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SIMULATIONS AND EXPERIMENTS FOR DYNAMIC APERTURE STUDIES IN THE LHC ION OPERATION

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Abstract

Dynamic Aperture (DA) studies, based on single-particle tracking simulations including important non-linear fields such as beam-beam effects, have played a crucial role in guiding the operation of the Large Hadron Collider (LHC) in proton-proton collisions. The correspondence between DA computed through simulations and the actual beam lifetime during operation has been established for proton beams through dedicated experiments at the LHC. However, such an approach has not yet been applied to the Pb ion operation of the accelerator, as the simulation tools have not been rigorously benchmarked against experimental data yet. This paper presents the simulation studies and experimental tests performed to establish the correlation between DA and beam lifetime for Pb ions. The main focus lies on exploring the beam-beam limit when the crossing angle is significantly reduced in all LHC experiments as compared to the nominal configuration. This approach opens the possibility to operate with reduced crossing angles or reduced β^* within the beam-beam limit, potentially leading to an enhanced performance of the collider with ions.

INTRODUCTION

The LHC operation includes a heavy-ion program that mainly focuses on lead ion collisions ($^{208}_{82}$Pb), typically lasting for a few weeks per year [1–4]. This program, which will continue for the rest of Run 3 (until 2025) and Run 4 (from 2029), aims at accumulating the highest possible integrated luminosity in a limited amount of time. This can be achieved by optimizing the beam and machine parameters for highest performance. A standard practise for proton operation is to use the DA from tracking simulations as a guiding tool [5–8]. A correlation between DA from simulations and operational beam lifetime has been established through dedicated experiments. A DA of 6 σ ensures that the beam lifetime contribution from nonlinearities significantly exceeds the proton burn-off one ($\approx$ 25 h). This target was defined by tracking an initial polar distribution of particles in the $x - y$ space with 5 angles and for 10^6 turns. The goal of the study presented here is to determine if a similar optimization strategy can be applied with ions and whether reducing parameters such as β^* and the crossing angle in all experiments can still result in acceptable DA levels while enhancing the integrated luminosity. It must be noted however that LHC ion collisions are less impacted by beam-beam effects compared to protons, mainly due to much lower bunch intensity and larger bunch spacing, with a beam-beam tune shift in the order of 10^{-4} versus 10^{-3} for protons. Ions also have a much shorter beam lifetime from luminosity burn-off (5–6 h). Therefore, the 6 σ target cannot be directly applied to ions and needs to be re-evaluated based on a combination of simulations and experimental tests.

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DA STUDIES

As a first step, tracking simulations are performed with the nominal Run 3 parameters for Pb ion operation [9] such as a bunch intensity of 1.8×10^8 ions per bunch, 1240 circulating bunches and a beam energy of 7 Z TeV where Z=82 is the atomic number. Figure 1 illustrates the Frequency Map Analysis (FMA) in the absence (top) and presence (bottom) of beam-beam interactions [10–13]. The color code indicates the tune diffusion, where blue represents stable particles and red particles that are encountering resonances and experience larger tune diffusion. Comparing the tune spread and the tune diffusion in these scenarios reveals that, unlike proton operation, beam-beam effects, and particularly head-on interactions, have a much smaller impact for ion collisions.

