Manufacturing and test experience of small solenoids at INFN-MI

S. Sorti on behalf of LASA HTS team

INFN LASA
Istituto Nazionale di Fisica Nucleare
Laboratorio Acceleratori e Superconduttività Applicata

12/12/2024

Outline

- Introduction and ancillary campaigns (technologies related to coils)
- Past campaigns and lessons learnt
  - Non-insulated coils
  - Insulated coil
- Ongoing campaign and related activities
  - Motivation and objectives
  - Running developments

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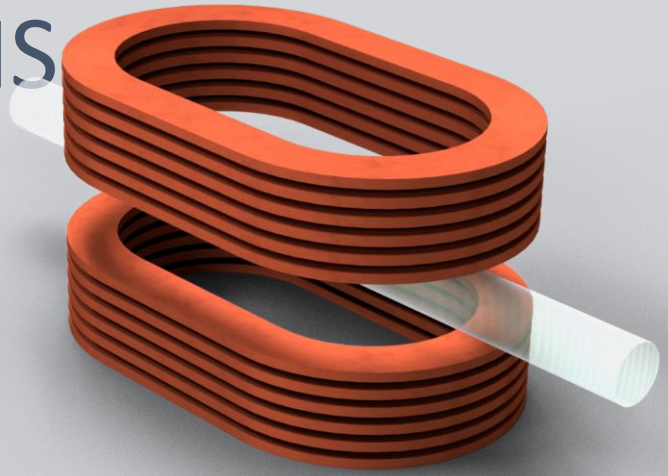
General Framework of INFN-MI R&D on HTS

PNRR IRIS



HFM & MuCol

Magnet design and forecasted prototypes

Small Coils

Purchasing machines

Conductor properties

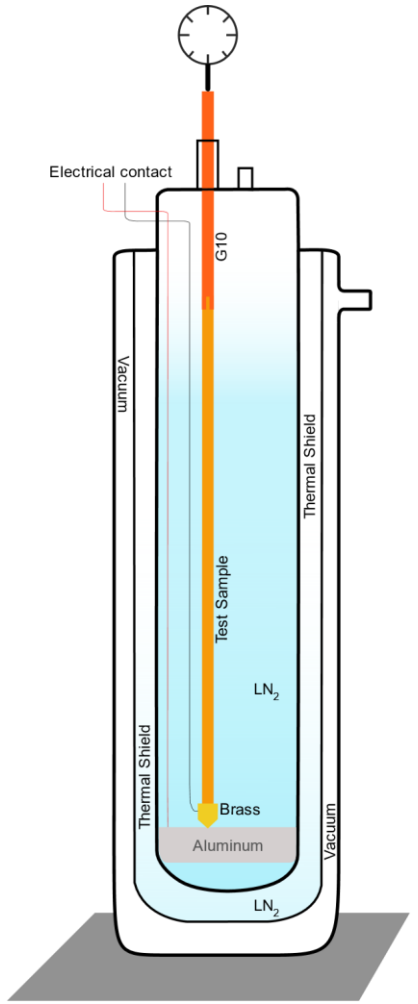
Quench simulations

IRIS: Conductor Properties

Balconi, Crespi, Pedrini, Santini, Sorti

- We supply the conductor
  = provide **properties** and **QA**
  - Transport measurement @ LN_2
  - Thermal contraction of tape
  - Visual inspections

