Increasing High Luminosity LHC dynamic aperture using optics optimizations[1]

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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.

1. Optics challenges

The Run 4 optics scenarios [1] for protons should accommodate numerous challenges spanning very different aspects:

- Dynamics aperture (DA) from large beam-beam effects and large octupoles for Landau damping due to high intensity, high brightness beams.
- Potential incoherent effects from e-cloud [2].
- large range of β^* at the flat top and the end of levelling.

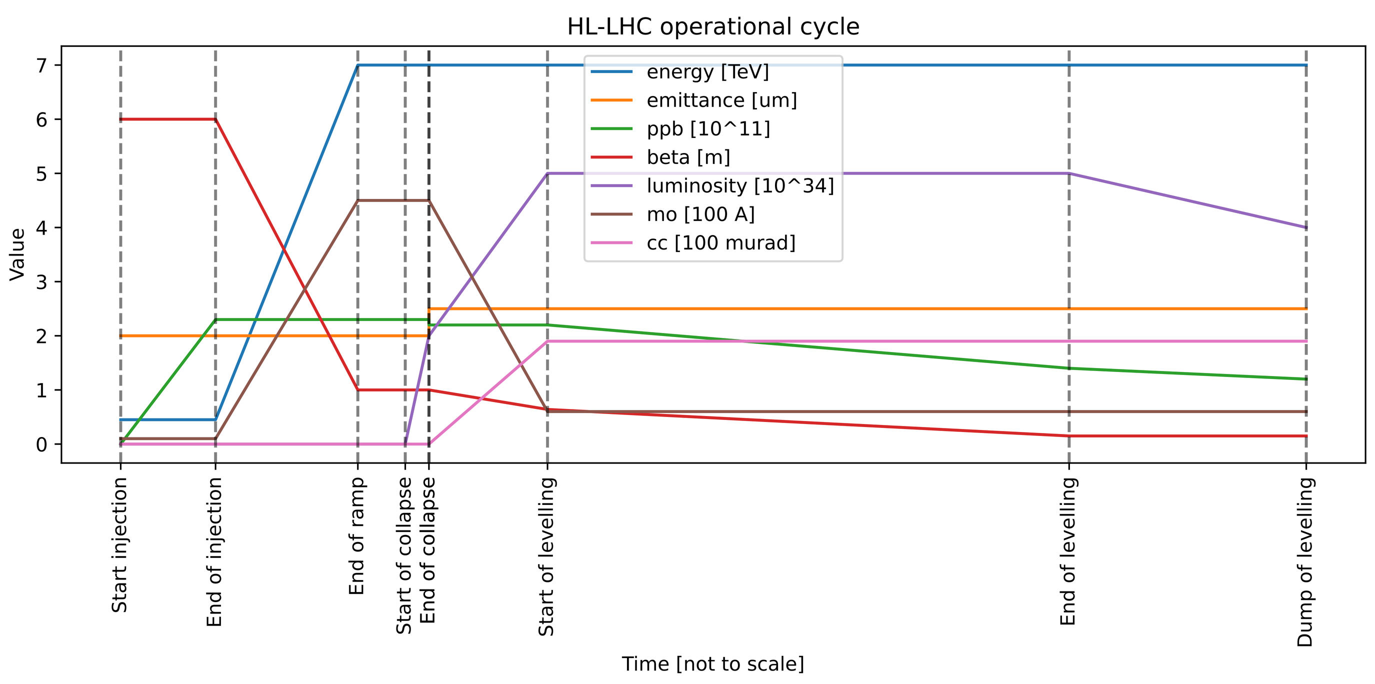

Figure 1: *Schematic evolution of main quantities throughtout the an HL-LHC cycle for proton*

Besides what is needed for the tune and ATS optics, additional phase advance constrains are being considered in the optics design:

- TCP to the TCT must be optimised to avoid an increase in background [3]
- Phase advance from the CCs to the TCPs should be below 35° to mitigate the effects of CC failures
- 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

