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Harmonic sextupoles for the Advanced Light Source low emittance upgrade

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ABSTRACT

The Advanced Light Source is a 3rd generation light source in operation since 1993. This light source is providing state of the art performance to more than 40 beamlines and their users thanks to the upgrades that have been completed over the last few years. Higher photon beam brightness is expected to become available to users in the near future through a new upgrade with the introduction of 48 sextupoles in the ALS lattice. Introducing new combined function magnets in an existing storage ring is a challenge due to the limited space available and a balance had to be found between magnet performance and spatial constraints. Moreover, the existing steering magnets will be replaced by the harmonic sextupoles. Therefore predicting the hysteresis behavior of the harmonic sextupole steering functions became critical for those included in the fast-orbit feedback loop (22 of them). After a brief introduction to the motivation for the upgrade and the scope of the project, we develop in this paper the different constraints driving the three required combined function magnet designs as well as their expected performance.

1. Introduction

The Advanced Light Source (ALS) is planning on increasing the brightness of the photons delivered to the users. After the vertical emittance reduction obtained from the recent successful Top-Off upgrade, the new low emittance upgrade project is expected to reduce the horizontal emittance by about a factor of 3 in the bending magnet beamlines and about a factor of 2 in the undulator beamlines [1]. Different lattice options compatible with horizontal emittance reduction were investigated and lattices close to the nominal lattice were first studied [2]. Then more systematic methods were applied to find global optimum lattices [3,4].

The chosen baseline lattice solution requires an increase of the Storage Ring (SR) quadrupoles strength that is still within their operational range, but the existing sextupoles located in the arc sections are not strong enough. Therefore, additional sextupole strength is added in the straight sections allowing for the existing arc sextupoles to operate within their nominal range. Due to the limited storage ring space, the additional sextupole field will be added by replacing the existing 46 horizontal and vertical steering corrector magnets with six-pole combined function magnets and by inserting 2 additional six-pole electromagnets in the injection straight section. These magnets will then be able to provide horizontal and vertical correction for beam steering, skew quadrupole correction to compensate for Elliptically Polarizing Undulator effects and sextupole correction to improve electron beam dynamics degraded by the increase of the quadrupole strength.

2. Magnet yoke designs

Adding 48 new electromagnets (four per sector) in a Storage Ring initially commissioned in 1993 with currently more than 40 beamlines in service is a challenge. General requirements regarding the field strength to be provided by the magnets are defined in Table 1. Then we review in this section the space constraints that determine the envelop in which the magnet should be contained.

There are several mechanical interference constraints to overcome while inserting new magnets in the SR and the main one is the external shape of the SR vacuum chamber, which varies from location to location and drives the magnet pole design close to the bore diameter.

Arc Chambers (*Type G magnets*): The ends of the arc chambers are part of the SR straight sections and 24 magnets (two out of the four magnet per sector) are to be installed at these locations. These magnets have a large bore diameter (116 mm) and a C-shaped yoke is required since for half of them there is a user beamline coming out of the vacuum chamber. Due to nearby beamline vacuum valves at certain locations, the open side of the C shape is modified to avoid any possible interference. The required 6-fold symmetry of the yoke cross-section had to be broken to allow for the introduction of the vacuum chamber in the magnet aperture. The 6-fold symmetry can be kept for the

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Table 1
Field strength requirements.

Field type	Field strength
Sextupole	19 T/m
Horizontal steering	15 mT m
Vertical steering	15 mT m
Skew quadrupole	0.14 T

