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QUAPEVA: VARIABLE HIGH GRADIENT PERMANENT MAGNET QUADRUPOLE

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Abstract

The magnetic and the mechanical design of a high and variable gradient Permanent Magnet Quadrupole (PMQ) is presented. Seven of them with various lengths, ranging from 26 mm up to 100 mm, for different integrated quadrupole strengths were manufactured. The measured magnetic performance of these devices is also reported. These devices were successfully commissioned to transport laser plasma accelerated electron beam.

INTRODUCTION

Current accelerator projects require strong quadrupole magnets to focus particle beams to ever smaller size. They rely on the very mature resistive magnet technology for gradient below typically 100 T/m. For larger gradient, Permanent Magnet (PM) technology seems to be attractive alternative as the highest gradient value ever reported with a PMQ is 575 T/m for a 2.75 mm bore radius [1]. However, since the first proposal of PM multipole design in the early eighties [2], their use in accelerators stayed marginal. Their relative poor field quality and the small field tuning has limited them to specific applications such as final focus system in colliders [3-5] or in projects where PM technology offers a clear and substantial saving over resistive technology [6].

A fixed gradient quadrupole targeting standard field quality of light source accelerator magnet, which smears the difference between the magnetic performance obtained with resistive and PM accelerator magnets, was recently developed at the ESRF [7].

We present hereafter the design of the QUAPEVA, a variable high gradient PMQ, i.e. with a gradient larger than 100 T/m and 50 % tunability [8-11]. As far as the amplitude of the gradient adjustment is concerned, this design also brings PM accelerator magnet closer to resistive magnet. One prototype and two triplets were manufactured for an experiment dedicated to the demonstration of a COherent X-ray source INferred from Electrons accelerated by Laser (COXINEL) [12]. We first introduce the concept and the parameters for QUAPEVA COXINEL, we then present the magnetic performance of the seven built items.

QUAPEVA CONCEPT

General Description

The magnetic design of QUAPEVA is shown in Fig. 1. The magnet structure is made of two concentric quadrupoles. The inner quadrupole follows the Halbach hybrid arrangement of PM and soft iron poles to drive the PM magnetic flux into the gap. The soft iron poles also smooth the PM magnetic imperfections and thus help improving the field quality. The outer quadrupole is dedicated to the field gradient tuning and is composed with a set of four cylindrical PM magnetized in radial direction. Each magnet is located at the top of one of the inner quadrupole soft iron pole. The soft iron shield placed behind each rotatable magnet limits the field leakage from the outer quadruple.

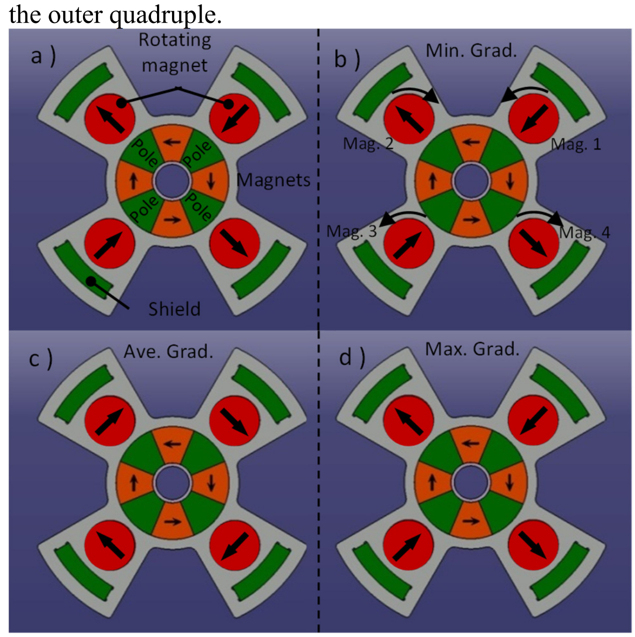

Figure 1: Schematic of the QUAPEVA magnetic design (a). Orientation of the four rotating magnets at minimum gradient (b), average gradient (c) and maximum gradient (d).

