EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

Magnets

Lucia Sabbatini / INFN – LNF

8th EuPRAXIA@SPARC_LAB Review Committee 25.11.2024

Funded by the
European Union

Functional layout & list of magnets

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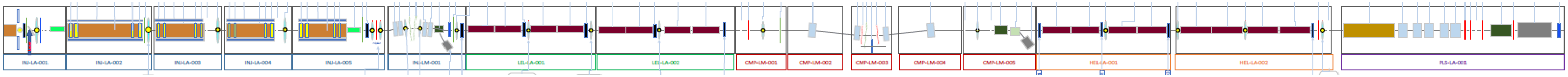

TYPE	SECTION	QTY	NOTES
SOLEN.	INJ (GUN)	1	
	INJ	2	on S-band accelerating sections
DIPOLES	INJ	4	Laser Heater chicane (1 is spectrometer)
	CMP	4	chicane
	CMP	1	Spectrometer
	PLS	5	Permanent magnets

TYPE	SECTION	QTY	NOTES
QUADRUPOLES	INJ (GUN)	2	normal + skew embedded in sol.
	INJ	4	w. Steerer, 2 on BPM
	LEL	3	
	CMP	8	2 w. Steerer, on BPM
	HEL	6	1 w. Steerer & BPM
	PLS	5	Permanent magnets

TYPE	SECTION	QTY	NOTES
STEERERS	INJ (GUN)	2	
	INJ	4	HV on S-bands, inside solenoids
	INJ	3	w. BPM
	INJ	4	on QUAD, w. BPM
	LEL	4	on bellows
	CMP	3	w. BPM & QUAD
	HEL	4	

Naming convention:

SECTION SYSTEM FAMILY TYPE SEQ. NUMBER

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

EuPRAXIA

Magnets for the gun (1/2)

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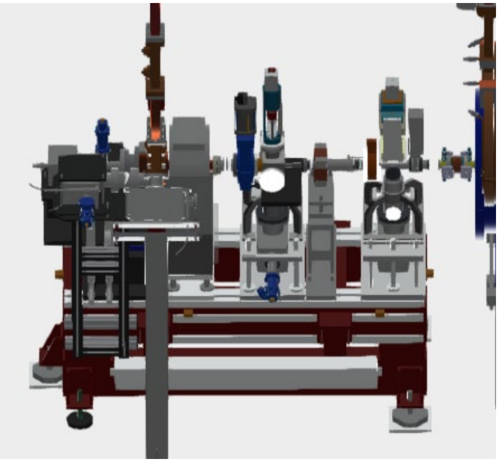
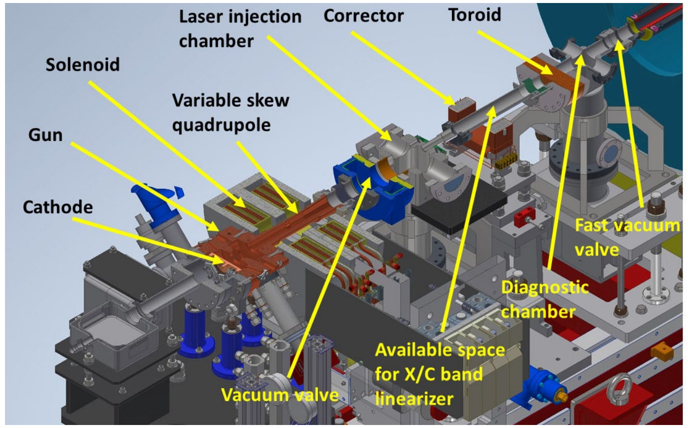


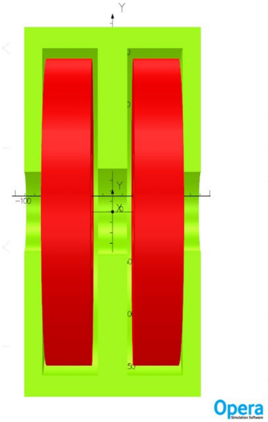
The EuPRAXIA gun is based on the recent successful experience with the new SPARC_LAB photo-injector. From the magnetic point of view, it integrates a solenoid, a quadrupole, and a steerer:

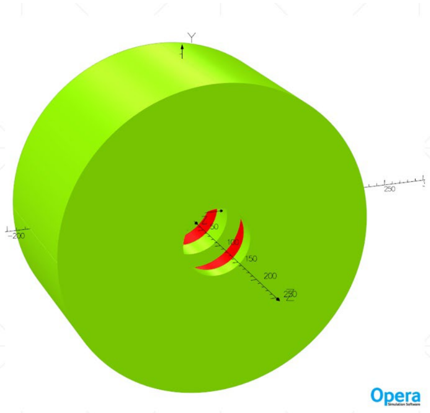
✓ The **solenoid,** designed to compensate for emittance growth, is equipped with remote control for the transverse position adjustment and features:

- an integrated longitudinal field component of 62.6 T mm with an integrated field quality of less than 5x10^{-4} in a good field region of 30 mm radius
- a focusing strength (i.e. the field integral of B_z^2 along z direction) of at least 0.015 0 T^{2m}
- minimization of the field on cathode (less than 15G) to avoid undesired emittance growth

	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



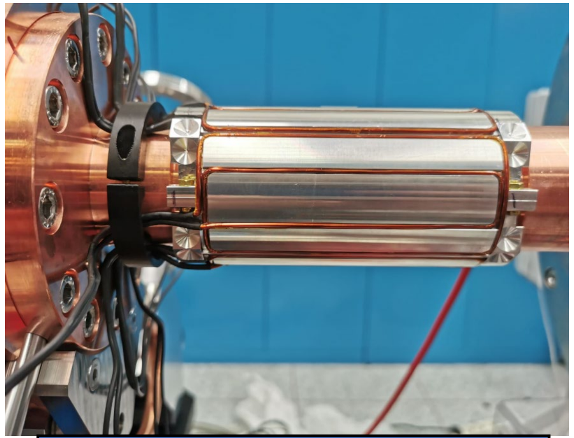




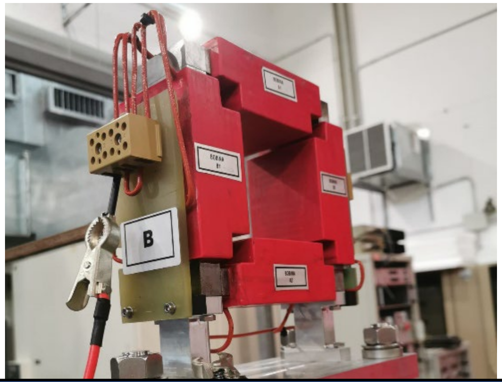
Alesini D. et al. "The new SPARC_LAB RF photo-injector" 13th Int. Particle Acc. Conf. IPAC2022, doi:10.18429/JACoW-IPAC2022-MOPOMS019
Vannozzi A. et al., "Design and realization of new solenoids for high brightness electron beam injectors", 12th Int. Particle Acc. Conf. IPAC2021

Magnets for the gun (2/2)

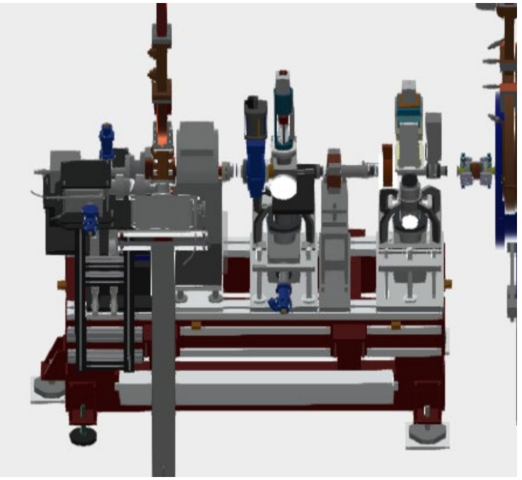
- ✓ The **normal** and a **skew quadrupole** with variable polarity, embedded in the solenoid, are used for tuning the x-y emittances and compensating for residual transverse beam spot asymmetries. The quadrupole is mounted on the vacuum chamber at the center of the solenoid.
- ✓ The **HV steerer is used** for trajectory optimization and beam energy measurements. These features enable the bending of the electron beam, with an energy of about 6 MeV, by approximately 19 mrad.

