

THE SOLEIL II MAGNETS

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Abstract

The SOLEIL II upgrade relies on a lattice combining 7BA and 4BA High-Order Achromat (HOA) cells. Strict compactness constraints and energy efficiency objectives have driven the adoption of permanent magnet based technology for the main bending and focusing elements, while quadrupole correctors, sextupoles, and octupoles remain resistive to preserve operational flexibility. This paper presents the latest progress in the design, optimization, and prototyping of the SOLEIL II magnet system.

INTRODUCTION

SOLEIL II, the upgrade project of the SOLEIL booster and storage ring, aims at reducing the horizontal emittance of the electron beam to 85 pm-rad. To achieve this goal, the lattice combines 7BA and 4BA HOA cells [1–3]. This performance requires an exceptionally dense magnet system, with approximately 1300 magnets integrated into the existing storage ring tunnel, which currently accommodates 312 magnets, imposing severe constraints on compactness and integration. This was addressed by designing more compact magnets with improved performance. This paper summarizes the current status of the magnet development program for SOLEIL II at the launch of the construction phase [4, 5].

PERMANENT MAGNET BASED DIPOLES AND QUADRUPOLES

Dipoles, quadrupoles and reverse bends of SOLEIL II are iron dominated magnets, using low-carbon steels combined with Samarium Cobalt ($\text{Sm}_2\text{Co}_{17}$) permanent magnet blocks. The list of all permanent magnets designed for SOLEIL II is presented in table 1.

Dipoles

Based on the initial design [6], two dipole prototypes, a short dipole and a three region 3T long dipole (figure 1) were produced to validate the design. Measurements on these prototypes were conducted using a single stretched wire (SSW)

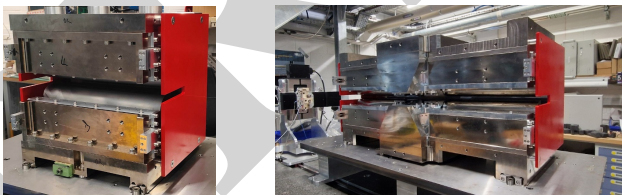


Figure 1: Dipole prototypes with shielding plates. short dipole (left), 3 region 3T long dipole (right).

system [7] and Hall probe measurements. Good agreement was observed between both measurements and the calculated fields, with less than 0.5% error in the integrated field and less than 1% error in the integrated gradient. All magnetic calculations are performed using OPERA software suite [8]. Due to the compactness of the machine, magnetic crosstalk induces additional multipole components [6]. To mitigate these effects, magnetic shielding was tested on the prototypes and subsequently adopted for all dipoles. Several modifications to the initial design were introduced for the final configuration. The short dipoles length was reduced while maintaining the same magnetic field strength. Single region long dipoles were introduced and replaced all the 1.2 T three region dipoles, with only 12 higher-field three-region dipoles (1.7 T and 3 T) retained. In addition, the three regions were physically separated, resulting in three-part dipoles. These modifications reduced design complexity while increasing overall compactness. Figure 2 shows 3D models of the final dipole configuration. In addition to the standard 7BA/4BA cells, the lattice contains one special 7BA cell with 3 special permanent magnet chicane dipoles designed in order to accommodate two canted undulators on the same straight section.

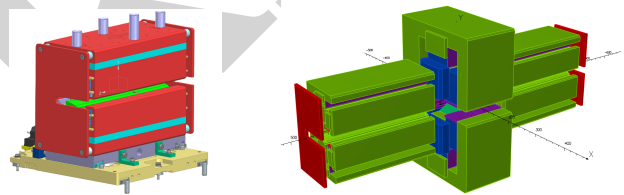


Figure 2: 3D models of the dipoles with shielding plates. short dipole (left), 3 part long 3T dipole (right).

