# Magnetic measurement activities at CERN

## Part I: projects, infrastructure and collaborations
## Part II: instrumentation and techniques

Marco Buzio on behalf of the Test & Measurement Section

International Magnetic Measurement Workshop IMMW23, Bad Zurzach, 07.10.2023

# Projects, infrastructure and collaborations

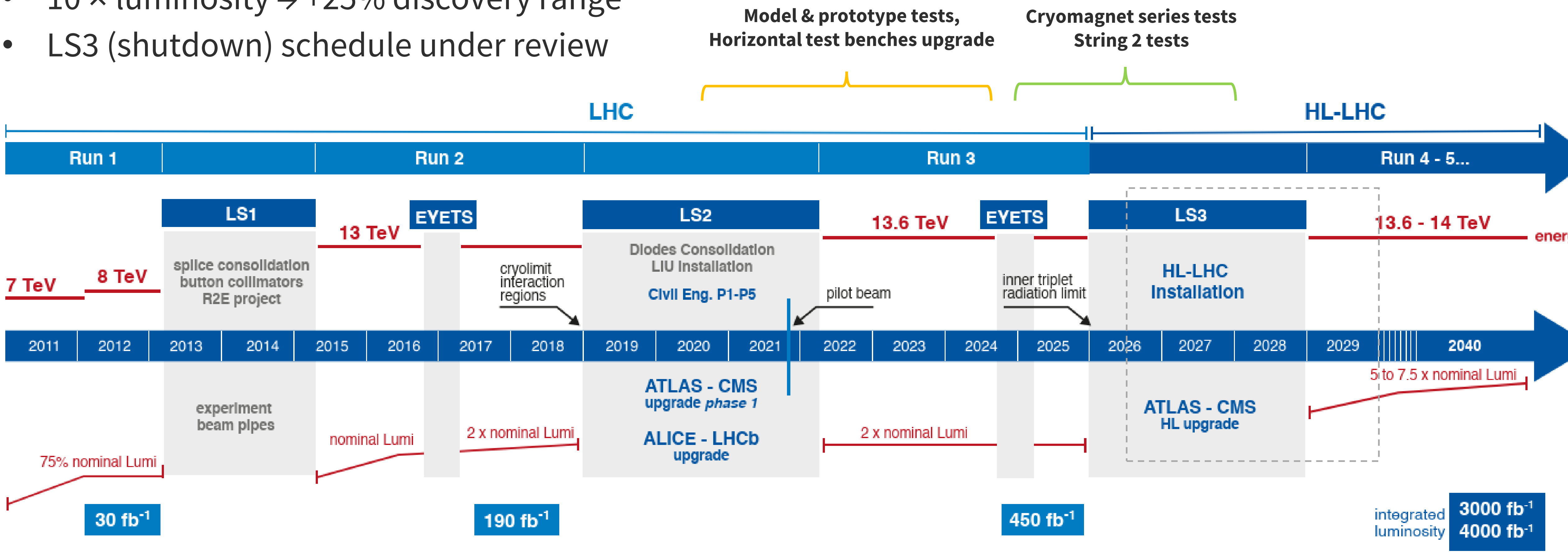
## Ongoing and upcoming



# High-Luminosity LHC

Highest-priority CERN project:

- replace rad-damaged IR quads
- 10 × luminosity → +25% discovery range
- LS3 (shutdown) schedule under review



# HL-LHC magnet tests

- ~50 cryoassemblies, **14 types** of main/corrector magnets
- First operational accelerator-quality $Nb_3Sn$ magnets
- Magnetic measurement challenges:

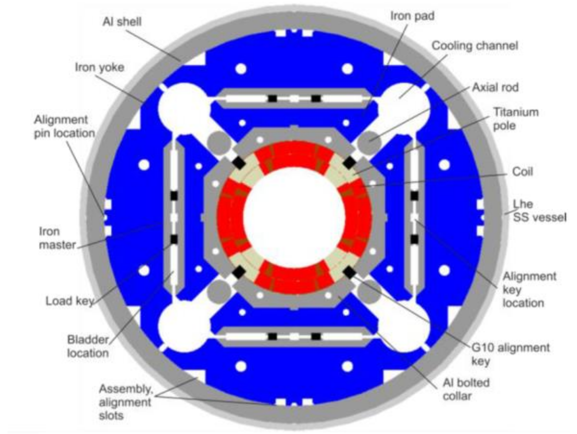
  - Up to ∅**109 mm anticryostat bores,** 15 m rotating coil systems

  - high measurement **accuracy** required (IR region):
  5 units absolute $B_2$, 0.1 units multipoles

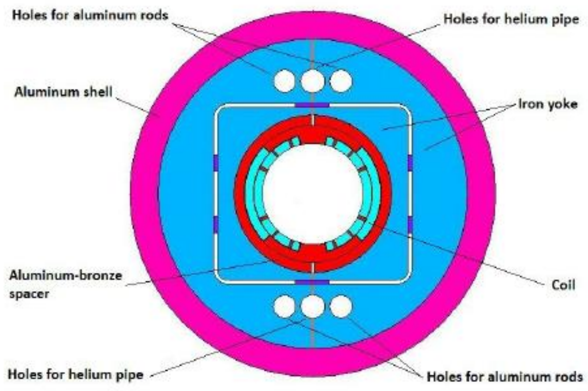
  - 3× warm rotating coil systems to be **maintained remotely**
  on the manufacturer's premises (2 units $B_2$, 0.1 units multipoles)

  - warm/cold **magnetic vs mechanical axis, longitudinal alignment** of IR triplets (~5 mm)

**Mariano Pentella**
this IMMW




23× $Nb_3Sn$ triplet quads (MQXF)
∅150 mm bore, 4.2/7.15 m, 132 T/m (~11 T peak) @ 16.2 kA



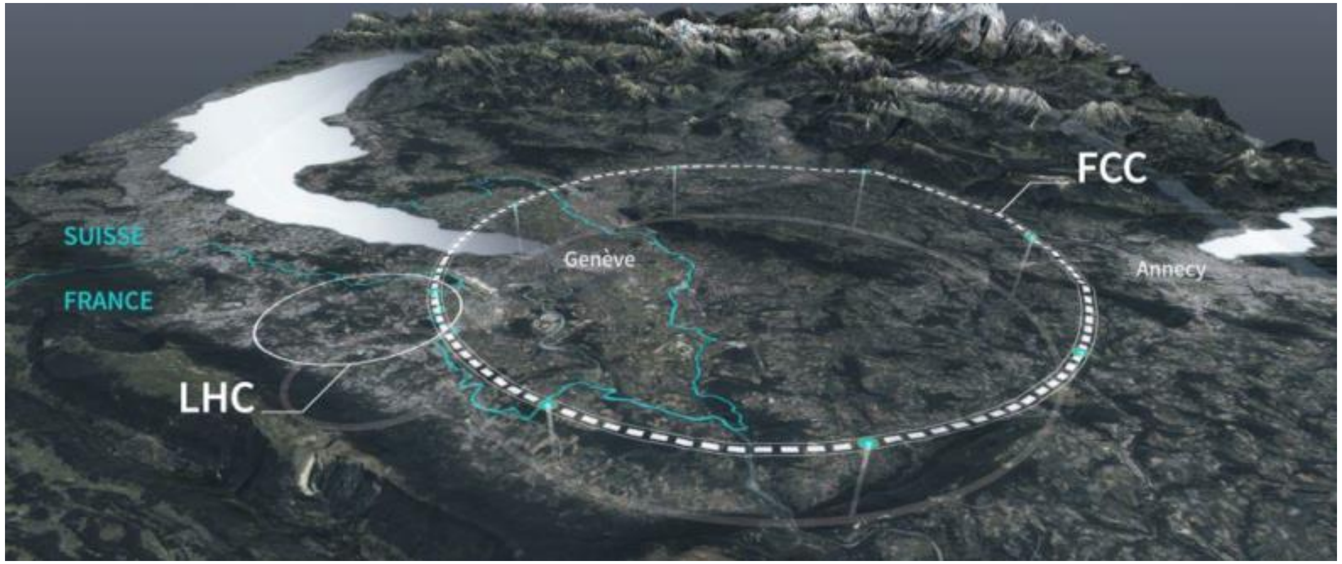

7× NbTi separation/recombination dipole (MBXF )
∅136.7 mm, 6.3 m, 5.6 T @ 12 kA

# SM18 cryogenic test station upgrade

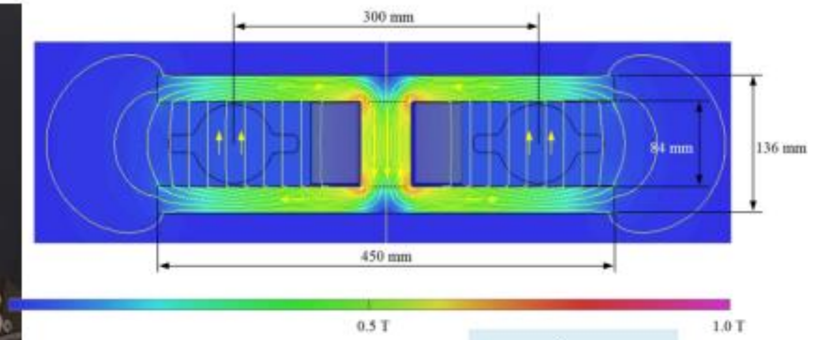
- 4/10 horizontal benches upgraded for HL-LHC cryomagnets, 1/10 for SC Link, 1/10 for coil shaft storage
- Preparations for String 2 under way (25 → 60 g/s Lhe liquefaction, 14 g/s pumping @ 12 mbar)
- Power circuits upgrade: 2×20 kA, 10V converters, 4×2kA auxiliary circuits, load and polarity switches
- DAQ and protection: quench heathers, energy extraction switches, UQDS, CLIQ, PLC & fast interlock systems, anticryostat heaters …

# FCC - Future Circular Collider

- Z, W, H factory with highest luminosity, lowest cost and risk for E frontier collider
- feasibility study ongoing, momentum rapidly building up
- key roadmap milestones:
  2026: EU strategy update
  ~2028: approval
  ~2045: FCC-ee commissioning
  ~2070, FCC-hh operation
- L=90 km, ρ=10.7 km
- e-e collider: E=46 to 182 GeV, 2900× 24 m bending dipoles with $B_1$=14 .. 57 mT, 2900× 3.1 m, 10 T/m focusing quads
- e-e booster: $B_1$=6.3 mT (inj.) ... 58 mT (ext.)