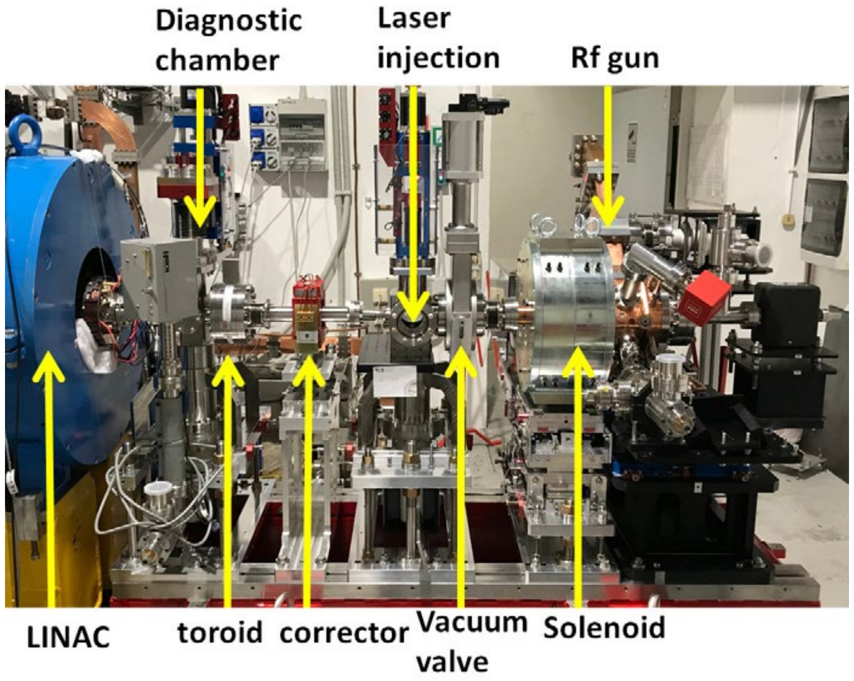


Quadrupole	
Maximum gradient	32 mT/m
Lmag	100 mm
Air cooled	



HV Steerer	
Bmax	25 G
Lmag	152 mm
Good field region radius	15 m
Integrated field quality	2E-3

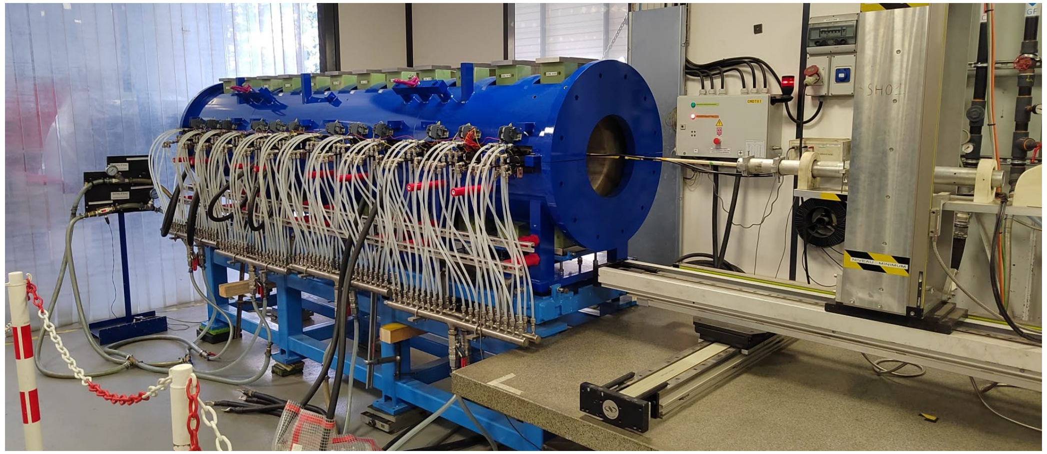




Injector: solenoids

EuPRAXIA's solenoids are based on the experience gained within the SABINA project, that provided new solenoids for SPARC_LAB (installed in January 2024):

- **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.



