UNIVERSITÀ DEGLI STUDI DELLA TUSCIA | DIPARTIMENTO DI ECONOMIA, INGEGNERIA, SOCIETÀ E IMPRESA

Design of HTS coils for LN2 cable testing

MAG – S.01.06-T014EU-CN Deliverable: D001

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EU-CN Collaboration · Museo Nazionale Etrusco | Villa Giulia · October 28, 2026

This work has been partially carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No. 101052200—EUROfusion). The views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union nor the European Commission. Neither the European Union nor the European Commission can be held responsible for them

Task Overview & Design Objectives

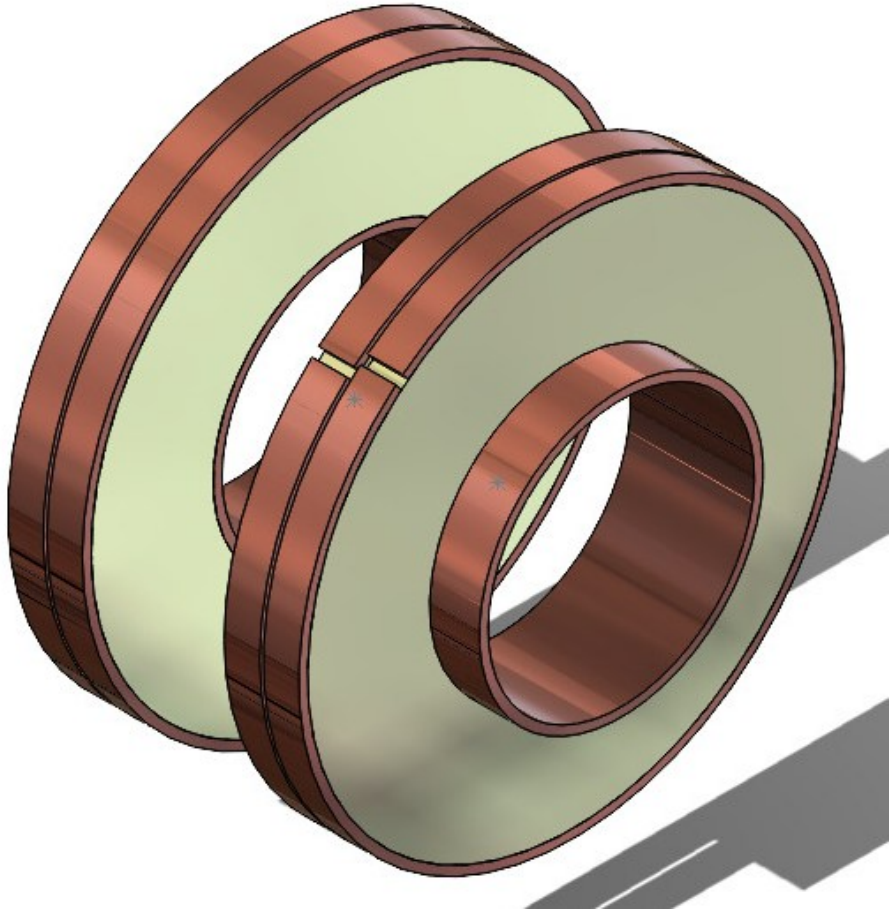
THE CHALLENGE

High-current testing of short HTS cables (1–5 m) in liquid nitrogen can be affected by termination resistance and local heating, making critical current measurements difficult to interpret.

THE SOLUTION

A dedicated magnetic system enables cable testing under controlled magnetic fields, helping to reduce the influence of termination-related effects.

TARGET FIELD	DESIGN CONSTRAINS
0.5 – 1 T	**Mechanical - Thermal - Economic**



Proposed final design

01

Design Development

Iterative design of HTS coil configurations

Starting Point

Proposed HTS Conductor

SST2207 - Shanghai Superconductor

High field, low temperature HTS tape

- 10 mm width
- 86 μm thickness
- 507 A @ 77 K, self-field

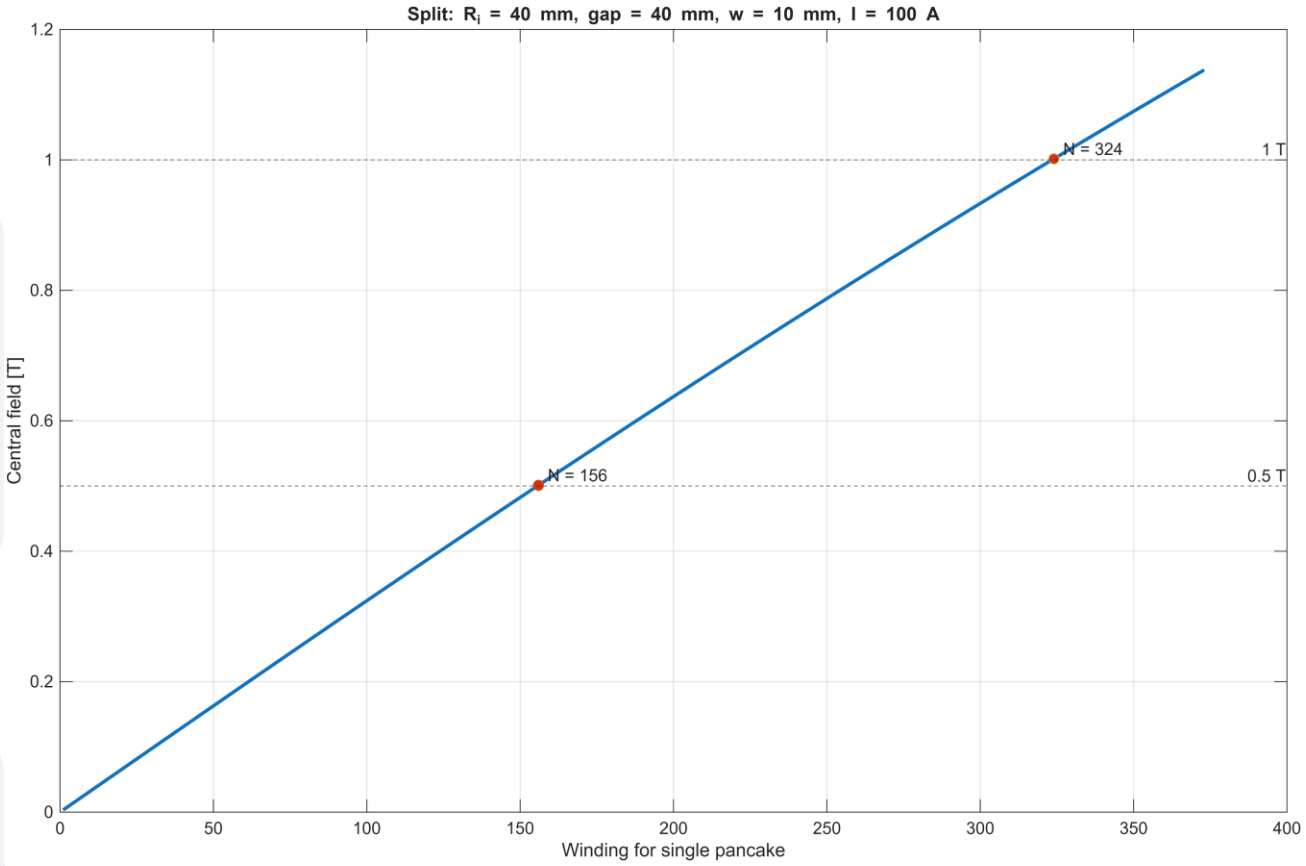
Geometric parameters

Double-/four-pancake split-coil configuration

Initial split-coil configuration

- 40 mm Winding Pack Inner Radius
- 40 mm gap
- 350 turns per pancake

Electromagnetic quantities evaluated at 100 A (reference current).



Preliminary Magnetic Field Assessment

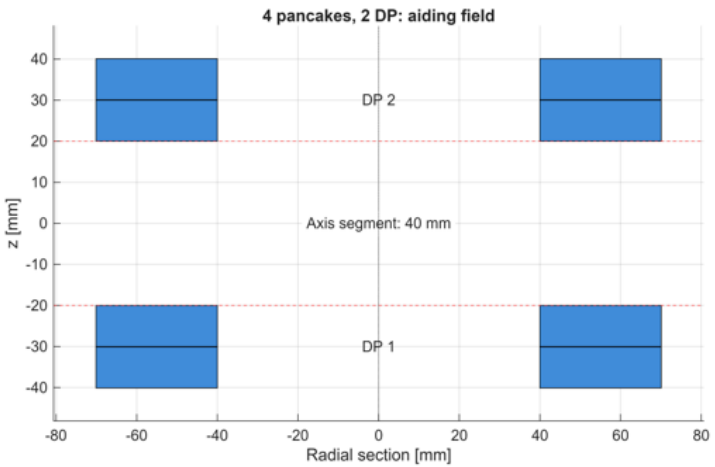
0.5 T Target	1.0 T Target	Baseline
156 turns/pancake	**324** turns/pancake	**350** turns/pancake

Ist Design Iteration

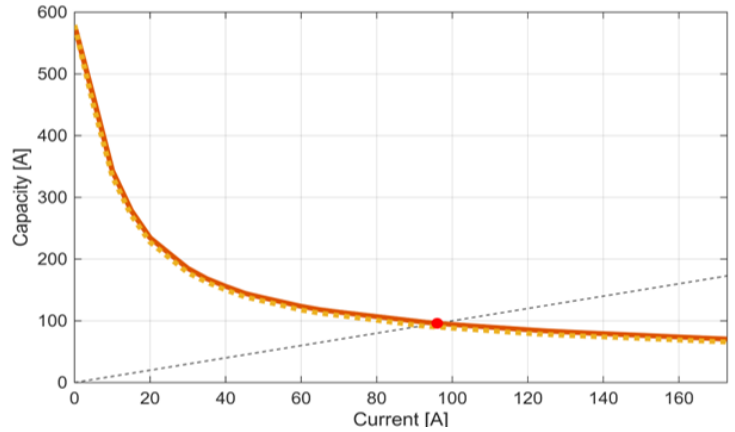
Field-to-current ratio **10.74** mT/A	Central field @100 A **1.074** T
Estimated inductance **140.13** mH	Stored energy @100 A **700.67** J