Prototype e-e collider bending dipole

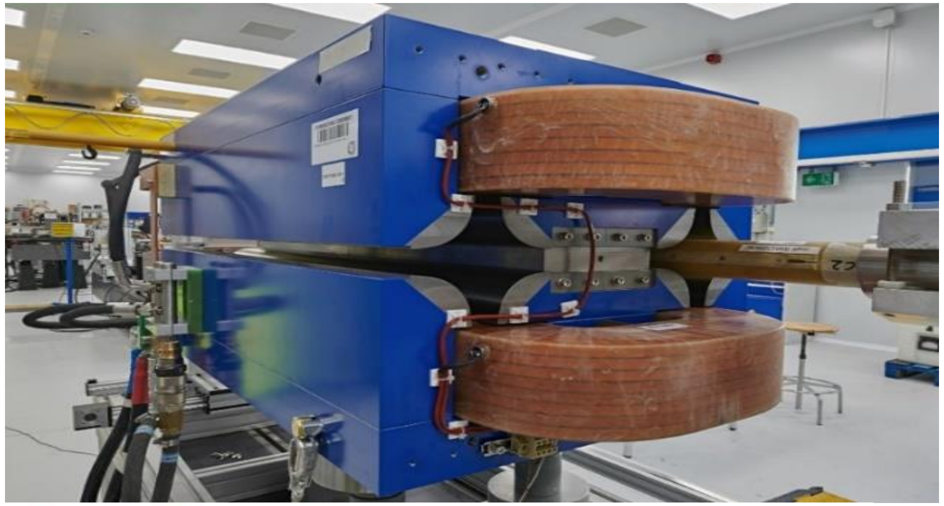


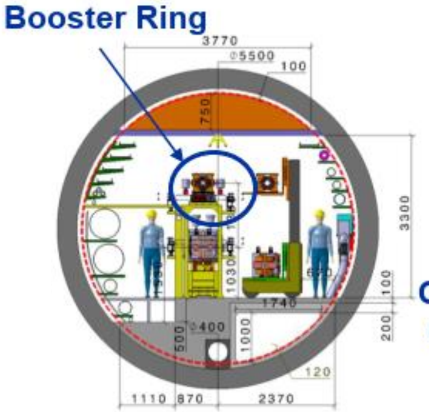

A. Milanese

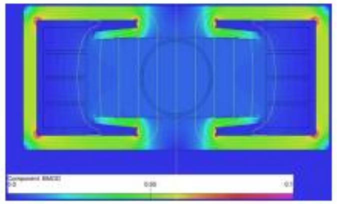
# Prototypes for FCC

Credit: **Carlo Petrone**

## FCC-ee magnets

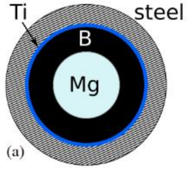




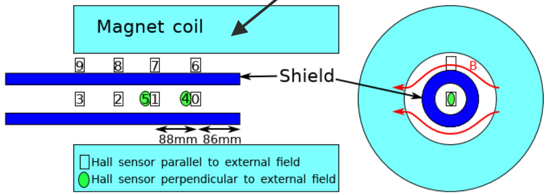
Conceptual design of FCC-ee booster dipole magnet 7 mT (20 GeV) – 63 mT (182.5 GeV)

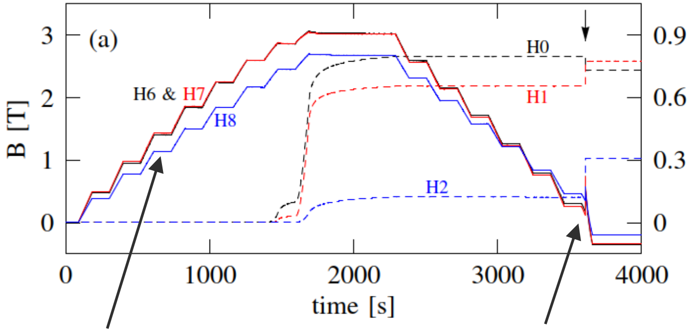
## SuShi (passive $MgB_2$ shield for 3T FCC-hh septa)




8.3 mm $MgB_2$ thickness after reactive Mg infiltration

10 × 8 Arepoc HHP-NP (200 mV/T @ 20 mA) cross-calibrated at RT (relative measurement)




gradual penetration from end

flux jumps at lower field on ramp-down

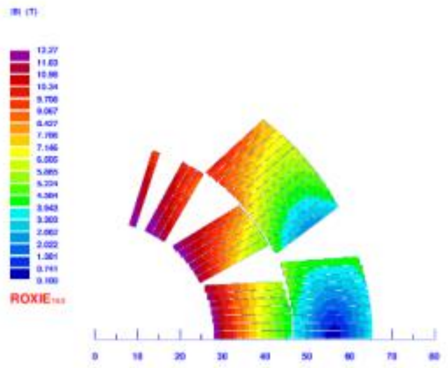
# HFM – High Field Magnets program

- Recent project reorganization, including clear setting as *direct R&D* towards FCC-hh
- Collaboration with PSI, INFN, Uppsala, CIEMAT, CEA and several universities

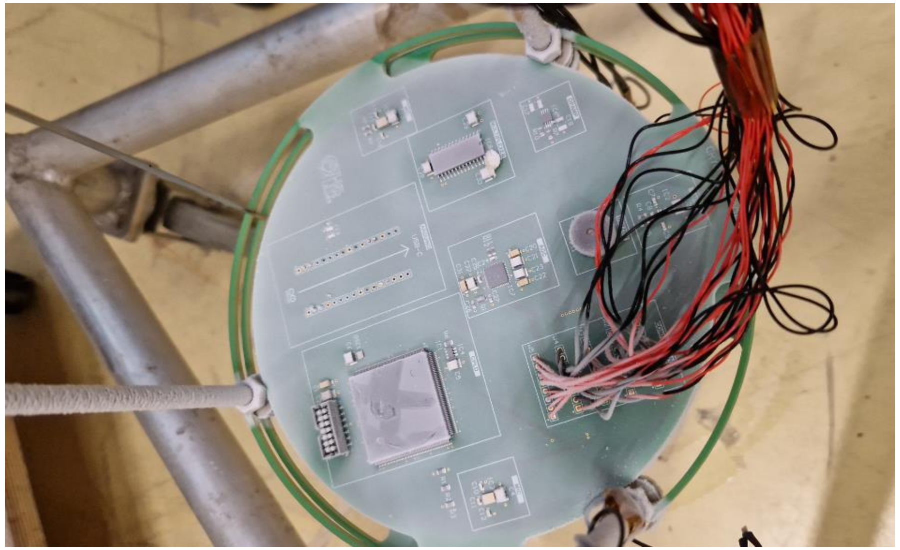
Program highlights:

- Robust Cos$\theta$ $Nb_3Sn$ dipole up to 12 T (FalconD);
- Target: 14 T dipole for 90 TeV FCC-hh in ~2050
- Roadmap for feasibility of HTS for accelerator magnets
- Non-FCC activities: 20/40 T Muon Collider solenoids

HFM
High Field Magnets




**Conceptual design of 12 T robust dipole magnet X-section (based on MQXF cable)**

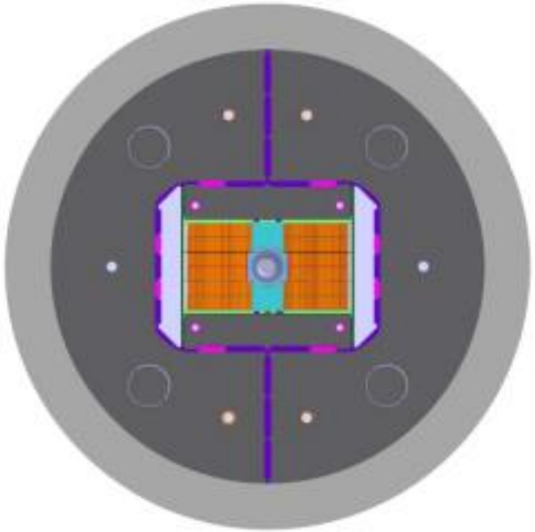


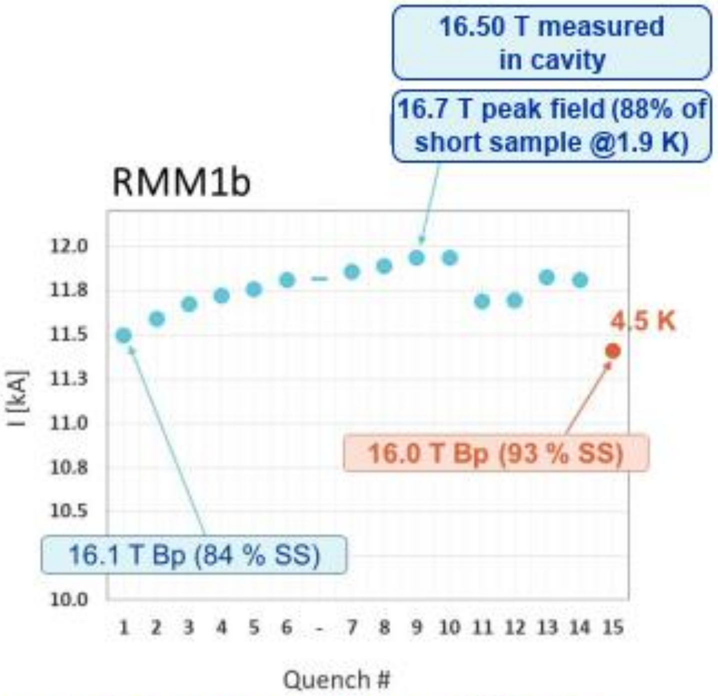
**Vincenzo Di Capua**
this IMMW

Tests of electronic sensors and acquisition chain components in LHe @ 1.9 K and 4.5 K

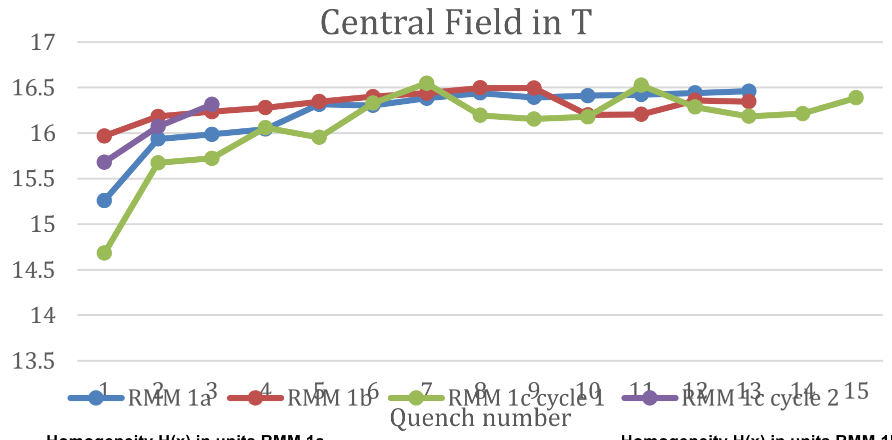
# HFM: Racetrack Model Magnet (RMM)

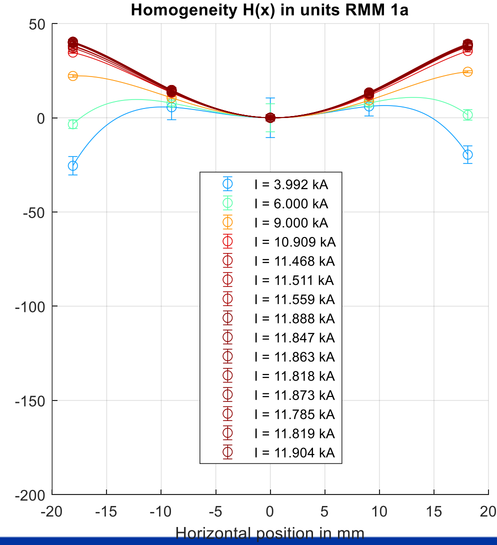
- Family of demonstrator magnets based on eRMC (racetrack coils) to explore full potential of $Nb_3Sn$
- RMM1d designed to reach a peak field of 16.7 T, in a 50 mm aperture, at 12 kA

