MACHINE DEVELOPMENT FOR RUN 2

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Abstract

An overview of the four years of Machine Development (MD) during Run 2 is given. Statistics of the different topics and time slots assigned are presented, highlighting focus points and chosen priorities. The impact of MDs on machine operation is assessed. Organisational and machine protection aspects of the MDs are 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 is also given.

REVIEW OF RUN 2

Hours assigned and efficiency

The year 2018 was a record year with a total of 573 hours assigned to Machine Development (MD), corresponding to almost 24 days. In 2015 there were the least number of MD days, with 16 days. An overview of the number of days of MDs for the different years in Run 2 is given in Fig. 1. It shows that the assigned hours on the schedule, the effective MD hours, the turnaround and fault hours (as indicated on the MD schedule) and the fault hours as recorded in AFT. The efficiency (MD hours/total number of hours) increased from 70 % to 75 % over Run 2. Figure1 clearly shows that availability strongly improved over the years. In 2015 the recorded availability during the MDs periods was 72 %, which increased to 90 % for 2018.

Highlights for the years 2015, 2016 and 2017

It is difficult to make a choice between the many MDs and to determine the highlights. Going through the proceedings of this 8th LHC Operations Evian Workshop and the many references to MDs give a good indication of the importance of the many MDs performed.

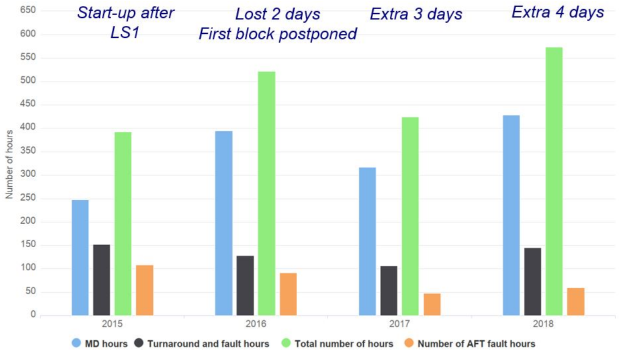

Figure 1: Number of MD hours on the schedule (green) together with the effective MD time (blue). Turnaround time (black) and fault hours (brown) are also indicated.

For the year 2015 the following MDs deserve a special mention:

- Ramp and squeeze commissioning;
- The $\beta^* = 40$ cm commissioning;
- The demonstration of β^* levelling;
- Crystal channelling at 6.5 TeV;
- Longitudinal bunch flattening made operational;
- 8b4e appeared in the LHC;
- Instability thresholds being tracked.

For the year 2016 the following MD can be highlighted. It clearly shows the large diversity of the many different MDs:

- DOROS BPMS used for transverse coupling correction;
- Single bunch instabilities studied, slowly being clarified;
- Crossing angles scans, then used in physics already in 2016;
- The use of RF full detuning of cavities;
- Reached experiments pile-up of about 160.;
- Clear impact on lifetime of non-linear IR corrections;
- ATS telescope with β^* down to 10 cm used for probe bunches, required mechanics tested successfully.

In 2017 the following MDs deserve a special mention:

- Many collimator MDs took place including low impedance collimator measurements, wire collimator tests and collimation with Xe;
- Crossing angle anti-levelling was studied;
- IR non-linear corrections used in operations;
- Ballistic optics for BPM calibration;
- ATS flat optics started, use of 'stronger ATS round' optics;
- eCloud studies, 8b4e saving operation with 16L2;
- Diamonds and UFOs, quench heaters and orbit;
- Q4 quench tests – TCDQ vs. TCT retraction, bunched asynchronous dump.

Focus points and highlights for 2018

For 2018 a comparison between the MDs performed and the MD strategy as announced at the Chamonix 2018 workshop [1] can be made. Two focus points (**FP**) were defined for 2018 together with some other important MDs (**IM**). They are reviewed below.

FP1: E-cloud. Aim: Understand the e-cloud and heat-load and prove 8b4e as back-up for HL operation together with preparing doublets for scrubbing.

Five MDs were performed on this topic in 2018. The 8b4e filling pattern was checked against the models and agreement was found. Heat load measurements with different bunch lengths were made and the expected decrease of heat load with increasing bunch length was found. This indicates that the heat load is dominated by the dipole magnets. A large

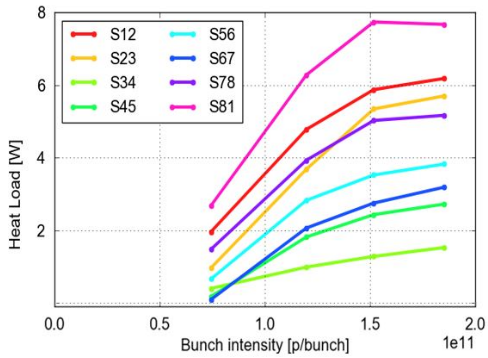

Figure 2: Intensity scan with 12b trains at injection energy. The component from beam screen impedance is subtracted [2].

