INCOHERENT BEAM-BEAM EFFECTS AND LIFETIME OPTIMISATION

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Abstract

In 2017, three major developments with important implications on the beam lifetime took place: the deployment of the crossing angle orchestration (allowing to act on it even in stable beams), the reduction of β^* from 40 to 30 cm and the switch to 8b4e (and later BCS) beams. These actions have been closely followed up with Dynamic Aperture (DA) simulations and, when possible, also Machine Developments (MDs), aiming at maintaining the beam lifetime on the optimum for the luminosity production. The fill-by-fill follow-up was enabled by new tools for the LHC performance analysis based on modelling and measurements. While the predictions of the machine settings massively rely on CERN's computing resources, the performance analysis requires inputs from several instruments; the difficulties encountered in both cases will be presented together with recommendations for the future.

INTRODUCTION

The performance optimisation of the Large Hadron Collider (LHC) relies on a careful tuning of a number of operational parameters, balancing many conflicting constraints. Tunes, optics, bunch intensity, crossing angle, emittance, chromaticity and current in the Landau octupoles, they all play a role in the maximisation of the luminosity, the mitigation of non-burnoff losses and the prevention of beam instabilities.

The duration of the LHC cycle, which typically extends up to several hours, together with a number of constraints from machine protection, does not allow to probe such a vast parameter space in an experimental manner. It is therefore essential levering on detailed computer simulations aimed at identifying the possible steps for improvements, to be validated in Machine Development sessions or directly applied to the machine.

Extensive multidimensional parameter scans of the dynamic aperture (DA) response have proven to be a reliable tool, allowing the exploitation of the LHC performance margins while maintaining acceptable lifetimes. In addition levering on data from Machine Development (MD) sessions, substantial progress has also been made in the understanding of the correlation between lifetime and DA making the DA targets more clear and solid, with an immediate return of value for the simulations probing the HL-LHC [1].

SIMULATION SETUP

The simulations are performed in a weak-strong approximation in which only a single beam is tracked and the beam-beam lenses (for both the 6D head-on and the 4D long-range interactions) are static. This simplification allows for a substantial computational speed up and applies well to the LHC case, where the beam-beam induced kicks are relatively small and do not perturb significantly the beam profile.

The model relies on the MADX [2], SixTrack [3], SixDesk [4] environment and includes all the IPs. The tolerances on alignment and multipolar errors are such that they can be effectively corrected and, on average, no significant effect apart from an extra uncertainty of the order of 0.5 σ, is observed in presence of beam-beam effect [5].

We consider the minimum value of DA determined over 1×10^6 turns for 5 angles equally spaced in the positive quadrant of the configuration space. Although the statistics may appear limited, the fine granularity of the parametric scans compensates for it, proving to be adequate in most of the cases. The studies focussed on Beam 1, which has shown the weakest lifetime along the entire Run 2.

PARAMETER SENSITIVITY

Tune

Simulations performed for a variety of machine configurations (e.g. Fig. 1) pointed out a high sensitivity to tune adjustments, predicting a DA loss of 1 σ to 2 σ within a few 1×10^{-3} trims. In addition better DAs were consistently foreseen when moving from the nominal tunes: (.310, .320), closer to the diagonal.

The first test based on this predictions was performed towards the end of 2016 and resulted in an immediate lifetime improvement when bringing the tunes close to the expected optimum: (.313, .317) [6]. Lifetime optimisations based on small tune trims became a routine task in 2017, e.g. when going in collision and after the crossing angle steps.

Figure 2 shows that the tune optimisation allows for a reduction of the crossing angle by about 30 μrad, resulting

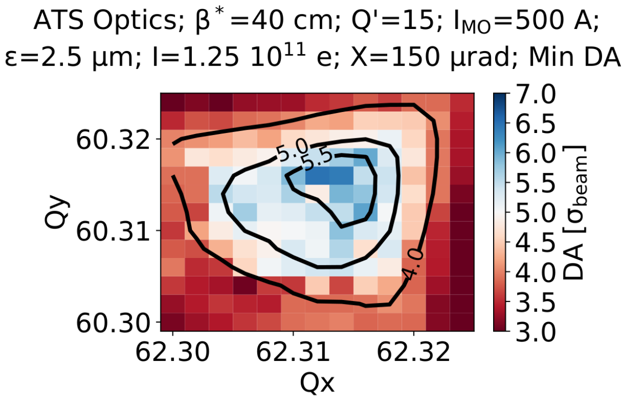

Figure 1: DA response in the tune space in the vicinity of the nominal tunes: (.31, .32).

