INFN
Istituto Nazionale di Fisica Nucleare
Sezione di Napoli

INFN LNF
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Frascati

INFN Milano
Istituto Nazionale di Fisica Nucleare
Sezione di Milano

HARMONIQ

Halbach Array for Rotational MOdulation of NdFeB Integrated Quadrupoles

Project Proposal to CSN5 for 2026

Alessandro Vannozzi

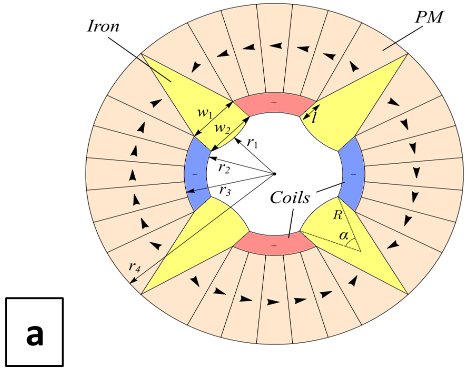
EuPRAXIA BTF SPARC LAB

Context: PMQ for Plasma Acceleration

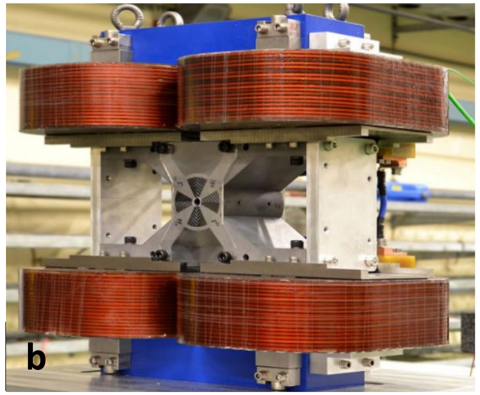
- Laser Plasma Accelerators (LPA) have exhibited considerable promise through the utilization of plasma wakefields, enabling the attainment of gradients on the order of **several GeV/cm**
- Beams entering in the plasma require for µm scale beams to be achieved in very compact (cm scale) focusing sections.
- Beams exiting from plasma accelerator module show high divergence (few mrads) and high energy spread (few %) and need trasfer line to experimental station able to avoid chromatic effects convert in emittance dilution and/or charge losses through the downstream beamline
- A **strong focusing near the particle beam injection in the plasma and near the extraction from the plasma** is the more reliable solution to handling these drawbacks. Plasma modules works in **UHV** environment: a compatibility it is crucial.
- Currently there are two devices under investigation to fulfill the PA requirements:
  - **Permanent Magnet Quadrupole (PMQ)** is the state of the art technology since it makes possible to provide very high gradients (up to hundreds of T/m) with very compact devices. The ones devoted to PA shows exotic design providing **«online» tunable gradients in a wide range**, in order to increase the **machine energy acceptance**. On the other side the «online» tunability led to **undesired multipolar skew components ,** magnetic axis stability and **higher transverse dimensions** with respect to the constant gradient PMQ.
  - **Plasma Lens:** not yet state of the art technology, **APL** are subjected to emittance degradation and charge reduction due to highly non-linear focusing arising from current discharge non-uniformity. For **PPL** focusing properties depend on the electron beam itself and can present aberrations.
- The main purpose of this proposal is to overcome the tunable PMQ drawbacks, in particular **reducing the multipolar** skew components with **more compact** devices offering an energy acceptance higher than 40%.

Context: PMQ Focusing Tuning Techniques

COMBINATION PERMANENT MAGNETS + NC Coils



Quadrupole for an interdigital H-mode drift tube linear accelerator (Peking Univ.)

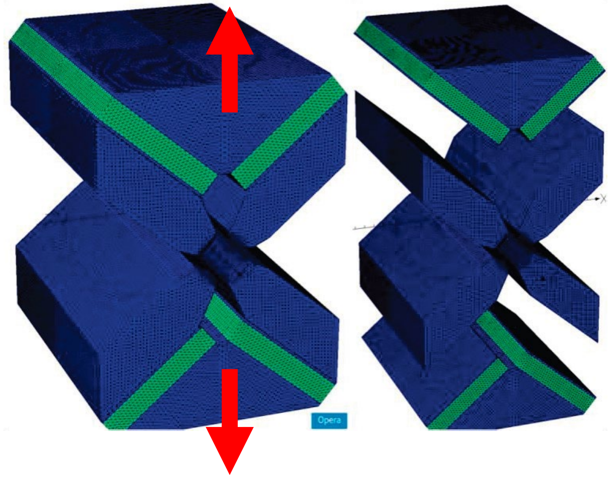


QD0 for CLIC final focus

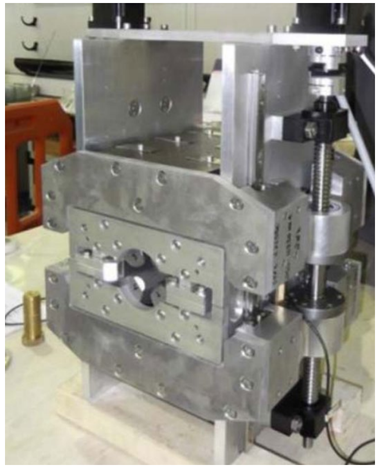
	PROJECT	Radius – WxHx L [mm]	Mean G	Tunability
a	Linac Acc.	12,5- 40x40x -	84 T/m	±30%
b	CLIC	4,13 – **436x 436**x2700	338 T/m	±55%

- Easy tuning
- Stability of magnetic axis for quadrupoles
- **Coils not compatible with Ultra High Vacuum environment**
- Necessity of electric power and possible water cooling
- Less compactness

BLOCKS SHIFT



High-energy quadrupole design for CLIC at STFC at maximum (left) and minmum (right) gradient configuration.

