New Tunable High Gradient Permanent Magnet Quadrupole for Plasma Wake Field Acceleration at SPARC_LAB

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Abstract. Applications such as colliders and plasma wake field acceleration require high gradient quadrupoles, in the range of 400-500 T/m and with a bore of few millimeters in diameter.

The design of a tunable high gradient permanent magnet quadrupole (PMQ), based on the QUAPEVA design [1] developed for the SOLEIL synchrotron, is presented. The quadrupole has a fixed part made of a Halbach quadrupole array [3, 4] surrounded by four permanent magnet cylinders with a radial orientation of the magnetic momentum. The gradient is regulated by rotating the cylinders, reaching a tunability greater than the 25%.

The quadrupole has been designed for the COMB plasma wake field beam driven experiment for the SPARC_LAB test-facility at INFN-LNF [2], one of the candidates to host the EuPRAXIA project [7, 8]. The present layout foresees two triplets where the focusing strength tuning is performed by moving two quadrupoles of each triplet along the beam axis. The new quadrupoles have bigger gradient and less multipolar content than actual ones, moreover it has a tuning system that does not need any shift of the magnet.

1. Introduction

SPARC_LAB, Sources for Plasma Accelerators and Radiation Compton with Lasers and Beams [9], is a test facility located at the INFN National Laboratories in Frascati, merging the potentialities of the SPARC_LAB high power high intensity laser system, named FLAME [11], and the former SPARC project

The SPARC project, installed at the INFN National Laboratories in Frascati, has been mainly devoted to the R&D activity on ultra-brilliant electron beam photo injector and on FEL physics. The FLAME[11] laser system is a nominal 250 TW laser linked to the SPARC linac and mainly devoted to explore laser-matter interaction, laser-plasma acceleration of electrons and protons both in the self injection and external injection modes.

This unique combination of a high brightness electron linac and high power laser, enables to explore a wide spectrum inter-disciplinary leading-edge research activity based on advanced radiation sources - as FEL experiments, X-rays generation by means of Thomson back-scattering and high peak power, narrow-band THz radiation and to investigate the plasma acceleration with different configurations. The scheme layout of the test facility is reported in Figure 1.
The current activity at SPARC\_LAB test facility is focused on the realization of plasma-based acceleration experiments to provide accelerating fields of the order of several GV/m while maintaining the overall quality (in terms of energy spread and emittance) of the accelerated electron bunch.

All these efforts are oriented to investigate the possibility to put forward the Laboratori Nazionali di Frascati (LNF) in Italy as host of the Eu-PRAXIA European Facility with the goal to design and to built new multi-disciplinary user-facility, equipped with a soft X-ray Free Electron Laser (FEL) driven by a $\sim$1 GeV high brightness linac based on plasma accelerator modules in the framework of the Eu-PRAXIA project [7].

PWFA applications, need beam transverse dimensions in the order of few microns [12] so, aiming to achieve such tight transverse beam sizes, a focusing system with short focal length and very high gradient (several hundreds of T/m) is needed. Moreover, a tunability of the system is necessary to adjust the focusing of the system to different beam energies considering also the possible future linac upgrade. In detail, the experimental apparatus for the PWFA includes a capillary tube where the plasma is hosted, beam diagnostics, plasma diagnostics and two symmetric permanent magnet quadrupoles (PMQ) triplets [12] based on Halbach Structure [3, 4]. Since all the focusing system is hosted in a ultra-high vacuum chamber, its compactness is fundamental and solutions such as tunable permanent magnet quadrupole [5] or hybrid high gradient quadrupole [6] are not feasible.

Figure 1. SPARC\_LAB layout: the RF gun (1); two S-band and one C-band TW structures (2), a THz source station and a vacuum chamber devoted to plasma-acceleration experiments (3); 14 degree dipole (4) FEL physics line (5) SASE and with seed-laser (10), beam diagnostics (6), Thomson back-scattering experiment (8) FLAME laser external injection (7) FLAME laser (11).

Figure 2. SPARC\_LAB linac layout labelled with all the main elements names (left) and a detail of the PMQ triplets (right). Each triplet is composed by one "long" PMQ (labelled with 5 and 2) and two short "PMQs" (labelled with 1, 3, 4 and 6).

Figure 2 shows the location of the PWFA module in the SPARC\_LAB linac and a detail of the
PMQ triplets at the inlet and at the outlet of the capillary. In Table 1 the measured parameters of the current PMQs are resumed in the columns named “Current Short” and “Current Long” where the Max $C_n/C_2$ is the maximum integrated multiple component normalized to the quadrupole.