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Table 1: Main Characteristics of the COXINEL QUAPEVA

COXINEL QUAPEVA	Bore Radius	Good Field radius	Material	Length [mm]	Max Grad [T/m]	Tuning Range [T/m]	Max. Int. Grad [T]	Tuning Range [T]	B6 [unit]	B_{10} [unit]
Prototype	6 mm	4 mm	Magnet: $N_2dFe_{14}B$ Remanence: 1.26 T Pole: Fe-Co Alloy Saturation: 2.35 T	100	201	92	21.3	9.7	300	100
1st Triplet				20.6	164	78	5.3	2.5		
				40.7	180	85	8.4	3.9		
				44.7	183	86	9.3	4.3		
2nd Triplet				47.1	184	86	9.8	4.5		
				66	190	88	13.9	6.4		
				81.1	195	89	17.2	7.8		

Gradient Tuning

Changing the orientation of the four magnets magnetization by rotating them around their centre allows for the tuning of the QUAPEVA gradient. There is only one configuration to reach the extremum of the QUAPEVA gradient, while rotating four magnets to set the QUAPEVA gradient to any arbitrary value in between minimum and maximum gradient, offers an infinite combination. However the QUAPEVA being a quadrupole, it is preferable to use the rotation rule defined in Fig. 1 which preserves the symmetry of the quadrupole field, as the soft iron poles of the inner quadrupole can enhance any undesired multipole component generated from the outer structure At minimum gradient the four rotating magnets are oriented so that their magnetization opposes to the one in the soft iron poles. To vary the gradient magnets two magnets are rotated in one direction, the two others in the opposite direction. At intermediate gradient, the magnetic field of the outer quadrupole loops around the inner quadrupole. At maximum gradient, the four rotating magnets are oriented so that their magnetization adds up to the one in the soft iron poles.

COXINEL QUAPEVA

Main Magnetic Characteristics

The main characteristics of the prototype item and the two triplets for COXINEL are listed in Table 1. The first (resp. second) triplet aims at super-matching a 180 (resp. 400) MeV LPA electron beam with a typical 1% energy dispersion into an undulator located several meters downstream the triplet [13]. Except for their magnetic lengths, all these magnets have identical characteristics as indicated in Table1.

The PM design associated with the small bore radius leads to a compact structure of only 90x90 mm² magnetic section while a gradient as high as 201 T/m with a tuning range of 92 T/m is achieved. However the required field quality is less stringent than typical 10^{-3} field quality necessary for light source magnets. Thus, with a normalized dodecapole B_6 and icosapole B_{10} harmonics which the magnitude are respectively 300 and 100 units, the tolerances on systematic multipole errors are relaxed.

Mechanical Layout

A picture of a built QUAPEVA is shown in Fig. 2. The magnetic system is encapsulated in an Aluminium support frame to maintain the poles and the magnets in their positions. The Aluminium support rests on a translation table which allows 10 mm vertical and horizontal displacement. Translation tables are naturally convenient during the installation and the alignment of QUAPEVAs in the COXINEL transport line. They were found to be important equipment for COXINEL, as they enable the implementation of a key feature of the transport line, the so-called Beam Pointing Alignment Compensation (BPAC) [14].

Each magnet of the outer quadrupole is connected to a 3 Nm brushless motor from the manufacturer HARMONIC DRIVE, with in between a 1 to 100 gear ratio reducer. An incremental rotary encoder is fixed to the back of each motor. This solution is compact as the motor and the incremental encoder fits within an envelope of 50x50x50mm³. The rotary encoder coupled with the gear reducer provides a resolution better than 30 µrad.

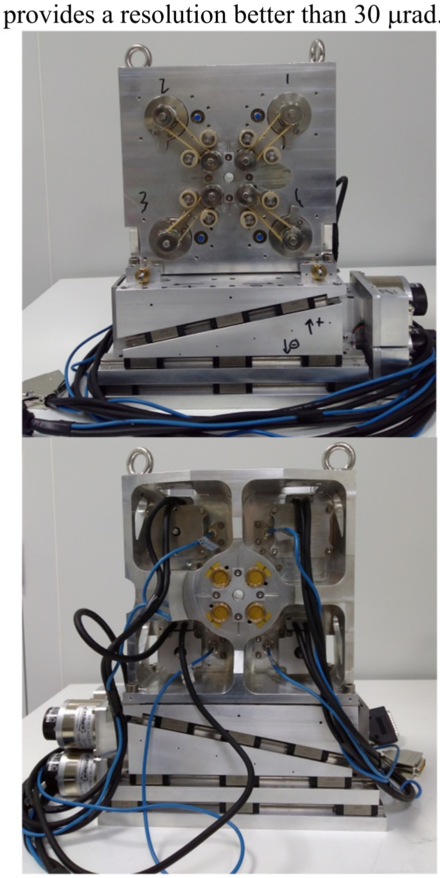

Figure 2: Front (top) and back (bottom) view of an assembled QUAPEVA.

