Scalable HTS coils for TRUST experimental fusion device: Design and Manufacturing at Tuscia University

Prof. Giuseppe Calabrò - giuseppe.calabro@unitus.it
Dr. Simone Carusotti - simone.carusotti@unitus.it
Prof. Pierluigi Fanelli – pierluigi.fanelli@unitus.it
Dr. Andrea Marchegiani – andrea.marchegiani@unitus.it

and the **TRUST Team**

UNITUS4FUSION
School of Engineering and Design

- ~500 Students, ~50 Staff (Prof., PostDoc, Ph.D.)
- **Bachelor's Degree in Industrial Engineering (L-9)**
- **Master's Degree in Mechanical Engineering (LM-33, English Language)**

  Focused on fusion : Plasma Physics and Technologies for Nuclear Fusion, Non-Destructive Measurement Methods, Modeling of Mechanical Systems, Special Technologies and Manufacturing, **Machine Design**, Tools and Technologies for Additive Manufacturing, **New Materials for Energy**
- **PhD Program in Engineering for Energy and Environment**

Member of

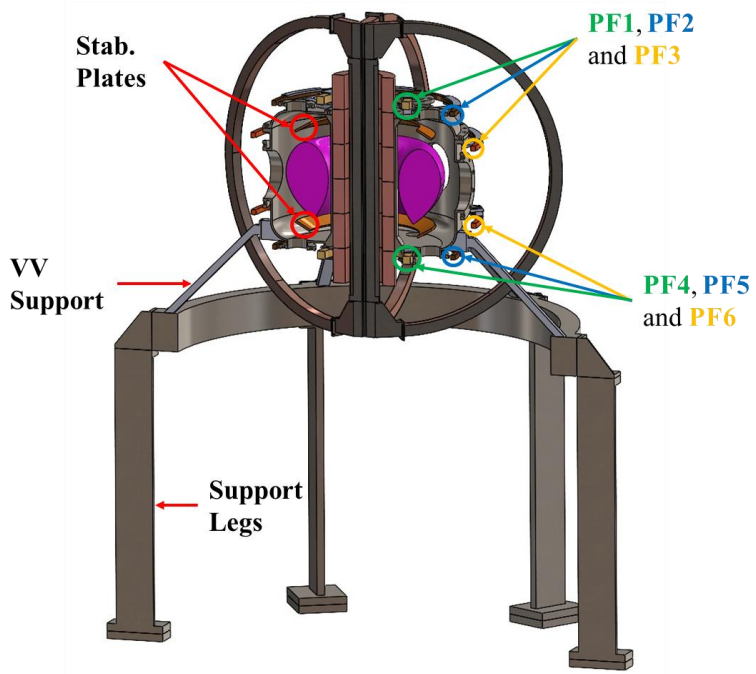
EUROfusion

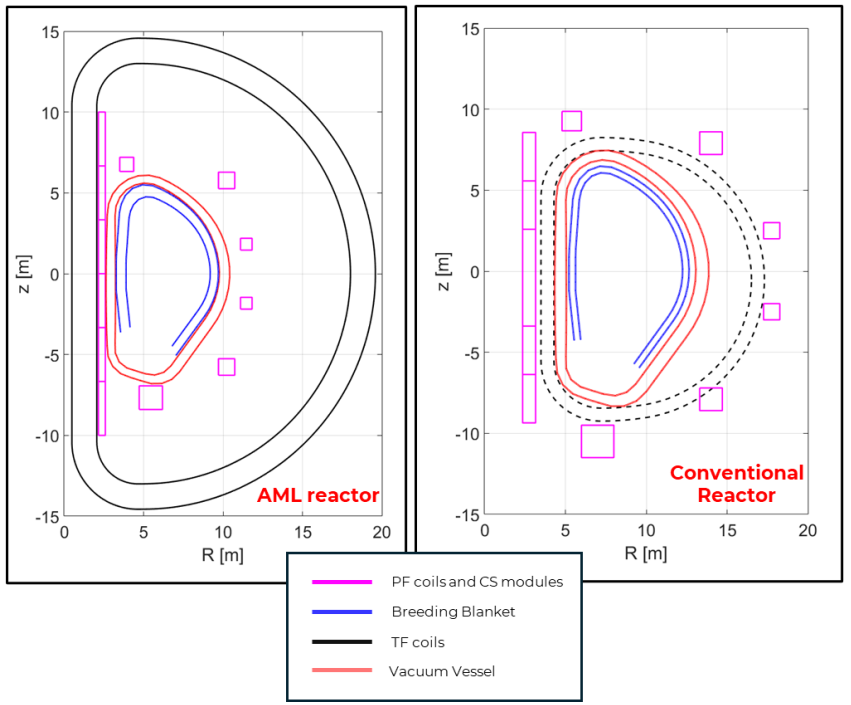
FuseNet
The European Fusion Education Network

TRUST PROJECT
Research Plan

TRUST (Tuscia Research University Small Tokamak) [1][2], a new modular and compact tokamak designed as a **research and educational experiment at University of Tuscia (UNITUS):**

- Provides **training for students and researchers** adopting interdisciplinary and **industrial** collaboration. **(Building completed within 2026)**
- Test advanced technologies **as high-temperature superconductors (HTS) and metamaterials. (First HTS coil on TRUST within 2028)**
- Introduction of the **Alternative Magnetic Layout (AML)**, a pre-conceptual **design aimed at simplifying and reducing the size of fusion reactors while maintaining operational efficiency**.