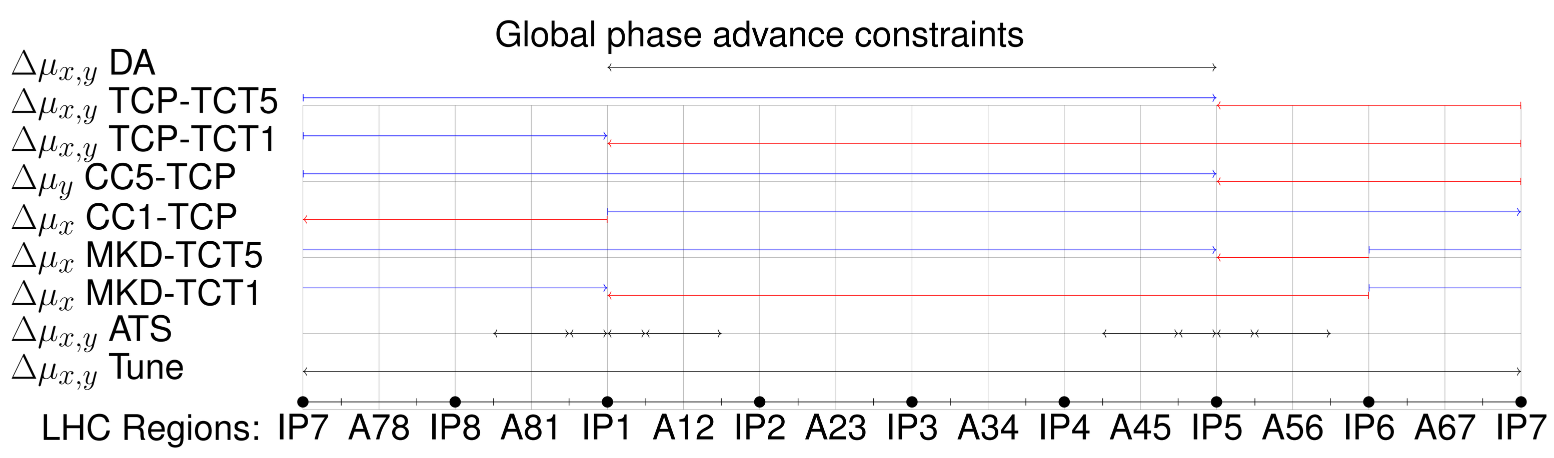

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Figure 2: *Phase-advance constraints considered during optics design during physics, for Beam 1 (blue), Beam 2 (red) and both beams (black). The LHC has the flexibility to change the phase advance in the 8 arcs and 16 half-straight sections around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

Table 1: *Critical phase advance in degrees (modulo $360°$) for the end-of-levelling optics ($\beta^* = 15$ 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 $70 - 110° \mod 180$. 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).*

Phase	**Baseline**				**Optimization**			
CC-TCP	B1 Left	B1 Right	B2 Left	B2 Right	B1 Left	B1 Right	B2 Left	B2 Right
CC1 H	88.21	86.76	28.77	29.93	16.21	14.76	13.87	15.02
CC5 V	21.19	19.74	-52.65	-36.87	21.19	19.74	6.16	7.55
MKD-TCT	A.B1	O.B1	A.B2	B.B2	A.B1	O.B1	A.B2	B.B2
TCTH1	-4.85	1.35	-18.7	-14.74	-4.75	1.45	-18.67	-14.71
TCTH5	-29.87	-23.67	-30.97	-27	-29.77	-23.57	-30.94	-26.97
TCTH8	3.55	9.74	57.16	61.12	4.27	10.47	48.58	52.54
TCP-TCT	B1 H	B1 V	B2 H	B2 V	B1 H	B1 V	B2 H	B2 V
TCT1	23.75	-81.71	81.78	-31.38	-84.25	-81.71	-83.31	-75.79
TCT5	-1.27	-85.69	69.52	-13.25	-29.77	-23.57	-30.94	-26.97
TCT8	32.14	77.75	-22.36	-82.54	-75.23	77.45	-16.07	50.96

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 [4] in the HL-LHC for different optics.

