EUROPEAN
PLASMA RESEARCH
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APPLICATIONS

EuPRAXIA Preparatory Phase

WP9 – Magnets

Lucia Sabbatini & Alessandro Vannozzi – INFN-LNF

EuPRAXIA_PP Annual Meeting, 23-27.09.2024

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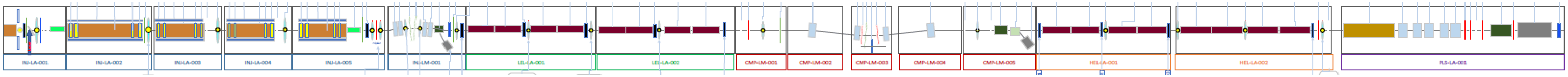
outline

We report the ongoing work of INFN-LNF magnet group on the design of the magnets for **EuPRAXIA@SPARC_LAB**:

- functional layout & list of magnets
- recent experience on the design of:
  - magnets for the gun
  - solenoids
  - permanent magnets for plasma section
  - air dominated steerers
- work in progress on the other magnets
- upgrade of the magnetic measurements laboratory

Functional layout & list of magnets

Funded by the European Union



TYPE	SECTION	QTY	NOTES
SOLEN.	INJ (GUN)	1	
	INJ	4	on acc. sections
DIPOLES	INJ	4	Laser Heater chicane
	CMP	4	Compressor chicane
	PLS	5	Permanent magnets
	INJ/CMP	2	Spectrometers

TYPE	SECTION	QTY	NOTES
QUADRUPOLES	INJ (GUN)	2	normal + skew embedded in sol.
	INJ	4	3 w. steerer
	LEL	3	3 w. steerer
	CMP	8	2 w. steerer
	HEL	6	4 w. steerer
	PLS	5	Permanent magnets

TYPE	SECTION	QTY	NOTES
STEERERS	INJ (GUN)	2	1 w. BPM
	INJ	8	on acc. sects., inside solenoids
	INJ	5	w. BPM
	INJ	3	w. BPM & QUAD
	LEL	3	w. BPM & QUAD
	CMP	2	w. BPM & QUAD
	HEL	4	w. BPM & QUAD

Naming convention:

SECTION SYSTEM FAMILY TYPE SEQ. NUMBER

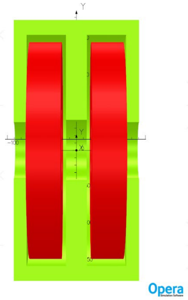
e.g. **HEL-M-QUAD-SHRT-006**

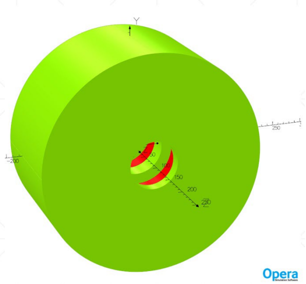
Magnets for the gun

Funded by the European Union

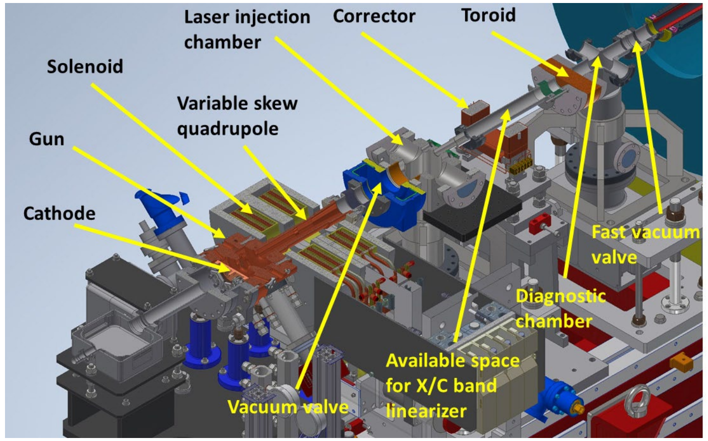
The SPARC_LAB photo-injector has been recently replaced. The new one integrates:

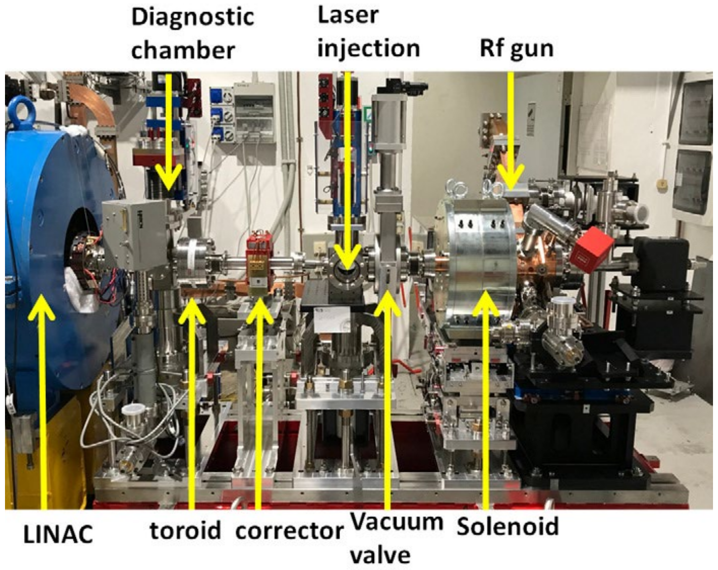
- ✓ a **solenoid** for emittance growth compensation with remote control of the transverse position.
- ✓ a **normal** and a **skew quadrupole** with variable polarity, embedded in the solenoid, for tuning the x-y emittances and compensating for residual transverse beam spot asymmetries.
- ✓ a **corrector** magnet for trajectory optimization and beam energy measurements.





	Simulated
Bmax in ++ Config.	3 943 G
Bmax in +- Config.	3 629 G
Yoke Material	St.37
IB on Axis	0.062 6 Tm
IFQ	4E-5
Good Field Radius	30 mm
FS on Axis in +- Conf.	0.015 5 T^{2m}
Bmax on Cathode	8.5 G
Number of Turns per Coil	136
Cooling	Water cool
Conductor Dim.	5x5/bore 3 mm
Water Pressure Drop	3 bar
Water Flow Rate	4.2 l/min
Water ΔT	25 °C
Nominal Current in ++/+- Config.	182/192 A
Nominal Voltage	35 V
Inductance	35 mH
Resistance	191 mΩ





Alesini D. et al. "The new SPARC_LAB RF photo-injector" 13th Int. Particle Acc. Conf. IPAC2022, doi:10.18429/JACoW-IPAC2022-MOPOMS019
Vannozzi A. et al., "Design and realization of new solenoids for high brightness electron beam injectors", 12th Int. Particle Acc. Conf. IPAC2021