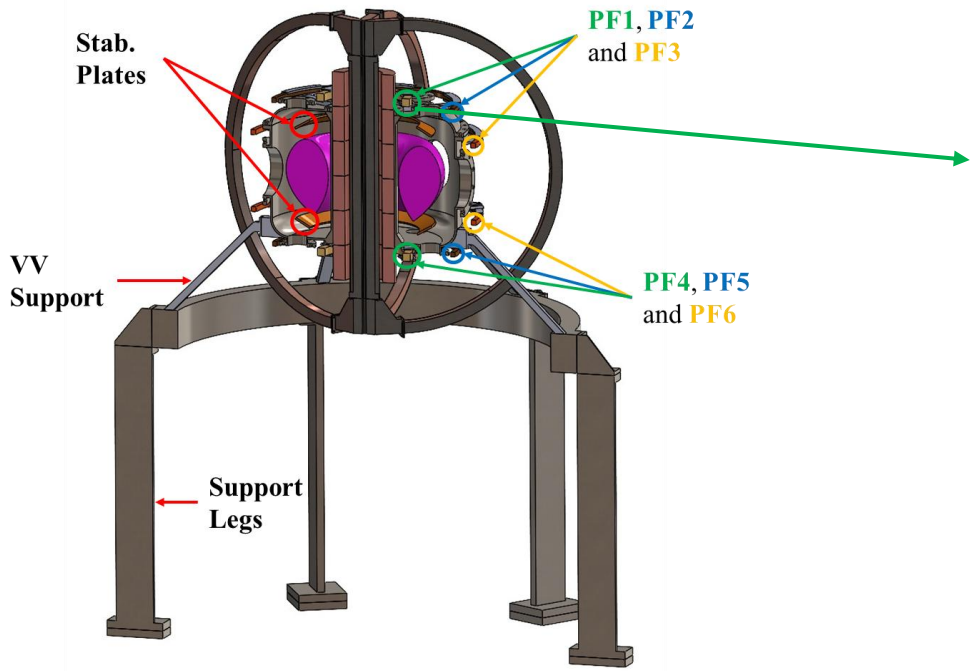


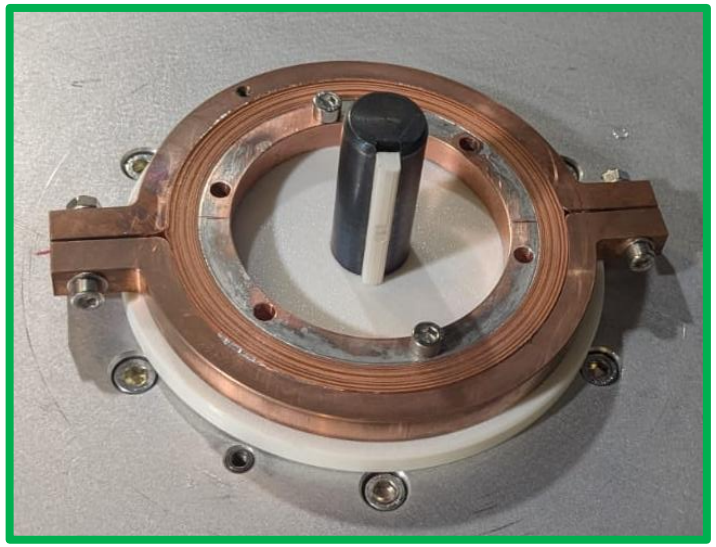
[1] Preliminary study on alternative magnetic layout (AML) for tokamaks reactors in the TRUST project framework - ScienceDirect
[2] Overview of university-class Tokamak TRUST: Preliminary characterization of plasma scenario and disruption studies - ScienceDirect

TRUST PROJECT
Research Plan

TRUST (Tuscia Research University Small Tokamak) [1][2], a new modular and compact tokamak designed as a **research and educational experiment at University of Tuscia (UNITUS):**

- Provides **training for students and researchers** adopting interdisciplinary and **industrial** collaboration. **(Building completed within 2026)**
- Test advanced technologies **as high-temperature superconductors (HTS) and metamaterials. (First HTS coil on TRUST within 2028)**
- Introduction of the **Alternative Magnetic Layout (AML)**, a pre-conceptual **design aimed at simplifying and reducing the size of fusion reactors while maintaining operational efficiency**.





HTS TRUST-like PF1 coil

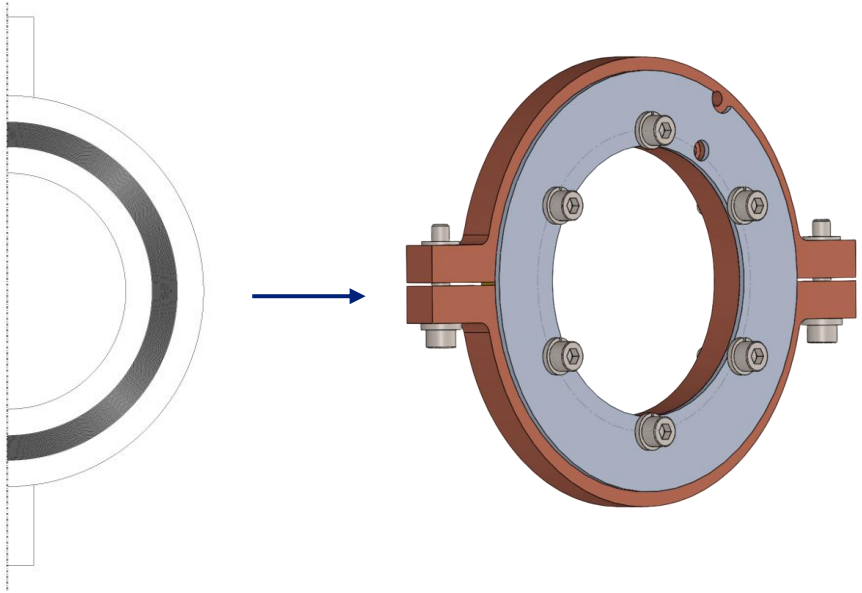
[1] Preliminary study on alternative magnetic layout (AML) for tokamaks reactors in the TRUST project framework - ScienceDirect
[2] Overview of university-class Tokamak TRUST: Preliminary characterization of plasma scenario and disruption studies - ScienceDirect

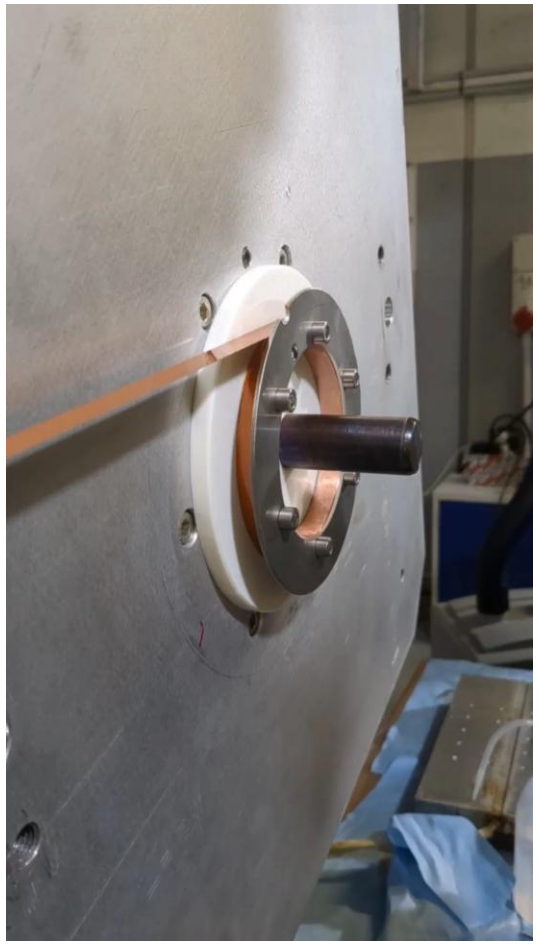
TRUST PROJECT
Scalable HTS coils

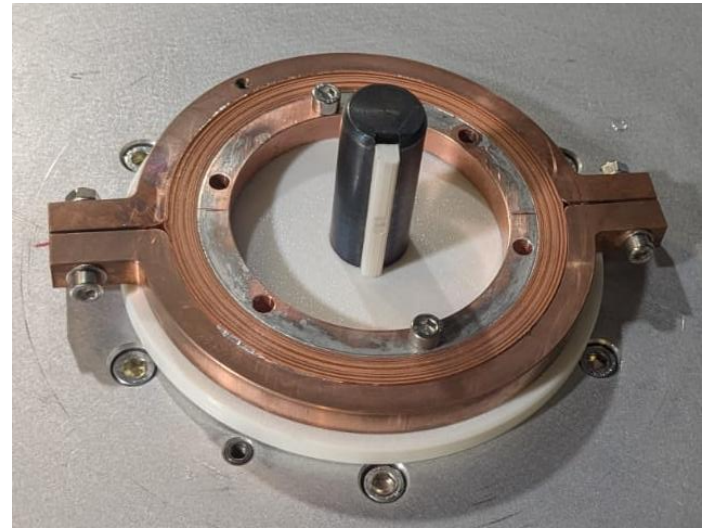
First HTS scalable coil within the TRUST project has been designed and realized in collaboration with *ASG Superconductors* to acquire knowledge on manufacturing and testing of coils.

