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COMPACT QUADRUPOLE-SEXTUPOLE MAGNET UNITS FOR THE FLUTE-CSTART INJECTION LINE

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Abstract

One of the major goals of the cSTART project (compact STorage ring for Accelerator Research and Technology) at KIT is injecting and storing ultra-short bunches from the FLUTE linac into a very large-acceptance compact storage ring. To cope with the spatial constraints of the injection line connecting FLUTE with the storage ring three meters above, compact quadrupole-sextupole magnet units were designed, fabricated, and characterized.

In this contribution, we describe the magnetic design of these units and the underlying considerations, particularly with respect to cross-talk effects and their mitigation by design. We present the results of rotating coil and Hall probe measurements validating the magnetic design.

INTRODUCTION

The cSTART project at KIT has the objective to inject and store ultra-short electron bunches generated by a laser-plasma accelerator (LPA) in a compact, large-acceptance storage ring and to study the non-equilibrium dynamics of those bunches in conditions far from equilibrium. The conventional linear accelerator FLUTE will serve as a second injector into the cSTART storage ring. Both accelerators, FLUTE and cSTART, will be accommodated in the same bunker of 15 m × 15 m floor space, at two levels: FLUTE at the ground level and the cSTART ring about three meters above [1]. This arrangement results in a rather complex geometry of the injection line and puts tight spatial constraints to it. The purpose of the injection line is not only to transport the electron bunches to the injection point, but also to longitudinally compress them down to ≤100 fs. The initial optical layout of the injection line called for combined-function quadrupole-sextupole magnets [2]. To provide maximum experimental flexibility, the quadrupole and sextupole strength of these combined-function units, however, should be individually adjustable. Thus the design challenge for these units was to accommodate a set of single-function magnets of the required integrated multipole strengths in a fixed space, limited to 300 mm maximum total mechanical length. Next to actually achieving the basic magnetic design parameters under the given spatial constraints, the main design challenge for these combined magnet units was to mitigate cross-talk between the single-function magnets forming the unit.

For symmetry reasons, a triplet design (quadrupole-sextupole-quadrupole) of the combined-function units was favoured initially. It turned out, however, that such an arrangement would not leave any space for the simpler measures to suppress cross-talk, and the triplet design was therefore abandoned in favour of a doublet (sextupole-quadrupole) design.

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Table 1: Main Field and Field Quality Parameters of the Quadrupole-sextupole Unit, Requirements compared to Measured Values

	req.	meas.
pole gap radius [mm]	22.5	22.5
max total unit length [mm]	300	300
int. quadrupole strength [T]	±2.5	±2.7
int. sextupole strength [T m^{-1}]	±100	±102
good-field radius [mm]	15.0	15.0
integrated harmonics $n \neq 2, n \neq 3$, normalized to B_2	$\leq 10^{-3}$	2.9×10^{-4}

As of today, the design of all magnets and the mechanical arrangement of the FLUTE injection line are settled and the majority of the magnets is already on KIT site. The properties of the combined quadrupole-sextupole magnet units are being considered in the ongoing beam optics optimization process [3].

CROSS-TALK MINIMIZATION IN FINITE-ELEMENT SIMULATIONS

The requirements and the finally achieved and experimentally confirmed design parameters for the quadrupole-sextupole units are summarized in Table 1. The design challenge was to achieve at the same time the required integrated quadrupole and sextupole strength and a high field quality at all combinations of excitation levels under the mechanical boundary conditions of a 22.5 mm pole gap radius and a maximum total mechanical length of 300 mm. As will be discussed in more detail below, the field quality in terms of integrated circular multipole components is perturbed by cross-talk between the quadrupole and the sextupole magnet.

A design study was performed to investigate possible ways to mitigate these cross-talk effects and so to meet the field quality requirements. The strategy was to investigate possible solutions of increasing complexity, starting (1) from the already mentioned doublet design, over (2) introducing a field clamp between the magnets, (3) adding trim coils to cancel cross-talk effects, to (4) applying asymmetric pole shapes, with a termination as soon as a viable solution was found. All FEM calculations presented were done with Opera 3D.

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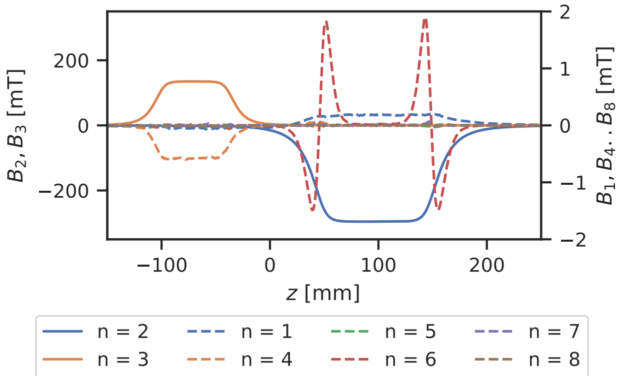

Figure 1: FEM-calculated upright circular harmonics of the radial flux density component as a function of position along the magnet center axis with both magnets powered to 100 % of their nominal current (note the different scales used for the main and other harmonics on the primary and secondary ordinate, respectively).