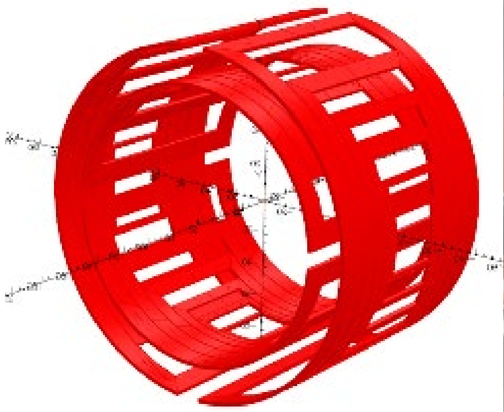
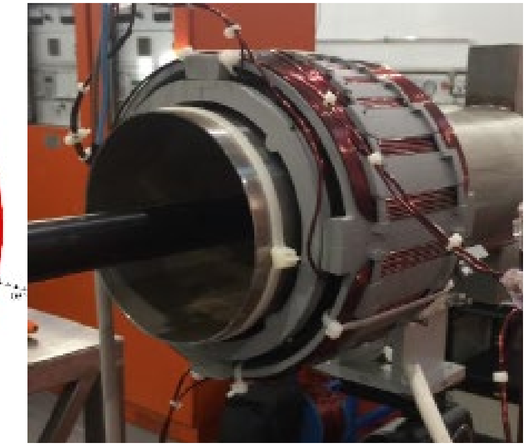
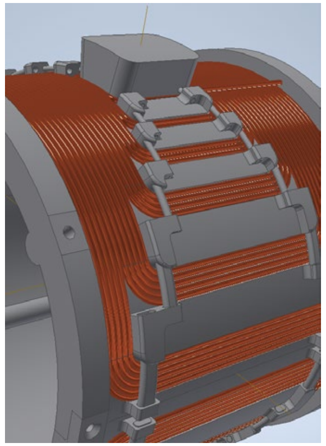
PARAMETER	VALUE	PARAMETER	VALUE
Quantity	2	Maximum current (A)	190
Number of coils	12	Maximum voltage – series of 3 coils (V)	100
Bmax in ++ config. (G)	1800	Inductance – series of 3 coils (mH)	13
Integrated Bz on axis (Tm)	0.5273	Maximum pressure drop (Kpa)	200
Integrated field homog. in ++ config	5E-4	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		

Funded by the European Union

HV steerers on accelerating structures

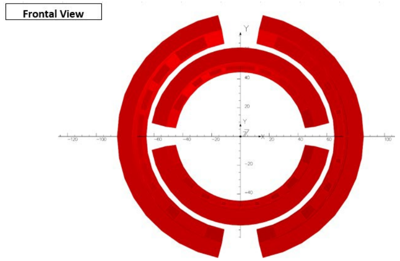
- HV steerers are included at the beginning and end of each S-band accelerating structure to correct the beam position during the acceleration phase.
- Air-dominated cosθ steerers, with strict geometrical constraints
- A single design to meet the requirements for both accelerating structures: excitation current is adjusted accordingly to the energy levels and correction angle (Thermal studies and tests indicates that this choice is thermally acceptable).
- Prototypes have been designed, built, tested and installed at SPARC
- Mechanical support are 3D printed

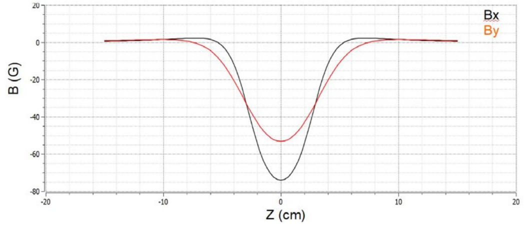
HV steerers for accelerating structures	
B (internal/external)	7 G / 6.7 G
Integrated field	830 / 915 G mm
Magnetic length L_{mag}	118 / 136 mm
Deflecting angle θ	2.5 / 2.7 mrad
Int. field quality ΔʃB/ʃB	8 10^{-4} / 7 10^{-4}
Current density J	1.7 / 2.4 A/mm^2
Internal radius	79 mm
External radius	100 mm
Longitudinal length	134 mm


