EVIAN WORKSHOP 2018 SUMMARY OF SESSION 2: "2017 OPERATION AND PERFORMANCE"

K. Fuchsberger, B. Salvant, CERN, Geneva, Switzerland

INTRODUCTION

This second session of the workshop focused on feedback from the main direct users of the machine during commissioning and physics (experiments, operation team, optics team, collimation team), as well as on several chosen aspects of machine performance or issues in 2018 (16L2 events, cryogenics system performance with high intensity, transverse instabilities and incoherent effects).

FEEDBACK FROM THE EXPERIMENTS ON THE 2017 RUN

J. Boyd thanked all teams in the LHC complex for the outstanding performance in 2017. CT-PPS and ATLAS Roman pots were inserted without issues during high luminosity running and special runs.

J. Boyd provided feedback on the many machine features used in 2017 (RF full detuning, crossing angle change in stable beams, ATS optics with β*=30 cm, levelling by separation, 8b4e). The main remarks were the low number of collisions in LHCb with the non-BCS 8b4e filling scheme, complications linked to ATS as it gave worse acceptance for CT-PPS and it is not compatible with older configurations for special runs and Van der Meer scans. Initial issues with short trains in 8b4e were dealt with thanks to dedicated correction. Instabilities (other than those dumping the beam) and beam backgrounds were not an issue in 2017, with the notable exception of the background for the special run at injection energy. **J. Boyd** noted that it would have been useful to have the flexibility to keep isolated non-colliding bunches in all physics filling schemes. Praising the teamwork between machine and experiments, **J. Boyd** identified potential areas of improvement in communication between the machine and experiment.

Discussion:

M. Lamont expressed his thanks to Jamie for all the years in his role as LHC physics-coordinator. Further, he reminded about the fact that in 2016 we were tracing a significant luminosity imbalance between Atlas and CMS. He asked if this disappeared. **J. Boyd** answered that the beams seemed to be rounder in general this year and that the luminosity difference between experiments was less than 1% in 2017. He referred to the upcoming talks for more details.

G. Arduini mentioned that the experiments were seeing parasitic collisions, as soon as the crossing angle was reduced to less than 120urad. He asked, if these parasitic collisions were observed inside the experiment or further away. **J. Boyd** answered that he did not have the exact data at hand at the moment, but it could be provided.

LHC OPERATION: EXPERIENCE AND NEW TOOLS

T. Argyropoulos gave a brief overview of the 2017 Run, with highlights on the machine improvements performed along the year: ATS with β* to 30 cm, enhanced combined ramp and squeeze, tighter collimator settings, CMS IP shift of -1.5 mm, full detuning, small emittances with standard and 8b4e beams, crossing angle anti-levelling, separation levelling and bunch length levelling. He also mentioned the difficulties: fast losses in 16L2, high pile-up and beam lifetime degradation mainly for beam 1.

He then said that the existing control system had been stable and described the new tools that were put in place during the Run: beam coupling measurements using the ADT, accelerator cockpit, luminosity scan.

Discussion:

H. Timko commented that the decision whether the bunch flattening should be used or not is up to the LPC. She reminded that for longitudinal stability reasons, it should be used as soon as the bunch length goes down to 0.95 ns. **T. Argyropoulos** answered that loss of landau damping was not observed at a bunch length of 0.95ns, because the bunch intensity was already reduced at this time. Even if the bunch shortening got unnoticed, as it happened several times, the beams survived.

T. Lefevre commented on the lack of notification mechanism for instabilities. He confirmed that the instability trigger was designed mainly in view of BE-ABP use cases and that it was true that there is currently nothing in place for the operation crew. He mentioned that some guidelines/requirements would be appreciated to know what is needed. **T. Argyropoulos** answered that one approach could be to simply inform the experts about instabilities automatically, even if there were false positives. This would greatly ease the work for experts (mainly BE-ABP) to follow up instability events. **T. Lefevre** reminded that too much alarm because of false positives would be problematic. **B. Salvant** confirmed that there are many fake positive triggers with the current trigger on the BBQ system.

R. Bruce commented on the gain of luminosity by squeezing to 30cm, which was quoted in the presentation to be 8%.These 8% were calculated under the assumption of keeping the crossing angle constant. In combination with the lower crossing angle the gain is even higher.

