INCREASING HIGH LUMINOSITY LHC DYNAMIC APERTURE USING OPTICS OPTIMIZATIONS*

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Abstract

CERN's Large Hadron Collider (LHC) is expected to operate with unprecedented beam current and brightness from the beginning of Run 4 in 2029. In the context of the High Luminosity LHC project, the baseline operational scenarios are currently being developed. They require a large octupole current and a large chromaticity throughout the entire cycle, which drives a strong reduction of dynamic aperture, in particular at injection and during the luminosity production phase. Despite being highly constrained, the LHC optics and sextupole and octupole corrector circuits still offer a few degrees of freedom that can be used to reduce resonances and the extent of the tune footprint at constant Landau damping, thereby leading to an improvement of the dynamic aperture. This contribution presents the status of the analysis that will be used to prepare the optics baseline for LHC Run 4.

INTRODUCTION

The HL-LHC project [1] aims at upgrading the insertion regions of the high luminosity experiments and ancillary systems all around the LHC run, enabling the collection of over 3000 fb^{-1} proton-proton luminosity in ATLAS and CMS and, at the same time, providing collisions to the ALICE and LHCb experiments.

Run 4 is the first run with the new HL-LHC hardware, notably Nb_3Sn triplet magnets, crab cavities (CC), full remote alignment system, new collimation system, and additional cryogenic plants. The first year is expected to be mostly dedicated to commissioning activities, with luminosity production reaching the yearly integrated luminosity target of 250 fb^{-1} by the end of Run 4, while still integrating a substantial amount of luminosity (750 fb^{-1}) in the first 4 operational years [2–4].

OPTICS CHALLENGES

The Run 4 optics for protons should accommodate numerous challenges spanning very different aspects, among which the dynamic aperture is one of them. Before addressing the dynamic aperture, it is useful to recall the optics challenges.

Run 4 will use for the first time magnets based on the novel Nb_3Sn technology, in particular the triplets in IP 1 and 5, that could be critical for optics control and correction. Therefore, the lowest β^* at the end of the luminosity levelling is expected to be difficult to commission [5]. At the same time, the population of the bunch is expected to be lower than the HL-LHC baseline to match the bunch charge achieved during Run 3 [1, 3]. Similarly, in the first year of Run 4 it is planned to use β^* values close to those already achieved in Run 3. It is also important to prepare an optics cycle that allows pushing β^* during Run 4 and even further for the machine studies in preparation for Run 5. In this respect, Run 4 optics should be prepared to support a large range of β^* at the flat top and the end of levelling.

Table 1: Critical phase advance in degrees (modulo 360°) for the end-of-levelling optics ($\beta^* = 15\,\mathrm{cm}$) without optimizations. The values are marked red when close to the worst possible case, orange when not yet ideal, and black for those close to the best case. Red values are not a blocking issue but require mitigation, such as relaxing the collimator hierarchy and thus limiting the optimum β^* reach. Crab-cavities (CC) to tertiary collimators (TCP) phase advance should be smaller than 30° mod 180°. Dilution kickers (MKD) to TCT phase advance should be smaller than 30° mod 180°. The primary collimators (TCP) to TCT should be either below 30° or in between 70 – 110° mod 180°.

CC-TCP	**B1 Left**	**B1 Right**	**B2 Left**	**B2 Right**
CC1 H	88.21	86.76	28.77	29.93
CC5 V	21.19	19.74	-52.65	-36.87
MKD-TCT	**A.B1**	**O.B1**	**A.B2**	**B.B2**
TCTH1	-4.85	1.35	-18.7	-14.74
TCTH5	-29.87	-23.67	-30.97	-27
TCTH8	3.55	9.74	57.16	61.12
TCP-TCT	**B1 H**	**B1 V**	**B2 H**	**B2 V**
TCT1	23.75	-81.71	81.78	-31.38
TCT5	-1.27	-85.69	69.52	-13.25
TCT8	32.14	77.75	-22.36	-82.54

