SESSION 4: "BEAM PERFORMANCE DURING RUN 2"

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Abstract

During Session 4 of the 9th LHC Operations Evian Workshop, the LHC beam performance during Run 2 was presented and discussed. Multiple aspects were considered. The topics addressed during the session were the evolution of the collimation configuration, the beam emittance and intensity preservation and their modeling during the fill, the analysis of special losses in the machine and the impact of the e-cloud on beam performance and heat load. The session concluded with a summary on transverse and longitudinal beam stability observations and a report on the MD studies.

R. BRUCE - MACHINE CONFIGURATION

During LHC Run 2, the LHC machine configuration evolved significantly. Starting from a very conservative approach in 2015, with the priority on stability and ease of commissioning, the machine settings were pushed further during the run, which ended with an optimized 2018 scenario with excellent performance. This contribution summarized the evolution of different machine parameters, with the focus on the collimation settings, aperture and β^* which are tightly linked to the peak luminosity performance of the machine. The key changes and the reasons behind were reviewed, as well as the lessons learned for the future.

Discussion

M. Lamont acknowledged the excellent evolution of the collimator configuration and congratulate the team for the fabulous achievement for the LHC performance.

J. Jowett commented that, for the heavy-ion run, the present vertical bump of IR2 will be removed after LS2 therefore more aperture will be made available for further optimization and possible reduction of β^*. **R. Bruce** confirmed that the collimation configuration for the ions has still some margins and they could be reconsidered with the usual attentive and systematic approach.

M. Schaumann asked if there is any residual margin in the collimation settings to be spent for performance gain during Run 3. **R. Bruce** commented that an analysis on how to optimize the collimation configuration will be performed during the LS2.

S. PAPADOPOULOU - TRANSVERSE EMITTANCE BLOW-UP

To describe and follow the evolution of the LHC luminosity, a model based on the effects of intra-beam scattering, synchrotron radiation, elastic scattering and luminosity burn-off, was developed. These effects are the main mechanisms leading to beam emittance growth and losses. Concerning the beam emittance growth along the LHC energy cycle, the evolution of the measured emittances was presented for Run 2 and compared to the model results. This comparison is useful for estimating the extra emittance blow-up, i.e., the effects not-included in the model, both at Flat Bottom (450 GeV) and at Flat Top (6500 GeV) energies. The agreement of the model with the data during collisions helped to quantify the impact of different degradation mechanisms on the delivered luminosity and guide the further studies. The comparison of different emittance measurements coming from the BSRT, ATLAS/CMS luminosity and emittance scans was used as a data quality validation test.

Discussion

M. Lamont asked about the strategy used to compute the e-cloud contribution to the emittance blow-up, in particular if it is the output of a simulation or if it an observation derived from special assumptions. **S. Papadopoulou** explained that the effect of the e-cloud is obtained by the LHC data, comparing a cluster of bunches positioned at the head of the 48 bunch train and another one situated in the tail. **G. Iadarola** added that the underlying assumption is that the first cluster does not suffer from the e-cloud whereas the second one does.

E. Chaposhnikova commented that the difference performance of the bunches could also be related to the phase shift along the train due to the machine impedance. **G. Iadarola** commented that the emittance growth is expected to be driven by an incoherent effect since no significant coherent motion is detected.

G. Trad commented that the luminosity model had difficulties to predict the emittance evolution especially during the β^*-leveling test and suggested to verify the model performance in the fills without β^* leveling. **G. Trad** thanked the luminosity team for its helpful monitoring of the BSRT performance and commented that the delay between the detection and the cure of the problem is due to delays in scheduling the tunnel access and/or the BSRT calibration fill.

V. Kain commented that, despite the systematic observation of the emittance blow-up since Run 1, the mechanism behind it is not yet fully clarified. **S. Papadopoulou** noted that part of the blow-up can now be connected with the e-cloud phenomena, and, in addition, investigations on the contribution of the noise are ongoing.

I. Efthymiopoulos emphasized the importance to invest energies and MD time to understand the emittance growth during the ramp. He observed that this blow-up has a significant cost in term of integrated luminosity.

W. Hofle asked if there were attempts to correlate the actual noise level of the ADT with the observed emittance blow-up of the beam. **S. Papadopoulou** answered that this

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topic was experimentally addressed by a measurement campaign proposed by **X. Buffat**. At flattop the growth rate obtained from the measurement by **X. Buffat** are compatible with the one observed in the machine. On the other hand, at injection, they underestimate the observed growth rate by a factor three.