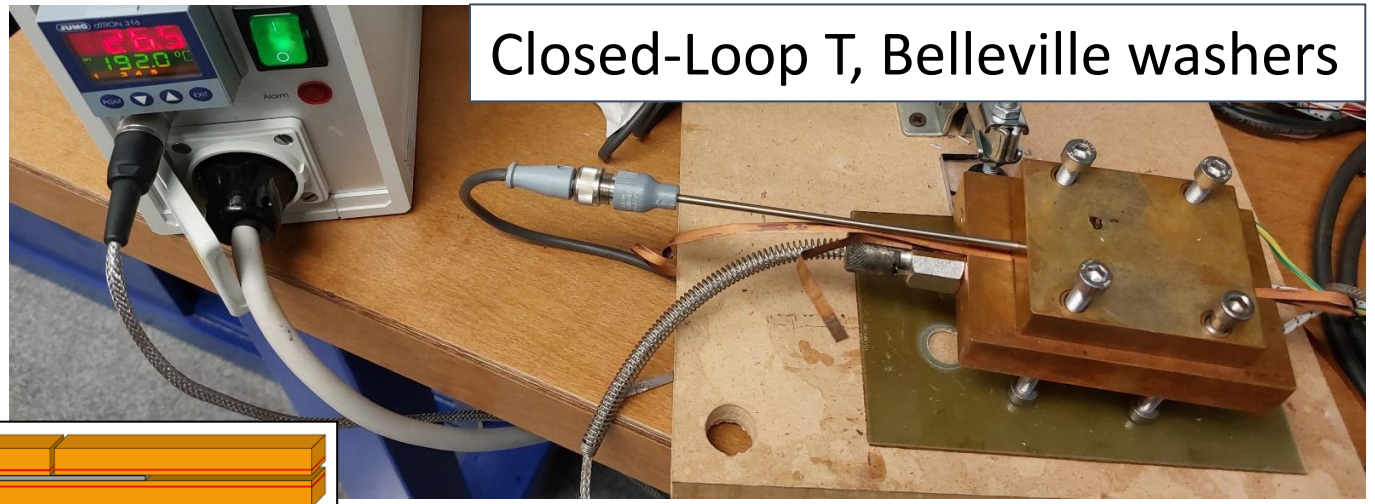
Purchasing ad-hoc machines

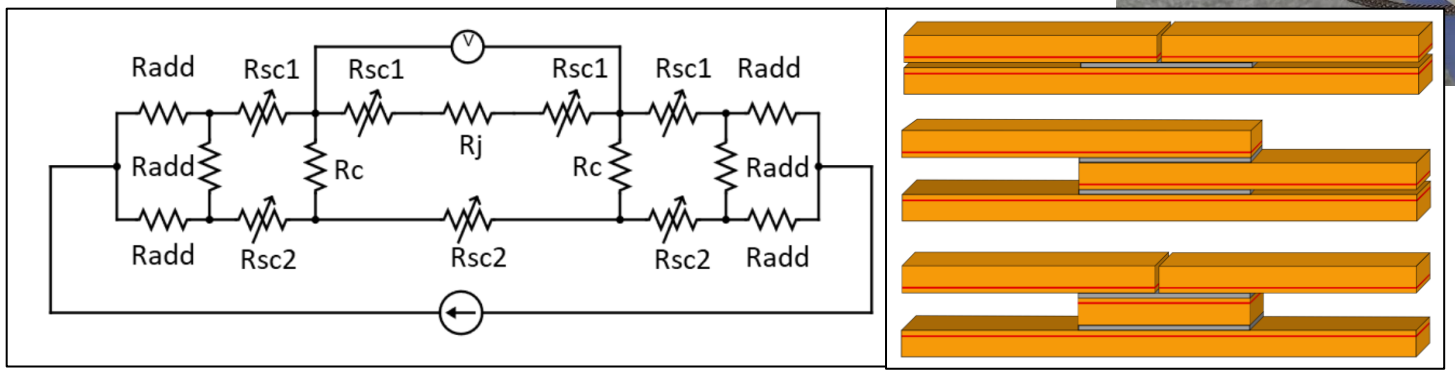


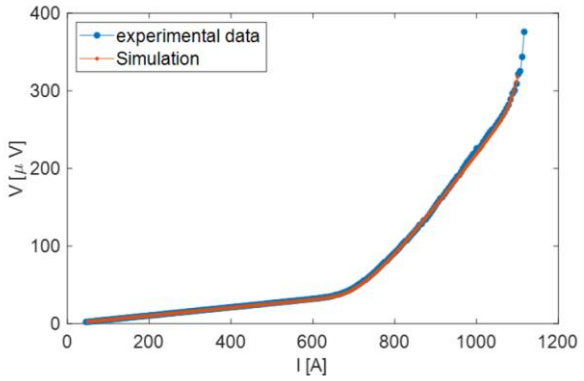
Splicing technology

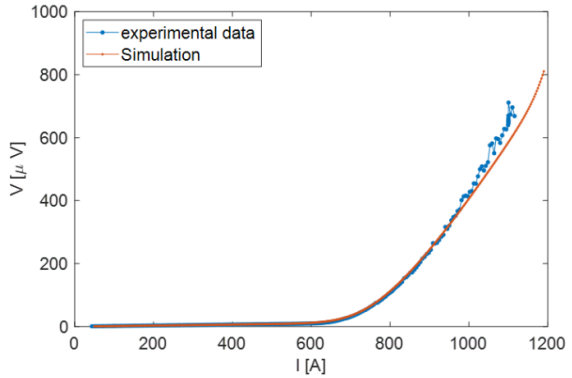
Balconi, Crespi, Pedrini

- 12 mm lap, bridges + others with different brazing
- Road to systematic splicing →









Goal of purchasing ad-hoc machines

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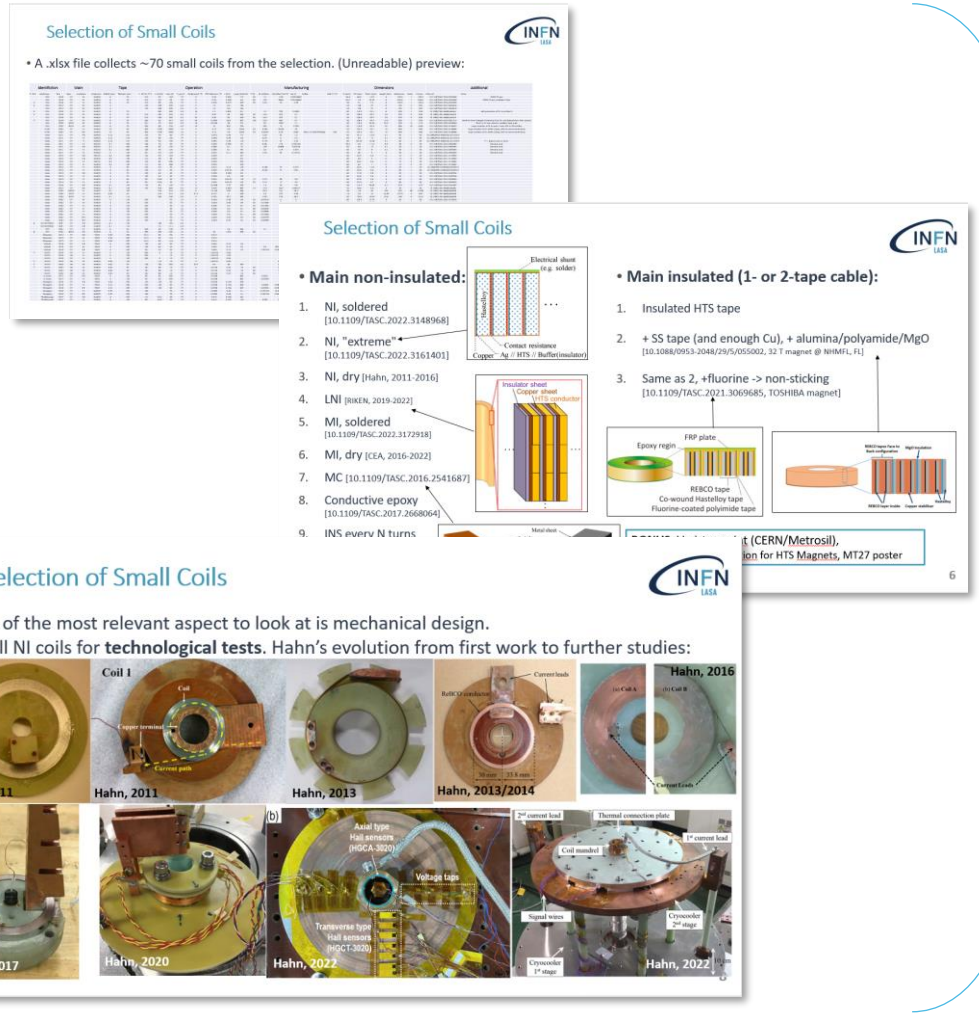
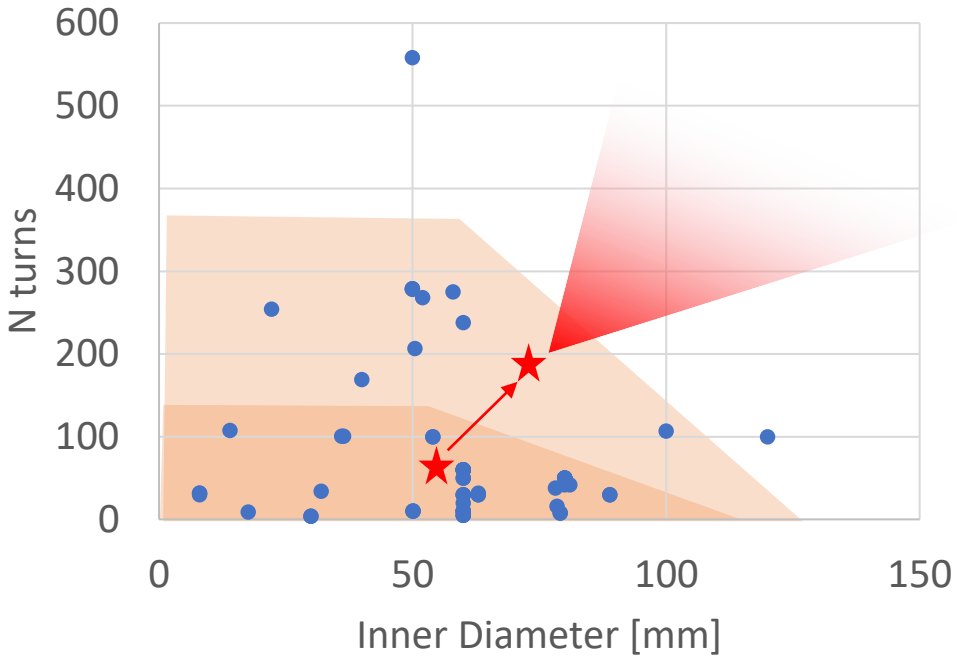
Beginning of the activity

- Need for an in-house small-coils activity. We started looking at literature:



Small coils map (March 2023)
+ INFN-MI **small** coils line

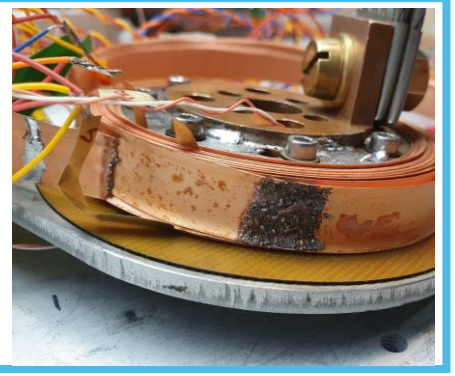


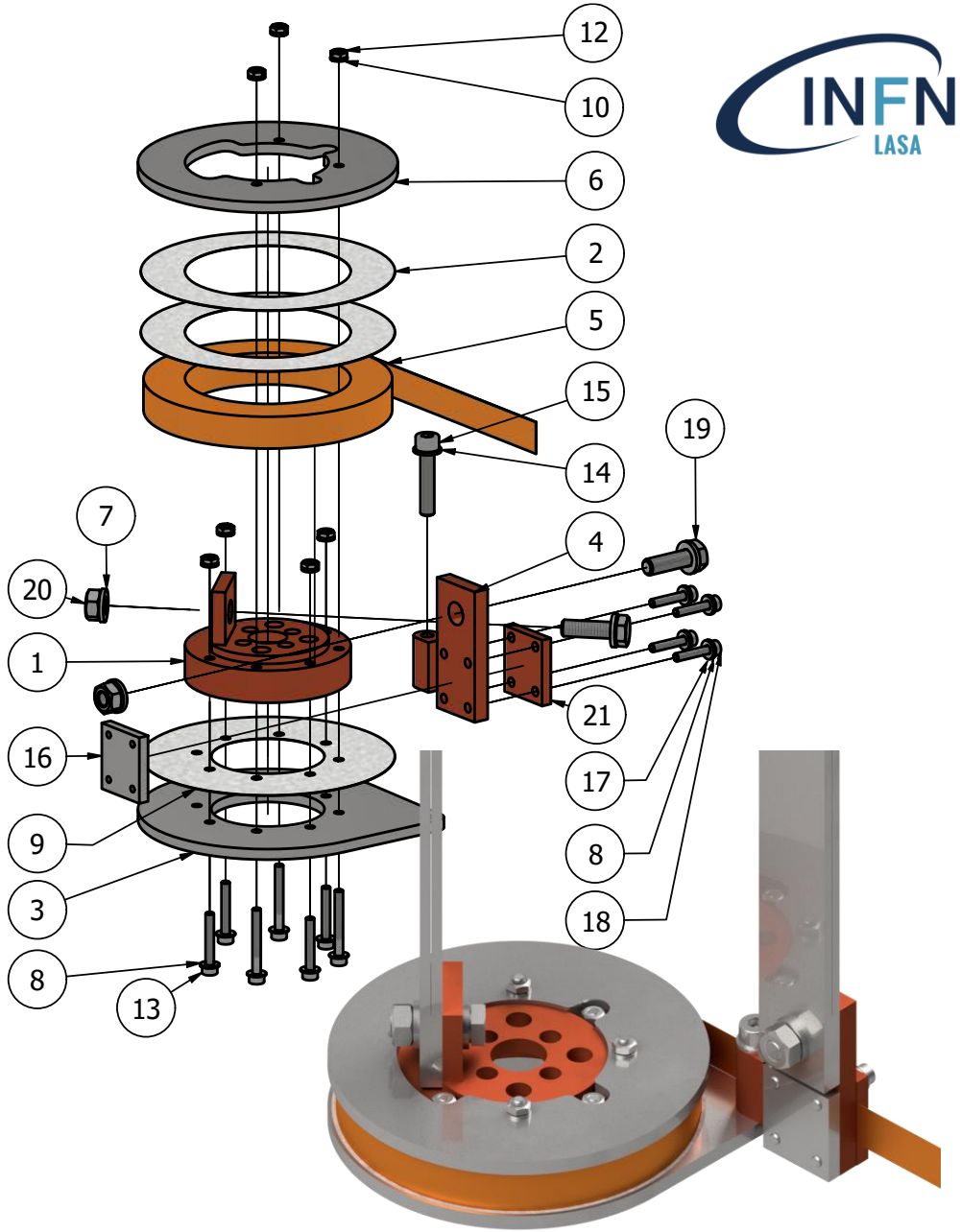
Beginning of the activity

- Standard-like small coils (ID 60 mm, OD 90 mm, future OD up to 180 mm), 12 mm *RE*BCO tape.
- First family: dry-wounded Non-Insulated (NI) coil. First series of test at 77 K, self-field. Goals:

1. Assess handling and winding of tape at different tensions;
2. Validate a first round of formulas and models.
3. Validate the support design for 77 K tests

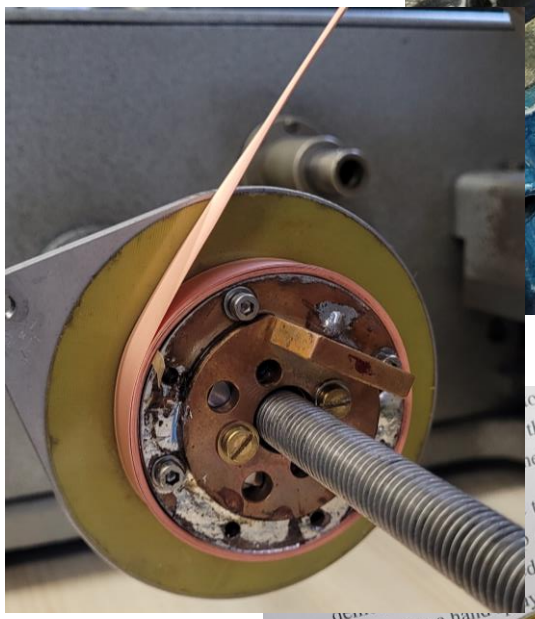
Lesson Learnt 1:
flexibility is not always
an added value

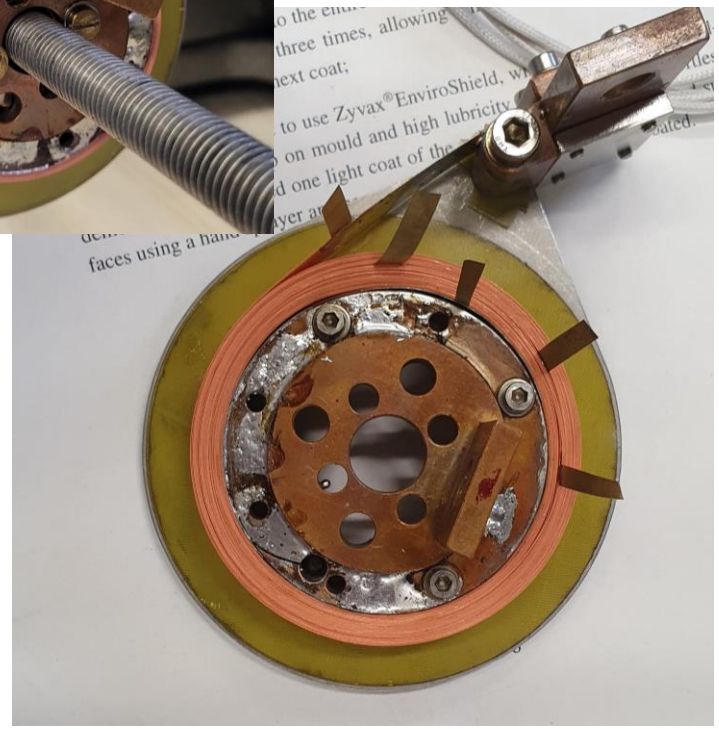




Set-up construction

- Hand-made assembly:
  good to control over process (slow, small forces)
  bad for troublesome steps (like brazing tape →)
- Passive winding tension control
  (need to use in-house machine)
- Acquisition system:
  - National Instruments cFP
    (+ multi-channel Analog Input)
    100 Hz sampling of 3-10 µV signals
  - Distributed V taps (1 mill brass foils inserted in winding)
  - Hall sensor and/or pick-up coil in the centre





Purchasing winding machine

Main campaign

Balconi, Giordano, Pedrini, Sorti

- Bruker 12 mm tape, about 100 A of I_c in self-field at 77.5 K

Reference Bruker REBCO tape	
Substrate (material/Thickness)	Stainless steel / 50 µm
Cu stabilizer (type/thickness)	Electroplated / 20 µm per side
REBCO thickness	≈2.5µm
Dimensions (width × thickness)	12.1 mm x 0.11 mm