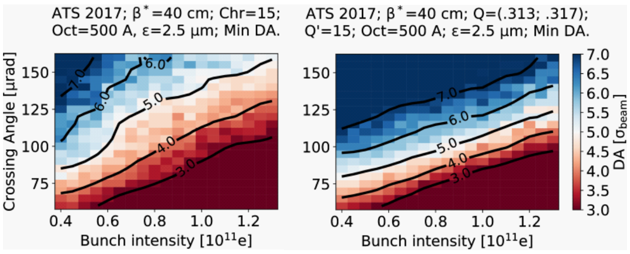

Figure 2: Comparison of the DA response to the bunch intensity and crossing angle for two different tune settings: left: nominal (.310, .320) and right: optimised (.313, .317).

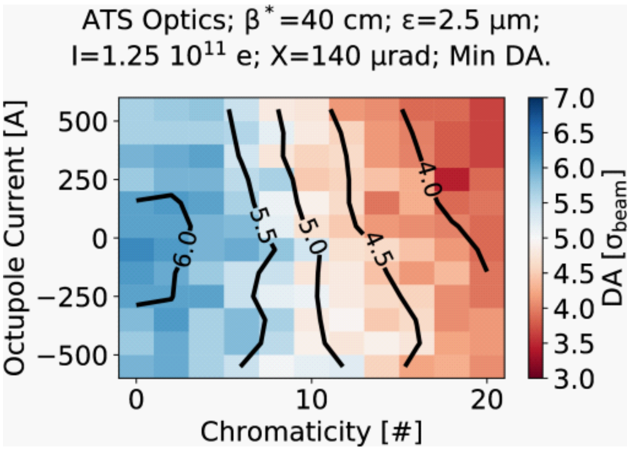

Figure 3: DA response to chromaticity and octupole settings for aggressive crossing angle configuration, as part of the investigations for the setup for 2017.

in a 10 % increase of the integrated luminosity for typical bunch intensities.

The possibility to approach the diagonal was made possible also thanks to the excellent optics control and coupling correction achieved in Run 2 [7]. Still care was taken in order to avoid to excessively reduce the tune split, which could lead to instabilities.

Optimised tunes are now considered a "must" for the lifetime and are always deployed in DA studies aiming at finding the operational settings.

Octupoles and Chromaticity

Chromaticity and Landau octupoles are important knobs for guaranteeing the stability of the beam. However their use also impacts on lifetime. Figure 3 shows how octupoles and chromaticity impact on the DA. In particular 1 σ DA is lost for every 10 units of chromaticity. With ATS optics [8] octupoles are observed to have a mild impact, especially in the range between 300 A to 500 A, where they are normally operated. A gain of DA is observed for negative octupoles [9] as they partially compensate for the long range beam beam interactions, however in order to fully exploit this scenario, larger tele-indexes are needed for an increased effective octupolar strength. This scenario has recently been demonstrated in MD [10].

The switch to the BCS beam production scheme that took place on October 2nd, 2017 allowed to reduce the emittance from 2.3 µrad to 1.8 µrad and was accompanied by an increase of octupole current from 330 A to 450 A in order to preserve the beam stability. Figure 4 shows the effective cross section computed as: $\sigma_{\text{eff}} = -\frac{dN/dt}{L}$ (intensity loss rate normalised by the total luminosity) averaged over few fills before and after the octupole increase. The very small impact predicted by simulations is confirmed by the measurement lying withing their respective uncertainties.