P. Collier asked if, to further cross check the e-cloud contribution to the emittance growth, a similar analysis was performed on the 8b4e period in 2017. **Y. Papaphilippou** answered positively: the 8b4e fills analysis was performed and presented in the 8^{th} LHC Operations Evian Workshop and confirmed that an important role of the e-cloud on the mechanism of the emittance blow-up.

G. Arduini replied to **V. Kain**'s comment that the observation in Run 2 have allowed identifying e-cloud and the noise as very important contributors to the emittance blow-up but they still cannot explain completely the present observations.

S. KOSTOGLOU - LUMINOSITY, LIFETIME AND MODELLING

During Run 2, the continuous monitoring of the luminosity evolution has revealed the existence of lifetime degradation sources, beyond burn-off. By employing a bunch-by-bunch analysis, beam-beam effects but also e-cloud have been identified as significant contributors to these additional losses. In order to mitigate these effects and improve performance, multi-parametric Dynamic Aperture (DA) simulations have been used as a guide to establish the optimum machine parameters during operation. The impact of the reduction of chromaticity and octupole current, as well as the crossing angle anti-leveling and levelling techniques of 2018 were further detailed.

Discussion

M. Lamont acknowledged the quality of the analysis and the improvement in the understanding of the underlying physics. He asked if there is a simulation framework to correlate the e-cloud and the machine dynamic aperture. **G. Iadarola** answered that there is not a fully consistent framework for the moment. This topic was never studied before and requires a paradigm change. It is presently under investigation and considered a priority. The problem is challenging and demanding from the computation point of view. Simulations with GPU are being presently considered and a Ph. D. student joined the team to work on this subject. A framework for simulating the beam DA in presence of e-cloud is expected to be ready by the end of LS2 but, being an uncharted territory, the actual progress pace cannot be easily evaluated in advance.

D. MIRARCHI - SPECIAL LOSSES

A thorough review of special beam loss scenarios during Run 2 was presented, with main focus on studies and actions taken to mitigate them. An overview of Beam Loss Monitor (BLM) threshold strategy aimed at reducing the machine downtime caused by the interaction of the beam with Unidentified Falling Object (UFO) is given. The UFO rate evolution during Run 2 is also provided, together with an estimation of UFO rate at the beginning of Run 3. An unexpected aperture restriction has been detected in the half-cell 15R8 in 2015: the so called Unidentified Lying Object (ULO). Local aperture measurements, ULO evolution during Run 2, mitigation strategy adopted and possible interventions to remove this restriction during the Long Shutdown 2 (LS2) were shown. Sudden increase of losses in the half-cell 16L2 has been the main machine intensity limitation in 2017. Mitigation strategy, lessons learnt and actions taken to avoid repetition of the most probable causes were discussed. Several dumps with similar signature of oscillating orbit with 10 Hz frequency were experienced in the last months of the 2018 run. The present understanding of these events, possible actions and mitigation approach to be taken in future runs were reported.

Discussion

About the 10 Hz oscillations, **P. Collier** commented that even if the location of the problem, for the ion dumps, was localized, the source of the problem appears still unclear. **D. Mirarchi** agreed and commented that the source of the problem is still under investigation. **P. Collier** added that the investigations of such rare events could be eased by implementing a generic post-mortem event triggered on demand. **R. Steerenberg** agreed and confirmed that the OP team will investigate with BE-CO how to implement it. Offline comment by **J. Wenninger**: the PM event cannot be used for any other triggering because this would block all PM buffers and prevent data collection in case of an dump. The PM buffers are reserved and cannot be used for measurements. Other trigger modes and buffers must be used for such studies.

R. Steerenberg asked if there is a model to study the UFO conditioning and deconditioning mechanism. **A. Lechner** answered that there is no model. At the moment we are not able to predict the UFO observed behaviour given the complexity of the physics processes involved. **R. Steerenberg** put in evidence the critical impact of the UFO event on the machine availability in particular in view of the Run 3. **A. Lechner** acknowledged the importance of the topic and proposed to investigate more in details if there is a different trend in the UFO conditioning/deconditioning with respect to the injection or flattop energies.

B. Petersen asked if the UFO conditioning is linearly related to the time or the proton integrated intensity. **A. Lechner** answered that it is difficult to discriminate the two dependencies given the limited time resolution. **A. Siemko** observed the a conditioning proportional to the proton intensities would slow down during the machine technical stops.