One of the key ingredients to obtain low-β^* in ATLAS and CMS is to run with the tightest possible hierarchy of collimators. The minimum gap of collimators is limited by several constraints of various origins. These constraints can be mitigated by special optics design. The primary and secondary collimator gaps are limited by impedance. New special optics [6] are being studied and tested to increase the β-functions and thereby the gap at the collimator, during the ramp and flat top, as the geometrical emittance reduces. Furthermore, the phase advance from the TCP to the TCT must be optimised to avoid an increase in background [7] and the phase advance from the CCs to the TCPs should be

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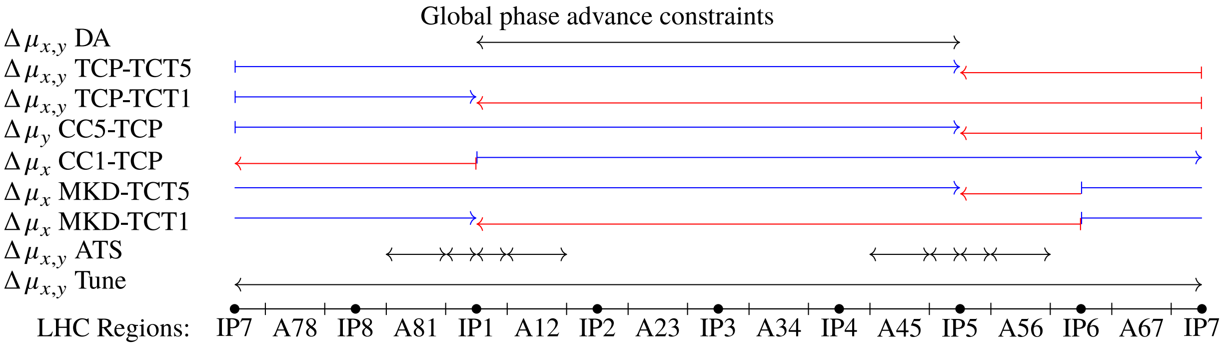

Figure 1: Phase-advance constraints considered during optics design during physics, for Beam 1 (blue), Beam 2 (red) and both beams (black). The LHC has the flexibility to change the phase advance in the 8 arcs and 16 half-straight sections around the IP. Although tune and ATS are strict constraints, the others could be fulfilled with some flexibility, which allows for some optimisation.