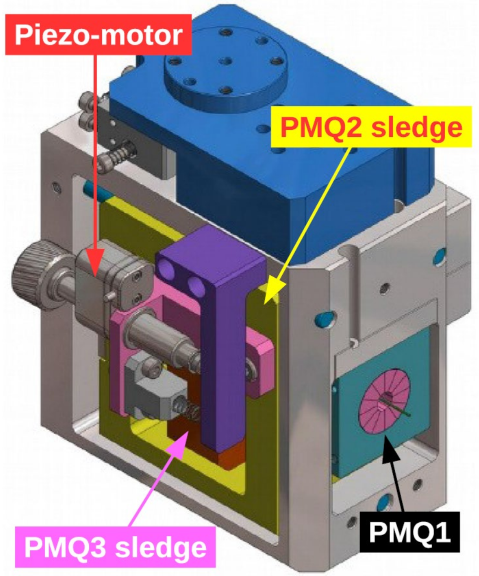


High-energy quadrupole prototype for CLIC at STFC

PROJECT	Radius – PM size (WxHx L) [mm]	Max G	Tunability
CLIC	13,6 – 18x100x230	97 T/m	±30%

- Less power demand
- Compatibility with Ultra High Vacuum environment
- High field quality
- Difficult tuning, dealing with high forces (tens kN)
- Less compactness
- Need transverse shift to adjust magnetic axis position on the beam

Context: PMQ Focusing Tuning Techniques



Mechanical layout of the PMQ movable system @SPARC_LAB

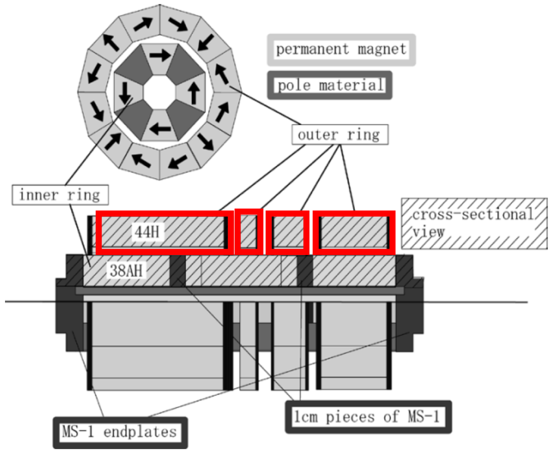
LONGITUDINAL SHIFT OF THE QUADRUPOLES

- In the SPARC_LAB (LNF) test facility it is installed the COMB beam driven plasma acceleration experiment.
- A focusing system of two PMQ triplets have been installed both upstream and downstream a plasma acceleration module where the tuning of the gradient is gained keeping the PMQ1 fixed on the main support, while the other two are held on two mechanical sledges that can be moved by two piezoactuators along the beam trajectories.
- With this method is possible to **tune** the triplet focus **length only for some%** considering also the limited longitudinal space availability.
- Magnets shifts vary the attractive force between magnets leading to possible errors in the longitudinal position shifting.

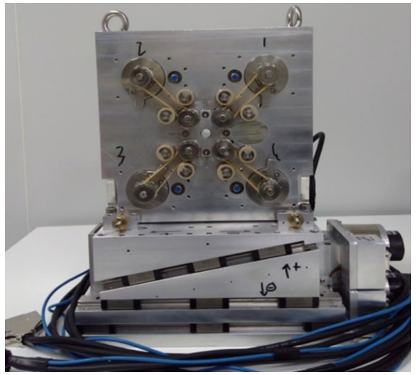
PROJECT	Radius – single PMQ size (WxHx L) [mm]	Max G	Tunability
SPARC_LAB	3 – 40x40x10/20	520 T/m	±2,5%

- Less power demand
- Compatibility with Ultra High Vacuum environment
- Very low tunability
- Difficulties in positions reproducibility
- Low longitudinal compactness

Context: PMQ Focusing Tuning Techniques



Kyoto / NIRS PMQ. Outer ring front (up) and side (down) views


QUAPEVAs for COXINEL facility (SOLEIL)

a

BLOCK ROTATIONS

	PROJECT	Radius – WxHx L [mm]	Mean G	Tunability
a	Linear Collider	10- 50x50x230	50 T/m	±45%
b	SOLEIL	6 – **100x100x100**	160 T/m	±22%

b

- High compactness (particularly for QUAPEVA)
- High Tunability
- Compatibility with Ultra High Vacuum environment
- Need transverse shift to adjust magnetic axis position on the beam
- Kyoto NIRS PMQ solution (a) shows a very high tunability but it can be reached by rotating single outer ring longitudinal section (highlighted in red). **It needs** at least longitudinal length of several cm.
- Concerning QUAPEVA the tunability is lower than Kyoto NIRS, but still suitable for several applications, it could be more compact.
- High compactness is a crucial allows to get closer the PMQ to the plasma injection and extraction.
- **QUAPEVA design has taken into account as design baseline for the HARMONIQ proposal.**

Halbach Array for Rotational MOdulation of NdFeB Integrated Quadrupoles (HARMONIQ) project proposal

The main goal of HARMONIQ is to realize and test TPMQs based on QUAPEVA design but optimized in terms of **compactness** and **reduced multipolar skew components.**

MAIN INNOVATIONS

1. **Compactness**: the optimized design allows to reduce the radial dimensions.
2. **Unique gradient and tunability combination**: from the litterature this design push forward the state of the art in terms of **high gradients** and **high tunability** offering an **energy acceptance larger than 40%.**
3. **Reduced power cost:** Very small power demand.
4. **Reduced skew components** with respect to QUAPEVA design.
5. **Reduced production cost**: PMQ performances feasible with NdFeB and AISI 1010 materials. Cost reduced compared with other solutions like FeCo alloy (higher saturation threshold) instead to AISI1010 (cheaper).