D. Wollmann added that a better understanding of the geometry of the problem would improve its modeling. For that purpose several MD studies were scheduled and performed.

G. Trad asked about the conclusions of the experimental campaign based on the non-colliding 12 bunches blow-up.

D. Wollmann explained that the team is still digging in the data, and presently there is a discrepancy between the observation with the dBLM, measuring most of the UFO events during the ramp, and the observation based on the 12 bunches, more sensitive to the UFO events at flattop.

Concerning the 10 Hz oscillation, **J. Jowett** suggested considering the problem critically with an open mind. In particular, even if the reduction of β^* in IP2 pushed to 0.5 m might be a plausible explanation for the appearance of the problem, it could also be due to some new effect appearing in the machine meanwhile. **S. Fartoukh** suggested to verify and try to correlate the 10 Hz oscillation with the power supply stability of D1.

G. IADAROLA - ELECTRON CLOUD AND HEAT LOADS

During Run 2, the 25 ns bunch spacing was routinely used for proton physics operation at the LHC. With this bunch spacing, electron cloud effects are significantly more severe than with the 50 ns spacing, which had been used for luminosity production in Run 1. Beam-induced scrubbing allowed to mitigate the electron cloud formation enough to allow an effective exploitation of 25 ns beams for physics operation. Nevertheless, even after years of conditioning of the beam chambers, e-cloud effects remain very visible, affecting beam stability and beam quality preservation, and generating a significant heat load on the beam screens of the superconducting magnets. Surprisingly, the eight LHC arcs show very different behaviors, with the heat load being much higher for some of them (S12, S23 and S81) compared to the others. In these sectors, the heat loads are very close to the nominal cooling capacity delivered by the corresponding cryoplant, which is a concern in view of the planned upgrade programme. A dedicated interdepartmental Task Force has been setup to investigate this issue. This contribution summarized the relevant observations and studies conducted during Run 2, the interventions planned for LS2 and briefly discussed prospects for Run 3.

Discussion

R. Steerenberg asked to comment about the expected duration of the scrubbing run after LS2. **G. Iadarola** answered that all predictions in this sense are difficult. An optimistic target could be 7 days but one should consider some margin and allocate 10 days. He also suggested that the scrubbing run could be organized in multiple shorter sessions to be interleaved with the other phase of the beam commissioning. For this to take place, the beam commissioning should give the higher priority to the injection energy plateau commissioning with high intensity.

V. Kain asked if the e-cloud will limit the Run 2 to a bunch population of 1.8×10^{11} ppb. **G. Iadarola** commented that from the simulation the 1.8×10^{11} ppb intensity corresponds to the maximum of the heat load on the arc-cells. He added that in that respect, provided that the assumptions of the simulations hold, one could also increase the bunch intensity beyond this value, at least concerning e-cloud driven limitations.

V. Kain commented that getting the intensity needed for the LHC scrubbing at the very start of the Run 3 will be very challenging for the Injector Chain. **H. Timko** added that the commissioning of the SPS RF system will be a major time-consuming effort.

E. Chaposhnikova asked why the sectors showing a different initial SEY saturate at different SEY also after the scrubbing whereas the same final SEY should be expected. **G. Iadarola** explained that this conclusion holds only assuming an equivalent behaviour of the surface exposed to the e-cloud. In reality one should assume that the surfaces are contaminated with different oxides and impurities, causing the different SEY after the scrubbing process.

M. Lamont asked if there is a scaling law between e-cloud and dynamic aperture and if an increase of the beam intensity could increase the relative beam losses. **G. Iadarola** explained that the instability driven by the e-cloud are not proportional to the bunch current. This is due to the modification of the e-cloud transverse distribution with the intensities. In addition to the simulation also the observation in the machine (pop-corn instability) showed that the critical bunch intensities for the e-cloud driven instability is between $0.8 - 1.0 \times 10^{11}$ ppb and that stability of the bunch is not degraded with bunch population in the $1.2 - 1.9 \times 10^{11}$ ppb range.

M. Pojer asked if a correlation between UFO and e-cloud heat load could be established. **A. Lechner** answered that the analysis of the data showed no correlation, for instance with the 8b4e train no reduction of the UFO event's rate was observed. In addition, the sectors more active with respect to the UFO event's rate are not the ones showing higher heat loads.

