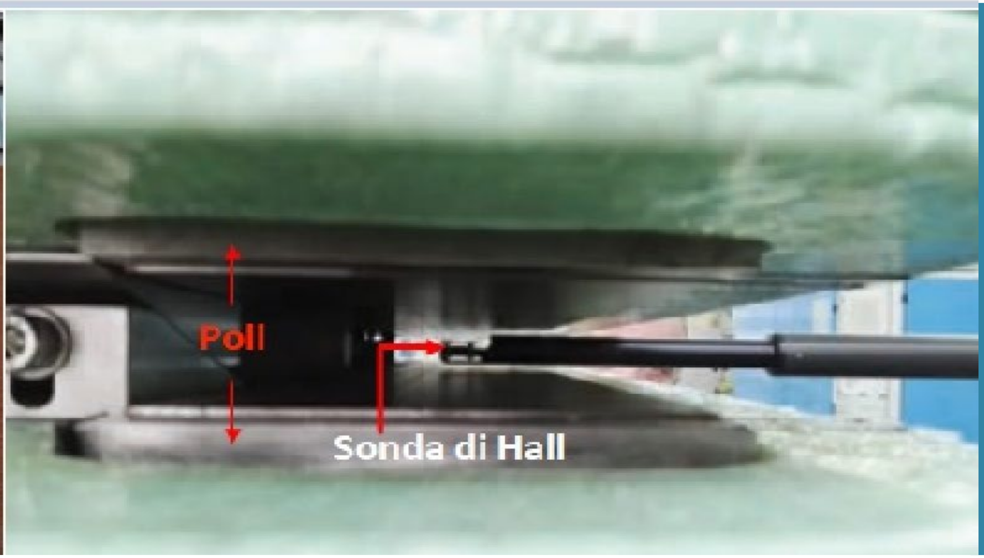
INFN – LNF Magnetic Measurement Laboratory Status and Upgrade

23rd International Magnetic Measurement Workshop (IMMW23)



Alessandro Vannozzi

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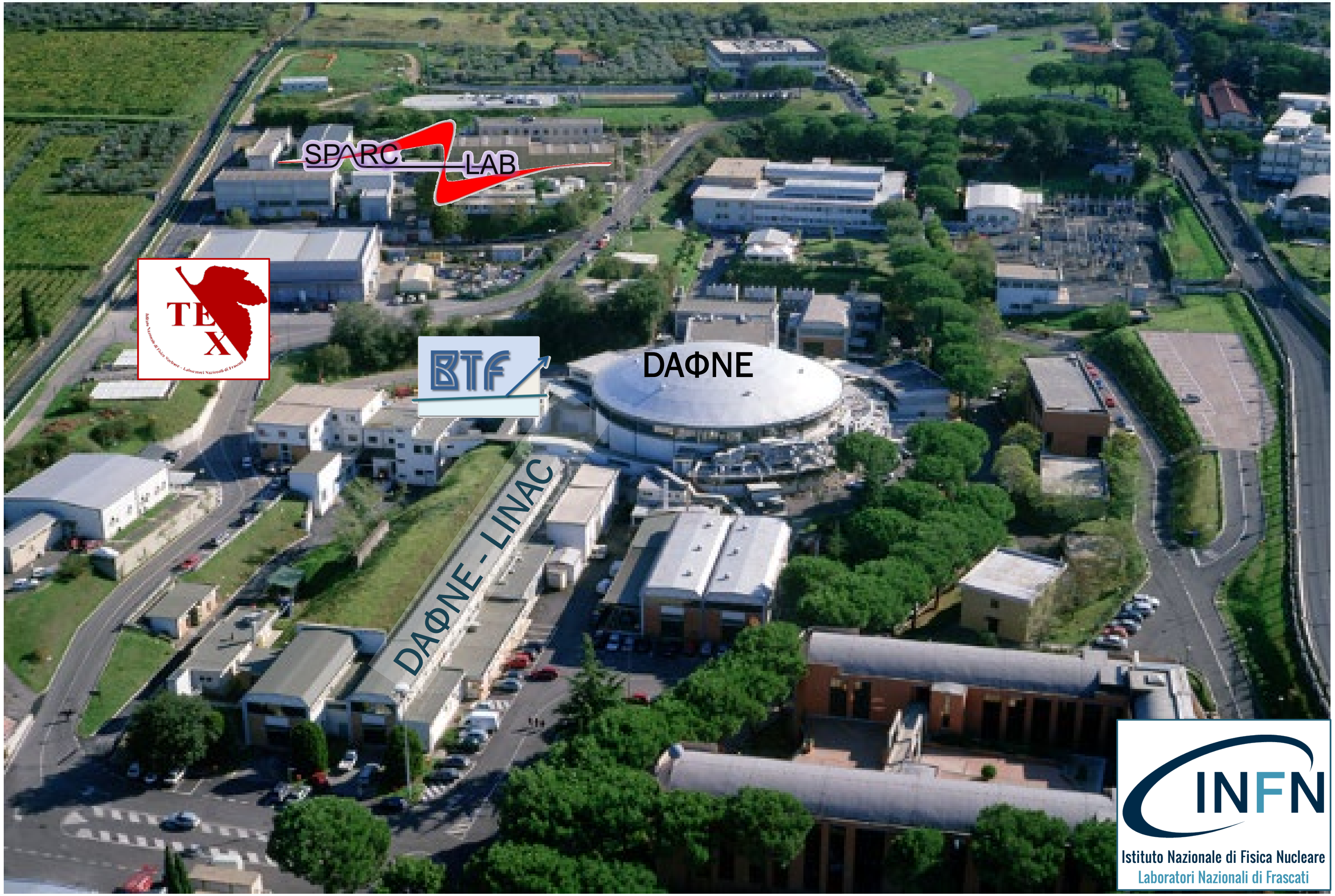
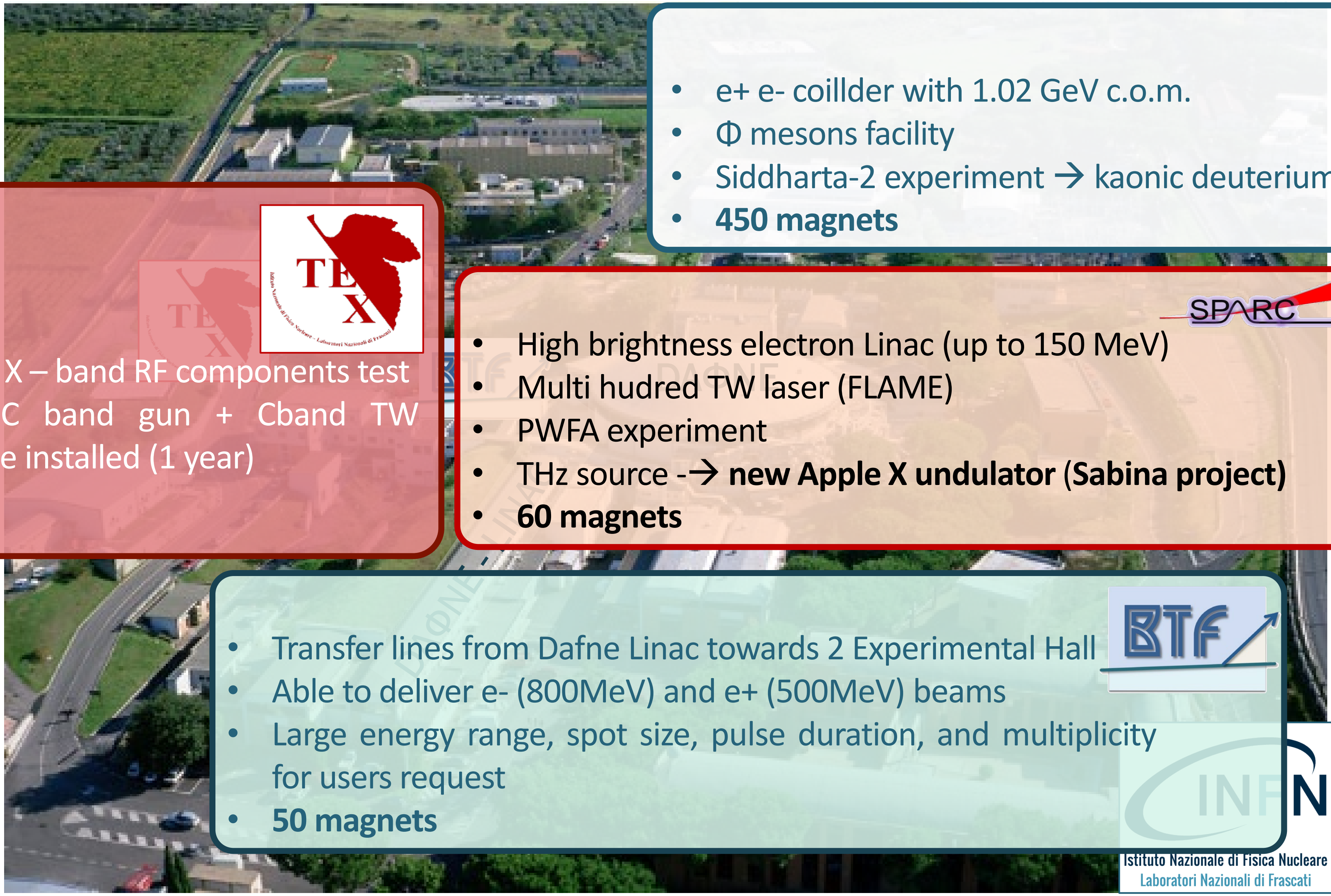
Accelerator Division – Head of Electric Engineering Service