The parameters of the TPMQs will be tailored on the basis of **EuPRAXIA** project requirements for the beam based plasma acceleration.

TPMQ for EuPRAXIA Plasma Acceleration Module

- In the Eupraxia linac the X-band booster upstream the plasma capillary is able to drive the electron beam up to 500 MeV, while in the plasma module it can reach an energy of about 1GeV.
- Since the machine could work at several repetition rates, **up to 400 Hz**, this TPMQ solution show the advantage to work at any repetition rate with respect to other focusing techniques.
- FODO quadrupoles have been foreseen in the layout to focus the beam close to the inlet and outlet of plasma capillary. The quadrupoles with "full length" and "half length" have been defined as long and short PMQ.
- In details the EuPRAXIA layout foreseen a **PMQ triplet** upstream the plasma acceleration module and 13 magnets downstream the plasma module: a "short" PMQ for the first and the last magnet while all the others are "long" type

UPSTREAM PLASMA MODULE

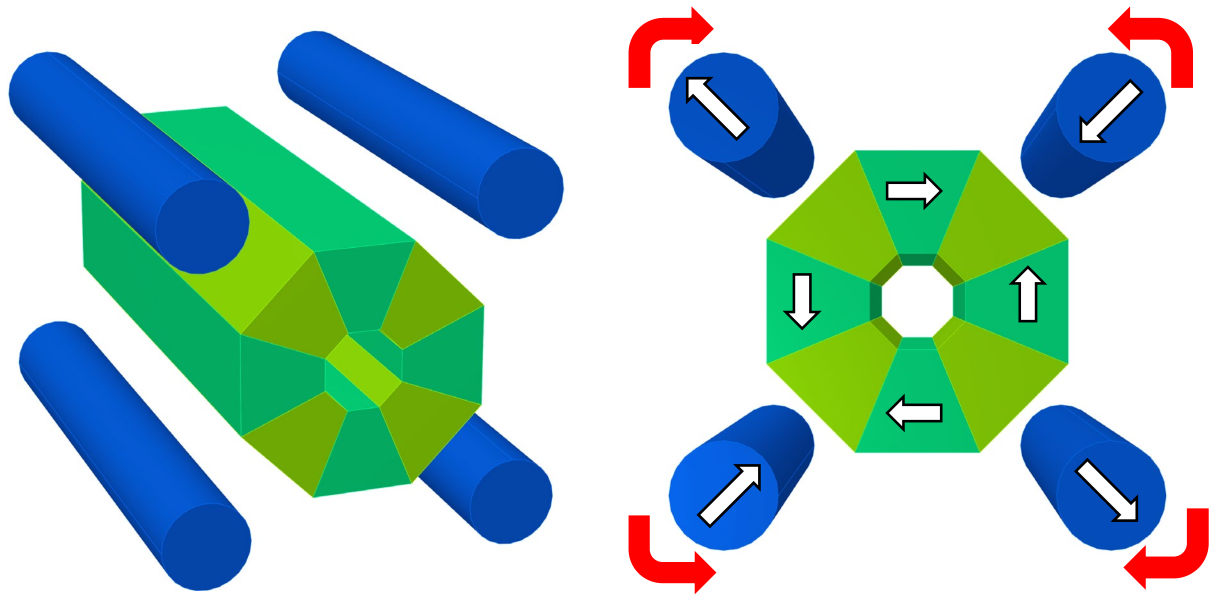
	Short PMQ	Long PMQ
PARAMETER	Value	Value
Energy	500 MeV	500 MeV
Aperture Diameter	7 mm	7 mm
Average Gradient	300 T/m	300 T/m
Tunability	± 10% (± 30 T/m)	± 10% (± 30 T/m)
Magnetic Length	55 mm	100 mm
Integrated Gradient range	16,5 ± 1,7 T	30 ± 3 T
Distance Between PMQs	10 mm	10 mm

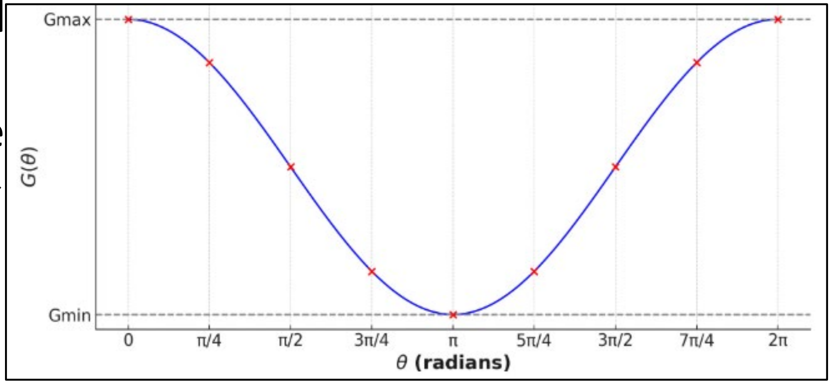
DOWNSTREAM PLASMA MODULE

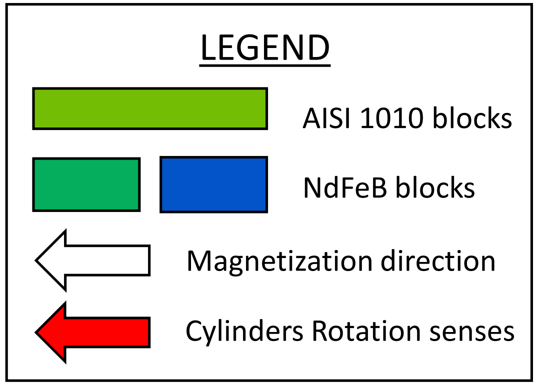
	Short PMQ	Long PMQ
PARAMETER	Value	Value
Energy	1GeV	1GeV
Aperture Diameter	7 mm	7 mm
Average Gradient	510 T/m	510 T/m
Tunability	± 17% (± 90 T/m)	± 17% (± 90 T/m)
Magnetic Length	17,5 mm	35 mm
Integrated Gradient range	8,9 ± 1,6 T	17,85 ± 3,2 T
Distance Between PMQs	40 mm	40 mm