W. Höfle asked if a damper with improved capabilities in terms of power or bandwidth could help in alleviating the problem connected to the e-cloud. **G. Iadarola** commented that an increase of its bandwidth would help but simulations are needed to be quantitative on that respect. For the moment the tuning of octupoles and chromaticity are expected to be sufficient to cope with the bunch intensity increase.

A. Siemko asked if the SEY that can be inferred from the measured heat-load can be always considered as physical for the individual magnets. **G. Iadarola** answered positively, the observed SEY can be considered physical and therefore there is a high confidence that the observed heat-load is e-cloud driven.

P. Collier asked if the doublet beam could improve the e-cloud conditioning on the quadrupoles. **G. Iadarola** answered that the e-cloud dependence on the magnetic field is presently in the shadow of the sector-to-sector or cell-to-cell SEY variation.

X. BUFFAT - TRANSVERSE INSTABILITIES

The observations of coherent instabilities in all operational phase of the LHC during Run 2 were summarised, describing their impact on the beam performance. The evolution of the mitigation strategies and of the beam instability models since the start up of the LHC were described and serve as a basis for the development of a strategy for Run 3. An emphasis was put on the new diagnostics and tools implemented for the understanding of the instability mechanisms that affected the operation, as well as the future needs concerning additional diagnostic.

Discussion

G. Sterbini summarised that the studies on e-cloud driven instabilities at injection with trains of 12 bunches and bunch intensities up to 1.8×10^{11} ppb showed promising results, but also noted that those high intensity beams have larger emittances with respect to the one expected in Run 3. He asked whether emittance effects were predicted by simulation. **X. Buffat** answered that there is no effect of the emittance expected from the Landau octupole since they were turned off. **G. Iadarola** replied that studying the effect on the emittance in e-cloud simulation is CPU-wise very heavy. In the few cases it was studied the effect was mild. These studies are dominated by the reduced Landau damping, but there is a large margin because the octupoles were zeroed during the MD. These simulations are sensitive to chromaticity, which depends on longitudinal structures that do not change in the simulation. In addition the BCMS beam has a similar brightness to the LINAC4 beams that are expected in the future. **G. Iadarola** added that they mainly investigated Run 2 and HL-LHC brightness scenarios. Run 3 parameters should be in between the two and therefore no limitation is expected.

P. Collier asked whether the inconsistency of the coupling measurement for high and low bunch intensities is understood and why coupling is the parameter that drifts the most in the machine. **J. Wenninger** answered that the coupling is not drifting more than other quantities. The interpretation of measurements however becomes complicated when going away from the single bunch case, since it depends on which bunch is measured. Same is also true for the tune control, as tune varies from bunch to bunch. **X. Buffat** mentioned an example from MDs where long-range interactions were removed, which changed the coupling and instabilities arose from the extra correction. This is understood and studied for HL-LHC. If long-range interactions are misaligned, they contribute to linear coupling, which needs correction. **J. Wenninger** added that, if most of the coupling decay at injection comes from the MCS circuits, it could be corrected and is not critical. At flattop, however, slow evolution over the year is observed. **R. Tomas** replied that this drift of the MCS was observed before, but it is very slow and does not pose any issue. **T. Persson** said that long-range effects influence the coupling, which was tested during an MD, but that the magnitude is relatively small. **X. Buffat** replied that long-range effects are not expected from theory and that if the crossing angles are perfectly aligned the effect should be zero. However, already the CMS IP vertical shift introduces a non-negligible contribution of the coupling even in a perfect machine.

G. Arduini commented that in some cases kicks have been observed during the injection cleaning and during the ramp. Those triggered instabilities and blow-up and their origin has not been understood. **X. Buffat** added that there is no clear indication for blow-up in the beginning of the ramp. Even with the slow drifts of the BSRT calibration jumps should have been visible, but they were not observed. ADT activity was indeed observed at the beginning of the ramp, but the source is still under investigation.

H. TIMKO - LONGITUDINAL DYNAMICS

During the LHC Run 2, many advances have been made on the beam dynamics in the longitudinal plane. The controlled longitudinal emittance blow-up used in the acceleration ramp was improved and bunch flattening was implemented for bunch length control during collisions. In order to minimise RF power consumption and improve longitudinal stability at injection, the capture voltage was optimised and the full-detuning beam-loading compensation scheme was made operational for the ramp and at top energy. With the present half-detuning beam-loading compensation scheme at injection, the maximum voltage achievable limits the bunch intensity to about 1.8×10^{11} ppb in Run 3. Various experimental and simulation studies helped to improve operation and prepare for the future runs at increased intensities. Open and remaining questions were addressed as well.