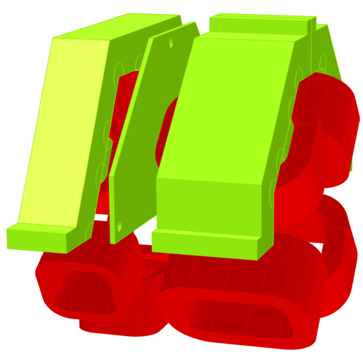

Figure 2: 3D model view of the quadrupole-sextupole unit with field clamp (generated and investigated using the Opera 3D FEM software).

For minimizing cross-talk effects, a maximal distance between the magnets is, in general, favored. Since a limit is set to the total length of the unit, however, increasing the distance between the magnets results in decreasing the yoke length, thus increasing also the magnet strength in order to keep the integrated strength constant, which leads to unwanted saturation effects. Several iterations led to a "best-compromise" design for the doublet, yet not meeting the field quality requirements. Figure 1 shows the calculated field harmonics as a function of z along the longitudinal axis for both magnets powered to 100 % of their nominal current. It can be seen that the most significant contributions to the spurious integrated harmonics arise from an octupole component present in the core of the sextupole field, and a dipole component in the quadrupole field.

Therefore, in the second step of the investigation, a soft-magnetic shielding mask was inserted between the two magnets as a field clamp, as depicted in Fig. 2. Because the influence of field clamp on the fringe fields reduces also the integrated strengths of the main multipole components, the geometrical and electrical layout of the two magnets had to

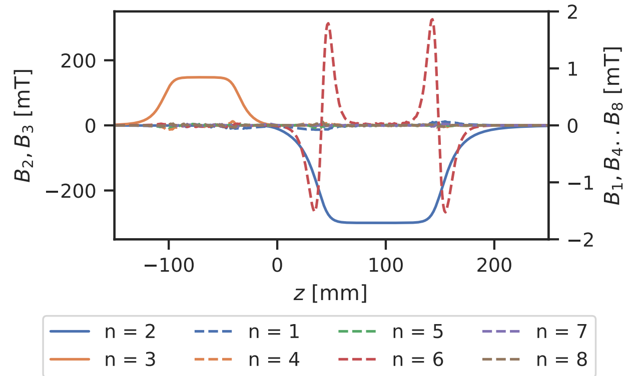

Figure 3: FEM-calculated upright cirular field harmonics as a function of z with field clamp.

be re-adjusted. Again, particular attention had to be paid to avoiding saturation issues. In this step, also a choice for the power converters was made, and the magnetic design was additionaly adjusted to the output parameters of the chosen power converters. This iteration resulted in the final design. As shown in Fig. 3, the the field clamp effectively suppresses cross-talk-induced harmonics.

EXPERIMENTAL VALIDATION

Three quadrupole-sextupole units have been manufactured by Scanditronix according to the described design, which was validated by two sets of measurements: rotating coil field integral measurements performed as part of the factory acceptance test at Scanditronix, and Hall probe field maps measured at KIT.

Rotating Coil Measurements

The measurements were performed with the rotating-coil set-up at Scanditronix with a custom-made pick-up coil set covering the complete combined-magnet unit. The field integrals were measured at the specified good-field radius r_0 = 15 mm. The mutual alignment of the magnet unit and the rotating coil set-up was done means of Scanditronix' coordinate measurement machine.

Figure 4 shows, using the example of quadrupole-sextupole unit 03, the measured integrated upright harmonics (a) for both magnets powered, normalized to the quadrupole strength, and (b) for only the sextupole magnet powered, normalized to the sextupole strength. The results of the corresponding model calculations are shown for comparison. Note that in case (b) the residual field of the quadrupole is present, which is not the case in the model calculations. The measurements in general are in good agreement with the expectations based on the model calculations, and confirm the absence of unwanted harmonics due to cross-talk. The the maxiumum harmonic contributions for $n \neq 2$ and $n \neq 3$ comply with the field quality requirements.