HARMONIQ Design Baseline

- Each PMQ is composed by a 8 sector Halbach configuration surrounded by 4 NdFeB cylinders radially magnetized. Based on QUAPEVA design [1].
- The fixed parts alternate NdFeB magnetized blocks with AISI1010 blocks that act as poles.
- Gradient tuning by rotating the 4 cylinders around the longitdunal PMQ axis (parallel the beam direction).
- **Opposite rotation senses of cylinders reduce the skew quadrupole components w.r.t. the original QUAPEVA config. at a 50 % of gradient range.**
- Aiming to increase gradients it would be possible to change AISI 1010 blocks with FeCo ones. → higher costs ; FeCo activation?







[1] Marteau, F., et al. "Variable high gradient permanent magnet quadrupole (QUAPEVA)." Applied Physics Letters 111.25 (2017)

HARMONIQ Design Baseline

- Simulation campaign performed with Opera 3D software.
- The integrated gradient range is taken as the simulations figure of merit. It comply the required range for all the design

- **The design is unique combination for tunability, compactness and gradient magnitude.**
- For downstream PMQ the dimensions grows up significantly. A **more compact** design have been proposed

UPSTREAM PLASMA MODULE

	SHORT TPMQ		LONG TPMQ	
	Requirements	Simulations	Requirements	Simulations
Energy	500 MeV	500 MeV	500 MeV	500 MeV
Aperture Diameter	7 mm	7 mm	7 mm	7 mm
Average Gradient	300 T/m	307 T/m	300 T/m	294 T/m
Tunability	± 10% (± 30 T/m)	± 12% (± 36 T/m)	± 10% (± 30 T/m)	± 14% (± 40 T/m)
Magnetic Length	55 mm	54 mm	100 mm	102 mm
Integrated Gradient range	16,5 ± 1,7 T	16.4 ± 1.75 T	30 ± 3 T	30 ± 4 T
(WxHxL) [mm]	-	32x32x50	-	36x36x100
Weigth	-	200 g	-	400 g