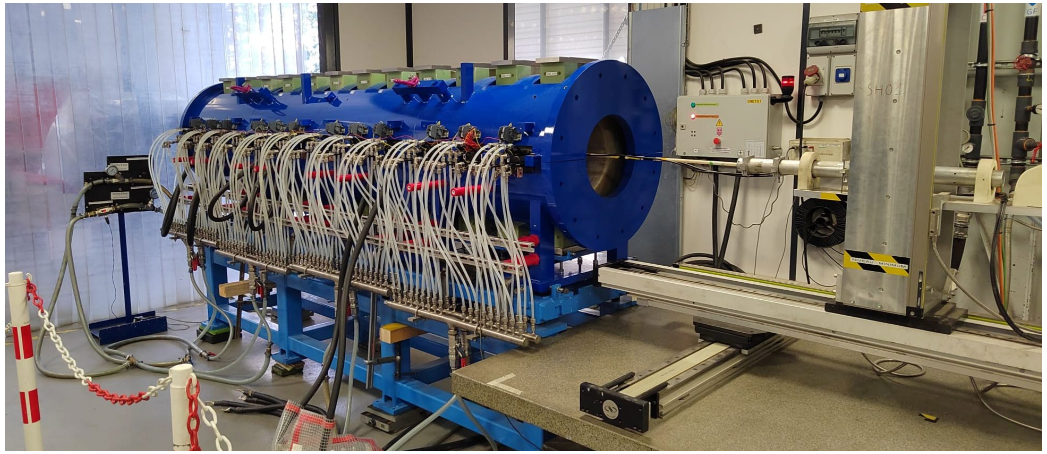
Solenoids

Funded by the European Union

In January 2024 the SPARC_LAB solenoids have been replaced:

- **Solenoids** are designed to surround the first two S-band accelerating structures, where velocity bunching RF compression takes place.
- **Alignment** of the magnetic axis: the required tolerance is 140 μm (i.e. the axis is contained in a cylindrical surface of radius 70 μm relative to the alignment reference frame).
- **Mechanical design**: each one of the 12 coils has a dedicated support for position adjustment and a set of fiducials.
- **Measurements & alignment campaign**: performed at SigmaPhi.

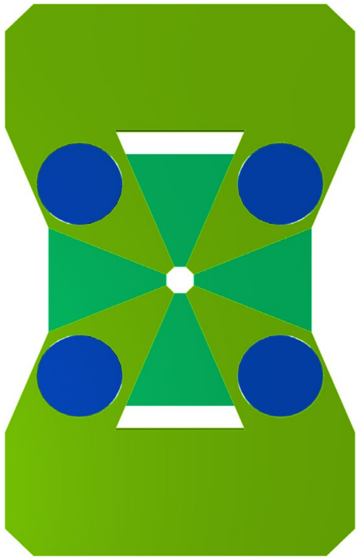
✓ The solenoids are currently working on SPARC and a similar solution is going to be implemented on EuPRAXIA@SPARC_LAB.



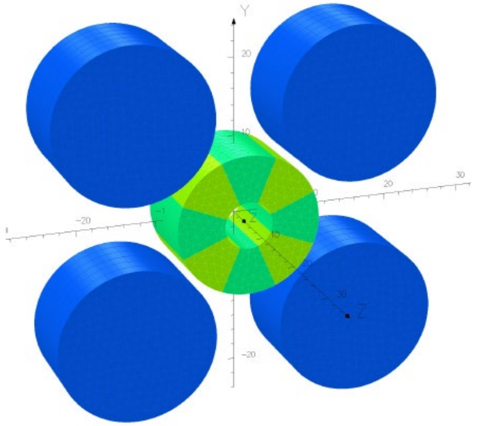
PARAMETER	VALUE	PARAMETER	VALUE
Quantity	2	Maximum current (A)	190
Number of coils	12	Maximum voltage – series of 3 coils (V)	100
Bmax in ++ config. (G)	1800	Inductance – series of 3 coils (mH)	13
Integrated Bz on axis (Tm)	0.5273	Maximum pressure drop (Kpa)	200
Integrated field homog. in ++ config	5E-4	Maximum total water flow (m3/h)	3.6
Good Field Radius (mm)	30	Inlet waer temperature (°C)	32
Length (mm)	3000	Max. magnetic axis misalignement (μm)	70
Max field at 300mm (G)	20		

