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MAGNETIC DESIGN OF THE cSTART MAGNETS

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Abstract

The KIT project cSTART (compact STorage ring for Accelerator Research and Technology) aims to store ultra-short electron bunches in a very large-acceptance compact storage ring. The magnetic lattice of the storage ring is laid out for a variety of beam optics, including ultra-low positive and negative alpha as well as isochronous optics. These put high demands on magnet quality and alignment. In addition, KIT wants to contribute to the development of compact, resource-efficient accelerators. This imposes further challenges on the magnet design. In this paper, we give an overview of both the challenges and solutions for the cSTART storage ring magnet design.

INTRODUCTION TO THE DESIGN REQUIREMENTS

The cSTART very-large-acceptance storage ring will be a unique tool to study the dynamics of ultra-short electron bunches in a storage ring far from equilibrium. The ring lattice will provide a sufficiently large momentum acceptance to inject laser-plasma-generated electron bunches (LPA). An injection line to generate and inject highly compressed electron bunches from the FLUTE linear accelerator is foreseen for initial commissioning and experiments. The different injection schemes will offer a variety of initial beam properties in terms of bunch charge and duration, energy, and momentum spread. Correspondingly, the magnetic lattice of the ring allows for a variety of possible beam optics, from a robust double-bend achromat (DBA) over reduced-momentum compaction to quasi-isochronous optics [1, 2]. This flexibility of the lattice, together with the operating energy ranging from 40 MeV to 90 MeV requires all magnets to be fully tunable, i.e. all magnets are laid out as electromagnets.

In the foreseen operating electron energy range, radiation damping will be virtually absent, and the particle dynamics will therefore, in general, not reach a steady state. The effects of magnetic field fluctuations will not be damped out, which puts high demands on the field stability. For the more advanced beam optics, crucial parameters such as the linear and higher-order components of the momentum compaction factor and, in turn, the achievable bunch compression and momentum acceptance are highly sensitive to magnetic field errors in terms of higher harmonic content, spill-down, and skew components due to translational and roll-angle misalignments, as well as deviations of the magnetic properties within the magnet families. This sensitivity translates into tight tolerances for the field quality of individual magnets

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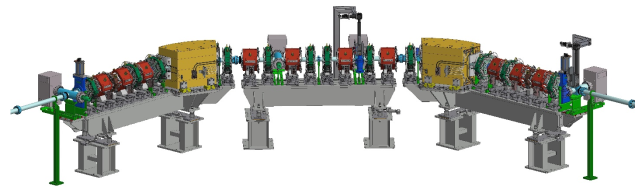

Figure 1: 3D view of one of four arcs of the cSTART storage ring.

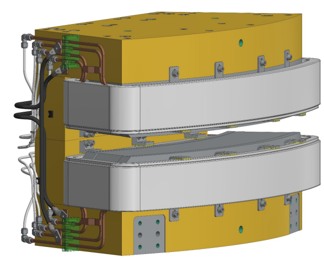

Figure 2: 3D-model of the cSTART dipole magnets.

and magnet families, and the precision of the positioning units and alignment procedures [3].

These tolerances must be met under the boundary condition of a very densely packed magnetic lattice (cf. Fig. 1), owed to the highly compact layout of the complete facility, which combines the FLUTE accelerator, a complex injection line from FLUTE to the cSTART storage ring, the ring itself, and two LPA injection lines in a $15 \times 15\,\mathrm{m}^2$ bunker. The dense packing gives rise to crosstalk, particularly between neighbouring quadrupole and sextupole magnets. These unwanted effects will be mitigated by soft-magnetic field clamps, which were taken into account in the magnet design right from the start.

Further general design decisions were to make all magnets from solid iron, as the operation modes of the storage ring will be quasi-static, and to make them directly water-cooled (except for the very low-power octupole and corrector magnets) to stay within the limits of the air-cooling capacity in the experimental hall.

The main parameters of the cSTART ring magnets are summarized in Table 1. In the following, special aspects of the magnetic and the technical design of different magnet types are discussed in some more detail.

THE DIPOLE MAGNETS

The cSTART dipole magnets are C-shaped sector magnets with 45° deflection angle and 45 mm pole gap, as shown in Fig. 2. The magnetic lattice of the storage ring is com-

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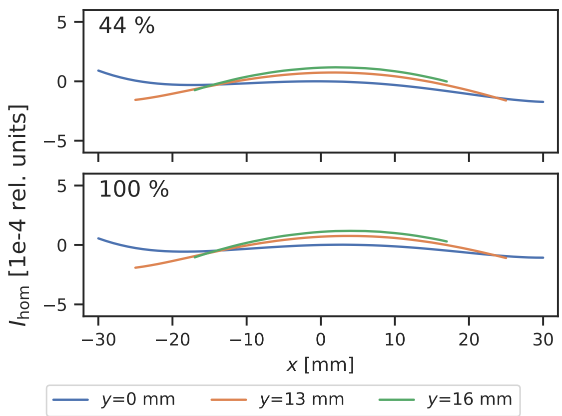

Figure 3: Integrated field homogeneity of the dipole field in the good-field region at excitation levels 44 % (40 MeV) and 100 % (90 MeV), applying the criterion defined by Eq. (1).

posed of four mirror-symmetric cells with two dipoles, five quadrupole, six sextupole, and one octupole family each, in the basic version, forming a double-bend achromat. A C-shaped structure was chosen for the dipoles to accommodate vacuum chambers with "light ports" for the extraction of THz radiation and for options with injection of an electron beam in the tangential direction from outside the ring [4].