Constraints

- Internal Radius: 45 mm
- Windings: 50 turns
- Minimum current per turn: 100 A
- Operating Temperature: 77 K







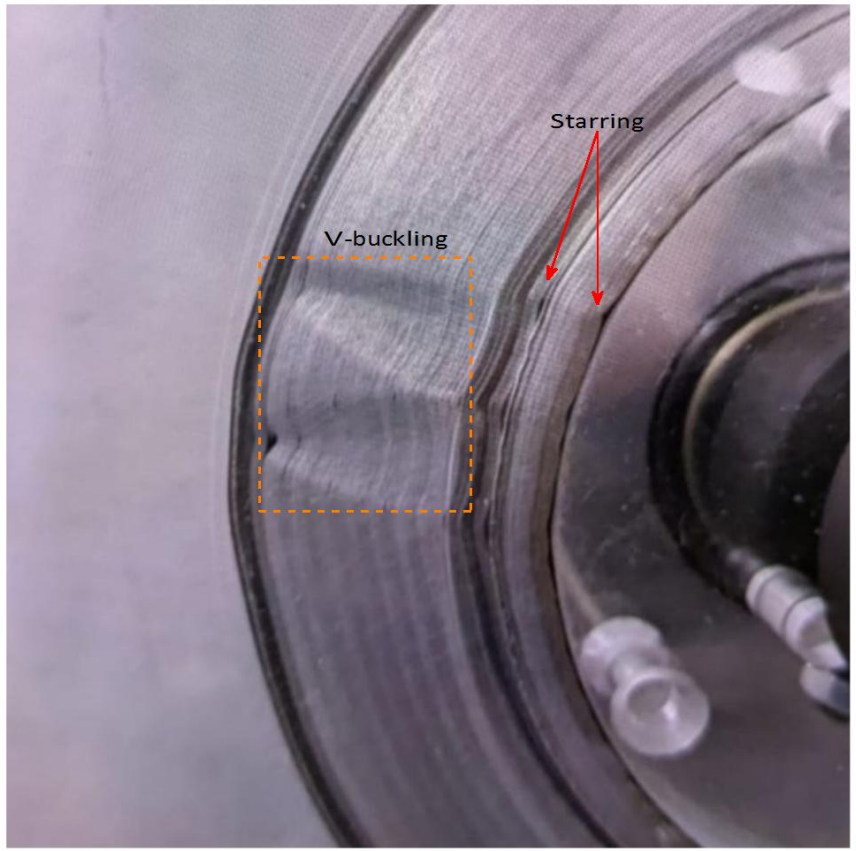
SuNam SCN12600

SC layer	Manufacturer	Tape width [mm]	Tape thickness [mm]
GdBCO	SuNam	12	0.14

Thanks to M. Marabotto and A. Cappelluto

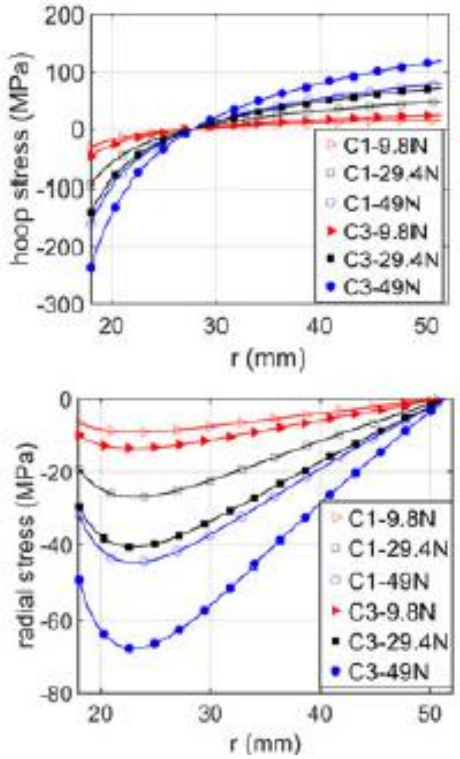
TRUST PROJECT
Scalable HTS coils

Design challenges: avoid the instability issue during the winding procedure experimentally observed at *ASG Superconductors* and modeled in a preliminary form considering different Winding Tension

