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A DISTRIBUTED SEXTUPOLES LATTICE FOR THE ALBA LOW EMITTANCE UPGRADE

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Abstract

The first lattice studied in 2019 for the ALBA upgrade was a hybrid 7 BA (H7BA) lattice with two dispersion bumps, for localised chromatic correction. That lattice had limited dynamic aperture and momentum acceptance. In 2020 we started to explore a different approach to find a multi-bend achromat (MBA) lattice with distributed chromatic correction that meets the same emittance goal with larger dynamic aperture and momentum acceptance. The choice of the number of bends per cell, as well as the tuning of the magnet gradients, is carried out by developing a light weight solver that performs both the emittance and chromaticity optimisation of the arcs and the matching of the linear optics in the straight sections. We present the status of the storage ring upgrade studies, the performance of the new developed lattice, together with the issues related with the injection scheme.

INTRODUCTION

The ALBA-II project aims to upgrade the 3rd-generation ALBA storage ring [1] to a diffraction-limited source of soft x-rays that retains an energy of 3 GeV, matches the current insertion devices (IDs) source points and re-uses the existing injector.

The first studied solution [2] was a H7BA cell relying on two dispersion bumps, where two paired chromatic sextupoles and two anti-bends are installed, that delivers an emittance of 155 pm·rad with no longitudinal gradient bends. A key issue with this approach is the very limited horizontal dynamic aperture (DA) of ±1 mm, that would require a new injector for on-axis injection.

We have therefore investigated the approach where distributed sextupoles are employed in the arcs to correct chromaticity at its source and all the focusing quadrupoles serve also as anti-bends [3].

LATTICE DESIGN

The first step to design an ultra-low emittance MBA cell for ALBA-II is to keep the minimum necessary space to the straight sections and dedicate all the rest to the magnets. Assuming we retain a 268.8 m circumference, 16-fold symmetry and the current 4 m long straight sections for IDs, this leaves no more than 12 m available for magnets in each arc.

We start building an MBA arc consisting of M-2 unit cells plus two dispersion suppressors and two matching cells at the ends. Each unit cell consists of a defocusing dipole and a radially offset focusing quadrupole which also serves as reverse bend. A sextupole is inserted at either end of the dipole (vertical sextupole) and of the quadrupole (horizontal sextupole). The dispersion suppressor is derived from one half of a unit cell. Finally, a quadrupole triplet is inserted between the arc and the straight section to match the beta functions either to the IDs or to the injection.

The parameters to control the unit cell linear optics are essentially the two angles and the two gradients of the bend and anti-bend. The anti-bend angle is much smaller than the bend angle, while the angle of the bend is essentially fixed by the number of bends of the arc. The larger the number of bends, the smaller the angle and consequently the emittance. This scaling law in the end is limited by the increasing strength needed in focusing gradients. Assuming a bore radius for magnets of 10 mm, a rough estimate shows that the maximum quadrupole gradient is 90 T/m and the sextupole gradient 5000 T/m^2.

With this constraints we varied the number of bends in the arc from five to nine and optimised the other parameters (the two magnet gradients and lengths and the anti-bend angle) in order to minimise the emittance and find the optimum number of bends. This resulted in a 6BA cell (Fig. 1), with no longitudinal gradient in a first approach. The resulting angle of the bend is 4.5º plus a slight addition to compensate for the reverse bend that can be tuned to minimise the emittance.

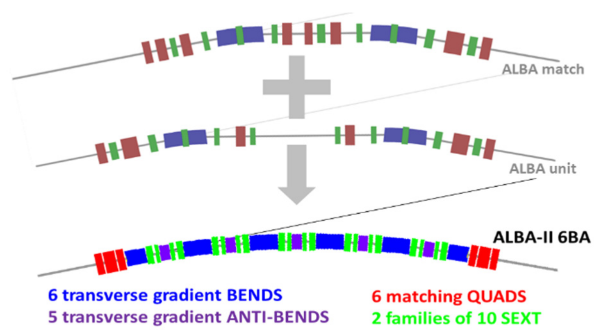

Figure 1: In ALBA-II, the two types of DBA cell (8 matching cells plus 8 unit cells) of the current lattice are replaced by 16 identical 6BA+anti-bend cells.