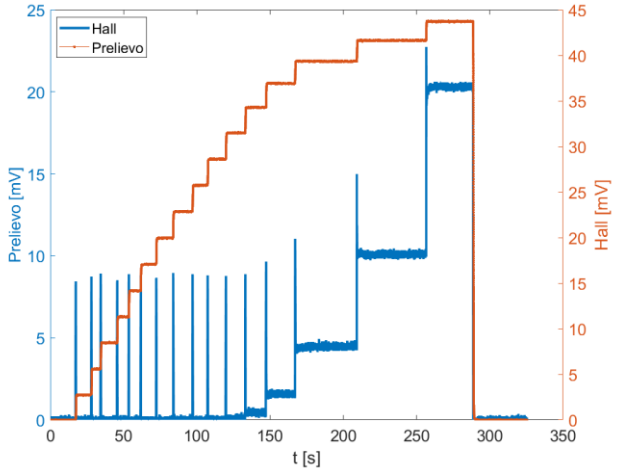
	C0	C1	C1-fiber	C1-wax	C1-film	C2
Turns	5	30	30	30	30	45
Ins	NI	NI	INS	INS	PI	NI
tau	< 1 s	1 s	/	/	/	1 min
Estim. T [N]	10	10	15	15	15	30

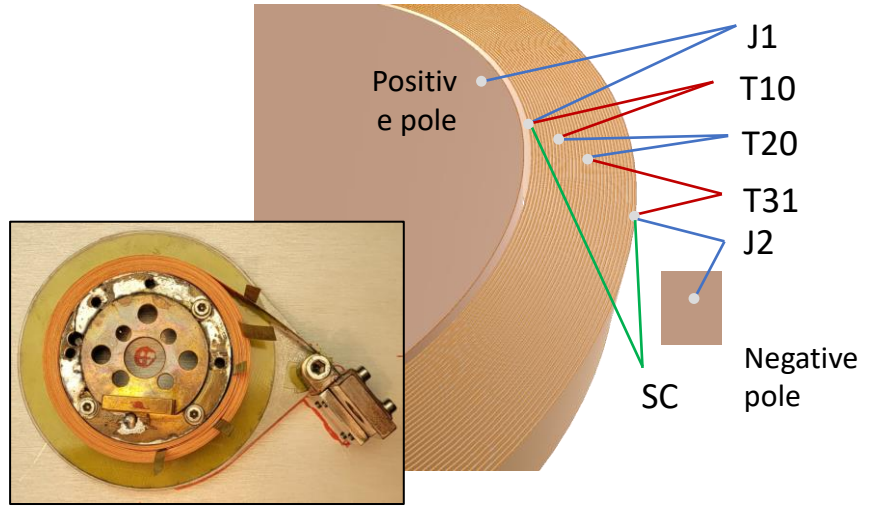
Lesson Learnt 2: must carefully control tension to control coil

