TUNABLE HIGH-GRADIENT QUADRUPOLES FOR A LASER-PLASMA ACCELERATION-BASED FEL*

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Abstract

The magnetic design and characterization of tunable high gradient permanent magnet based quadrupole, or so-called QUAPEVAs, are presented. To achieve a high gradient field with a compact structure, permanent magnets are chosen rather than usual electro-magnets due to their small aperture. The quadrupole structure consists of two superimposed quadrupoles capable of generating a gradient of 210 T/m. The first quadrupole is composed of permanent magnets in a Halbach configuration shaped as a ring which attains a constant gradient of 160 T/m, and the second is composed of four permanent magnet cylinders surrounding the ring and capable of rotating around their axis in order to achieve a gradient tunability of ±50 T/m. Each tuning magnet is connected to a motor and is controlled independently, enabling the gradient to be tuned with a rather good magnetic center stability (20 μm and without any field asymmetry. Seven quadrupoles have been built with different magnetic lengths in order to fulfill the integrated gradient required. A set of QUAPEVA triplet are now in use, to focus a high divergent electron beam with large energy spread generated by a laser plasma acceleration source for a free electron laser application [1].

INTRODUCTION

Accelerator physics and technology have recently seen tremendous developments especially in the synchrotron radiation domain, which is actively investigating low emittance storage rings with multibend achromat optics for getting closer to the diffraction limit and providing a high degree of transverse coherence [2]. In addition, Laser Plasma Acceleration (LPA) can now generate a GeV beam within a very short accelerating distance, with high peak current of ~10 kA, but the high divergence (on the order of a few mrads) and large energy spread (a few percent) can present problems.

All these recent developments require high gradient quadrupoles that can not be provided by usual room temperature electro-magnet technology. To achieve a high gradient, one is more likely to choose either superconducting or permanent magnet [3] technologies. Permanent Magnets (PMs) can be arranged in the so-called Halbach configuration [4], to provide a quadrupolar field. Interest in permanent magnet quadrupoles has been recently renewed because of their compactness and their capability of reaching high field gradient, alongside the absence of power supplies, letting them to be a solution for future sustainable green society.

DESIGN

The QUAPEVA is composed of two superimposed quadrupoles, one placed at the center following a Halbach configuration, surrounded by another that consists of four rotating cylindrical magnets to provide the gradient variability, illustrated in Fig. 1). Figure 1 also shows three particular configurations of the tuning magnets; (a) maximum gradient: tuning magnets easy axis towards the central magnetic poles, (b) intermediate gradient: the tuning magnets are in the reference position, *i.e.* their easy axis is perpendicular to the central magnetic poles, (c) minimum gradient: tuning magnets easy axis is away from the central magnetic poles. Table 1 shows the QUAPEVA parameters alongside the characteristics of the magnets and poles.

Table 1: QUAPEVA Parameters.

Parameters	**Value**	**Unit**
Gradient (G)	110 - 210	T/m
Remanent Field (B_r)	1.26	T
Coercivity (H_{cj})	1830	kA/m
Good-Field Region	4	mm
$\Delta G/G$	< 0.01	at 4 mm

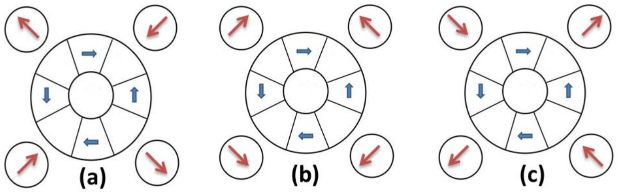

Figure 1: (a) maximum gradient, (b) intermediate gradient, (c) minimum gradient.

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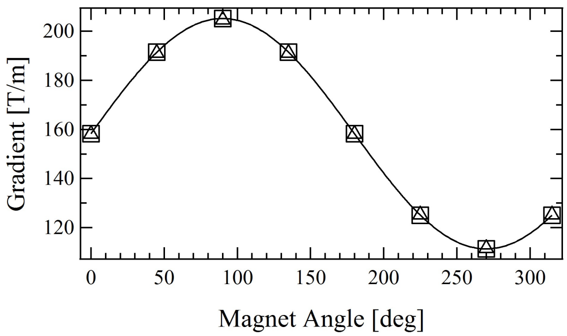

Figure 2: Magnetic field gradient computed as the cylindrical magnets are rotating for the 100 mm magnetic length of the QUAPEVA. (□) RADIA, (△) TOSCA.