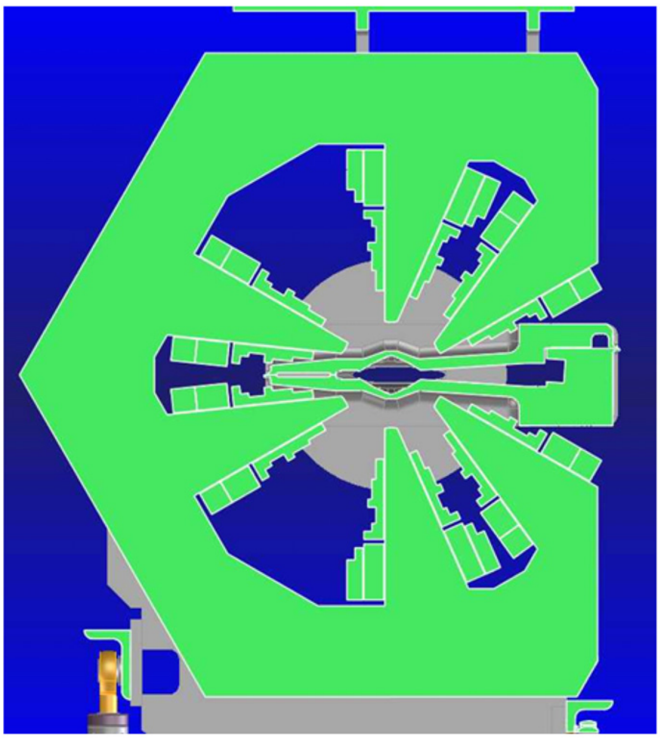

Fig. 1. Type G magnet and vacuum chamber cross-section.

pole tip surface, but only a 3-fold symmetry distribution can be given to the pole bodies. Otherwise, the magnet would have a bigger aperture and it would not be able to provide the required field strengths. The C-shape gives a global up and down symmetry as described by Fig. 1.

Elliptical chambers (*Type E magnets*): This category covers 22 out of the 24 remaining locations. These magnets have a smaller aperture (92 mm) and a closed magnetic circuit geometry. The steering functions of these magnets will be used in the fast-orbit feedback loop operated at 1 kHz which is an additional requirement regarding the magnet hysteresis performance. Moreover, at one location there is a beamline that would interfere with the general type E magnet design. In this location a modification of both the beamline layout and the type E baseline design is required. The general design becomes the type E1 and a type E2 design is created by removing some lamination material from the original design. E1 and E2 designs are identical (yoke, coils) except for the lack or excess of magnetic material on both sides.

Injection section chambers (*Type F magnets*): The two categories above cover the replacement of the 46 existing steering correctors but all straight sections have to be provided with sextupole field (total of 48 magnets) [1]. Consequently two special magnets will be fabricated for these specific locations where the vacuum chamber is wide and short along the beam direction. To reduce the magnet bore diameter, these chambers have to be modified so that the minimum magnet bore can be 126 mm. As these two magnets are very short, it led to compromised requirements

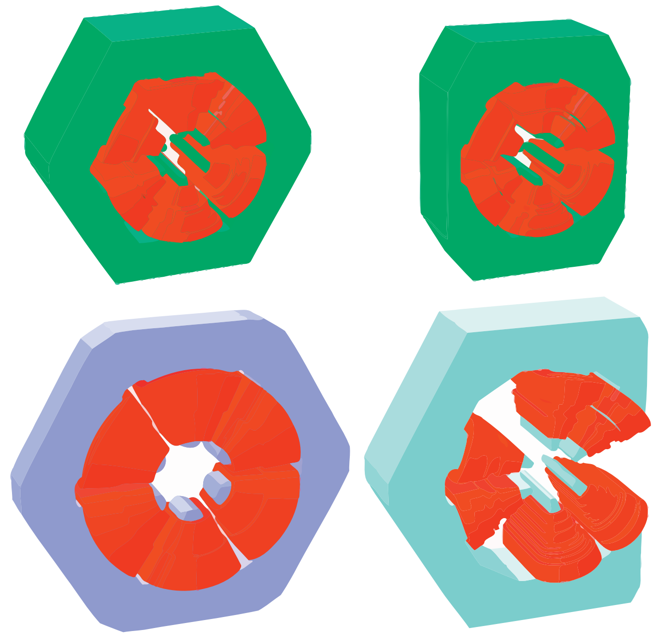

Fig. 2. Top: Type E1 and E2; Bottom: Type F, Type G magnets.

regarding the field: limited sextupole strength of 15 T/m (instead of 19 T/m) and no other functions provided (no steering and skew quadrupole corrections). All magnets described above can be seen on Fig. 2.

