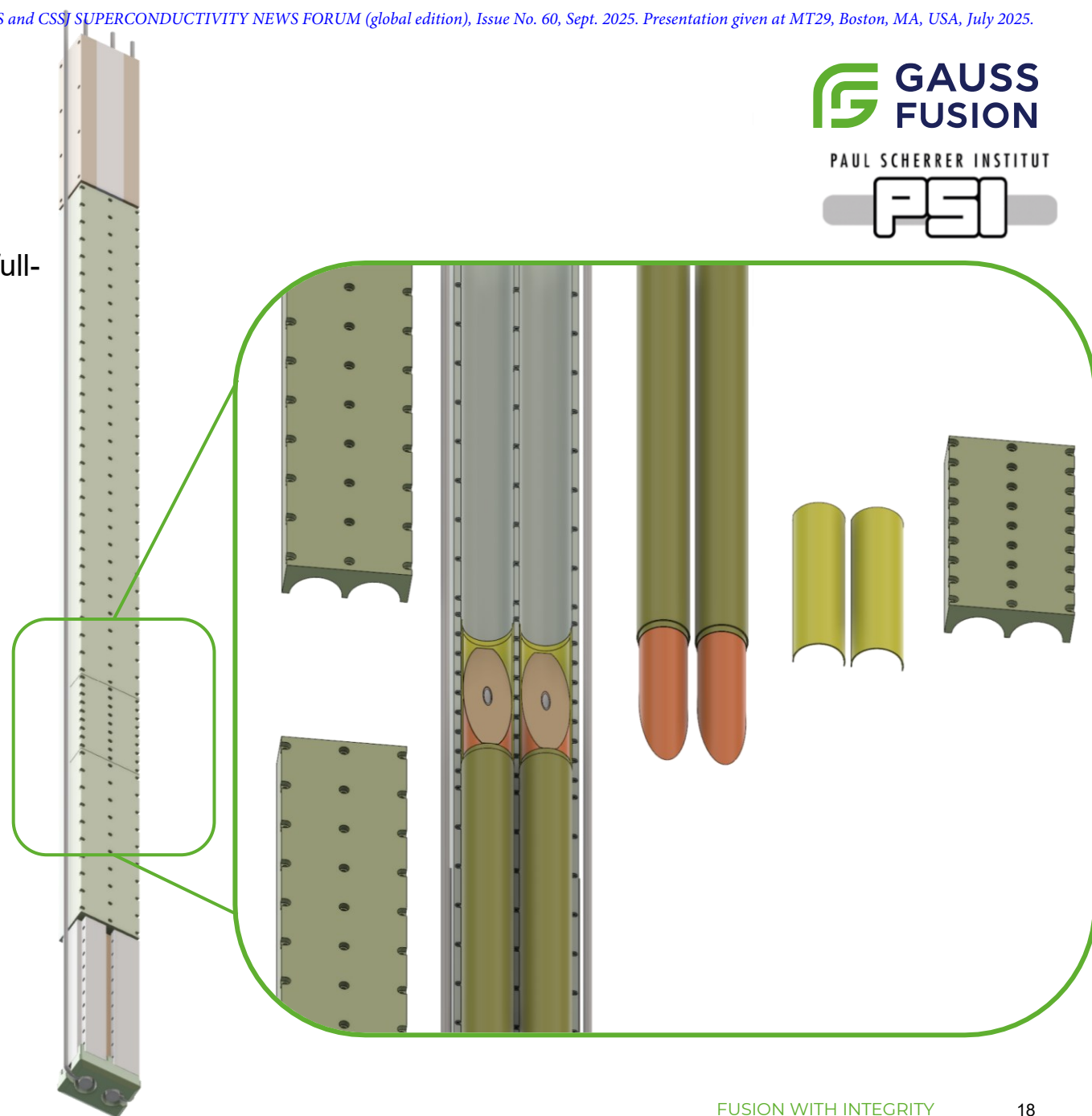
- **Sample with two joints**
- **Cut from same conductor batch** used in the 1:1 mock-up

Test Conditions

- **Current level comparable to operating condition**
 - up to 100 kA, maximum current influenced by joint resistances
- Background field up to 11 T
- Simulates realistic electromagnetic loading conditions