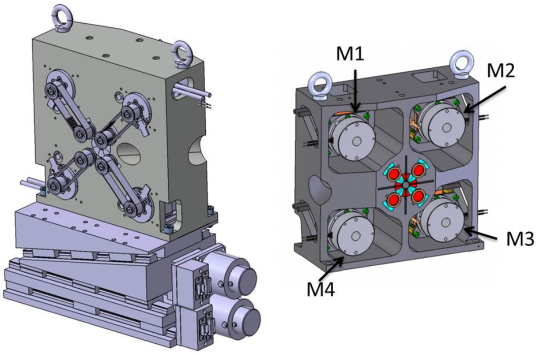

Figure 3: QUAPEVA design mounted on a translation table.

In order to optimize the geometry and magnetic parameters, QUAPEVAs are modeled using two numerical tools: RADIA, a magnetostatic code based on the boundary integral method where materials are meshed [5], and TOSCA, a finite element magnetostatic code [6].

Figure 2 shows the gradient computed as the cylindrical magnets rotate in the case of the 100-mm magnetic length system. The intermediate gradient is $\sim$160 T/m, and due to the rotating magnets it can be increased by $\sim$50% up to 210 T/m.

The motors have sufficient torque to counteract the magnetic forces induced by the magnetic system, are very compact (48.5 x 50 x 50 mm^3), and have an encoder within a 31-µrad resolution. The magnetic system is mounted on an Aluminum frame and the motors are placed at the four corners of the frame to avoid perturbations of the magnetic field as shown in Fig. 3. A non-magnetic belt transmits the rotation movement from the motor to the cylindrical magnets. Each magnet is connected to one motor to allow for a precise positioning of each magnet and minimizes the magnetic center shift at different gradients. The quadrupole is mounted on a translation table (horizontal and vertical displacement) used to compensate any residual magnetic axis shift when varying the gradient, to perform electron beam based alignment or for the magnetic measurements benches.

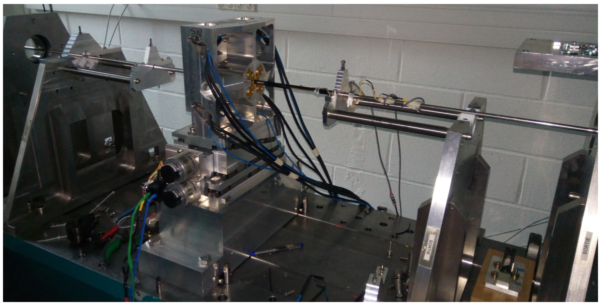

Figure 4: Rotating coil bench installed at SOLEIL.

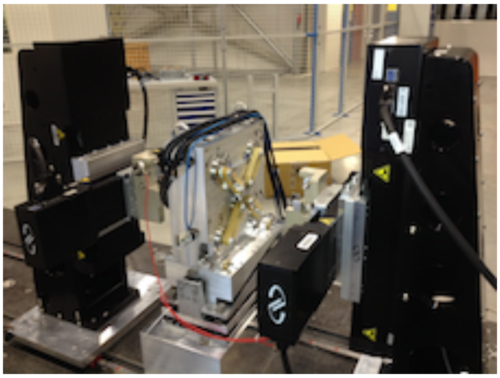

Figure 5: Stretched wire bench at ESRF.

MAGNETIC MEASUREMENTS

Displayed in Fig. 4, a dedicated 10-mm diameter, radially rotating coil was built for the SOLEIL magnet characterization bench [7], to fit the quadrupole inner diameter of 10.5 mm. In order to qualify the accuracy of the rotating coil, a permanent magnet quadrupole with a 76-mm diameter bore has been measured first with a reference coil and then with the 10-mm diameter coil. The geometrical parameter of the new coil has been determined in order to find the same harmonic content with both coils at 4 mm.

The integrated gradient of the seven systems with different magnetic lengths is measured with the rotating coil and compared to the simulations of RADIA and TOSCA, where they showed good agreement with a difference no larger than 4%.