The main good-field criterion for the dipole magnets is the integrated field homogeneity

$$I_{\text{hom}} = \left| \frac{\rho_0}{\rho_0 + x} \frac{\int_{\mathscr{S}(x,y)} B_1 \mathrm{d}s}{B_{1,0} L_{\text{eff}1}} - 1 \right| \leq 5 \times 10^{-4} \qquad (1)$$

for x, y in the super-elliptic good-field region defined by $\frac{x^3}{a^3} + \frac{y^3}{b^3} \leq 1$, with half axes $a = 30$ mm and $b = 17$ mm, respectively. This quality criterion was met using Rose shims (horizontal) and chamfers (longitudinal). Figure 3 shows I_{hom} as a function of transverse position within the good-field region, calculated from the finite-element model of the dipole magnet.

For the foreseen tangential injection of electron bunches from a laser plasma accelerator (LPA), it is important to bring the magnetic field in the according dipole magnet

Table 1: Main Parameters of the cSTART Ring Magnets

Dipole	
Deflection angle ϑ	45°
Nominal field $B_{1,0}$	0.295 T
Quadrupole	
Nominal field gradient $B_{2,0}$	3.2 T m^{-1}
Families/magnets per fam.	5/8
Sextupole	
2nd order field gradient $B_{3,0}$	87.1 T m^{-2}
Families/magnets per fam.	6/8
Octupole	
3rd order field gradient $B_{4,0}$	1728 T m^{-3}
Families/magnets per fam.	1/8

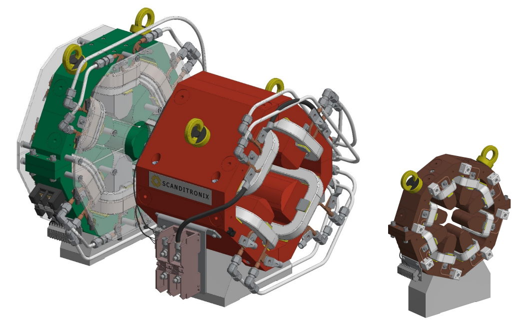

Figure 4: 3D models of the sextupole, quadrupole and octupole magnets for the cSTART storage ring. The field clamps attached to the sextupole magnets are shown translucent.

to zero. The magnets are designed to operate well below saturation — the maximum magnetic flux density in the yoke is 1.6 T; this will minimize hysteresis effects. To additionally suppress remanent fields, which are assumed not to exceed 1 % of the nominal excitation, the dipoles at the tangential injection and extraction points will be equipped with trim coils.

THE QUADRUPOLE, SEXTUPOLE, AND OCTUPOLE MAGNETS

To enable series production and later on sorting of the magnets for minimizing the deviation of field properties within magnet families, the magnetic and geometric design is the same for all quadrupole and, respectively, sextupole families, as shown in Fig. 4. The relatively large gap radius of 31.5 mm for all magnets is therefore defined by the beam-stay-clear and good-field requirements in the high-dispersion regions of the storage ring.

The magnet lengths required for maintaining a large dynamic aperture and momentum acceptance of the ring result in a very densely packed lattice.

Considering the wide gap and the close placement of the quadrupole and sextupole magnets, a major concern for the design of these magnets was possible cross-talk between neighbouring magnets of different multipole orders [5]. The strategy for mitigating such cross-talk is to use field clamps, which are attached to the sextupole magnets on both sides and were taken into account from the beginning of the magnet design process. A detailed analysis was carried out based on a finite element model of a magnet group consisting of one sextupole with field clamps, surrounded by two quadrupoles. The integrated field harmonics at the good-field radius $r_0 = 24$ mm were investigated for this magnet ensemble under the condition of different symmetric and asymmetric excitation of the sextupole and quadrupoles at levels of 8 %, 50 % and 100 % of the nominal excitation. These were compared to the sum of the integrated harmonics calculated for independent magnets. The result is shown in Fig. 5. The difference between the magnet group model and the sum of single-magnet models shows harmonics of