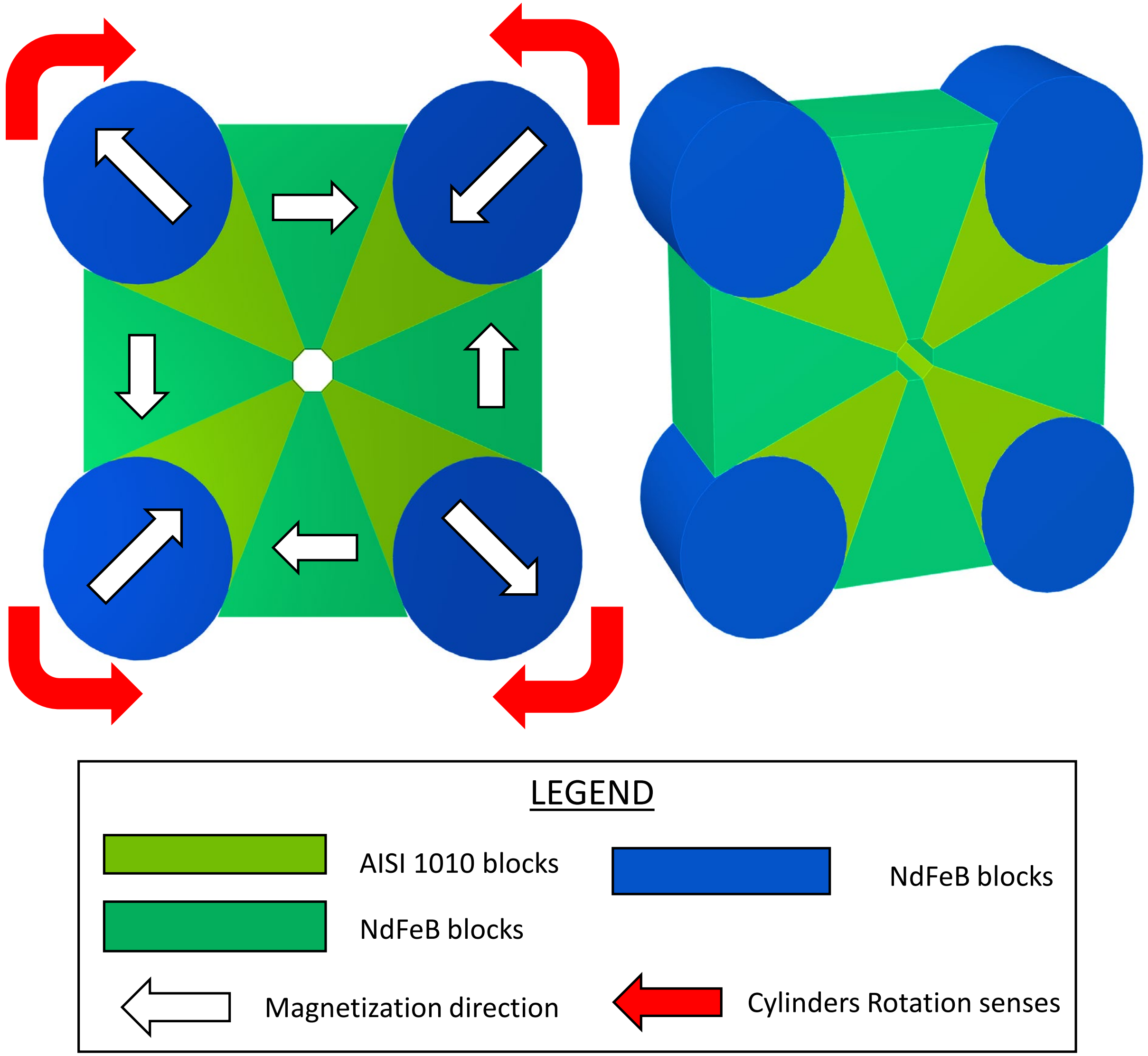
DOWNSTREAM PLASMA MODULE

	SHORT TPMQ		LONG TPMQ	
	Requirements	Simulations	Requirements	Simulations
Energy	1GeV	1GeV	1GeV	1GeV
Aperture Diameter	7 mm	7 mm	7 mm	7 mm
Average Gradient	510 T/m	433 T/m	510 T/m	492 T/m
Tunability	± 17% (± 90 T/m)	± 22% (± 94.5T/m)	± 17% (± 90 T/m)	± 19% (± 92 T/m)
Magnetic Length	17,5 mm	21 mm	35 mm	35 mm
Integrated Gradient range	8,9 ± 1,6 T	8,82 ± 1,7 T	17,8 ± 3,2 T	17,4 ± 3 T
(WxHxL) [mm]	-	125x125x17	-	125x125x33
Weigth	-	1,2 kg	-	2,3 kg

HARMONIQ «Compact» Design Baseline

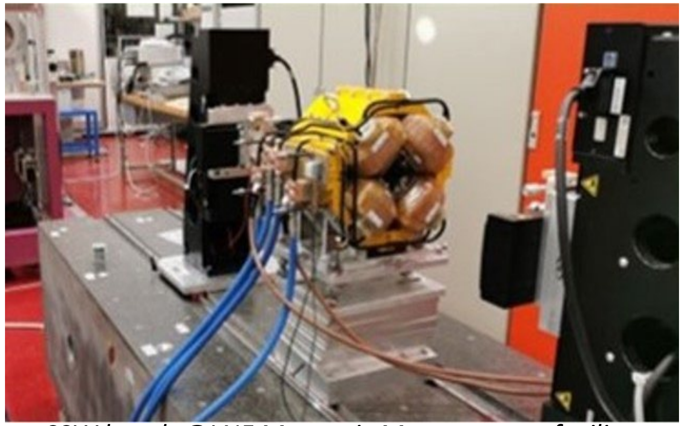
- **For the downstream short quadrupole, a compact design has been done approaching the rotating cylinders towards the PMQ axis and shaping the AISI 1010 pole blocks to house them.**
- Higher gradients achieved with a more compact and lighter magnet.

	Short Compact Design	**Short Normal Design**
PARAMETER	Value	Value
Energy	1GeV	1GeV
Aperture Diameter	7 mm	7 mm
Average Gradient	495 T/m	433 T/m
Tunability	± 15% (± 72 T/m)	± 22% (± 94.5T/m)
Magnetic Length	23 mm	21 mm
Integrated Gradient range	11.385 ± 1.7 T	8,82 ± 1,7 T
Overall Dimensions (WxHxL)	45x45x20 mm	125x125x17 mm
Weigth	1,0 kg	1,2 kg

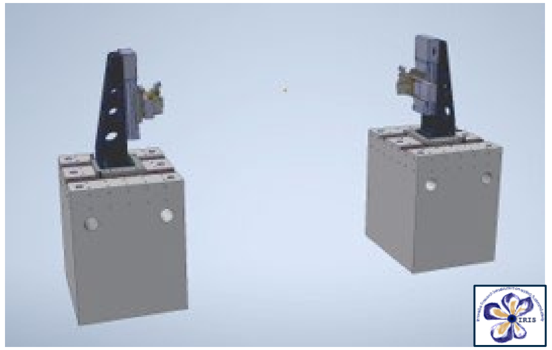


Methodology

- **Complete magnetic design** with cross talks between magnets and completing a block stress preliminary analysis.
- **Beam Dynamics** (BD) **design validation** inserting field maps and/or integrated harmonics in Elegant BD code where **EuPRAXIA linac** have been modelled.
- Magnetic blocks and servomotors purchasing.
- **Mechanical design and production** performed by CECOM srl company of one PMQ per type starting from the compact and the short design downstream the plasma.
- **Full magnetic characterization at LNF magnetic measurement facility** by means of Single Stretched Wire (SSW) bench (available) and a Vibrating Wire (VW) bench (available from half of 2026) to crosscheck the **magnetic axis position** repeatability in the full range of gradient tuning. In this phase a **INFN-Na** support will be crucial for measurement data analysis.
- BD validations of measured PMQs on the Eupraxia requirements



