CERN-ACC-NOTE-2023-XXX MD

11 October 2024

`pascal.hermes@cern.ch`

MD 7224: LHC collimation quench test with protons

P. Hermes, A. Abramov, R. Bruce, D. Calzolari, M. D'Andrea, M. Giovannozzi, C. Hernalsteens, A. Lechner, B. Lindström, D. Mirarchi, C. E. Montanari, S. Morales Vigo, J.-B. Potoine, S. Redaelli, V. Rodin, B. Salvachua, M. Soderen, J. Uythoven, D. Valuch, C. Wiesner, D. Wollmann, C. Zamantzas, M. Zerlauth
CERN, CH-1211 Geneva, Switzerland

Keywords: `LHC, Collimation system, Main dipoles Quench Limit, ADT, BLM system`

Summary

This note describes a collimation quench test performed at the CERN Large Hadron Collider. The test was designed to quantify whether a primary beam power load of 1 MW on the betatron collimation system, the High Luminosity LHC design specification, can be sustained without quenching the superconducting dipole magnets in the dispersion suppressor downstream of the straight section housing the collimation system (DS). Beam losses of more than 650 kW were induced using the LHC transverse damper at a beam energy of 6.8 TeV, without magnet quench. By retracing the secondary LHC collimators, the amount of collimation debris scattered into the DS magnets was increased by roughly 50 %, also without magnet quench.

Contents

1 Introduction

1.1 Context of the experiment

The CERN Large Hadron Collider (LHC) relies on 1248 superconducting dipole magnets that provide bending to the rigid LHC beams. If high-energy protons hit the magnet coils, they can deposit enough thermal energy to disrupt the superconductivity and quench the magnet. In situations of high beam losses on the LHC collimators, even the tiny fraction of protons scattered out of the collimation system and lost in the superconducting dipoles in the dispersion suppressor (DS) (on the order of 10^{-4} of the protons lost in collimators) could be enough to induce a quench.

In view of the luminosity upgrade, (HL-LHC) [1], the increased beam intensities and the expected beam loss rates will increase the risk of beam-induced quenches from collimation losses. The LHC and HL-LHC collimation system is specified to be able to sustain beam lifetimes of 12 min over 10 s without interruption of operation [2]. This corresponds to a primary beam loss of 946 kW with HL-LHC intensities. If collimation losses generated at this primary beam loss rate would induce magnet quenches, the only way to be compatible with the aforementioned minimum beam lifetime would be a reduction of the stored beam intensity or a collimation hardware upgrade. Without the latter, an undesired loss of achievable luminosity would be inevitable.

An initially envisaged HL-LHC hardware upgrade aimed at mitigating the DS magnet quench risk induced by collimation debris, using local collimators in the IR7 DS (TCLD). To free up space for these collimators, the concept envisaged the installation of stronger (11 T) dipoles. This upgrade, described in detail in the context of the collimation system in [3], was postponed and future installation is uncertain.

With the information available before the 2022 collimation quench test, there was a non-negligible uncertainty about whether the achievable HL-LHC proton beam intensities might be limited due to the quench risk. As will become clear throughout this paper, the results of the collimation quench test carried out in 2022 reduced this uncertainty.

Insofar as the motivation for the test is concerned, we will continue this introduction with a quantitative overview of quench tests and quench limit estimates. In the following chapter, we give an overview of the initially envisaged MD plan and preparation work carried out for the MD. This is followed by an overview of the MD procedure. Then, we will describe the main observations made during the test and calculate the figures of merit: achieved primary beam loss rate and the power deposition achieved in the IR7 DS magnets. We close the report by drawing conclusions, describing residual uncertainties, and an giving outlook for possible future tests.