90 A < I_c < 96 A

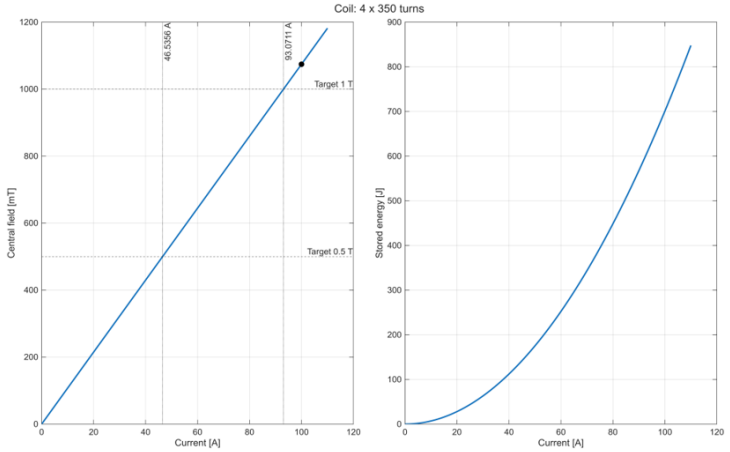
Reference geometry



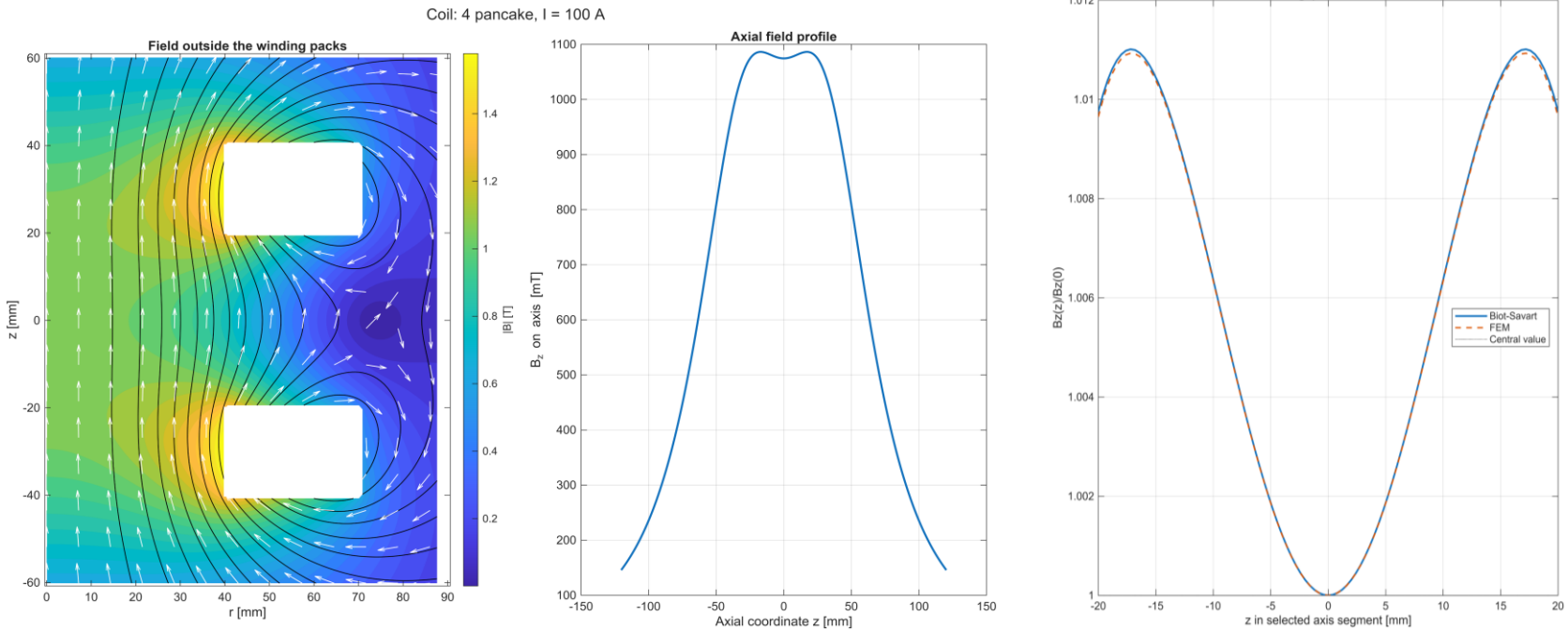
Critical current prediction



Operating conditions



Magnetic Field Uniformity

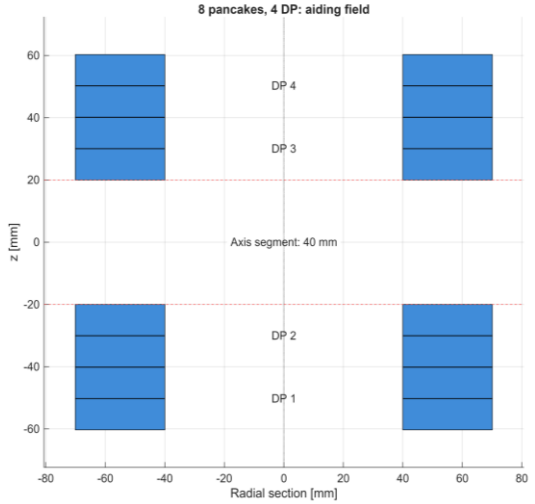


IInd Design Iteration

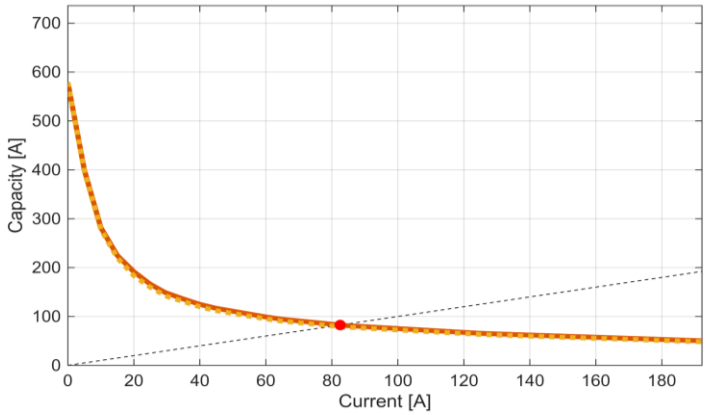
Field-to-current ratio **17.12** mT/A	Central field @100 A **1.712** T
Estimated inductance **441** mH	Stored energy @100 A **2204.95** J

80 A < I_c < 84 A

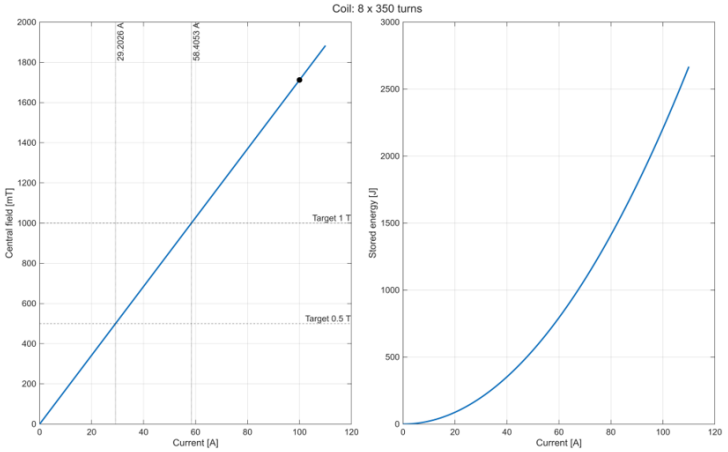
Reference geometry



Critical current prediction

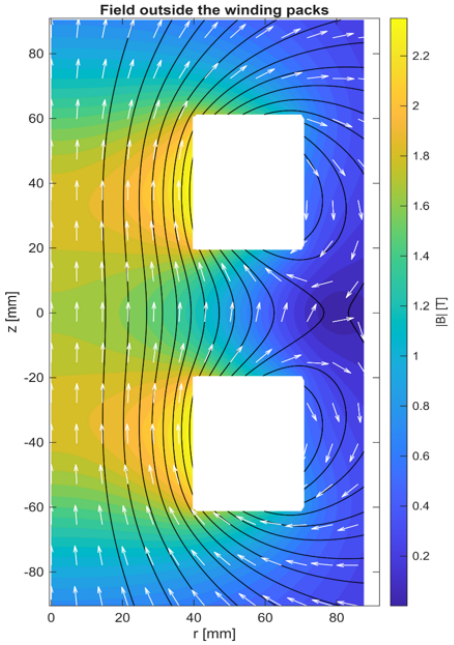


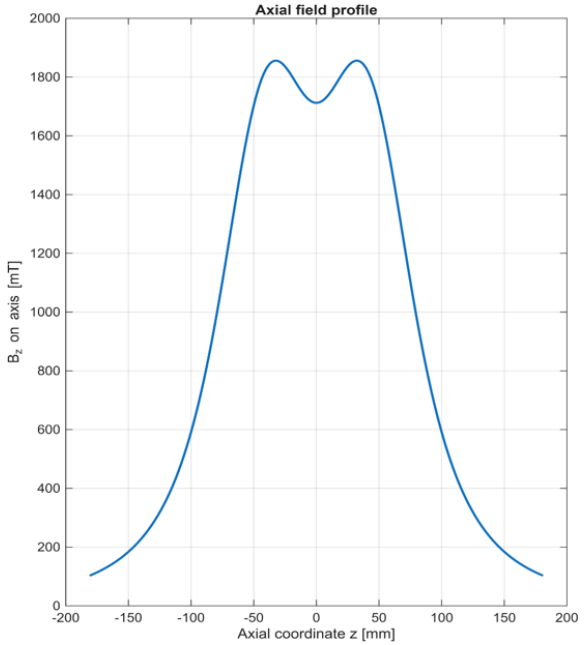
Operating conditions

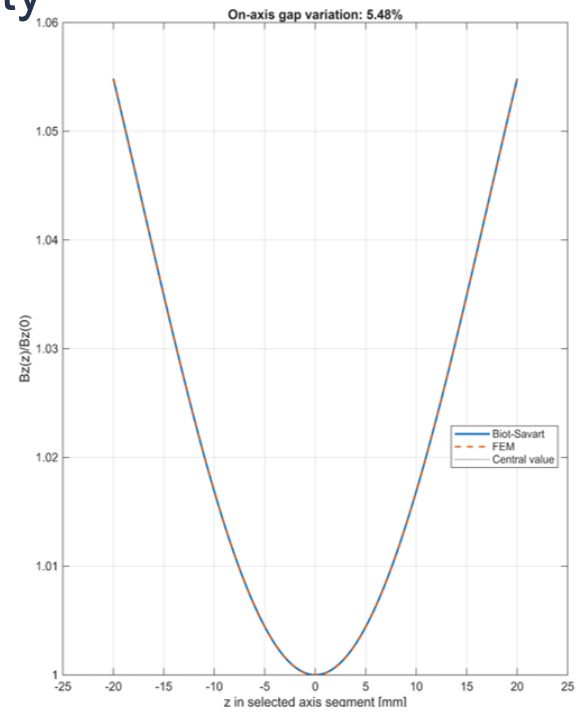


Magnetic Field Uniformity

Coil: 8 pancake, I = 100 A





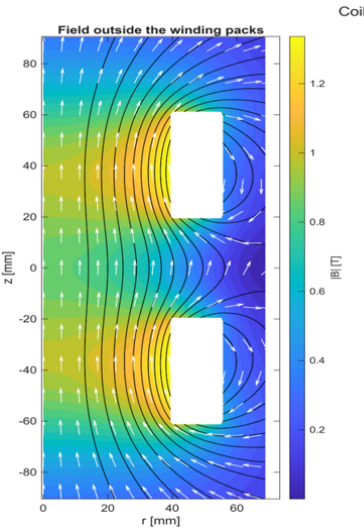


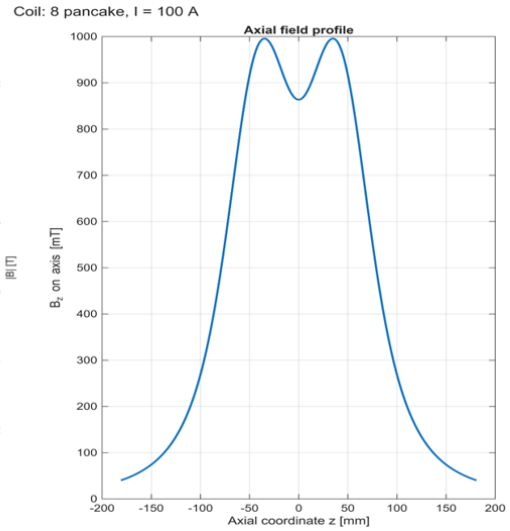
IIIrd Design Iteration

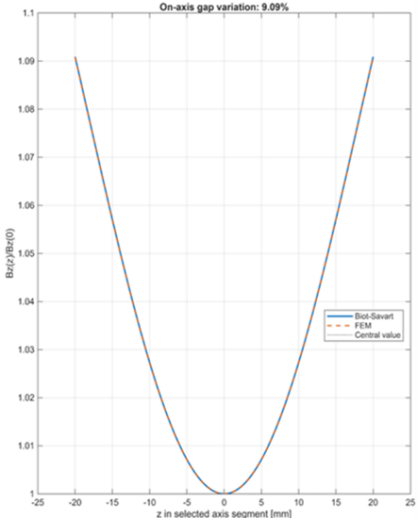
Field-to-current ratio **8.63** mT/A	Central field @100 A **863.5** mT
Estimated inductance **97.8** mH	Stored energy @100 A **489.2** J
N = 175	**97 A < I_c < 103 A**

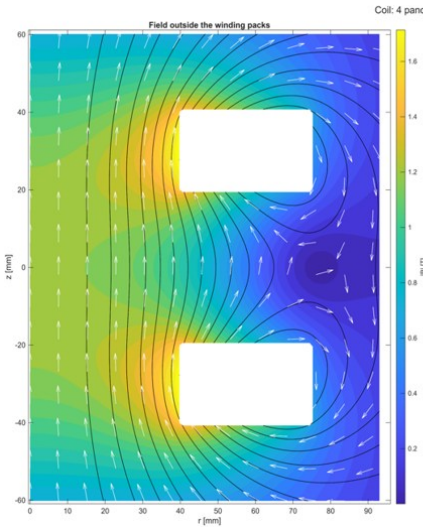
IVth Design Iteration

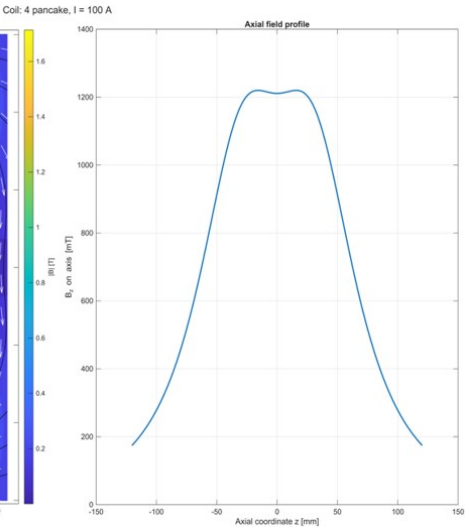
Field-to-current ratio **12.11** mT/A	Central field @100 A **1.211** T
Estimated inductance **187.82** mH	Stored energy @100 A **939.1** J
N = 400	**89 A < I_c < 93 A**