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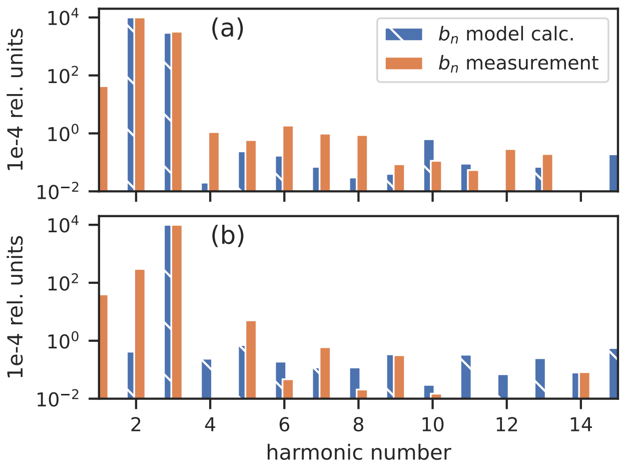

Figure 4: Integrated upright circular field harmonics for both magnets powered to 100 %, normalized to the quadrupole strength (a), and the sextupole powered to 100 % with quadrupole off, normalized to the sextupole strength (b). The rotating coil measurements are compared to the FEM calculations

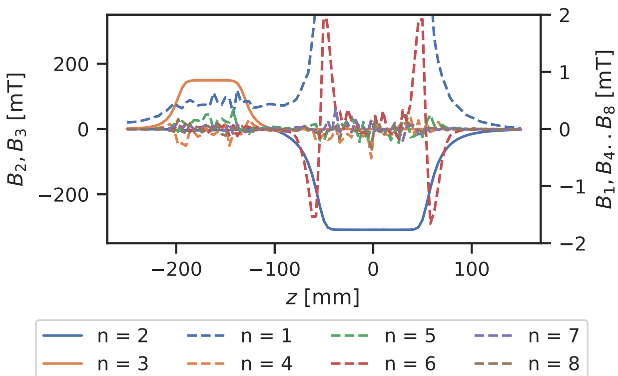

Figure 5: Upright circular field harmonics as a function of longitudinal position, calculated from Hall probe maps with both magnets powered to 100 %.

Hall Probe Maps

The Hall probe maps were measured using the KIT magnetic measurement system described in Ref. [4]. The mapping was done with a M3H5 digital teslameter from Senis AG, Switzerland.

To acquire data directly comparable to the FEM calculations presented above, the field of the combined-magnet unit was mapped on a cylindric surface with radius $r_0 = 15$ mm and the cylinder axis aligned to the magnet axis. The transformation from magnet coordinates to mapper coordinates was established by coordinate measurements carried out with a FARO Quantum-S arm. The harmonics for each longitudinal scan position were calculated by a discrete Fourier transformation from the radial field measured on a circular path by the 3-D Hall probe.

Figure 5 shows the measured harmonics as a function of longitudinal position for both magnets powered to 100 % of their nominal current. Figure 6 shows the results of partial mappings (from magnet center to magnet center) for only the sextupole and only the quadrupole powered, respectively. For these maps, both magnets had undergone a degaussing cycle before powering one of the magnets.

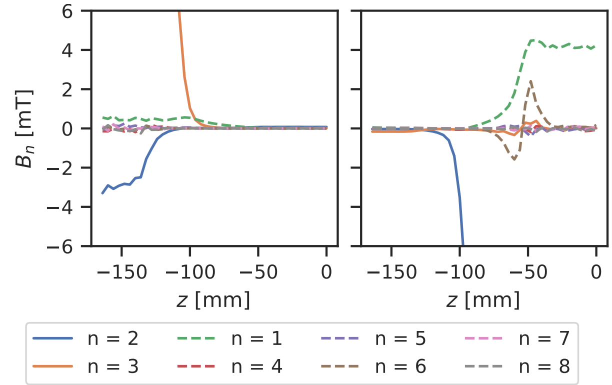

Figure 6: Upright circular field harmonics as a function of z, calculated from Hall probe maps, with only sextupole powered (left), and only quadrupole powered (right), respectively. The longitudinal measurement range was restricted from magnet center to magnet center.

Also these measurements clearly show the absence of spurious harmonics induced by cross-talk between the magnets. Harmonics A_1, B_1 in case of the quadrupole and A_2, B_2 in case of the sextupole can be identified as spill-down harmonics, caused by a constant in-accuracy of the Hall probe position of $(x, y) = (0.4\,\text{mm}, 0.2\,\text{mm})$. The map shown in Fig. 5 is in good agreement with the model calculations shown in Fig. 3.

SUMMARY

Combined-magnet units for the FLUTE-cSTART injection line, composed of a quadrupole and a sextupole magnet, fit into a total length of 300 mm, have been studied, designed, manufactured and characterized. The main challenges for the design of the units were yoke saturation on the one hand and cross-talk between the magnets on the other, leading either to non-linear excitation and hysteresis effects or compromising the field quality, or both. Introducing a soft-magnetic field clamp between the magnets led to effective mitigation of the cross-talk and to a design with satisfactory field quality. The design was successfully validated by rotating-coil measurements and Hall probe maps.

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