Frascati National Laboratories



Frascati National Laboratories



DAΦNE

- e+ e- coillder with 1.02 GeV c.o.m.
- Φ mesons facility
- Siddharta-2 experiment → kaonic deuterium measurements
- **450 magnets**

TEX

- Test Facility for X – band RF components test
- **Fringe Linac** C band gun + Cband TW structure will be installed (1 year)
- **10 magnets**

SPARC LAB

- High brightness electron Linac (up to 150 MeV)
- Multi hudred TW laser (FLAME)
- PWFA experiment
- THz source -→ **new Apple X undulator (Sabina project)**
- **60 magnets**

BTF

- Transfer lines from Dafne Linac towards 2 Experimental Hall
- Able to deliver e- (800MeV) and e+ (500MeV) beams
- Large energy range, spot size, pulse duration, and multiplicity for users request
- **50 magnets**

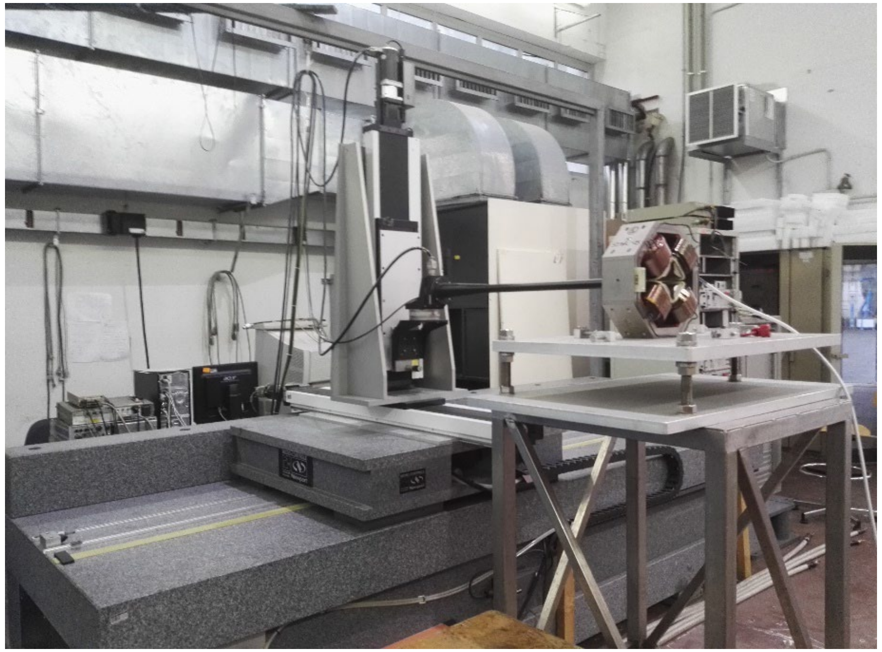
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Frascati National Laboratories

- X - band linac + Plasma acceleration of e- up to 1,2 GeV
- Soft X ray FEL driven by the linac
- **80 magnets**

LNF Magnetic Measurements Background and Upgrade

- From early 1990s the Magnetic Measurement Lab performed deep magnetic characterization for various projects including the DAΦNE collider, the Beam Test Facility and the SPARC_LAB linear accelerator of LNF, CNAO.
- Equipment included a Hall probe Bench (Digital movement system of Microcontrole + Group 3 Hall probe), Rotating coil Multipole Measurement System "Model 692" (DANFYSIK) and a NMR (Metrolab).
- 2010 to 2016 there was a “freezing” of lab measurement lab due to facilities run and no request of new measurement from internal and external users. The activities of the group was oriented towards the power supplies maintenance



Magnetic Measurements Upgrade Pillars

- From 2016 LNF facilities required several magnets upgrades
- The instrumentation was old and needed a deep revamping to face new projects and to keep the laboratory up to date with current technologies in the magnetic measurement scenario
- The EuPRAXIA magnets requirements have been almost defined. A Magnetic Measurement Lab will be crucial for their validation after the FAT.

- Project, supported by "Regione Lazio" (Regional funds)
- Magnetic measurements laboratory as part of an open **research infrastructure aimed to support industries** and the scientific community
- Rotating coil system (prototype with CERN)
- Single Stretched Wire (purchased from ESRF)

Innovative Research Infrastructure on applied Superconductivity
IRIS

- Goal: create a distributed infrastructure for applied superconductivity)
- INFN-LNF pole is in charge to provide magnetic measurement to test superconducting coils and magnets at **room temperature**
- 3D hall probe mole system,
- Pulsed wire bench,
- DC power converters
- Probe calibration system
- New the linear stages of the current Hall probe bench
- Mezzanine to gain and optimize the space inside the lab

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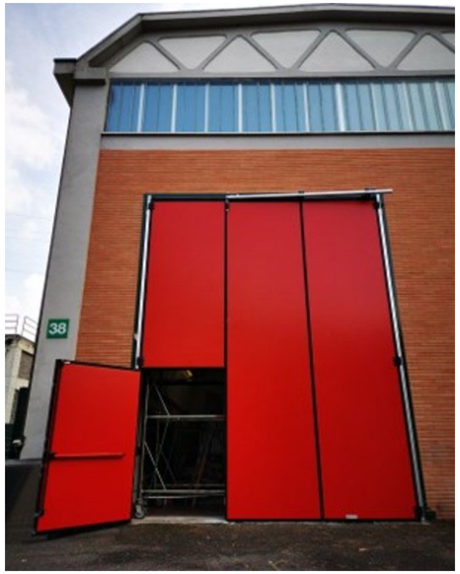
LNF Magnetic Measurements Facility



INFRASTRUCTURE

- 20x10 m hall footprint
- 20 T crane able to lift loads up to 5,5 m from the ground
- Dedicated Dry cooler. Secondary circuit able to deliver up 60 l/min demineralized water flow at a maximum pressure of 8 bar
- Maximum electric power available 430 kVA.
- Mezzanine design finalized, building will start since early 2025.

STAFF

- 2 Technologists
- 1 Post doc
- 6 technicians

SERVICES

- Room temperature magnet design
- Support for CAD design
- Procurement
- Magnetic Measurements
- Test of PS
- PS and Magnets Maintenance & Repair
- Spare

Equipment – Hall Probe Bench

MAIN FEATURES	
Positioning accuracy for linear stages	< 10mum
Positioning accuracy for angular stages	< 10mdeg
X axis max throw	3000 mm
Y axis max throw	500 mm
Z axis max throw	250 mm

PROBES	
CURRENT: Group 3 MPT 141 (1-axis)	Range up to 3 T Resolution 0.1 mT Accuracy ±0.01% of reading + 0.006% of full scale
FUTURE: MetroLab THM1176MF (3-axis)	Range up to 3 T Resolution 0.1 mT Accuracy ±1 % of reading or resolution

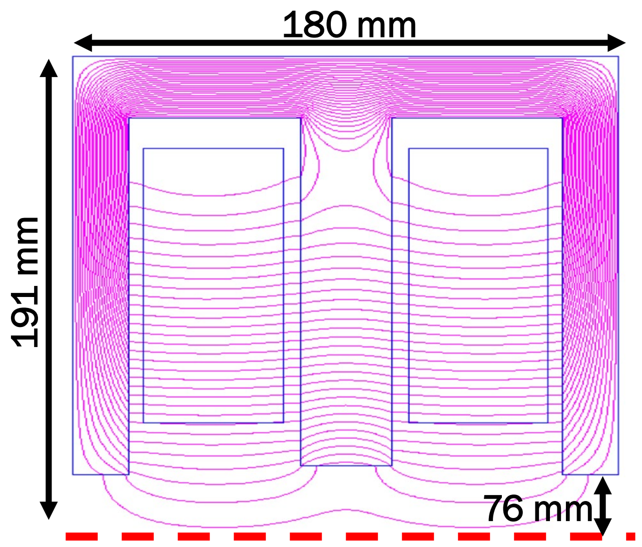
A high precision instrument for field mapping by moving the Hall probe along six axes (the 3 Cartesian axes and the 3 pitch, roll, yaw angles)

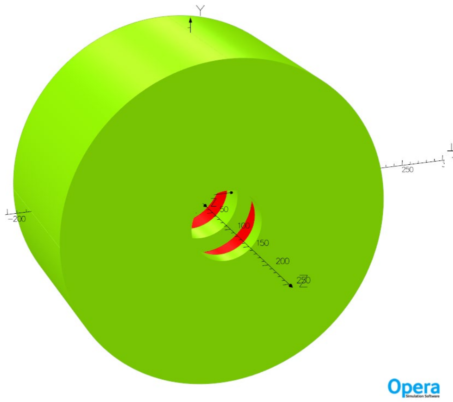
- 3-meter-long granite bench (x-axis on a compressed air system)
- Several aluminum Hall probe holders have been designed internally by LNF staff with 30 and 25 mm outer diameter.
- Motion Control unit NewPort XPS
- DAQ with NI boards and LabvView dedicated VIs

