LHC MACHINE DEVELOPMENTS IN 2011-12

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Abstract

In 2011 and 2012 LHC Machine Development (MD) sessions were performed during dedicated slots of beam time. These MD studies were scheduled and planned well in advance. Study topics reflected the previously agreed priorities, such as further optimizing machine performance, exploring beam parameters beyond design targets, assessing machine limitations, testing new concepts and machine settings, preparing future LHC running in view of the 2013/14 LHC Shutdown (LS1) and the re-commissioning of the LHC at close to nominal beam energy in 2014/15. We describe the planning, preparation, execution, review, and documentation of these LHC beam studies and highlight a few key results.

INTRODUCTION

The Large Hadron Collider (LHC) [1] at CERN, Geneva, is a high-energy proton and heavy-ion superconducting accelerator and collider, located in a 27-km long circular underground tunnel. The LHC design features a proton energy of 7 TeV per beam and a peak luminosity of $10^{34}\,\mathrm{cm^{-2}s^{-1}}$. The LHC had first collisions in 2010 and carefully ramped up the beam intensity during that year. The following two years saw routine operation, with periodic Machine Development (MD) sessions.

The term "MD" designates a dedicated accelerator and beam study aimed at improving the machine performance or preparing for new modes of operation either in the short term (weeks or months) or with a longer-term view (e.g. for planned LHC upgrades). As an example, the feasibility of a new optics is typically tested in an MD (as was the case, e.g., for the commissioning of several high β^* m optics for diffractive physics by the TOTEM and ALFA experiments. When such new optics is later used for actual physics operation, the remaining commissioning (such as qualification for high intensity beams with beam loss maps) is done during physics time. Similarly, the first feasibility test of creating beam conditions with a higher-than-usual event pile-up were demonstrated in an MD, while the subsequent data taking by the experiments was scheduled in physics time.

Flexibility in sharing allocated times between MD, commissioning and physics has helped accomplishing major LHC goals. A similar flexibility is hoped for in the future.

For smooth and successful MD execution a close tie between the MD team and the LHC operations group (OP) is essential, since OP is familiar with the procedures, tools and constraints of beam operation. Therefore, each MD team included at least one OP member to advise on the feasibility of each step and to help preparing the MD in detail.

LHC Schedule and MD Periods

A typical yearly LHC run extends from March to December over 260–290 days. This total time is subdivided into commissioning with beam (at the beginning of the year, consisting of about 3 weeks at low intensity, plus 2–4 weeks for initial intensity ramp-up), 3–5 technical stops for scheduled maintenance (amounting to about 20 days in total, plus 5 days for recovery), proton physics (about 125 days), ion physics run (about 4 weeks, including commissioning), special runs (such as with high beta optics, accounting for some 10 days total), and time dedicated to electron-cloud scrubbing with beam (about one week each, in 2011 and 2012). The time devoted to beam studies (MDs) amounted to 22 days in both 2011 and 2012.

LHC STUDIES WORKING GROUP

The organization of the LHC MD time is coordinated by the LHC Studies Working Group (LSWG), chaired by Ralph Assmann (until August 2012) and Frank Zimmermann, and helped by Giulia Papotti as scientific secretary.

The mandate of the LSWG includes collecting MD requests, their discussion and prioritization, optimizing resources and beam time, preparation of a draft MD schedule, its presentation to the weekly LHC Machine Committee (LMC) for approval, coordination during execution, review of MD results and follow-up of the MD documentation in the form of written MD notes.

Generally, in 2011-2012 one to two LSWG meetings were held prior to each MD block in order to define the MDs to be scheduled next and to organize them in detail (the last of these preparatory meetings was normally taking place at least 2 weeks before the MD block). During these preparation meetings also the beam requests for the injectors were collected and information was compiled for defining the Machine Protection (MP) classification of each MD study (see next).

Another one or two LSWG meetings were held after each MD block in order to review the results. A written documentation of results in the form MD notes, ideally to be published within 1–2 weeks after the MD, was mandatory and followed up regularly during the meetings. Further MD time was not allocated to the same MD team unless a note reporting the previous results had been published.

The LSWG website [2] contains detailed information about Indico meeting pages and minutes, the list of MD requests, and the MD notes issued by the various teams.

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Machine Protection Classification

All MDs were classified by Machine Protection (MP) experts into four categories according to the involved risks from the MP point of view:

- type A ("safe"): MDs with"setup" beams only (at 0.45 TeV, $< 5 \cdot 10^{11}$ ppb and at 4 TeV $< 3 \cdot 10^{11}$ ppb);
- type B: MDs with non-setup beams, and no changes to MP systems;
- type C: MDs with non-setup beams, and changes to MP systems (e.g. collimator positions);
- type D: potentially dangerous MDs, not to be carried out unless the plan is modified.

For critical MDs, i.e. those of type C and D, formal documents were required to be prepared by MD teams and channelled to the Machine Protection Panel (MPP) for safety assessment and approval (prior to execution).

Documenting the MD plan proved useful for a cleaner preparation, for information to the MPP and shift crews, and as a check-list for setting changes and definition of responsibilities. For these reasons, it is suggested that when the LHC resumes operation after the LS1, all MD proposals should provide a written document detailing the MD plan.

SCHEDULING

The 22 MD days in 2011 and 2012 were grouped into four blocks of on average five days preceding the technical stops. The length of individual MD in such a block varied between 1 and 16 h, with most MDs lasting between 4 and 10 h. If the machine was ramped to top energy in an MD, 2 h of recovery time were assigned after the MD before the start of the next MD. The additional 2 days were called "floating MDs" and could be scheduled more flexibly and according to need. They were often scheduled close to special runs. A number of short studies were carried out outside of MD time if urgently needed for physics operation ("operational developments"). A few studies were carried out as "end-of-fill" or in parallel to physics operation, when the machine conditions allowed for it (e.g. non-colliding bunches for the observation of beam parameter evolution in the absence of beam-beam interaction).