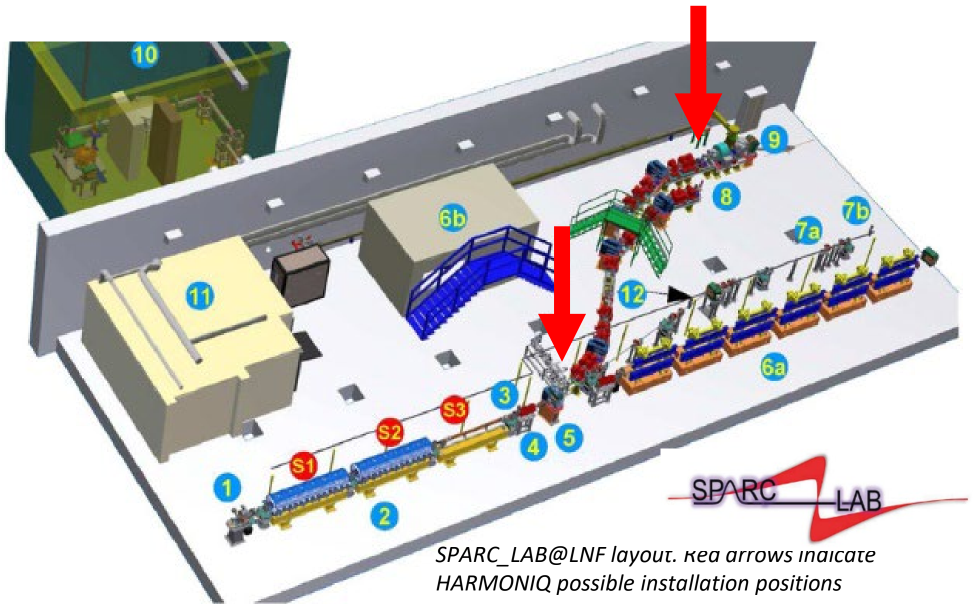
SSW bench @LNF Magnetic Measurement facility



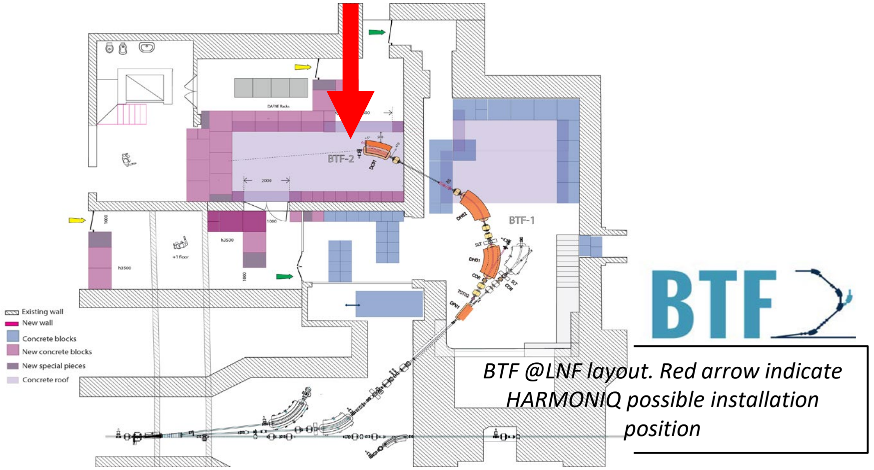
VW3D view and granite blocks (down) @LNF Magnetic Measurement facility

Methodology

- **Installation in an electron beam linac** to check the PMQ performances on a real beam.
  - Main candidate is **SPARC_LAB linac @LNF** where it will be available the EXIN line or it could be implemented in the COMB vacuum chamber.
  - In alternative also the **BTF @LNF**. In this case a vacuum chamber and diagnostic station will be produced to host the PMQs and the diagnostic.
- A preliminary check with Beam Dynamics machine teams will be done (respectively INFN-LNF and INF-MI who is in charge of STAR BD) for HARMONIQ implementation.
- HARMONIQ machine installation will give the chance for a first machine implementation test of the Genetic Interface for OpTimising Tracking with Optics (**GIOTTO**) AI driven software to perform a PMQ magnetic axis beam base alignment and to test GIOTTO implementation under EPICS control system. The software will be developed by **INFN-MI** staff who made a dedicated proposal to CSN5



SPARC_LAB@LNF layout. Red arrows indicate HARMONIQ possible installation positions



BTF @LNF layout. Red arrow indicate HARMONIQ possible installation position

HARMONIQ Work Packages Breakdown

WP1 - Magnetic Design
Responsible: **A. Vannozzi (LNF)**
Staff: L. Sabbatini (LNF), A. Trigilio (LNF)

WP2 - Magnetic Measurements
Responsible: **A. Esposito (NA)**
Staff: P. Arpaia (NA)

WP3 - Servomotors Control
Responsible: **S. Pioli (LNF)**
Staff: G. Latini (LNF)

WP4 - HARMONIQ for EuPRAXIA Beam Dynamics Simulations
Responsible: **A. Giribono (LNF)** | Staff: C. Vaccarezza (LNF)

WP5 Mechanical Machine Integration and Installations
Responsible: **A. Liedl (LNF)**

WP6 HARMONIQ implementation at SPARC_LAB
Responsible: **R. Pompili (LNF)**

WP7 PMQs Beam Based Alignment with GIOTTO SW
Responsible: **Illya Drebot (MI)**
Staff: A. Bacci, E. Puppin (MI)

WP8 HARMONIQ implementation in BTF
Responsible: **L. Foggetta (LNF)**
Staff: B.Buonomo