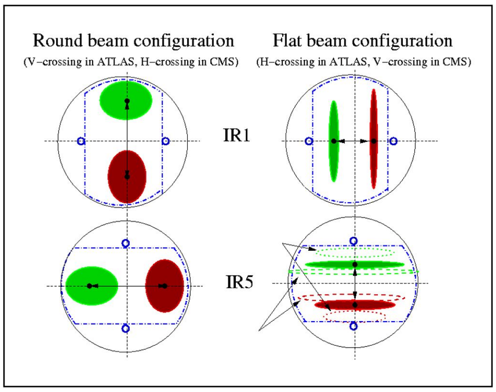

Figure 3: Illustration of the Round and Flat ATS configurations [3].

telescope optics (ATS) which high bunch intensities was tested. One of the most important results found is that the flattening of the heat load with increasing bunch intensity was experimentally confirmed. The results are summarised in Fig. 2, More details on the findings during 2018 can be found in [2].

FP2: ATS optics. Aim: Fully demonstrate HL-LHC optics and operational modes. This concerns both the round and the flat ATS optics and the linear and non-linear correction required, see Fig. 3.

The round ATS optics was operationally proven, with bunch trains and a total of 2×733 bunches, reaching a peak luminosity of $L = 3.6 \times 10^{33}\,\mathrm{cm^{-2}s^{-1}}$ with a $\beta^* = 65\,\mathrm{cm}$ and a crossing angle of 120 µm. Tests have been made with bunch intensities up to $1.6 \times 10^{11}\,\mathrm{p^+/bunch}$, however losses occurred at the end of the energy ramp. Negative octupole polarities have been used, reaching beam lifetimes between 50 and 100 hours. Several stability studies were made and the octupole polarity was successfully swapped with the beams in collision. The principle of TCDQ levelling was tested successfully. More details can be found in [3].

The flat ATS optics was tested in collision, with trains of up to 60 colliding bunches. A negative octupole polarity was used. An instability when performing the crossing of the bump rotation remains to be solved. Optics corrections have been performed, allowing for safe operation, but the corrections are significantly poorer than those obtained for the round optics, even after several iterations.

IM1: Proof of operational modes. Many gymnastics were operationally proven in MDs. The β^* can be changed as desired and levelling performed under full control. It is technically possible to use β^*-levelling (i.e. perform a further squeeze) with the beams colliding. Machine protection aspects remain to be studied in further detail.

IM2: Luminosity gain from BBLR wire collimators. In total 36 hours of MD on Beam-Beam Long Range compensation using the wires in the special collimators were performed. The wires were powered in operation using bunch trains. A very clear effect of the compensation with trains and reduced crossing angle was shown. A gain of crossing angle of about 10 µrad with the wires powered was demonstrated.

IM3: Demonstration of crystal ion collimation. A full program of crystal ion collimation tests with ions was completed. A complete characterisation of all crystal devices with Pb ion beams was performed. Loss map campaigns with different settings to be compared with the standard collimation settings and previous measurements were made. The crystals were kept in the beam during the squeeze and tests with sustained losses on all four planes at the same time were performed.

IM4: Emittance preservation and understanding of beam blow-up. A significant amount of time was invested by the the different teams to understand the beam stability and related blow-up. Special studies were made to understand the 50 Hz lines in the beam spectrum, perform beam lifetime optimisation at injection and study the so-called stable islands. There is presently no full understanding on emittance preservation throughout the cycle and a good line of attack for further studies needs to be defined.

IM5: Understanding beam loss dynamics and distribution, causing magnet quenches including asynchronous dumps. Finally no dedicated quench tests were made. The beam losses could not be studied with the limited bunch intensities available. Asynchronous beam dump tests with bunched beam were performed at flat top. The quench behaviour or the Q8/Q9 is now understood as a secondary quench of MB.A8 (and not due to beam losses). The quench behaviour of MB.A/Q4 is consistent with the quench limits and simulated beam impact parameter for Beam 1. The Beam 2 behaviour needs further analysis. Also the Q5 quenches are still under investigation, considering longitudinal variations in the beam and the measured losses.