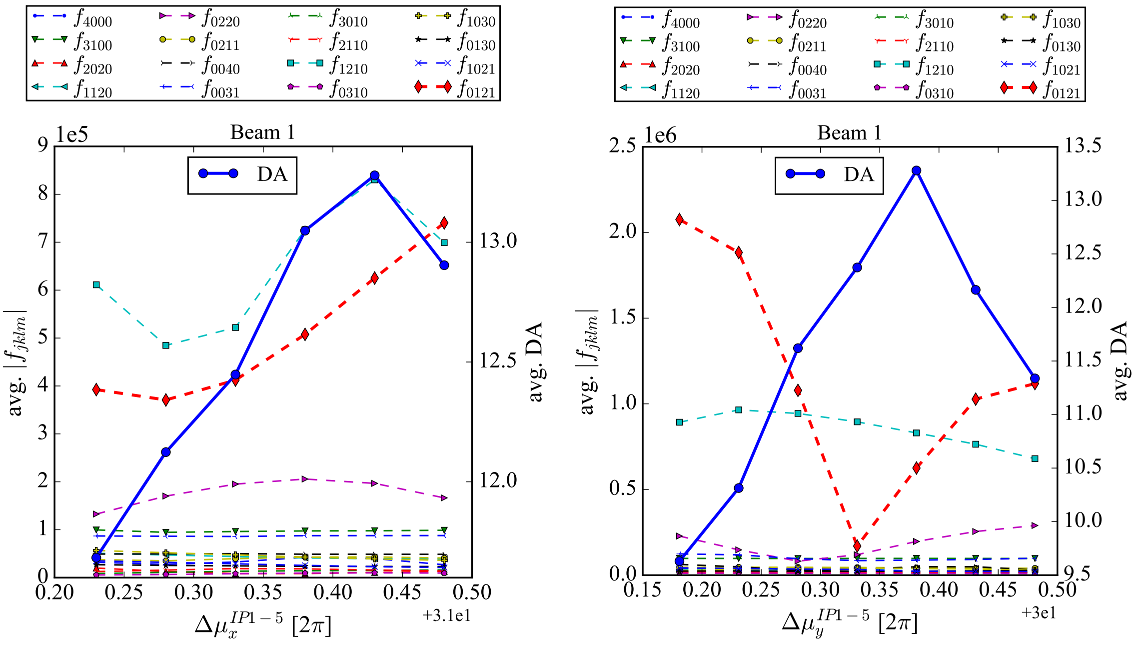

Figure 2: Octupolar resonance driving terms (RDT) and average dynamic aperture (DA) as a function of the horizontal (left) and vertical (right) phase advance between IP1 and IP5 (left) for the 15 cm β^* round baseline optics at the end of levelling. The DA is simulated without multipolar imperfections, with crossing angle, dispersion correction, and Landau octupoles set to their maximum strength of -570 A, after 10^6 turns and calculated over 60 angles.

below 35° to mitigate the effects of CC failures [8]. The gap between secondary and tertiary collimators can be minimal only if the phase advance between the dump kicker (MKD) and the tertiary collimators (TCT and TCL) in Points 1 and 5 is below a threshold such that an asynchronous beam dump will not damage these collimators, which are not designed to absorb large losses. All these constraints, in addition to those resulting from quadrupole strength limitations and a few others [9], increase the complexity of the optics design (see Fig. 1). Despite the large number of constraints, it was possible to find an optimisation (see Tables 1 and 2).

DA Optimisation

Given that most of the phase advance constraints are soft inequalities, there is still some margin to use phase advances to improve DA. Phase advance between Points 1 and 5 can be used to improve DA in the presence of beam-beam and strong octupoles [10–12] in the HL-LHC for different optics.

Although at injection a correlation was found between the strength of the main octupolar resonances, $2Q_x - 2Q_y$, $4Q_x$ and $4Q_y$, and DA [12–14], for optics at smaller β^* a correlation with RDTs has not been established. For example, a study for the optics at the end of levelling ($\beta^* = 15$ cm), see Fig. 2, does not show a clear correlation with the octupolar RDTs, more studies will be pursued to verify these

Table 2: As Table 1 with optimization using the flexibility of Arc 23, 34, 67, 78 and insertion 2, 8, 3, 4. Most of the critical phase advance could be improved, besides MKD-TCT5 (tertiaries in Point 5) which have very little flexibility (only the left side of insertion region IR6).

CC-TCP	**B1 Left**	**B1 Right**	**B2 Left**	**B2 Right**
CC1 H	16.21	14.76	13.87	15.02
CC5 V	21.19	19.74	6.16	7.55
MKD-TCT	**A.B1**	**O.B1**	**A.B2**	**O.B2**
TCTH1	-4.75	1.45	-18.67	-14.71
TCTH5	-29.77	-23.57	-30.94	-26.97
TCTH8	4.27	10.47	48.58	52.54
TCP-TCT	**B1 H**	**B1 V**	**B2 H**	**B2 V**
TCT1	-84.25	-81.71	-83.31	-75.79
TCT5	70.73	-85.69	84.42	-72.06
TCT8	-75.23	77.45	-16.07	50.96