Air dominated steerers

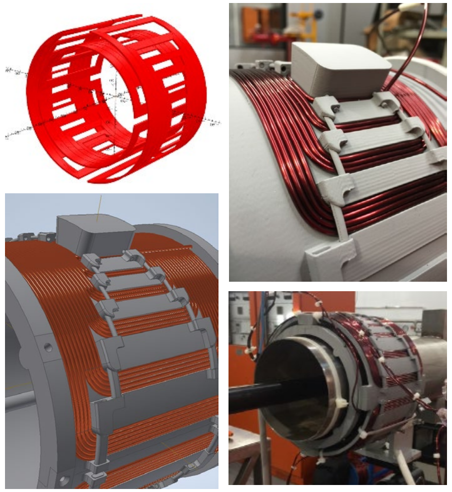
Funded by the European Union

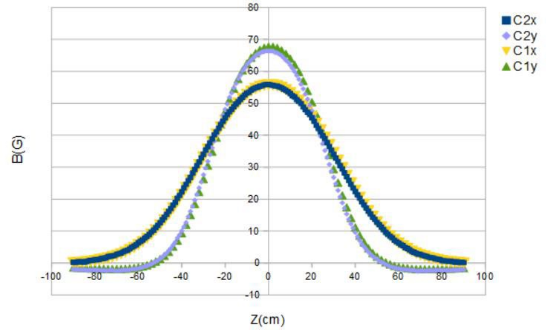


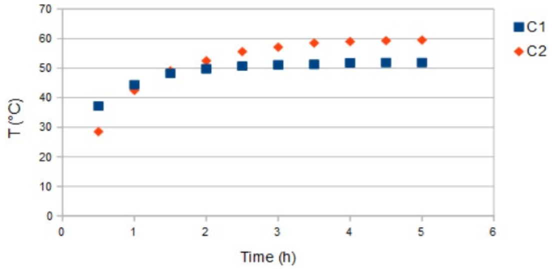


INFN-LNF team has extensive experience in the design, manufacturing and testing of air dominated beam steeres:

- ✓ 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.





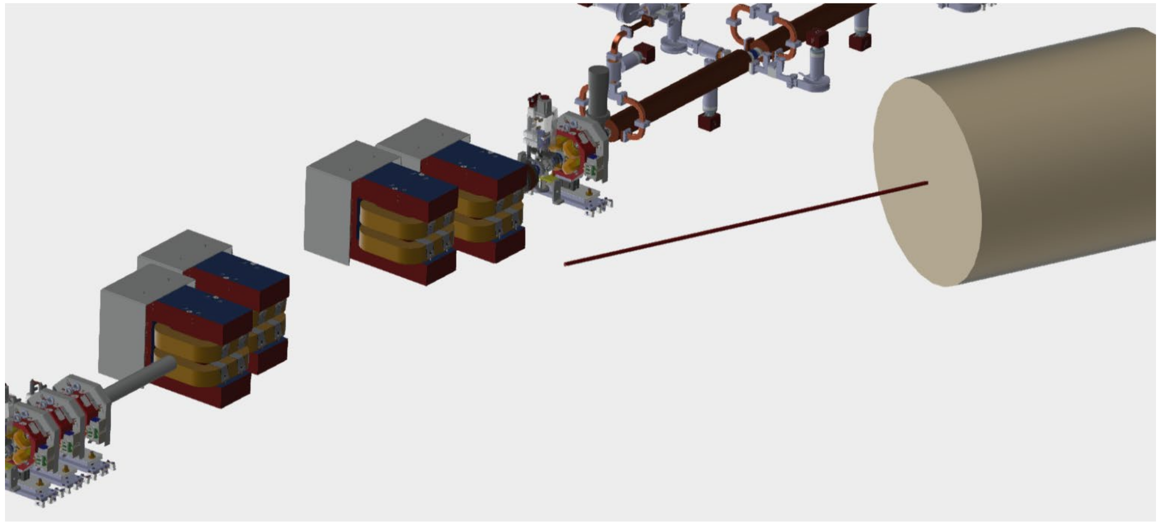


Del Franco et al. "3D printed beam correctors", 15th Int. Particle Acc. Conf. IPAC2024
Selce A. et al. "Intra-undulators magnets for the SABINA THz FEL line: magnets design, manufacturing and measurements", 15th Int. Particle Acc. Conf. IPAC2024

Laser Heater chicane dipoles

Funded by the European Union

- Preliminary design was based on previous experience on ELI dipoles (similar field, gap, optimization of longitudinal length by reviewing the coils configuration)
- Recent change of layout: the first dipole serves also as spectrometer
  - C dipoles
  - Bipolar power supplies



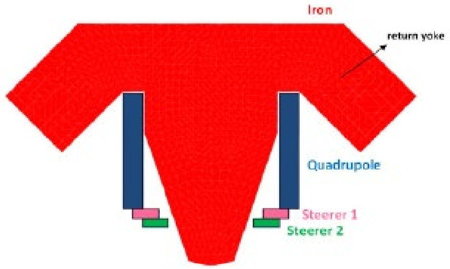
MAIN PARAMETERS	VALUE
Dipole type	C
Energy (MeV)	250
Gap (mm)	30
Deflection angle (mrad)	235 (13.46°)
Deflection angle as spectrometer	384 (22°)
Magnetic Length (mm)	250
B_0 (T)	0.87
B_{spect} (T)	1.38
Overall length (mm)	340