NEW OPTICS CORRECTION APPROACHES IN 2017

E. Maclean reported the change in optic measurement and correction strategy in 2017:

- local corrections applied in 2016 were kept, and only a global correction was performed in 2017
- Linear and non-linear optics commissioning were combined (b4 before global correction, a3/b3/a4 afterwards).

E. Maclean stressed the impact of octupole errors on the tune footprint and increasing degraded transverse beam stability for decreasing β*. Local correction with MCOX in IR1 and IR5 was used to mitigate this effect and also turned out to reduce noise of BBQ tune measurements. Correction of the b3 allowed improving stability of linear optics as well as reducing both the dependence of tune on crossing angle and the strength of the 3Qy resonance. Global correction of non-linear errors improved significantly beta-beating, β* and luminosity balance between IP1 and IP5.

New tools put in place to automate analysis and correction, as well as integrate new observables and correction techniques were instrumental to these successes. He described in particular the ADT-AC dipole application put in place in a collaboration between BE-RF, BE-OP, BE-CO and BE-ABP, and that allows reliably measuring and correcting linear coupling during operation.

E. Maclean detailed the changes to the strategy planned for 2018 (MCO, measurements during the ramp, start with non-linear corrections in place to gain time, emphasis on a4 compensation), amounting to a total of 6 shifts for 2018 commissioning. The new challenge is to count the number of animals in the slides.

Discussion:

J. Wenninger commented on the commissioning strategy for 2018, because it seems to be very modest in the number of commissioning shifts. He assumed that the optics team would base this on the assumption to re-use the ramp-and-squeeze of this year. He asked if the optics team would take the optics at 30cm for granted and was wondering if they would not need at least a shift to remeasure it.

E. Maclean answered that the OMC team has planned about half a shift for re-measuring the optic with the hope to be more efficient in 2018 than 2017.

M. Solfaroli recommended revisiting the strategy of the MCS circuits to see if they could be removed from the interlocked circuits, as more and more of them are failing. **E. Maclean** answered that the effect of each circuit is not huge on Q'', and therefore, in practice it would not be a problem to switch them off at injection.

S. Fartoukh commented on the fact that β* was measured with crossing angle. He asked if there was a special strategy and if it would mean that β* would change if the crossing angle is changed. **E. Maclean** answered that this effect should be small. He added that we only have 2 corrector sextupoles in IPs.

S. Fartoukh noted that going to 25cm would mean that we will really enter the telescopic part. Therefore we should aim for the nicest possible correction at 40cm as a basis. Probably a correction at 30cm might not even be necessary in this case.

R. Tomás asked if we would collide next year at 40cm and then would do beta* levelling. **Y. Papaphilippou** answered that the proposed basic strategy would be to start the machine up with BCMS at 30cm and referred further discussion to his presentation on Thursday.

G. Trad asked if something was learnt on the luminosity imbalance between ATLAS and CMS. He wondered if the fact that this imbalance vanished in 2017 could be due to a better controlled optics. **E. Maclean** answered that from k-modulation measurements they concluded that errors on beta* of about 1-2% were removed in 2017.

E. Todesco asked about the ratio of the current in the sextupoles, skew sextupoles and octupoles with respect to their maximum current. **E. Maclean** answered that the current would be far away from the maximum current (in the order of 25%). He stated that the magnitude of the effects is close to the FIDEL model.

W. Kozanecki expressed his surprise about the fact that the luminosity imbalance to the predicted ratio is that tiny. He wondered if there could be a reproducibility error. **E. Maclean** answered that there are errors on the tune measurement for k-modulation. **R. Tomás** stated that there was not much statistics available with high resolution and that the reproducibility would usually be 1% or below. However, there could be more contributions. **W. Kozanecki** asked, if there could be a systematic uncertainty which could be even bigger than this. **E. Maclean** confirmed that this could be indeed the case.