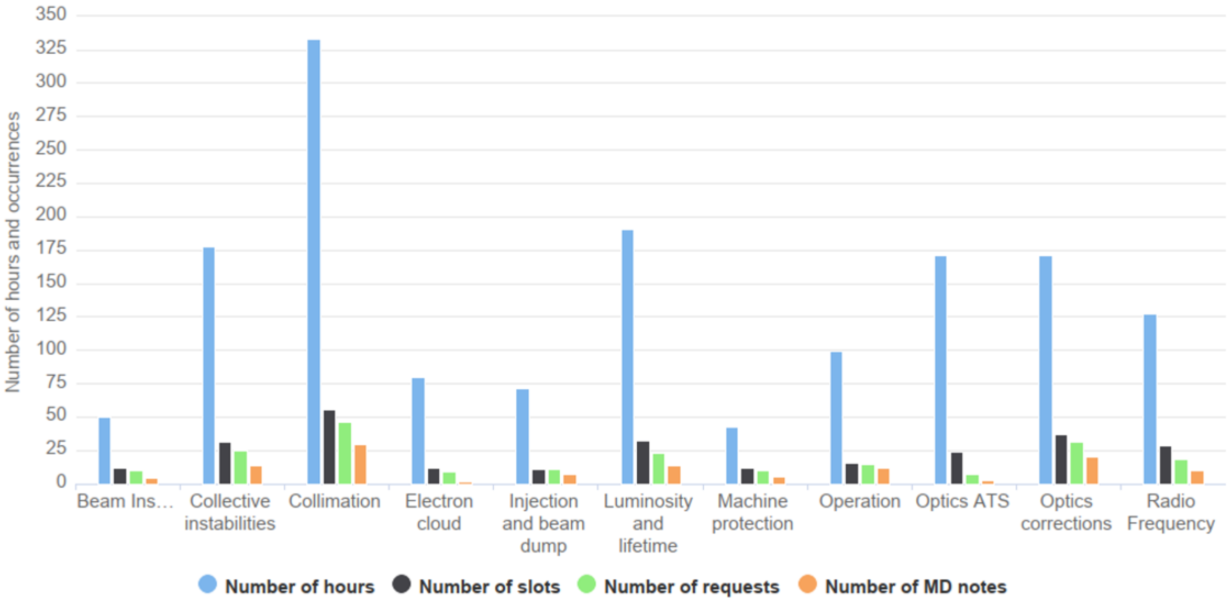

Figure 4: Statistics for the different MD categories over Run 2 (2015 to 2018). It shows a total of 1514 hours of MD, for a total of 272 slots, 205 different requests and 121 MD notes.

IM6: Special MD requests. The following special requests were made for 2018. They are listed with a brief summary of the results:

- Injection tests at 225 GeV. This MD would have needed a large invested of time. It was kept on the list for a very long time and only cancelled rather late, because of a lack of priority.
- ATS with a full telescope and more than 1000 bunches: this was done successfully (see under ATS MD above).
- Physics beyond colliders asked for a measurement of the lifetime of $^{208}Pb^{81+}$. At injection a lifetime of about 10 hours was measured and at flat top a lifetime of 40 hours. This exceeded the expectations, extrapolated from SPS MD results.

STATISTICS OF MDs PERFORMED

The MDs performed during Run 2 have been categorised in 11 different main topics. For each topic the number of MD hours, number of MD slots, the number of MD requests and the number of MD notes at the moment of the workshop is given in Fig. 4. It shows that most of the MDs can be classified as related to collimation, which can be explained to the many instances of new hardware under tests in preparation for High-Lumi LHC. The second largest group is collective instabilities, closely followed by luminosity and lifetime and optics related studies.

If the same classification is made for 2018 only, the ATS optics studies form the largest category of studies, closely followed by again collimation, collective instabilities and electron cloud studies. The total number of MD notes written for the 2018 MDs is only 4 at the moment of the workshop.

Over the complete Run 2, the percentage of MD notes written relative to the number of MD requests is the highest for the Operation related MDs, with 80 % and the lowest for electron cloud studies with 20 %.

ORGANISATION AND TOOLS

The percentage of the number of MDs performed relative to the number of MDs requested is around 60 %. This value is very constant over the different years of Run 2. This means that more than half of the MDs requested actually take place.

The criteria to decide if an MD is going to take place are: priority relative to the defined 'focus points'; can the results of the MD be used in operation; readiness (to be checked by the LSWG); distribution of MD time between groups; feedback of the LMC on the above and the rMPP green light concerning the machine protection aspects.

