BEAM DYNAMICS STUDIES FOR THE MAX 4^{U} LATTICES

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Abstract

MAX 4^{U} is an upgrade of the 3 GeV storage ring at MAX IV Laboratory, meant to considerably reduce the emittance of the present machine (328 pm rad), limiting changes to the present infrastructure, keeping the same beamline source points and minimizing costs and dark time for the MAX IV user community. The paper reports on the beam dynamics studies performed during the conceptual design stage resulting in two lattice candidates at 95 and 65 pm rad, showing pros and cons for an informed choice of the final lattice, presently aiming at less than 75 pm rad.

INTRODUCTION

The global quest for reduced emittance machines is the main drive at the core of the MAX 4^{U} project. At the beginning of 2024, as part of the Conceptual Design Report (CDR) [1], we started a thorough study of the possible candidates for an upgraded machine, initially aiming at a lattice delivering less than 100 pm rad with minimal impact on the present infrastructure, a process often described as a *surgical intervention* [2]. These starting goals rapidly produced two lines of investigation: a more conservative one, with reduced intervention on the machine aiming at the control of costs, and a more aggressive path, where the economic factor was relaxed to gain a smaller emittance in return. The two cases, named Absolute Requirement (AR) and Stretch-Goal (SG), are examined in this paper, showing the main differences and weighing pros and cons.

Both the designs stem from the 3 GeV ring of MAX IV [3], a 7BA machine (Fig. 1) and both make use of reverse bends to effectively push emittance reduction [4]. In the AR design these new magnets are located in the central unit cell (UC3), whereas in the SR lattice reverse bends are distributed over five of the seven achromat cells. Another key difference is the introduction of a new combined function dipole family for AR, needed to compensate for the flanking reverse bends, for a total of three bending dipole types (D1, D2 and D3), whereas the SR is based upon two dipole families (D1 and D2). In both architectures, the D1s belong to the matching sections of the achromat. In the next sections, we detail the main traits of the two designs.

Absolute Requirement Lattice

Figure 1 illustrates the transformation from the current 3 GeV lattice to the new designs. One of the main guidelines in its realisation is the preservation of the vacuum system with limited modifications of the magnets whose positions are kept. For AR there is a new sextupole family (S6), while the QF quadrupoles turn into the R1 reverse bends. Sextupoles S1, S3, and S6 have also a quadrupolar component. As said in the previous paragraph, the central dipole in UC3 is modified to compensate for the anti-bending effect, which causes a local change in orbit, confined around the cell. Conversely, the orbit outside the reverse bend region is unchanged, in particular in the matching cell area, where it is important to limit the entry angle at D1 (currently 1.5°) to avoid an excessive power deposition. The Twiss parameters for this lattice are summarized in Fig. 2 (top), whereas a comprehensive collection of parameters is given in Table 1.

In the optimisation process of the lattice, attention was paid to the phase advance between the unit cells, following the robust design philosophy based on the suppression of the resonance driving terms (RDT). In the AR case this approach is highly relaxed due to the non-symmetric nature of the lattice. The RDT cancellation happening every four achromats still results in a machine exhibiting good performance parameters as reported in the relevant section.

Stretch-Goal Lattice

With respect to the AR case, the SG lattice presents distributed reverse bends, which is key to push the emittance down to 65 pm rad. The total orbit variation is therefore more pronounced than in the AR case, although spread over the whole achromat (see Fig. 3). The new orbit entails a reduced entry angle at D1 (1.3°) which could require the replacement of vacuum chambers in this region. The issue is presently tackled both from the engineering perspective and via an optimisation of the original SG design. This lattice considers an achromat-wise RDT cancellation, resulting in a highly-symmetric layout (see Twiss parameters in Fig. 2) with a large robustness in the key performance parameters discussed in the next section.