BEAM LOSSES, LIFETIME & COLLIMATORS HIERARCHY

A. Mereghetti reviewed the LHC beam aperture, losses and collimation system performance in 2017. The minimum beam aperture could be improved by 1.5 σ as compared to 2016 thanks to the reversed sign of IR1 crossing angle, despite the CMS bump. Following encouraging MD results in 2106, collimator hierarchy was pushed in 2017 to decrease β* to 30 cm with primaries at 5 σ (instead of 5.5 σ) and secondaries at 6.5 σ (instead of 8 σ). Angular alignment became important and the automation of the validation helped reducing the time needed for loss maps. Crossing angle anti-levelling required moving collimators during stable beams, which had never been done before.

Stored energy reached 300 MJ in 2017 and cleaning efficiency improved in all planes. Losses increased as compared to 2016 and beam 1 suffered more losses than beam 2. Loss levels are currently not an issue for LHC operation. The squeeze down to 30 cm at the end of the year caused more losses in adjust.

During the EYETS, a prototype low impedance collimator TCSPM, tungsten collimators with in-jaw wires, crystal collimators and a TCP with BPMs were installed, commissioned and tested with beam. 8 dumps could be directly attributed to collimation system in 2017.

Discussion:

J. Wenninger noted that the collimation commissioning time improvements is now saturating. He proposed - at least as a test - to put the beam at 2018 restart on the same orbit as 2017 and then check how the loss maps look like. **S. Redaelli** confirmed that this is what the collimation team has in mind for next year, and use this as a base for the first alignment. **A. Mereghetti** noted that shifts of about 50 µm had been observed from one alignment to the next, which indicates a good stability. **J. Wenninger** added that the orbit stability is also in the range of 50 µm.

S. Redaelli commented that accumulated offsets of the collimators were found after several accesses. He said that the team is working on machine learning to detect spikes, to avoid wrongly stopping the whole alignment system on these spikes. So, improvement is still ongoing and will be put in place next year.

R. Steerenberg asked about the consequences of CMS sinking down even more, e.g. by another ½ mm. **R. Bruce** answered that this would reduce the aperture, but this would still stay in the shadow of IR1. Still, this assumption would have to be verified at smaller β* which we may want to try next year.

INCOHERENT BEAM-BEAM EFFECTS AND LIFETIME OPTIMISATION

D. Pellegrini presented the analysis of the sensitivity of tunes, chromaticity and octupoles on dynamic aperture and beam lifetime in operational conditions (with varying β*, crossing angle and filling schemes). This analysis was performed with simulation campaigns, observations during physics fills and measurements in the machine.

The tune in stable beams is a critical parameter and small changes were shown to have a strong impact on beam lifetime. Tune was routinely optimised in 2017 during physics fills. The impact of chromaticity on lifetime is simulated to be much smaller, while the effect of octupoles is barely visible.

After TS2, β* was reduced to 30 cm, keeping the crossing angle constant, thereby reducing the beam-beam separation from 10 σ to 8.5 σ. This reduced dynamic aperture from 6 to 5 σ for standard beams, but the switch to 8b4e improved the situation.

Extensive studies were performed to identify optimal parameters for crossing angle anti-levelling in terms of integrated luminosity.

D. Pellegrini stressed that simulation studies were heavily affected in 2017 by the switch to HTCondor. The situation improved towards the end of the year.

Discussion:

M. Lamont asked more information on the higher beam loss at the start of stable beams. **D. Pellegrini** answered that these losses are not understood.

M. Wendt suggested using the Schottky coherent signal to get the tune. **J. Wenninger** answered that this this was looked at parasitically: tunes at flat top and squeeze were credible, but not in collision. **M. Wendt** commented that one needs to check the setting of the gate. **D. Pellegrini** added that they have tried the excitation with the ADT on non-colliding bunches.

R. Bruce said that tails do not contribute to lumi. **D. Pellegrini** agreed, and added that one needs to quantify the loss of performance better. **R. Bruce** asked if the crossing angle could be smaller without affecting performance. **R. Steerenberg** remarked that affecting tails could be detrimental to performance if they are lost and continuously repopulate. **O. Brüning** said that in principle the tails should not repopulate. **Y. Papaphilippou** noted that a dynamic aperture as low as 3 to 5 sigma, lead to depopulation, which changes distribution, which in turn can cause emittance blow up that will eventually influence luminosity and cause performance loss. **G. Arduini** said that one needs to assess the emittance blow-up for different crossing angles.