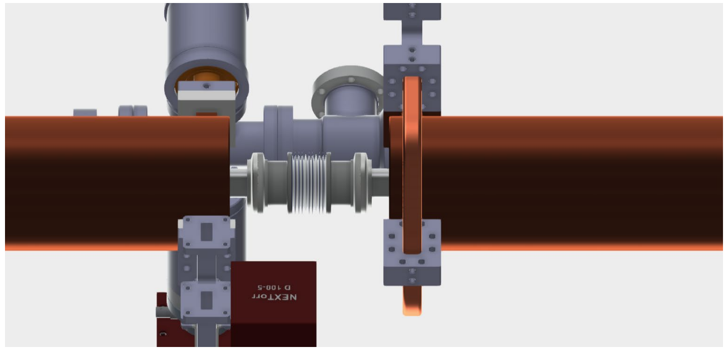
- New design is ongoing
- **Cross talk** must be verified
- The gap could potentially be reduced, which would help shorten the longitudinal length.

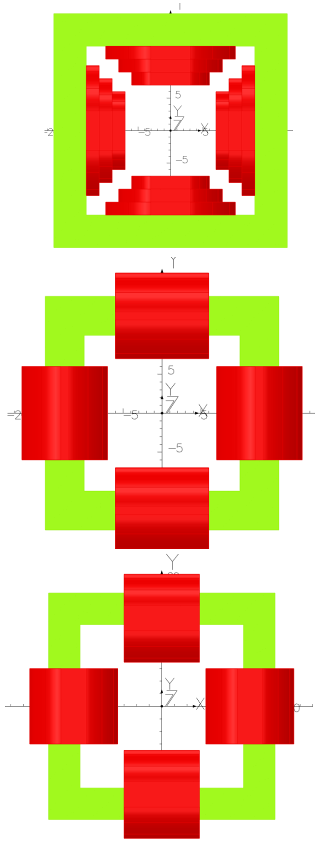
HV steerers (between X-band structures)

Funded by the European Union

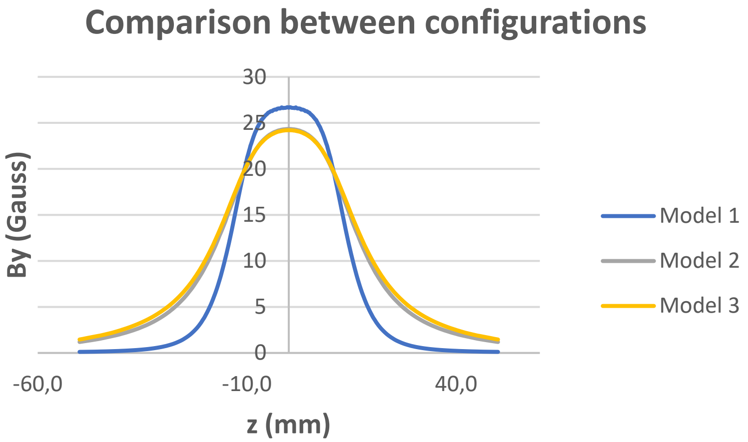
- Preliminary layout of the machine required a combined quadrupole + HV steerer between X band structures → works was ongoing
- With reduction in beam pipe diameter, decoupling of these magnets was allowed
- Anyway, the steerers must be located on bellows → aperture at least 26mm – to be confirmed

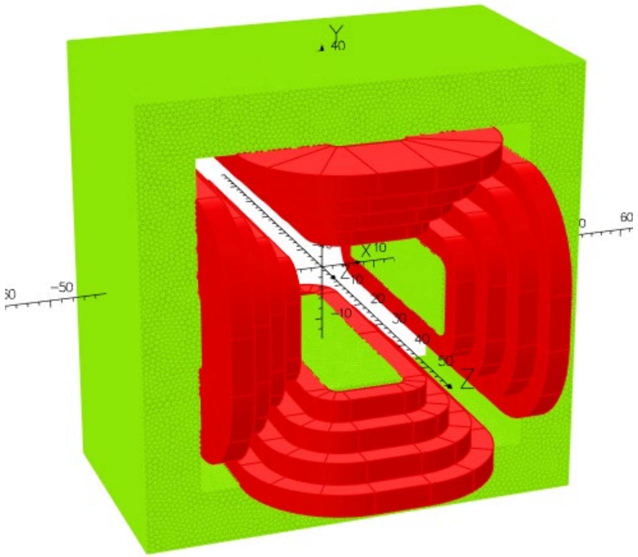






- Parametric studies to compare different configurations
- A preliminary design of the steerer now exists (optimization ongoing), while quadrupoles are still under analysis