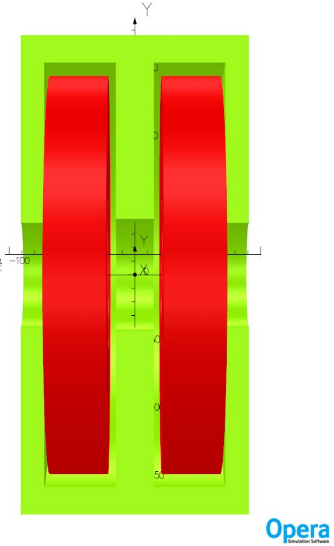
UPGRADES

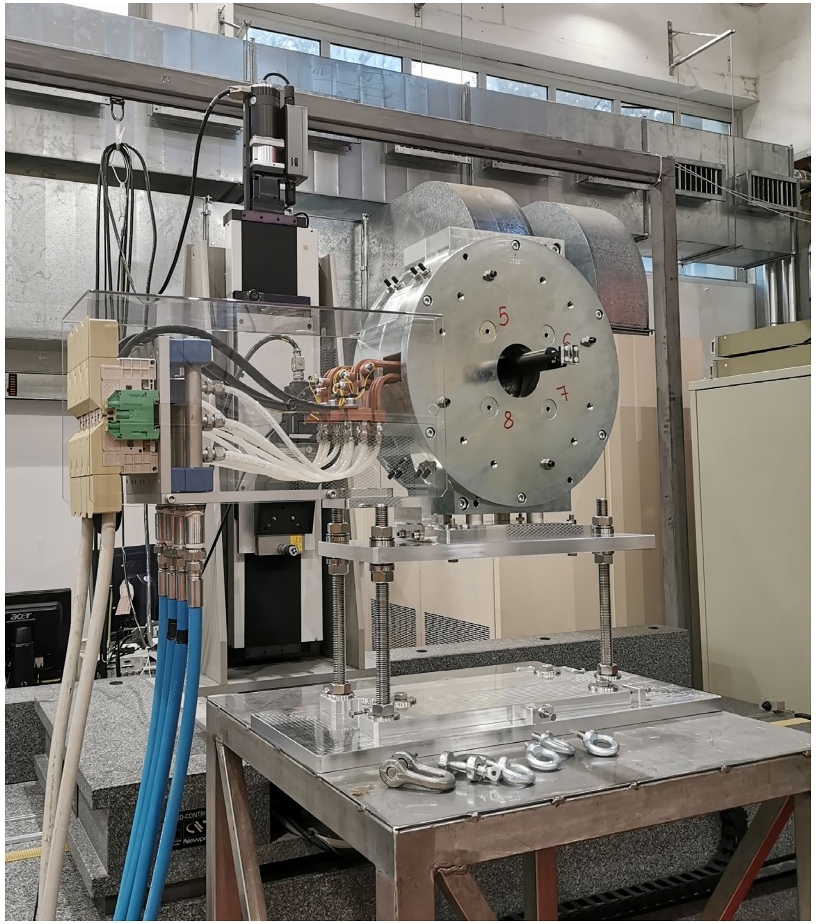
- replacing the motorized linear and rotational stages
- New XPS controller
- replace the 1 axis Hall probe with a 3-axis one
- additional thinner carbon fiber (ϕ 20mm), probe holder, for small gap magnets.

SPARC_LAB Gun Solenoid Measurement – Hall Probe Bench









Solenoid for SPARC_LAB S-BAND GUN on the hall probe measurement bench at LNF

	Unit	Simulated	Required
Bmax in ++ config.	G	3943	
Bmax in +- config.	G	3629	
Yoke Material	-	Steel 37	
IB	Tm	0,0626	≥0,062
IFQ	-	4E-5	<5E-4
Good Field region: radius	mm	30	
FS on axis in +- config.	T^2m	0,0155	≥0,0150
Bmax on cathode	G	8,5	≤15G
COIL SPECIFICATIONS			
Number of Turns per coil	-		
Conductor dimension	mm	5x5 / bore 3	
Cooling water pressure drop	bar	3	≤3
Cooling water flow rate	l/min	4.2	
ΔT cooling water	°C	25	≤30
ELECTRICAL INTERFACE			
Nominal current in ++ /+- config.	A	182/192	
Nominal Voltage (2 coils in series)	V	35	
Inductance (Total)	mH	17	
Resistance (Total)	mΩ	191	

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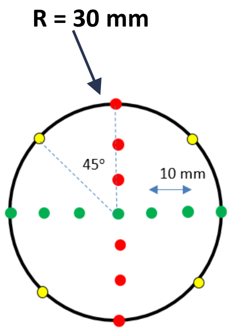
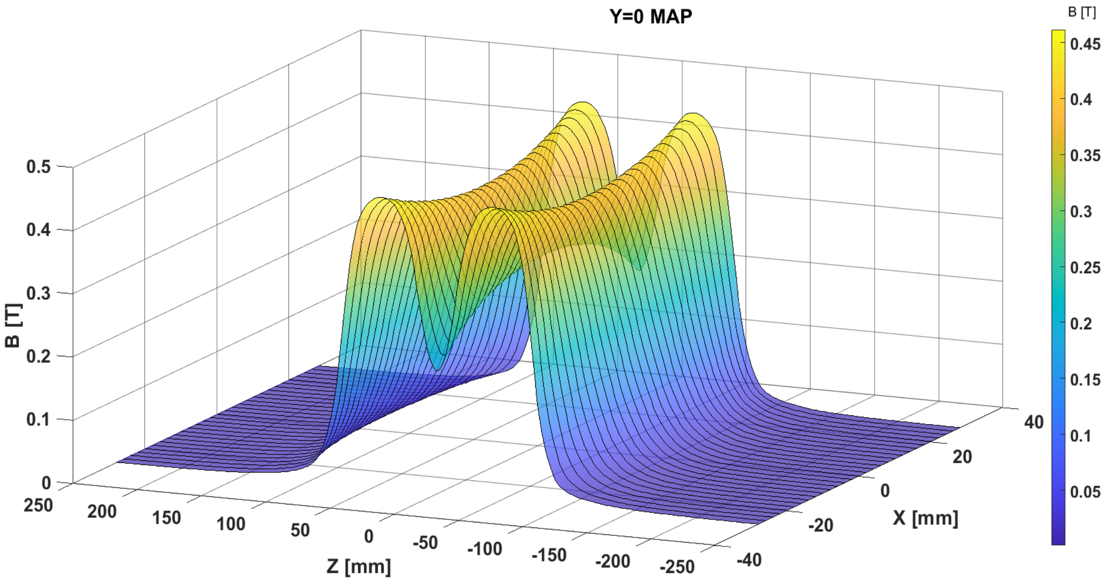
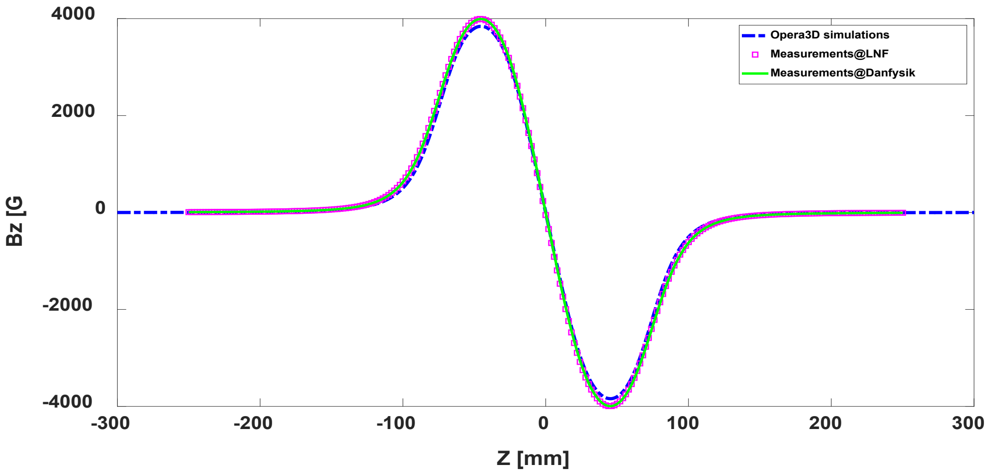
SPARC_LAB Gun Solenoid Measurement – Hall Probe Bench

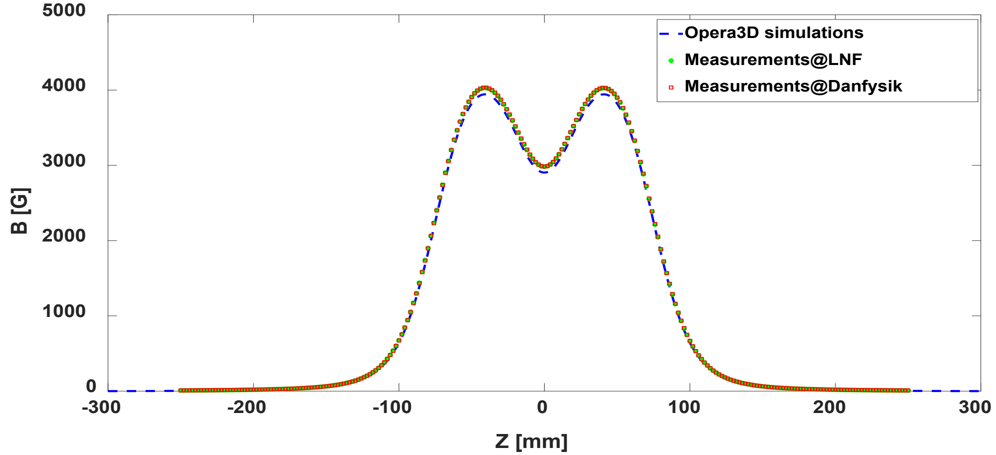




Measurements performed at Danfysik on the solenoid horizontal plane paths (green dots)