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MAGNETIC MEASUREMENTS

Most generally, the magnetic measurement goal of a conventional accelerator magnet is to ensure that the manufactured magnet performs as designed and to locate the magnetic axis of the device. For a QUAPEVA, magnetic measurements are also required to align properly the magnetization of the four rotating magnets, prior to validate its magnetic performance. Indeed one disorientated magnet prevents the QUAPEVA from reaching its theoretical extremum gradient. It also causes the QUAPEVA to exhibit a large magnetic center excursion.

Measured gradient tuning

The measured variation of the integrated gradient with respect to the rotation angle of the four magnets is shown in Fig. 3. As expected the variation with the respect to the rotation angle is closed to a sine-like function and the gradient reaches it extremum at $\pm\pi/2$.

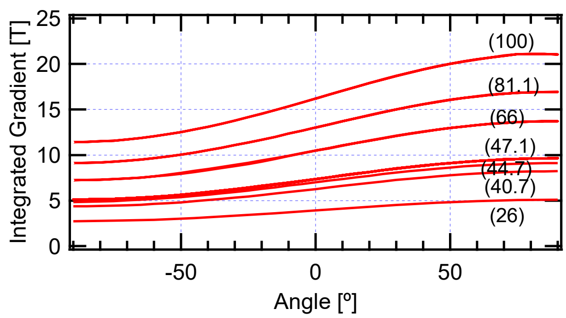

Figure 3: Measured integrated gradient of the seven QUAPEVA. The QUAPEVA length is given in mm in parenthesis.

Figure 4 compares the measured maximum value of the integrated gradient to the design value. Only the gradient of prototype QUAPEVA exceeds its design value, by a small margin, i.e. less than 0.5%. The two triplets exhibit a smaller maximum gradient than designed for. The difference increases as the length decreases and top at almost 4% for the thinner device. A slight discrepancy between the fringe field of a manufactured QUAPEVA and the numerical model would explain this difference as its contribution to the total field decreases with the quadrupole length.

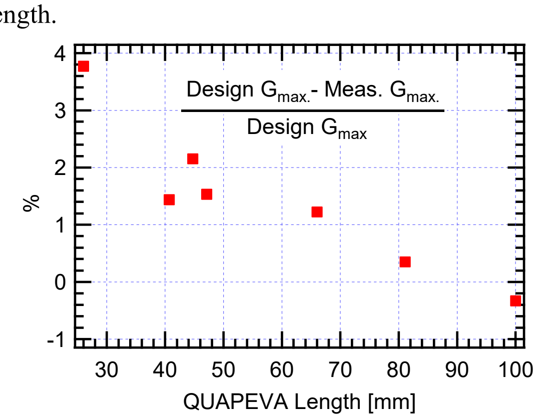

Figure 4: Normalized difference between the maximum measured integrated gradient and the design maximum gradient.

We observe that the variation of the systematic harmonics with respect to the rotation angle of the four magnets is also closed to a sine-like function. The systematic harmonics are at maximum value when the amplitude of the integrated gradient is also at maximum. The first systematics harmonics, measured at maximum gradient along the circle with a 4 mm radius are given in Table 2. The dodecapole harmonic is well within specification while the icosapole component slightly exceeds the 1% target.

Table 2: First Systematic Harmonics Measured at Maximum Gradient and at 4 mm Radius

QUAPEVA Length [mm]	26	40.7	44.7	47.1	66	81.1	100
B_6	195	211	223	209	232	227	221
B_{10}	115	112	119	119	116	120	123

CONCLUSION

The design and the measurement of seven PM quadrupole have been presented in this paper. The built QUAPEVA perform almost as designed and successfully offer a high gradient and a wide gradient tuning. The first triplet was successfully installed and used on COXINEL beam transport line.

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