16L2: OPERATION, OBSERVATIONS AND PHYSICS ASPECTS

L. Mether presented the status of the understanding of the abnormal fast losses in the 16L2 half-cell, which caused more than 60 beam dumps in 2017.

The assumption is that air entered the beam pipe when the sector was cold towards the end of the EYETS and gas species froze on the surfaces of the beam pipe and beam screen. These frozen flakes may (1) outgas, generating the locally observed steady-state losses by beam-gas scattering, (2) detach and enter the beam, causing the locally observed UFO-like spikes and (3), if the deposited energy is large enough, undergo a phase transition to a gas, causing the large transient losses that could last for tens of ms, and eventually leading to a beam dump.

The phase transition to local dense gas (10^{20} to 10^{22} atoms per m^3) could explain the long transient losses and the very fast transverse instabilities. Observations of positive tune shift during the instability and the impact of dipole corrector and filling scheme are indications that electrons are involved in the process. Simulations with electrons show that these observations can be reproduced by the interaction of the proton beam with a very dense electron cloud, but that this very dense electron cloud cannot be sustained. One mechanism that is currently envisaged is that the presence of the dense gas in the chamber can provide large densities of both ions and electrons following beam impact. The dynamics of these species together interacting with the proton beam could explain the build-up and the fast instabilities. The development of macroparticle simulations accounting for the proton beam, the electrons and the ions are ongoing and should shed light on the possibility that this mechanism can indeed occur.

Despite these unexpected dumps, operation could be eventually restored by resorting to several non-standard tricks: change of corrector strength, beam screen regeneration (it was attempted but turned out to worsen the situation as there was much more gas than expected at the time), switch to low heat-load filling schemes, and installation of a solenoid around the affected interconnection. In addition, many tools were put in place to analyse this complex sequence of events, and helped in the understanding of what happened. Existing bunch by bunch diagnostics (e.g. ADTObsBox, Headtail monitor and Diamond BLMs) were heavily used and could be dedicated to understanding the sequence of events.

Under some assumptions, the overall cost of 16L2 events on LHC performance in 2017 was estimated to be of the order of 7 to 10 fb^{-1} (i.e. 14 to 20% of 2017 total integrated luminosity).

Discussion:

J. Wenninger commented that the raw luminosity loss estimate due to 16L2 does not account for the larger pile-up and the reduction of performance for LHCb that were the consequence of the switch to 8b4e. He stressed that one should not count on continuing running like this in 2018.

R. Steerenberg asked what the intensity limit is. **L. Mether** answered that we do not know.

E. Bravin asked about the dumps in the special physics run. **L. Mether** and **D. Mirarchi** answered that the optimization of the corrector current was not put in place at first

E. Shaposhnikova noted that the model assumes a plasma with 10 cm length and asked how sensitive the model results are to that length, since bunch length is 30 cm. **L. Mether** answered that what matters is the density of the plasma, not so much the length.

D. Delikaris said that sector 12 is now at 80K and noted that it is a decision point to stop or continue the warm-up, since it would trigger lots of actions if we continue. TE-VSC presented the latest status, and the presence of N_2 and O_2 inside the machine vacuum was confirmed. The air is being pumped out and it is estimated that there are 2% of water remaining, i.e. a remaining quantity of water of less than 1 g. Very long discussions took place. Since up to 98 % of the problematic gases were pumped out, the outcome of the meeting is for the moment to stop the warm-up and stay stable at 80 K for 1 week. The subject was taken to the directorate and the outcome was to stay below 100 K. Following that decision from the CERN management, TE-CRG will re-cooldown sector 1-2 20 K as all other sectors.

OUR UNDERSTANDING OF THE INSTABILITIES AND MITIGATION TOOLS/STRATEGY

X. Buffat reported the status of transverse instabilities in 2017. There were many flavours of transverse instabilities throughout the cycle and along the year, but their impact on performance was not critical, and they did not represent a limitation (with the notable exception of the 16L2 instabilities).

Still, electron cloud instabilities at injection have required using high chromaticity, ADT gain and octupole current. Large transverse coherent motion and related emittance blow-up on trailing bunches of trains of circulating beam was observed when the injection cleaning is switched on. That effect is under study and was significantly reduced with 8b4e, indicating that electron cloud is an important ingredient for that issue.