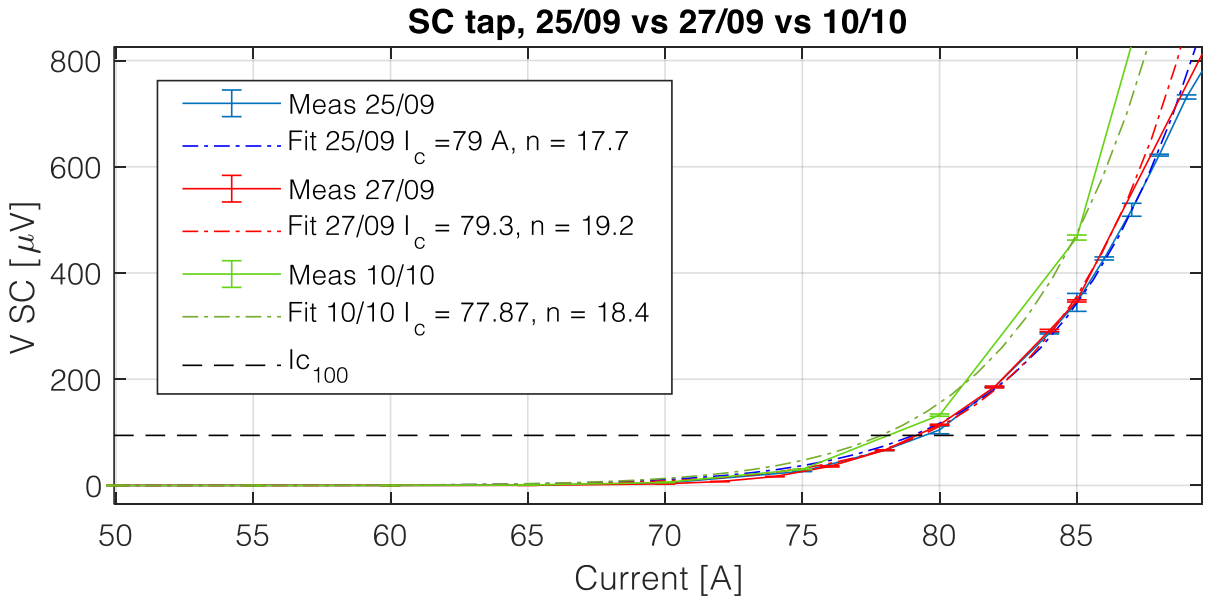
Non insulated small coils

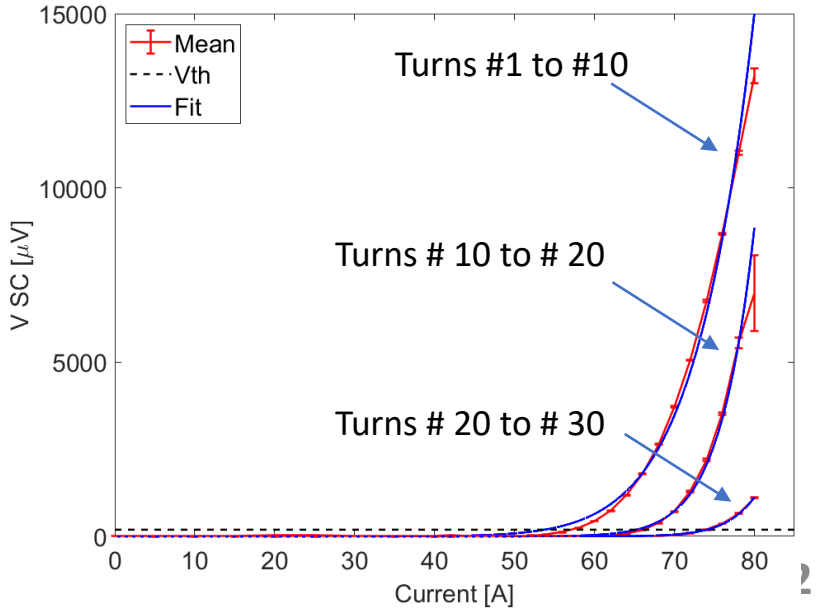
Balconi, Giordano, Pedrini, Sorti

1. Cooling and heating cycles shown no degradation
2. Measurements of staircases and ramps



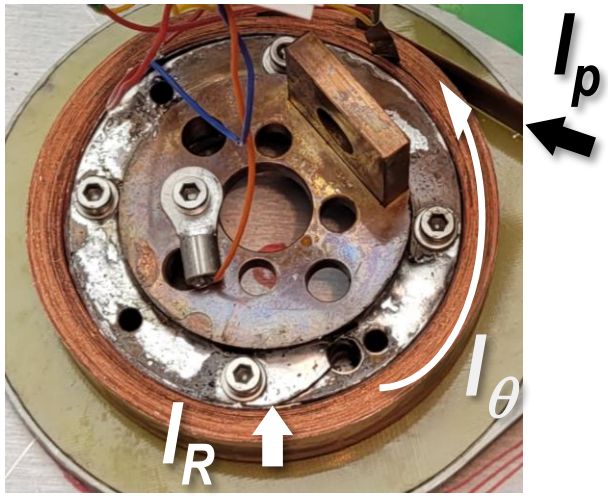


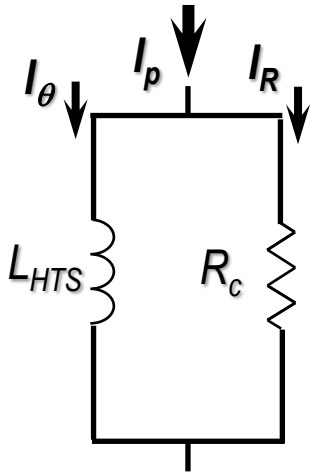




Modelling

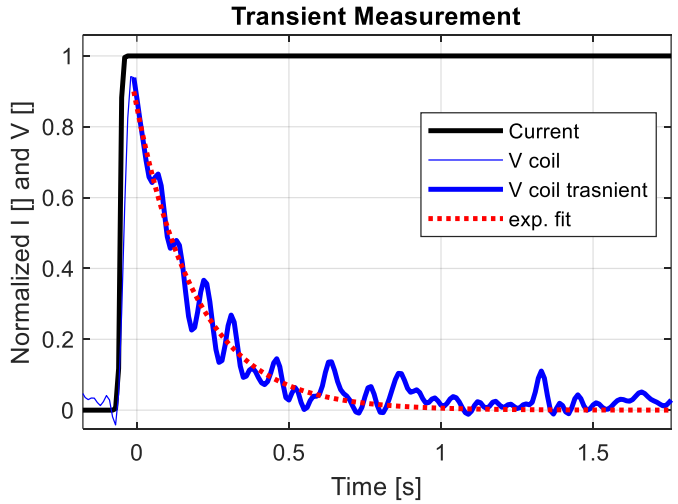
Balconi, Giordano, Pedrini, Sorti



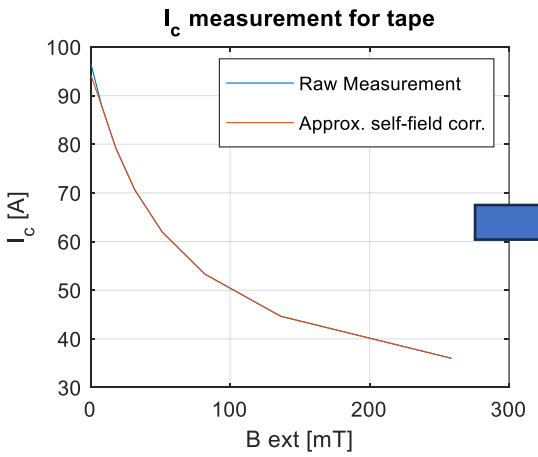


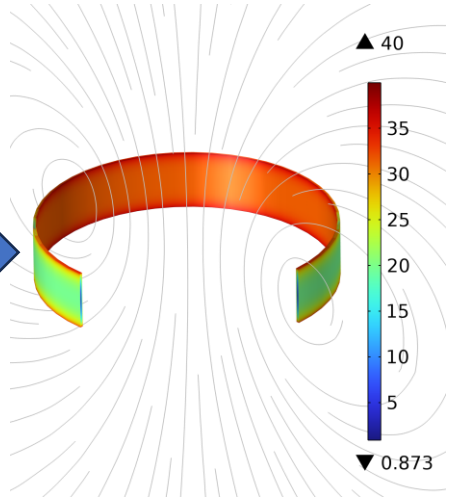
$$V(t) = V_0 e^{-\frac{t}{\tau}}$$

$$\tau = \frac{L_{HTS}}{R_c}$$



COMSOL simulation of superconductors (H-formulation)



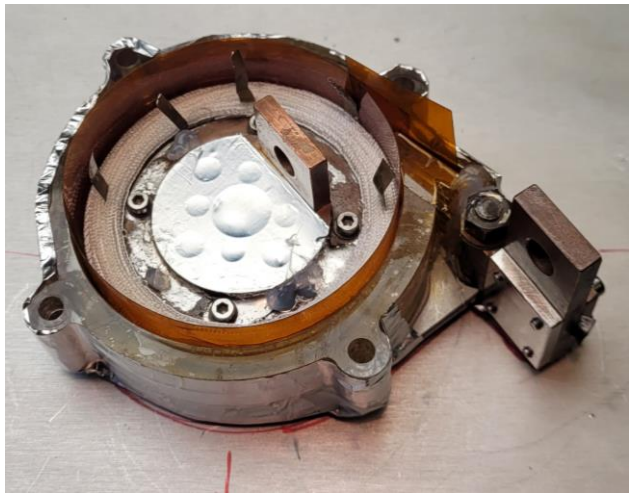


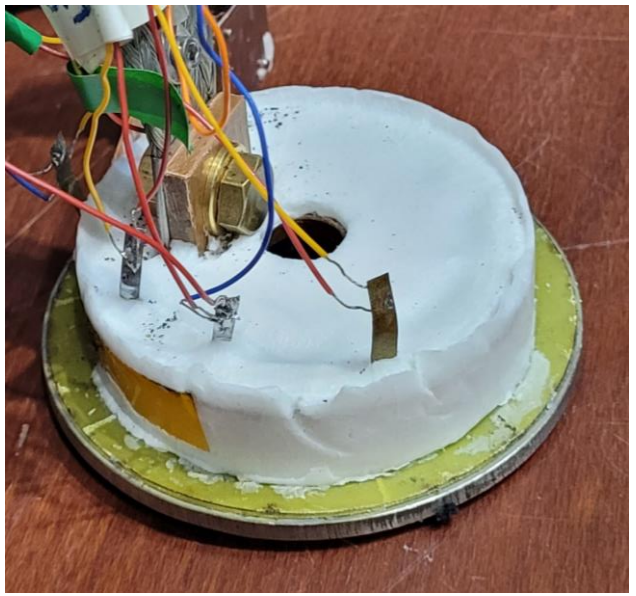
Source	Ic100
Measurement	80.5 A
Sim. $J_c(\|\boldsymbol{B}\|)$	76.5 A
Sim. $J_c(B_\perp)$	85.5 A
Sim. no redistr.	73 A

Insulated coil

Balconi, Giordano, Pedrini, Sorti

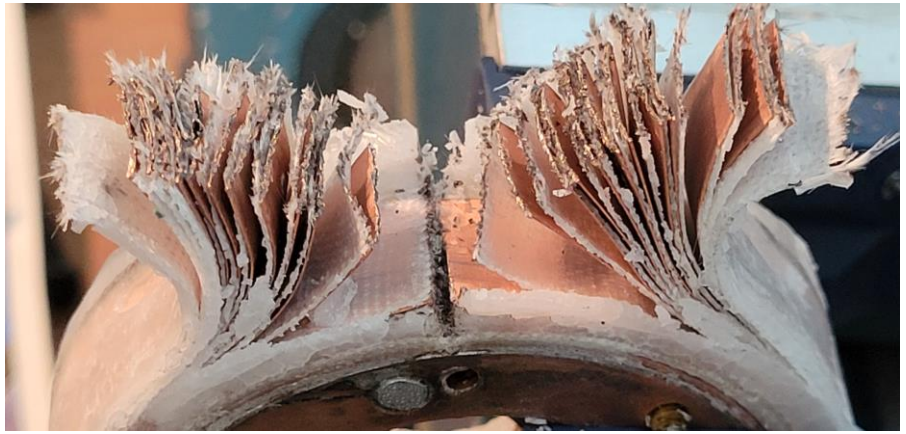
- We manufactured and tested also an **insulated coil**: wax + fiberglass.
- Coherent with the wide-perspective of the program about HTS technologies
- Wax as a non-delaminating filler, ideally also to protect NI coils
- Results: **no** conductor degradation, > 150 GΩ @ 2.5 kV insulation