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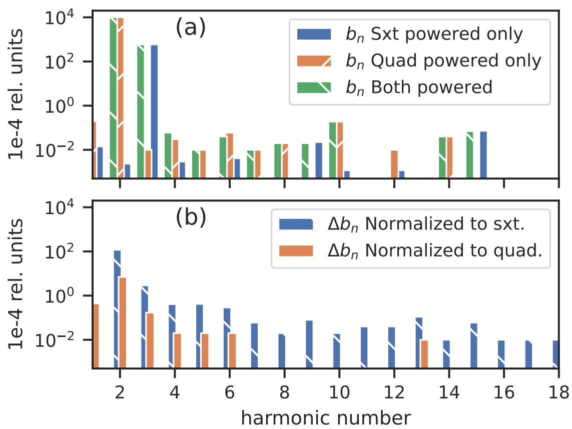

Figure 5: Investigation of integrated field harmonics induced by cross-talk between sextupole and quadrupole magnets, (a) upright harmonics for different powering schemes, (b) difference between the integrated harmonics of an ensemble of magnets (QSQ) with field clamps and the sum over single, independent magnets. For all harmonics of order 4 and greater, the difference, normalized to the sextupole component, is below 10^{-4} relative units. Cross-talk between the magnets is effectively mitigated by the field clamps.

order > 3 (normalized to the sextupole component) well below one relative unit of 10^{-4}, virtually indistinguishable from numerical effects.

However, the field clamps come with side effects. The pole geometry of the sextupole magnets needs to be optimized with the field clamps at a fixed distance in order to meet the field quality criteria, which is why the field clamps are considered and realized as an integral part of the sextupole magnets. An integrated harmonic distortion

$$F_d = \frac{1}{\int B_{rN} \mathrm{d}z} \left[\sum_{n>N}^{k} \left(\int B_{rn} \mathrm{d}z \right)^2 + \left(\int A_{rn} \mathrm{d}z \right)^2 \right]^{\frac{1}{2}} \quad (2)$$

below 1.8×10^{-4} is achieved, with A_{rn} and B_{rn} the skew and upright harmonics of the radial magnetic flux density evaluated at the reference radius $r_0 = 24$ mm, up to a harmonic number $k = 15$ (2^{nd} allowed order). For the quadrupole magnets, on the other hand, the effective length depends on the distance to the field clamps of the neighbouring sextupole magnets, which is taken into account in the positioning of the magnets on the girder. The integrated harmonic distortion of the quadrupole field is virtually unaffected by the field clamps and, summing over harmonics up to order $k = 18$ (3^{rd} allowed order), stays below 0.7×10^{-4}.

Due to the limited space in the arcs, there will be no dedicated orbit corrector magnets. Instead, all sextupole magnets will be equipped with trim coils (10 turns for each, horizontal and vertical correction, on the four horizontal poles, and 20 turns for vertical correction on the two vertical poles) allowing for horizontal and vertical correction fields for 1 mrad deflection of 90 MeV-electrons in each direction.

The octupole magnets with a 3^{rd} order flux density gradient of 1728 T m^{-3} are very weak. By design, they feature an excellent field quality with a harmonic distortion below 0.3×10^{-4}.

Table 2: Types and Basic Operating Parameters of the Power Converters for the cSTART Main Magnets

Magnet family **power converter**	**I/A** **drift/ppm**	**U/V** **efficiency**
Dipoles (2 groups à 4) CAEN NGPS 100A-100V	88 <10	72 >90 %
Quadrupoles Q1 – Q5 CAEN NGPS 100A-100V	92 <10	44 >90 %
Sextupoles S1 – S6 CAEN FAST-Bi 1K5 50A-40V	46 <10	8.8 >80 %
Octupole iTest BE2850 2A-50V	0.53 <40	0.4 >80 % (full load)

As already mentioned, spill-down and skew harmonics resulting from misalignments must also adhere to tight tolerances. All multipole magnets will therefore be equipped with extensions for survey targets as an integral part of the yoke assembly. These extend the base length for angle measurements to meet the requirements particularly for the accuracy of the roll-angle adjustment.

MAGNET POWER SUPPLIES

Apart from the purity of the multipole fields of the individual magnets and the deviation of magnetic properties within each magnet family, the temporal stability of the magnetic fields is of crucial importance for the operation of the storage ring under conditions far from equilibrium. The magnets will be powered by state-of-the-art commercially available power converters providing high stability. The selection of the power converters and the electrical design of the magnets and family powering circuits are matched to each other in a way that, at nominal excitation, the power converters are operated at an optimal level of normalized stability and efficiency. Table 2 lists the type and main specifications of the power converters used.

PRODUCTION STATUS AND OUTLOOK

The technical design for the quadrupole and dipole magnets has been finalized. The small series production of the quadrupole magnets has started in the second quarter of 2025. The fabrication of all magnets, including on-site magnetic characterization at Scanditronix, is followed by the assembly of the girders on the RI site and the installation of the assembled girders on the KIT site.

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