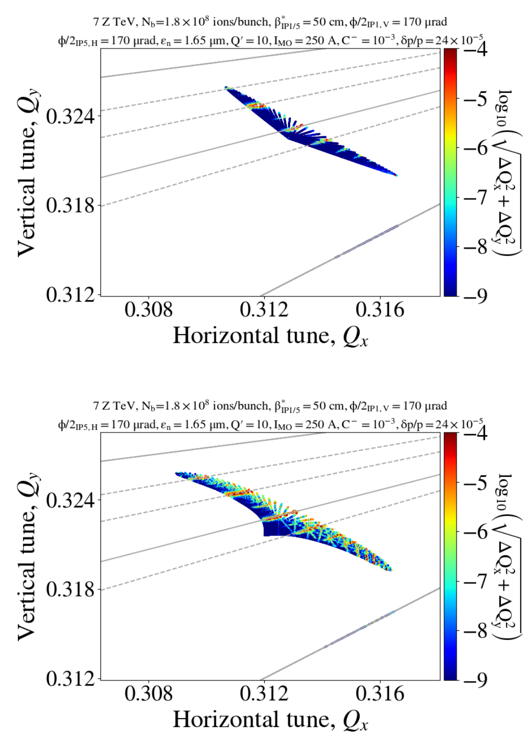

Figure 1: Frequency map analysis of the LHC ion operation without beam-beam (top) and with beam-beam interactions (bottom).

As a result, the DA with the nominal beam and machine parameters exceeds 12 σ. To probe larger beam-beam ef-

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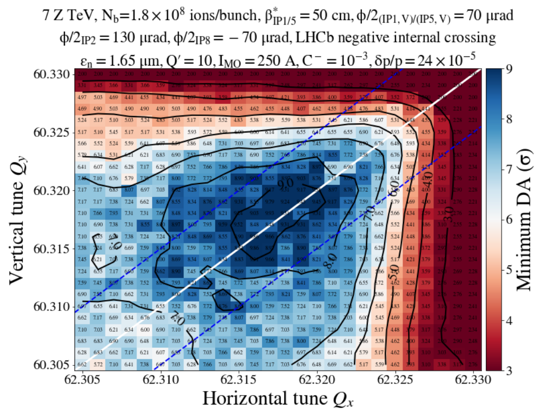

Figure 2: Tune scan color-coded with the DA in an aggressive crossing angle configuration for all experiments.

fects, the crossing angles are significantly reduced in the four LHC experiments: from 170 to 70 μrad for the half crossing angle in ATLAS, CMS and ALICE and from 170 to 130 μrad in LHCb. An important feature of ALICE and LHCb is the presence of a dipole spectrometer magnet, which introduces an additional crossing angle (referred to as "internal") in addition to the aforementioned ones (referred to as "external"). The overall effect on the crossing angle depends on whether, based on the spectrometer's polarity, the internal and external angles counteract or add up. In the present simulations, ALICE's internal half crossing angle is 70 μrad with an opposite polarity to the external angle, while the one of LHCb is 135 μrad having the same polarity as the external one. Consequently, the total crossing angle in ALICE is vanishing in the simulations. Figure 2 illustrates a scan in the horizontal and vertical tunes color-coded with the DA for this scenario. Although beam-beam effects are significantly enhanced, a DA region of at least 8 σ is still present suggesting that operating in a more aggressive configuration of crossing angles and, consequently, higher luminosity could be feasible without significantly affecting the beam lifetime.

EXPERIMENTAL RESULTS

To validate the simulation results and establish the correlation between DA and beam lifetime for ions, dedicated experiments were conducted during the 2023 LHC Pb ion run at a 6.8 Z TeV beam energy. These tests were carried out at the end of a standard fill. The main limitation of this setup is the reduced bunch intensity at this stage of the fill that results in relatively weak beam-beam interactions. The crossing angles of all experiments were decreased by 100 μrad, in steps of 5 μrad from their nominal values. Table 1 presents the beam parameters during the tests.

Figure 3 shows the normalized beam-beam separation in the $x-y$ plane at the start (blue) and end (orange) of the tests for the four experiments. The markers represent the location of the beam-beam interactions, both head-on and long-range. A clear reduction of the beam-beam separation is visible when reducing the crossing angle, particularly in

Table 1: Beam and Machine Parameters During the Tests

Parameter	Value
Number of Bunches	961
Initial bunch inten. (10^7 ions/bunch)	6.9
Initial/Final $\phi/2_{\mathrm{ATLAS}}$ (μrad)	170/70
Initial/Final $\phi/2_{\mathrm{CMS}}$ (μrad)	170/70
Net Initial/Final $\phi/2_{\mathrm{LHCb}}$ (μrad)	270/170
Net Initial/Final $\phi/2_{\mathrm{ALICE}}$ (μrad)	100/0
β^* ATLAS/CMS/LHCb/ALICE (m)	0.5/0.5/1.5/0.5

IP2 where the net crossing angle becomes zero, resulting in several bunches colliding head-on around the interaction point.