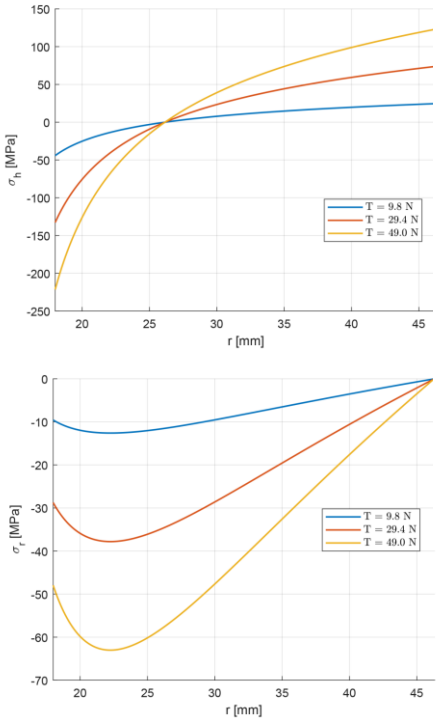


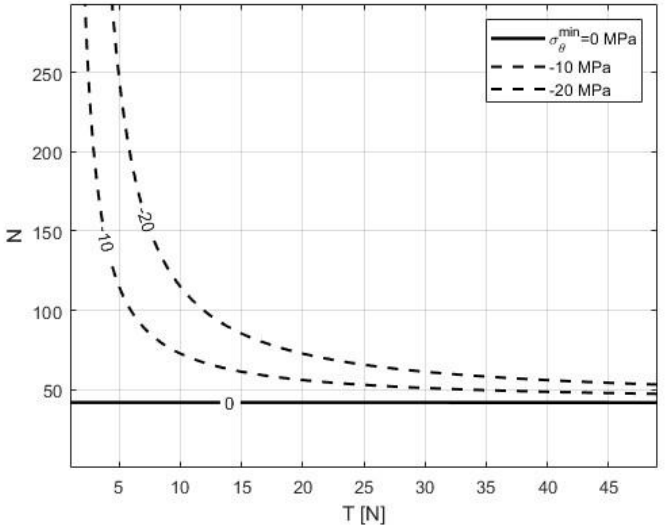
Courtesy of A. Capelluto

Wang et al., DOI: 10.1109/TASC.2017.2778739



Numerical validation

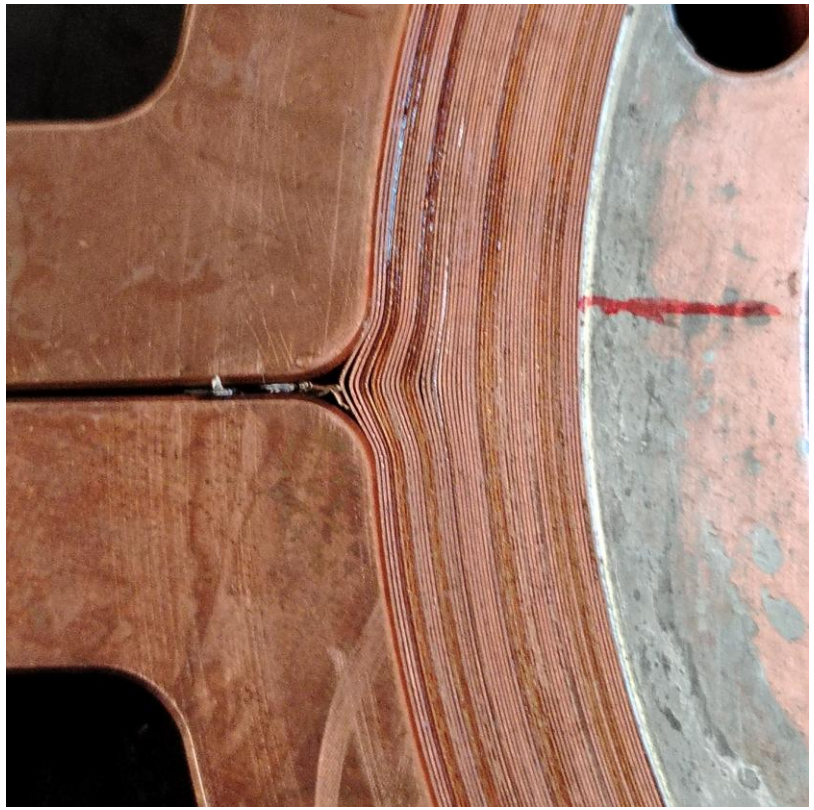


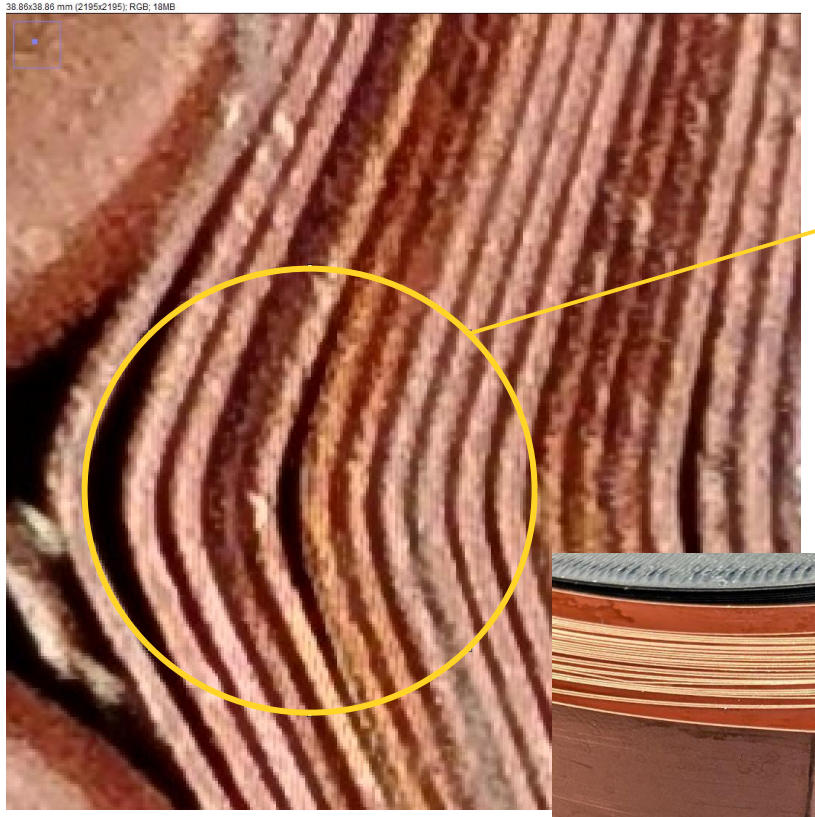


A 0 MPa threshold was set as the critical limit lo limit instabilities for TRUST scalable coil

*Andrea Marchegiani Master's Thesis (2025)

Instability was avoided, but we encountered a **different problem during the closing phase of the external ring** due to machining tolerance adopted.





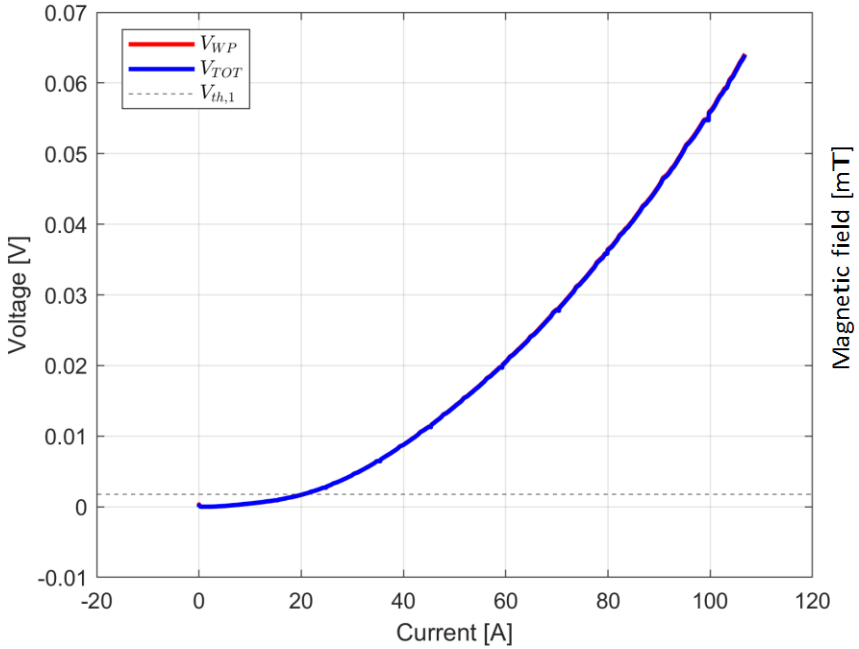
ImageJ
Image Processing and Analysis in Java