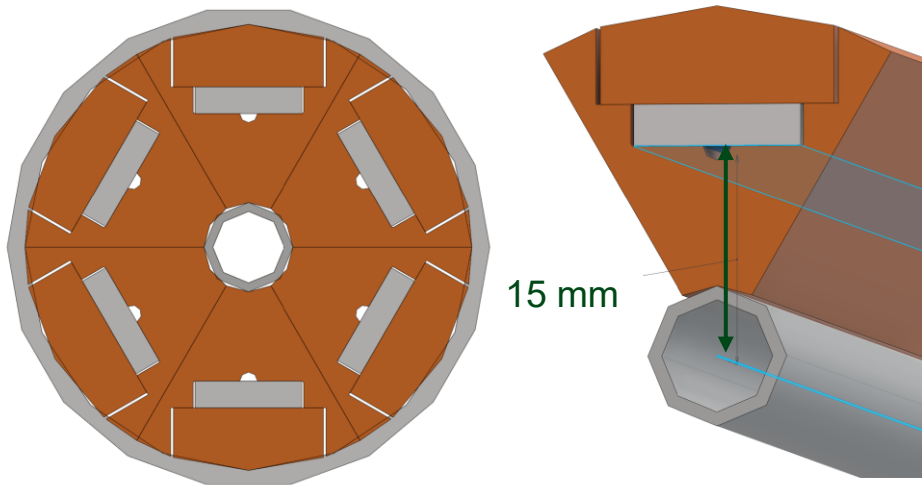
Outcome

- Measure **joint resistance, mechanical stability, and thermal behavior** under relevant working conditions
- Confirm performance under simultaneous **I + B loading**
- Provide data for final design validation and scaling decisions



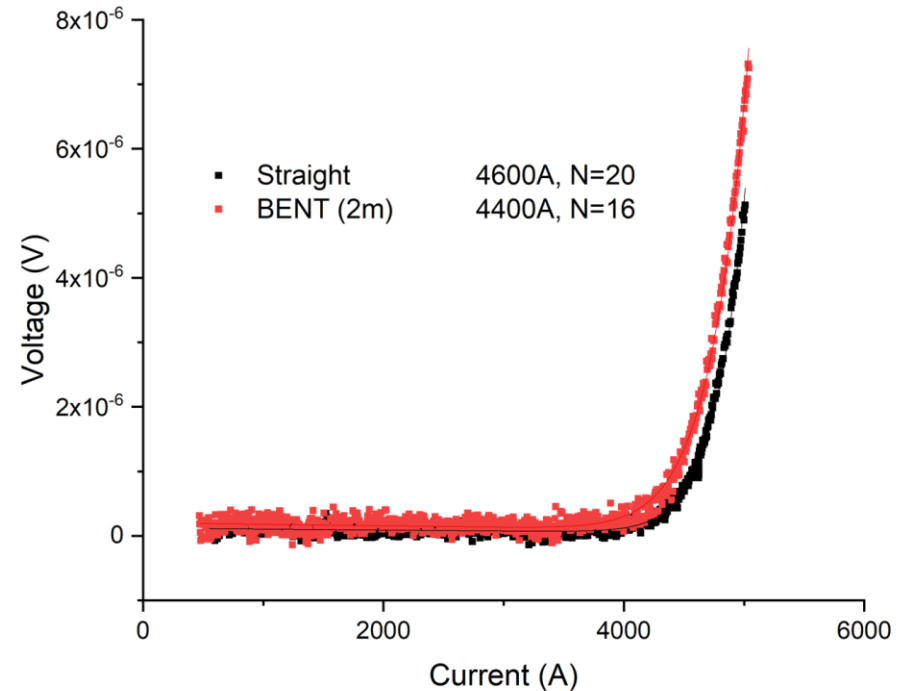
HTS JOINT DEVELOPMENT

HTS Conductor Development



HTS conductor development:

- $I_{op} = 100 \text{ kA (@ 12 T, 20 K)}$
 - Prototype design based on SST REBCO tapes
 - Sub-conductors manufactured and tested at ENEA to study effect of degradation with bending