Performance Comparison

The key parameters utilized to benchmark the performance of the two lattices are the Dynamic Aperture (DA) and the Local Momentum Aperture (LMA). The latter comes also with a determination of the Touschek Lifetime (TLT). In the design process, we also control the amplitude and momentum dependent tune shifts (Fig. 4), which is key to avoid potentially dangerous drifts of the working point towards resonance bands. Figure 5 shows the on-energy DA calculated at the mid-point of straight 1, for the AR (red) and the SG (blue) cases. Individual mis-alignments and gradient errors are introduced, the orbit is corrected and tunes are set to the nominal working points for every error seed. This set of simplified error is a proxy for a more thorough treatment which includes an optics fitting of the machine, presently

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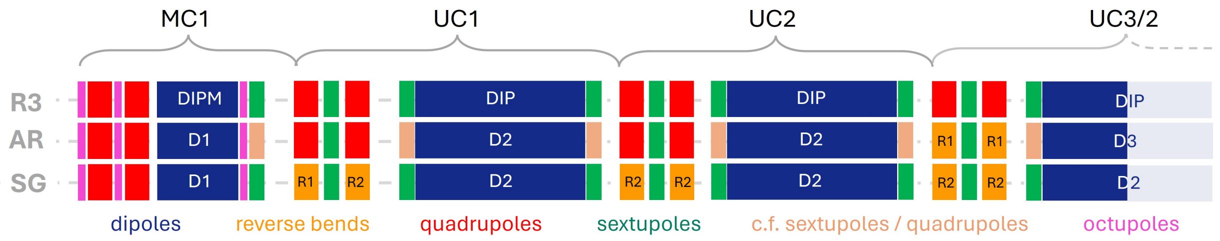

Figure 1: Genesis of the AR and SG lattices starting from the present architecture. Top: the MAX IV 3 GeV structure for half achromat. Centre: the AR case, where the main change is the introduction of four reverse bends (yellow boxes) flanking the central UC3 bending magnet. Bottom: the SG case, where reverse bends are distributed over the entire achromat, except for the matching cells.

Table 1: Lattice Parameters for the present machine (R3, column 2) and for the cases explored in the CDR phase: AR, column 3 and SG, column 4.

	R3	**AR**	**SG**	**units**
ϵ_X	328	95	65	pm rad
$\delta E/E$	7.69	7.55	8.46	10^{-4}
β @ long straights	(9.0, 2.0)	(6.8, 3.3)	(4.2, 4.4)	m
natural bunch length	8.8	6.7	5.7	mm
(ν_X, ν_Y)	´(42.20, 16.28)	(55.28, 16.20)	(58.29, 17.15)	
(ξ_X, ξ_Y) natural	(-50.0, -50.2)	(-89.2, -56.6)	(-97.4, -57.6)	
(ξ_X, ξ_Y) corrected	(1, 1)	(2, 2)	(2, 2)	
mcf (α_1, α_2)	(3.06, 1.62)	(0.95, 2.92)	(0.54, 3.63)	10^{-4}
Total deflection angle	360	396.2	442	deg
D1 deflection angle	1.5	1.5	1.3	deg
energy loss / turn	364	414	474	keV
damping times (H, V, L)	(15.73, 29.05, 25.19)	(14.75, 25.51, 20.08)	(11.44, 22.29, 21.18)	ms

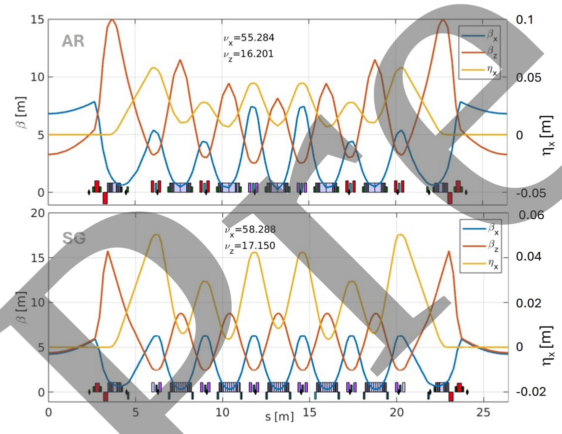

Figure 2: Twiss parameters for the AR (top) and SG (bottom) options. The symmetry in the beta functions is relaxed in the AR case, whereas is strictly achieved in the SG case, allowing a more controlled RDT cancellation. In the SG case we also appreciate the reduced beta functions at the long straights, playing a role in further brightness reduction.