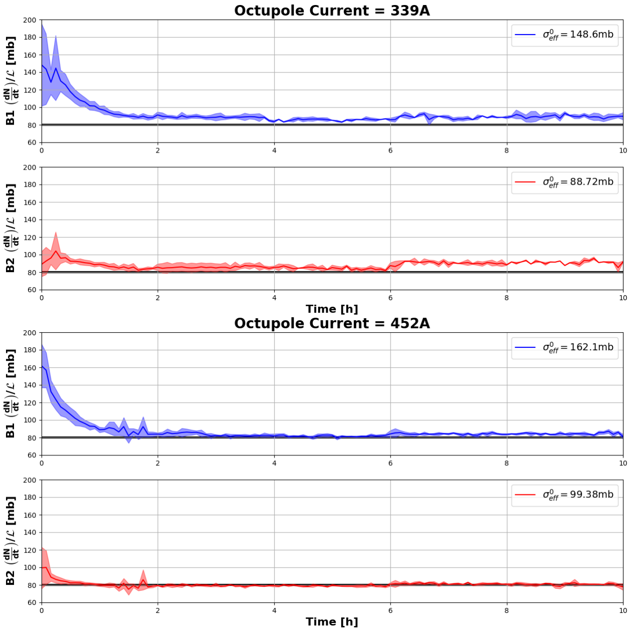

Figure 4: Effective cross section averaged over few fills before (top) and after (bottom) the increase of octupole current in coincidence with the switch to BCS beams.

BETA* REDUCTION AND 8B4E

After TS2 the machine was restarted with β^* reduced from 40 cm to 30 cm. This required to review the DA and in particular to identify the new crossing angle for operation. One can adjust the crossing angle so that its value normalised with the beam divergence at the IP remains constant, however by levering on the significant margin gained by the better tune control, it was decided to preserve the physical half crossing angle of 150 µrad, therefore reducing the beam-beam separation from 10 σ to 8.5 σ.

Figure 5 shows how this decision took the DA closer to 5 σ, although some margin was recovered by switching to the 8b4e filling scheme [11]. 8b4e beams present 4 empty buckets every 8 bunches. They were developed as a mitigation option for the electron cloud build up, however they also come with a reduced number of long-range encounters, therefore allowing to decrease the crossing angle even more.

An interesting finding observed both in MD and simulation is that the 8 bunches in the 8b4e mini-trains do not present the same DA and lifetime. The position inside the 8-bunch mini train determines which long range encounters are missing, taking into account that few long range

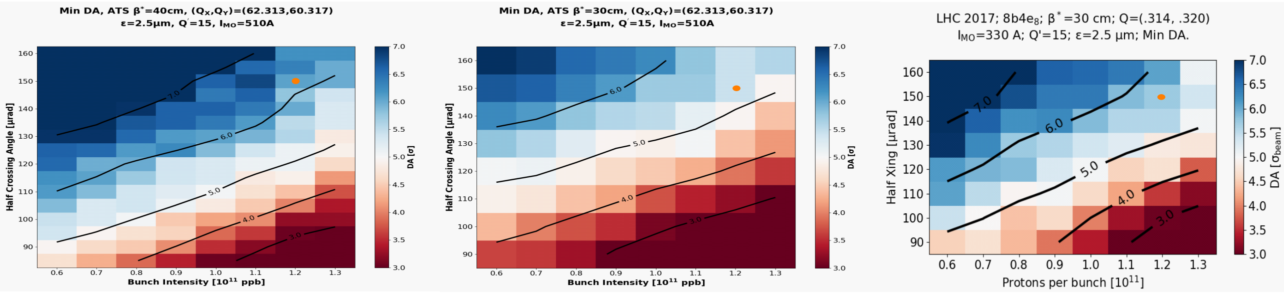

Figure 5: Intensity-Crossing angle scans presenting the DA landscape along 2017: left β^* =40 cm, center β^* =30 cm, right β^* =30 cm and 8b4e filling scheme. The dot marks the value choosen for the beginning of stable beams.

encounters take place at a reduced separation in the triplet, the observations might be explained.

CROSSING ANGLE ANTILEVELLING

Plots such as the ones presented in Fig. 5 expose in a very effective way the idea behing the crossing angle antilevelling. The natural intensity decay along the fill increases the DA. It is therefore possible to progressively reduce the crossing angle following the iso-DA contour, with the advantage of increasing the integration of luminosity by acting on the geometric reduction factor.