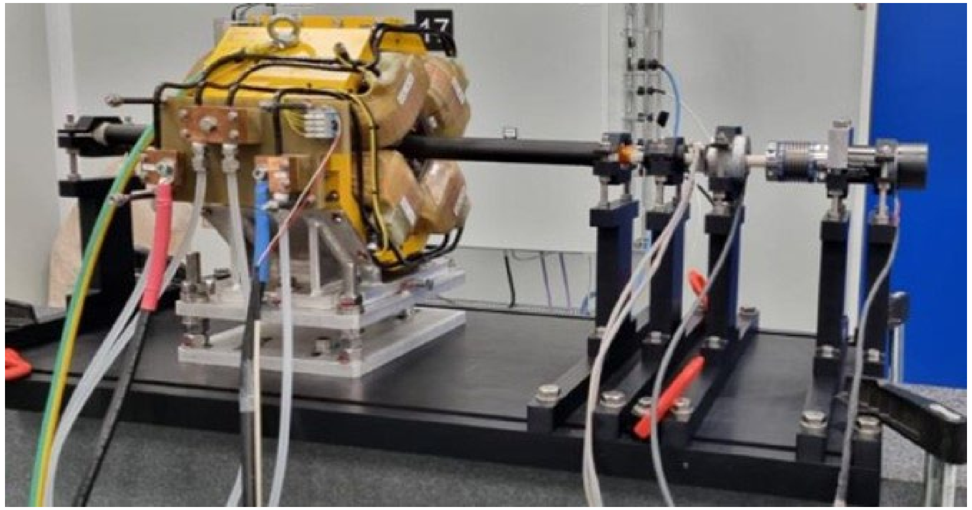
	Requested	Danfysik F.A.T.	LNF meas.
IB on axis [T m]	0.0620	0.06200	0,06195
FS on axis [T^2 m]	0.0155	0.0150	0,0150
IFQ	5.00E-04	2.01E-04	2,01E-04





- F.A.T. at Danfysik included: 3D mapping of Bz on several trajectories, Excitation curve, Dimensional check and Coil test (electric and hydraulic).
- Magnetic measurement at LNF for misalignment check included a 3D mapping on few trajectories measured in the F.A.T.
- Danfysik and LNF meas. fit → NO misalignment due to shipment
- Measurements show higher integrated field w.r.t. magnetic design → stronger focusing

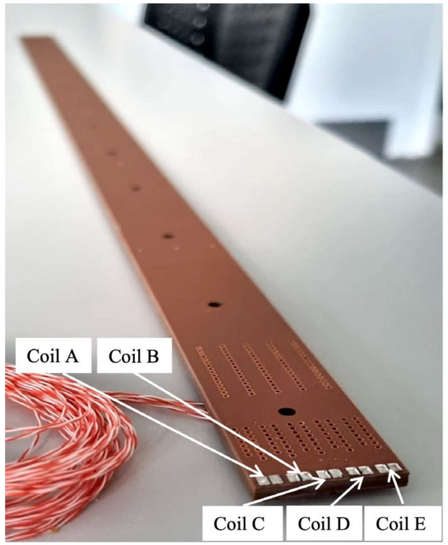
Equipment – Rotating Coil Bench



CERN-INFN design (collaboration agreement KR4708/TE)

- Optimization for small-bore multipole magnets
- PCB magnetometer (5 coils, 256 turns each) calibrated with a Quadrupole of LNF—BTF according to in-situ calibration [1, 2]
- Carbon fiber tube, 26 mm external diameter, 620 mm length tailored to EuPRAXIA quads preliminary requirements.
- Tailored design of PCB could be done depending on the magnets' features
- Commercial DC brush-less motor, high-resolution incremental encoder, slip-ring, data acquisition system, open-source software based on LabView (DAQ & mot. Control) and Mathlab (data analysis)
- First prototype tested
- A new design performed by INF is ongoing:
  - Adjustable distance between ball bearings
  - Reference for shaft rotation axis wrt the magnet

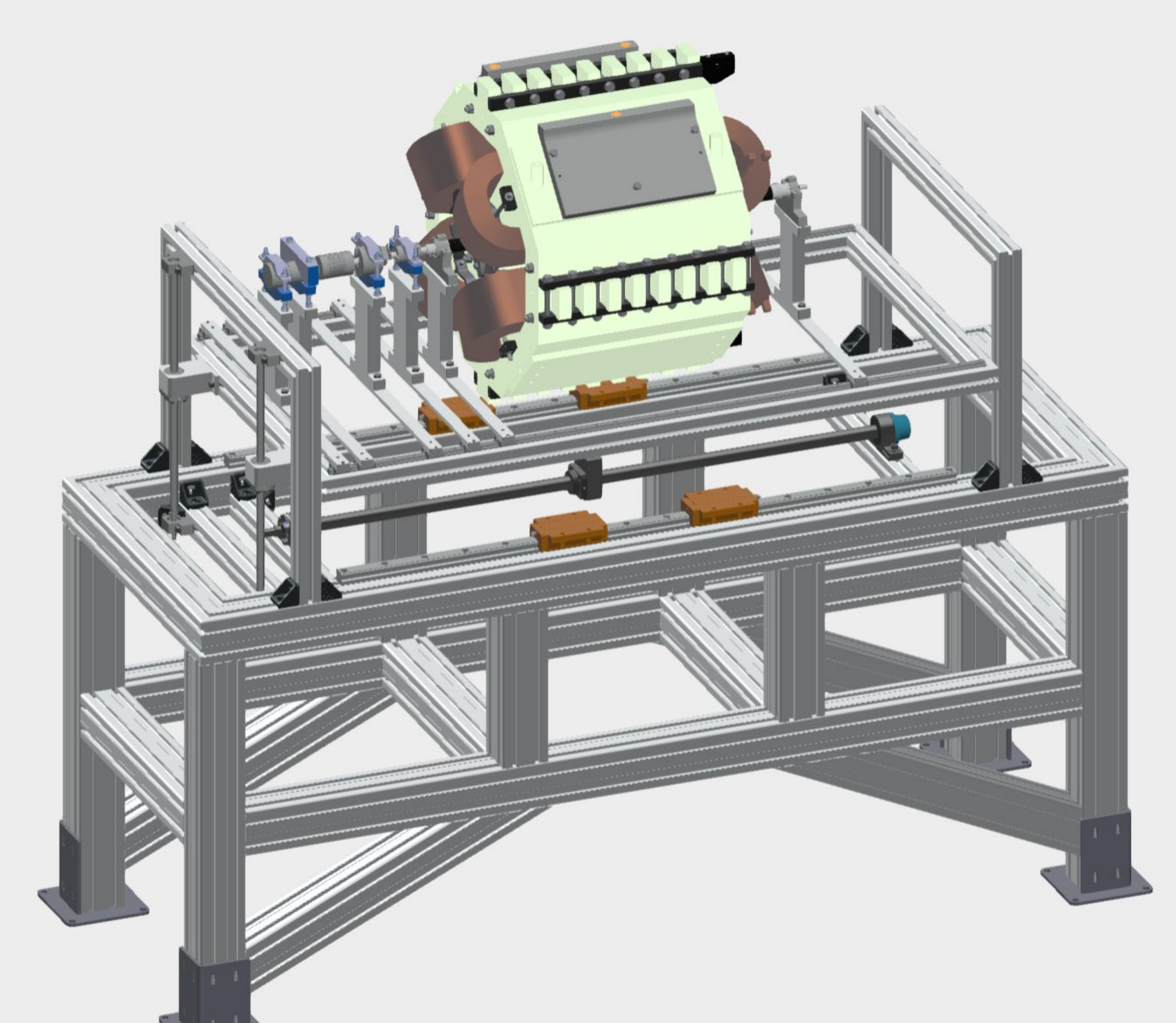
MAIN FEATURES	
Main integrated gradient	
Absolute accuracy	50 ppm
repeatability	10 ppm
High order compensated harmonics	
Accuracy	100 ppm
repeatability	10 ppm



[1] Arpaia, Pasquale, et al. "In-situ calibration of rotating coil magnetic measurement systems a case study on Linac4 magnets at CERN." 17th Symposium IMEKO TC4, Kosice, Slovakia. 2010.
[2] A. Lauria, et al. "Rotating-coil measurement system for small-bore-diameter magnet characterization." Sensors 22.21 (2022): 8359.