The stretch-wire bench developed at ESRF [8] has been used for magnetic field integral measurements (see Fig. 5). The wire is positioned inside the magnet gap and its resonance frequency is tuned. Its sag depends on its tension. A voltage proportional to the variation of magnetic flux is induced and measured with a Keithley nanovoltmeter, resulting in the first field integral. A granite table supports the linear stages and the measured magnet. The stretched wire bench enables fast measurements to be performed with good precision and good repeatability.

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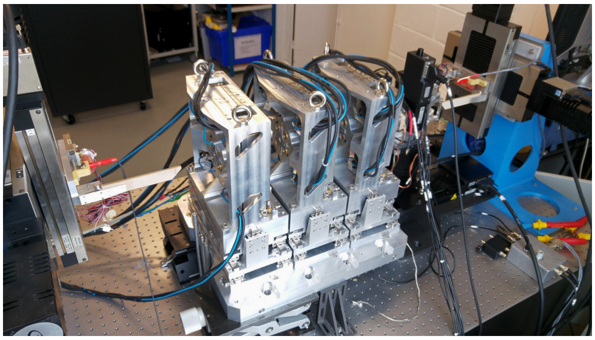

Figure 6: Pulsed wire system setup with three QUAPEVAs (26 mm, 40.7 mm, and 44.7 mm mechanical lengths).

This method has been used to calculate the magnetic center excursion as the gradient is varied. The center stability is found to be within ±10 µm.

The pulsed-wire method has been used to align the magnetic center of the three QUAPEVAs (see Fig. 6) before their installation at COXINEL transport line [9]. It is based on applying a square current pulse through a wire placed in a magnetic field, which induces an interaction due to the Lorentz force. This force leads to wire displacement which is measured using a motion laser detector [10].

A first triplet of QUAPEVA was checked with the pulsed wire technique in view of the COXINEL application. The three QUAPEVA were directly installed on the bench, with a medium gradient value setting and with random values for the horizontal and vertical positions of the translation stage. The pulse wire measurements for such a deviation show deviations of the magnetic axis from the axis. Then, the three QUAPEVA were centered one by one, starting from the 40.7 mm, then the 44 mm and finally the 26 mm. Such an adjustment had been performed with only two iterations for each quadrupole: the first measurement is performed for the actual position and the second one while the quadrupole has been displaced 250 µm in the vertical and horizontal planes. As the field is proportional to the displacement, the new positions are calculated from these two measurements to recover the center position. The pulsed wire technique was thus used for checking the final alignment and the absence of cross talk between the magnets.

COXINEL

A first triplet (26-mm, 40.7-mm, and 44.7-mm mechanical length) is used for focusing the electron beam produced by laser plasma acceleration at Laboratoire d'Optique Appliquée in view of electron qualification with a Free Electron Laser application. The results from the pulsed wire measurement have been used for QUAPEVA alignment during COXINEL experiment. Figure 7 shows the electron beam, using a lanex screen placed 3 m away from the electron source, with and without the triplet. The large divergent beam is well focused.

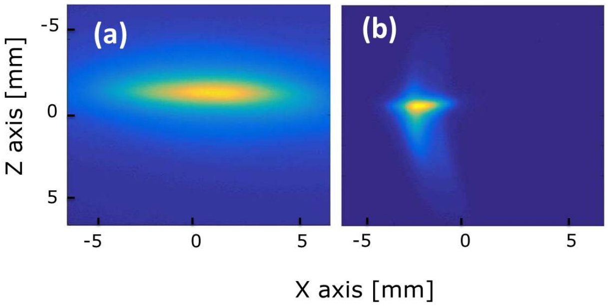

Figure 7: Measured electron beam on a Lanex screen placed 3 m away from the electron source. (a) without QUAPEVAs, (b) with QUAPEVAs.

CONCLUSION

The design and magnetic measurements of a permanent magnet based quadrupole of variable strength have been presented. A high gradient (~210 T/m) with a wide tuning range (~100 T/m) is obtained with such a design. The measurement using different methods are consistent and in good agreement between themselves and the simulations. The quadrupoles have been installed successively at COXINEL beam line, and are able to achieve good focusing with a highly divergent large energy spread beam.

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