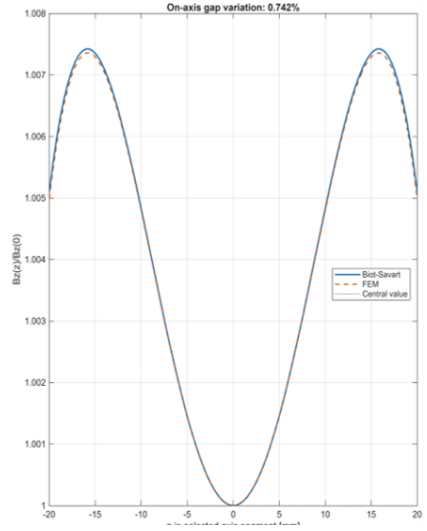












Vth Design Iteration

Field-to-current ratio **11.35** mT/A	Central field @100 A **1.135** T
Stored energy @100 A **1235.4** J	Estimated inductance **247.1** mH

N = 400

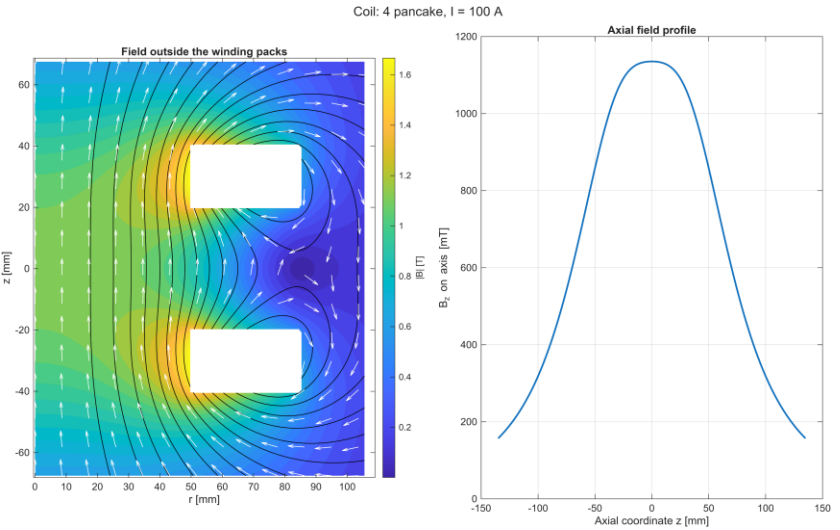
WP IR = 50mm

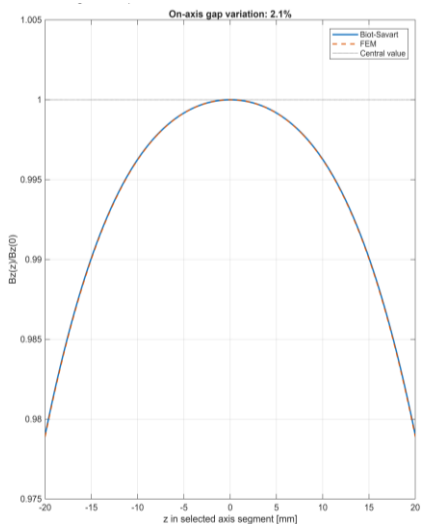
90 A < I_c < 94 A

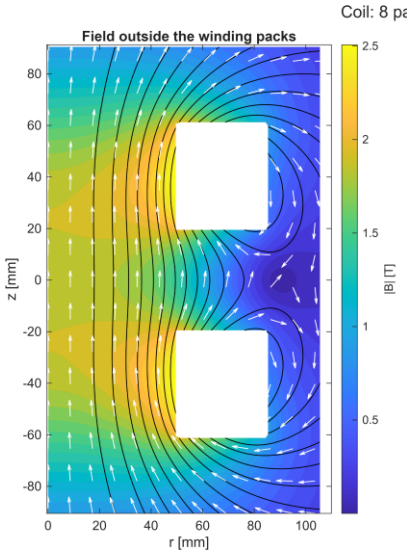
VIth Design Iteration

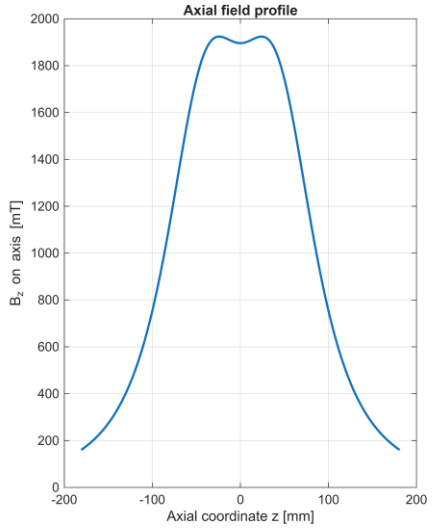
Field-to-current ratio **18.96** mT/A	Central field @100 A **1.896** T
Stored energy @100 A **794.56** J	Estimated inductance **3972.83** mH

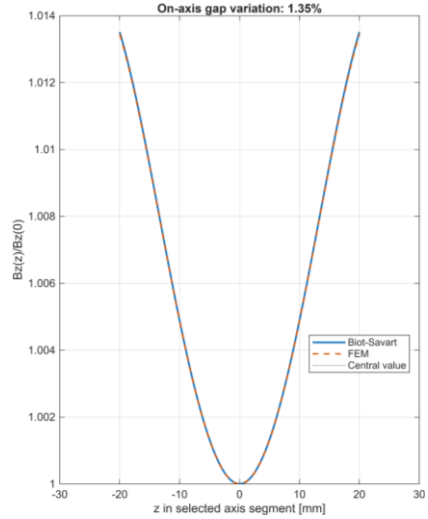
78 A < I_c < 80 A











VIIth Design Iteration

Field-to-current ratio
10.31 mT/A

Central field @100 A
1.031 T

Stored energy @100 A
5810.74 J

Estimated inductance
1162.15 mH

88 A < I_c < 92 A

N = 550

WP IR = 100mm

VIIIth Design Iteration

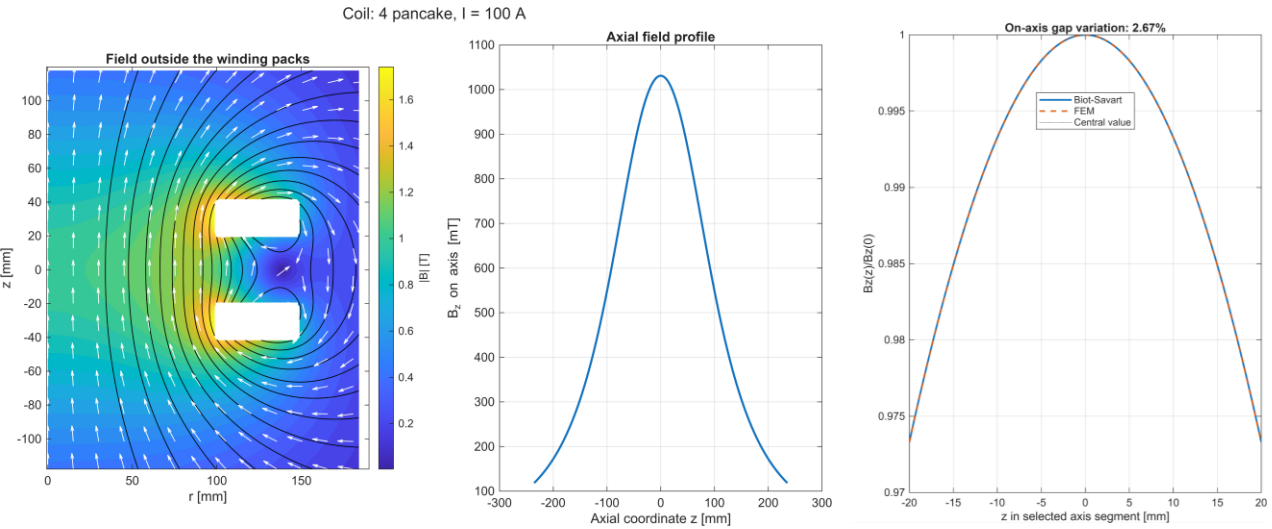
Field-to-current ratio
19.2 mT/A

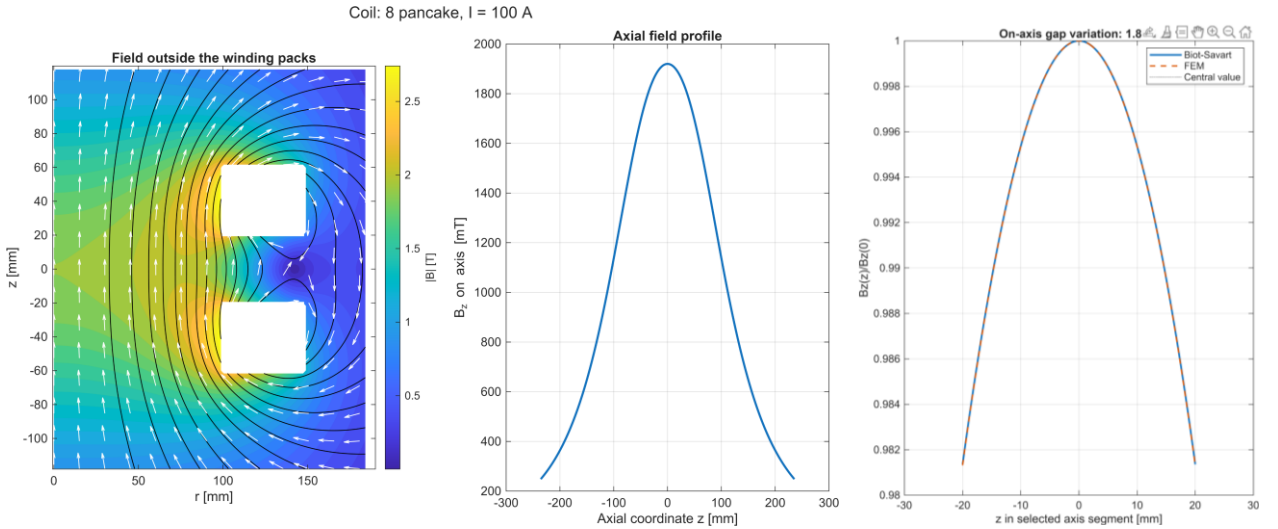
Central field @100 A
1.920 T

Stored energy @100 A
19762.1 J

Estimated inductance
3952.4 mH

75 A < I_c < 77 A





Design Iterations — Comparative Assessment

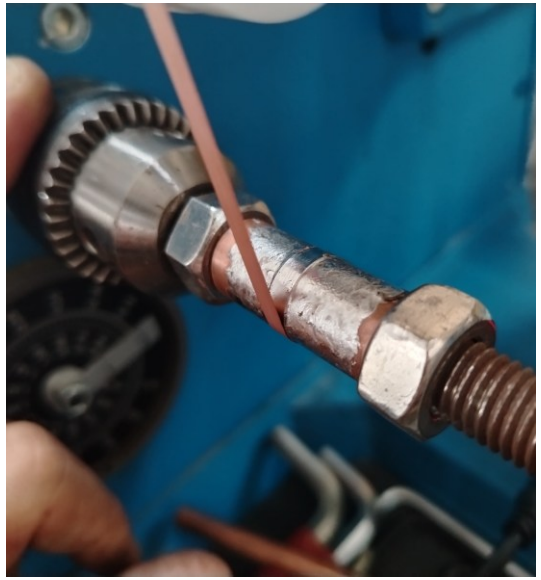
Design	Inner radius [mm]	Configuration	Turns / pancake	Total tape length [m]	Min. Ic [A]	I required [A]	Current margin [%]	Field variation [%]
01	40	Split 2 DP	350	500	90	93	−3.3	1.1
02	40	Split 4 DP	350	1000	80	58	+27.5	5.5
03	40	Split 4 DP	175	420	97	116	−19.6	9.1
04	**40**	**Split 2 DP**	**400**	**580**	**89**	**83**	**+6.7**	**0.7**
05	50	Split 2 DP	400	660	90	88	+2.2	2.1
06	50	Split 4 DP	400	1330	78	53	+32	1.3
07	100	Split 2 DP	550	1715	88	96	-9.1	2.7
08	100	Split 4 DP	550	3430	75	52	+30.7	1.9