OPTICS OPTIMISATION

The optics tuning has been performed developing a light weight optics code (a simplified code that simulates lattices adopting several approximations) used to speed up the optimisation in three steps. First, the unit cell is generated from a set parameters (bending angle, magnet lengths and gradients), then a random-walk approach is employed to optimise the magnets parameters: thousands of candidate solutions are randomly varied, tested and selected in a process that minimise a cost function which takes into account mainly emittance and chromaticity. In a second

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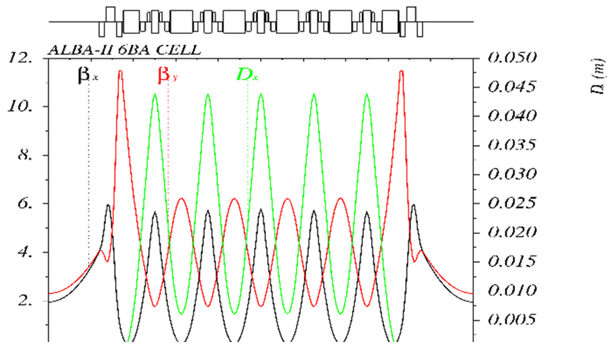

Figure 2: Optics in one 6BA cell for ALBA-II.

step, the quadrupole triplet is adjusted to match the optics either of the IDs or of injection. Finally, the cost function is evaluated again including the DA and lifetime and all the parameters of the arc and the matching cell are re-optimised together. The final solutions are checked against MAD-X, Elegant and AT [4-6].

When performing this optimisation we realised that the solutions with minimum emittance (about 130 pm·rad) coincided with the isochronous condition for the cell. The parameter that drives the momentum compaction factor is the anti-bend angle. Varying the small and negative anti-bend angle around -1.5º, the momentum compaction crosses the zero value. For the 6BA lattice we have detuned the anti-bend angle to smaller values and targeted the momentum compaction to $1 \cdot 10^{-4}$, which renders an emittance $\varepsilon_x = 140$ pm·rad. This choice provides a momentum compaction large enough to guarantee acceptable lifetime and stable longitudinal motion, while also delivering an emittance below that of the H7BA lattice (Table 1).

Table 1: 6BA Lattice Main Parameters (Rightmost Column) Compared to the H7BA Lattice and the Current DBA Ring

	Current DBA	H7BA	6BA
Emittance	4.5 nm·rad	155 pm·rad	140 pm·rad
Energy	3 GeV	3 GeV	3 GeV
Circumference	268.8 m	269.0 m	268.8 m
N.of cells	8+8	16	16
N. of straights	4 / 12 / 8	16	16
Straight length	7.8 / 4 / 2.3 m	4.3 m	4.0 m
Straight ratio	36%	25%	24%
Working point	18.15, 8.36	43.26, 13.26	43.68, 11.67
Chromaticity	-39, -29	-94, -92	-94, -51
Mom.comp.fact.	$8.9 \cdot 10^{-4}$	$1.8 \cdot 10^{-4}$	$0.8 \cdot 10^{-4}$
Energy spread	$1.0 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	$1.1 \cdot 10^{-3}$
Energy loss/turn	1023 keV	630 keV	843 keV
Damping times	4 / 5 / 3 ms	4 / 8 / 12 ms	3 / 6 / 6 ms

The matching cell has three quadrupoles which are tuned to provide low betas at the ID source points. All the constraints (maximum quadrupole strength, chromaticity and emittance) provide $\beta_{x,y}^* \approx 2$ m (Fig. 2), about twice the betas of the matched electron to diffraction limited photon emittance (L_{und}/π) over the present 2 m long undulators.

So far non-linear optics tuning has been performed setting the phase advances and the two sextupole strengths such that they cancel the chromaticity and the first order resonance driving terms (RDTs). This condition sets the sextupole gradients close to 5000 T/m^2, leaving small room for further DA optimisation.

Realistic magnet lengths have been chosen for all magnets and minimum magnet separation has been set to no less than two magnet gaps in order to limit the cross-talk. The bending magnets field is 1 T combined with a maximum defocusing gradient of 15 T/m. The anti-bend magnets have 0.35 T field and 70 T/m focusing gradient.

Drift space for up to 160 BPMs and vacuum equipment has been provided, while no space has been set aside for corrector magnets assuming they can be implemented as additional winding on sextupoles and quadrupoles.

INJECTION SCHEME

An injection scheme that uses the existing injector – a booster in the same tunnel as the storage ring with an emittance as small as $\varepsilon_x = 10$ nm·rad – has to be designed. The choice currently under study consists of an off-axis injection scheme with both septum and non-linear kicker (NLK) [7] placed in one of the 4 m long straight sections.

A rough estimate shows that, under the space constraint, the horizontal DA needed to guarantee 100% injection efficiency is -8 mm.

The initial DA simulations for a lattice with 16 identical cells with $\beta_{x,y}^* \approx 2$ m delivered a DA of ±3 mm, three times larger than the one of the H7BA, yet not enough. As a consequence, in order to enlarge the horizontal DA, the horizontal beta function in the injection straight section is increased to $\beta_x^* = 12$ m only by changing the strength and polarities of the three matching quadrupoles (Fig. 3).