Discussion

G. Arduini asked whether the the difference in bunch length damping rate in physics correlates with different beams used over the years. He explained that a similar effect was observed in the SPS and was related to the e-cloud electrons introducing longitudinal scraping. **H. Timko** replied that a clear difference is visible on the leading bunches and a dependency on the bunch structure is under investigation together with **S. Papadopoulou** and **S. Kostoglou**.

G. Arduini asked further details about the capture voltage requirements at injection. **H. Timko** answered that the matched bucket voltage of 2 MV, cannot be used because the bucket length difference between SPS-LHC is about a factor of two and therefore the capture losses would be too high. The optimal setting used today corresponds to the minimum voltage, which still gives acceptable capture losses. Too high voltages are detrimental for stability. A scaling to the expected SPS dp/p gives the presented minimum capture voltages for the future.

P. Collier asked if there is an intermediate option between half and full detuning. **H. Timko** answered positively, this is included in the studies on alternative injection schemes and is under investigation.

G. Papotti asked for clarification on the drift of the energy matching and whether more diagnostics are required. **J. Wenninger** answered that energy matching was done only at the beginning of 2015 and 2016, nothing corrections were made in 2017 and 2018, corrector settings were reused that incorporated the matching. Only when optimising the injection voltage to 4 MV the margins became tight and more investigations were launched. The beam was observed with the BPMs in the first octant on the first turn after injection on a fill to fill base. The mean value over time is stable, while large outliers up to 2×10^{-4} are observed. The reason is not understood for the moment. In order to disentangle the SPS drift from the LHC ones, one can look at the tune trims. If on LHC side the momentum changes, all tunes go in the same direction, but that does not correlate with the first turn data. Tune trims on all beams and planes are correlated, but that seems to be caused by the tune decay. The changes in energy matching therefore are suspected to come from the SPS. **H. Timko** added that this data had to be corrected for the filamented bunch length and that tomography would be an extremely useful tool to investigate this problem further. **J. Wenninger** continued that the IQC has already a rich set of information, but it is not extracted and analysed. **W. Höfle** added that the ADT pickup at Q9 is in a location with large dispersion and its signals could be used to look at energy oscillations of the last run and to disentangle injection errors for every single batch. This data could also be used in the IQC for analysis. However, this data is limited only to one point. **J. Wenninger** said that the energy during the filling is stable and that one adjustment per fill would be sufficient. The unanswered question is why it jitters from fill to fill.

J. Jowett mentioned the strong radiation damping in physics during heavy-ion operation. He asked whether the longitudinal blow-up in physics could be applied to reduce IBS in the transverse plane and gain from smaller horizontal emittances. **H. Timko** answered that there is no problem to implement this technique for ions as it is already successfully put in operation for protons.

J. UYTHOVEN - MACHINE DEVELOPMENTS

An overview of the four years of Machine Development during Run 2 was given. Statistics of the different topics and time assigned were presented, highlighting focus points and assigned priorities. The impact of MDs on machine operation was assessed. Organisational and machine protection aspects of the MDs were presented, including end-of-fill MDs and the role of the different meetings and bodies. A look forward to Run 3 MDs and its organisation was also given.

Discussion

J. Wenninger commented that the crossing angle levelling MD was done in 2016. In 2017 it was already operationally used.

D. Wollmann underlined that rMPP has not often canceled MDs but frequently asked to adjust MD parameters to a safer regime.

G. Iadarola suggested to involve the injector team from early on in the preparation of the MDs, such that they can already give feedback to the LSWG on the expected work load to prepare the requested beams.

P. Collier commented that the end-of-fill MDs should be continued and that they rely on a negotiation between LPC and MD teams. At the end of 2018, four extra MD days were included in the schedule and, because this extra time was already granted, the LMC asked to reduce end-of-fill activity. He also took note of the request to involve special bodies earlier in the process and confirmed that strategies will be defined, using the LMC as a possible platform.

S. Redaelli mentioned that more and more high intensities MDs are scheduled and that this puts a high load on several teams during the MD period (collimation setup, optics and aperture validation, etc.). He asked to consider the question of sustainability of this strategy in view of the availability of teams from e.g., operation, MPP and collimation. **J. Uythoven** answered that high intensity MDs are as well high priority. But he agreed that all needs have to be balanced.