02

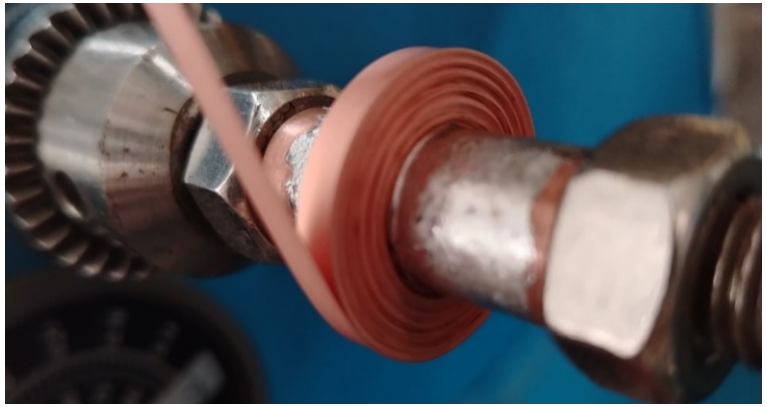
Prototype Testing

Experimental assessment of winding techniques and electrical joints

Resistive Double-Pancake Prototype

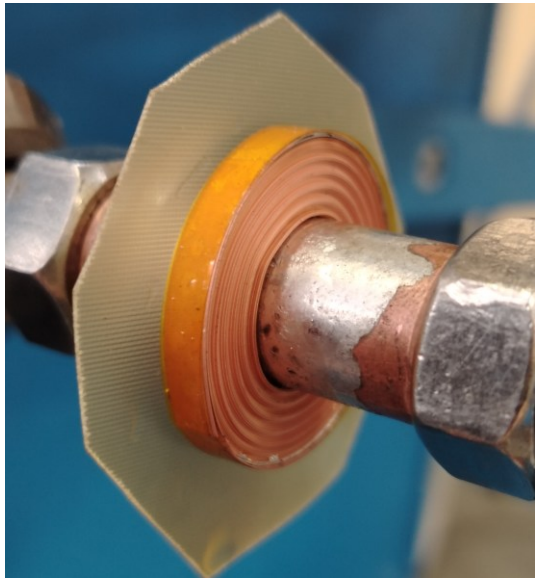


1. Single Pancake soldering

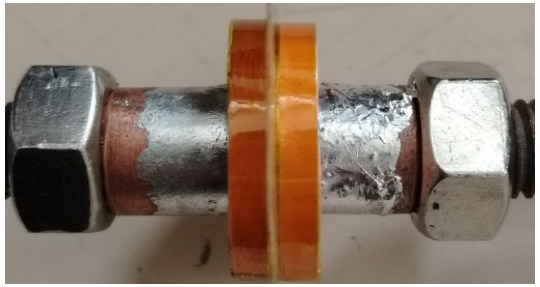


2. Single Pancake winding

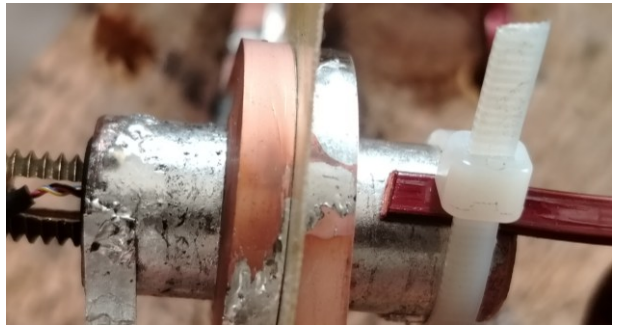
WPIR	7.5	mm
Windings	50	
Non insulated		



3. Inter Pancake insulation



4. 2nd Pancake winding



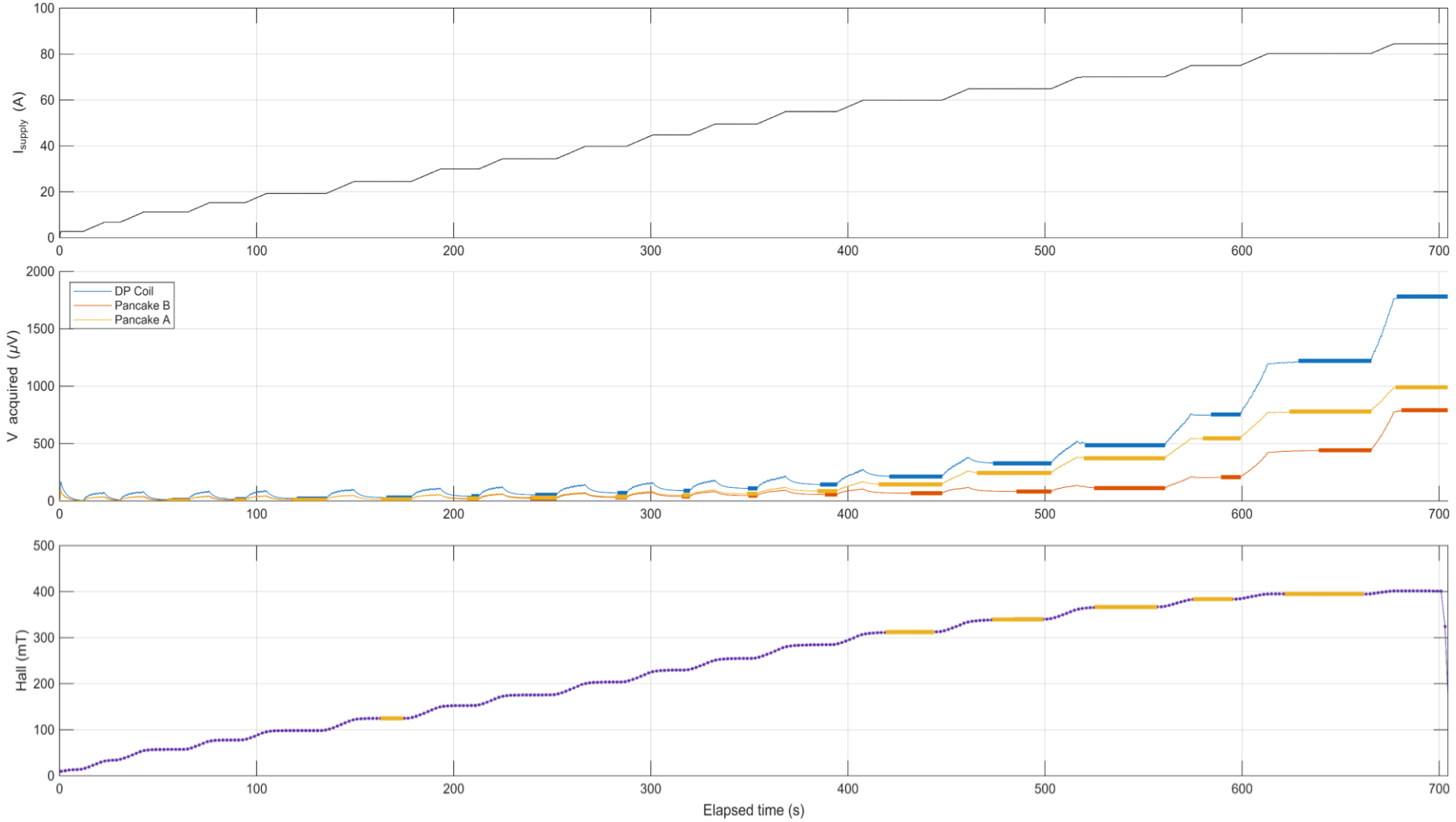
5. Double Pancake energization

SuNam SCN04200

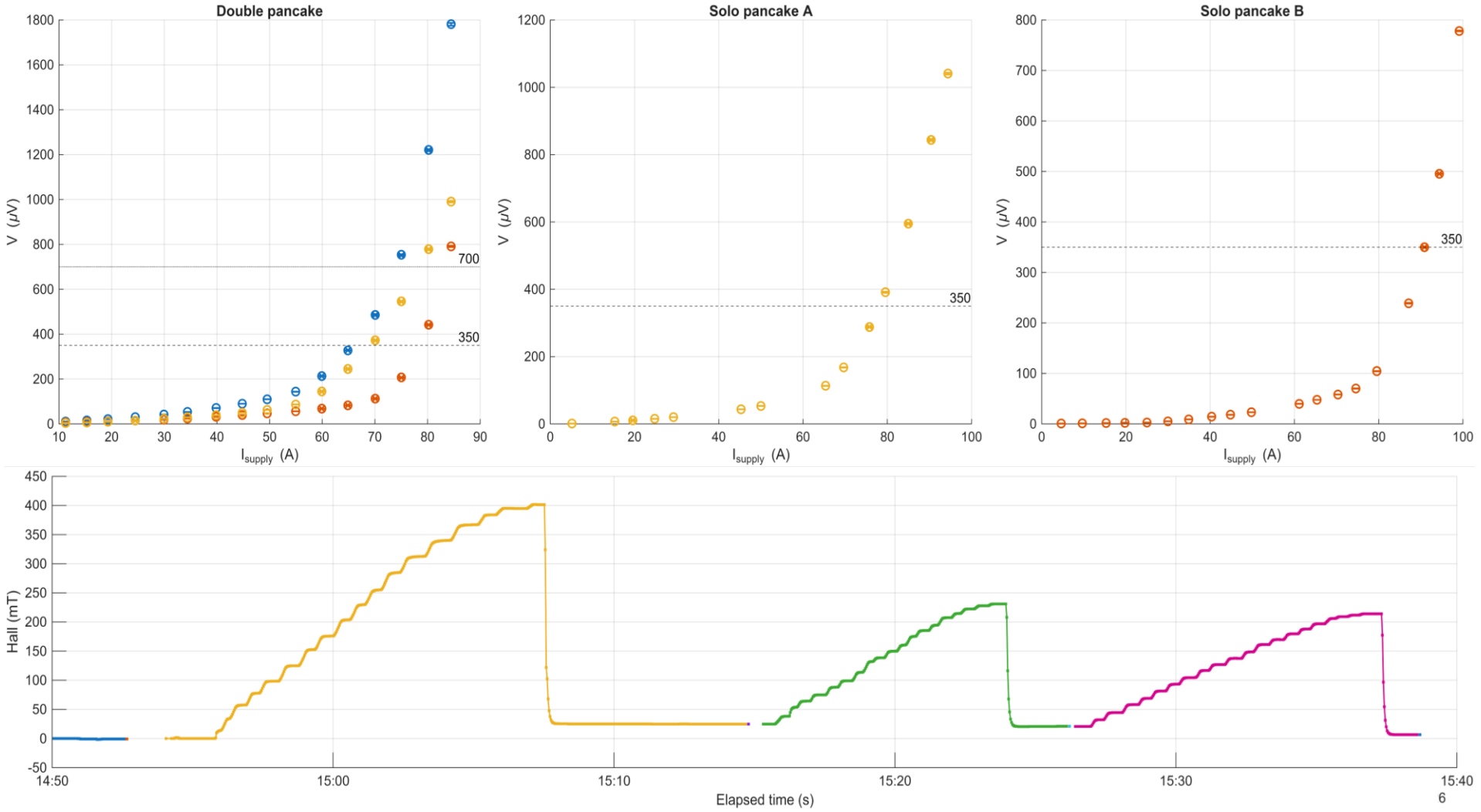
SC layer	Manufacturer	Tape width [mm]	Tape thickness [mm]
GdBCO	SuNam	4	0.14

Resistive first-turn connections provide a faster and simpler prototyping approach, avoiding the complexity of superconducting joints and crossovers.

Resistive Double-Pancake Prototype



Resistive Double-Pancake Prototype

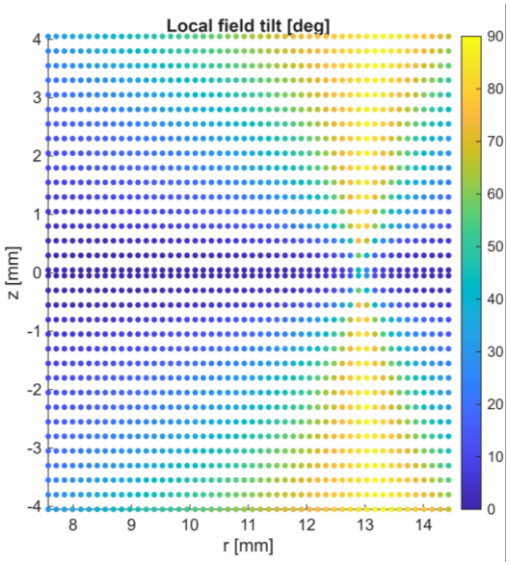


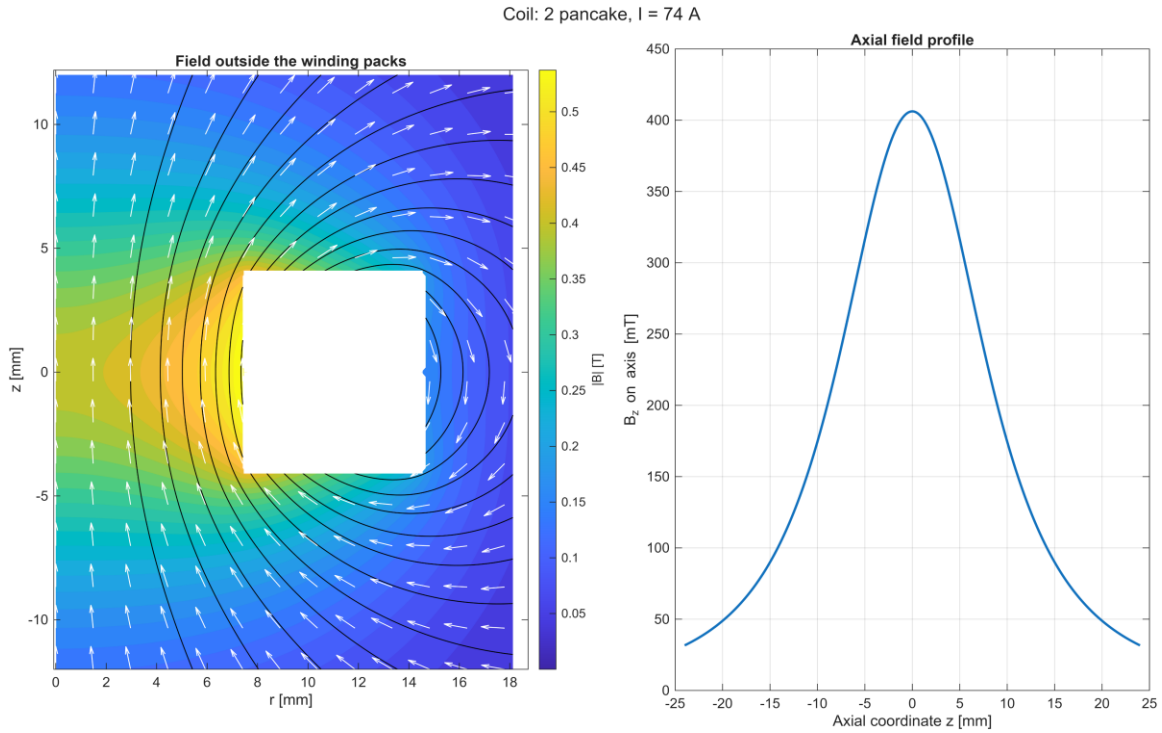
Post-Transient Analysis
Similar plateau behavior
DP: 74 A
Coil A: 78 A
Coil B: 69 A