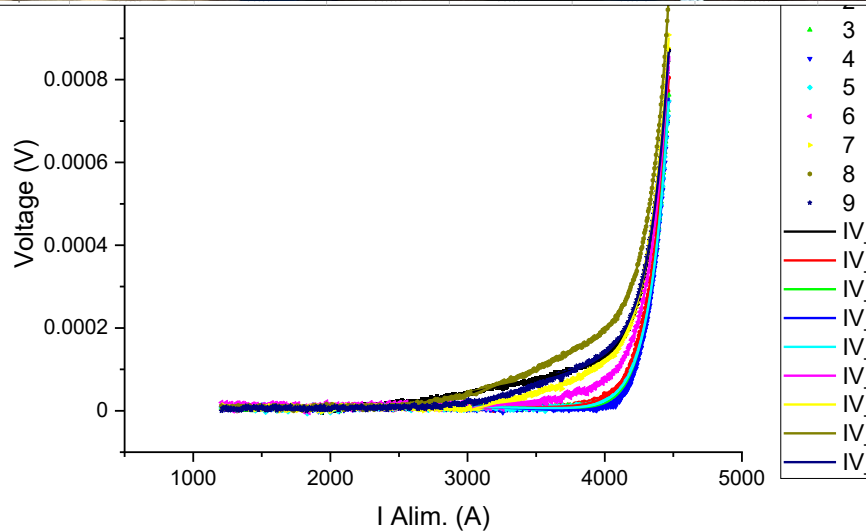
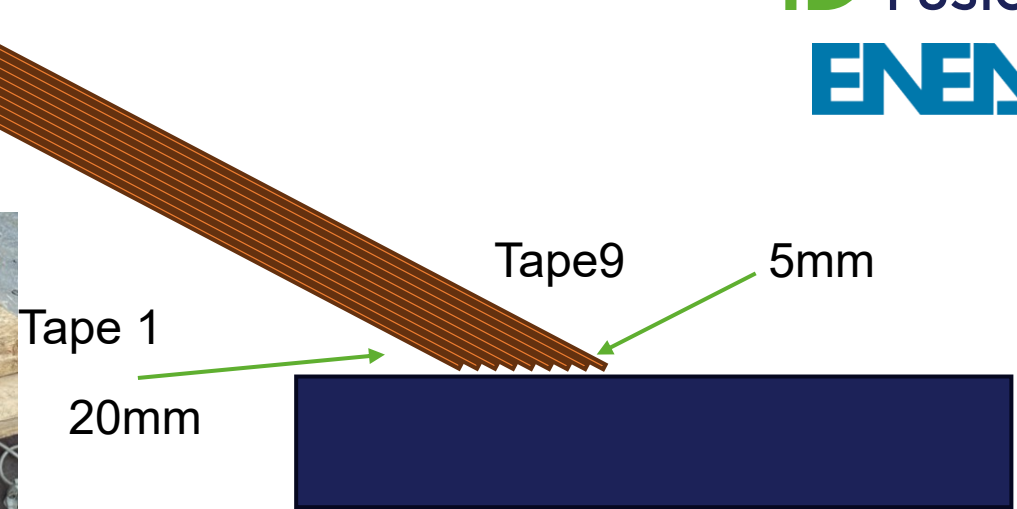


Jig R=2m

HTS JOINT DEVELOPMENT

HTS contact resistance study

Assess the resistance of a termination with a consistent number of tapes



LN₂ testing, self field

- $I_c > 4000A$
- Total resistance ~ 270nΩ
- Complex current redistribution between tapes.
- Under investigation to assess the behavior of each tape and measure termination resistance.

DEMOUNTABLE MODEL COIL



Next Steps After Mock-up Testing

Model Coil Design

- **4 planar plates**
- **5 turns** per plate → total of **20 conductors**
- **40 demountable joints** (2 per conductor segment)
- Uses same conductor design as GIGA → **100 kA @ 20 K**