Permanent magnets for plasma section

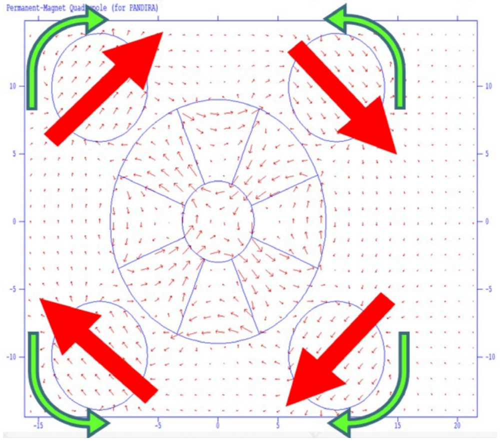
- In the recent past, the magnet design group has deal with PMQs for plasma wake field based experiments at SPARC_LAB test facility.
- For **COMB** experiment, a design of **tunables PMQs** [1] based on an optimization and scaling of QUAPEVA PMQs[2]
- For External-Injection experiment (**EXIN**) proposal at SPARC LAB More challenging requirements in terms of **higher gradients** and **tunability** have been achieved with a new design.
- Both the designs are based on a fixed part of Halbach array and rotating magnetized cylinders who can tune the gradient depending on their angular position.
- This will be the baseline for Eupraxia PMQs for beam injection and extraction from the plasma module



PMQ cross section for EXIN experiment



3D view of PMQ for COMB experiment

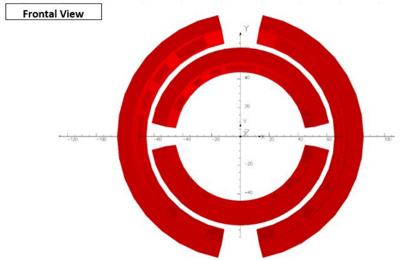


PMQ cross section for COMB experiment

	DESIG FOR COMB	DESIGN FOR EXIN
Grad and tuning	480 ± 50 T/m	270 ± 90 T/m
Internal bore aperture	6 mm	10 mm
Dimensions (WxHxL)	125x200x17 mm	45x45x20 mm

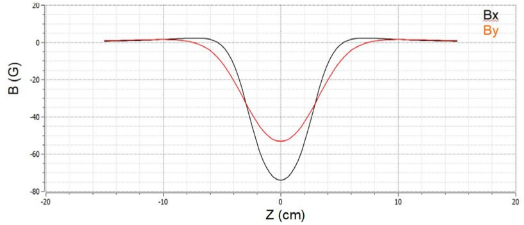
[1] Vannozzi et al. "New Tunable High Gradient Permanent Magnet Quadrupole for Plasma Wake Field Acceleration at SPARC _LAB" 2020 J. Phys.: Conf. Ser. 1596 012009
[2] F. Marteau, et al., Variable high gradient permanent magnet quadrupole (QUAPEVA), Appl. Phys. Lett. 111, 253503 ; doi: 10.1063/1.4986856

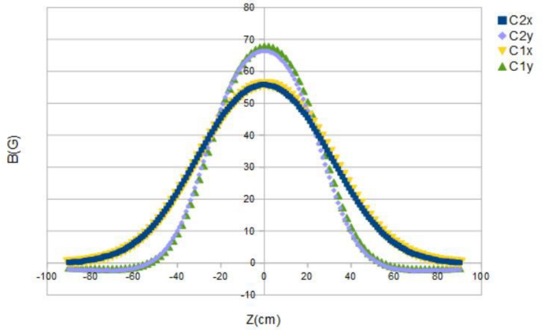
Air dominated steerers

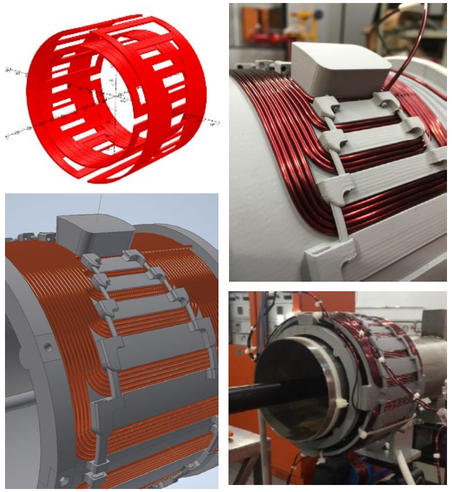


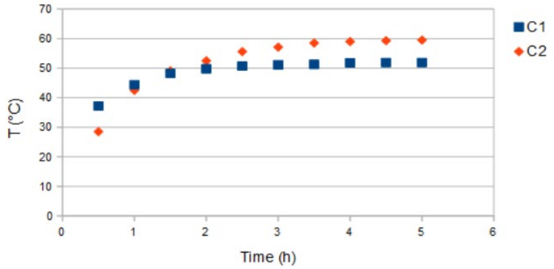
INFN-LNF team has extensive experience in the design, manufacturing and testing of air dominated beam steeres:

- ✓ Magnetic design with Opera.
- ✓ 3D support designed and printed @LNF (windings commissioned to firm): ideal for specific geometries, or where space is limited or where multiple components need be assembled together (e.g. diagnostics).
- ✓ Different prototypes steerers have already been realized and are currently used on SPARC.
- ✓ Magnetic, electrical and thermal measurements performed @LNF.









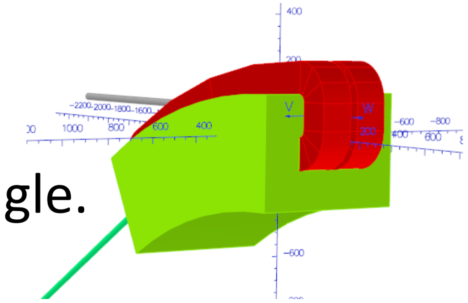
Del Franco et al. "3D printed beam correctors", 15th Int. Particle Acc. Conf. IPAC2024

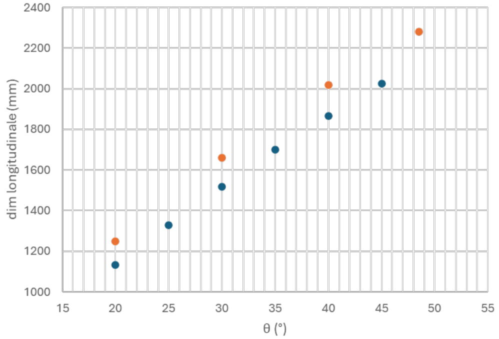
Selce A. et al. "Intra-undulators magnets for the SABINA THz FEL line: magnets design, manufacturing and measurements", 15th Int. Particle Acc. Conf. IPAC2024

Work in progress

Dump dipole

- Geometric constraint given by the building.
- Parametric preliminary design in order to fix the deflection angle.