No instability was observed during the ramp, but the beam may be subject to significant sources of noise there, and could be a reason for the emittance growth that was observed.

Several transverse instabilities were observed at flat top. The octupole threshold to damp single bunch instabilities is a factor of about 2 larger than predicted and the reason is not yet understood. Instabilities at the head of the train also came and went without clear reason. While the understanding of the impact of non-linear optics correction has advanced, an important unknown along the cycle is the beam distribution evolution and the related Landau damping. Besides, coherent instabilities were also observed during Van der Meer scans as Landau damping is reduced for instance when colliding with an offset of ~ 2 sigma at IP8.

X. Buffat stressed the importance of proper diagnostics to understand instabilities and propose efficient solutions to mitigate them. The ADTObsBox allows for bunch by bunch position measurement and the Headtail monitor for bunch by bunch intrabunch diagnostics. Both could be triggered by the LHC Instability Trigger Network (LIST) when abnormal coherent motion is detected from one of the diagnostics. These diagnostics have been extremely helpful in 2017 to catch and characterize instabilities.

Discussion:

C. Schwick asked if going back to 25 ns BCMS with higher intensity would be significantly worse. **X. Buffat** answered that the effects scale with brightness for impedance effects but the scaling is not trivial for electron cloud. **G. Iadarola** added that there are plenty of assumptions, and that they are studying the dependence with intensity. He said that he would be surprised if we hit a hard wall.

G. Arduini mentioned the worry that the TMCI threshold seems not too far in intensity. He asked if the same result is obtained for beam 2. **X. Buffat** answered that there were issues and the error bar is huge in beam 2 H. It was asked if octupoles can damp TMCI. **G. Arduini** answered that it is not sure, and that one needs to understand the source.

D. Valuch said that on the instrumentation side, he is working on tune measurement, so that it can be measured parasitically on demand. He is also getting new storage and a powerful server, so that the analysis can be done close to the box. It will allow to store "bunch-by-bunch everything" for almost 2 days, which will require 3 years to read the data.

S. Redaelli asked if we think we are in a position to rule out tighter collimators in IR7. **X. Buffat** answered that since we do not know the source of the discrepancy, he would advise to be conservative, and would put the discrepancy on the secondary collimators. In that assumption, tighter collimators in IR7 could indeed be prohibitive.

CRYOGENICS EXPERIENCE WITH HIGH LUMINOSITY RUNNING & CONTROLS

G. Ferlin reported the performance of the cryogenic system in 2017 and the expectations for 2018. Cryogenics availability was good and reached 97.9% in 2017, but ageing effects start to be visible on equipment that date from LEP times.

Thanks to leak search campaign during the EYETS, helium losses during operation were decreased to 5.4 t, a factor 2 less compared to 2015, and a factor 6 less than in 2010.

The cryogenic limitations for beam screens are 160 W per half-cell and 270 W per triplet. The cryogenic capacity for sector 1-2 is important to be measured in 2018. 3 other low load sectors are missing (sector 4-5, 5-6, and 6-7). Triplet magnet temperature could be kept below 2 K during the test fill without levelling and constant luminosity at 2 10^{34} $cm^2.s^{-1}$.

Individual half-cell feed-forward that was tested in sector 8-1 after TS2 will be deployed in 2018 in order to optimize the available cooling power.

Discussion:

R. Steerenberg asked why there is more cooling power available for the triplets than for the arcs, if they are connected to the same cooling plant. **G. Ferlin** answered that the cooling plant is the same but the cooling circuits are different, and have different cooling power. **R. Steerenberg** asked if more electron cloud means less margin for triplets, and whether we could run at 2 10^{34} $cm^2.s^{-1}$ with the BCMS scheme. **G. Ferlin** answered that we should be able to do both in parallel, but we would be close to limit. He stressed that this is why we need the calibration of sector 1-2.

R. Steerenberg asked confirmation that one can stand larger transient for some time. **G. Ferlin** agreed that one can "bufferize" for some time, i.e. use the liquid helium as a buffer, but that there is a limit.

G. Arduini noted that the heat load from electron cloud in triplets should be negligible.