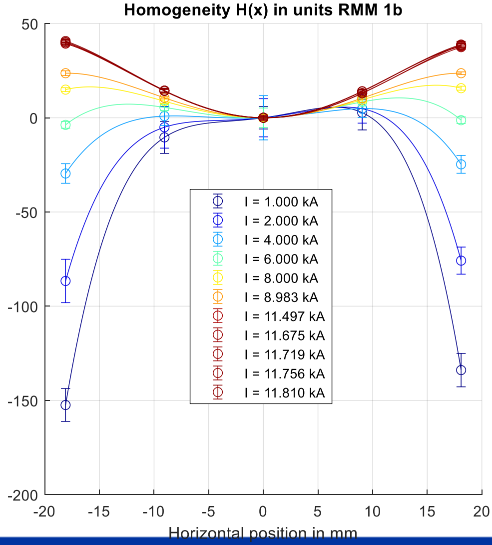





**Exploring the limits of in-coil performance of $Nb_3Sn$**



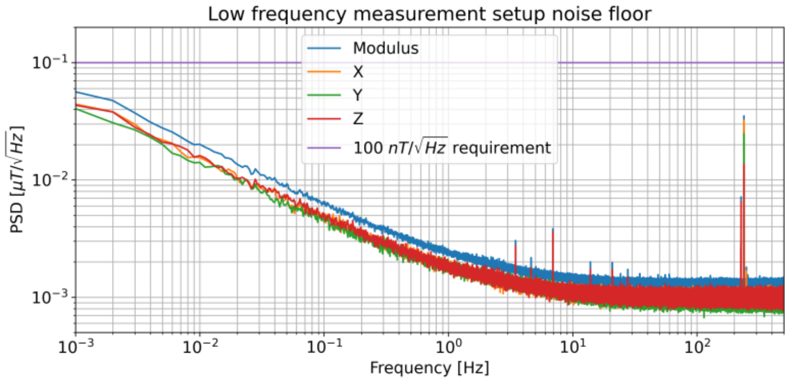




Credit: **Carlo Petrone, Mariano Pentella, Melvin Liebsch**

# Physics Beyond Collider Experiments

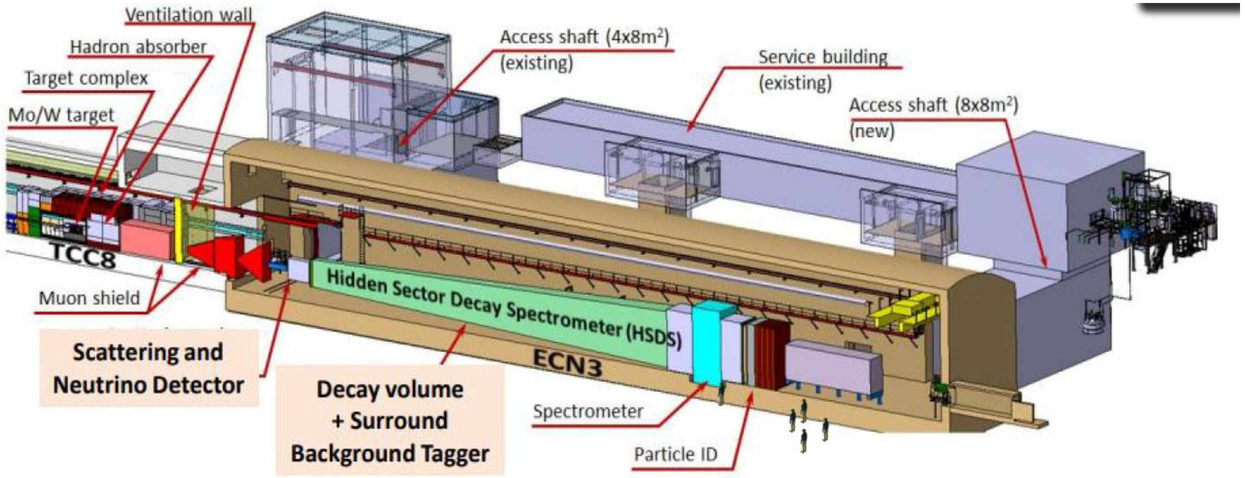
## AION

- Atom Interferometer Observatory and Network for dark matter/gravitational wave detection in PX46 pit
- B field fluctuations → systematic errors
- In-situ measurements DC-300 Hz with a fluxgate


## SHiP

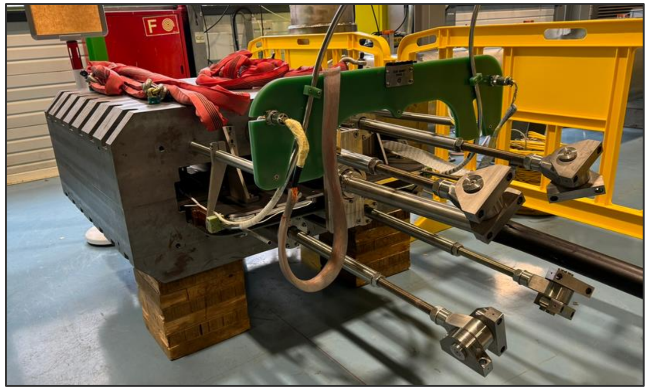
- Search for Hidden Particles (dark matter/neutrinos) detector based on CERN SPS beam dump
- Needs a 0.15 T, 4×6×3.5 $m^2$ spectrometer that would consume 1.2 MW if resistive → $MgB_2$ option

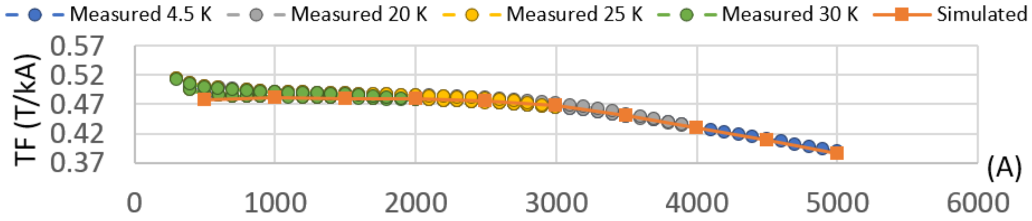


# Other Superconducting Magnet Projects

## EESD Spectrometer demonstrator

- 20K, $MgB_2$ Energy Efficient Superferric Demonstrator (for SHiP experiment) @ 4000 A DC without ohmic losses
- Phase I/II tests with cold coil/yoke at 1.9 to 30 K completed; Phase III tests with warm yoke scheduled soon
- Field dynamics measured with standard rotating coils + hybrid coils/Hall sensors embedded in the coils






## FUSILLO demonstrator

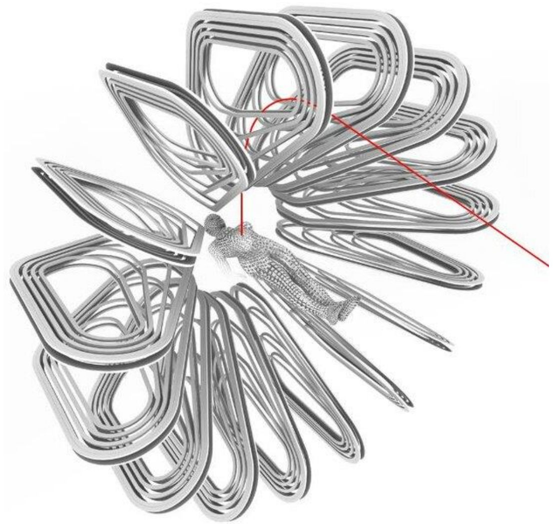
- Magnet demonstrators of strongly curved CCT NbTi superconducting dipole for medical application gantries
- Two subscale models with 2-turns coil fully tested. Full-scale 3-T model under construction and scheduled for testing by end of 2024.

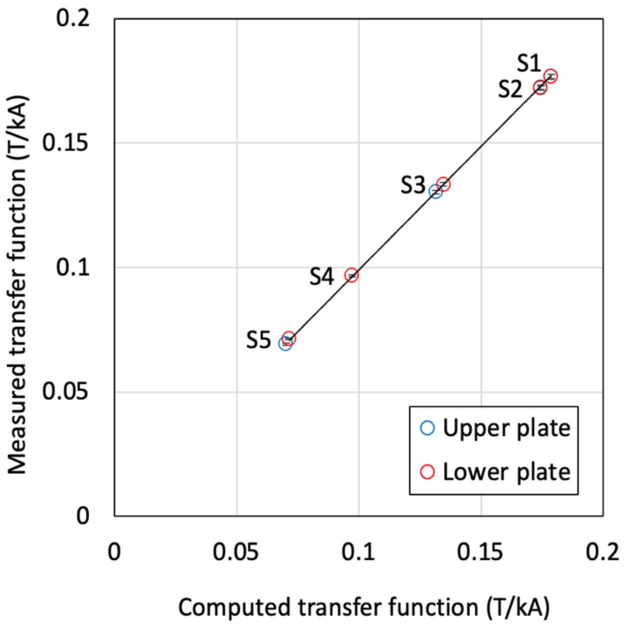
Credit: **Carlo Petrone, Mariano Pentella**

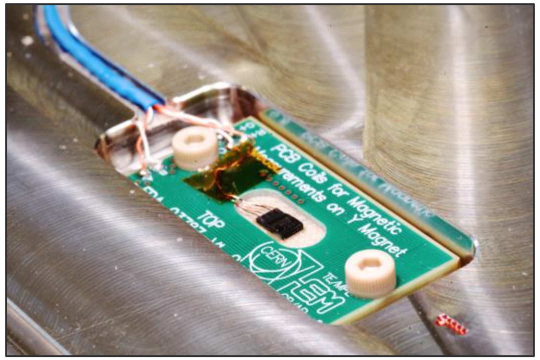


# Hadron therapy gantry: GaToroid

- Concept: toroidal gantry for hadron therapy, replacing rotating components with 1/r tokamak-like toroidal field
- Initial models tested:
  - ReBCO version, powered only up to 15 A at 20 K
  - NbTi version, powered above nominal without performance limitations
- Measurements performed at 1.9 K and 4.5 K via hybrid sensors consisting of PCB coil and Hall sensor





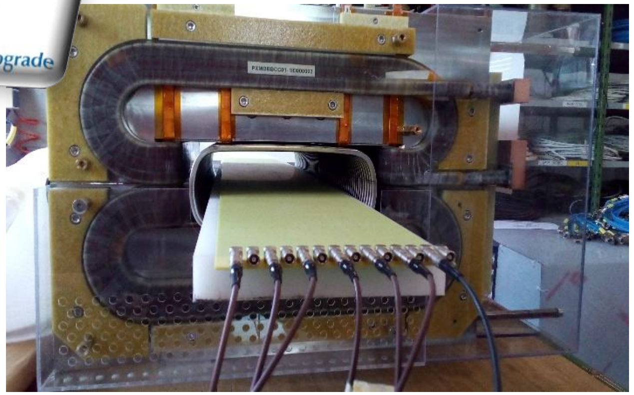
Credit: **Luca Bottura, Carlo Petrone, Mariano Pentella**

# Refurbishment/upgrade of resistive magnets

- Ageing stock of 5000+ beam line normal-conducting magnets (EOL bathtub curve)
- Common failures: water leaks, insulation integrity → **consolidation and preventive maintenance**
- Occasion for power consumption optimization: DC → pulsed excitation

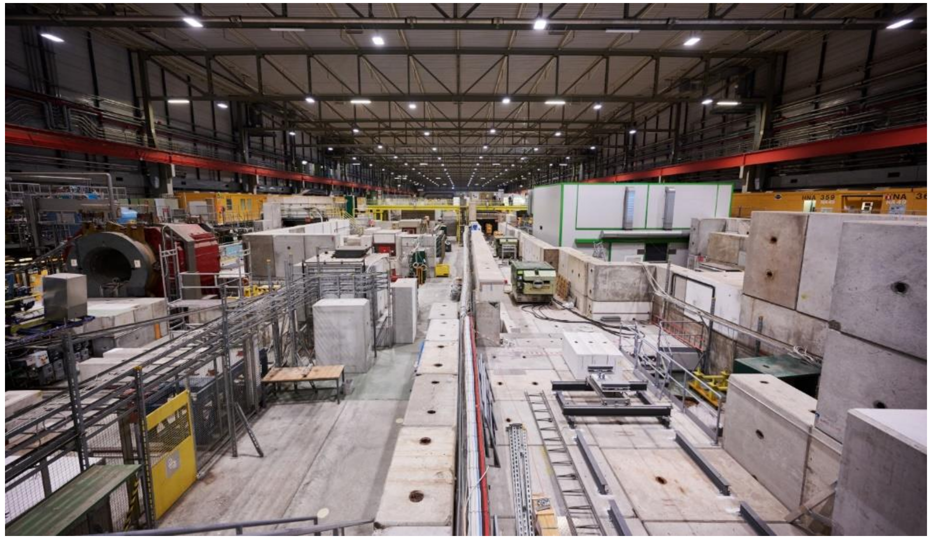
SPS fixed-target East Area
58 magnets in 2021

LHC Injectors Upgrade



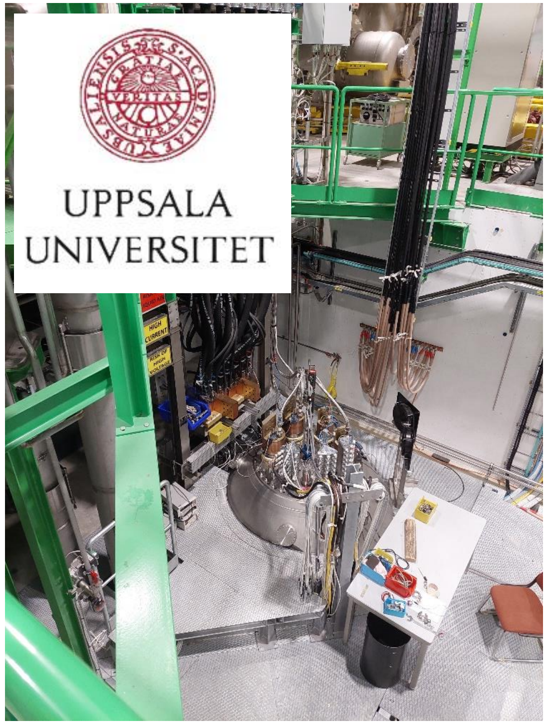
new PS extraction bumper with pole face loops
for passive sextupole compensation