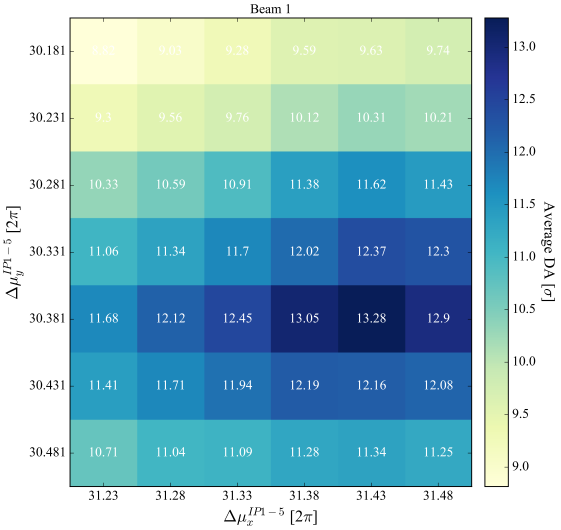

Figure 3: Average DA for Beam 1 for the baseline, in the same conditions of the Figure 2.

results and reveal correlations. Octupoles are the strongest source of amplitude detuning in the simulation. Indeed, higher-order aberrations involving both sextupoles and octupoles were suspected as the origin of the tune footprint distortion and possibly the DA drop. Despite the absence of a clear source, DA simulations consistently show potential increases of about 1σ in DA when scanning phase advances, see Figs. 3, 4 and 5.

In addition, octupole strength could also be modulated, rather than being equally powered among the different arcs, to reduce the amplitude of RDTs. This optimization was proven to be effective [11], showing that the strength of octupole families at locations with large β-functions should be minimized.

These encouraging results need to be incorporated in the Run 4 optics scenarios. The interplay between phase advance constraints, collimation optics and settings, and β^* reach, still requires additional iterations to converge towards an optimal scenario.

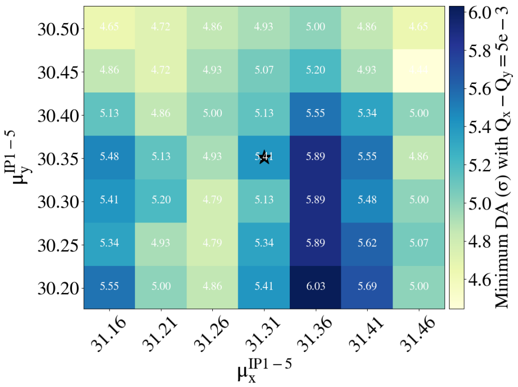

Figure 4: Minimum DA as a function of horizontal and vertical phase advance between IP1 and IP5 for the injection optics [15]. The working point at each study corresponds to the one with the largest minimum DA from the left plot. The nominal IP1-5 phase advance is also shown (star-shaped marker).

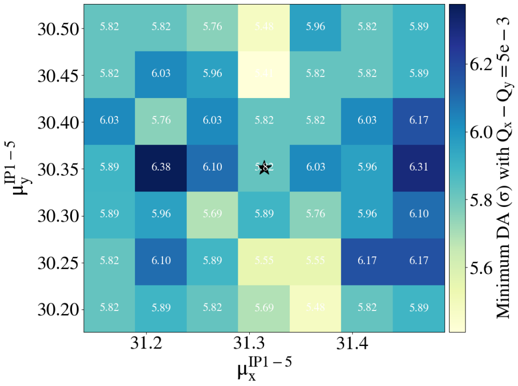

Figure 5: Minimum DA as a function of horizontal and vertical phase advance between IP1 and IP5 for the start of levelling optics $\beta^* = 1\,\mathrm{m}$ [15]. The nominal IP1-5 phase advance is also shown (star-shaped marker).

CONCLUSIONS

The HL-LHC optics have some flexibility in adjusting phase advance between collimators, dilution kicker, and the interaction points. These phase advances determine the machine protection thresholds and collimation efficiency that in turn define the minimum protected aperture, and therefore β^*. At the same time, the DA shows a strong sensitivity with phase advance between IP1 and 5, which will determine the beam lifetime at the end of levelling or during the collapse process. Phase advance optimisation is planned to be included in the next iteration of the Run 4 scenario.

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