Quadrupoles and Reverse Bends

The quadrupole and reverse bend designs remain unchanged and follow the geometry proposed by ESRF [9]. Fourteen mechanical families are designed to produce 24 magnetic families by adjusting the thickness of magnetic

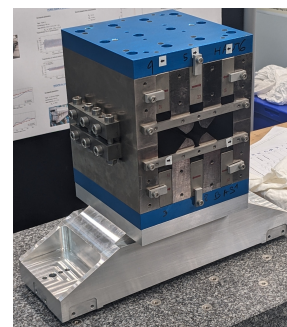


Figure 3: Quadrupole prototype 2.

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Table 1: Main Parameters of the Dipole, Quadrupole and Reverse Bend Configurations

Magnet type	Gap/Diameter [mm]	Deviation [mrad]	Mechanical length [mm]	Gradient integral [T]	Quantity
Short dipole (DNC)	23	41.1	411	7.586	22
	23	39.3	411	7.586	16
	23	40.2	411	7.586	1
	18.4	47.2	411	7.586	1
One part long dipole (DNL)	23	68.5	839.5	14.495	46
	23	65.5	839.5	14.495	16
	23	68.6	839.5	14.495	1
	23	68.2	839.5	14.495	1
Three part long dipole	18/11	68.6	834.3	15.109	7
	22/14	68.6	834.3	15.109	5
Chicane dipole (CHIC)	20	-12.7/+19.2/-11.8	200/200/100	0	3
Long reverse bend (DIL)	21	-3.0	126	11.12	95
	21	-3.0	126	11.33	10
	21	-2.9	126	11.12	32
	21	-2.8	126	11.12	1
Short reverse bend (DIC)	18	-0.8	106	12.17	24
	18	-0.8	106	12.17	16
Quadrupole	16	0	58/70/76/98	7.29 to 14.01	128
	21	0	126/180	11.45 to 16.75	12
	23	0	80/106/120	6.12 to 9.63	22

shunts and the positioning of the magnets. Two prototypes were produced. For the first prototype, the profile was left unoptimized in order to assess manufacturing precision requirements, and showcase a specific signature during magnetic measurements [6]. The second prototype (figure 3) was designed with an optimized profile, and feedback from the first prototype permitted significant simplification of the mechanical design. With this optimized profile, the impact on multipoles is significantly reduced.

ELECTROMAGNETS

The electromagnets of SOLEIL II are based on assemblies of independently manufactured laminated steel sectors. Measurements on the sextupole prototype have highlighted the need for improved control of hysteresis effects, leading to increased attention in the electromagnet design. Accordingly, commercially available steel grades have been carefully selected to combine low coercivity with good magnetic performance at high excitation. Low coercive fields are essential to mitigate the hysteresis effects observed during prototype testing, while favorable high field properties ensure the widest possible linear operating range. The list of electromagnets is presented in table 2.

Quadrupole Correctors

The final lattice contains 212 normal quadrupole correctors able to generate a 1 T integrated gradient. Two quadrupole corrector families are implemented, with yoke lengths of 24 mm and 29 mm. Achieving the nominal in-

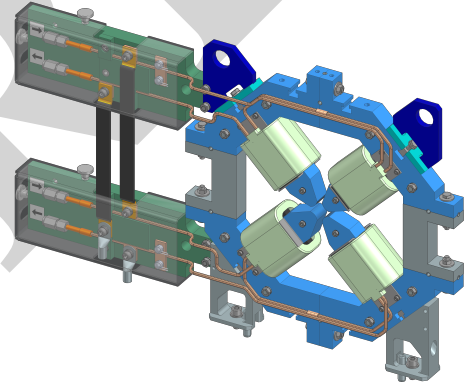


Figure 4: Normal quadrupole corrector.

tegrated gradient within these compact yokes requires coil currents up to 40 A, which imposes the use of water-cooled conductors. Figure 4 presents the current design of the quadrupole with its auxiliary cooling circuits. A prototype of this quadrupole is currently under fabrication.

