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DEVELOPMENT OF PROTOTYPE MAGNETS FOR THE ULTRALOW EMITTANCE STORAGE RING ALBA II

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Abstract

The ALBA synchrotron light source is in the process of a significant upgrade, aiming to become a fourth-generation facility by reducing its emittance by at least 20 times. The initial phase of this project involves a comprehensive prototyping program designed to validate various critical technologies, such as magnets, vacuum systems, girders, etc., essential for facilitating the impending upgrade. This paper focuses on the development of the prototype magnets to implement the MBA lattice designed by our Beam Dynamics group. The lattice presents unique challenges, notably a remarkable degree of compactness necessitating magnet-to-magnet distances of just a few centimeters. Additionally, stringent strength requirements are imposed on both the quadrupolar (up to 110 T/m) and the sextupolar (up to 5000 T/m^2) magnets. In this paper we will describe the design details of the initial set of resistive-type prototypes, as well as the preliminary efforts to develop alternative designs making use of permanent magnets.

INTRODUCTION

ALBA is working on an upgrade project that will transform the actual storage ring, in operation since 2012, into a 4th generation light source, in which the soft X-ray part of the spectrum shall be diffraction limited. The storage ring upgrade is based on a MBA lattice which has to comply with several constraints imposed by the decision of maintaining the same circumference (268 m), the same number of cells (16), the same beam energy (3 GeV), and as many of the source points as possible unperturbed [1].

On 2021 it was launched a NGEU-funded project to produce prototypes for the new ALBA II storage ring. One of the workpackages of this prototyping project is dedicated to the development of the storage ring magnets for the ALBA II upgrade, with the aim of designing, producing and testing all the required types of magnets. Magnets prototypes will allow verifying the magnetic performance of the different designs, mechanical accuracy aspects, check the performance of cooling circuits, analyze mechanical integration aspects and study cross-talk effects between adjacent magnets.

MAGNET REQUIREMENTS

At the time of starting the magnet design work, the reference lattice was the 6BA described in [2] and shown in Fig. 1. The primary set of magnet requirements for that lattice is summarized in Table 1. The lattice includes combined function bending magnets (QD and QDS) and reverse bends

Table 1: Magnet requirements for 6BA lattice for ALBA II upgrade. The symbol L_{eff} stands for the effective length of each magnet, and the symbols B, G, and S correspond to its dipolar, quadrupolar, and sextupolar strength, respectively.

Function	Types (# per cell)	L_{eff} [mm]	B [T]	G [T/m]	S [T/m^2]
Bending	QD (4)	680	1.250	−26.173	
	QDS (2)	460	1.157	−4.878	
Rev. Bend	QF (8)	200	−0.222	+70.13	
	QFS (2)	200	−0.449	+70.05	
Quadrupole	Q1 (2)	120		−78.6	
	Q2 (2)	350		+89.4	
	Q3 (2)	220		−95.0	
Sextupole	SH (5)	320			+5000
	SV (9)	160			−5000
Fast Corr.	CORR (4)	40	0.5 mrad in both planes		

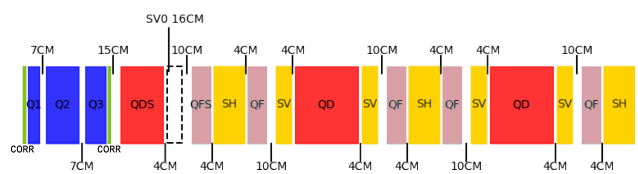

Figure 1: Schematic view of half a cell of the 6BA lattice designed for ALBA II. The quadrupole triplet on the left side is facing a straight section, and the sextupole on the right side sits in the middle of the cell. The first SV on each cell has been removed in order to ease the extraction of the photon beam from the upstream insertion device. The distances in [cm] between the effective lengths of each pair of magnets are indicated.

(QF and QFS), sextupoles (SH and SV), a triplet of pure quadrupoles (Q1, Q2 and Q3) on both sides of each cell, and a couple of dedicated fast correctors (CORR) on both sides of each straight section (surrounding the triplet). The orbit steerers to correct the electron beam orbit inside each cell, as well as skew quadrupolar correctors, will be integrated on the sextupoles.

One of the main challenges of ALBA II lattice is its compactness. Dividing the 268 m of the ring among 16 cells with 4 m-long straight sections, leaves only 12.7 m to fit the 40 magnets of the 6BA cell. Compared to the currently operating DBA lattice, which is much more sparse, the magnet-to-total length ratio will increase from a 50% (ALBA) up to a 80% (ALBA II). As a consequence, magnet-to-magnet distances have been drastically reduced, with separations between the effective length of adjacent magnets as small as 40 mm, as indicated in Fig. 1. Such small distances are a challenge both from a mechanical integration point of view and in terms of cross-talk between neighboring magnets.