Scheduling five continuous days of machine studies is very demanding for the accelerator experts. The creation of a draft schedule is difficult in itself, as the time allocation must take into account the availability of all team members, and the participation of few key people (e.g. for the RF system or the transverse damper) in several of the MDs (sometimes only few hours apart) can be exhausting and entail a risk of inefficiency.

The motivation for scheduling long MD blocks attached to technical stops was the wish to minimize the impact on physics production. In late 2012, though, an MD block was not followed by a technical stop due to other constraints and the impact on the following physics restart turned out to be minimum (only one interlock mask was left behind by mistake). This is an indication that shorter MD blocks (e.g. 2–3 days long) could be attempted in the future to help the machine experts while minimizing the impact on physics efficiency. This would move towards the rhythm of machine studies in other machines (e.g. 24-hour blocks with weekly periodicity at RHIC and SPS).

CATEGORIES & PRIORITIES

In both 2011 and 2012, the number of MD requests and the total amount of time needed to execute them (see Table 1) by far exceeded the available time (22 days, i.e. 66 8-hour shifts or 576 hours). It was the responsibility of the MD coordination to merge similar MDs when possible (e.g. separate requests submitted from different MD teams to study operation with a working point close to the half integer resonance).

Long-term priorities, reflecting the input received at the yearly Chamonix workshop as well as at the weekly LMC meetings, governed the allocation of MD time. Short-term priorities were defined for each MD block, reflecting also the actual operational issues and needs, plus the outcome of previous MDs (e.g. the steering of the third MD block of 2011 towards studies for lower β^*, which was immediately exploited in operation [4]).

For example, among the highest priorities defined in the LHC Performance Workshop held in Chamonix (February 2012) for operation in 2012 there were studies to quantify quench levels [5] and understanding of beam heating effects around the LHC ring [6]. Among the priorities defined in 2012 for future running there was the characterization of operation with the nominal 25 ns bunch spacing [7].

IMPACT OF MACHINE AVAILABILITY

It is worth noting that the scheduled time suffers from general machine availability issues. In order to absorb some of the unforeseen delays into the schedule, for the preparation of the machine from top energy to the next in-

Table 1: Number of MD requests for 2011 and 2012. For more details on time allocations in 2011 and 2012, see [3].

MD title	2011		2012	
	#	[h]	#	[h]
beam-beam	12	164	8	128
RF (and ADT)	9 (1)	116 (6)	10 (4)	120 (30)
optics	14	194	13	122
25 ns and e-cloud	3	86	2	56
inj., TDIs, TCDQ	10	182	6	96
collimation	8	90	15	128
impedance	5	22	4	24
BI	9	58	15	100
ion or p-Pb	1	24	3	48
quenches	7	42	8	90
instabilities	2	28	5	56
others	9	68	6	56
total	90	1080	99	1054

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jection (recovery, or "ramp down") after an MD 2 hours were always allocated, while the minimum time in which this can be achieved is about 1 hour.

Other than this though, it was decided that MDs would not be delayed in case of problems, but that the schedule would hold over the course of the five-day MD block. In this way, the impact of issues would be confined to the ongoing MD. Only in case of major causes of downtime (e.g. faults that would impair availability for at least a day, cancelling de facto many MDs at once), a new schedule would be worked out taking into account the priorities.

Some MD blocks were luckier than others with respect to availability: for some the availability was excellent (e.g. the first MD block in 2011, where the machine was available for 89% of the scheduled time), in others the schedule had to be re-worked twice during the 5-day period (e.g. the third MD block in 2011, which suffered from a 27 h cryogenic stop and a 9 h downtime due to thunderstorms).

HIGHLIGHTS OF MD RESULTS

Some MD highlights from 2011 were: no head-on beam-beam limits were encountered with 3× nominal brightness and total beam-beam tune shift of 0.03 with ATLAS and CMS collisions [8]; the Achromatic Telescopic Squeeze (ATS) optics with different integer tunes was established from injection to 3.5 TeV [9]; and the collimation system with the operational physics settings reached 500 kW primary beam loss without quenches in the dispersion suppressor [10].

In 2012, the nominal collimation 7 TeV settings (in mm) were achieved and the collimator impedance was measured [11]; a record pile-up of 70 [12] and a record Piwinski angle of 1.1 [13] were demonstrated; the feasibility of luminosity levelling with β^* was proven [14]; the dynamic aperture was found to be in agreement with the predictions [15]; the chromaticity dependence on octupole strength was measured [16]; smaller than nominal β^* was achieved with low-intensity beams, i.e. $\beta^* = 40$ cm by squeezing the nominal optics [17] and even 10 cm with the ATS optics [18], albeit without crossing angle; and "cogging" [19] was demonstrated, namely one beam (consisting of two bunch trains) was shifted against the second beam by RF frequency manipulations around the circumference with little impact on beam lifetime or emittance.

CONCLUSIONS

In the years 2011-2012, the MDs proved the excellent performance potential of the LHC, and 22 days of beam time for machine studies per year were well invested. The gain from the MDs was tangible very early on: e.g. the decrease of β^* in early Sept. 2011 which directly paid off in integrated luminosity, and the feed forward of MD results into operational settings (e.g. for beam instrumentation).

The MD results also had a profound impact on the upgrade plans and directions: e.g. the delay of the LS1 collimation upgrade for the point 3 dispersion suppressors; the possibility of very small β^* with the ATS optics even before the 2020 upgrade of the Interaction Regions; and the path to very high brightness beams in the long term.

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