Sextupoles

SOLEIL II lattice requires 412 sextupoles distributed into several families with different integrated strengths. In addition to these functional distinctions, geometrical constraints imposed by the photon beam vacuum chambers require multiple mechanical variants, namely standard, notch, ear, and carved sextupoles. The combination of magnetic families and geometrical variants results in 12 sextupole families,

Table 2: Main Parameters of the Quadrupole Correctors, Sextupoles and Octupoles

Magnet	Bore diameter [mm]	Gap [mm]	Yoke length [mm]	Integral strength	Quantity
Quadrupole corrector	19	7	24	1 T	200
Quadrupole corrector	22	10	29	1 T	12
Sextupole	16	6.2	60	550 T/m	96
Sextupole	21	6.2	75	350 T/m	12
Sextupole	21	10	75	350 T/m	16
Sextupole	16	6.2	90	680 T/m	163
Sextupole	16	7	90	680 T/m	9
Sextupole	16	7.5	90	680 T/m	20
Sextupole	16	6.2	120	1000 T/m	96
Octupole	19	6.4	60	3300 T/m ²	143
Octupole	21	7.18	60	3300 T/m ²	17

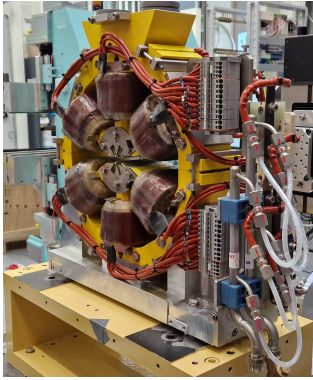


Figure 5: Notch sextupole prototype.

ensuring compatibility with all lattice configurations while preserving the required magnetic performance. Each sextupole is composed of six laminated steel sextants, each equipped with a main coil generating the sextupole field and one or two dipolar correction coils providing horizontal and/or vertical field components. The main coils operate up to 50 A and are water cooled, while the correction coils are rated up to 20 A and provide an angular correction up to 1 mrad. A prototype of a notch sextupole (shown in figure 5) was manufactured and magnetically measured. The measurement results confirmed the expected calculated performance; however, they also revealed strong sensitivity to hysteresis effects at the high magnetic field levels required.

Octupoles

All octupoles in the SOLEIL II lattice have identical strengths; however, as is the case for the sextupoles, 4 octupole families were developed to accommodate constraints imposed by the photon beam vacuum chambers, including 94 regular 6.2 mm gap octupoles, 19 notch octupoles, 30 ear octupoles, and 17 regular 7.18 mm gap octupoles. Each octant of the octupoles is equipped with copper coil blocks comprising 3 coils. The main windings generate the octupole field, while additional correction windings provide normal and skew quadrupole components. The main octupole coils and the skew quadrupole coils are wound using enamelled flat conductors, as they are designed to support 7 A and 13.33 A,

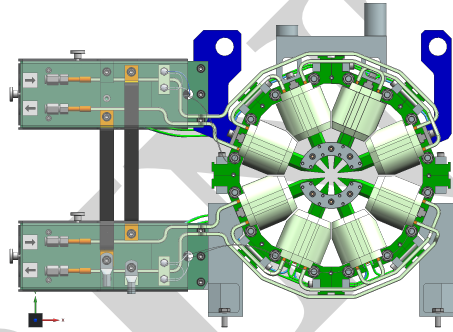


Figure 6: Normal octupole.

respectively. The normal quadrupole windings use hollow conductors with demineralized water cooling, as 40 A are required to reach the specified field. The normal and skew quadrupole correction coils provide an integrated gradient up to 1 T. An example of the current normal octupole design is shown in Fig. 6.

CONCLUSION

The magnets developed for the SOLEIL II upgrade now meet the lattice requirements, with dedicated design strategies implemented to address the specific constraints of each magnet type. Several prototypes have been manufactured and extensively characterised, providing essential feedback that is already being incorporated into the optimisation of the final designs. Further validation is ongoing, with the delivery of a sextupole–octupole doublet prototype and a normal quadrupole prototype planned before the end of this year. These efforts represent a key step toward ensuring the reliability and readiness of the SOLEIL II magnet system.

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