$$\bar{R}_B = \frac{\text{Major} + \text{Minor}}{4} \approx 1.37\ \text{mm}$$

$$R_B^{\text{Low, crit}} \approx 1\ \text{cm}$$

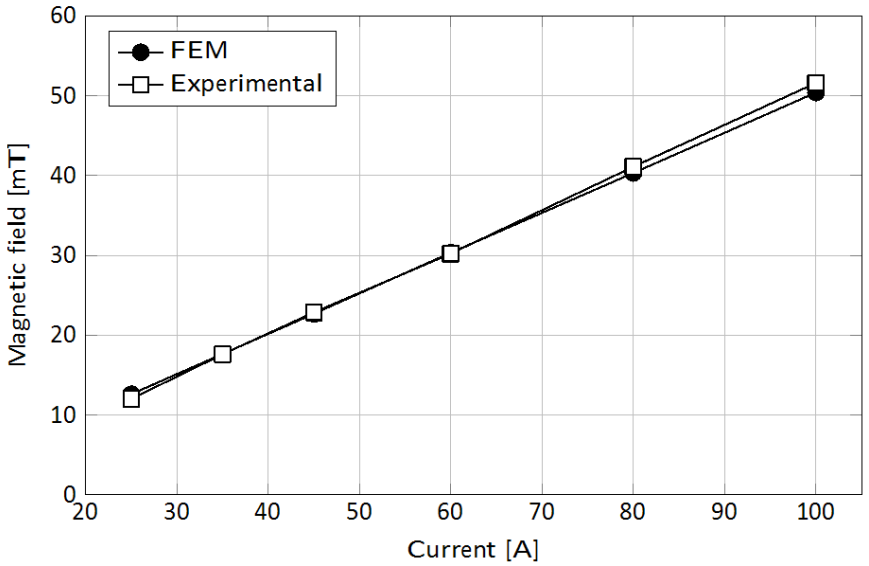
Critical damage on the tape

First test with unmodified coil: Resistive behavior due to the damage on the tapes, but the electrical continuity has been verified

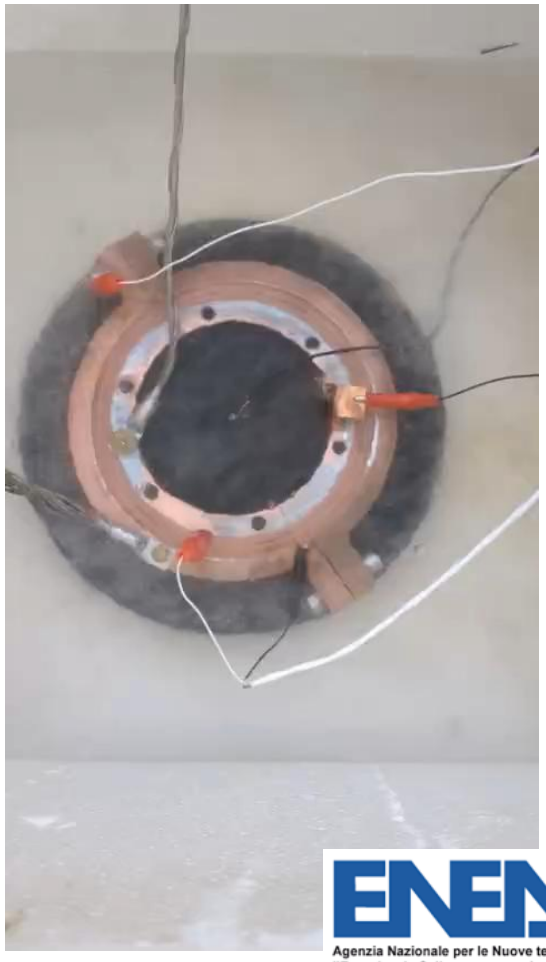


$$V_{\mathrm{th},1} = E_{\mathrm{crit}} \cdot L = 1.8 \times 10^{-3}\ \mathrm{V};$$

$$E_{\mathrm{crit}} = 1\,\frac{\mu\mathrm{V}}{\mathrm{cm}}; \quad L = 18\ \mathrm{m}; \quad 50\ \text{windings}$$



Current [A]	FEM [mT]	Experimental [mT]	Difference [%]
25	12.599	12.007	4.69
35	17.638	17.60	0.22
45	22.678	22.85	0.76
60	30.327	30.22	0.35
80	40.317	41.10	1.94
100	50.396	51.60	2.39

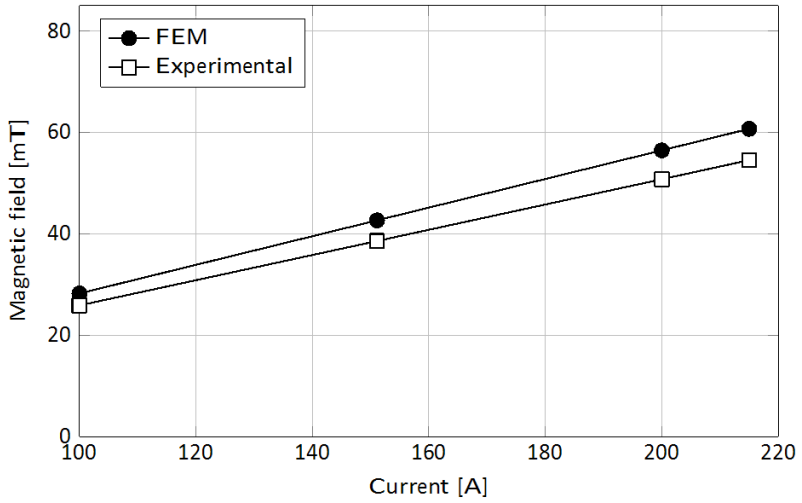


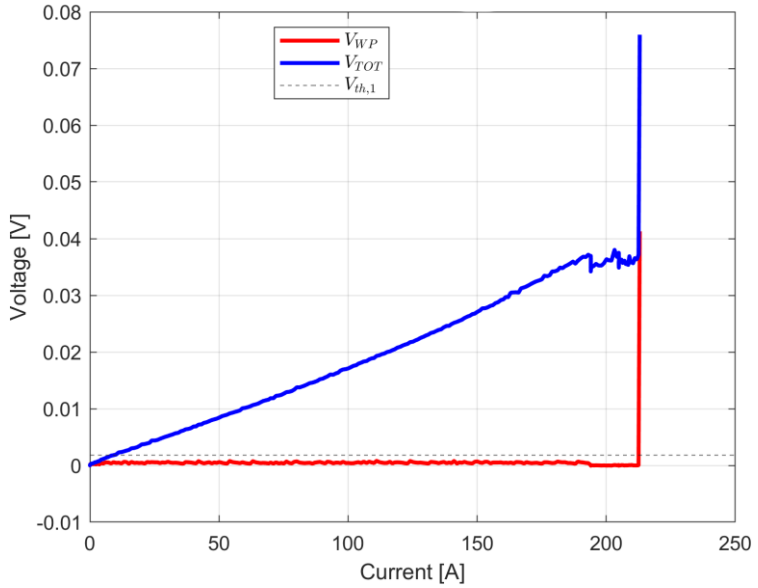
Agenzia Nazionale per le Nuove tecnologie, l'Energia e lo Sviluppo economico sostenibile

Thanks to G. Celentano and A. Masi

Second test with reduction of number of turns: the damaged windings have been temporarily bypassed.