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DESIGN CHOICES

Resistive vs Permanent Magnet Technology

One of the first decisions to be made when starting the design of the storage ring of a light source is the technology to be used for the magnets. Suitable choices are conventional resistive magnets consisting of an iron yoke and water-cooled copper coils, or designs based on permanent magnets (PM).

PM designs are becoming increasingly popular [3] due to their compactness, simplicity (no need for power supplies, cables, cooling water…), and reduced operational costs (no electrical power required). However, one of the main drawbacks of PM-based designs is the difficulty to make them tunable. As a consequence, in most of recent usages of this kind of solutions for ultra-low emittance storage rings they are implemented as fixed working point magnets, and the missing tunability is recovered by means of correctors. In the case of our 6BA lattice, with a highly packed distribution of combined function magnets, a preliminary evaluation indicated that such an approach was unpractical due to the lack of space to fit the required quadrupolar correctors (both normal and skew), even after taking into account the higher compactness of PM designs. As a consequence, it was decided to adopt conventional resistive technology for the baseline design of ALBA II magnets, and leave PM technology as an alternative choice for a few selected magnet types.

Magnet Efficiency and Other Requirements

During the design process of the geometry for the different magnet types, the main control parameter to evaluate the overall performance of a given design has been the magnetic efficiency, η, defined as the ratio between the real magnet's current and the ideal one that would correspond to a strictly linear version of the same magnet ($\mu_r \to \infty$). The design targets have been a 90% minimum efficiency for single-function magnets (bending magnets, reverse bends and pure quadrupoles), and a 98% for multi-function magnets (sextupoles with integrated correctors), in order to minimize the crosstalk between the different field configurations.

The minimum aperture limitation for all magnet types has been 20 mm, based on a reference design for the vacuum chamber with a cylindrical shape and an external diameter of 18 mm. Simulations to determine the magnetic performance of the different designs have been carried out using OPERA 3D [4] and RADIA [5], assuming a material choice for the magnets' yoke of low carbon steel AISI 1006. In order to keep the energy consumption of the resulting magnets at a reasonable level, current density in the coils has been limited to 5 A/mm^2.

DESIGN OF PROTOTYPES

A drawing of the developed prototypes is shown in Fig. 3, and the main parameters for each one of them are summarized in Table 2. The following design decisions for the different magnet types have been adopted:

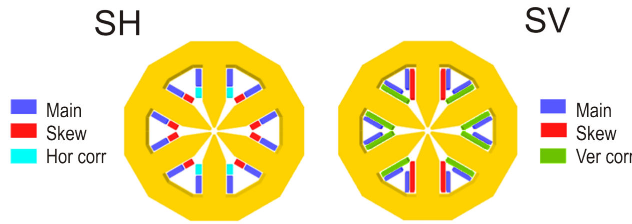

Figure 2: Proposed configuration of coils for horizontal and vertical sextupoles for ALBA II.

- Bending magnets (QD and QDS) have a moderate gradient-to-field ratio, and hence they have been implemented as conventional C-shape magnets with only 2 poles.
- The quadrupoles of the triplet (Q1, Q2, and Q3) have been designed sharing the same transversal geometry, and they only differ in their lengths (for this reason, only the prototype for Q3 will be manufactured). Despite the nominal working points listed in Table 1, they have been designed to reach gradients up to 110 T/m.
- Reverse bends require a high gradient (~ 70 T/m) and a moderate field ($\lesssim$ 0.5 T), and hence they have been implemented as pure quadrupoles displaced by a few millimeters. On top of this, given that the two types of reverse bends (QF and QFS) have the same length and almost the same working gradient, they will share one common design.
- Both types of sextupoles (SH and SV) shall achieve the same sextupolar strength S, and hence they have also been designed sharing the same transversal geometry. However, they differ in the configuration of the additional coils for correctors (see Fig. 2). The two families of sextupoles shall incorporate skew quadrupolar correctors, with a maximum integrated strength of 1 T; on top of this, horizontal (vertical) sextupoles will require horizontal (vertical) steerers, with an integrated strength of up to 10 T·mm.
- Fast corrector magnet (CORR) integrates a horizontal and a vertical steerer on the same yoke, both reaching 10 T·mm. With this aim we have adopted a 6-pole design similar to the one developed for ESRF-EBS [6], but with a symmetric version of the yoke frame.

Due to the already mentioned space constraints, special care has been taken in order to minimize the longitudinal footprint of the magnets. In order to do so, we have decreased the yoke-to-coil distances as much as possible (in some cases down to a minimum of 2 mm), and we have limited the number of layers for water cooled coils. As a consequence, most of the proposed designs have coils with only 2 layers, which in some cases has forced us to increase the transversal dimensions of the magnets in order to allocate the required number of turns. After taking all these precautions, we have managed to keep coil-to-coil distances between adjacent magnets above 10 mm.

