PROTOTYPING OF A TUNABLE PERMANENT MAGNET QUADRUPOLE*

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Abstract

Within the Research Facility 2.0 (RF2.0) project, one of the objectives is the development of novel permanent magnet technologies and refurbishment strategies aimed at reducing energy consumption in accelerator facilities. In this context, ALBA, ELYTT, and HZB are jointly developing a tunable quadrupole prototype based on permanent magnets, conceived as a demonstrator for next-generation, energy-efficient magnet systems. The prototype is designed to achieve high-gradient focusing while drastically reducing power consumption relative to conventional electromagnets, eliminating the need for large coils and water cooling. Its compact architecture also eases integration into densely packed storage-ring lattices. Tunability is provided through a hybrid approach combining movable soft-iron elements and small auxiliary coils, offering a wide operational range with minimal energy demand. This contribution presents the electromagnetic and mechanical design of the prototype, the assembly strategy, and the current status of the manufacturing and testing.

MAGNETIC CONCEPT

As part of the European funded RF2.0 [1] project, the three partners ALBA, ELYTT and HZB are developing a tunable permanent-magnet (PM)-based quadrupole (QP) magnet[1] to explore the feasibility of high-gradient focusing magnets in upcoming particle accelerators like ALBA II [2–4] or BESSY III [5–8] with extremely low power consumptions, but large operational ranges similar to existing electromagnets. The main advantage of this new design is an expected power consumption of less than 100W (during tuning) instead of up to 2 kW for a similar electromagnet design, maintaining a tuning range of up to ±20 %. In addition, no direct water-cooling system for the magnet is necessary, which further reduces the overall power consumption of the system, as well as the sources of vibrations. This magnet concept has the potential to reduce the overall CO2 footprint of highly stable future particle accelerators, without the loss of flexibility. The elimination of the large driving coils for an electro-quadrupole enables a more compact design, leading to more space between magnets in storage ring lattices. The initial magnet concept can be seen in Fig. 1. It is based on a PM-QP magnet where NdFeB PM blocks (yellow) are installed in the magnet yoke (grey), guiding the magnetic flux to the inner pole tip region with a small aperture diameter of ≈ 25 mm. Hereby, magnetic gradients of up to 110 T/m are possible. Additional tuning plates (purple) next to the PM blocks can be moved via motors into and out of the yoke gaps. This changes the amount of magnetic flux that goes through the magnet pole fingers and by this the magnetic gradient. A reduction by more than 40 % with respect to the maximum gradient can be achieved. For faster, but less efficient corrections, compact electric coils (orange) can be installed, to vary the gradient by a few percent.

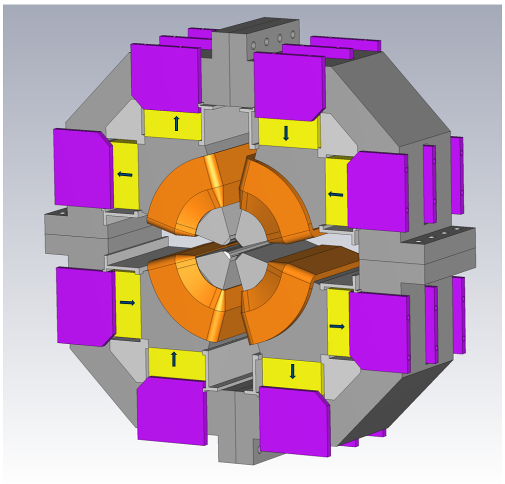

Figure 1: Tunable QP-PM concept, based on mechanical (purple) and electrical (orange) tuner techniques.