The name “antilevelling” can be understood in the sense that the limits of this technique come from the machine side (lifetime): it allows for an increase of the luminosity, but without being able to keep it constant, as opposed to the standard levelling where the delivered luminosity is capped due to limitations of the detectors.

The crossing angle antilevelling could be deployed and exploited for the whole 2017 thanks to a considerable effort of the OP and CO teams [12, 13]. Although a fill with continuous adjustment of the crossing angle was successfully performed, it was preferred to have discrete steps of 10 µrad at 2, 4 and 8 h in stable beams. These numbers were extracted from DA simulations, by taking into account the intensity decay along the fill. While they proved to be a good starting point, different injected intensities, burn-off rates and emittance blowup, could drive them away from the optimum. For these reasons it has been proposed to operate the crossing angle antilevelling with a feed-forward on the intensity, or, even better, with a feedback on lifetime [14].

Performances with the crossing antilevelling

As the reduction of the crossing angle comes with both extra losses and altered burn-off rate, the evaluation of the performance impact is not trivial.

Here we present an approach in which the effective cross section measured along a fill (with steps on the crossing angle) is fed to a luminosity model in order to compute the instantaneous and integrated luminosities along the fill. The result is compared to a case with an effective cross section profile including only the losses at the beginning of stable beam, and later stabilising as typically observed for the fills with fixed crossing angle.

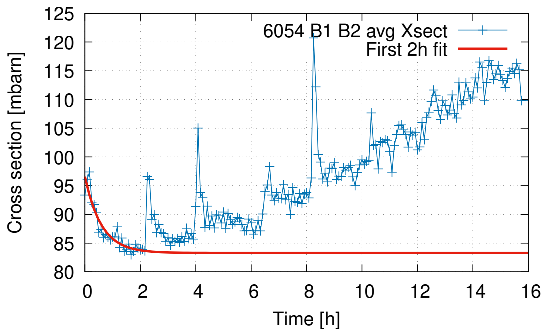

Figure 6: Effective cross section measured along fill 6054 (blue) and exponential fit over the first two hours (red), simulating a case without crossing angle steps. In the measured effective cross section one can note spikes corresponding to the crossing angle steps at 2, 4 and 8 h in stable beams and other spikes such as the ones occurring in coincidence with the bunch length blowup.

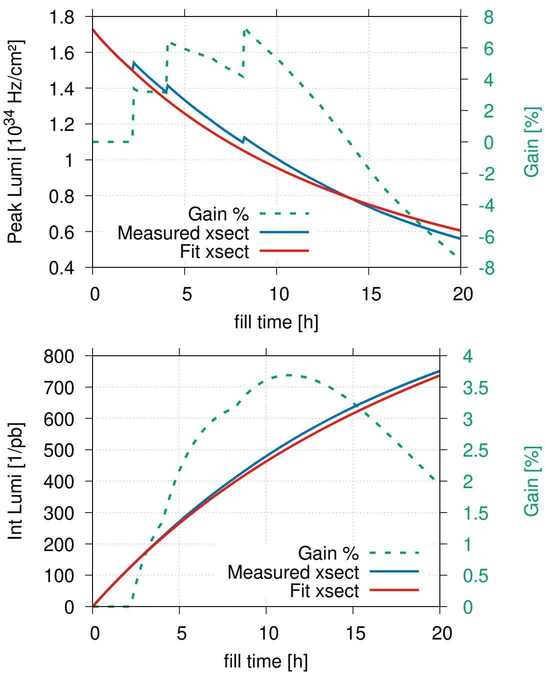

Figure 7: Instantaneous (top) and integrated luminosities (bottom) comparing the crossing angle antilevelling and fixed crossing angle using realistic cross sections.

The two cases are depicted in Fig. 6 where the measured cross section is taken from fill 6054 and the hypothetical cross section comes from an exponential fit on the first two hours.

As shown in Fig. 7 the instantaneous luminosity of the case with crossing angle antilevelling is larger from the first crossing angle step, up to about 14 h, when the reduced losses of the case with fixed crossing angle invert the trend. Figure 7 also shows a comparison of the integrated luminosities, where one observes a maximum gain of about 3.5 % at around 12 h in stable beam and, even extending the fill duration to 20 h, the case with crossing antilevelling is still providing 2 % more integrated luminosity.