The only exception to the described 2-layer coil configuration has been a version of the QDS magnet (labelled as

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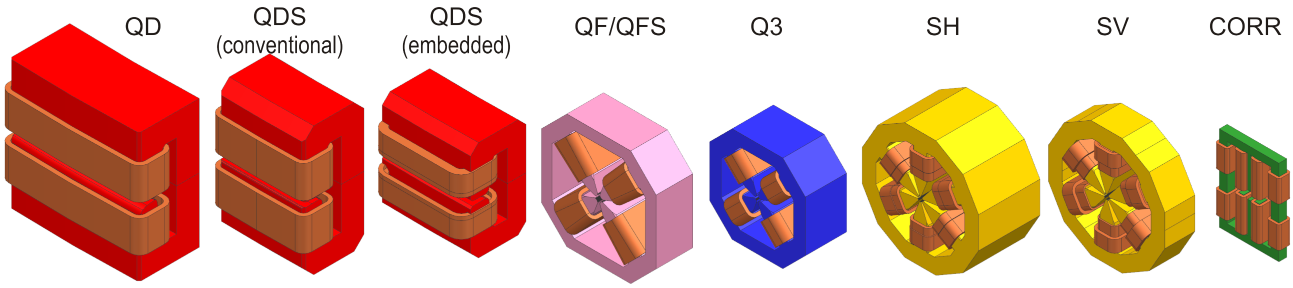

Figure 3: Isometric view of the magnetic models developed for 6BA lattice of ALBA II. In the case of the quadrupole triplet, only the Q3 magnet is shown.

Table 2: Design parameters of ALBA II magnets prototypes. The last column indicates the magnets' efficiency.

Type	Aperture diameter [mm]	Min. pole vert. dist. [mm]	Yoke length [mm]	Total length [mm]	Yoke width [mm]	Yoke height [mm]	# turns (# layers)	Current [A]	j [A/mm^2]	η [%]
QD	20	10.9	654.0	708.2	304	650	32 (2)	332	4.92	93
QDS (conventional)	20	17.5	427.0	471.8	304	650	36 (2)	266	4.96	97
QDS (embedded)	20	17.2	447.0	455.2	280	504	40 (4)	257	4.80	90
QF/QFS	27.8	11	185.7	219.7	580	580	46 (2)	QF 129.6 QFS 130.1	4.62 4.64	91
Q3	20	10	208.7	243.8	484	484	30 (2)	131.5	4.68	98
SH	23	7	310.5	340.5	588	588	main 20 (2) corr 60 (8)	103.2 7.5	4.92 1.88	99
SV	23	7	152.0	194.4	588	588	main 20 (2) corr 100 (4)	104.2 7.2	4.96 1.80	99
CORR	40	25	40	65.5	301	430	hor 528 (6) ver 354 (6)	2.5 2.5	1.0	—

"embedded" in Fig. 3 and Table 2) where we have implemented a design with the coils embedded inside the iron yoke, similar to the one that has been developed for the dipoles and quadrupoles of Elettra 2.0 [7].

MANUFACTURING AND TEST

On February 2024 a call for tender was launched for the manufacturing of the proposed set of resistive magnet prototypes. The tender is currently under evaluation process, and the contracts for the production will be signed by the end of June 2024. The engineering design is included in the scope of supply of the tender. In particular, for those magnets operating in DC (all but the sextupoles and the corrector), the choice between a laminated yoke or a yoke machined from a solid piece of material has been left to the manufacturers.

The prototypes will be delivered before the end of 2025, and will be carefully characterized at ALBA magnetic measurements laboratory.

OTHER DEVELOPMENTS

In parallel to the manufacturing of a set of resistive magnet prototypes that will cover the basic requirements of ALBA II lattice, we are also working in the design of some additional prototypes incorporating PM. These prototypes include:

- Given that the QDS magnet is the only one where tunability is not critical, we are developing an alternative design (QDS-PM) fully powered with NdFeB blocks.
- In order to increase the critical energy for some of the bending magnet beamlines we are designing an alternate version of the QD magnet with a high-field central pole, similar to the PM superbend developed at SIRIUS [8]. However, in our case we shall keep the tunability of a conventional QD magnet; as a consequence, our design combines a PM-powered central pole, reaching up to 3.2 T, with electromagnetic low field poles at both sides.

A view of those two ongoing designs is shown in Fig. 4. It is foreseen to launch a call for tender for their procurement on July 2024.

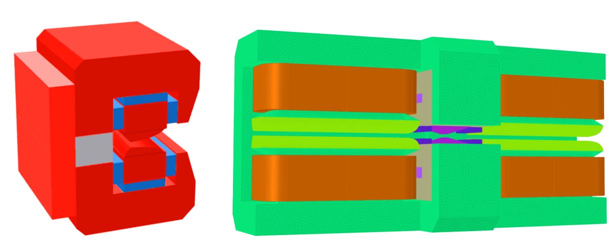

Figure 4: Designs under development incorporating permanent magnets. *Left:* PM version of QDS dipole. *Right:* 3.2 T superbend version of QD dipole.

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