Very special thanks to Marco Buzio, A. Lauria, M. Pentella and all the CERN staff

Equipment – Rotating Coil Bench



Courtesy of E. Di Pasquale

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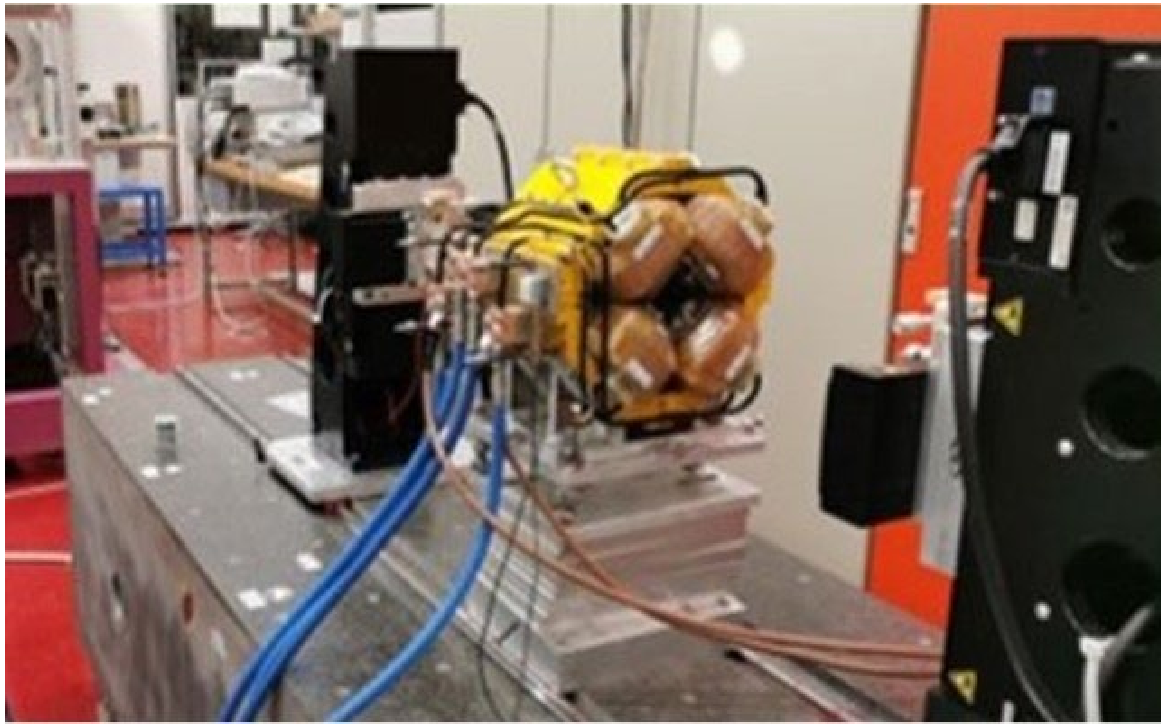
Very special thanks to Marco Buzio, A. Lauria, M. Pentella and all the CERN staff

Equipment – Single Stretched Wire

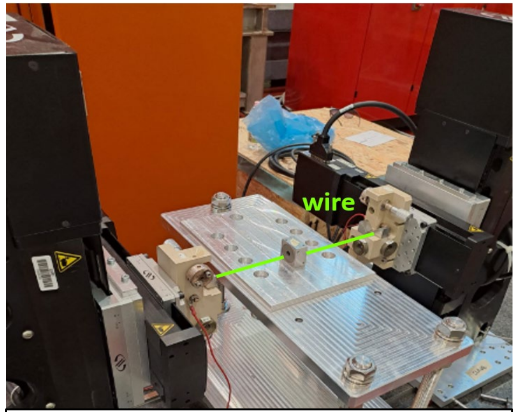
- Developed and constructed by ESRF [1]
- Delivered at LNF in October 2019
- 100 µm titanium wire
- four Newport linear stages for vertical and horizontal translations on both sides, guided by an XPS controller, for wire movement.
- Keitley 2182 nano-voltmeter for measuring the voltage induced
- acquisition with a NI board, data analysis with IGOR-based sw
- field multipole errors accuracy: few 10^{-4} of the main multipole (thanks to compensations of multipoles similar to bucked rotating coil system)
- integrated field precision depends on the measurement configuration and magnet parameters.



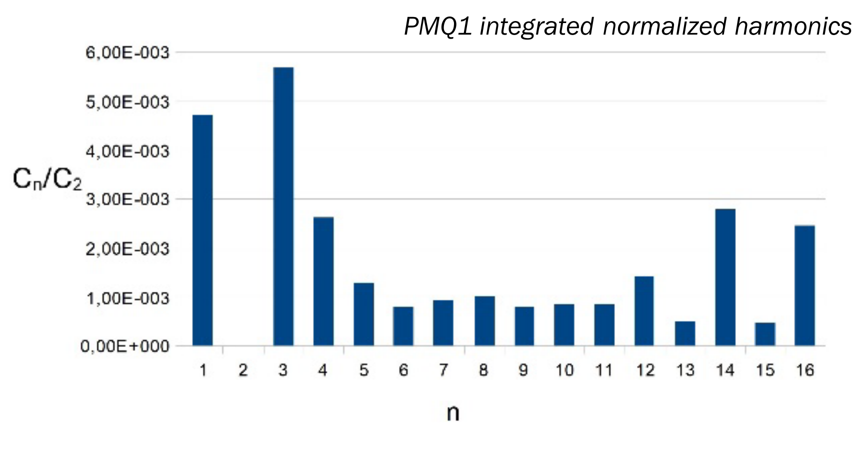
Typ. repeatability		
Magnetic center position	2	µm
Pitch and yaw angles	0.1	mrad
Roll angle	0.1	mrad
Integrated field	0.2	G m

[1]G. Le Bec, et al. "Stretched wire measurement of multipole accelerator magnets." Physical Review Special Topics—Accelerators and Beams 15.2 (2012): 022401.

SSW Measurement - PMQ for PWFA@SPARC_LAB



A "long" type PMQ (PMQ1).



PMQ SPECIFICATIONS		
Parameter	**Short PMQ**	**Long PMQ**
Quantity	2	4
Integrated Gradient	5 T	10 T
Magnetic Length	10 mm	20 mm
Inner/outer diameter	8/30 mm	8/30 mm
FQ*	<1E-2	<1E-2
B_r	1.32 T	1.32 T
PM Blocks Material	NdFeB	NdFeB

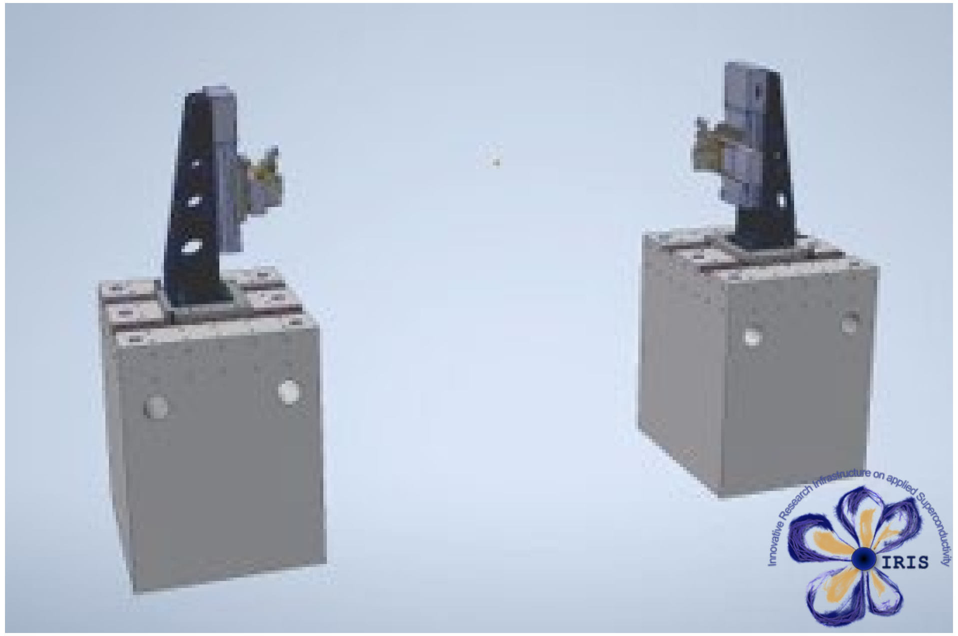
- Six new PMQs have been installed @ SPARC_LAB facility for e- beam focusing for PWFA application
- The PM blocks have been assembled by VACUUMSCHMELZE GmbH & Co but they we not characterized.
- **10 measurement for each PMQ** have been performed with SSW bench following these parameters:
  - Circumference radius 2 mm
  - Sampling time 20 ms
  - N sample/turns 8
  - Wire velocity 5,24 mm/s
  - Integration time 15 ms

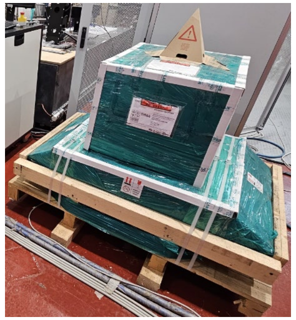
MEASUREMENTS RESULTS				
	PMQ type	Int.Grad [T]	Maximum Mulitple component	Roll ang. [mrad]
PMQ1	Long	7,81±0,01	n=3 ; 6.0E-3	10,9±0,3
PMQ2	Long	7,72±0,01	n=3 ;1.3E-2	7,6±0,1
PMQ3	Long	7,84±0,01	n=4 ; 2.5E-3	1,8±0,3
PMQ4	Long	7,77±0,01	n=3 ; 7.0E-3	25,3±0,1
PMQ5	Short	3,84±0,01	n=2 ; 4.5E-3	24,3±0,2
PMQ6	Short	3,87±0,01	n=2 ; 4.5E-3	5,3±0,1

Equipment – Vibrating Wire Bench

A vibrating wire bench is currently under design.
Main features:

- Two separate granite pillars to accommodate various magnet geometries, offering adaptability in the longitudinal direction.
- Pillars are equipped with pivoting wheels for easy movement and alignment.
- Each pillar has horizontal and vertical stages (Newport, the same of SSW), to support the wire tensioned along the magnetic axis of the magnet.
- Newport XPS for motion control
- Keysight electronics: pulse generator, voltage analyzer
- Optical elements for wire position transduction.
- The definitions of the electronics and optical elements is ongoing basing on the performance described in [1].
- *We are looking for a control, DAQ and data analysis SW already available→ companies? collaborations?*
- The granites pillars have been already delivered.