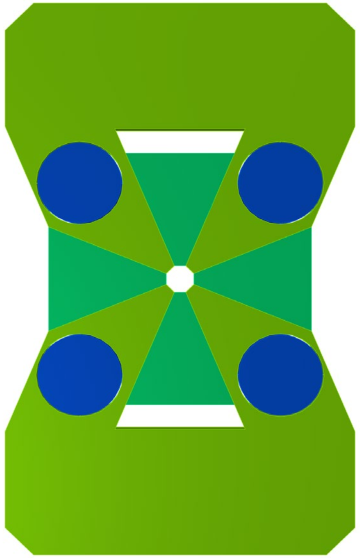




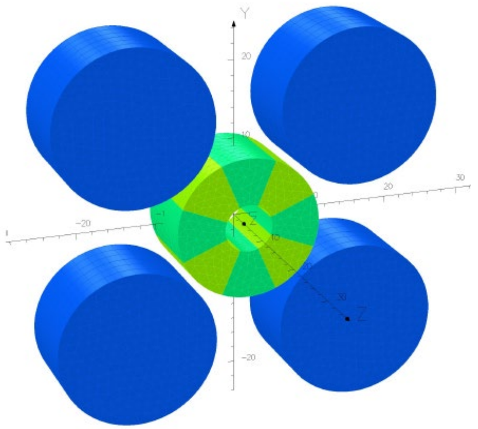
HV steerer	
Bmax	115 G
Integrated Field	7222 G mm
L mag	63 mm
L yoke	44 mm
L tot	80 mm (to be reduced)
Aperture	26 mm
Bending angle	0.2 mrad (@1GeV)

Permanent magnets for plasma section

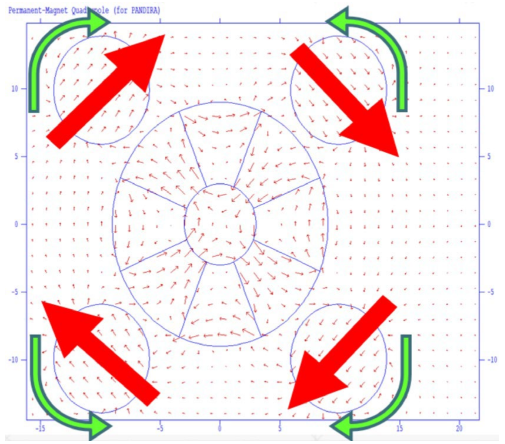
- In the recent past, the magnet design group has deal with PMQs for plasma wake field based experiments at SPARC_LAB test facility.
- For **COMB** experiment, a design of **tunables PMQs** [1] based on an optimization and scaling of QUAPEVA PMQs[2]
- For External-Injection experiment (**EXIN**) proposal 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

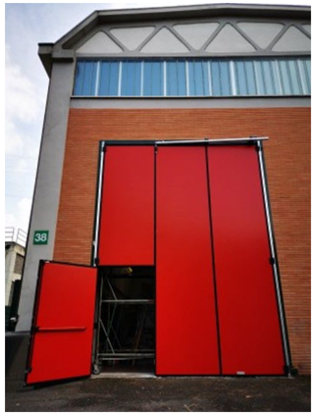
Upgrade of LNF magnetic measurements laboratory

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):

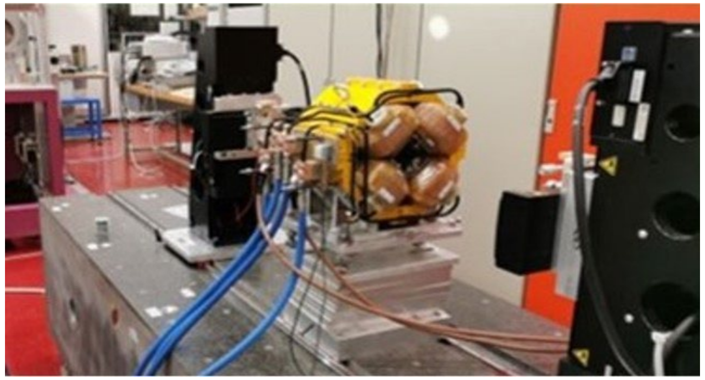
- ✓ civil engineering
- ✓ new personnel (technicians & technologist)
- ✓ upgrade of existing instruments and development of new benches