SETTING DA TARGETS: CORRELATION BETWEEN DA AND LIFETIME

The precise correlation between DA (easily computed from simulations) and lifetime (easily measured in the control room) is a long withstanding question. Many attempts have been made in the past both with analytical and numerical approaches [15, and references therein].

Here we present a hybrid approach applied to the LHC which, although being far from extreme accuracies, highlights the various difficulties in the task and estimates the uncertainties along with the correlation of numerical and experimental observables.

The idea consists in feeding to simulations all the available machine settings and measured beam parameters. Fills with significant lifetime degradation (such as the ones of the MDs investigating the crossing angle reach) are considered here. The DA is evaluated along the fill and compared with the measured lifetime extracted from the intensity decay:

$$\frac{1}{\tau} = -\frac{\partial I/\partial t}{I}. \tag{1}$$

The parameters feeded to the simulations from the machine side are:

- horizontal and vertical chromaticity,
- octupole current,
- crossing angle,
- the tunes were deliberately kept constant to the optimal value of (62.313, 60.317) due to their high sensitivity and difficult determination.

The ones from the beam side are:

- bunch intensity,
- beam emittance, the average between horizontal and vertical, beam 1 and beam 2 is used for simplicity.

These are collected from CALS and LSA using PyTimber [16] and PjLSA [17] respectively.

In order to extract the lifetime, the bunch-by-bunch intensity from the fBCT is corrected for burn-off according to the luminosity measured by the experiments. The bunches in the centre of the trains are then selected, their intensities are averaged and smoothed with a lowess filter, finally the lifetime is computed by numerical differentiation, according to Eq. 1.

The result of this analysis is presented in Fig. 8 for two fills: one considering high intensity 8b4e bunches (from MD 2209) and one with regular 25 ns BCMS beams (from MD 2201). One immediately notes a striking agreement between DA and burn-off-corrected lifetime. It is interesting to note that while the former is plotted on a linear scale, the latter is on a logarithmic scale, this can be justified from the predicted intensity decay [15]:

$$I(t) = I_0\left(1 - e^{-\frac{1}{2}\mathrm{DA}(t)^2}\right) \tag{2}$$

By discretising the derivative in eq. (1) and substituting eq. (2) one gets:

$$\frac{1}{\tau} = \frac{e^{-\frac{1}{2}\mathrm{DA}(t+\Delta t)^2} - e^{-\frac{1}{2}\mathrm{DA}(t)^2}}{\Delta}, \tag{3}$$

which better clarifies the exponential dependency between lifetime and DA.

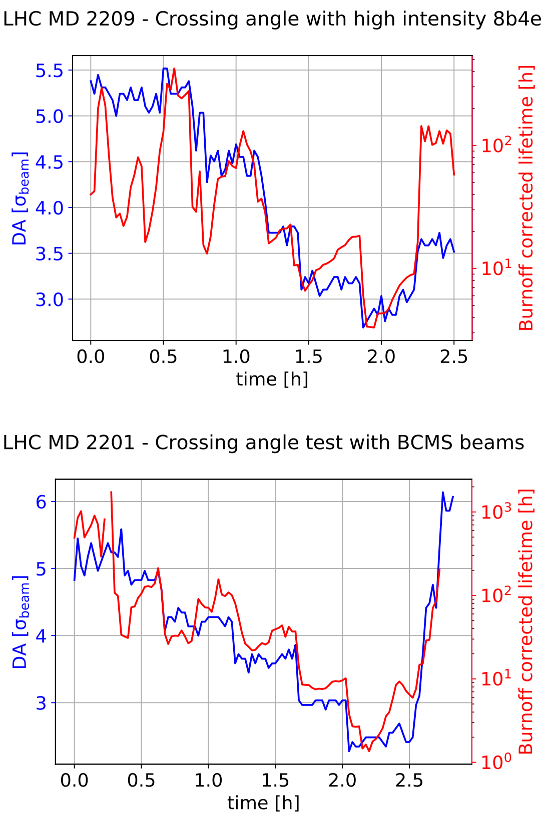

Figure 8: Measured burn-off-corrected lifetime plotted together with the corresponding DA along two MD fills for crossing angle reach studies.