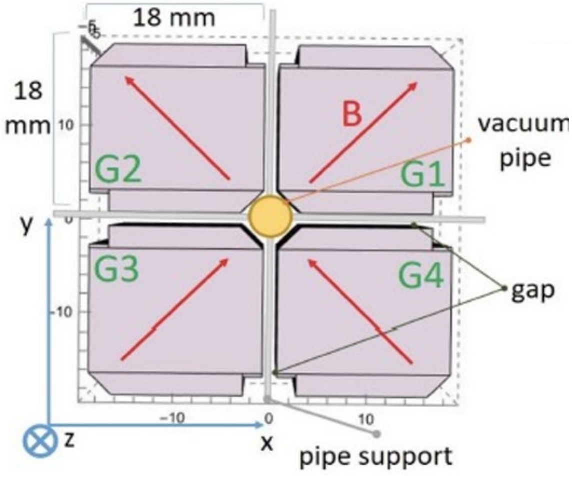


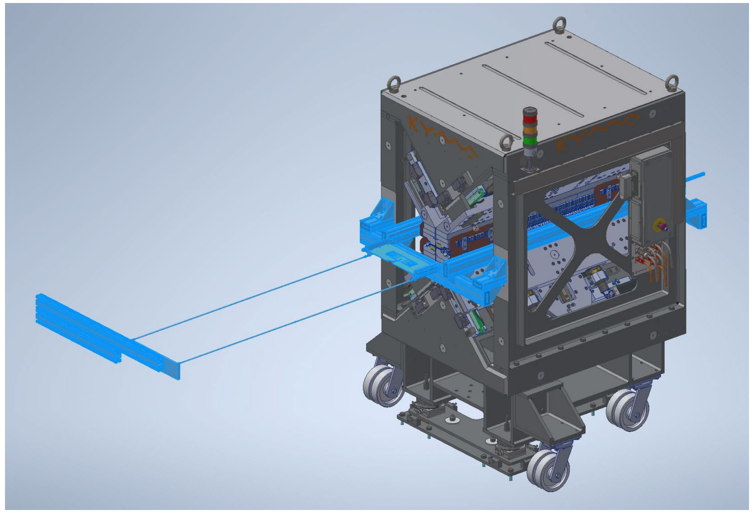
[1] P. Arpaia et al., “Advances in stretched and oscillating-wire methods for magnetic measurement”, 9th International Conference on Sensing Technology ICST), Auckland, New Zealand, 2015, pp. 555-559. doi: 10.1109/ICSensT.2015.7438460

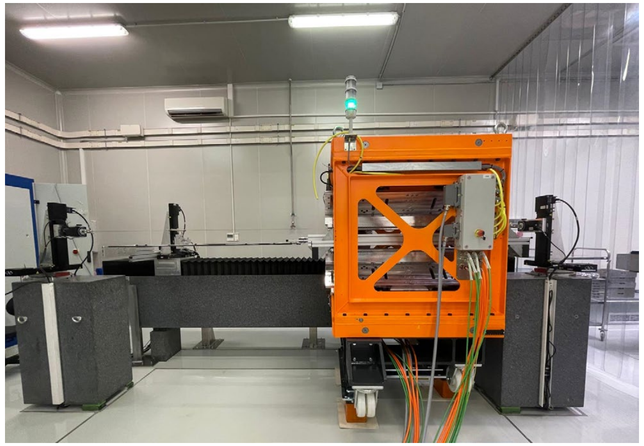
Equipment – Hall Probe Mole System

- A Hall probe mole measuring system is currently under development with KYMA company that already built a similar system for SPARC_LAB Apple X undulator.
- It is designed for field mapping of small gap magnets (i.e. undulators) and coils.
- It will be fully integrated into the existing Hall probe bench
- A compact 3-axis Hall probe, mounted on a thin mechanical support (thickness possibly within 2 mm). → **looking for supplier**
- Keysight digital multimeter
- These requirements could be feasible with the Apple X AQUA Eupraxia Undulator proposed design **(pipe ext. diameter 5,6 mm)**

Courtesy of A. Petralia
F. Nguyen

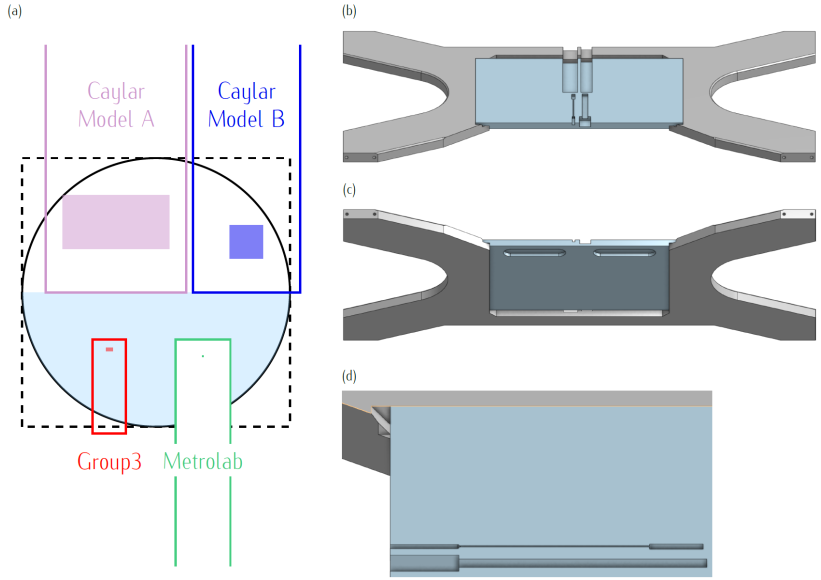




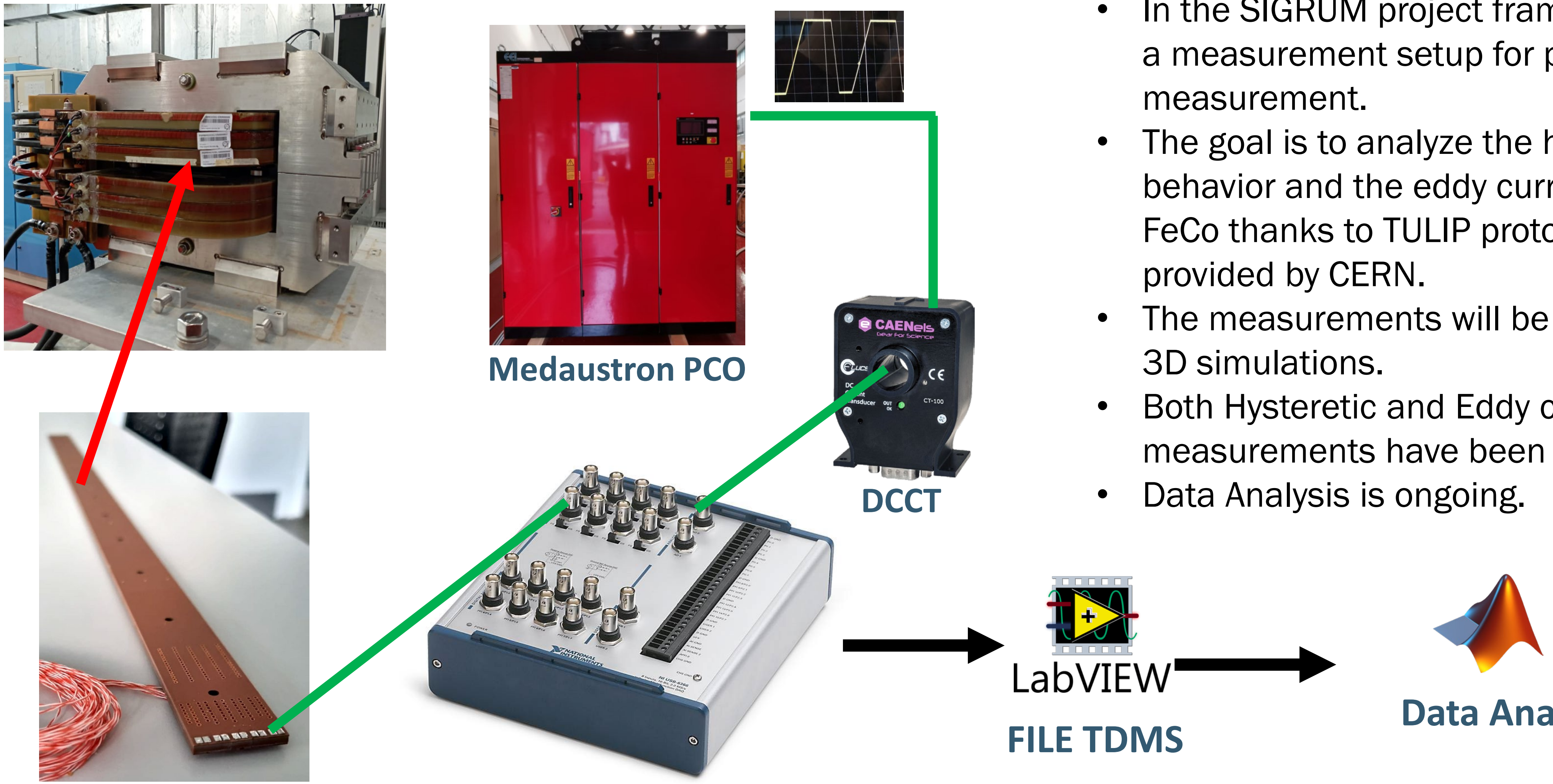


Equipment – Probe Calibration System

- The laboratory will be equipped with a reference system to calibrate probes and validate measurements.
- The design and manufacturing of the system has been awarded to Caylar S.a.S. Delivery is expected in February 2025.
- The system is composed by a 2 T dipole, with a **30 mm gap** and a **0,02% field homogeneity** over a volume of15x15x15 mm3.
- Also included in the system are the 4-quadrant power supply with 10ppm stability,
- 3 NMR probes to cover the range from 20 mT to 1.8 T and the related gaussmeters for readout.
- 20 mT – 100 mT
- 80 mT – 400 mT
- 360 mT – 1,8 T
- A future upgrade of the system involves the availability of a thermal chamber for calibration at variable T.