MAGNETIC MODEL AND OPTIMIZATION

Based on the magnet concept, we started an optimization of the magnet pole tip design with an aperture diameter of 23 mm to stabilize the main quadrupolar component and to reduce the higher order multipoles. The magnetic field $\mathfrak{B}$ in the central plane next to the geometric axis of the magnet can be described by Fourier components

$$\mathfrak{B} = \sum_n (A_n + iB_n)(x + iy)^{(n-1)} \tag{1}$$

with A_n and B_n as the real (skew) and imaginary (normal) amplitudes of the multipole-components of order n, at transverse distance from the magnetic axis given by x and y. These amplitudes will be measured along a reference circle with radius r_{ref}.

Because of symmetry and boundary conditions, for quadrupole magnets only the amplitudes B_2, B_6,B_{10}, B_{14}, etc. are non-zero. Here, B_2 describes the main quadrupolar

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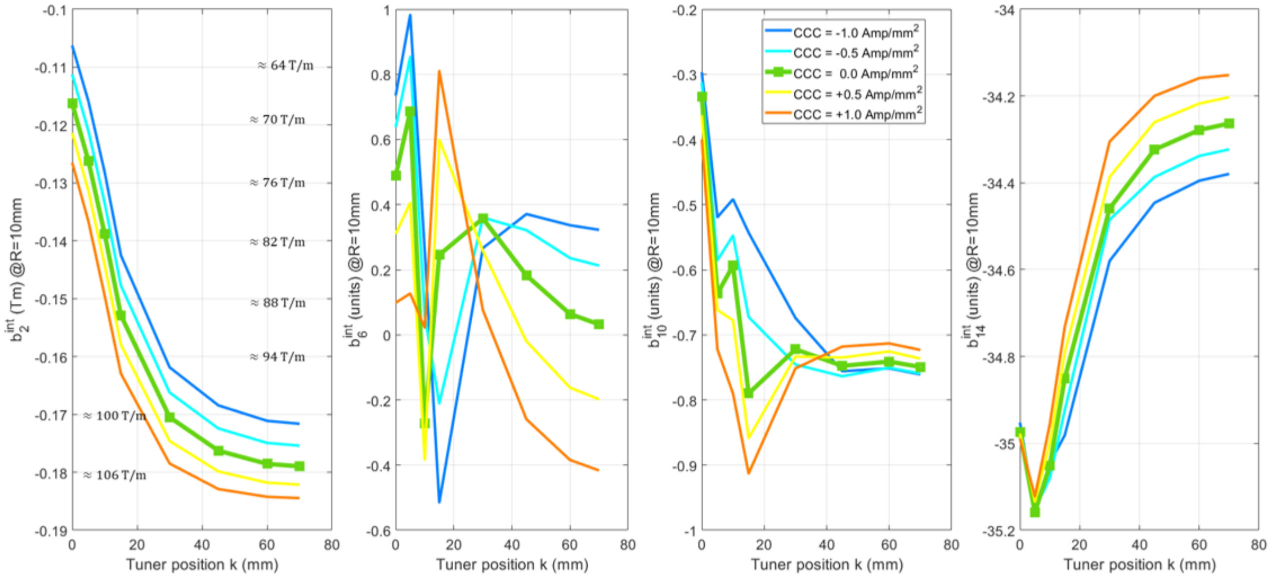

Figure 2: Integrated magnetic multipoles b_n as function of both tuning procedures (mechanical and electric).

component whereas the other terms give the higher-order multipolar components. To describe the effect of the magnetic field on a particle beam crossing the magnet's aperture the field components must be analyzed along the magnet axis as relative integrated multipole values in "units":

$$b_n^{(\mathrm{int})} = \frac{\int B_n dz}{\int B_2 dz} 10^4. \tag{2}$$

For the first step, the pole tip profile was defined by a split polynomial to have independent geometric parameters for the individual adjustment of magnetic multipoles. Here, the basic hyperbolic function is given by:

$$P_m(\zeta) = \sqrt{R_m^2 + k_m \zeta^2} \tag{3}$$

with the pole aperture radius R and the weighting factor k_m of the second order polynomial in the region ζ. For pole tip half-width G corresponding to the pole gap and the polynomial edge position a, the final shape can then be defined as $[\ P_2(\zeta)|_{-G}^{-a}\ ,\ P_1(\zeta)|_{-a}^{a}\ ,\ P_2(\zeta)|_{a}^{G}\ ]$. An example can be seen in the left picture of Fig. 3.