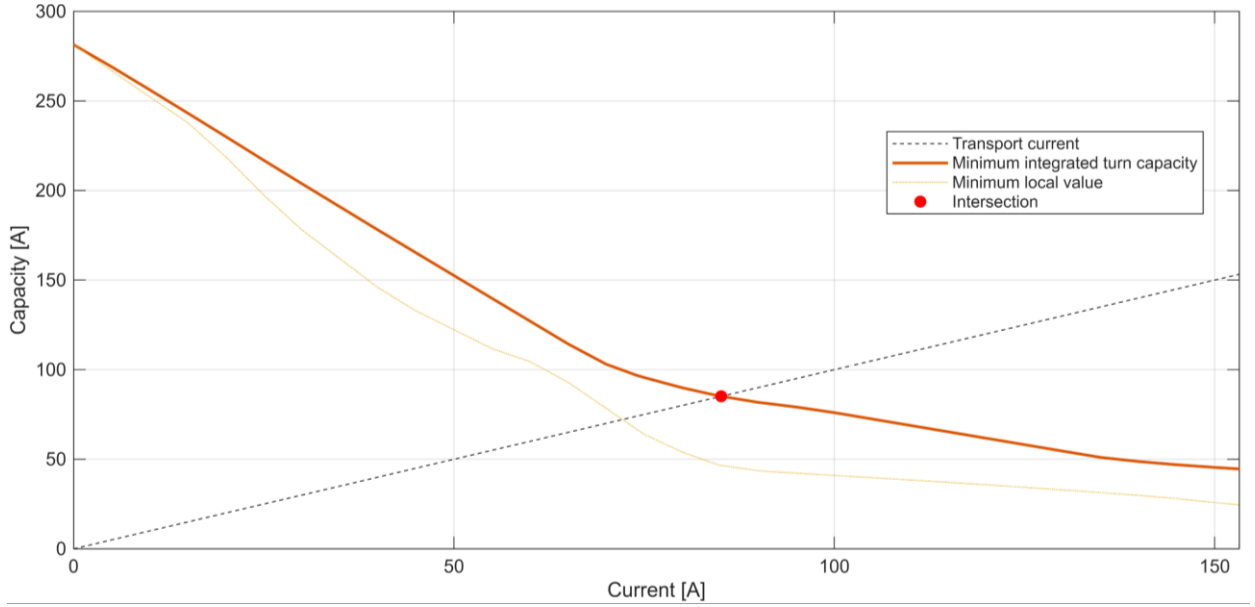
Magnetic Field
~0.4 T at the bore, measured at the DP critical current.

Resistive Double-Pancake Prototype

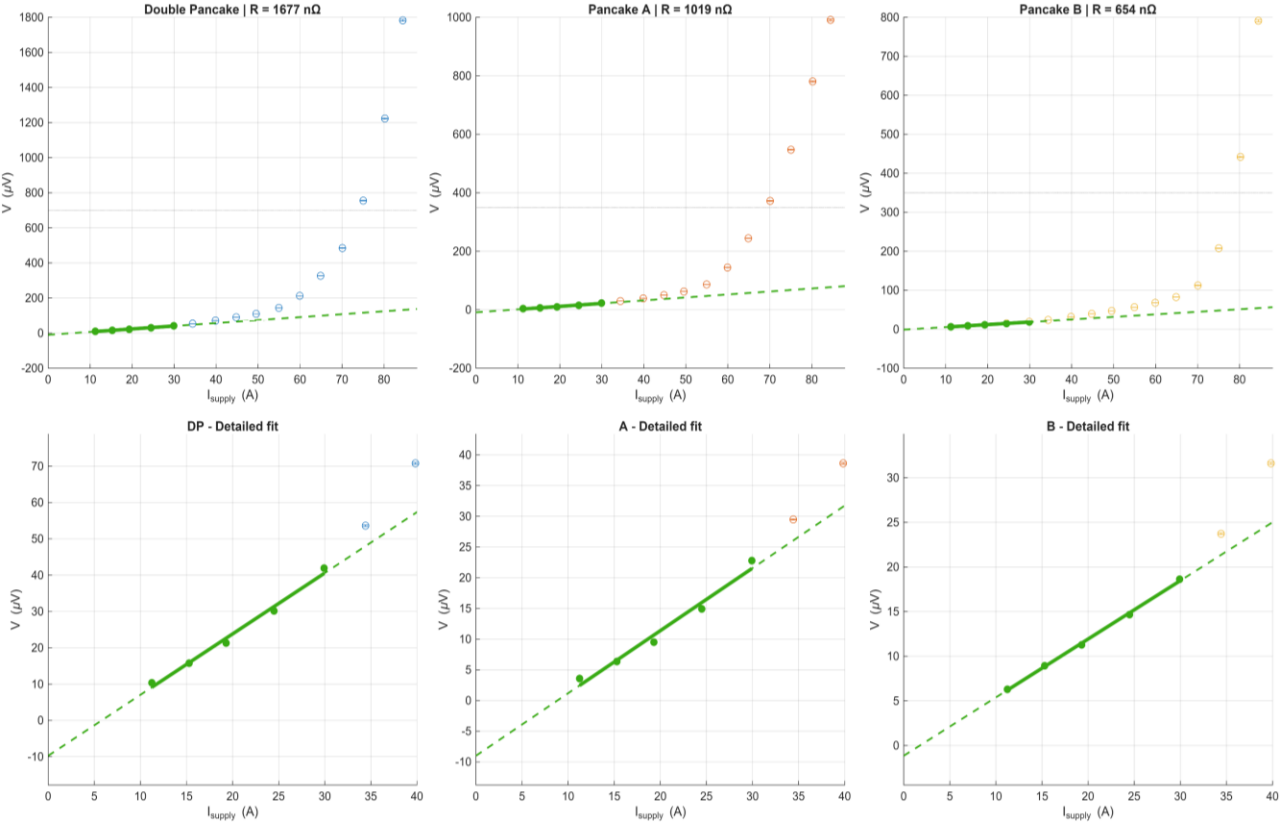
Another successful experimental comparison
Predicted critical current: **70–85 A**
Measured critical current: **74 A**
Predicted central field: **~0.4 T**
Experimental results fall within the predicted range.





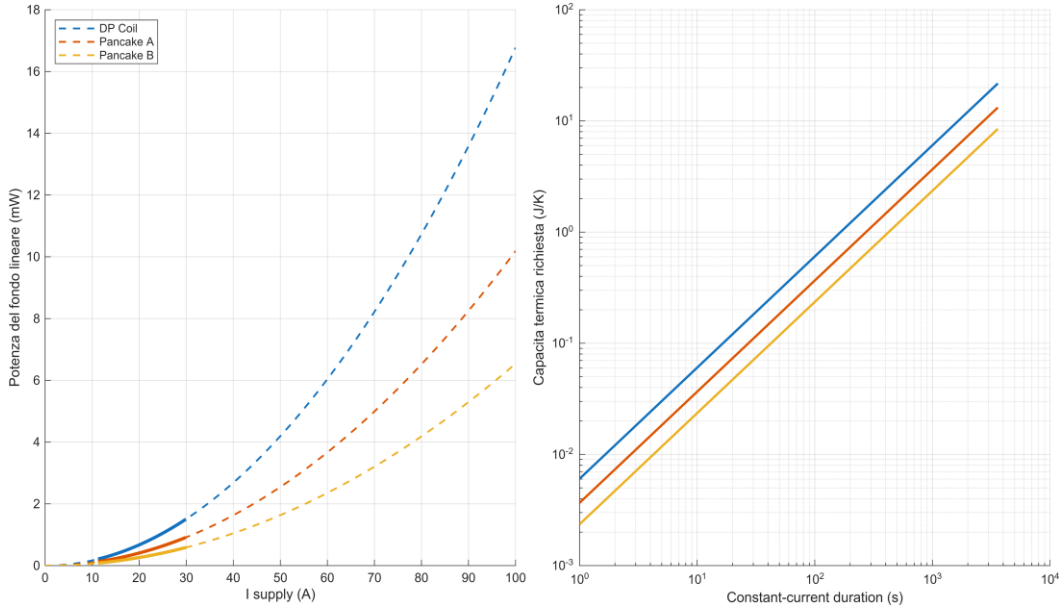


Electrical Characterization



Double Pancake	Pancake A	Pancake A
1.677 nΩ	**1.019** nΩ	**654** nΩ

Steady-state thermal simulations were performed to evaluate local temperature rises caused by resistive heating, considering heat conduction through copper and cooling at the inner and outer boundaries.



Thermal Assessment

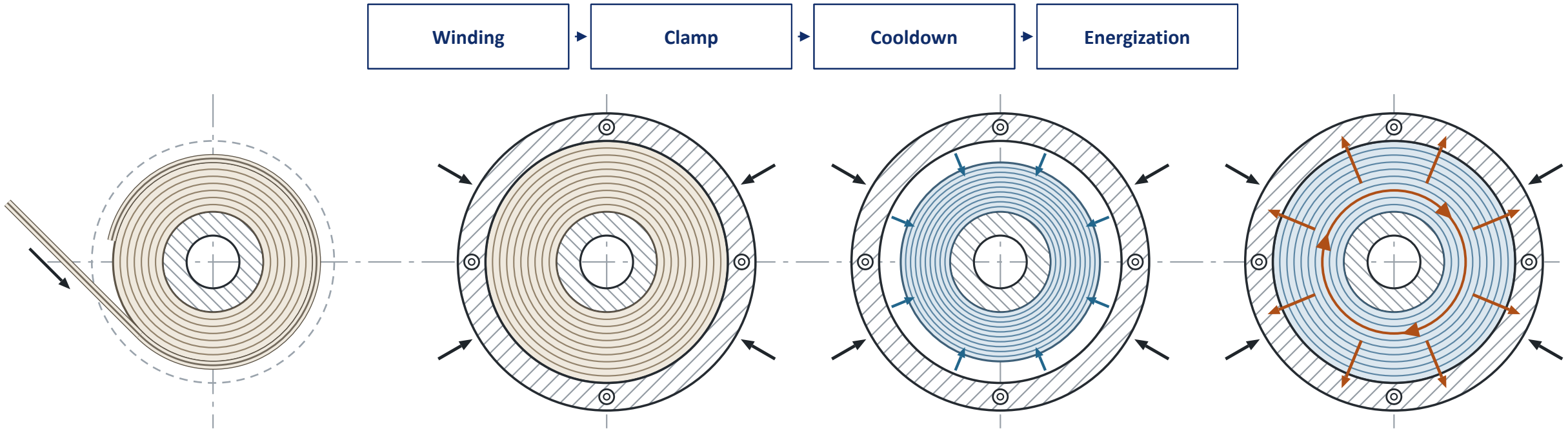
Evaluation of local heating from resistive joints, considering copper heat conduction and cooling at the coil boundaries.