After cryogenic tests (above) and final insulation tests

Before (left) and after impregnation



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Lessons learnt

- Mostly **do** (for the next coils):

1. Do design coil easy to **assemble** in a **repeatable** way → Novel mandrel design with higher repeatability and robustness (ex. Copper leads soldered with machine)
2. Do Non-Insulated coil with controlled, measured and repeatable **winding tension** → Have a reliable winding machine (incoming, mitigating with a new in-house ne)
3. Do know your **conductor** well, otherwise difficult to infer from local sensors → Mitigated by using modern conductor better characterized (Tapestar, etc)

Novel coil: insulated racetrack

Cavities to save 3D printed material

Pick-Up coil

Mandrel in PPGF
(PolyPropilene Glass Fiber)

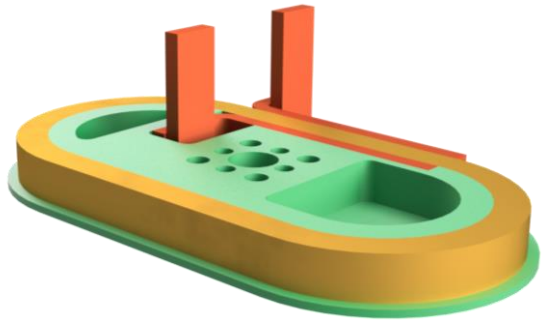
PPGF thermal contraction:
0→77K = 6 mm/m
Eppgf = 4.5 Gpa
σ = 80 Mpa @ break

Current leads

Stainless steel insterts to constraint thermal contraction
(< 20 Mpa thermal stress, factor 4 of safety)

Cavities to insert sensors

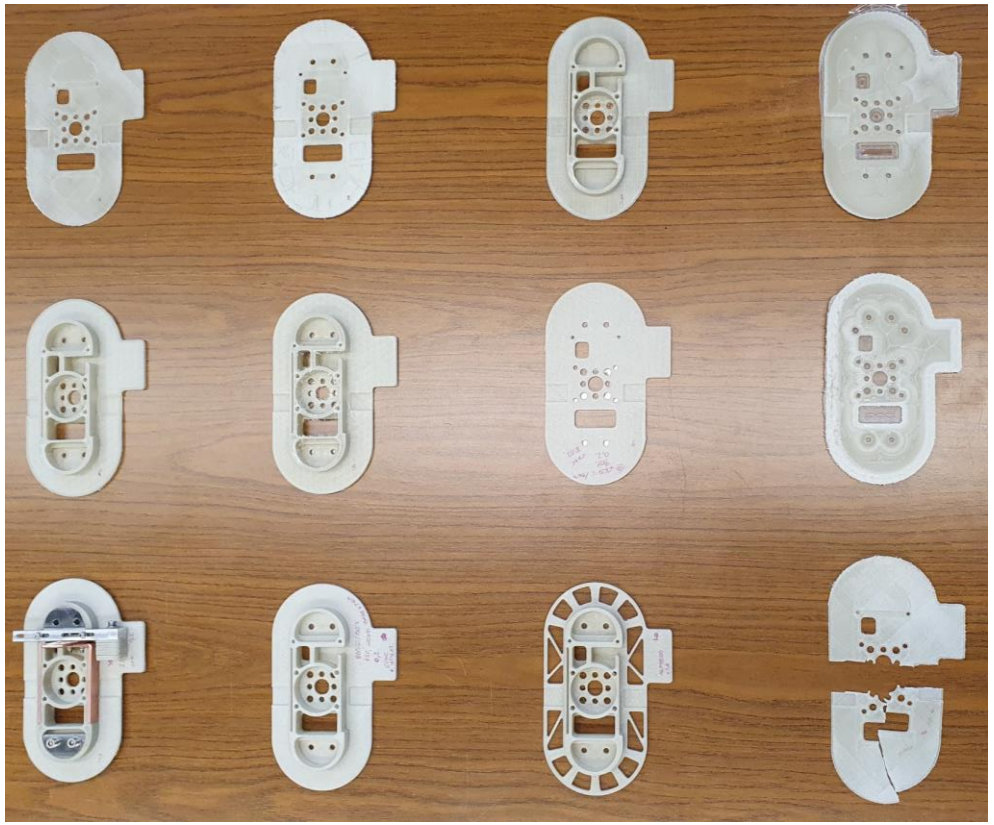
Aluminum support to hold the outer current lead

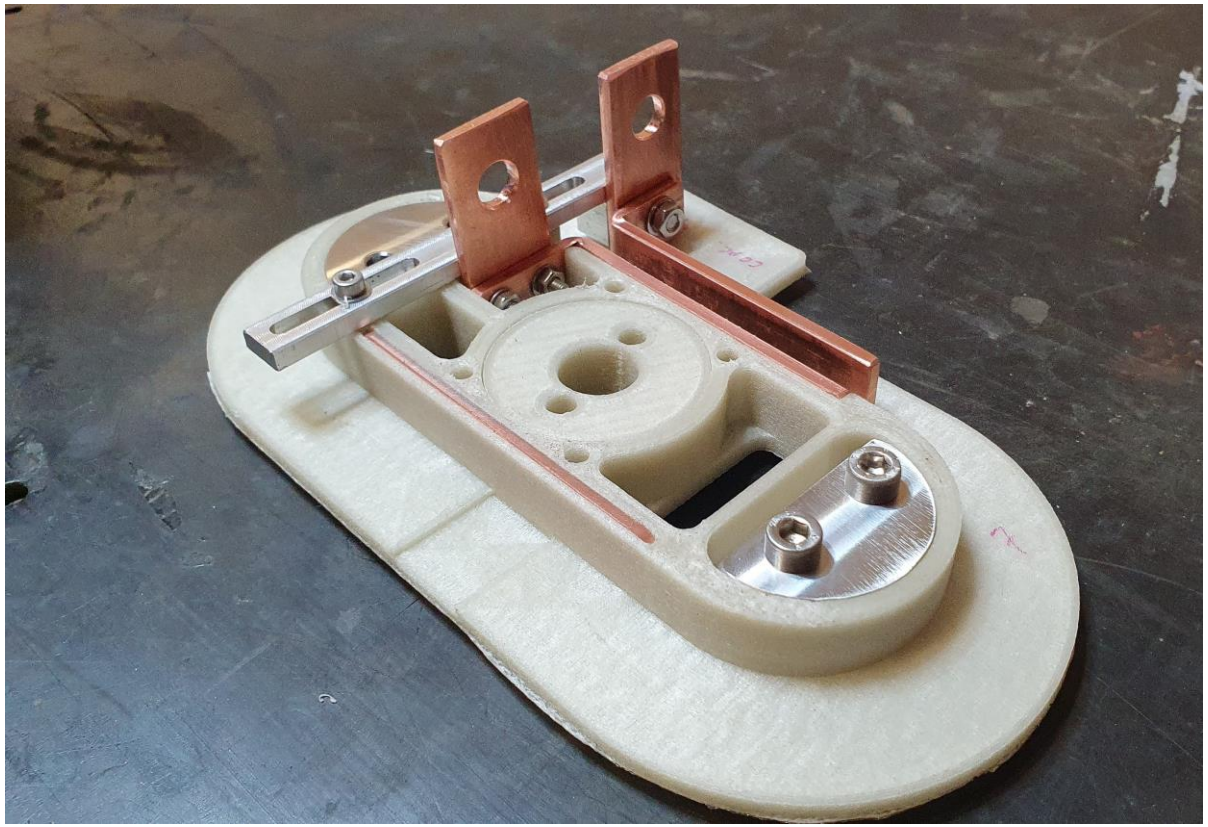


Geometry concept comes from ASC24 oral about HTS modelling (soon published)