Resources

Risorsa	Struttura	Ruolo	FTE
A.Vannozzi (RN)	LNF	Tecnologo	0,5
L. Sabbatini	LNF	Tecnologa	0,2
A.Trigilio	LNF	Assegnista	0,2
P. Arpaia	NA	Prof. Ordinario Associato	0,1
A.Esposito (RL)	NA	RTD A - Associato	0,2
S. Pioli	LNF	Tecnologo	0,1
G. Latini	LNF	Assegnista	0,1
A.Giribono	LNF	Ricercatrice	0,1
C. Vaccarezza	LNF	Tecnologa	0,2
A.Liedl	LNF	Tecnologo	0,1
R. Pompili	LNF	Ricercatore	0,1
I. Drebot (RL)	MI	Ricercatore	0,3
E. Puppin	MI	Prof. Ordinario Associato	0,1
A. Bacci	MI	Ricercatore	0,1
L. Foggetta	LNF	Tecnologo	0,2
B. Buonomo	LNF	Tecnologo	0,2

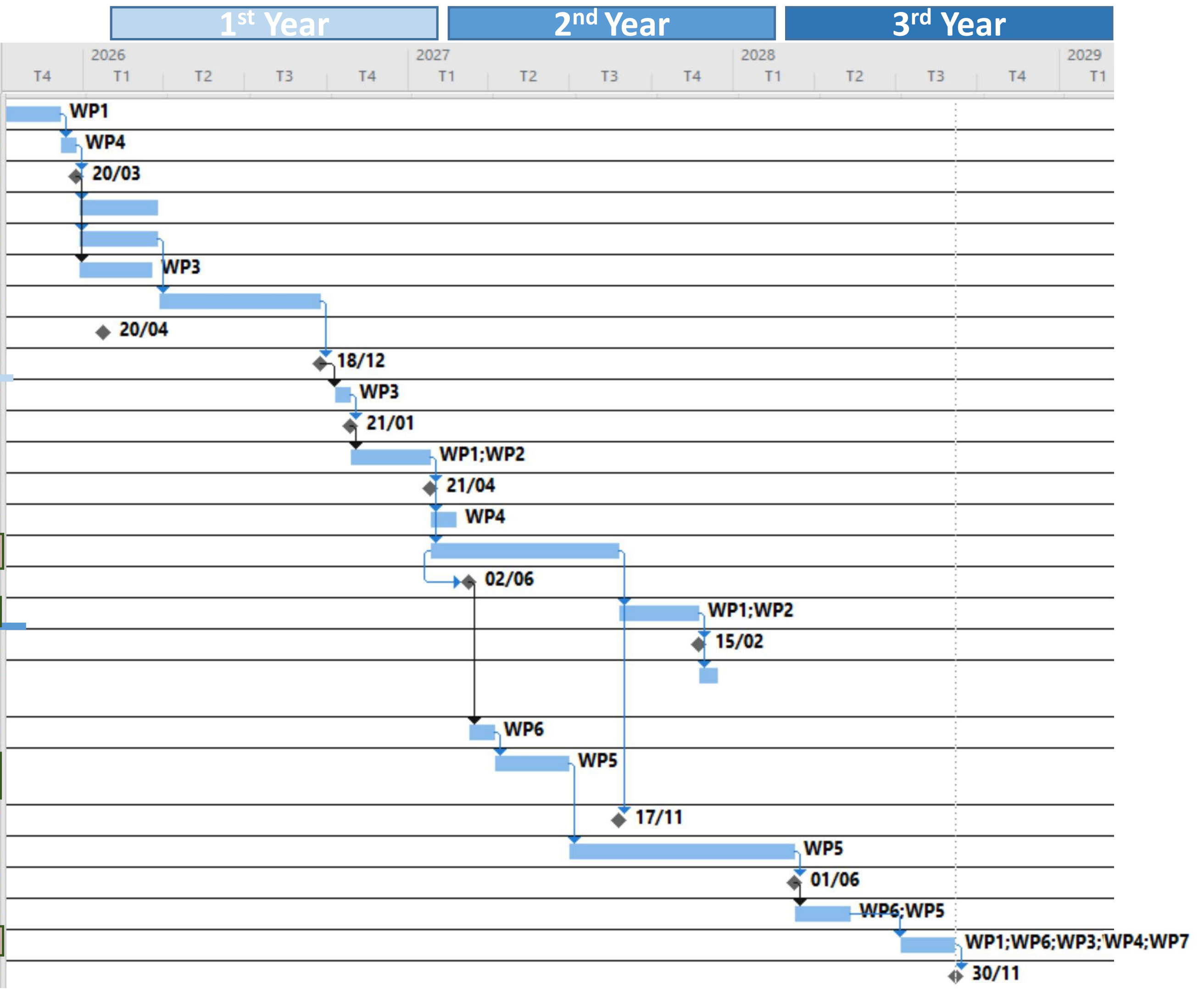
Ripartizione FTE	
Struttura	**FTE**
LNF	2,0
NA	0,3
MI	0,5
TOTALE	**2,8**

During LNF Magnetic Measurement Facility measurements, there will be a support of the technical staff of Accelerator Division Electrical Engineering Service