03

Design Refinement

From selected configuration to preliminary CAD design

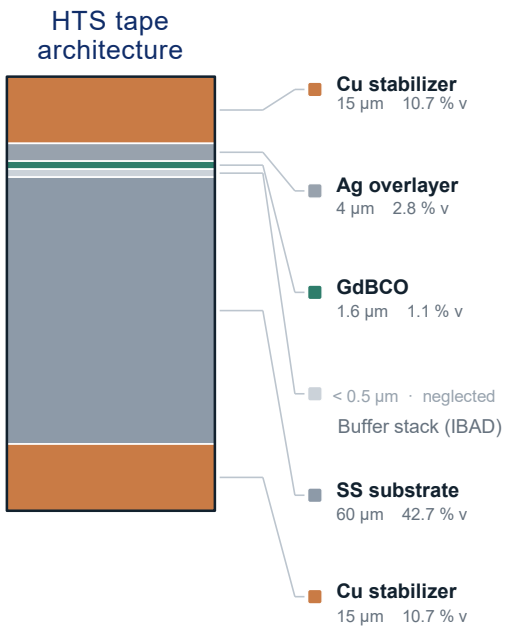
Stress assessment – Design 04



$$\ddot{u} + \frac{\dot{u}}{r} - \frac{s^2}{r^2}u = -\frac{\overbrace{f_r}^{EM}}{E_r} + \frac{\overbrace{\varepsilon_{th,r} - s^2\varepsilon_{th,h}}^{CD}}{\mathrm{r}}; \qquad s = \frac{E_h}{E_r}$$

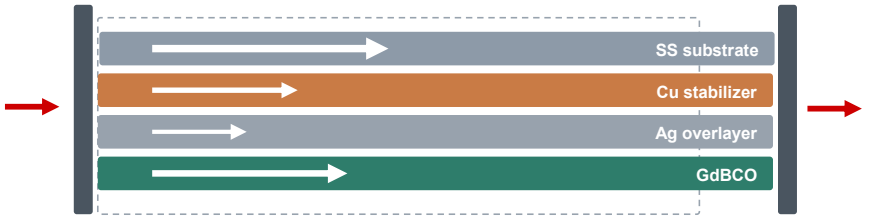
Material Characteristic assessment: The linear model

A. Marchegiani et al, “A Design-Oriented Analytical Framework for Tension-Wound Orthotropic Cylindrical Assemblies”. Manuscript submitted to Engineering Proceedings (MDPI).



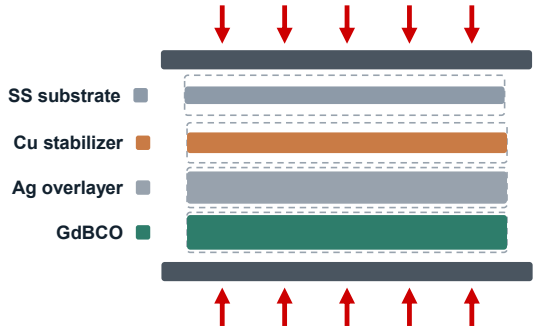
EQUIVALENT VOLUME FRACTION MODEL

ISO-STRAIN: Voigt Rule



$$E_\theta = 172.1\ \text{GPa}$$

ISO-STRESS: Reuss Rule

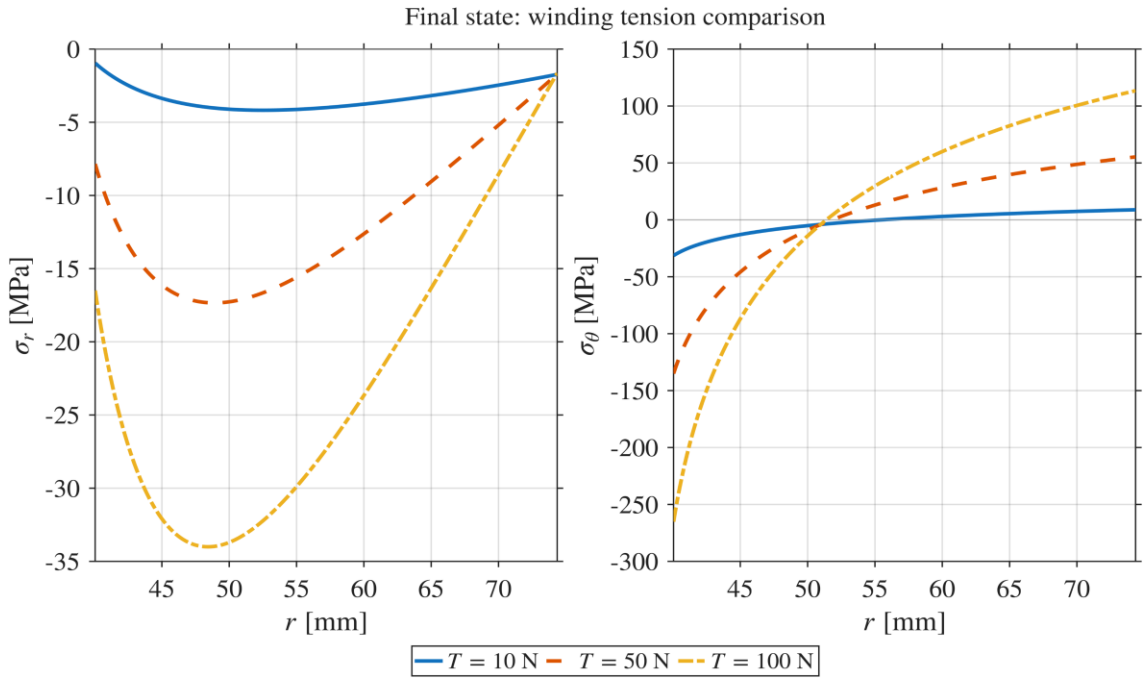


$$E_r = 162.2\ \text{GPa}$$

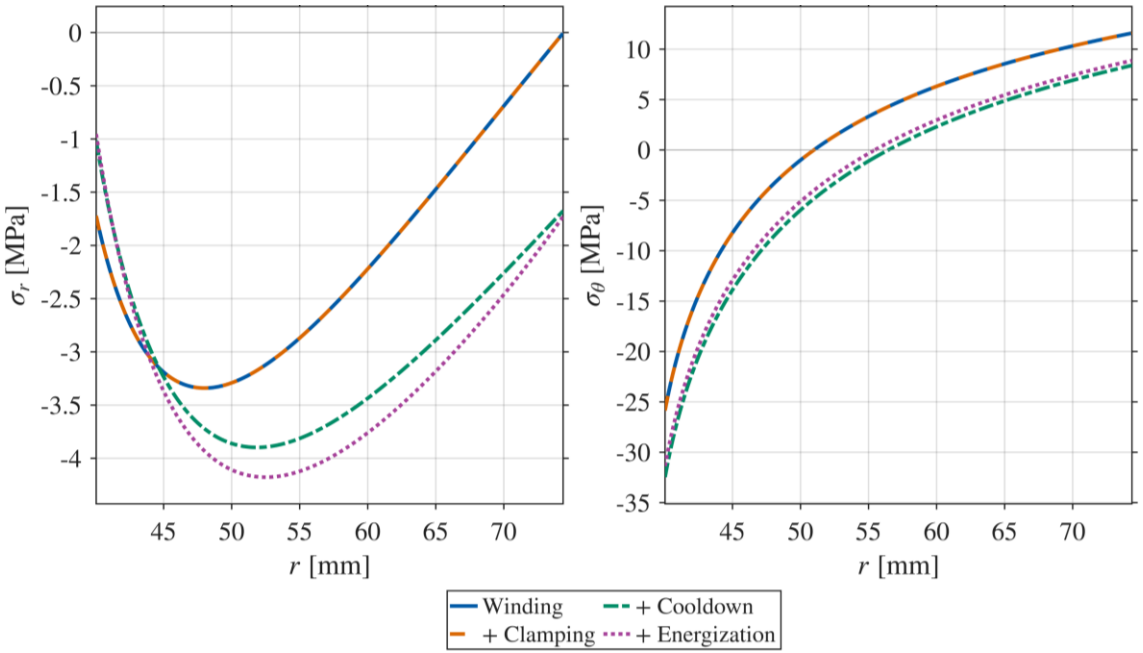
Load Path — SP Stress Comparison, final state

WT [N]	Min σr [MPa]	Max σr [MPa]	Min σθ [MPa]	Max σθ [MPa]
10	−4.177	−0.953	**−31.377**	8.871
50	−17.341	−1.721	**−135.051**	55.303
100	−34.005	−1.647	**−265.207**	113.454

J = 96.51 A/mm² **Bz(Rc) = +0.8046 T** **Bz(Rext) = −0.3987 T**



Winding tension
10 N



Load Path — DP Stress Comparison, final state

Four-pancake split assembly (two double pancakes) | Final load case at I = 83 A

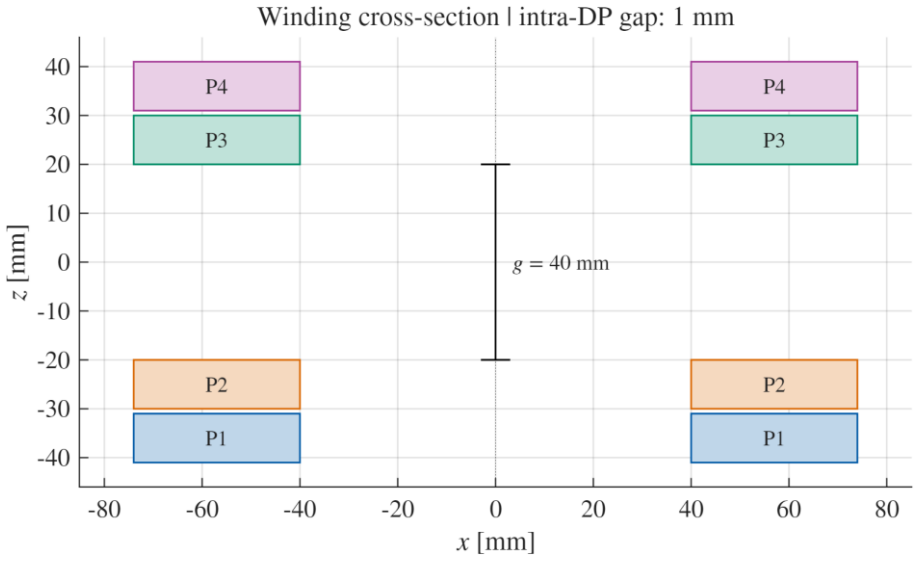
SELECTED WINDING TENSION
10 N
Per winding

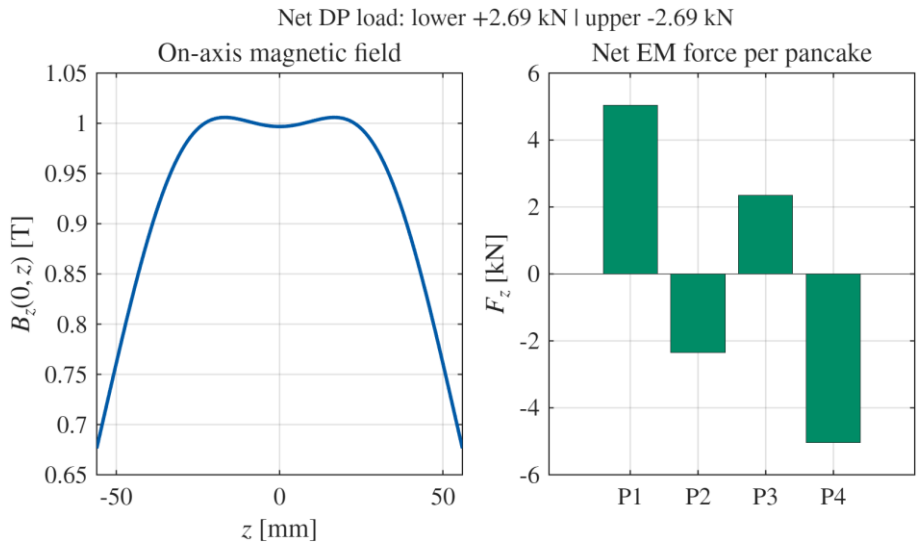
FIELD AT SPLIT CENTRE
0.995478 T
Bz (r = 0, z = 0)