Preliminary external current lead





$V_{\text{th},1} = E_{\text{crit}} \cdot L = 0.9 \times 10^{-3}$ V; $I_{\text{crit}} \approx 215$;

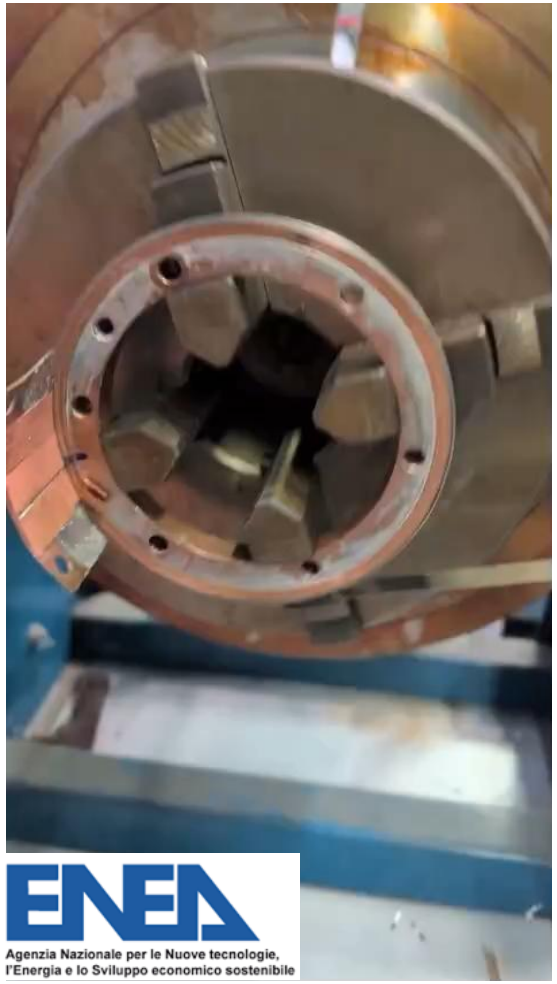
$E_{\text{crit}} = 1 \frac{\mu\text{V}}{\text{cm}}$; $L = 9$ m; 25 windings

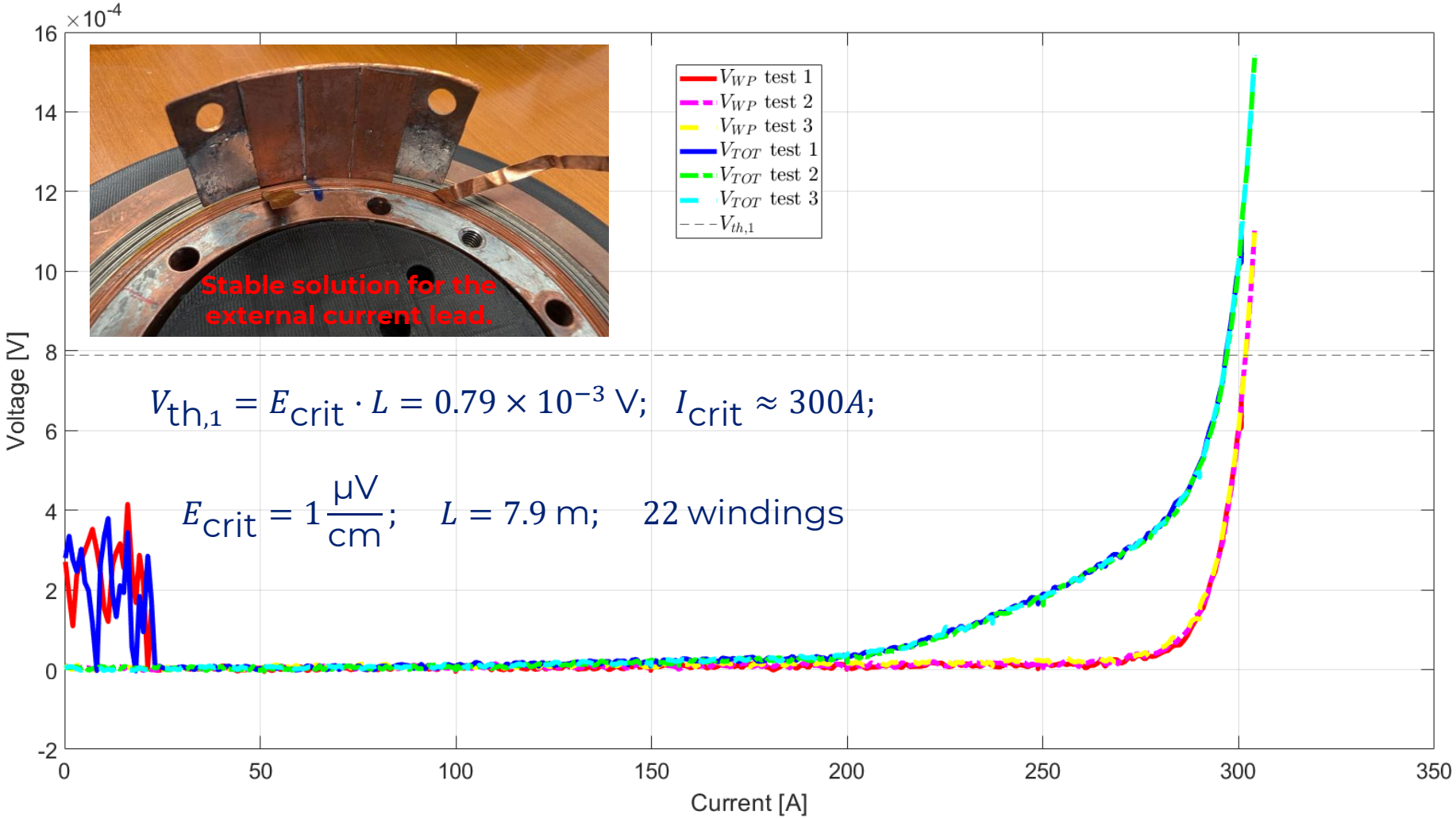
Current [A]	FEM [mT]	Experimental [mT]	Difference [%]
50	14.11	13.40	5.03
100	28.22	25.86	8.35
151.1	42.64	38.56	9.56
200	56.44	50.74	10.10
215	60.68	54.51	10.17