1.2 Quench limit and power deposition estimates

The most recent estimate for the quench limit of the LHC main dipole magnets is $20\,\mathrm{mW/cm^3}$ to $30\,\mathrm{mW/cm^3}$ [4] of deposited power per volume of the magnet coils. It applies for magnets powered to 7 TeV with losses of around 1 s in duration. The expected peak power deposition in the HL-LHC DS dipoles without the TCLD collimator in IR7 is on the order of $15\,\mathrm{mW/cm^3}$ (from FLUKA simulations [5] of protons at 7 TeV, assuming 946 kW primary beam loss). Both figures are derived using simulations that replicate complex dynamics and have uncertainties that cannot be reliably estimated.

The experimental assessment of the collimation cleaning performance and quench limit under operating conditions can provide the most solid indication of the attainability of the HL-LHC target intensities. In practice, this requires one to generate high losses of beam particles inside the superconducting LHC main dipoles. Different techniques could, in principle, be used to create the required beam losses, but in the context of proton collimation, the best representativeness of the test is reached if we artificially generate the loss scenario against which protection should be provided. In our case, this scenario is the specification of a beam lifetime of 12 min over 10 s, corresponding to 946 kW primary beam loss at 7 TeV.

1.3 Previous LHC quench tests

LHC quench tests have been considered important from the beginning of operation and have been carried out since 2011. An overview of the quench tests performed at the LHC is given in Table 1.

Table 1: Overview of quench tests carried out in the LHC.

Year	**Species**	**Energy [Z TeV]**	**Test type**	**Power [kW]**	**Quench**	**Ref.**
2011	Protons	3.5	Collimation	510	No	[6]
2013	Protons	4.0	Collimation	1050	No	[7]
2015	Protons	6.5	Collimation	585	No	[8]
2015	Pb ions	6.37	Collimation	13.7	Yes	[9]
2015	Pb ions	6.37	BFPP	-	Yes	[10]
2022	Protons	6.8	Collimation	666 ± 37	No	
2023	Pb ions	6.8	BFPP	-	Yes	

It should be noted that quenches have only been reached in three quench tests. All were carried out with heavy-ion beams, one using collimation debris and two using collision debris from an electromagnetic process called bound-free-pair production [11], BFPP. The properties of collimation debris generated from proton beams differ from those of heavy-ion beams. This difference leads to an increase of the local DS collimation inefficiency (energy lost in the magnet aperture w.r.t. the energy lost in the collimators) for heavy-ion beams by roughly two orders of magnitude. Therefore, quenches from collimation debris can be induced with heavy-ion beams using much lower primary beam loss rates. This was confirmed by past experience, when attempting to quench the DS dipole magnets with collimation debris from proton beams never resulted in a quench.

The quench limit (quantified in terms of the energy deposited per volume of the magnet coil and time, $\mathrm{mW/cm^3}$) decreases with increasing magnet current. Therefore, the chances of achieving a magnet quench with proton collimation debris were unprecedented, considering the highest-ever particle energy of 6.8 TeV achieved in 2022.

1.4 Conventions and Definitions

In order to allow for easier reading of the remainder of this note, we provide in this section the most relevant definitions and conventions that are used throughout the document.

Beam Size and Parameters

We define a transverse beam σ with respect to the nominal transverse RMS normalised emittance of 3.5 µm rad used by convention in the LHC and used to define the collimator settings. The measurements presented in this note were carried out with proton beams at 6.8 TeV beam energy, corresponding to Lorentz factor of $\gamma_{\mathrm{top}} = 7247.4$.

Dates and times

All dates and times mentioned in this document refer to local time in Geneva, CH.

2 Experimental design and procedure

The aim of the experiment is the generation of high beam losses on the LHC collimators in a controlled way, to probe whether or not the superconducting DS dipole magnets would suffer a quench. In the preparation of the MD, it was necessary to create the conditions to allow for the required high beam loss and achieve a peak power deposition in the DS magnet coils, which would be useful in evaluating the quench risk in HL-LHC. At the same time, machine safety must not be compromised. We outline in the following the motivation behind the choice of boundaries and beam parameters used in the experiment.