LIU – 120 new/refurbished magnets
tested in 2016-2020



SPS fixed-target North Area
(planning under discussion)

# Collaborations




Vertical anticryostat for Bench Cluster D
up to ∅600 mm × 5.5 m magnet
1 × 30 kA + 2 × 2kA converters


**Pawel Kosek**
this IMMW

DIETI UNINA – Università degli Studi di Napoli Federico II – Dipartimento di Ingegneria Elettrica e delle Tecnologie dell'Informazione

IMPALAB Instrumentation & Measurement for Particle Accelerator Lab

Technische Universität Darmstadt

Paul Scherrer Institut PSI

iter
china eu india japan korea russia usa

INFN LNF
Istituto Nazionale di Fisica Nucleare

Politecnico Milano 1863

universität wien

L-Università ta' Malta

RWTH Aachen University

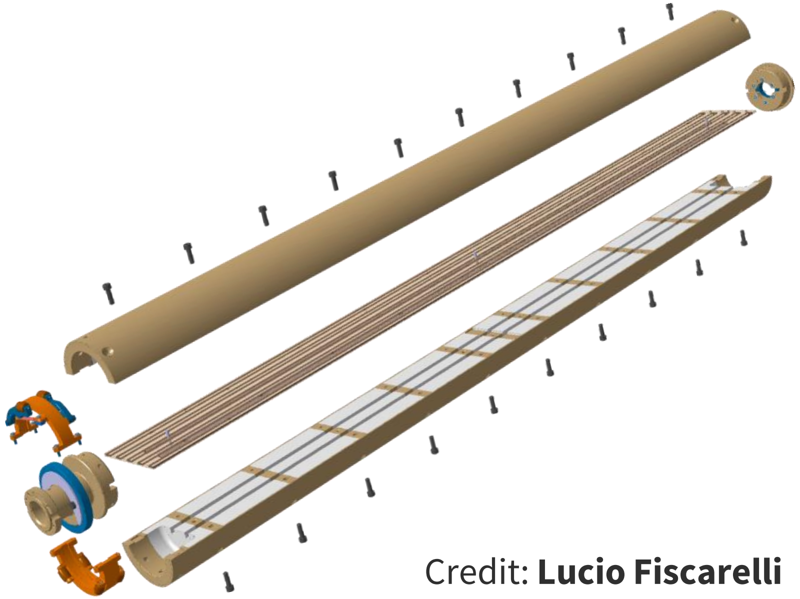
# Instrumentation highlights

## Sensors, probes and methods

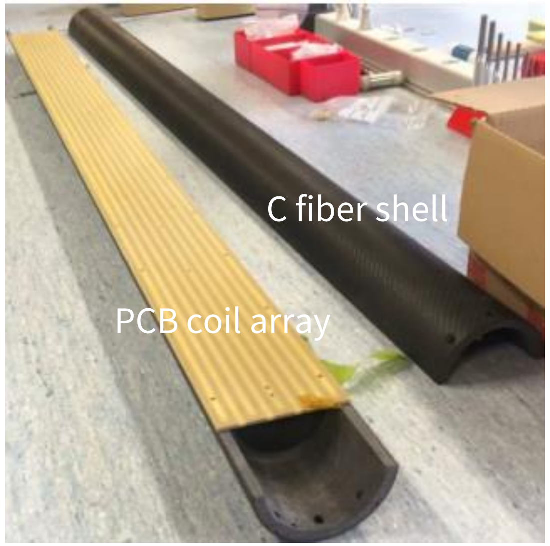
# Rotating coil systems for HL-LHC

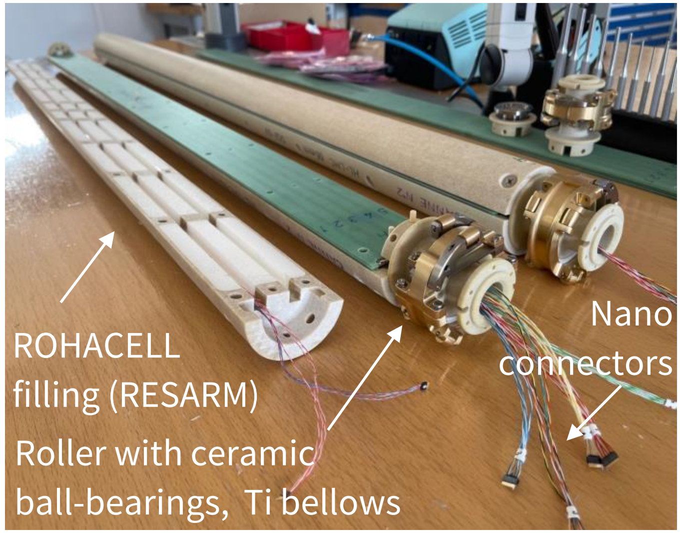
**Guy Deferne**
this IMMW

Quadrupole calibration setup based on CERN-standard rotating coil system



Credit: **Lucio Fiscarelli**



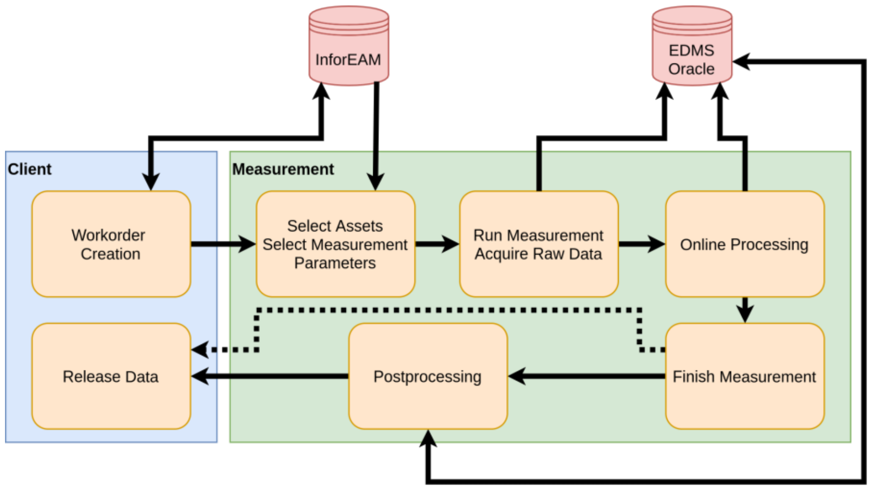





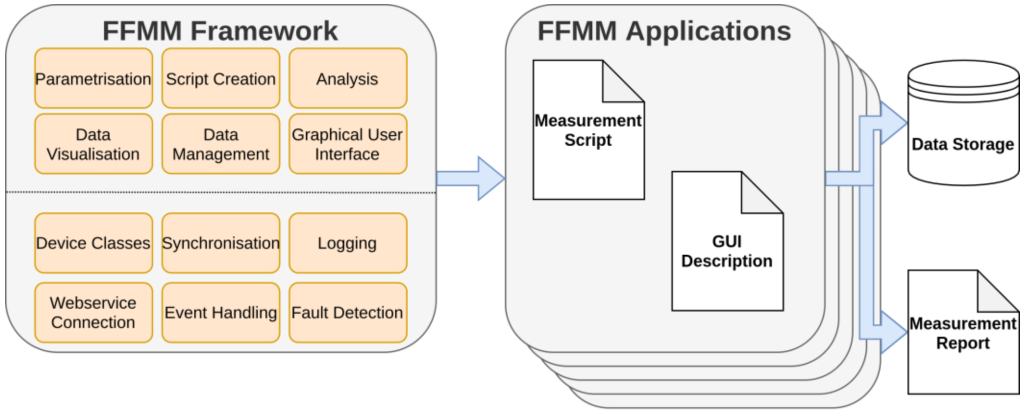
**Mariano Pentella**
this IMMW

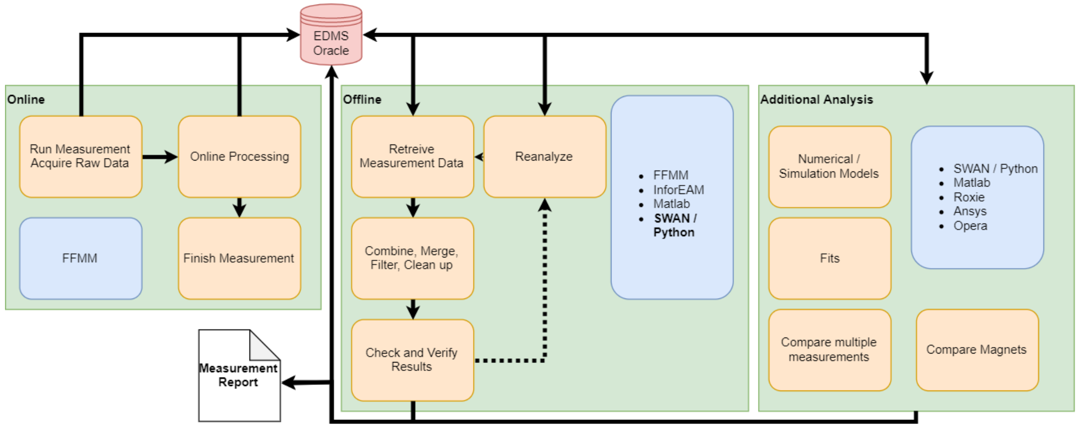
# Modelling and workflow tools

**Matthias Bonora**
this IMMW




- Python-based software framework to achieve fully traceable measurements from calibration, data acquisition (FFMM C++ framework) and analysis to the final measurement report.
- Combine FEM/BEM simulations (ROXIE, Ansys, Comsol …), analytical models and measurements to update magnet models to an as-built state in a DB



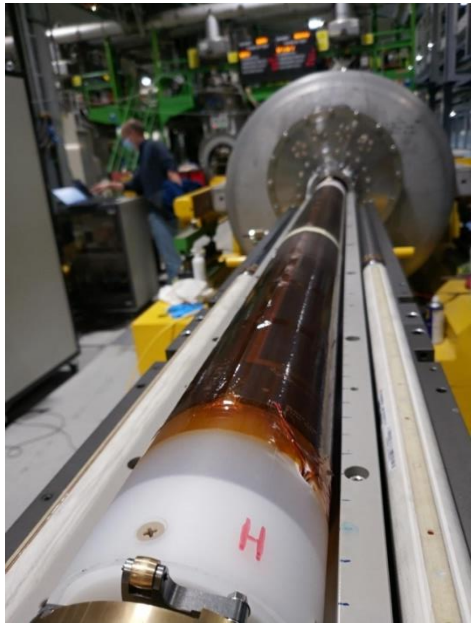



# Flexible-PCB Quench Antenna

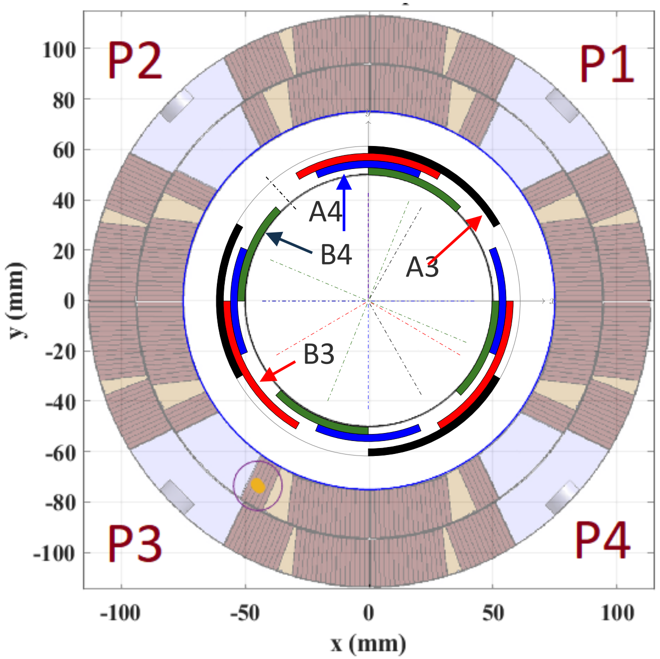
- Novel design concept: **rolled-up flexi PCB**, very easy to (dis-)assemble
- Optimized for MQXF (hard-wired analog bucking)
- Improved G=100~500 acquisition electronics (analog-bucking op-amp bypassed, $Z_{in}$ adapted to long coax capacitive load)