The electrotechnical eng. group



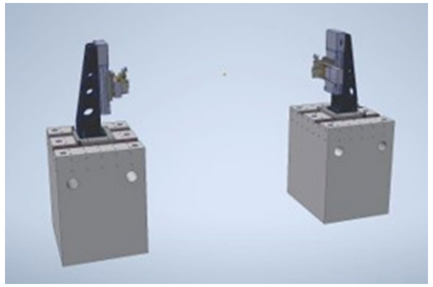
The building

Hall probe bench



Stretched wire

Calibration system



Pulsed wire

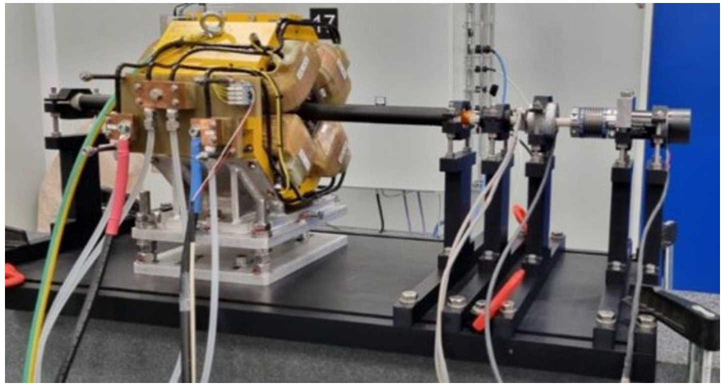
Sabbatini L. et al. "Upgrading of the INFN-LNF magnetic measurements laboratory" 15th Int. Particle Acc. Conf. IPAC2024
Vannozzi V. et al. "INFN – LNF Magnetic Measurement Laboratory Status and Upgrade", IMMW 2024
Rossi L. et al. "IRIS – A new distributed Research Infrastructure on Applied Superconductivity",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

Upgrade of LNF magnetic measurements laboratory

Funded by the European Union

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

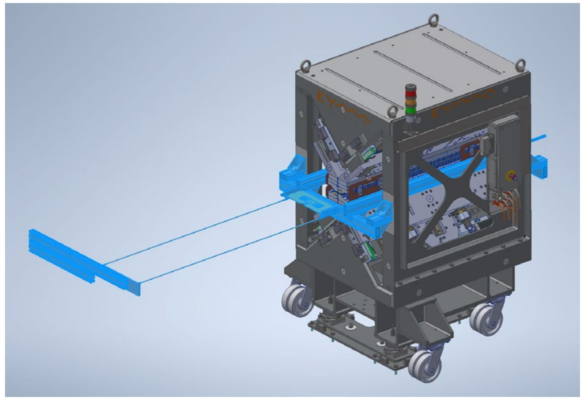
off the shelf components: PCB magnetometer (5 coils, 256 turns each); carbon fiber tube, 26 mm external diameter, 620 mm length; different configurations of PCB and shaft; commercial DC brush-less motor, high-resolution incremental encoder, slip-ring, data acquisition system, open-source software

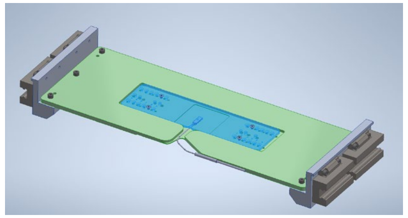


MAIN FEATURES	
Main integrated gradient	
Absolute accuracy	50 ppm
repeatability	10 ppm
High order compensated harmonics	
Accuracy	100 ppm
repeatability	10 ppm

✓**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

Next steps

Next tasks & Timeline

- Complete the laser heater dipoles design (Dec. 24)
- Provide a preliminary design for key elements:
  - Quadrupoles between X-band structures (Jan 25)
  - Beam Compressor Chicane dipoles (Jan 25)
  - Spectrometer (Feb. 25)
- TDR writing: a few paragraphs are already prepared
  - ✓ Gun (solenoid, quadrupole, steerer)
  - ✓ Solenoids for S-band accelerating structures & inner steerers
  - ✓ Steerers between X-band structures
  - Additional sections will follow after the definition of the design definition

Acknowledgements

- Alessandro Vannozzi, for sharing the work on magnets and power supplies
- A. Selce, A. Trigilio, for currently learning about magnetic design
- Mario Del Franco, for his support with the 3D layout
- Ilaria Balossino, for supporting the preparation of TDR document