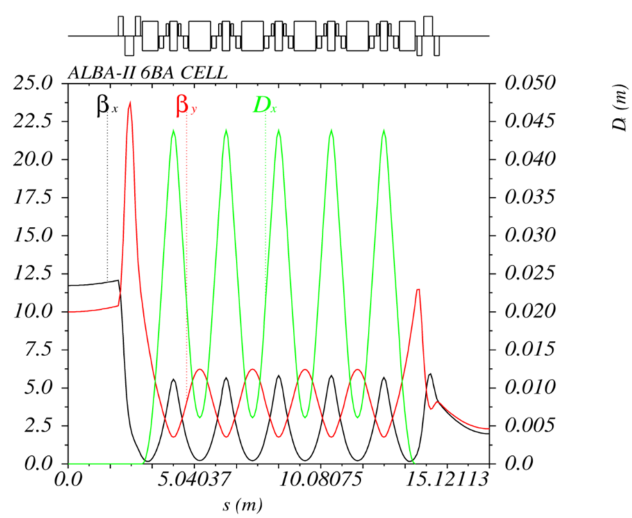

Figure 3: Optics of the injection cell.

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RESULTING PERFORMANCE

The DA that results from the optics tuning is ±6 mm in both planes according to 4D tracking with RF on (Figs. 4, and 5). The Touschek lifetime estimate with 0.5 mA per bunch and 3.6 MV RF voltage is 4.5 hours with 50% coupling (Fig. 6), which is a remarkable value taking into account the small momentum compaction factor. The stretching from high order RF cavities and the effect of intra-beam scattering is not included yet.

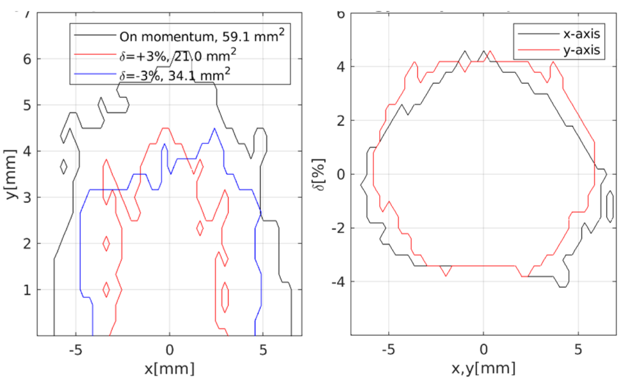

Figure 4: DA on and off-energy at the injection section with $\beta_x = 12$ m and $\beta_y = 10$ m, computed without errors.

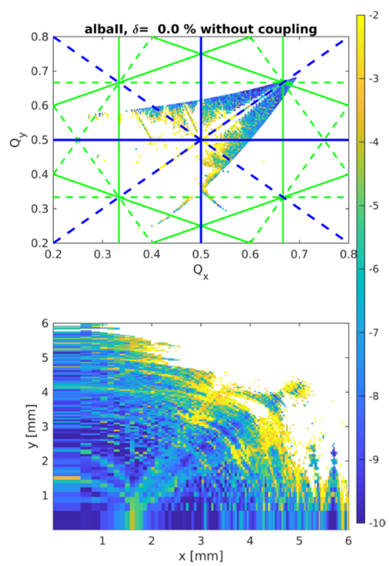

Figure 5: Frequency map analysis.

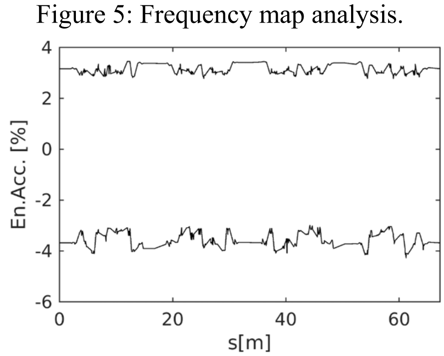

Figure 6: Local Touschek momentum acceptance in a quarter of ring (four cells) is above ±3%.

CONCLUSIONS AND OUTLOOK

The study to develop a ring based on a 6BA with distributed sextupoles is going to lead to the ALBA-II baseline lattice by the end of 2021. The work we are still carrying out is mainly aimed at improving the DA to provide an efficient injection and to introduce sources for the dipole beamlines.

The non-linear optics strategy currently under evaluation consists of splitting the two sextupoles into more families and adding sextupoles and octupoles in the matching cell to minimise the RDTs up to third order and the tune shift with amplitude dependence. For an intensive non-linear optimisation a specialized code running in cheap low-end GPU coprocessors is being developed, which moreover the use of many approximations allows to speed up even further the tracking. Reliability tests have returned only 10% discrepancy in DA computations when compared to MAD-X/PTC, while from a performance point of view it makes it possible tracking 10^5 particles for 1000 turns per second.

Concerning the source for the dipole beamlines, many experimental stations would be satisfied using the field of 1 T provided by the 6BA (critical energy of 6 keV), while for higher energy beamlines the impact on the lattice performance due to the insertion of very short 3 T field super-bend magnets [8] in the middle of up to eight of the arc bends has already been tested. The option of employing longitudinal gradient bendings is being evaluated and would be considered only if providing substantial advantages not only for the emittance but mainly for the non-linear performance.

Finally, misalignments and field errors tolerance studies are being carried out in order to assess the acceptable level in their effect on DA and lifetime reduction and to design both the beam based alignment strategy and the orbit correction scheme.

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