3. Magnet coil design

Mechanical interferences and existing power supply matching are the two main sources of constraints regarding the coil design. The sextupole coils are located close to the pole tip, whereas all the other coils are located close to the base of the poles. The different field functions are provided through a classical coil distribution found in many light sources design for combined function sextupole magnets [5]: six coils for the sextupole, six coils for the vertical steering, four coils for the horizontal steering and two coils for the skew quadrupole.

3.1. Coil mechanical interferences

Due to nearby equipment, little space is available for the coils upstream and downstream, especially for the type E and F magnets. Wide bore diameters and saturation minimization led to increased but reasonable magnet sizes (transverse magnet size $\leq$ 700 mm).

3.2. Power supplies

For cost reduction purposes, we decided to keep the power supplies of the steering correctors to be replaced. Therefore the steering coil designs match the characteristics of these power supplies which have given load resistance, inductance, maximum output power and voltage (i.e fixed current range). All these parameters combined therefore imposed the use of square hollow conductor (4 and 2.5 mm diameter cooling channel).

The ALS Storage Ring cable trays also provided a limitation for the maximum current flowing in the coils to be equipped with brand new power supplies as the trays can accommodate cables carrying 100 A at most for these coils.

Table 2
Expected field harmonic components: + subscripts denotes 2nd order multipoles due to the 3-fold symmetry of the type G magnet.

	Regular sext.	C sext. (Type G)
Sextupole	all a_{3k}	same, all a_{odd}
H. steering	all a_{odd} but a_{3k}	same, all a_k^+ but a_{3k}
V. steering	all b_{odd} but b_{3k}	same, all b_k^+ but b_{3k}
Skew quad.	all a_{even}	same, all a_k^+ and b_k^+

4. Preliminary analysis

Analytic [6,7], 2D and 3D [8] magnetic analyses were carried out to tailor the combined function magnets designs and performance. The new sextupole integrated field strength represents about 20% of the existing sextupole strength. Due to the wide bore diameter of the magnets, the expected combined function magnet harmonic field content is quite low in absolute value and represents few 10^{-3} (within beam dynamics requirements) of the main sextupole component at a reference radius, r_0 of 25 mm. Eq. (1) provides the definition of the magnetic field harmonics we used for our analysis

$$B^* = -i(B_y + iB_x) = -i\sum_{n=1}(a_n + ib_n)\left(\frac{z}{r_0}\right)^{n-1} \quad (1)$$

More generally from the symmetries of the magnets and [6], we can deduce the harmonic components of the magnets and they are listed in Table 2. The C-shape sextupole harmonics column shows that additional harmonic components are expected in addition to the regular ones. The limited sextupole tuning range will not affect the C-magnet alignment (quadrupole component variation). As the type E magnets will be incorporated in the fast steering correction (1 kHz), lamination material and thickness were chosen to minimize any hysteresis related effects. The lamination will be made of electrical steel with small coercive force (32 A/m after a magnetizing force of 2225 A/m) and core loss (3.85 W/kg at 60 Hz). Comparative analysis, simulations as well as measurements will be performed between the magnet final design phase and the magnet prototype acceptance tests to ensure the hysteresis is minimized and predicted.

5. Current status

The project to increase the Advanced Light Source horizontal brightness has started in 2009 and has been funded through American Recovery and Reinvestment Act funds. A baseline magnet design was prepared to receive proposals from magnet manufacturers. We are expecting to have all the magnets ready for installation in early 2012. While the magnets are being fabricated, some storage ring components will be modified so that the new magnets can be installed (beamline, injection section).

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