Credit: **Lucio Fiscarelli**

2 × double-layer flexi PCB glued together
4 × 16-turn tangential coils per layer



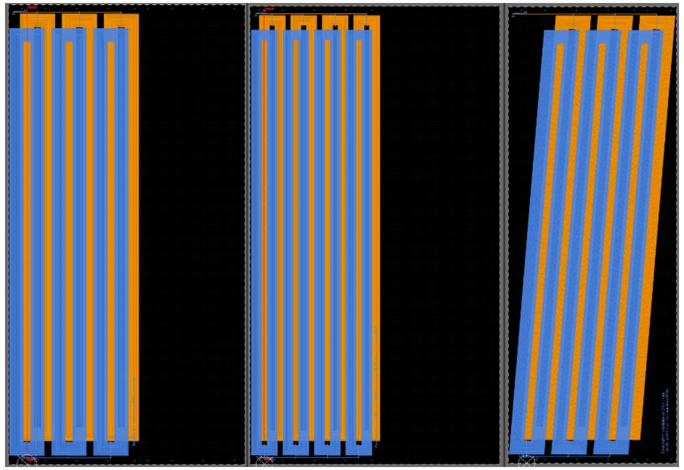
12 ×Ø100 mm, 0.6 m long segments




Per-layer harmonic bucking

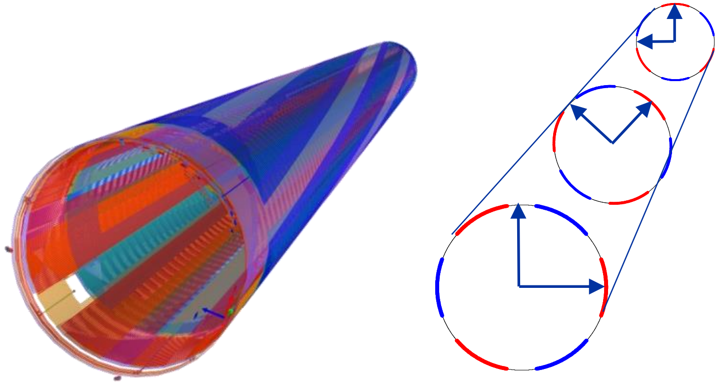
# Quench Antenna with twisted coils

- On one segment there are **3 sets of coils**:
  - **Straight** coils sensitive to B3,A3 and B4,A4
  - Additional **twisted** coils sensitive to B3,A3
- Flux jump/quench events modelled as **elementary magnetic moments**
- Transversal position obtained from $B_3$,$A_3$ and $B_4$,$A_4$ measured with straight coils.
- The longitudinal position *z* is proportional to the **phase shift** of the signals from twisted coils respect to the signals from the straight coils.




$$z = w \arg\left(\frac{B_3^* + iA_3^*}{B_3 + iA_3}\right)$$

*w* = twist pitch



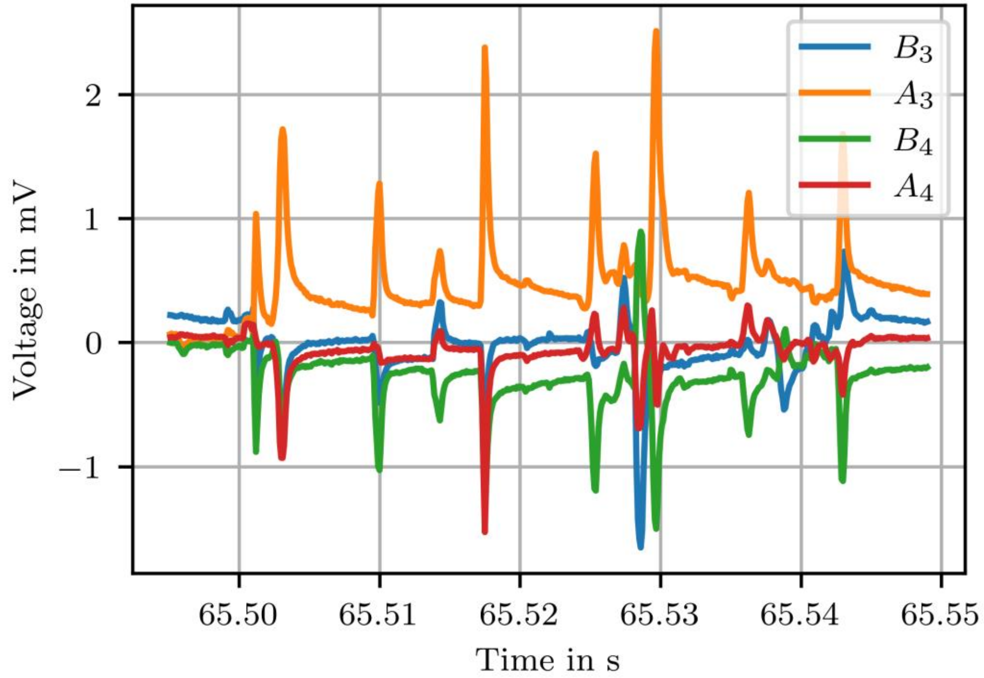
Credit: **Lucio Fiscarelli**

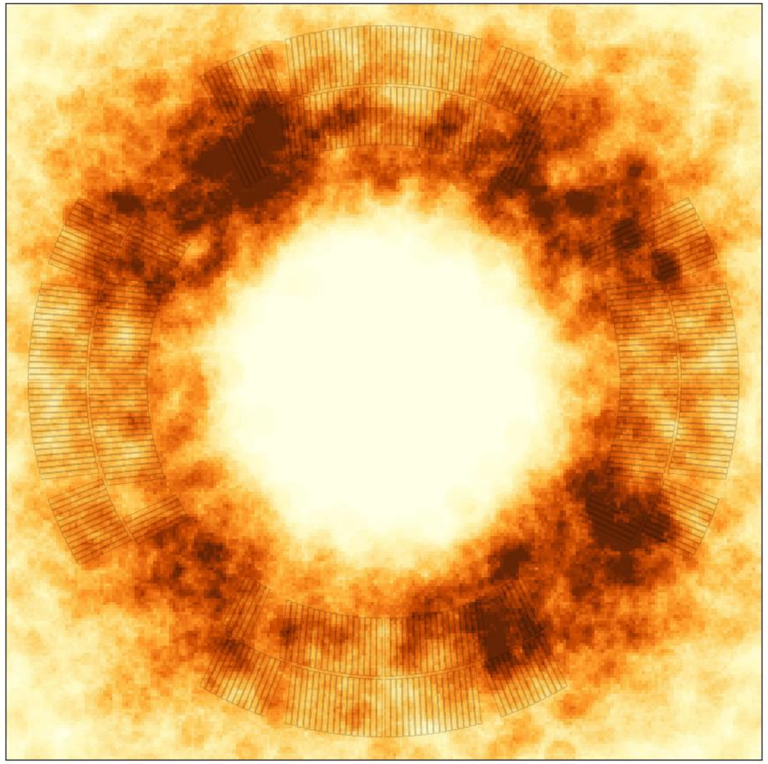
# Quench Antenna results

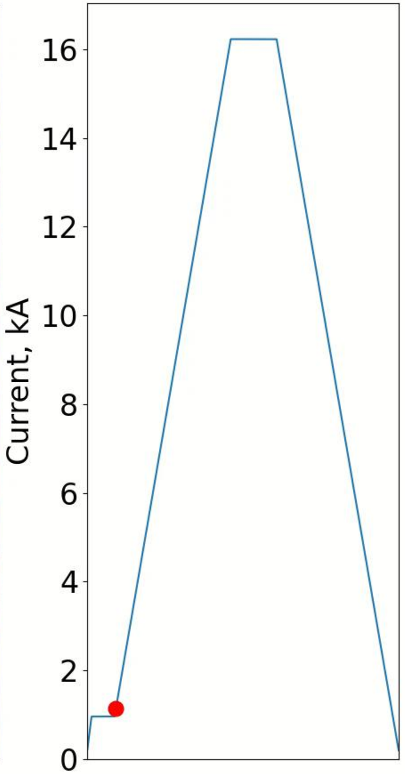
Credit: **Lucio Fiscarelli**

**Heatmap** of flux jumps during an energization ramp (darker color indicates more events)

- Low field: large number of jumps distributed mainly in the **inner layer**
- At intermediate level, they tend towards the **midplane of outer layer**
- From intermediate to high fields, the number of jumps **decrease**