Equipment – Search Coil for Pulsed Measurements



- In the SIGRUM project framework we've set a measurement setup for pulsed measurement.
- The goal is to analyze the hysteretic behavior and the eddy currents effects on FeCo thanks to TULIP prototype dipole provided by CERN.
- The measurements will be compared with 3D simulations.
- Both Hysteretic and Eddy currents measurements have been completed
- Data Analysis is ongoing.

Power Supplies and Other Equipment

Model	Specs	QTY
NGPS 200-50 + PI	200 A 50 V (10 kW)	2
POLARITY INVERTER (PI)	420A	1
NGPS 100 -100	100 A 100 V (10 kW)	1
FAST PS 2040 -600	±20 A ±40 V (600 W)	1
FAST PS 3020-600	±30 A ±20 V (600 W)	1
PS EASY DRIVER 1020	±10 A ±20 V (200 W)	6
HAZEMEYER HH	750 A 432 V (324 kW)	1

- Several new DC PSs have been purchased to cover a wide range of magnets. (up to 750 A – 320 V)
- Metrolab 3D Hall probe THM1176-MF:
    - 4 measurement ranges from 0.1 T to 3.0 T
    - Accuracy up to 50 μT (0.5 Gauss) or ±0.5% up to 1.5 T
- Resolution 2 μT without averaging
- Oscilloscope Rohde & Schwarz RTM3002 10 bit ADC 5GSa/s
- KEYSIGHT 34461A 6 ½ Digit Multimeter
- LCR Meter 10Hz – 2 kHz Teledyne

Conclusions

- After several years, the INFN – LNF Electrical Engineering Group came back to magnet design and magnetic measurements activities.
- Internal facilities upgrades and the need to keep the laboratory up to date with current technologies in the magnetic measurement scenario , lead to a deep revamping of the infrastructures and the equipment.
- Co-funded projects like **LATINO** and **IRIS** allows to start the update phase.
- Part of the equipment has been purchased but a relevant part of the equipment procurement phase is still ongoing
- The performances of the instrumentations have been defined according to the preliminary EuPRAXIA magnets requirements and in the optics of high flexibility also for external users.
- The end of the equipment procurement and of the infrastructure work is **estimated within the end of 2025 / beginning 2026.**
- The driver of this revamping is to raise up INFN-LNF laboratory as a key provider magnetic measurement for the whole INFN and to give a support for the whole scientific community.

	DESIGN	TECH. SPECS	ORDER PLACEMENT	MANUFACTURING	F.A.T.	DELIVERY
Hall Probe Bench Revamping						
Rotating Coil Bench Prototype						
Rotating Coil Bench Definitive Bench						
Single Stretched Wire Bench						
Vibrating Wire Bench						
Hall Probe Mole System						
Probe Calibration System						
Search Coil for Pulsed Meas.						
PS & Other Equipments						
Mezzanine and Space Organization						

Thank you for the attention

Special thanks to Electrical Engineering Group staff and to our Collaborators

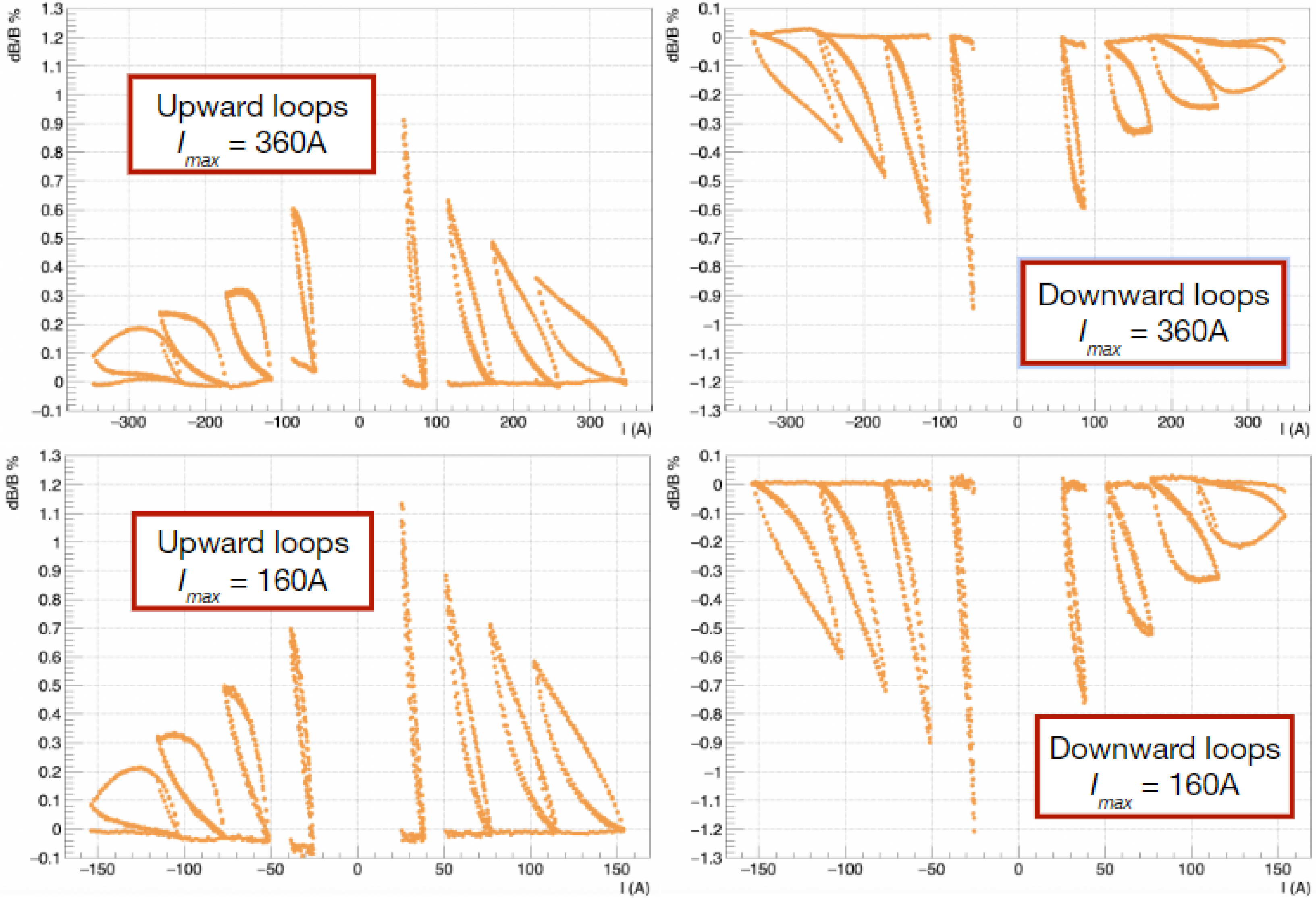
Lucia Sabbatini   Antonio Trigilio   Andrea Selce   Franco Iungo   Franco Sardone   Gustavo Armenti

Stefano Martelli   Alberto Casamatta   Lucas Capuano   Luca Petrucciani   Davide Cuneo