2.1 Choice of beam and instrumentation settings

Beam energy and optics

Considering that the situation with the highest quench risk in HL-LHC is at 7 TeV, the decision to carry out the experiment at the maximum reachable energy in 2022, 6.8 TeV, is obvious. Cleaning inefficiency in the DS region is, in principle, independent of the optics in the experimental insertion regions. To minimise the time needed for the experiment, the first point in the 2022 LHC cycle at the highest energy was chosen. It is the *flat top* configuration at the end of the energy ramp, with $\beta^* = 1.33\,\mathrm{m}$ in IP1 and IP5.

Beam and plane

It is known that the DS downstream of the betatron collimation insertion is the limiting location in terms of the quench risk. The specification of the LHC and HL-LHC collimation system refers to beam losses in the transverse plane. In principle, the choice of beam and plane in which the test is carried out is arbitrary. LHC Beam 2 (rotating counter-clockwise) was chosen to be aligned with previous quench tests. The same applies to the choice of horizontal plane. The initial reasoning behind these choices was that higher losses in the DS were observed compared to the vertical plane.

Beam loss time profile

The target beam loss that was envisaged for the experiment was a primary beam loss of 1 MW over 10 s. This is roughly equivalent to the design specification of the HL-LHC collimation system. The loss rate was envisaged to be increased slowly over roughly 15 s, to reduce the risk of triggering a dump on the interlocks for the short BLM integration times. Controlling the loss rate is done by applying white noise kicks to the beam particles using the transverse damper (ADT) [12].

Collimator settings

To achieve the losses needed for the quench test, beam intensities higher than the *setup beam* threshold of 3×10^{11} charges are needed. Therefore, machine protection constraints had to be considered when deciding which collimator settings to use in the quench test. An obvious choice for safe collimator settings is the validated nominal settings used during the 2022 operation with high-intensity proton beams.

Nominal Settings: Preparatory simulations with SixTrack [13] and FLUKA [14] have shown that with nominal collimator settings and a primary beam loss rate of 946 kW, a peak power deposition (PPD) in the DS coils (expected in the main dipole MB.A9L7) of roughly 14 mW/cm^3 is expected (see Fig. 2). With the expected PPD of 15 mW/cm^3 in HL-LHC being at 7 TeV [5], observing a quench with the nominal collimator settings would provide a strong indication that collimation upgrades would be necessary to tolerate the design specification loss scenario in HL-LHC.

Relaxed Settings: Simulations with SixTrack indicated that the collimation cleaning inefficiency in the IR7 DS can increase by 50% by opening the secondary collimators in IR7 by 2σ. Subsequent FLUKA simulations have indicated that the corresponding DS coil PPD increases by 70% with the use of relaxed settings, reaching 24 mW/cm^3 (see Fig. 2) at a primary beam loss rate of 946 kW. This is approximately 60% higher than the PPD expected in HL-LHC at 7 TeV. Therefore, not observing a quench with the target loss rate when applying relaxed collimator settings would deliver a strong indication that uninterrupted HL-LHC operation is not jeopardized by the risk of quench without the TCLD upgrade.

To validate the relaxed collimator settings before the MD, a B2H betatron loss map was measured parasitically during a crystal collimation study (time stamp 2022-08-11 17:26:25). Compared to the loss map recorded with nominal settings (2022-06-29 01:35:53), an increase in local cleaning inefficiency was observed in the IR7 DS from 0.98×10^{-4} with nominal settings to 1.5×10^{-4} with relaxed settings, in line with the SixTrack simulation. With the changes being limited to the secondary collimators in IR7, and considering that they were at larger than nominal settings, a dedicated asynchronous dump measurement was considered unnecessary. Furthermore, from aperture measurements, it was known that an aperture of more than 23σ is available for B2H at flat top.

Loss maps measured for B2H at flat top, both with nominal and relaxed collimator settings, are shown in Fig. 1. A complete overview of the nominal and relaxed settings used in MD is given in Table 2.