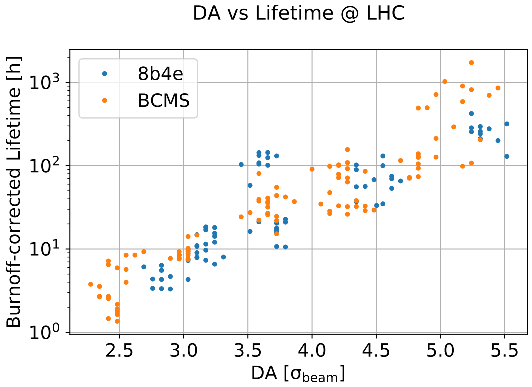

Figure 9: Collection of lifetime measurements and corresponding DA determinations for the two considered fills.

Figure 8 also presents some discrepancies between DA and lifetime. The transient dips in lifetime correspond to luminosity and tune optimisations which are masked in the DA computation. The lifetime also tends to grow for constant machine settings, which cannot be fully justified by the intensity decay and the emittance shaving. A possible explanation could arise from the time dependency of the DA, which is neglected in simulations, being always computed for 1×10^6 turns. Further investigations are on-going.

An additional discrepancy is observed with the crossing angle relaxation performed towards the end of MD 2209. It presents a large increase of lifetime for a much more moderate gain of DA. This can be explained by the fact that the lifetime is driven by losses in the beam halo, by shaving the halo by means DA reduction, there are no more particles to loose when the DA is stepped back. In this sense, when the DA is reduced the lifetime reflects the number of particle in the tails, while when it is increased it probes the tail repopulation and diffusion rates.

In order to better quantify these statement one would more detailed information on the tail population, allowing to precisely convert the DA simulation into lifetime ones by weighting the particle lost according to the beam profile.

Figure 9 collects all the determinations of DA and lifetime at the different time steps (the tune optimisations have been removed) and presents them on the same plot. On the top of a clear correlation between DA and lifetime, which also holds for the two different beams, the uncertainty of the method pops out. It is nevertheless a very useful plot for setting DA targets which are identified as follows:

- 4 σ: gives a lifetime comparable to burn-off (25 h).
- 5 σ: grants lifetimes around 100 h. This can be considered the minimum target for operation, it requires good control of the machine.
- 6 σ: guarantees additional margin, this is generally pursued for studies further in the future (such as HL-LHC [18]) which present larger uncertainties.

REMARKS ON COMPUTING AND INSTRUMENTATION

Each single DA plot as the ones presented before requires about 1 year of CPU time, therefore the simulations massively rely on the CERN computing resources. The switch to HTCondor did not come without an impact on the productivity, however the issues have been followed up by ABP-CWG, with slow improvements along 2017. With respect to this, it was also noticed that the ticket system was not always effective, but we profited from having a direct line with IT specialists. Still some issues occur from time to time (authentication, scheduler reachability) and are being reported, but the system is definitely bearable.

These studies also require data from multiple instruments: fBCT, BSRT, Luminosity Monitor, BLM, BBQ, Schottky; whose performance were always up to the task. The wishes for the future include a better tune determination in collision, where, presently, trims are often performed almost “blindly”; and more detailed information of the tails of the transverse profiles (up to about 6 σ) which would be desirable for guiding lifetime simulations. A considerable enhancement of these studies is expected after the deployment of the coronagraph.

CONCLUSIONS

By means of extensive simulations backed up, when feasible, by observations and measurements of the machine, the sensitivity to tunes, chromaticity and octupoles, was assessed. In collision the machine is sensitive to tune adjustments, at the level of 1×10^{-3} with significant impact of lifetime. Chromaticity comes with a milder contribution; while octupoles, in the typical range of positive polarities, are within the uncertainties.

The machine operation was followed up with spot-on predictions of the crossing angle requirements in various scenarios, including the steps for anti-levelling, which in the future could be further refined by taking into account the emittance evolution, or simply computed with a feedback on lifetime.

Progress has also been made bridging the experimental lifetime measurements with the DA simulations, coming with a better understanding of their correlation and the specifications for the DA targets.

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