Small Racetrack coil – Realization of the mandrel

- Many iterations to print correctly the mandrel, but worth it





Winding machine prototype

- Using in-house hardware, still a Work-In-Progress

Tension measuring system

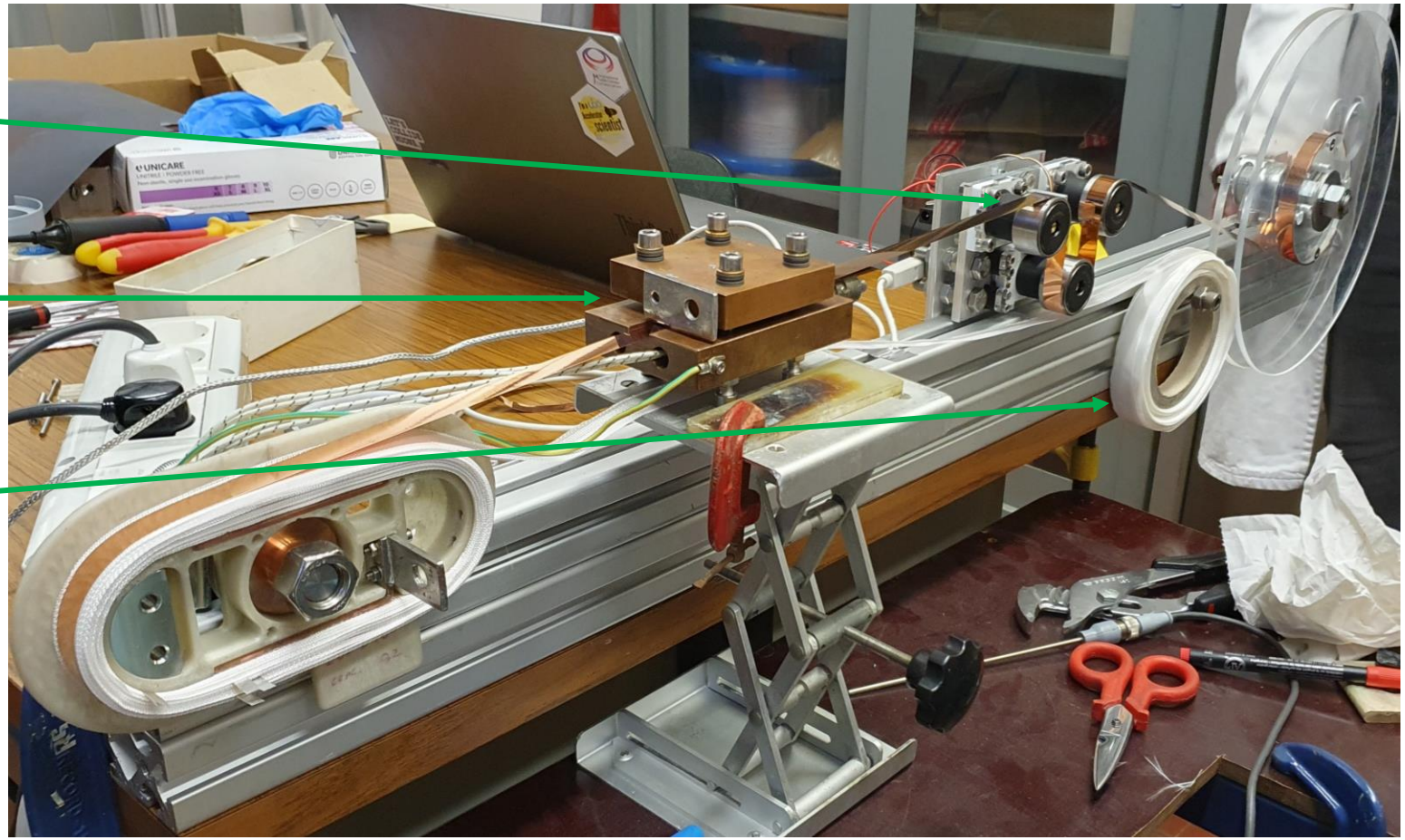
→ Measured winding tension: ~ 15N

On-Line solderng with SnIn @ 150 °C

→ Used to solder current leads

Fiberglass co-winding spool

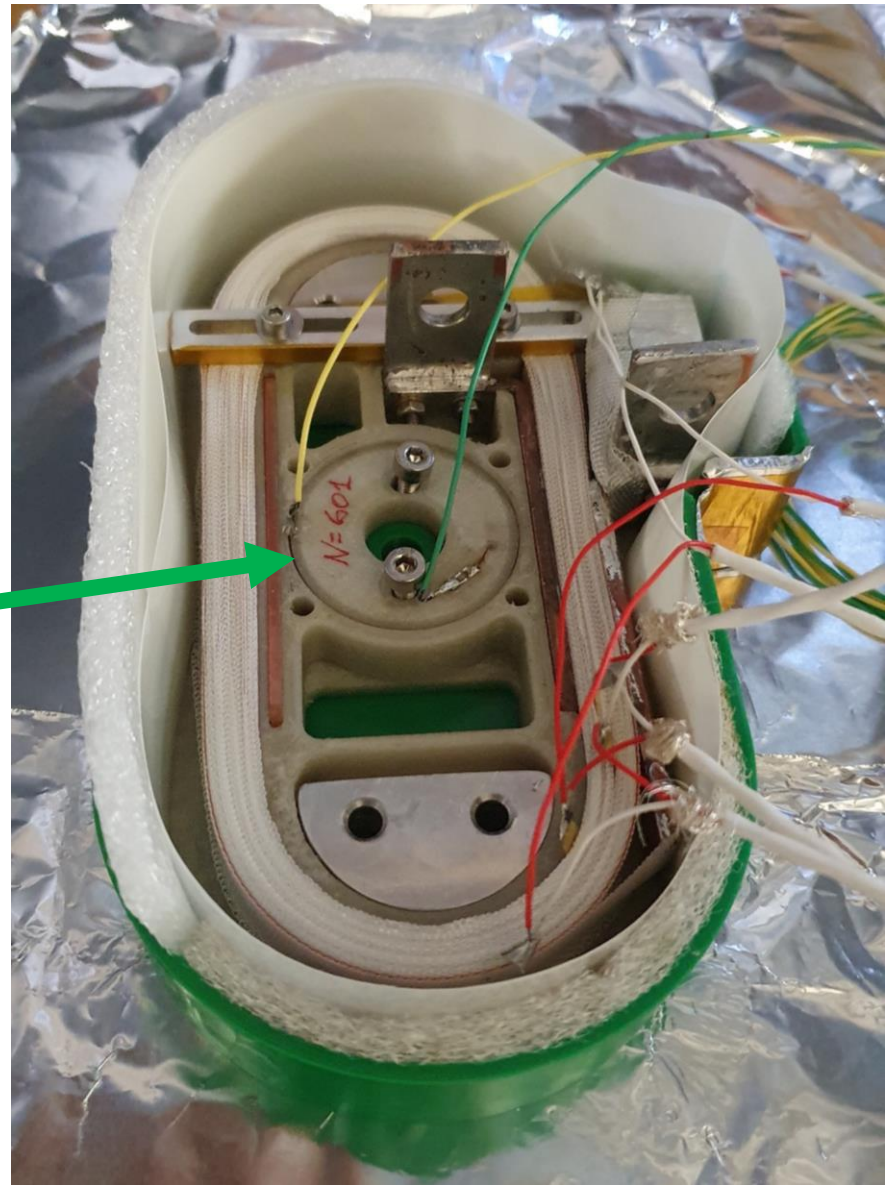
A total of **40 turns** wound



Coil finallization: pick-up coil and impregnation

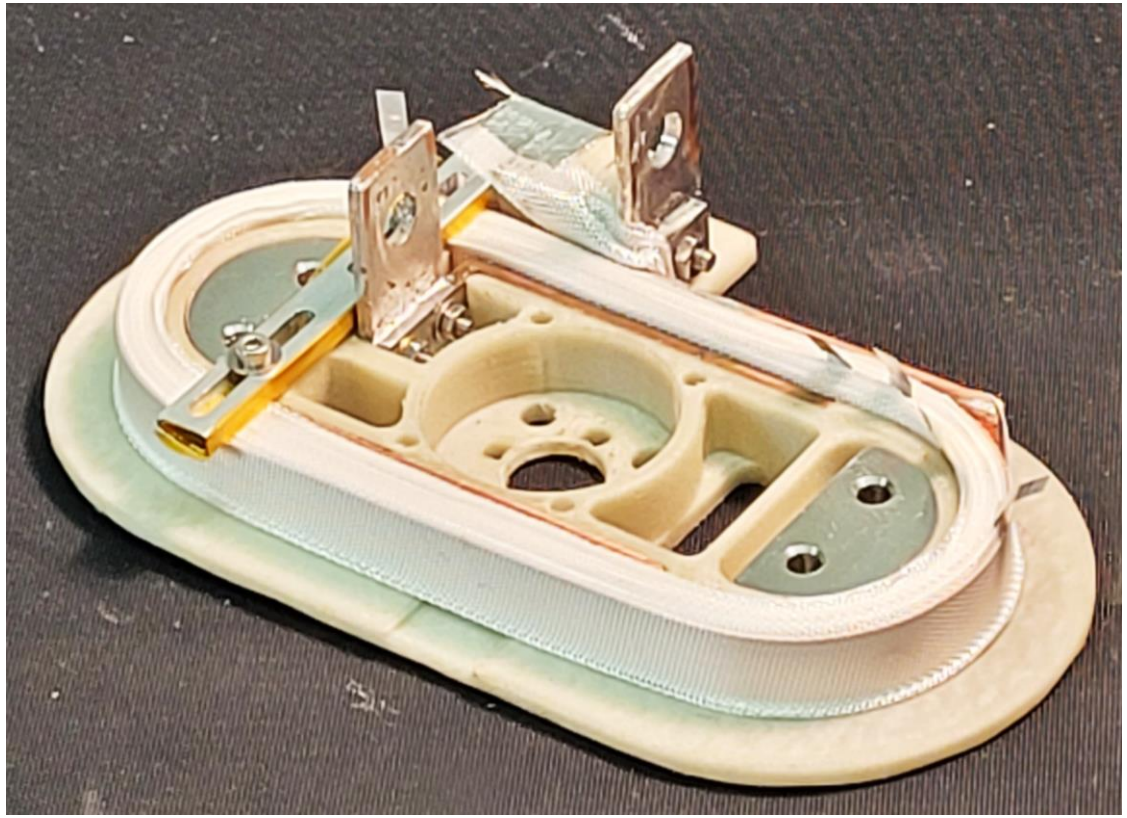
- Wax outgassing in vacuum
- Paraffin wax has been used
- Wax heated-up till ~60°C