Innovative Research Infrastructure on applied Superconductivity
IRIS

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Hysteretic Measurements

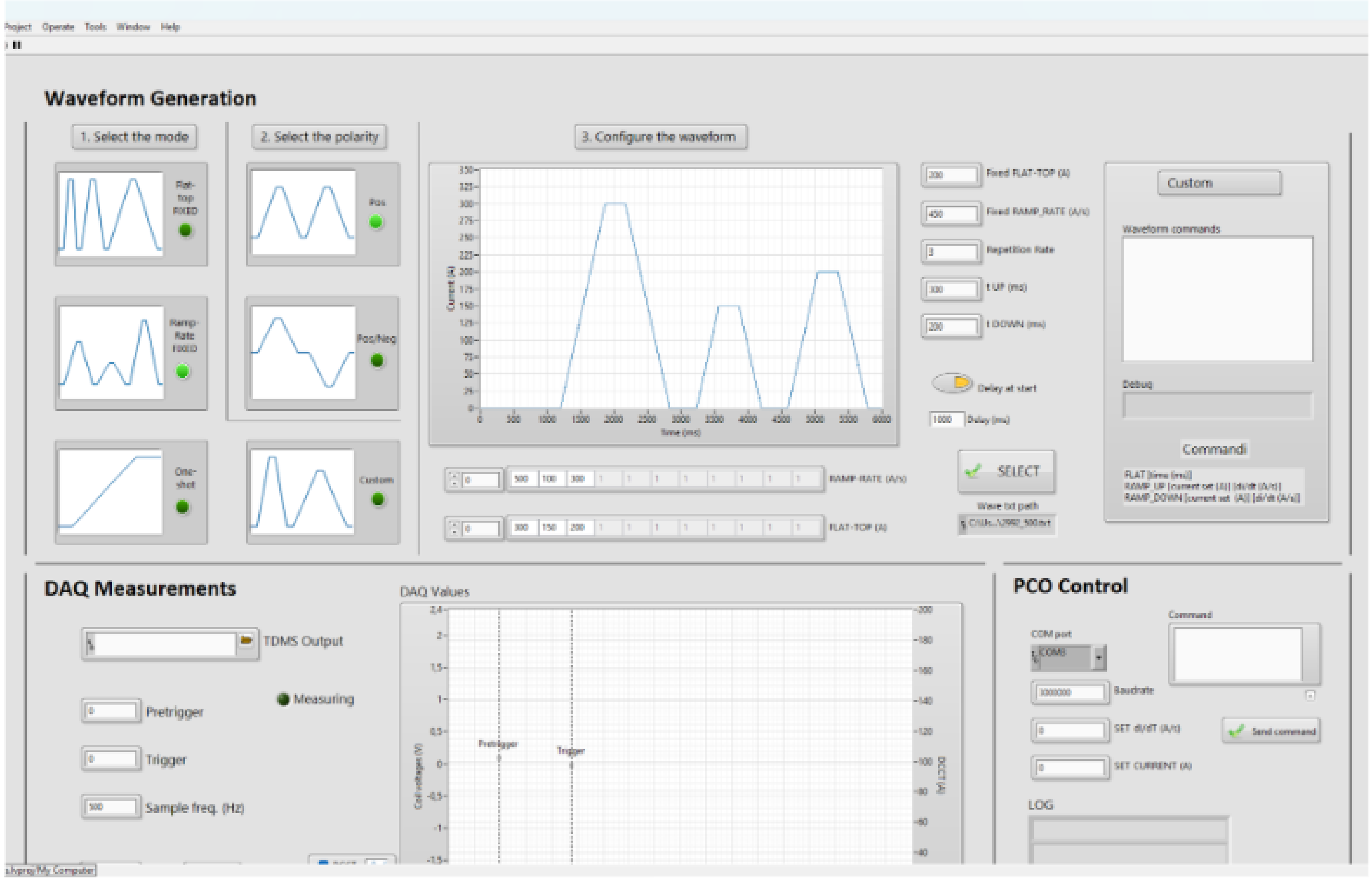


- We perform a fit with polynomial functions of 5th power, which serves as the baseline for comparing the relative differences in magnetic flux during minor (asymmetric) loops.
- As expected the relative difference decreases with field, and the shape depends on the proximity tc the region of greater deviation fron the linear trend.

Parameter	Value
Maximum current	380 A
Central field at max. current	1.81 T
Values of I_{set} for minor loops	80%, 60%, 40%, 20% of $\pm I_{max}$
Minor loop half-amplitude	20% of $\lvert I_{set} \rvert$
Number of steps up/down	16
Ramp rate	40 A/s

Courtesy of A. Trigilio

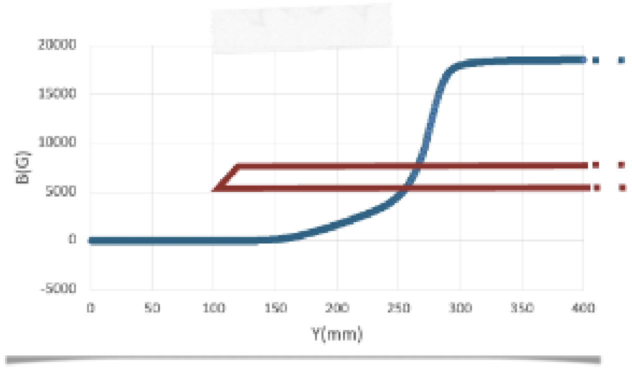
Eddy currents Measurements

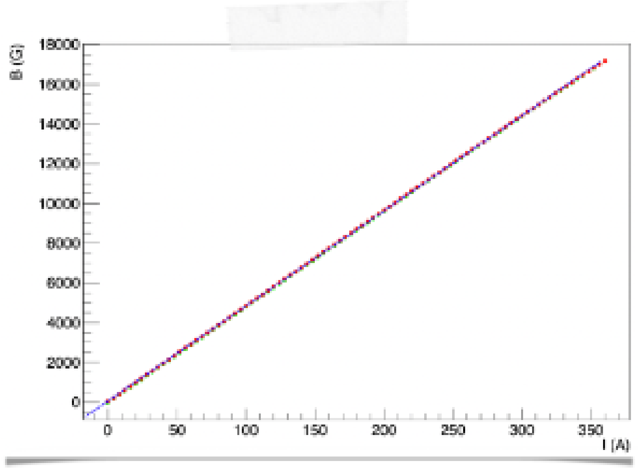


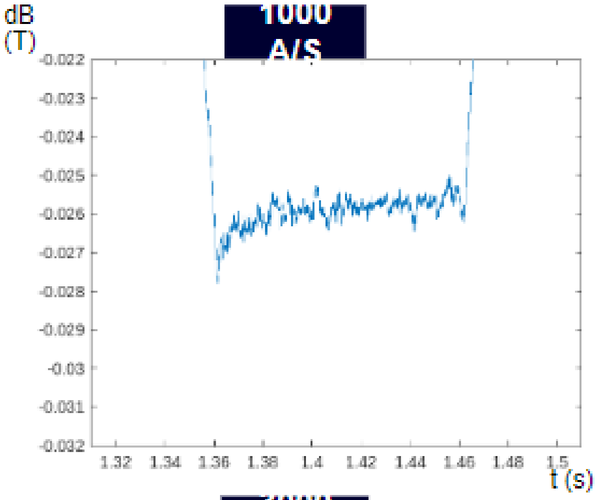
- An interface has been developed (all credits to our technicians) to feed the magnet with current values following customized waveforms.
- Digital filters are used on all signals with 50 Hz cutting frequency. Sampling is performed at 50 kHz.
- Integration is affected by drift due to constant offset of the coil voltages. For this reason, a portion of the waveform is flat and dedicated to calculating the appropriate drift subtraction.

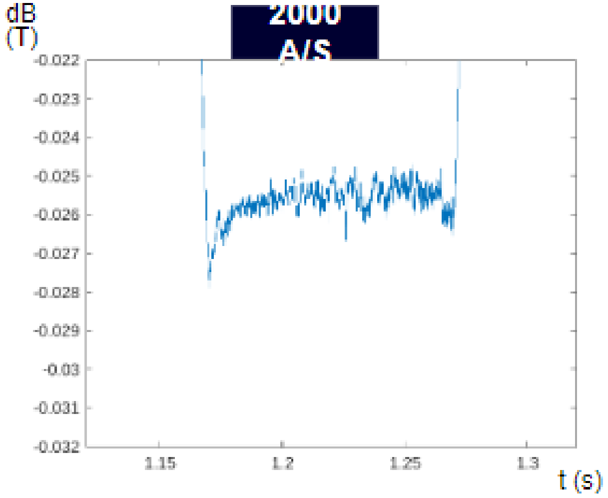
Courtesy of A. Trigilio

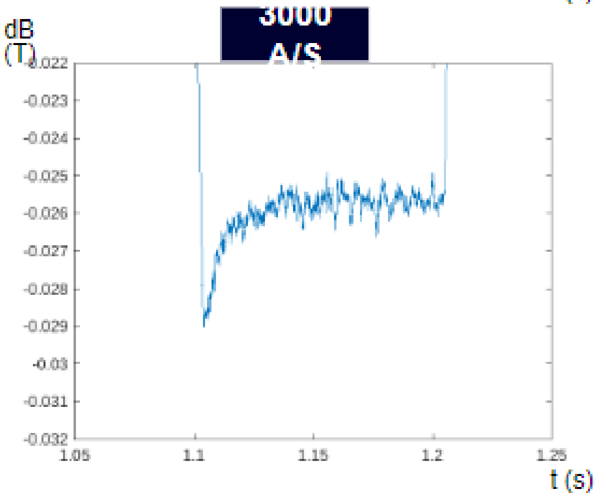
Eddy currents Measurements

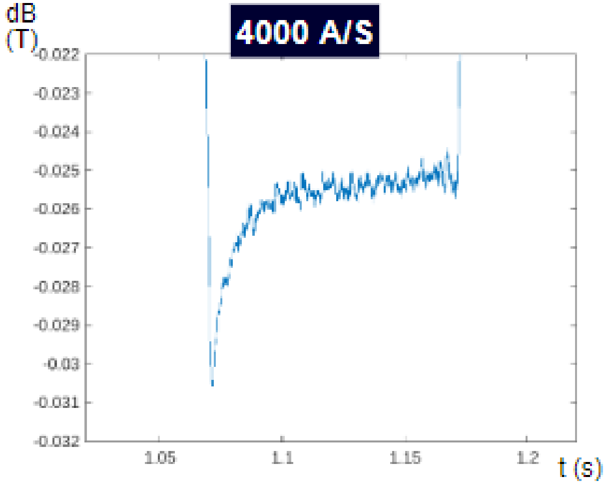












Courtesy of A. Trigilio