This focusing system allows to tune the whole triplet focal length of about 5% thanks to a longitudinal position shift of two quadrupoles of the triplet (in Figure 2 PMQ 4 and 5 for the output triplet and PMQ 2 and 3 for the input triplet). Aiming to increase the energy acceptance for PWFA experiments and extending the capability of SPARC_LAB facility for other experiment like PWFA laser driven [10], a higher tunability of the focusing system is required keeping the same maximum focusing strength.

2. Magnetic design of new tunable high gradient PMQs for PWFA

Taking into account the requirements for the new focusing system, a new PMQs design based on the following guidelines have been done:

(i) Keep the same mechanical length of the current PMQ, respectively 10.7 mm and 20.1 mm.
(ii) Keep the same aperture of 6 mm.
(iii) Reach a maximum gradient bigger than 500 T/m.
(iv) Reach a tunability of $\approx 25\%$.
(v) Maximum integrated multiple component normalized to the quadrupole $\leq 1E-3$.

The last item of the list above, came from the good results gained with the current PMQs. The magnetic design of the new tunable PMQ (TPMQ) have been based on the so-called QUAPEVA design [1], designed for the synchrotron SOLEIL, considering the very good performance in terms of maximum gradient, field quality and the very high tunability. These PMQs are composed by two parts: a fixed one that corresponds to a Halbach ring [3, 4] surrounded by four permanent magnet cylinders with a radial orientation of the magnetic momentum. The rotation of the cylinders allows to tune the gradient within a very high range (more than 25% as detailed later). All the parts of the TPMQ are composed by NdFeB since the PMQ will operate at room temperature environment and considering the high remanence of the material ($B_r \approx 1.3 T$).

The first step of the design was the definition of the number of the blocks forming the TPMQ fixed part (Halbach ring). For a quadrupole, with long magnetic length, the gradient can be expressed as follows [4]:

$$\begin{align*}
G &= 2KB_r \left( \frac{1}{R_i} - \frac{1}{R_o} \right) \\
K &= \frac{M}{\pi^2 \cos^2 \left( \frac{2\pi}{M} \right)} - \sin \left( \frac{2\pi}{M} \right)
\end{align*}$$

where $B_r$ is the remanence field, $M$ the number of segments, $R_i$ and $R_o$ are the inner and outer radius respectively. Figure 3 presents the computed field gradient versus the number of segments for a Halbach quadrupole with inner and outer radius of 3mm and 10 mm respectively (the same one of the current configuration). Choosing eighth sector, it’s possible to reach a gradient of 447 T/m that is almost the required 500 T/m. Taking into account that the gradient increasing due to the presence of the four tuning cylinders and that higher the number of sectors more complicated and more expensive to manufacture is the magnet, the eight sector have been considered as a good compromise.

After this, the four tuning cylinders have been added and several simulations with 2D Poisson Superfish Finite Element Analysis (FEA) software have been done fixing the inner radius to 3 mm and varying the Halbach ring outer radius ($R_o$) and the diameter of the tuning cylinders. An
increasing of the latter, led to a bigger gradient and also a higher tunability, while an increasing of $R_o$ led to a gradient increasing but to a reduced tunability. Therefore several simulations have been performed to find the best fit with the requirements. For each TPMQ simulation, a multipole analysis have been performed at a reference radius of 1 mm aiming to check that all the multiple component are within the required 1E-3. Several 3D simulations have been performed in Opera 3D FEA software for the definition of the magnetic length and their results are resumed in Table 1 where they are compared with the current PMQs properties. It must be pointed out that the values of the current PMQs are measured values while the new proposed TPMQ parameters are simulations results. Figures 4 and 5 show respectively a 3D view of the short TPMQ and three sketches of the TPMQs in three different configurations: maximum gradient (a) intermediate gradient (b) and low gradient (c).

| Table 1. Current PMQs and proposed TPMQ main parameters. | Current Short | New Short | Current Long | New Long |
|-----------------------------------------------------------|---------------|-----------|--------------|----------|
| Mechanical Length [mm]                                    | 10.7          | 10.7      | 20.1         | 20.1     |
| Bore diameter [mm]                                        | 6             | 6         | 6            | 6        |
| Outer diameter [mm]                                       | 20            | 18        | 20           | 18       |
| Tuning cylinders diameter [mm]                            | 20            | 24        | 20           | 24       |
| Max Gradient [T/m]                                        | 481           | 529       | 519          | 572      |
| Max $L_{mag}$ [mm]                                        | 11.48         | 11.8      | 20.1         | 20.7     |
| Max integrated $C_n/C_2$                                  | 1E-01         | 9.36E-04  | 5E-02        | 8.72E-04 |
| Good field radius [mm]                                    | 1             | 1         | 1            | 1        |
| Tunability [%]                                            | 5             | 25.5      | 5            | 27.9     |

Figure 3. Computed field gradient vs the number of segments. The red dot indicates that 8 segments have been chosen for the realization of the PMQ Halbach ring fixed part.