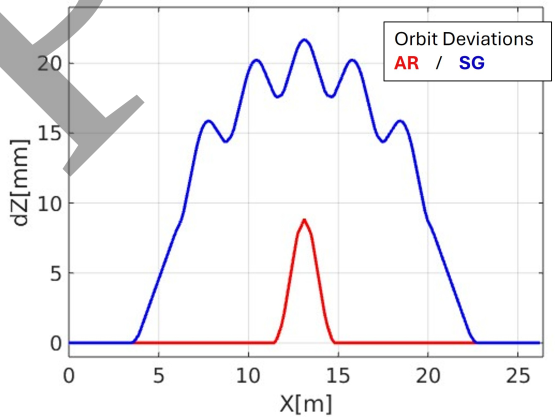

Figure 3: Orbit deviations with respect to the present 3 GeV machine, as due to the use of reverse bends. We note the confined change in the central cell for the AR case (red), as opposed to the distributed variation in the SG lattice (blue). The orbit reaches zero deviations at the centre of the long straights (no source points variation).

under study. The AR case displays a better overall horizontal DA, whereas the robustness of the SG solutions sticks out in the very small error band (5th to 9th percentile of 30 seeds). A similar comparison for the LMA is shown in Fig. 6, where we appreciate the large momentum acceptance, likely due to the strong request on RDT cancellation. When translated into TLT (Fig. 7) this results in figures of 9 (AR) to 19 (SG) hours, prior to any Landau cavity bunch stretching.

Injection Schemes

Possible injection schemes for MAX 4^{U} are currently under study and treated in detail in [5]. For the lattice cases

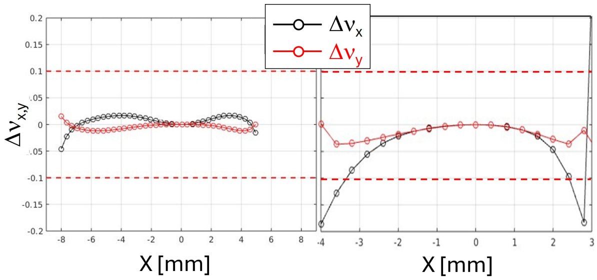

Figure 4: Amplitude Dependent Tune Shifts in the horizontal plane for the AR (left) and the SG (right) lattices. The dashed red lines at ±0.1 show a typical maximum limit allowed for the tune shifts.

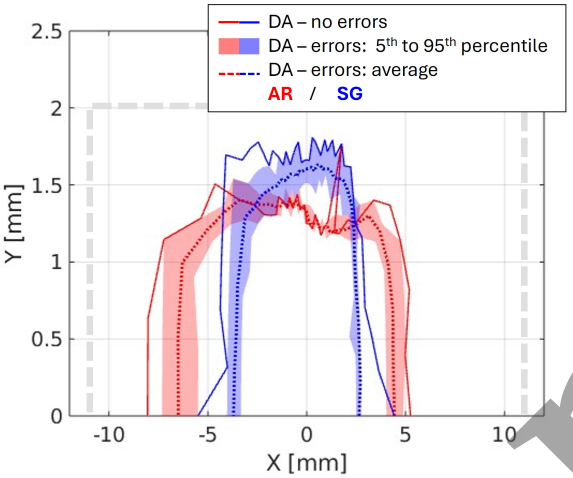

Figure 5: Dynamic Aperture plots for the AR (red) and the SR cases (blue). In both plots the ideal lattice is represented by a solid line, whereas the shaded band is the 5th to 95th percentile of 30 error seeds with machine errors. The dotted lines indicate the average of the error seeds. The gray dashed lines show the physical apertures considered for the CDR study: ± 11 mm in the horizontal plane (vacuum chamber) and ± 2 mm in the vertical plane (ID minimum gaps).