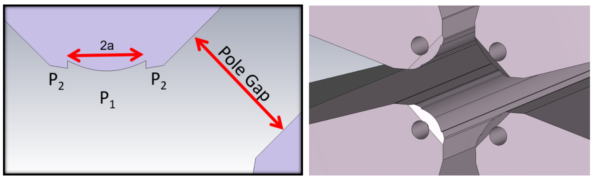

Figure 3: Polynomial pole-tip setup of the PM-QP for field optimization. Left: 2D profile example of two polynomial pole-tip design. Right: Optimized 3d profile with additional chamfers and fringe field stabilization holes.

The resulting fields were analyzed via FFT on a reference radius of 8 mm to determine parameter settings with suppressed higher-order multipoles. Numerical optimization allowed the determination of parameter combinations that minimize b_6 and b_{10} simultaneously (< 1 unit).

A reduction of $b_1$4 was not possible within the given parameter space of the pole tip, but its impact is negligible for most particle accelerators. In the second step, the best parameter settings were used for the 3D magnetic field calculation for a magnet length of 160 mm. Here, the integrated multipole components were calculated via FFT on the surface of a cylinder along the magnet axis with radius 8 mm. Due to saturation effects in the pole tip material at the longitudinal edges of the pole fingers, additional multipole fields (especially b_6) can arise in the fringe field region. A chamfer with optimized depth at those edges can reduce the multipole components.

However, due to the large field strength variation, it was not possible to compensate the multipoles by simple chamfering for all tuner setups, which resulted in a large variation of b_6 by more than 6 units. The solution was identified to be an additional longitudinal borehole near the pole tip that stabilizes the magnetic flux in this region at a high value. The behavior of the integrated multipoles was studied and optimized via parameter variations of the geometrical parameters over the complete tuning range of the magnet. The final geometry can be seen in Fig. 3. This geometry successfully stabilizes the first leading multipole components of the magnet below one unit with respect to the quadrupole parameter. Figure 2 shows the summary of the calculated fluctuation, including mechanical (k-value) and electrical tuning (colored curves for current densities between ±1 A/mm^2). In the left plot the overall QP gradient and the integrated quadrupole strength is plotted as function of both tuning parameters. In this setup the mechanical tuner can reduce the quadrupole field by more than 30 % and the electrical tuner can vary it by more than 5 %. This behavior was also tested and confirmed by means of CST [9], OPERA [10] and ANSYS [11] with numerical uncertainty of less than 1 unit. All three tools were used for further studies to minimize the temperature-induced variation of the magnetic field. A temperature compensation scheme based on NiFe alloy (THERMOFLUX) [12] was implemented. NiFe alloys possess high magnetic permeability and a relatively large temperature coefficient, typically on the order of 1 %, while NdFeB exhibit a remanence temperature coefficient of approximately 0.12 % [13]. As the temperature increases, both the remanence of the PM and the permeability of the NiFe alloy decrease, reducing the flux shunting effect. As a result, the total magnetic flux through the yoke and pole pieces remains relatively stable over temperature variations. According to the magnetic design and spatial constraints, two regions inside the Aluminum spacer next to the PM blocks can be filled with NiFe plates, reducing the thermal drift of the PM material by factor 20. Further reduction can be achieved by an active compensation with both tuning mechanism.