The integrated gradient behaviour with respect to the angular position of the cylinders is shown in the plots of figure 6 both for the long and short TPMQ.

From the plots it is possible to see the very high tunability of the integrated gradient that corresponds to 25.5% and 27.9 % respectively for the short and long quadrupoles.

In the proposed TPMQs the tuning cylinders are rotated with opposite rotation direction according to the black arrows illustrated in figure 5. This solution have been already investigated by Synchrotron SOLEIL staff [1] but in this paper a harmonic content comparison between

1 The values of current short and long PMQs, are measured values while the values of the new PMQs are simulation results.
Figure 5. TPMQ in the maximum (a), intermediate (b) and minimum (c) gradient configurations. Black arrows indicate the cylinders rotation spin for the focusing tuning. On the right, the intermediate gradient configuration (b') for the same direction of rotation case where red, blue and green arrows show respectively the magnetization of the tuning cylinders, the direction of roation and the magnetic field loop that led to a skew quadrupole component.

Figure 6. Integrated gradient evaluated at 1mm radius from the magnetic axis vs tuning cylinders rotation angle (theta) of the short (plot a) and long (plot b) TPMQs.

opposite and same rotation direction solution is presented. The main advantage of the opposite rotation direction, is the very high reduction of skew quadrupole component in the intermediate gradient configuration (configuration b in figure 5) as shown in the figure 7 hystograms.

Figure 7. Normalised skew harmonic components (a) and normalised skew harmonic component except the skew quadrupole (b) for the ”same rotation direction” configuration (yellow columns) and ”opposite rotation direction” configuration (blue columns). All the plots refers to configuration b of Figure 5 and are evaluated at a 1mm radius from the magnetic axis.

It is possible to see how all the harmonics are the same for both the configuration except for a huge skew quadrupole component that occurs in the ”same rotation direction” configuration that is almost the 16% of the main quadrupole component. This behaviour was expected because, in case of same rotation direction, the tuning cylinders magnetization orietnation led to a quadrupole skew component, as illustrated by the magnetic field loops (green lines)
in configuration b’ of Figure 5. Aiming to better evaluate the magnetic performance of the
cquadropoles, several harmonic analysis have been performed observing the amplitude of the
integrated harmonic content with respect to the angular position of the tuning cylinders. From
this analysis, it results that the bigger harmonic component is the normal octupole shown in
figure 8.
Comparing the octupole component illustrated in 8 with the harmonic content of a eighth sector
Halbach PMQ, with the same inner and outer radius reported in Table 1 and without the four
tuning cylinders reported in Figure 9, it’s possible to see how the octupole component is very
reduced with respect to the one in TPMQ in the minum gradient configuration. This is due
to a brake of the quadrupole symmetry in the configuration b of Figure 5 considering that the
octupole is not an harmonic due to the quadrupole symmetry (they are n=2,6,10,... with n
generic harmonic order). This is not a big issue considering that the maximum octupole fulfill
the required 1E-3.

Figure 8. Integrated normal octupole component evaluated at 1mm radius from the magnetic
axis vs the tuning cylinders angular position for the short (a) and long (b) TPMQ.

Figure 9. Normalized multipole component of a eight sector Halbach PMQ evaluated at a 1mm
radius. The red column is the octupole component.

3. Conclusions
The design of a tunable PMQ based on the one of QUAEVA PMQ for the Soleil synchrotron,
has been done tailoring its features on the requirements for the beam injection and extraction
from the capillary of the SPARC_LAB PWFA acceleration module. This design fullfill the
requirements for the new quadrupoles and show a higher tuability and an increase of the
maximum gradient with respect to the current PMQs. Another advantage could be the
different tuning method based on the rotation of four permanent magnet cylinders instead of a
longitudinal shift of the position of the quadrupoles, this could avoid any possible misalignment
that could occur in the quadrupoles shifting. Moreover, the field quality are within the
requirements (maximum normalised integrated multipole ≤ 1E-3) and harmonic analysis for the
tuning cylinders opposite rotation direction have been investigated showing a strong reduction
of skew quadrupole component. Further investigations about the forces between the magnetic
blocks have to be finalized as well as an accurate design of the tuning cylinders mover system.
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