Gantt Chart

	Nome	Inizio programmata	Fine programmata
1	Magnetic Design of all PMQs	gio 01/01/26	lun 02/03/26
2	Beam Dynamics Design validation for EuPRAXIA linac requirements	mar 03/03/26	ven 20/03/26
3	**Final Magnetic Design of all PMQs**	**ven 20/03/26**	**ven 20/03/26**
4	Servo-motor Procurement for all PMQ	lun 23/03/26	gio 18/06/26
5	Magnetic Blocks Procurement	lun 23/03/26	ven 19/06/26
6	SW Development for Servomotor Control System	lun 23/03/26	ven 12/06/26
7	Production of first two PMQ prototypes: Short and Compact	lun 22/06/26	ven 18/12/26
8	**Delivery of first two PMQ as-built drawings**	**lun 20/04/26**	**lun 20/04/26**
9	**Delivery of first two PMQ prototypes Short and Compact**	**ven 18/12/26**	**ven 18/12/26**
10	Test of Servomotor Motion Control	lun 04/01/27	gio 21/01/27
11	**Release of Servomotor Motion Control SW**	**gio 21/01/27**	**gio 21/01/27**
12	Measurements and analysis of first two PMQ prototypes	ven 22/01/27	mer 21/04/27
13	**First Measurement Report**	mer 21/04/27	mer 21/04/27
14	Beam Dynamics measurement validation for EuPRAXIA linac requirements	gio 22/04/27	gio 20/05/27
15	Manufacturing of all the remanents PMQ	gio 22/04/27	mer 17/11/27
16	**Delivery of all PMQ as-built drawings**	**mer 02/06/27**	**mer 02/06/27**
17	Measurement of all the remanents PMQ	gio 18/11/27	mar 15/02/28
18	**Final Measurement Report**	**mar 15/02/28**	**mar 15/02/28**
19	Final Beam Dynamics measurement validation for EuPRAXIA linac requirements	mer 16/02/28	mar 07/03/28
20	Beam Dynamics analysis for PMQ linac implementation	gio 03/06/27	gio 01/07/27
21	Design of vacuum chamber and diagnostic station for PMQ implementation in linac	ven 02/07/27	gio 23/09/27
22	**Delivery of all the remanents PMQ**	**mer 17/11/27**	**mer 17/11/27**
23	Procurement of vacuum chamber and diagnostic station	ven 24/09/27	gio 01/06/28
24	**Delivery of vacuum chamber and diagnostic station**	**gio 01/06/28**	**gio 01/06/28**
25	Experimental setup assembly and installation in a linac	ven 02/06/28	gio 03/08/28
26	PMQ test on beam	ven 29/09/28	gio 30/11/28
27	**Final Project Report**	**gio 30/11/28**	**gio 30/11/28**

1st Year (rows 1–9) · 2nd Year (rows 10–17) · 3rd Year (rows 18–27)



Milestones | Deliverables

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

HARMONIQ

Risk Analysis

RISK	RPN	MITIGATION
Delay in the Blocks and / or servomotor procurement	Severity: 3 Occurrence: 6 Detection: 2 **RPN: 36**	- Prepare the documentation for the calls for tenders in advance the T0 of the project. -Ask for other supplier -Push companies to speedup the manufacturing
Non-compliance of Magnetized Blocks	Severity: 7 Occurrence: 5 Detection: 9 **RPN: 315**	- Order a higher number of blocks - Stress the company to provide preliminar tests on blocks in short time
Non-compliance of first two PMQ prototypes in terms of **- Field quality** **- Magnetic axis position repeatability** **- Requested integrated gradient**	Severity: 8 Occurrence: 6 Detection: 9 **RPN: 432**	- Foreseen in the mechanical design some space available between blocks and chassis to introduce shims to adjust the position of the blocks. It can be done from the measurements - Preliminary blocks and assembly characterization with CMM at supplier premises. - Preliminary magnetic blocks characterization of the supplier with magnetization intensity and direction. Use these values in the Opera 3D simulations to shift the blocks. - Preventive magnetic blocks Sorting - Modify the PMQ support sleds increasing the horizontal and vertical shift ranges. - Try to adjust the Eupraxia working point to see if the PMQs performances are still compliant with the beam focusing matching requirements.
Non-compliance of remaining PMQ prototypes in terms of: **- Field quality** **- Magnetic axis position repeatability** **- Requested integrated gradient**	Severity: 8 Occurrence: 6 Detection: 7 **RPN:336**	- The PMQ supply is split in (at least) two step. From the previous supply is possible to detect some problems in advance to the next supply. - Follows the same mitigation strategy of previous PMQs. - Try to adjust the Eupraxia working point to see if the PMQs performances are still compliant with the beam focusing matching requirements. - Preventive magnetic blocks Sorting
Unavaibility or delay of the vacuum chamber and/or diagnostic station.	Severity: 8 Occurrence: 4 Detection: 3 **RPN: 96**	- Recover some vacuum chamber and diagnostic station already available and adapt to the machine setup.
Unavailability of SPARC_LAB facility for HARMONIQ machine implementation	Severity: 6 Occurrence: 5 Detection: 5 **RPN: 150**	- Design of vacuum chamber and diagnostic station compatible both with SPARC_LAB and BTF setup (save for some minor interfaces). - Check the availability of BTF facility.

Cost Estimation

COSTS OVER 3 YEARS	
Item	**Cost**
Motors+encoders	€ 37.000,00
Magnetic Blocks	€ 13.000,00
Personal Computers	€ 6.000,00
PMQs Design Production and Assembly	€ 171.000,00
Vacuum Chamber	€ 30.000,00
Diagnostic Station	€ 10.000,00
Missions	€ 24.000,00
TOTAL	**€ 291.000,00**

1st year	
Item	**Cost**
PMQs Design Production and Assembly	€ 74.000,00
Magnetic Blocks	€ 13.000,00
Motors+encoders	€ 37.000,00
Personal Computers	€ 6.000,00
Missions	€ 4.000,00
TOTAL	**€ 134.000,00**

2nd year	
Item	**Cost**
PMQs Design Production and Assembly	€ 97.000,00
Missions	€ 8.000,00
TOTAL	**€ 105.000,00**

3rd year	
Item	**Cost**
Vacuum Chamber	€ 30.000,00
Diagnostic Station	€ 10.000,00
Missions	€ 12.000,00
TOTAL	**€ 52.000,00**

Thank you for the attention

HARMONIQ

Halbach Array for Rotational
MOdulation of NdFeB Integrated
Quadrupoles