NET AXIAL LOAD PER DP
±2.704 kN
Equal and opposite loads

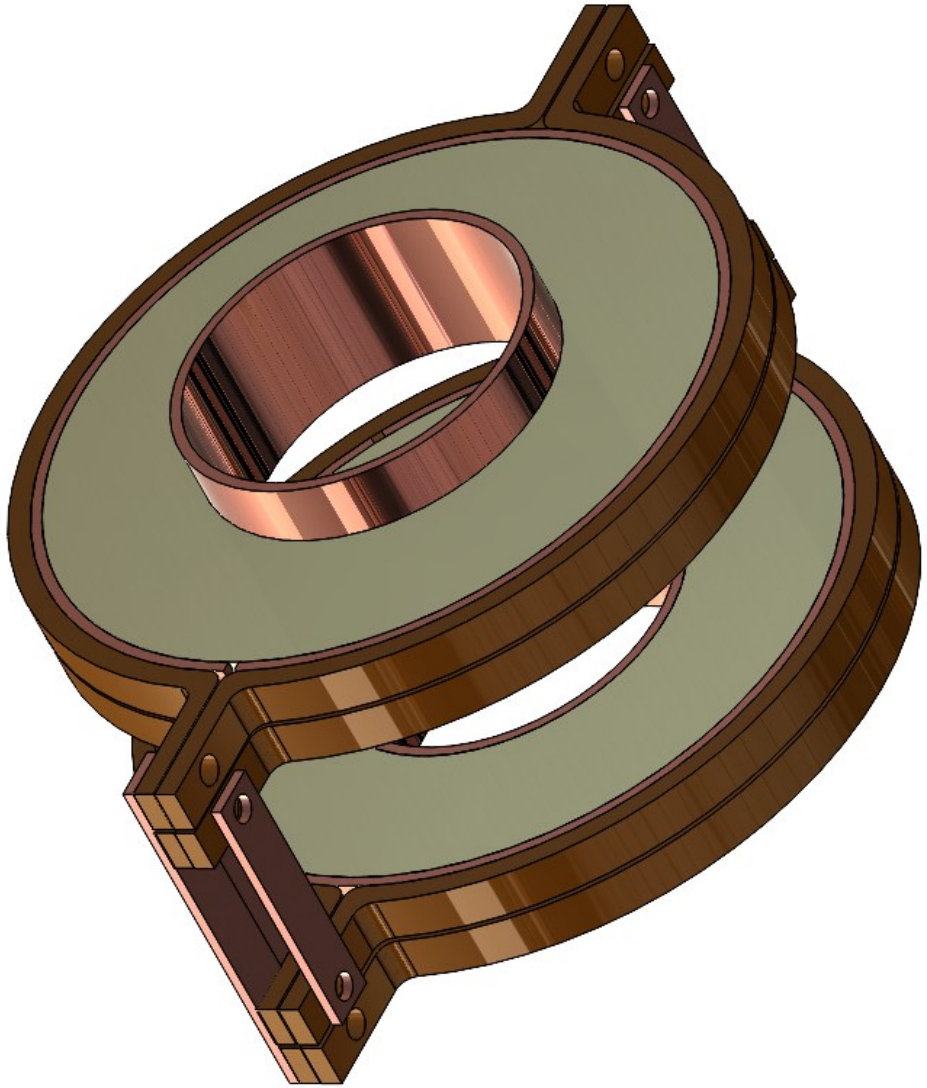
FINAL STRESS EXTREMA [Mpa]

Pancake	z [mm]	Min σr	Max σr	Min σθ	Max σθ
P1	−36.00	−4.3226	−0.8722	**−29.9647**	9.5746
P2	−25.00	−4.3308	−0.8650	−29.8400	9.6383
P3	+25.00	−4.3308	−0.8650	−29.8400	9.6383
P4	+36.00	−4.3226	−0.8722	**−29.9647**	9.5746





Design Proposal



04

Conclusions & Next Steps

Key Achievements and Future Developments

- **Experimental foundation**

HTS tape characterization and experimental activities supported the numerical modelling approach.

- **Design optimization**

Several HTS coil configurations were compared in terms of magnetic field, operating margins, field uniformity, and cost.

- **Numerical predictions**

Experimental critical currents fell within the predicted ranges, providing encouraging agreement between models and measurements.

- **Prototype testing**

Preliminary tests demonstrated the feasibility of the winding process and provided useful information on resistive joints and electrical connections.

- **Next steps**

Further design refinement, thermal assessment, and manufacturing tests towards the final HTS coil assembly.

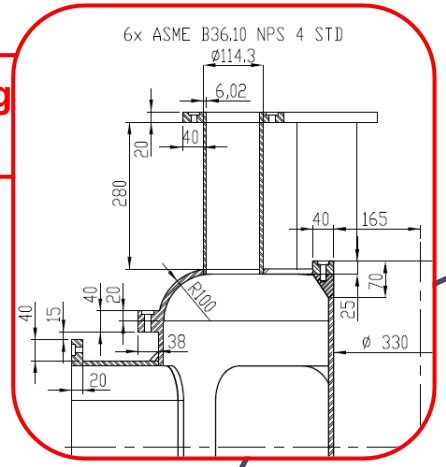
05

UNITUS Superconductivity lab

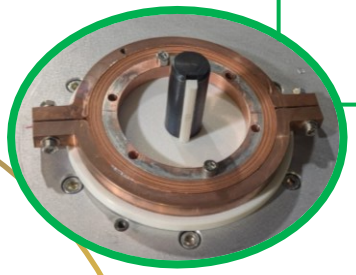
Joint research activities between ENEA and the University of Tuscia

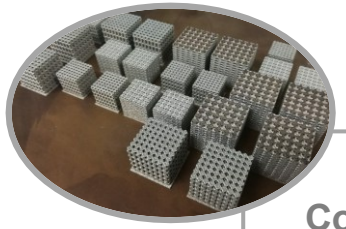
Tuscia Research University Small Tokamak

Tokamaks Engineering Design

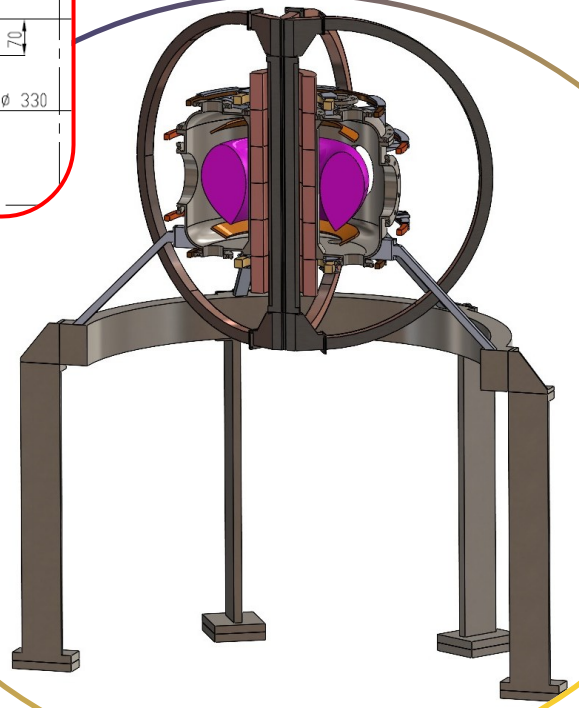


Copper and Superconducting Coils Manufacturing and Characterization

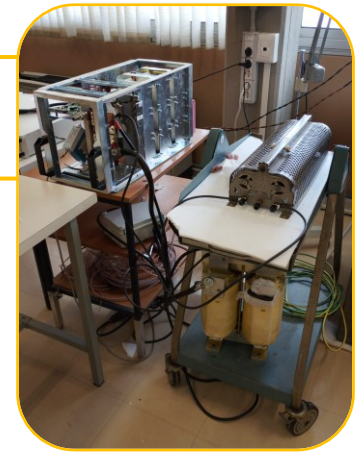


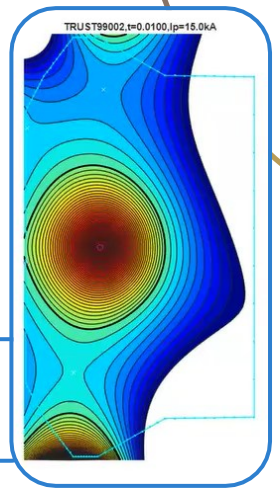


Plasma Facing Components Design, Integration and Test

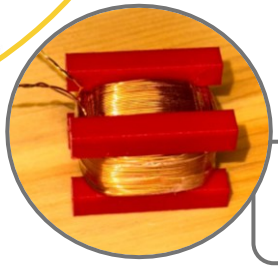


Power Supply Technology





Plasma Modelling & Equilibrium



Diagnostics, Control and Data Acquisition

TRUST Team

Mean age ≈ 32 years
More than 50% grow-up at University of Tuscia

Around **5 Master and Bachelor students/year** involved in Superconductivity

Professors


Prof. Giuseppe Calabrò


Prof. Pierluigi Fanelli


Prof. Flavio Crisanti

Researchers


Dr. S. Carusotti


Dr. M. Notazio


Dr. G. Liuzzo


Dr. M. Gambrioli


Dr. L. Melaragni

PhD Students involved in superconductivity


Dr. S. Azfal


Dr. A. Marchegiani


Dr. C. Porroni


Dr. R. Ruisi

PhD Students


Dr. L. Cacciapuoti


Dr. C. Avanzato


Dr. F. Desana


Dr. G. Di Pietro


Dr. C. Albanese


Dr. T. Fontana


Dr. F. Latini


Dr. E. Morucci


Dr. S. Notazio

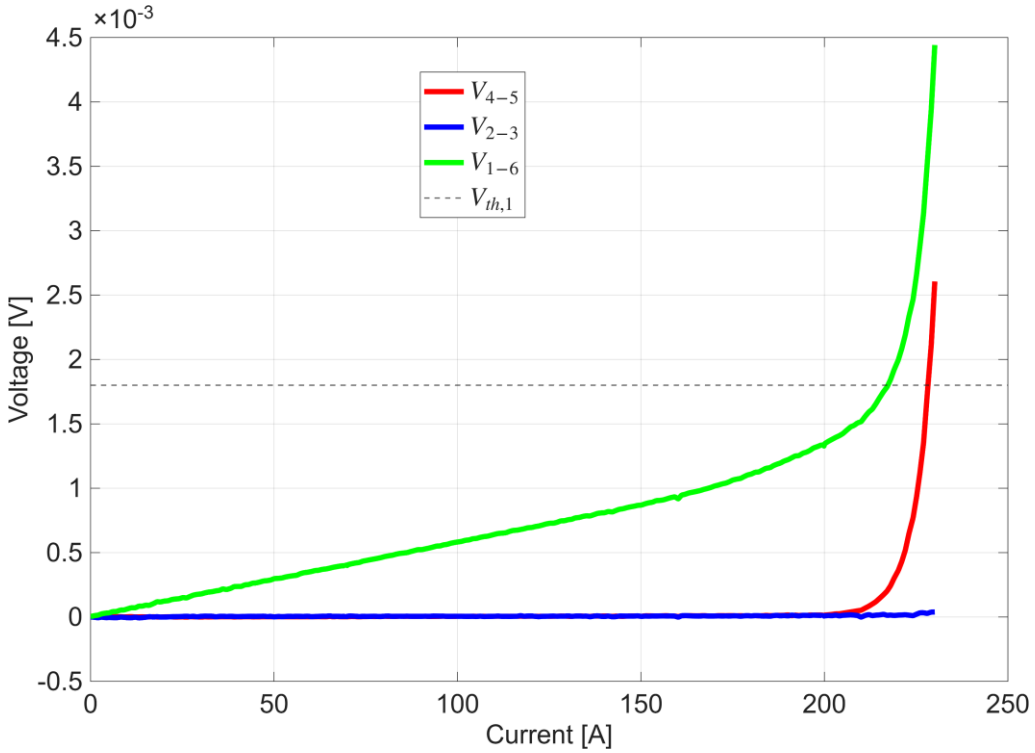

Dr. G. Bellizzi

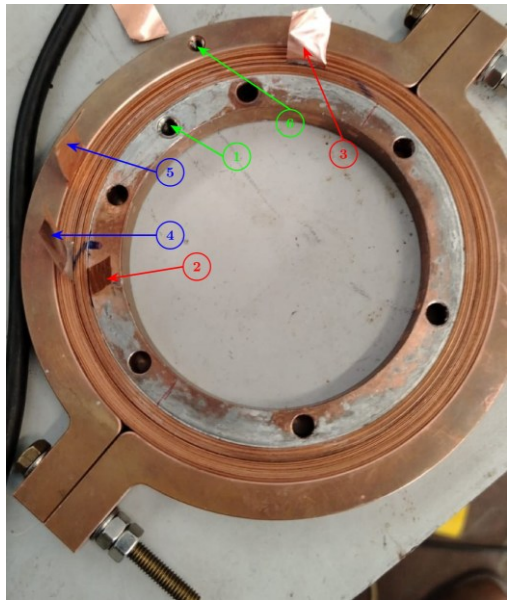

Dr. K. Benyahia

Single-Pancake Prototype

A. Marchegiani Master's thesis - October 24, 2025

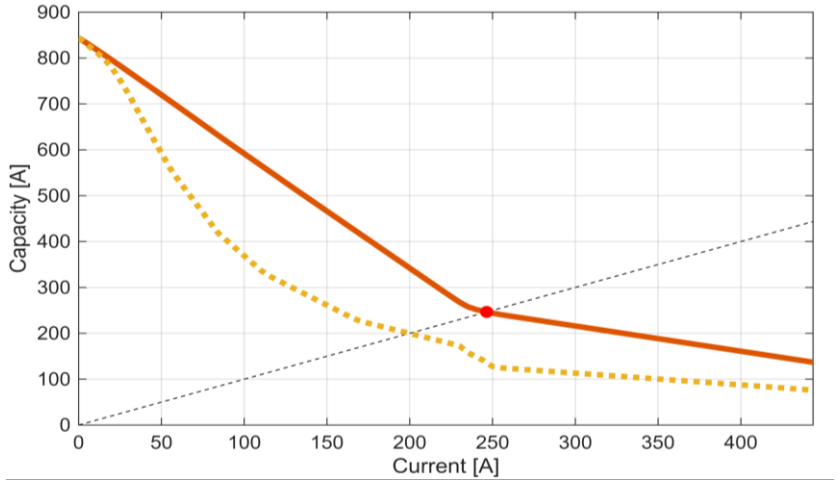
A single-pancake prototype was developed with ASG Superconductors to assess the feasibility of the manufacturing process, test electrical connections, winding models and identify possible issues before building larger coil assemblies.