Table 1: Technical Parameter of the Tuning PM-QP

aperture radius	11.5	mm
yoke material	ARMCO (yoke) CoFe (pole-tip)	
PM material	NdFeB (B_r =1.3 T)	
PM size	50 x 50 x 73	mm^3
number of PM blocks	32	
Magnet dimension (H x W x L)	570 x 570 x 160	mm^3
max. field gradient	108	T/m
min. field gradient	63	T/m
tuning plates thickness	16	mm
moving range	60	mm
max. power coils	34	W
max. power motors	80	W

The most relevant technical parameters for the magnet specifications can be seen in Table 1.

TECHNICAL SOLUTION

After the main magnet conceptual design was completed, we worked on the detailed mechanical model, including the assembly to add screw holes and attachment points. All four highly symmetric quadrants consist of an iron return yoke, connected via an aluminum spacer with the pole finger. The resulting gap will be filled with the 8 large PM blocks per quadrant. The return yoke also provides fiducial points for the magnet alignment in the lab and guiding channels for the tuning plates. As a first step, every quadrant will be mounted without inserting the PM blocks. Then they will be mounted together and the pole tips will be connected by means of steel holding arcs. This is essential for the wire-EDM-cut of the pole tips to their final precision geometrical dimensions as calculated before. After the pole tips are done, we will dismount the quadrants to insert the four corrector coils. The PM blocks will be inserted into the yoke gap using a compact custom tooling that was developed to handle the large forces of several hundred newtons. Here, we take advantage of the situation where attractive and repulsive forces between two PM blocks cancel each other out at a certain position, so that both can be pressed against each other with almost zero force. Afterward, both blocks can be safely guided into the yoke. If all PM blocks are installed, the magnetic forces will be completely compensated due to the highly symmetrical magnet design. The corrector coils will allow for small and fast changes of the magnetic field, but for the tuning of the main static field, pairs of pure iron plates will be used. These will slide on the yoke on top of some thin bronze plates to reduce friction. To adjust them, we have developed the tuning mechanism that will control the position of these plates. Since the tuning plates are subjected to a strong pulling force towards the magnets, a big bearing was needed to support the spindle that controls their movements. This left little room for a linear guiding mechanism. So, a linkage in the form of a Sarrus-mechanism is used to guide the linear movement, since it can flex outwards, needing a smaller space for the same rigidity.

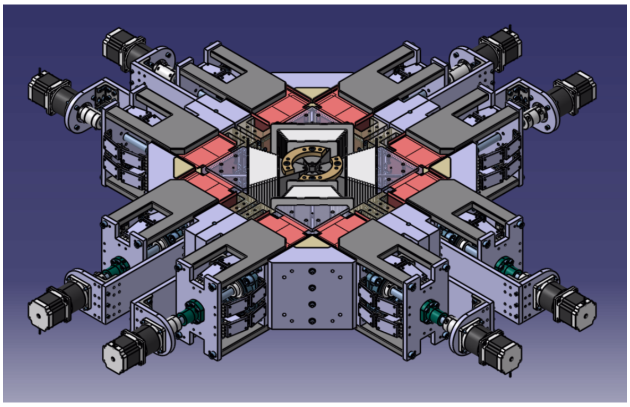

Figure 4: Final technical design of the PM-QP, including Sarrus-Motor-Tuning mechanism, electrical corrector coils and non-magnetic stabilization framework.

The Sarrus linkage consists of four links with equal length in two identical groups that are perpendicular to each other. Each hinge constrains the attached elements to remain in the same plane as the hinge. In our design, we use 2 of these linkages per tuning plate pair, acting on the same surfaces. The complete technical setup of the magnet, together with corrector coils can be seen in Fig. 4.

CONCLUSION

As part of the RF2.0 project for the development of more sustainable components for future accelerators, we target the design, fabrication, and testing of a PM-based tunable quadrupole magnet concept. In this paper we presented the numerical and technical details of it. All shown components (PM blocks, coils, yoke parts, motors, etc.) are in house and waiting for the last cutting steps of the yoke. Final assembly procedures of two prototype magnets are scheduled for June 2026. Both magnets will be tested and characterized up to December 2026 at ALBA and HZB.

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