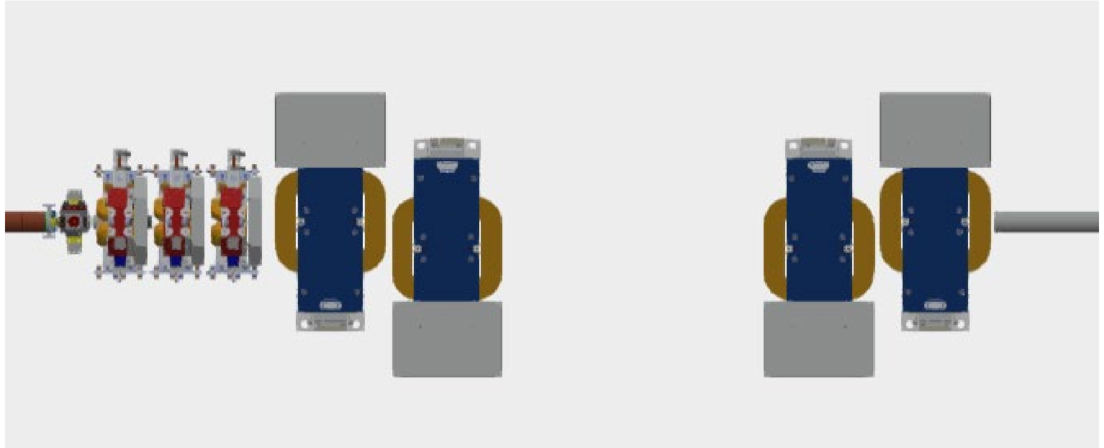


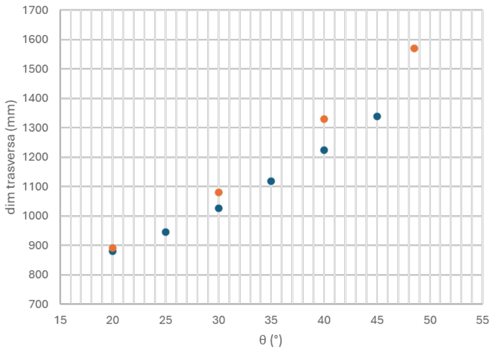


Laser chicane dipoles

- Preliminary magnetic design completed

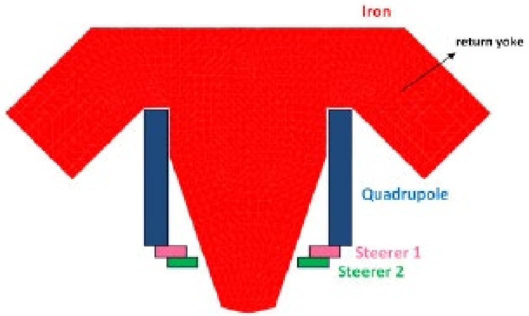
MAIN PARAMETERS	VALUE
Energy (MeV)	250
Gap (mm)	30
Deflection angle (mrad)	235
Magnetic Length (mm)	250
B_0 (T)	0.87
Overall length (mm)	340

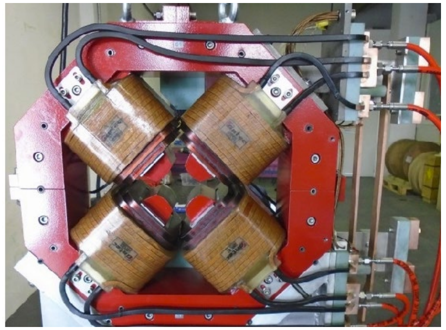




Combined quadrupole + steerer

- Studying different configurations (images from literature)





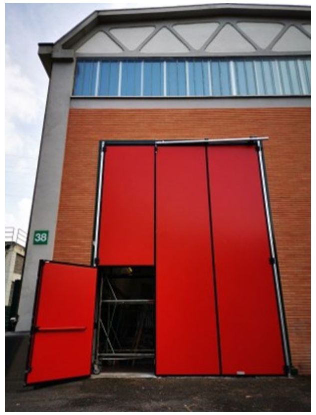
Upgrade of LNF magnetic measurements laboratory

Funded by the European Union

In the last few years, we have been upgrading the laboratory thanks to the external funded projects **LATINO** (cofunded by Regione Lazio) and **IRIS** (funded by PNRR program):

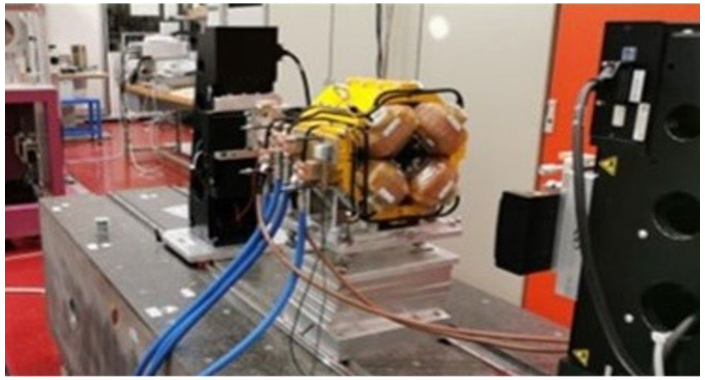
- ✓ civil engineering
- ✓ new personnel (technicians & technologist)
- ✓ upgrade of existing instruments and development of new benches