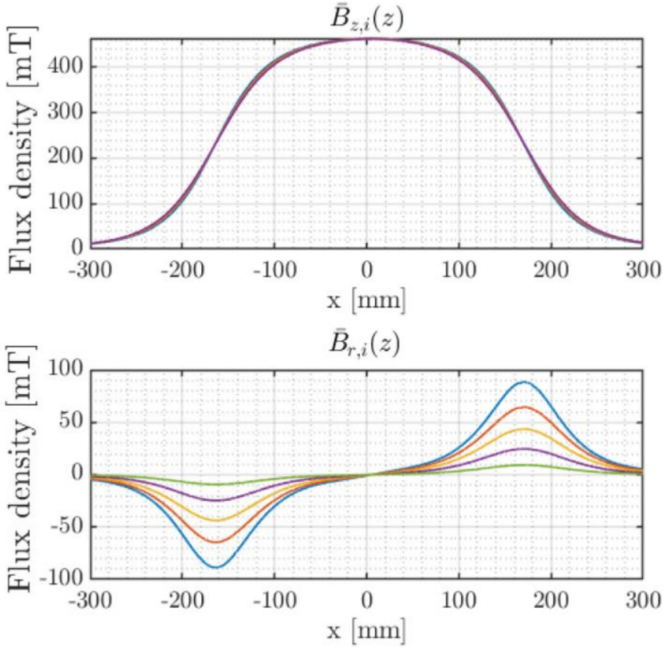


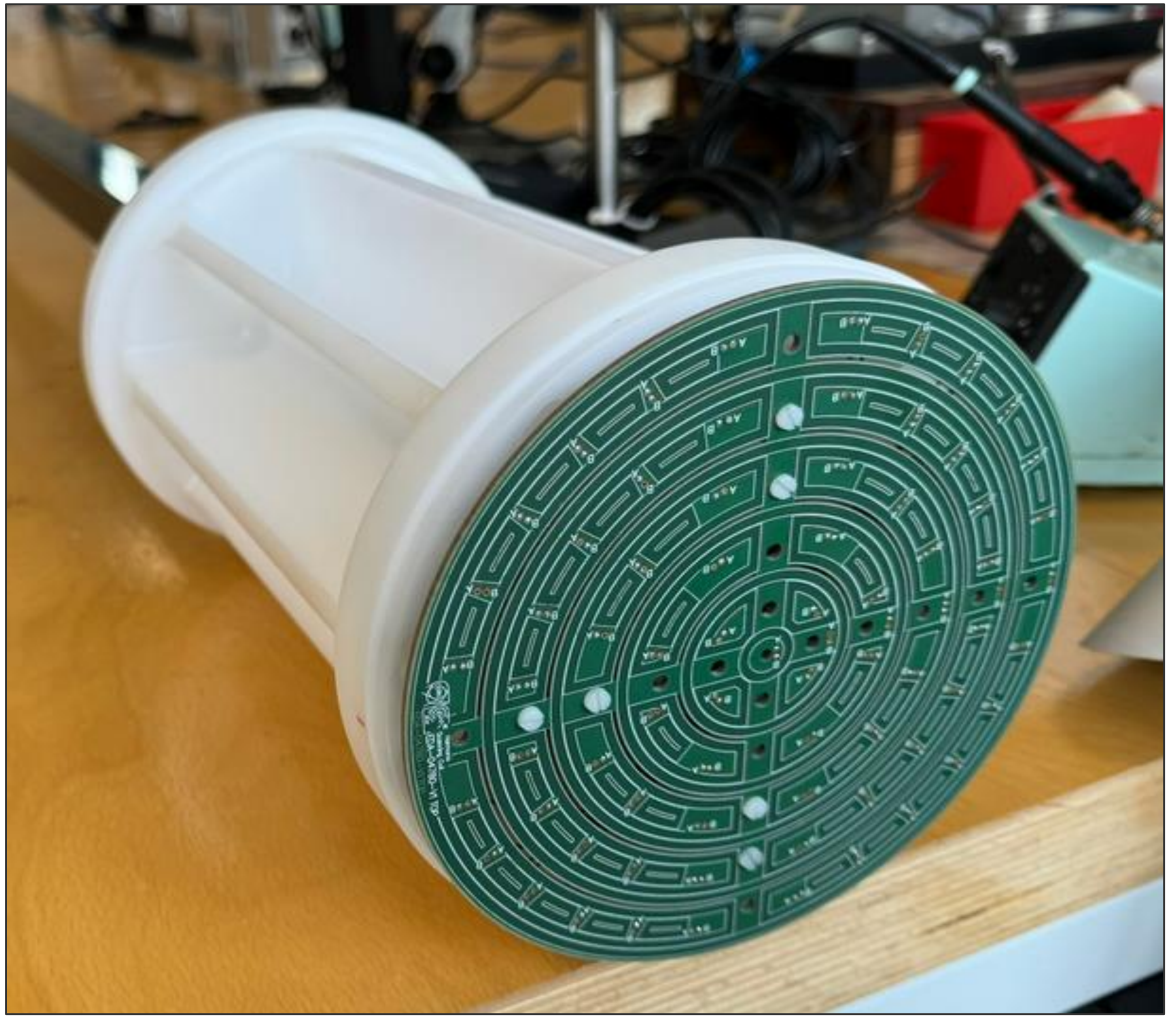


# Translating fluxmeter for solenoid mapping

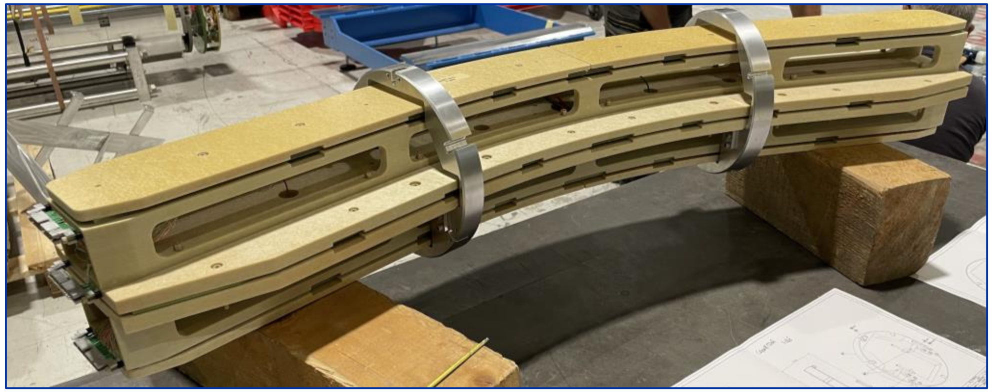
- PCB-based translating fluxmeter to map solenoids (motivated by CERN AD electron cooler)
- New design optimized for 60 mT, includes 20 azimuthal local coils/ring for improved axis and field error measurement.
- Fiducialization still a challenge. New approach based on 3D cylindrical harmonic description is being developed.




Credit: **Mariano Pentella**
**Carlo Petrone**

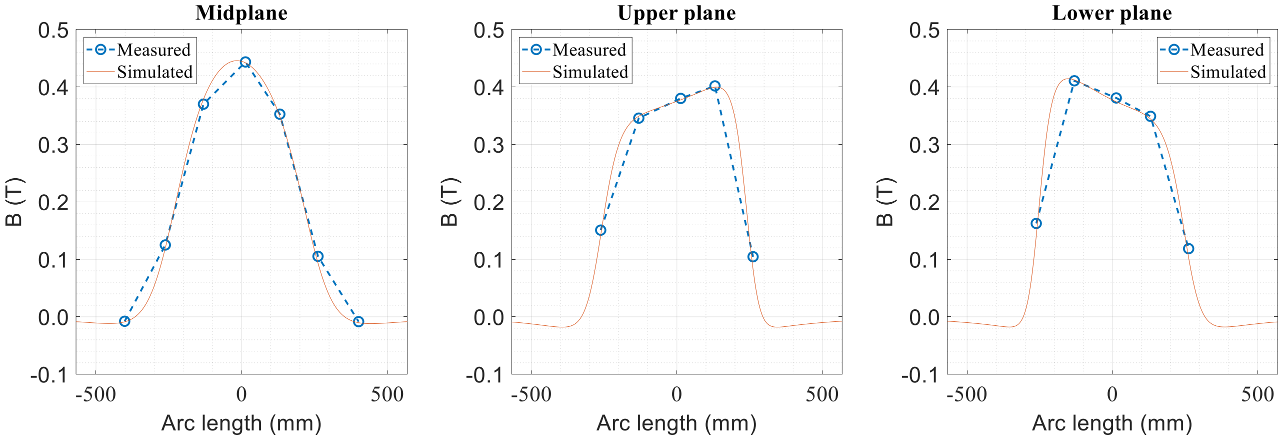


# Strongly curved PCB fluxmeter (FUSILLO)

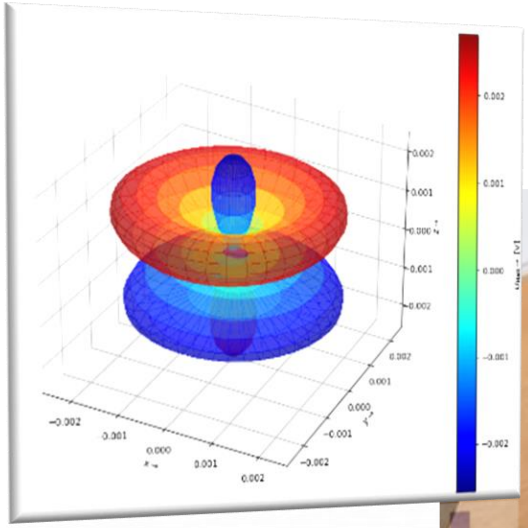
Credit: **Mariano Pentella, Unai Martinez**

- Piecewise PCB size < 500 mm for design flexibility, much lower cost and faster procurement
- Dense point-like local field probes for cross-calibration with induction coils, missing gap compensation in non-uniform field
- More complex mechanics, assembly and wiring procedure





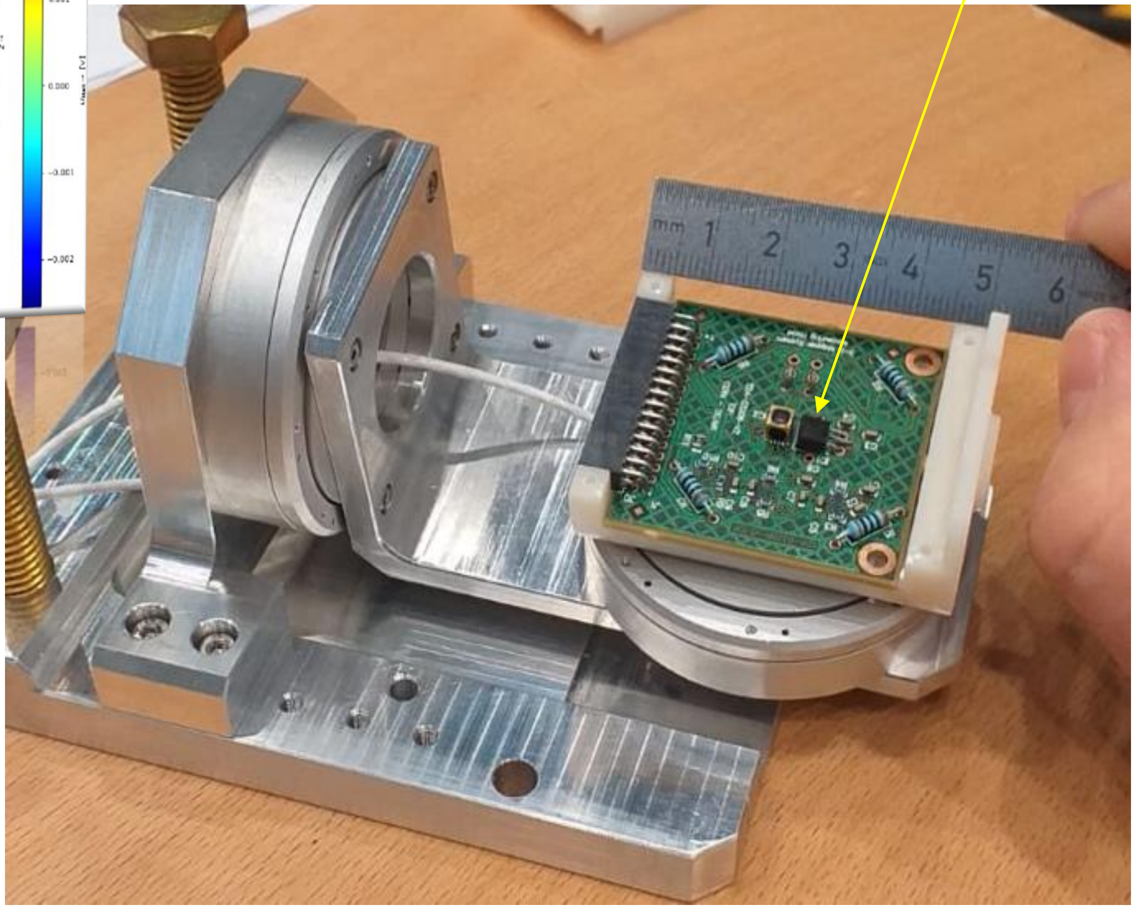

# 3D Hall probes

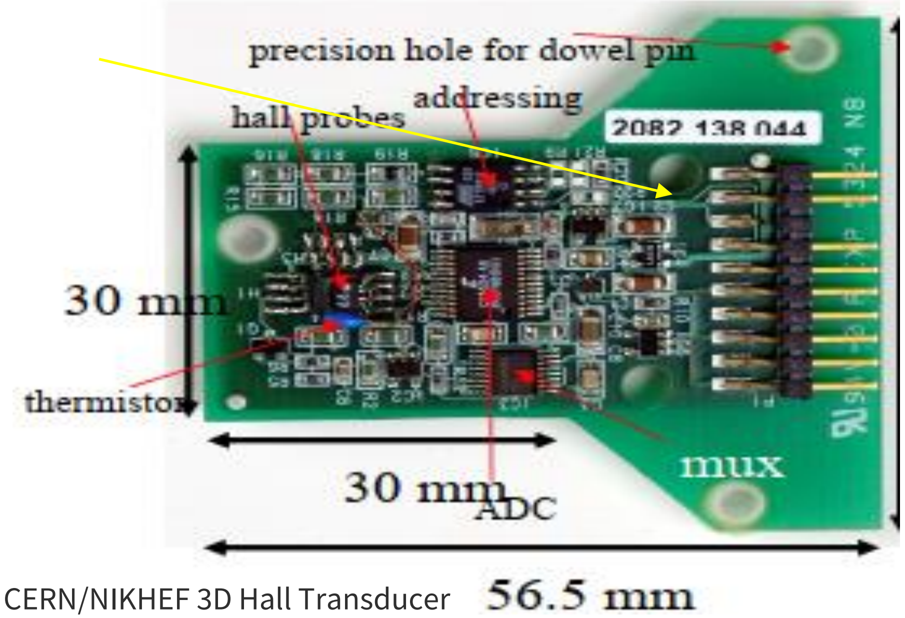


Piezo motor-based
Spherical harmonic calibrator

Credit: **Melvin Liebsch**

ASENSOR HE444 3D Hall sensor
(the last one !?)
8 mrad orthogonality, 0.3% non-linearity