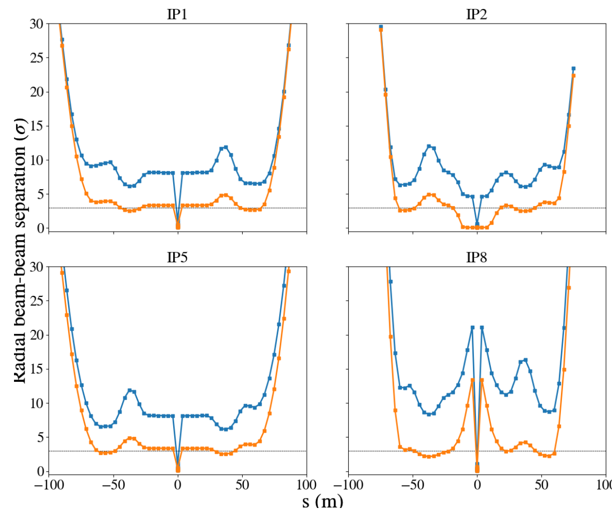

Figure 3: Radial beam-beam separation at the first step of the test with the nominal crossing angle (blue) and at the last step of the test after reducing all crossing angles by 100 μrad (orange).

Figure 4 summarizes the measured evolution of important parameters during the tests such as the lifetime (top), the luminosity (middle) and the crossing angle steps (bottom). First, the measured beam lifetime (dark blue) is compared to the burn-off lifetime (light blue) defined as [14, 15]:

$$\tau_{\mathrm{burn-off}} = \frac{N_b N}{L_{tot}\sigma_{\mathrm{total}}} \tag{1}$$

where N is the bunch intensity, N_b the number of bunches, L_{tot} the measured luminosity $L_{\mathrm{tot}} = L_{\mathrm{ATLAS}} + L_{\mathrm{CMS}} + L_{\mathrm{LHCb}} + L_{\mathrm{ALICE}}$ and σ_{total} the total cross-section due to hadronic interactions, bound-free pair production (BFPP) and various electromagnetic dissociation (EMD) processes $\sigma_{\mathrm{total}} = \sigma_{\mathrm{hadronic}} + \sigma_{\mathrm{BFPP}} + \sigma_{\mathrm{EMD}} \approx (8+281+226)$barn [3].

The measured lifetime reflects losses not only from burn-off but also from other mechanisms, including those induced by beam-beam. The comparison reveals that the beam lifetime is mainly driven by burn-off. The lifetime drop observed in the second half of the tests corresponds to the decrease in the burn-off lifetime following a luminosity optimization scan as depicted by the luminosity trends of ALICE

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(in blue), ATLAS (in orange), and CMS (in green). During luminosity scans the two beams are transversely displaced in steps and the luminosity is measured, which explains the large luminosity fluctuations [16, 17]. The best position that maximizes the luminosity is identified and, as shown in the figure, an increase in luminosity across all experiments and a drop in the burn-off lifetime was observed that was then reflected to the overall beam lifetime. Therefore, it is concluded that the lifetime drop is not related to the decrease of DA induced by the crossing angle reduction.

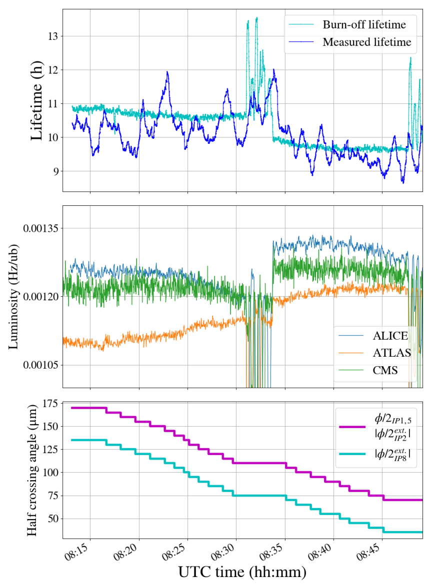

Figure 4: Burn-off (light blue) and measured (dark blue) beam lifetime (top) and luminosity evolution (middle) during the crossing angle reduction (bottom).