The electrotechnical eng. group



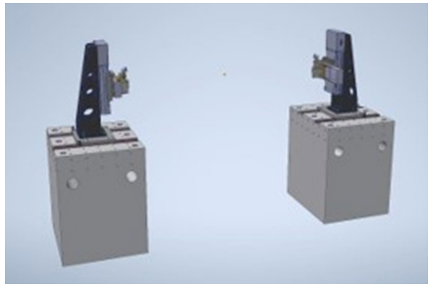
The building

Hall probe bench



Stretched wire

Calibration system



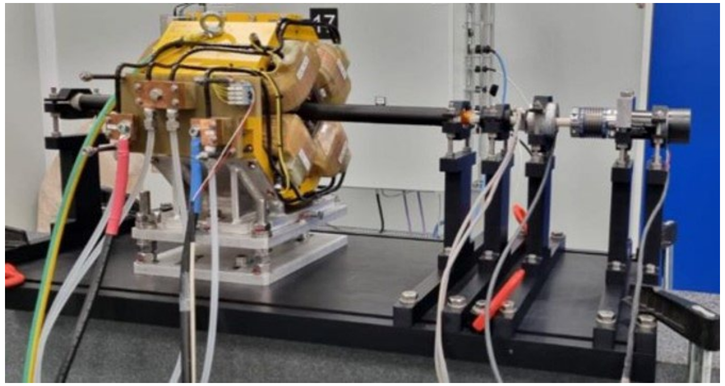
Pulsed wire

Sabbatini L. et al. "Upgrading of the INFN-LNF magnetic measurements laboratory" 15th Int. Particle Acc. Conf. IPAC2024
Vannozzi V. et al. "INFN – LNF Magnetic Measurement Laboratory Status and Upgrade", IMMW 2024
Rossi L. et al. "IRIS – A new distributed Research Infrastructure on Applied Superconductivity", IEEE Transactions on Applied Superconductivity, vol. 34, 3, 1-9, 2024

Upgrade of LNF magnetic measurements laboratory

✓**Rotating coil**: optimized for small-bore multipole magnets (CERN-INFN design)

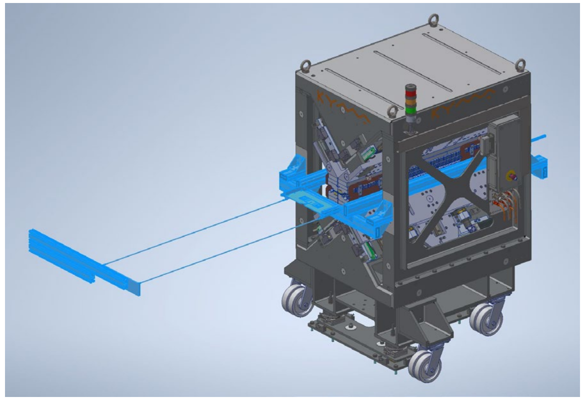
off the shelf components: PCB magnetometer (5 coils, 256 turns each); carbon fiber tube, 26 mm external diameter, 620 mm length; different configurations of PCB and shaft; commercial DC brush-less motor, high-resolution incremental encoder, slip-ring, data acquisition system, open-source software

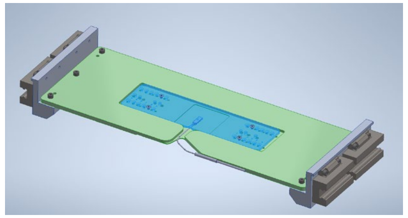


MAIN FEATURES	
Main integrated gradient	
Absolute accuracy	50 ppm
repeatability	10 ppm
High order compensated harmonics	
Accuracy	100 ppm
repeatability	10 ppm

✓**Mole Hall probe**: a travelling 3-axis probe sliding inside the magnet gap

compact 3-axis Hall probe, mounted on a thin mechanical support; Keysight digital multimeter; system similar to what already built for measuring SABINA's undulators





Lauria A. et al. "Rotating-Coil Measurement System for Small-Bore-Diameter Magnet Characterization", Sensors 2022, 22(21), 8359
CERN-INFN collaboration agreement KR4708/TE