Thanks to G. Celentano and A. Masi

TRUST PROJECT
Scalable HTS coils

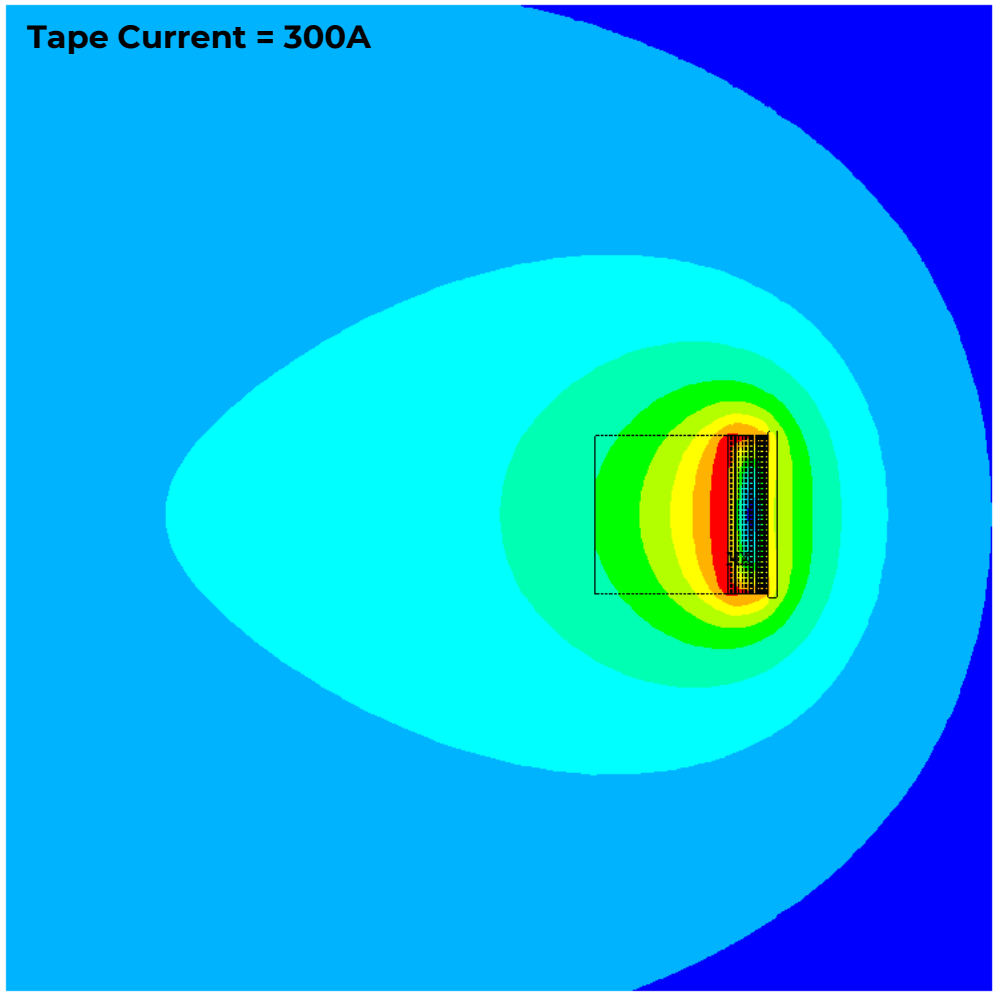
Third test final version for the coil: removal of damage tape and inserted stainless steel tape as filling material.

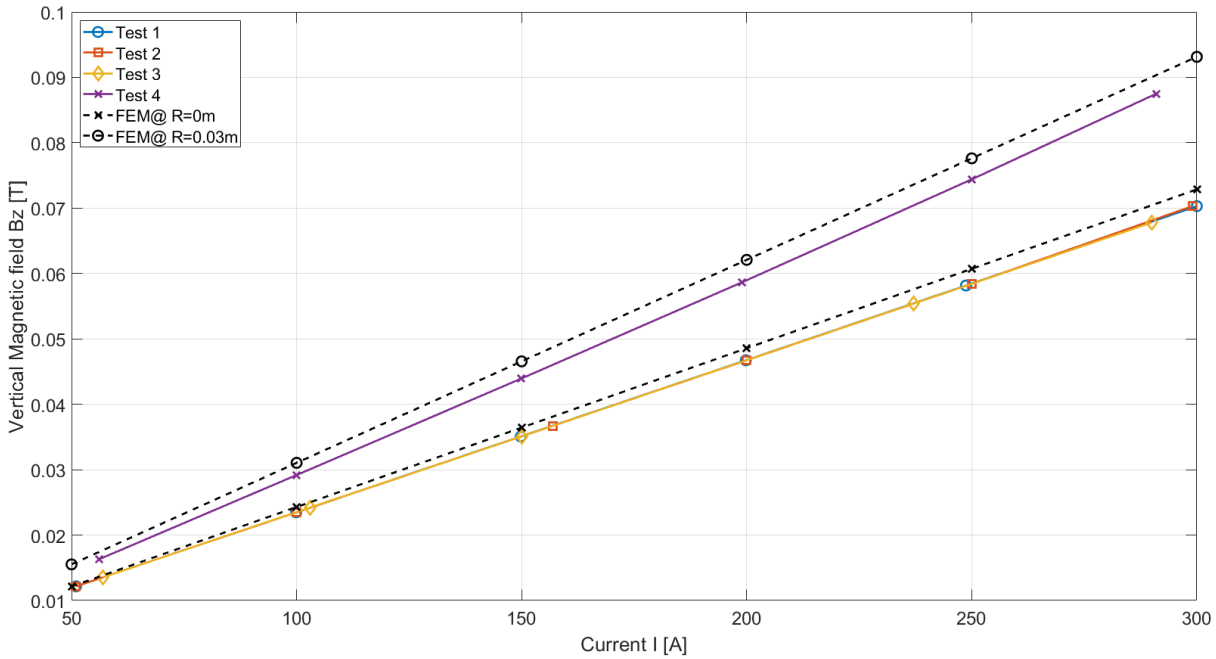




Thanks to G. Celentano and A. Masi

Third test final version for the coil: Comparison between vertical magnetic field measurements and FEM analysis





TRUST PROJECT

Scalable HTS coils

New Lab for HTS for electrical, magnetic and mechanical characterization of superconducting tapes and coils

Instrumentation

- Cernox Lake Shore Cryotronics sensors
- Magnetic field probe Lake Shore HGCA-3020
- Gaussmeter Lake Shore 475 DSP
- Supercapacitor IGBT power supply 1.2 kV at 600 A
- DC power supplies (120 A 40 V - 120 A 60 V - 1000 A, 10 V)
- 2182 A/E Keithley Nanovoltmeter
- Electromechanical Universal Test Systems (50kN)
- Test with external field through copper coil

We are investing also in human resources and courses

- 2 new PhD started in 2025 on HTS
- At least 1 PhD for the 2026
- Introducing the topic to Bachelor students
- Dedicated Laboratory course for the next Academic year

The lab is mandatory for the TRUST second phase and will be available for **new research activities on HTS** (not only fusion oriented)

Conclusion
Next Steps

- **Complete the TRUST facility** within the 2026;
- Opening the **HTS lab to perform measurement on HTS tape and coils** at 77K;
- Build a **new HTS coils exploring double pancake solution** and improving the current limits;
- **Improve the TRUST design maturity level** to start the construction at the beginning of the 2027;
- **Open to collaboration**

Thank You for the Attention!