presented in this paper and thoroughly analysed in the MAX 4^{U} CDR, we can conclude that an off-axis injection based on a multipole injection kicker (MIK) as in the present machine is still viable for the AR lattice, thanks to its large DA. The smaller horizontal DA of the SG lattice could be overcome with a better effective MIK, like the one presently under construction at Soleil [6] or possibly with a kick-and-cancel scheme as proposed for Diamond II [7]. However, to achieve high transparency avoiding the field imperfections along the MIK axis, we are considering a novel injection based on an on-axis, off-phase, on-energy scheme where the injected bunch is placed at a time separation of few nanoseconds from the stored bunch centre, yet inside the bucket. A fast stripline kicker (SLK), with falling times of less than 2 ns, is used to bring the injected beam on-axis. In this respect, the SLK is expected to impart kicks up to 2.5 mrad, with injection efficiencies very close to 100 % [1].

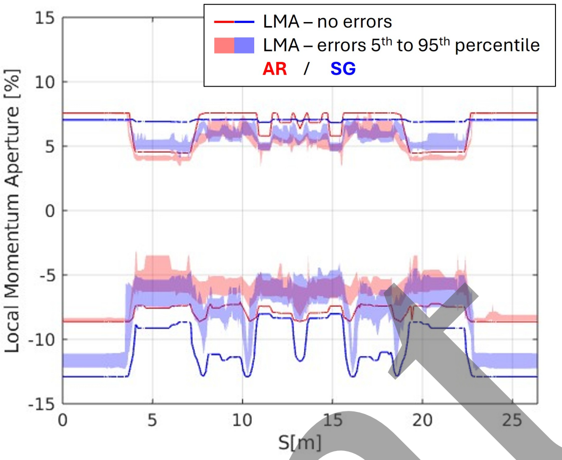

Figure 6: Local Momentum Aperture plots for the AR (red) and the SR cases (blue). As in the DA case, the ideal lattice is represented by a solid line, whereas the shaded band is the 5th to 95th percentile of 30 error seeds with machine errors.

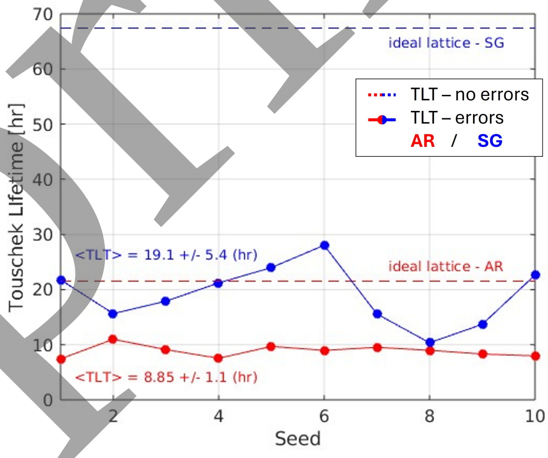

Figure 7: Touschek lifetimes for the AR (red) and SG (blue) lattices ($I_{\mathrm{beam}} = 500\,\mathrm{mA}$, $\epsilon_y = 8\,\mathrm{pm\,rad}$). Note the large values for the SG case, deriving from the better control of the LMA. In both cases no bunch stretching has been applied.

CONCLUSIONS

This paper summarizes the aspects of beam dynamics thoroughly treated in the MAX 4^{U} CDR, where the reader can find further details. The main conclusion of the studies performed during the CDR work was the realisation that the original goal of achieving a bare lattice natural emittance below 100 pm rad under restrictive time and cost boundary conditions could not only be met, but actually surpassed. As a result, the MAX 4^{U} technical design phase, initiated in January 2026, has set an updated target emittance below 75 pm rad. The starting point of the technical design phase is the TDR-1 lattice, which is a descendant of the SG lattice and is described in more detail in various contributions to this conference [2, 5, 8].

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