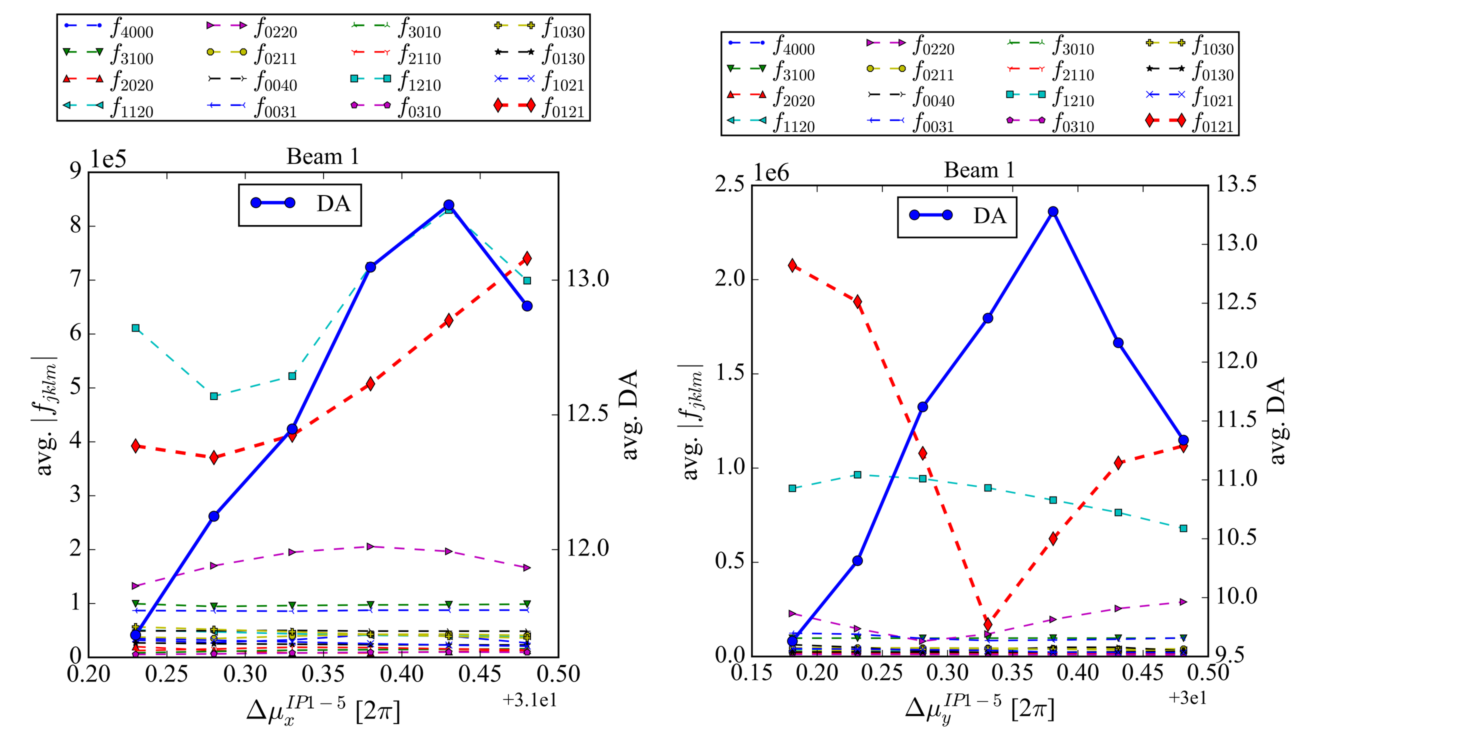

Figure 3: *Octupolar resonance driving terms (RDT) and average dynamic aperture (DA) as a function of the horizontal (left) and vertical (right) phase advance between IP1 and IP5 (left) for the 15 cm β^* round baseline optics at the end of levelling. The DA is simulated without multipolar imperfections, 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.*

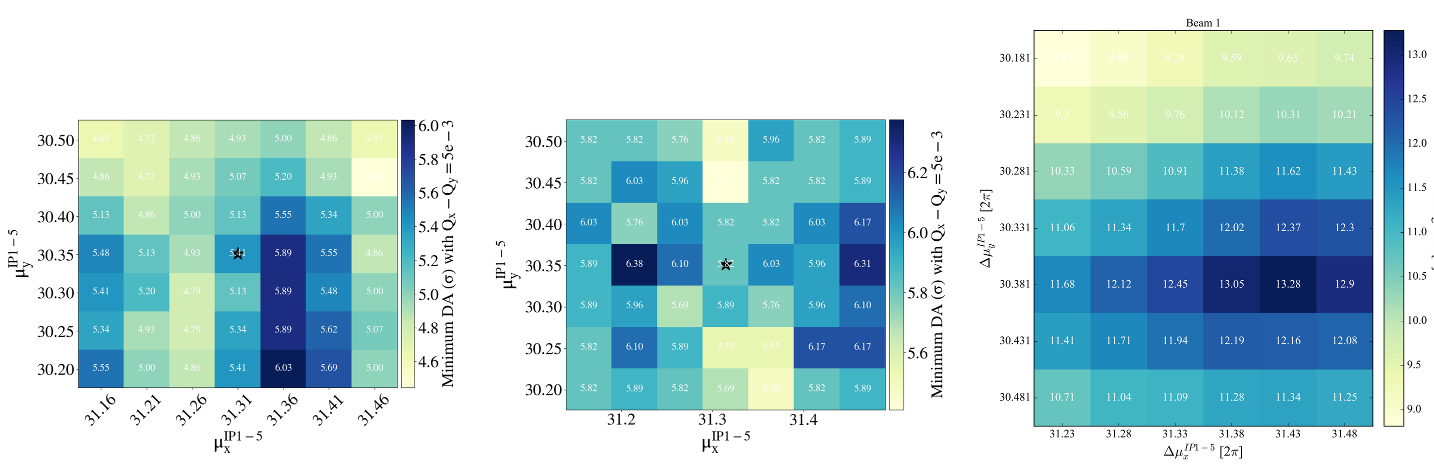

Figure 4: *Average (right) and minimum (left, center) DA as a function of horizontal and vertical phase advance between IP1 and IP5 for the injection optics (left), $\beta^* = 1$ m (center) [5] and end of levelling (right) [6]. The working point at each study corresponds to the one with the largest minimum DA from the left plot. The nominal IP1-5 phase advance is also shown (star-shaped marker).*

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.

3. 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.

References

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