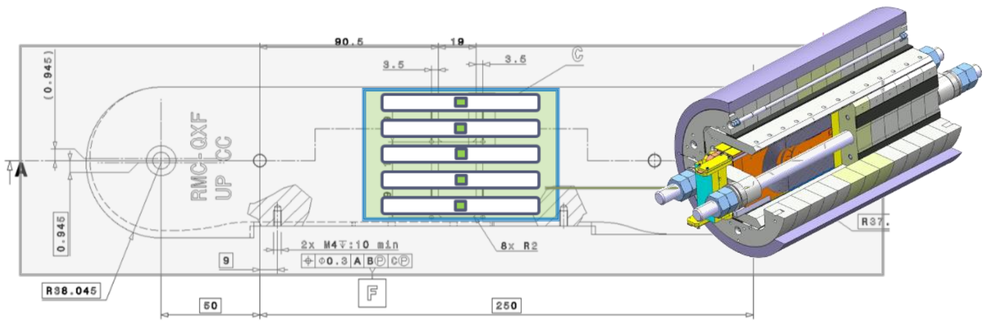

CERN/NIKHEF 3D Hall Transducer
(courtesy **N. Pacifico**, EP-DT)

Permanent-magnet double-cone
fiducialization reference

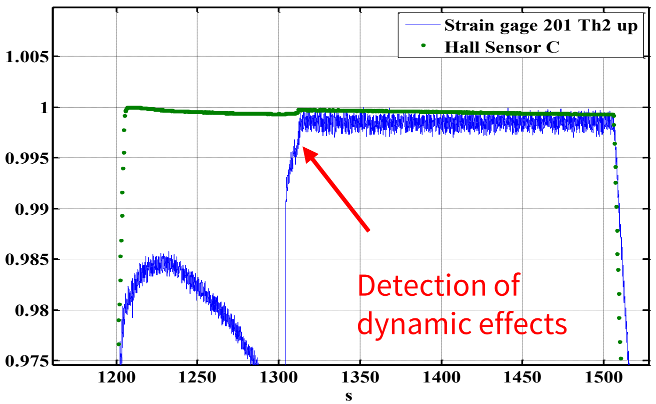
# Sensor fusion: induction coils + Hall probes

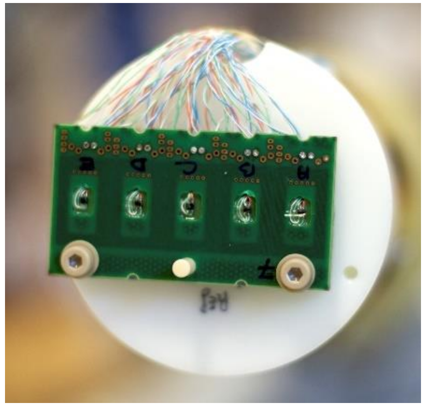
Credit: **Lucio Fiscarelli, Carlo Petrone**

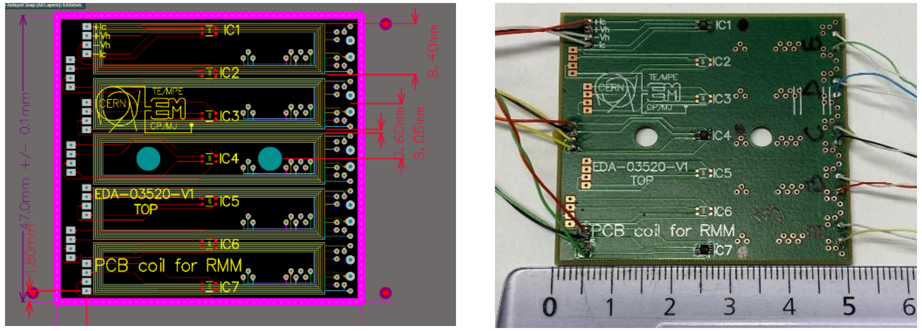
- Trend: combine both sensors on same PCB, whenever possible
- Trivial applications: magnetic length, center field, fringe profiles
- Real interest: cross-calibrate by exploiting coil's linearity, Hall sensor's absence of drift



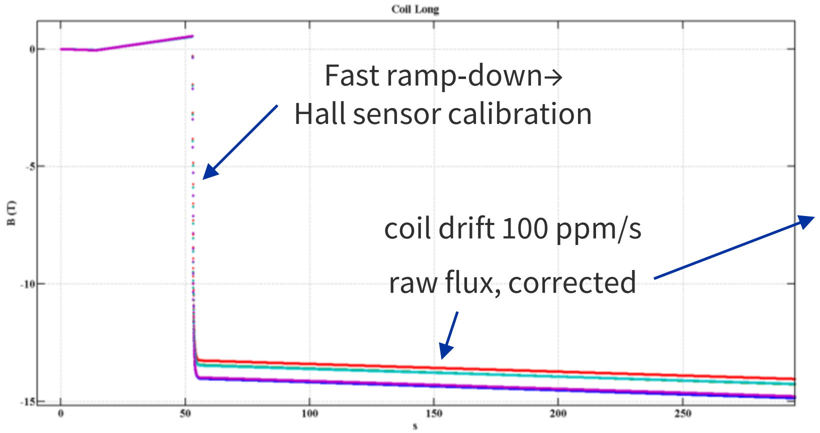
$Nb_3Sn$ racetrack model coils

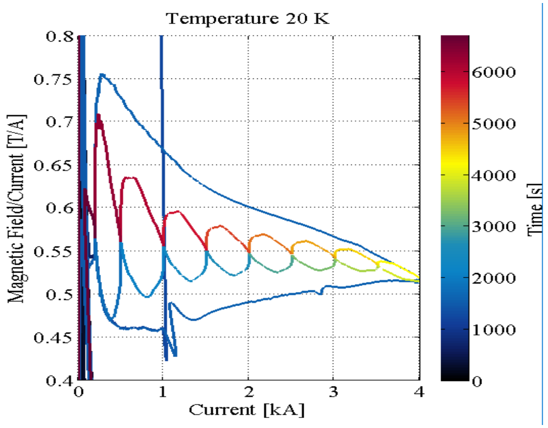




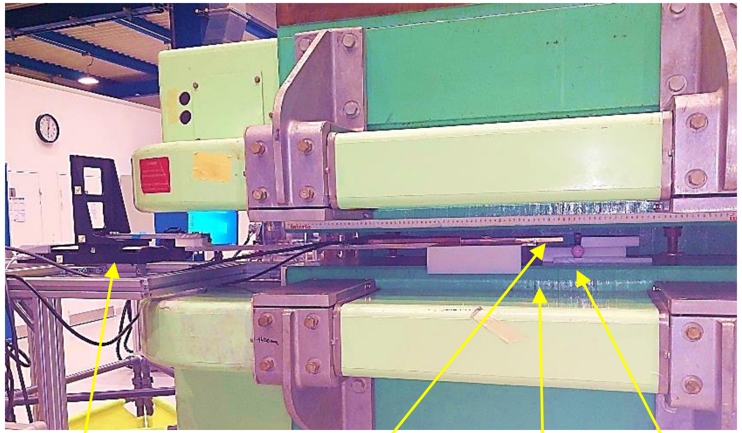

3× aerospace-grade LakeShore HGT 2101 Hall probes (highly nonlinear!)

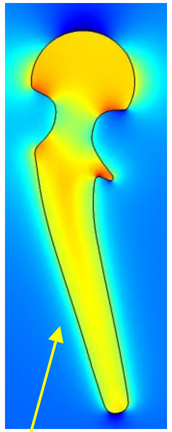


# Non-magnetic material properties

- Flux distortion method for very low permeability material (low $\mu_r$ → high field) @ room temperature
- Analytical treatment possible for simple geometries; arbitrary samples need FE simulations
- Typical accuracy 100 ppm, repeatability 10 ppm (best result: $\mu_r$ = 1.00085 of a W alloy sample, validated by vibrating sample)



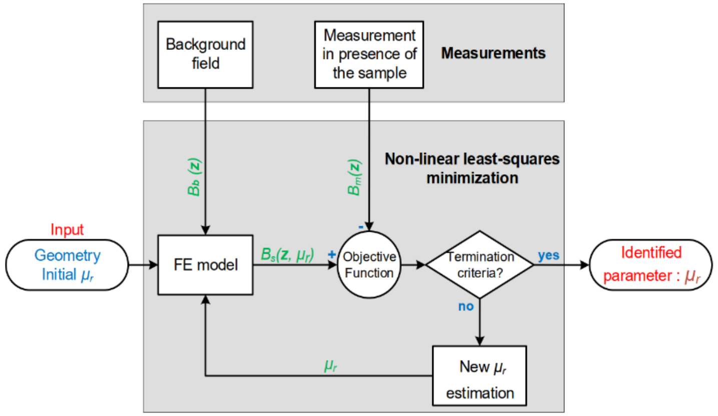


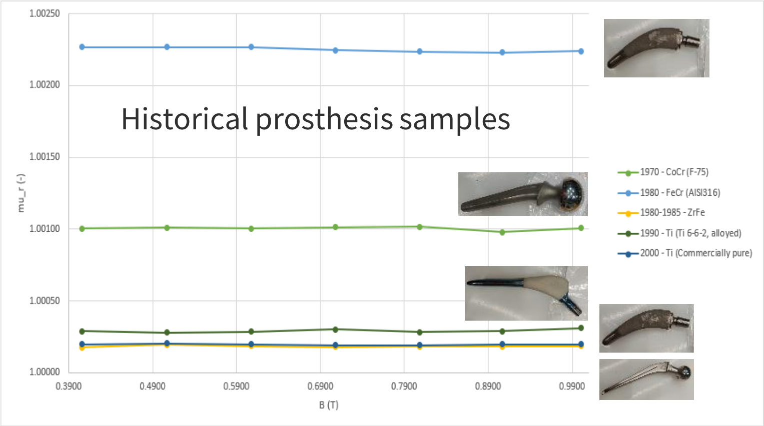
Translation stage

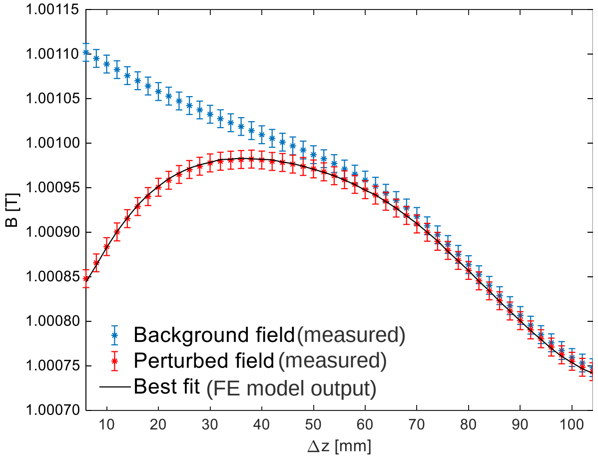
Moving NMR probe (5 ppm accuracy)

Sample: Ti hip prosthesis

1 T dipole, high uniformity background field




$$\frac{F_{\text{magnetic}}}{mg} = (1-\mu_r)\frac{B\nabla B}{\mu_0 g \rho}$$

Worst-case (Fe-Cr prosthesis): **$\mu_r$=1.0023**

$F_m$≈mg for B∇B≈42 T/m² (i.e. ~ 20 T MRI magnet!)