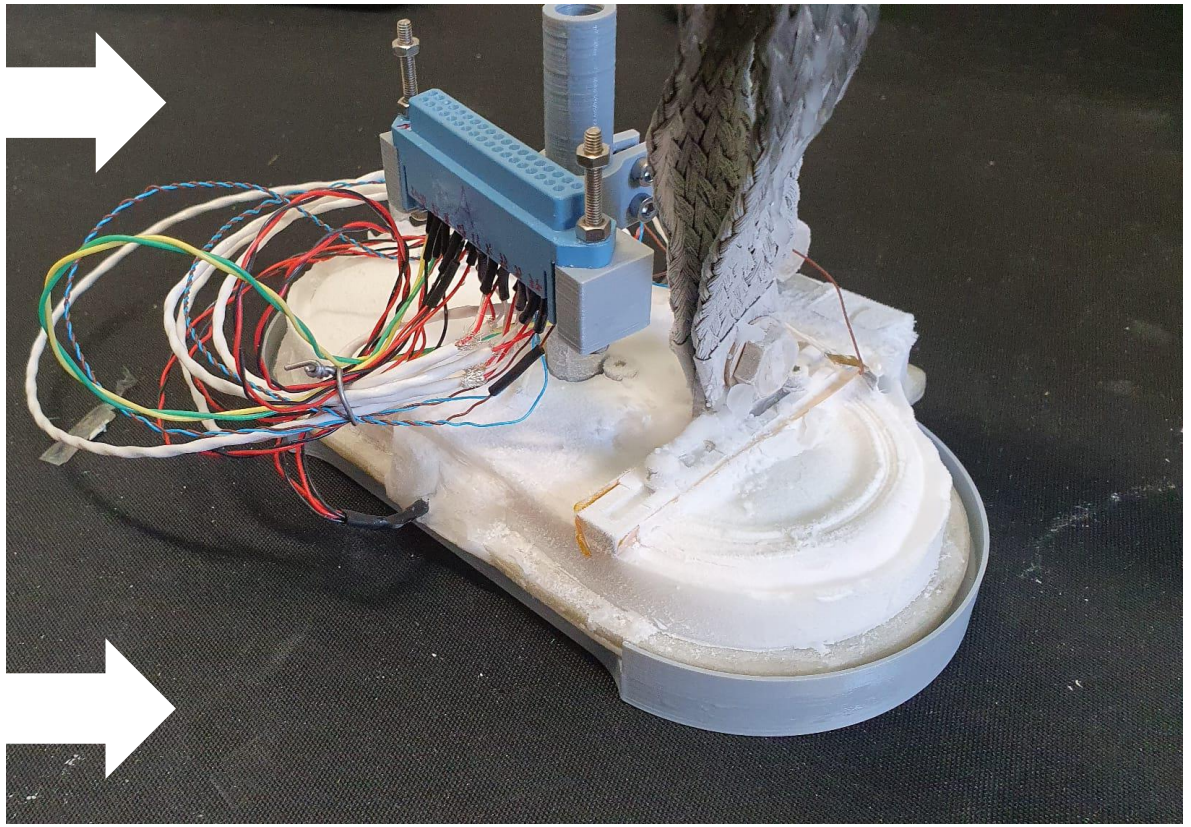
Pick-Up coil:
radius = 2.5 cm
Nt = 601



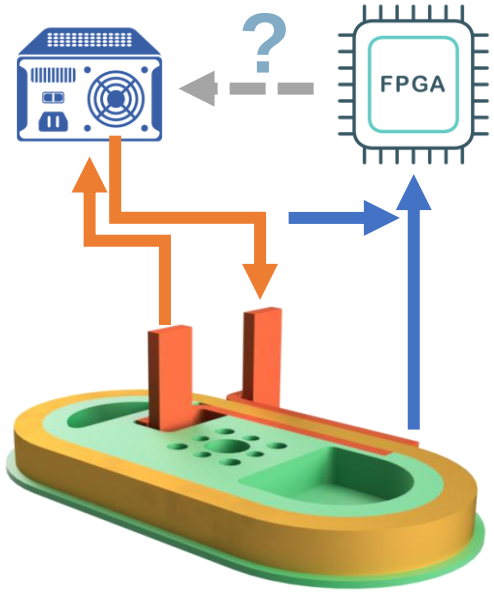
Finalized pick-up coil

- Added wiring (through connector) and current leads.
- 3D printed support





Small Coils: main next steps (long term)



- Have a **repeatable** process to build coils. (rediscuss insulation? Go toward multi-tape?)
- Build **larger** racetrack with an ad-hoc sensor network
- **Validate** electromagnetic + thermal model (soon to be published)
- Run a **real-time** reduced model on ad-hoc hardware (incoming) as sensor collector and online analyzer (road to digital-twin)

Tackle unresolved misteries (from past camapaign):