CRITICAL CURRENT ASSESTMENT

Predicted range	Measured value
200-250 A	**230 A**



Internal radius	45	mm
Windings	50	
Minimum current per turn	100	A
Fully insulated		

SuNam SCN12600

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

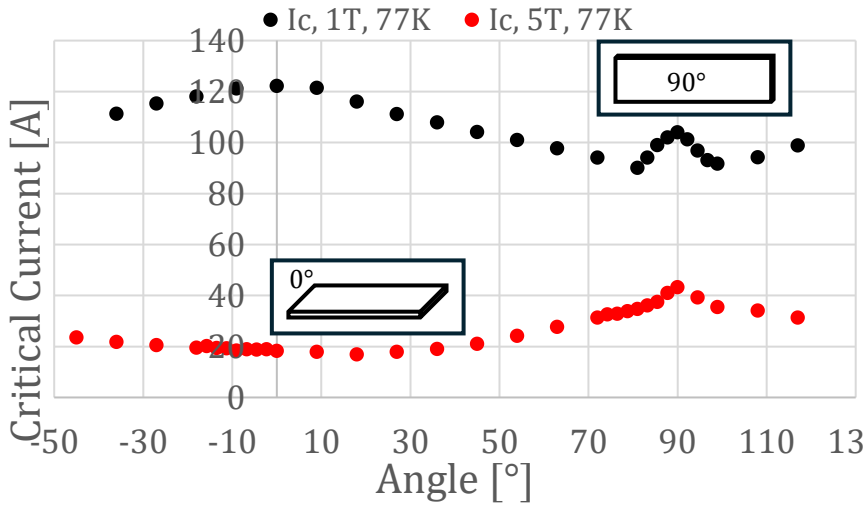
High-Temperature SuperConductors for nuclear fusion applications: Sample holder design and experimental characterization of tapes and small coils

E. Faperdue Master's thesis - October 24, 2025

- Angular dependence of critical current
- Impact of tape properties on coil performance

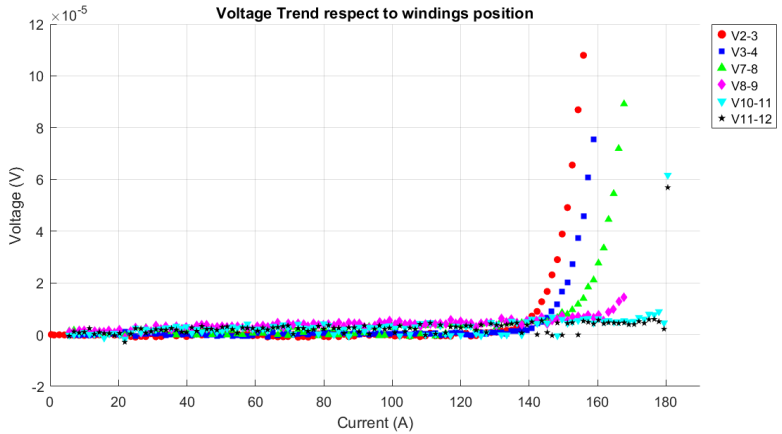


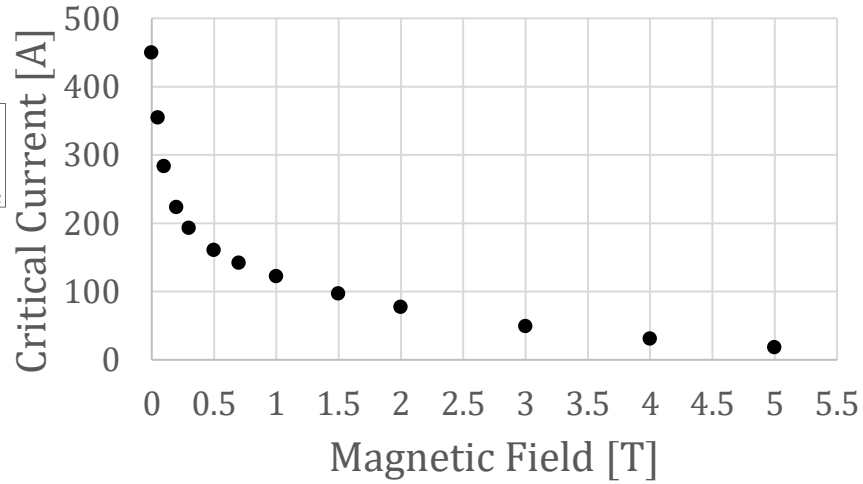
Angular Comparison











I_c Vs B (77 K)

Rotating Sample Holder, Angular Comparison, Magnetic Field Characterization, Coil realization and testing

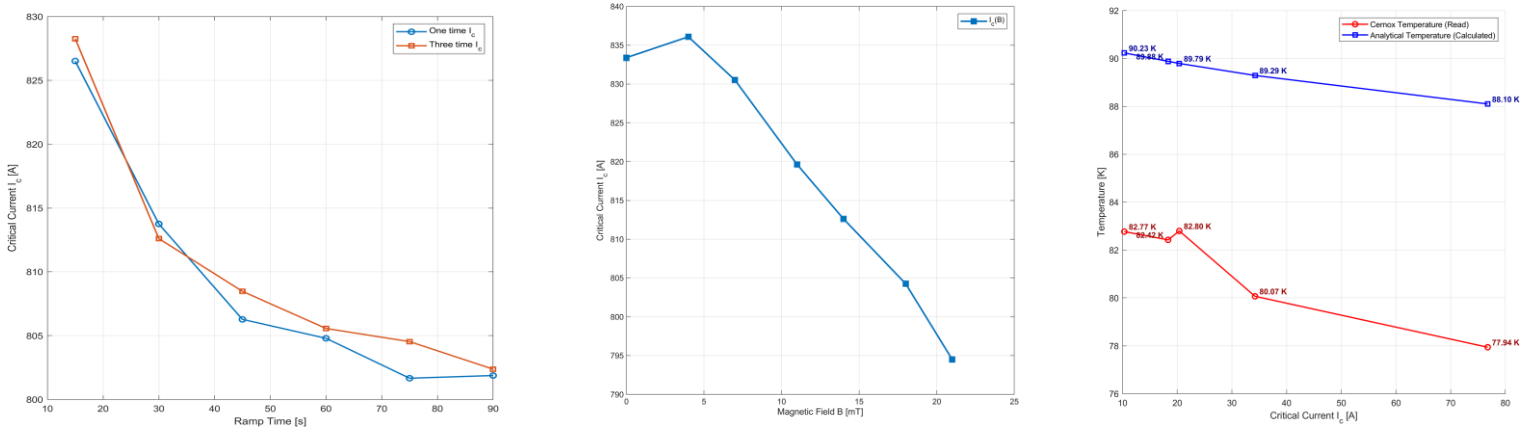
Thermoelectric Characterization Of High Temperature Superconduting (HTS) Tapes

G. Paesani Bachelor's thesis - October 23, 2026

- The thesis focuses on the characterization of a 12 mm-wide HTS tape through the development and validation of an experimental setup for critical current measurements under different operating conditions.



Sampleholder design, realization and operation.



Rampe rate, external magnetic field ad temperature characterization

Key Strengths

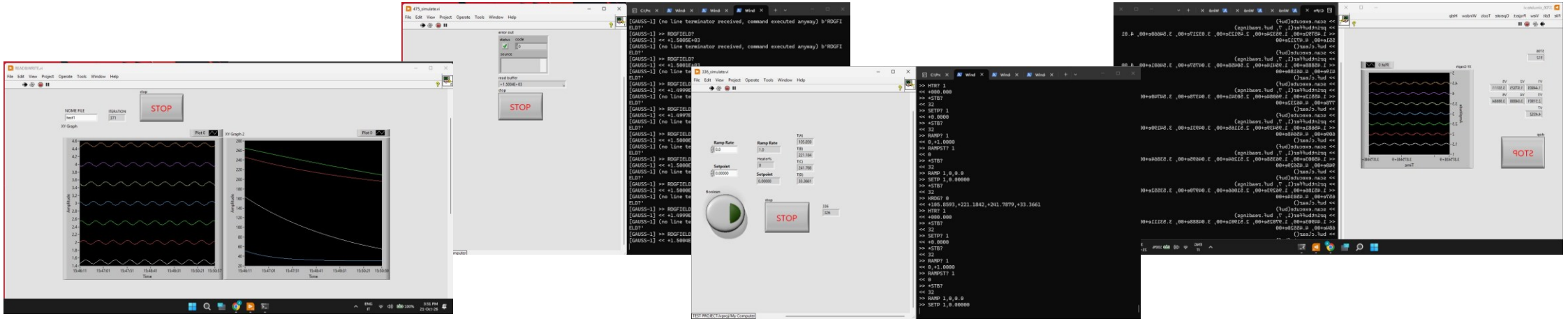
- Reliable and reproducible measurements
- Precise sample positioning within experimental setup at UNITUS

Future Developments

- Cernox® repositioning
- Additional voltage taps for improved onset detection
- Pressurized cryostat for lower operating temperatures

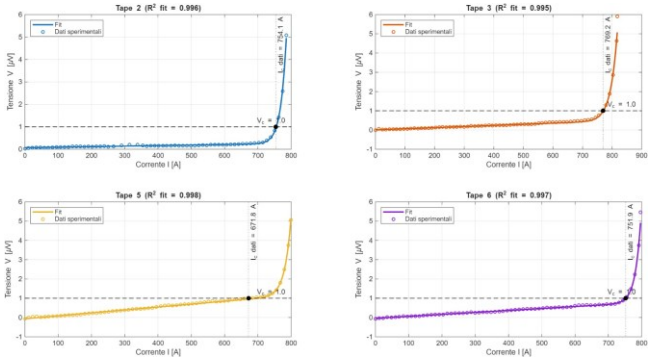
LabVIEW-Based Acquisition and Control of High-Temperature Superconductor Experiments

A. Rizzo Master's thesis – Work in progress

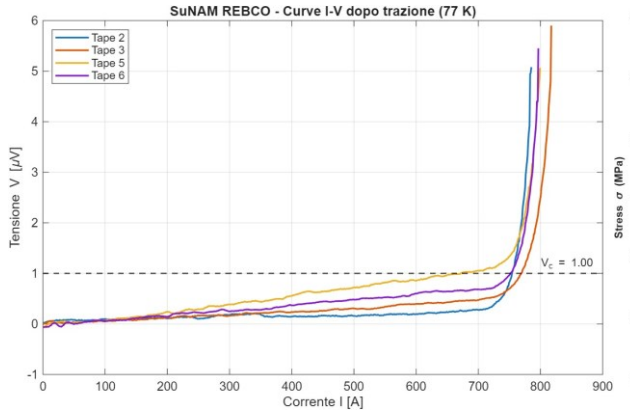


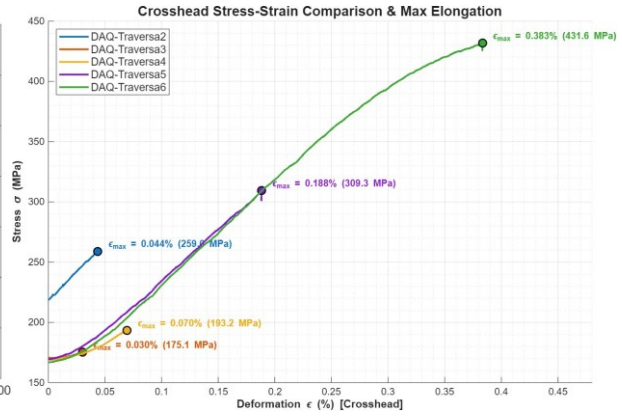
Experimental and Numerical Investigation of Tensile Strain Effects on REBCO Superconducting Tapes

I. Bemporad Master's thesis – Work in progress









UNIVERSITÀ DEGLI STUDI DELLA TUSCIA
DIPARTIMENTO DI ECONOMIA, INGEGNERIA, SOCIETÀ E IMPRESA

Thank you for your attention.

Questions & Discussion

Andrea Marchegiani
andrea.marchegiani@unitus.it

ENEA
TUSCIA RESEARCH UNIVERSITY SMALL TOKAMAK