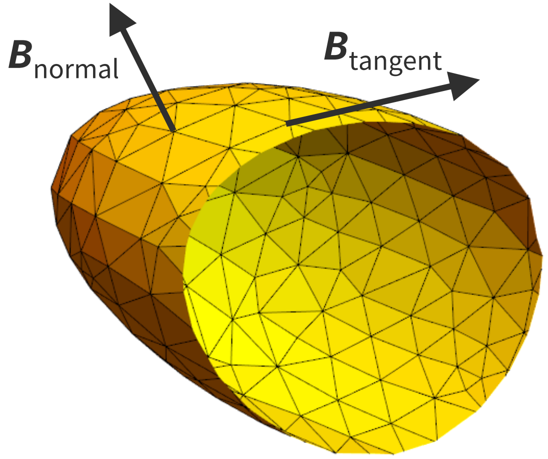
Credit: **Mariano Pentella**

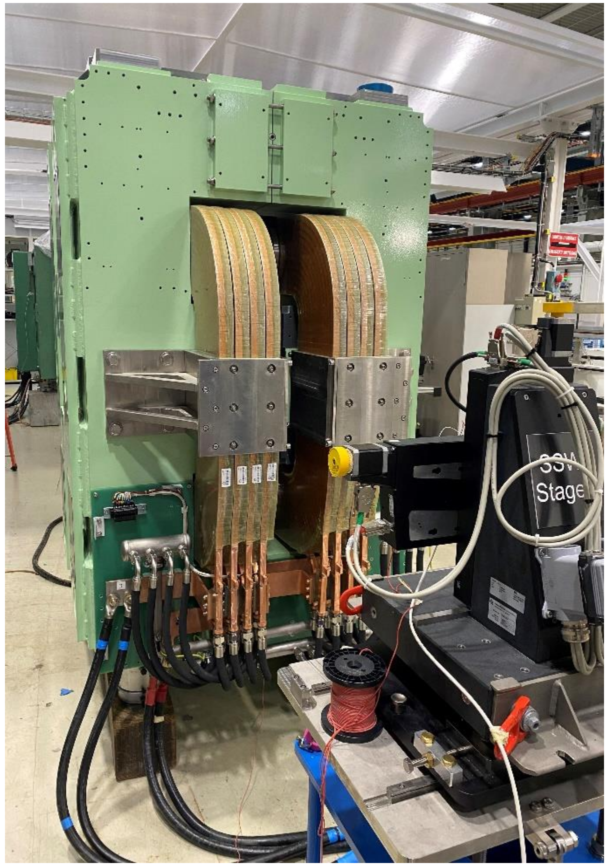


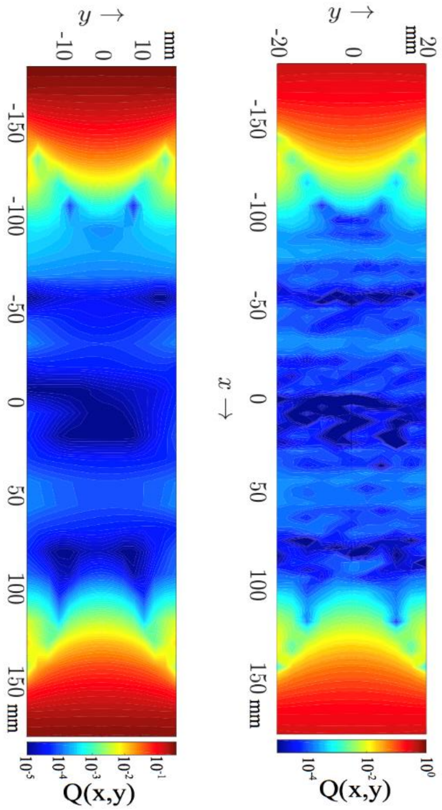
# FEM/BEM processing of boundary data

- Back to Maxwell: Unique solution of Laplace equation in a source-free domain + Neumann (normal field) or Dirichlet (tangential) boundary conditions (if: simply connected domain, smooth boundary)
- **Reduce problem dimensionality**: scan only the boundary, fit a BEM model to get interior values at arbitrary resolution (no volume mesh required !)

Credit: **Carlo Petrone**, **Melvin Liebsch**





BEM reconstruction — Full grid

- Back to Maxwell: Maximum Principle: extremal values always on the boundary → metrological advantage of interpolating the interior

2D example, cylindrical symmetry: $$B_n = C_n \left(\frac{z}{r_0}\right)^{n-1} \Rightarrow$$

Measurement uncertainty at $|z|=r_0$: $$\sigma(B_n(z)) = \sigma_B \left(\frac{z}{r_0}\right)^{n-1}$$

- R&D challenges: automated meshing and setup of BEM model; hybrid boundary conditions (e.g. integrals from flux measurements); incorporate arbitrarily scattered/multiple/interior points

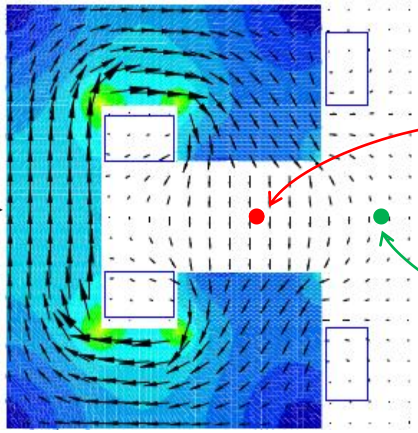
# Hybrid approach: data-driven Digital Twins

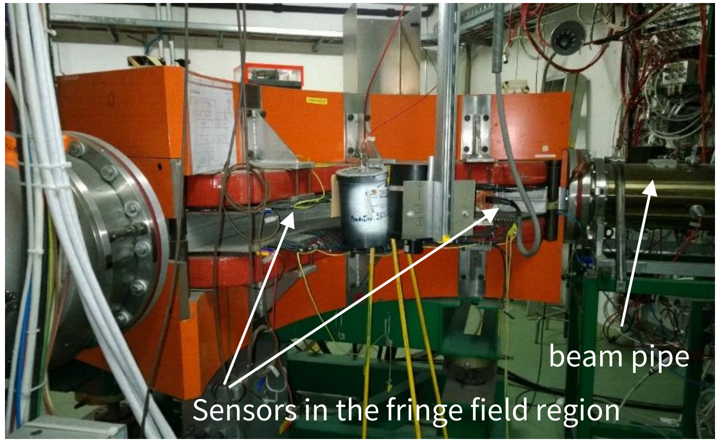
- Combine optimally the strong points of computer modeling and measurement
- Formalize and automate the comparison of computed and measured quantities
- Example: CERN ISOLDE 90° High Resolution Separator

**Melvin Liebsch**
CAS on Magnets 2023

**Parameters *p***
(g, $\mu_r$)

**Bayesian priors**
($g_0$,$\sigma_g$), ($\mu_{r0}$,$\sigma_{\mu r}$)



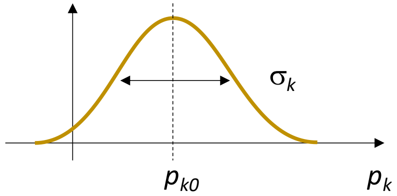




**Measurement uncertainty**
$\sigma_B$

computation

measurement

$$\chi^2(\boldsymbol{p}) = \sum_k \frac{(p_k - p_{k0})^2}{\sigma_k^2} + \sum_j \frac{\left(B_j^{\text{comp}}(\boldsymbol{p}) - B_j^{\text{meas}}\right)^2}{\sigma_B^2}$$




We don't know well these …

Minimization w.r.t. ***p***

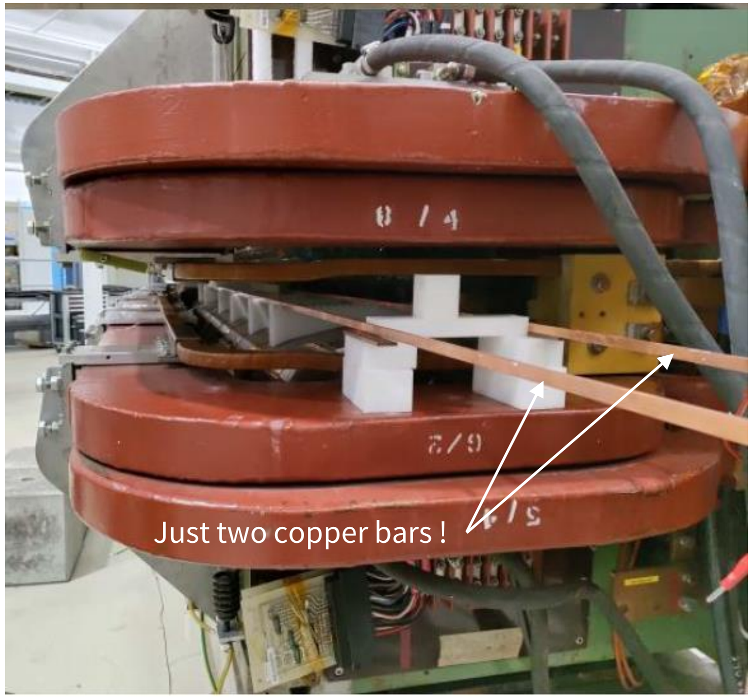
Indications for experiment design

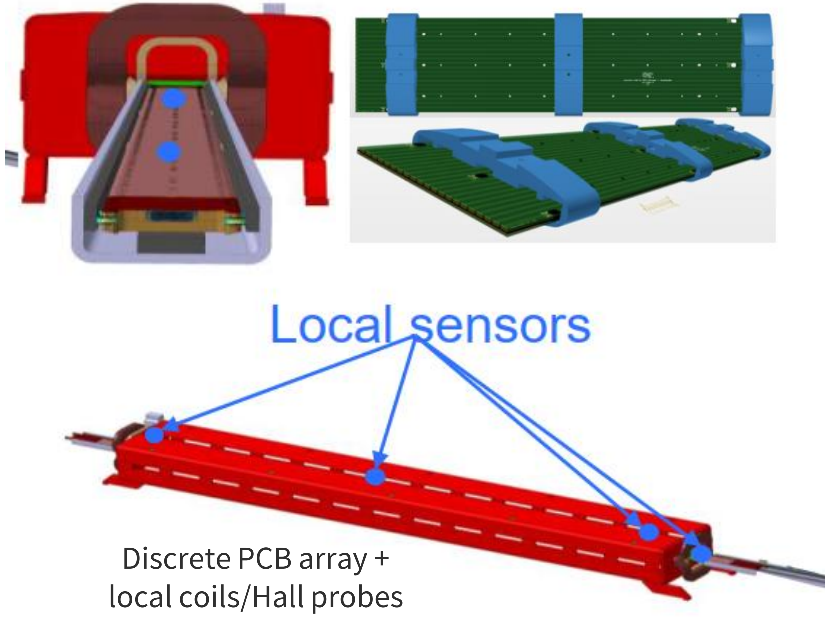
$$J = \frac{\partial B_j^{\text{comp}}}{\partial \boldsymbol{p}}, \quad H = \frac{\partial^2 B_j^{\text{comp}}}{\partial \boldsymbol{p}^2}$$

# Hysteresis measurement and modelling

Vincenzo DI Capua
this IMMW

- Instrumentation R&D to measure integral dynamic effects in fast-pulsed, iron-dominated magnets (CERN PS, SPS)
- **EPA** (Efficient Particle Accelerators) initiative: exploit Machine Learning to feed-forward hysteresis effect to machine control
- LLMs trained on B-train measurements provide excellent results on cycles within training parameter space envelope




Discrete PCB array +
local coils/Hall probes

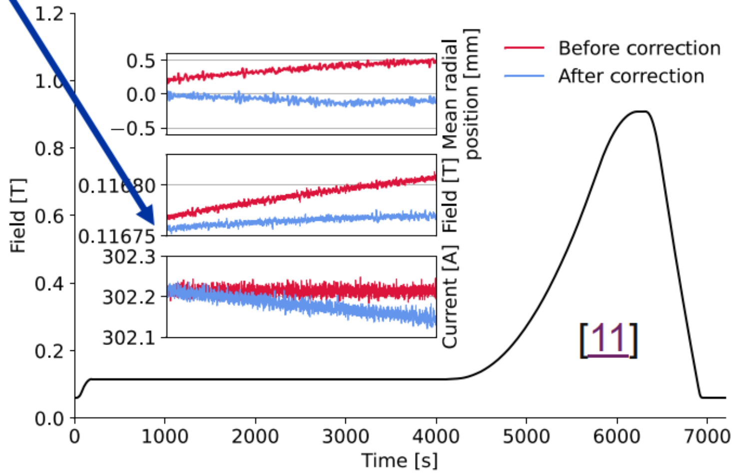
Integral coil setups for the main PS/SPS magnets

~ 0.018 % accuracy achieved with transformers

**Transformers**

$B = f(I, B_{old})$

With $B_{old}$ coming from the B-Train




Feed-forward correction of SPS operation

Credit: **Vincenzo Di Capua, Mariano Pentella, Anton Lu**

# Conclusions

- Spectrum of existing instrumentation technologies covers well all current requirements, with widely variable levels of accuracy, difficulty and cost

- Future demands are expected to push the envelope in terms of field strength, ramp rates, magnet size …

- Waiting for the definition of a future strategy, we must prepare to test magnets over a vast range of parameters