In Fig. 5, the measured lifetime (blue) is compared to the simulated DA for all points scanned in the measurements (black). In addition to the crossing angle steps (magenta and cyan curve in the bottom plot), the evolution of the average bunch intensity (dark red) and average bunch length (green) is also shown. The bunch intensity decrease is attributed to burn-off, while the bunch length reduction results from synchrotron radiation. The evolution of all these parameters are considered in the tracking simulations. The DA remains consistently above 11 σ, while the DA fluctuations are within the uncertainty of the simulations. It must be noted that, to reduce these fluctuations, the initial distribution's number of angles was raised to 20 from the typical 5 that is usually used in proton DA studies. Although fluctuations are also visible in the beam lifetime, there is no noticeable reduction correlated to the crossing angle steps apart from the lifetime reduction due to the luminosity optimization.

The analysis indicates that maintaining a DA of 11 σ ensures a lifetime of at least 9 hours, including burn-off. Although the tests were conducted at lower intensity levels because they took place at the end of a fill, the findings suggest that there is a substantial margin to reduce the crossing angles in all experiments without affecting the DA and the beam lifetime. Unfortunately, a DA-lifetime correlation could not be established as there was no noticeable reduction in either during the tests. This can also indicate that there is a lack of correlation between DA and lifetime for low intensity and for this reason it is necessary to conduct similar tests at nominal intensity.

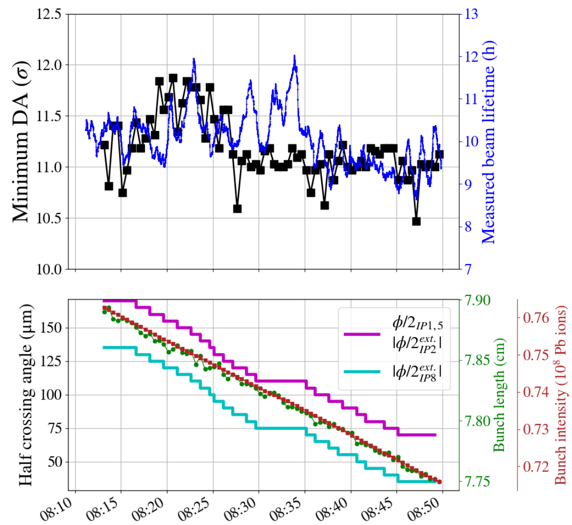

Figure 5: The measured lifetime (top blue) and the DA (top black) during the crossing angle reduction (bottom magenta and cyan). The evolution of the bunch intensity (red) and bunch length (green) is also illustrated.

CONCLUSIONS

The main goal of this paper was to investigate whether DA optimization strategies, which have proven successful in LHC proton operation via DA-lifetime correlation, are applicable to the ion operation and whether there is margin for a more aggressive crossing angle configuration as suggested by DA. During the experimental tests, all crossing angles were reduced by 100 μrad which led to a net zero crossing angle in the ALICE experiment. Throughout the duration of the tests, no significant lifetime reduction was measured, which is in agreement with the DA results. A small lifetime drop was observed at the second half of the tests due to the burn-off lifetime decrease after the luminosity scan optimization and there is no clear indication that this is related to beam-beam effects with the reduced crossing angle. The analysis points to the conclusion that a DA of 11 σ corresponds to at least 9 hours of beam lifetime including burn-off and that there is significant margin to reduce the crossing angles in operation. No clear DA-lifetime correlation could be established due to the absence of a significant reduction in either parameter. It must be noted that the experimental tests were done at the end of a nominal fill with low intensity. This motivates for further study, particularly at nominal intensities, to validate these results and identify the DA-lifetime correlation for ions.

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