So-called End of Fill MDs and floating MDs took place especially during the beginning of Run 2 but hardly took place towards the end of Run 2. The year 2016 saw an increase of the use of End of Fill and floating MDs: 15 were successfully executed with approved procedures. In 2017 and 2018 they were only very few. Towards the end of 2018 the LMC explicitly vetoed End of Fill MDs to increase the operational machine efficiency. Counter-balancing machine efficiency, End of Fill MDs are hard to schedule and they are hard to include in the rMPP approval round.

All MD procedures have been approved by the restricted Machine Protection Panel (rMPP) before the MD took place. Constructive discussion generally took place in the rMPP meetings. The review by the rMPP team assesses the likelihood that the MD will results in machine damage and often recommendations were made and it was asked to update the procedures for the MD accordingly. The requirement to have detailed procedures before the MD has not been a discussion point anymore. The most non-realistic MDs are generally cancelled at the level of the LSWG meetings, before any rMPP discussion. The rMPP discussions became very heavy in the case of the ion collimator coating MD. One MD by the MPE group was cancelled by the rMPP.

It is to be noted that the first responsibility for machine safety lies with the MD requester. The final responsibility lies with the EIC. The EIC can call an rMPP member in case of important deviations from the MD procedures. This happened only at a few, very rare occasions.

A typical MD organisation flow is given in Table 1. It shows the main steps between the moment of submitting the MD request (at least one month before the actual MD takes place) and the publication of the MD note. The bodies involved are the LHC Studies Working Group (LSWG), which is the platform to discuss MD proposals and MD results; the LHC Machine Committee (LMC); the Facilities Operations Meetings (FOM) and the restricted Machine Protection Panel (rMPP).

Table 1: Typical flow of steps in the preparation and follow-up of MDs.

Step	Days	Event
1.	$J - 34$ days	Deadline for MD request
2.	$J - 26$ days	LSWG presentations
3.	$J - 14$ days	Procedure written
4.	$J - 11$ days	LMC presentation and approval
5.	$J - 10$ days	MD schedule draft prblished
6.	$J - 8$ days	FOM presentation
7.	$J - 6$ days	rMPP meeting and approval
8.	$J - 5$ days	MD schedule, final
9.	J day	Start of MD block
10.	$J + 7$ days	LMC brief report results
11.	$J + 35$ days	LSWG presentation of results
12.	$J + 180$ days	MD Note published in CDS

The organisation of MDs has been relying heavily on the Accelerator Schedule Management tool (ASM), ASM was used for MD scheduling for the frist time in 2015. A new version was launched in 2018. It is now used in almost all stages of the MD process described in Table 1: initial MD request, submission of procedures, rMPP approval and scheduling. In 2018 flags were introduced on the schedule to indicate the requirements relative to the experiments and the cryogenic system. For each MD, the requirements from the injectors to deliver specific beams was also defined in ASM. It is foreseen to further automate this for Run 3. ASM is also used for statistics reporting and the statistics graphs in this paper have been produced with the ASM tool.

DISCUSSION AND CONCLUSIONS

In 2018 there was more input from other bodies or committees on the MD program than usual. This concerns the HL-LHC Technical Coordination Committee, Group Leaders, Project Leaders and Directorate. Ideally, this input should be collected as early as possibly and preferably the LMC has to be used as a forum for discussion of all parties involved, well before the assignment of MD time has started.

Further improvement can be obtained in the role of the OP contact person for the specific MD. A larger diversity of OP contact persons and at the same a closer involvement of the contact person is desired. Also the recovery and settings clean-up after each MD can still be improved.

The load on the injectors because of LHC MDs is very heavy. The injectors should be involved in the planning of the MD schedule as early as possible (aiming for two weeks, via FOM), which is difficult as the MD schedule is only established few days before the MDs take place (depending procedures to be completed and on other bodies like rMPP and LMC). It should be considered to have a provision on the injector schedule to prepare the LHC MD beams. The overlap of LHC MDs with injector MDs or fixed target users should be assessed and priorities defined as early as possible. This can be done by preparation meetings outside the FOM, with all parties involved.

It can be concluded that the Machine Development activity for Run 2 was very successful. The predefined goals have mainly been achieved and a huge amount of useful and interesting data has been obtained. No damage to the machine occurred during the MDs. The ASM tool was extremely useful in the preparation and scheduling of the MDs. The organisation of MDs seems to have become mature, although further improvements are foreseen for the Run 3 MD organisation.

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