Prof. Giuseppe Calabrò - giuseppe.calabro@unitus.it
Dr. Simone Carusotti - simone.carusotti@unitus.it
Prof. Pierluigi Fanelli – pierluigi.fanelli@unitus.it
Dr. Andrea Marchegiani – andrea.marchegiani@unitus.it

and the **TRUST Team**

The starting physics and **engineering design drivers for TRUST** are the following:

- The target **major plasma radius is *R ≤ 0.3 m*** and the **plasma aspect ratio** should be ***R/a ~ 2.3***.
- The CS driven **discharge in the order of magnitude tenths of a second**.
- Includes the **AML concept** with the integration **of HTS coils.**
- The **heat flux on the PFCs relevant** to test materials $q_{target} \geq 2\ MW/m^2$.
- A **Single Null (SN)** plasma configuration with **110 kA of plasma current**.

This parameters for TRUST are a **trade-off between** the need to build an **academic and economic tokamak** fully design and operated by students and the intention to **test advanced technologies for nuclear fusion**.

TRUST PROJECT
Research Plan

The **industries involvement in TRUST** represents one of the **key features of this project**. The main collaborations range from the physical aspects of the plasma that the experiment will produce to the design of the mechanical components required for the device.

Partners

Tokamak Energy

walter tosto
INNOVATION AND DELIVERY

ENEA
Agenzia Nazionale per le Nuove tecnologie, l'Energia e lo Sviluppo economico sostenibile

ASG SUPERCONDUCTORS

OCEM
AirfieldTechnology

Schedule

Operational Phase 1 – 2024 to 2027

Success of the **first plasma** and the positive execution of the foreseen target plasma scenario including the **commissioning of all the system.**

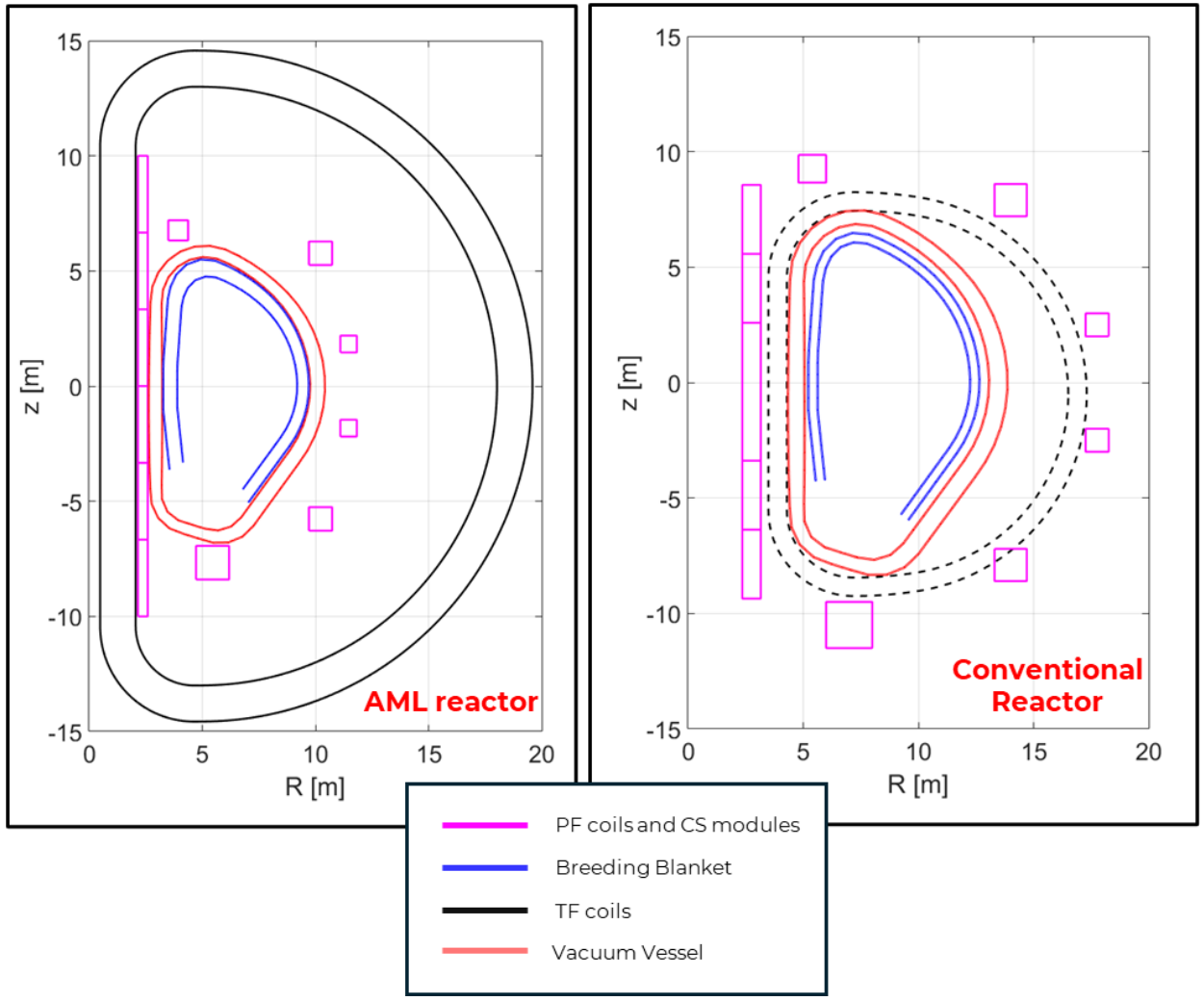
Operational Phase 2 – 2025 to 2029

Testing of a HTS coils by replacing at least one copper PF coil. Start the operation of HTS coils in a dedicated laboratory, before of their installation on TRUST.

Operational Phase 3 – 2028 to …

All the TRUST magnetic system upgraded from copper to HTS including the TF coils. **Addition of an ECH system** to perform plasma discharge with a duration in the order of magnitude hours

AML STUDIES
Concept



The **AML design** demonstrates a compact arrangement of the PF coils and structural components, achieved by **repositioning the CS around the central column of the TF coils**.

$$\psi_{CS} = \frac{\pi B_{CS}}{3}\left(R_i^2 + R_i R_e + R_e^2\right)$$

$$B_t(R) = \frac{\mu_0 \, N_{TF} \, I_{TF}}{2 \, \pi \, R}$$

since $\mathbf{B_t \approx 1/R}$, whilst $\mathbf{\psi_{CS} \approx R^2}$, a clear **reduction of the machine dimension** can be obtained, whilst maintaining the same engineering parameters (but the **current density on the TF coils must increase**)