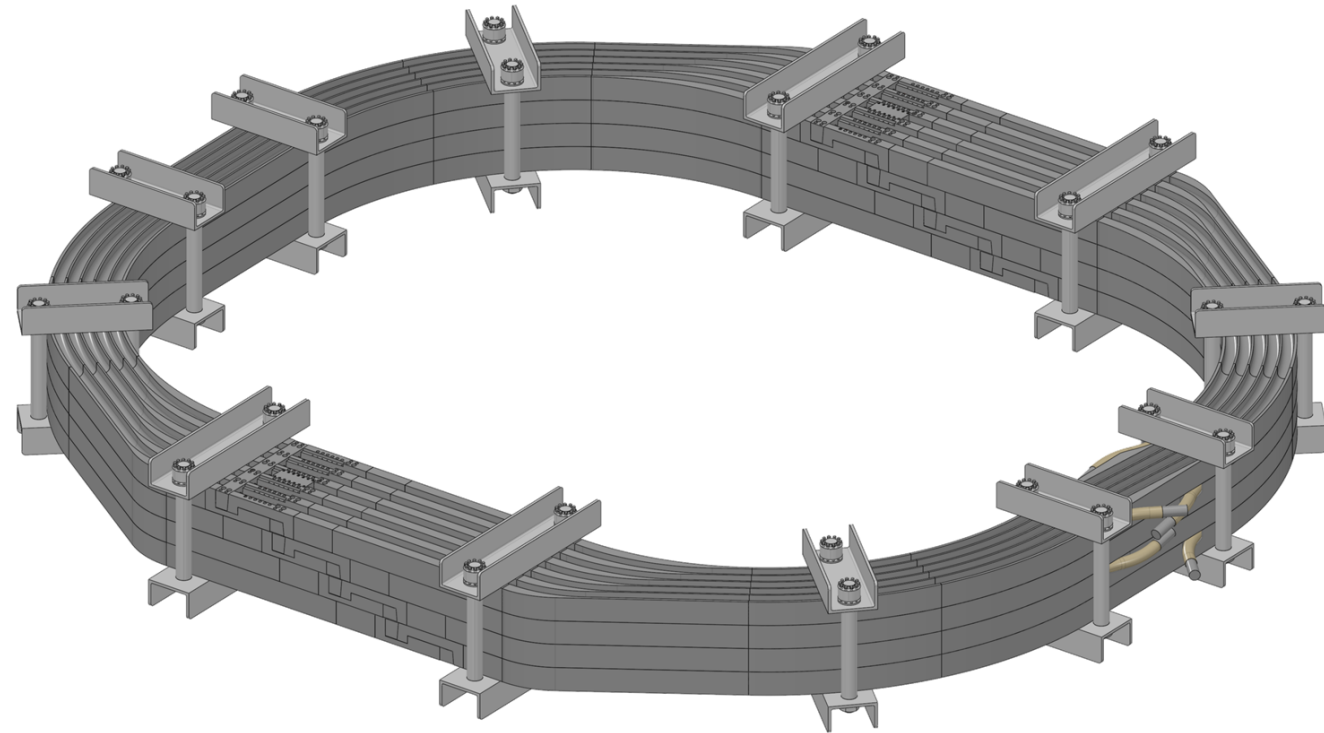
Technical Targets

- **Joint resistance ~1 nΩ per joint**
- Assess:
 - Electrical performance at nominal current
 - Thermal behavior of joint network
 - Mechanical stress distribution
 - Assembly and integration sequence at system scale

Outcome

- **Demonstrate readiness** for integration of **demountable joints** in full-size fusion-grade coils
- Provide **qualification data for final GIGA design**

1/2 full size
(17.5m perimeter, non-circular 6m diameter)



CONCLUSION

Key Takeaways



- Demountable superconducting coils enable easier access, maintenance, and assembly (especially beneficial for complex stellarator layouts).
- Target joint resistance of $\sim 1 \text{ n}\Omega$ is essential to limit cryogenic power losses in large coil networks. HTS could allow for higher resistance ($< 5 \text{ n}\Omega$), HTS joint development is ongoing.
- Single joint prototypes tested in FBI will validate mechanical and electrical performance under cryogenic and mechanical loading.
- A full-scale 1:1 mock-up is planned to prove joint reusability, with multiple thermal cycles, and automated assembly potential.
- SULTAN tests will confirm performance under high-field, high-current conditions.
- A demountable model coil is planned to demonstrate system-level integration and qualify the design for GFG fusion plants.

The background features a gradient from dark green at the top to light green at the bottom. It is decorated with several overlapping circles in various shades of green and blue. Two large circles on the left and right contain a grid of small dots that form a perspective effect, appearing to recede into the distance. The text "The time is now" is centered in a white, italicized font.

The time is now



Thank you for your interest



Dr. Tommaso Bagni
Sc. Magnet Engineer

tommaso.bagni@gauss-fusion.com