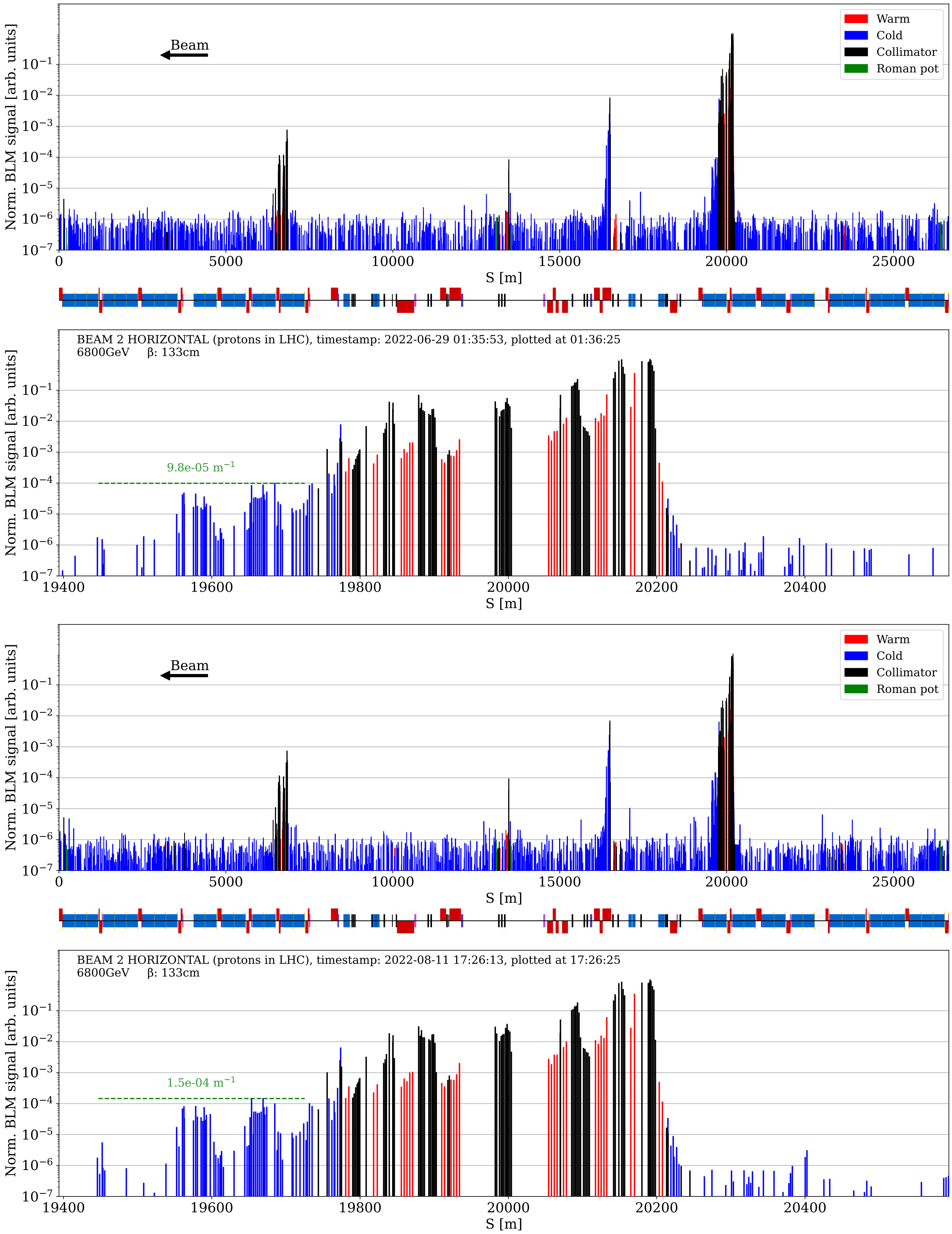


Figure 1: B2H qualification loss maps measured at flat top with nominal collimator settings (first two rows) and relaxed collimator settings (last two rows).

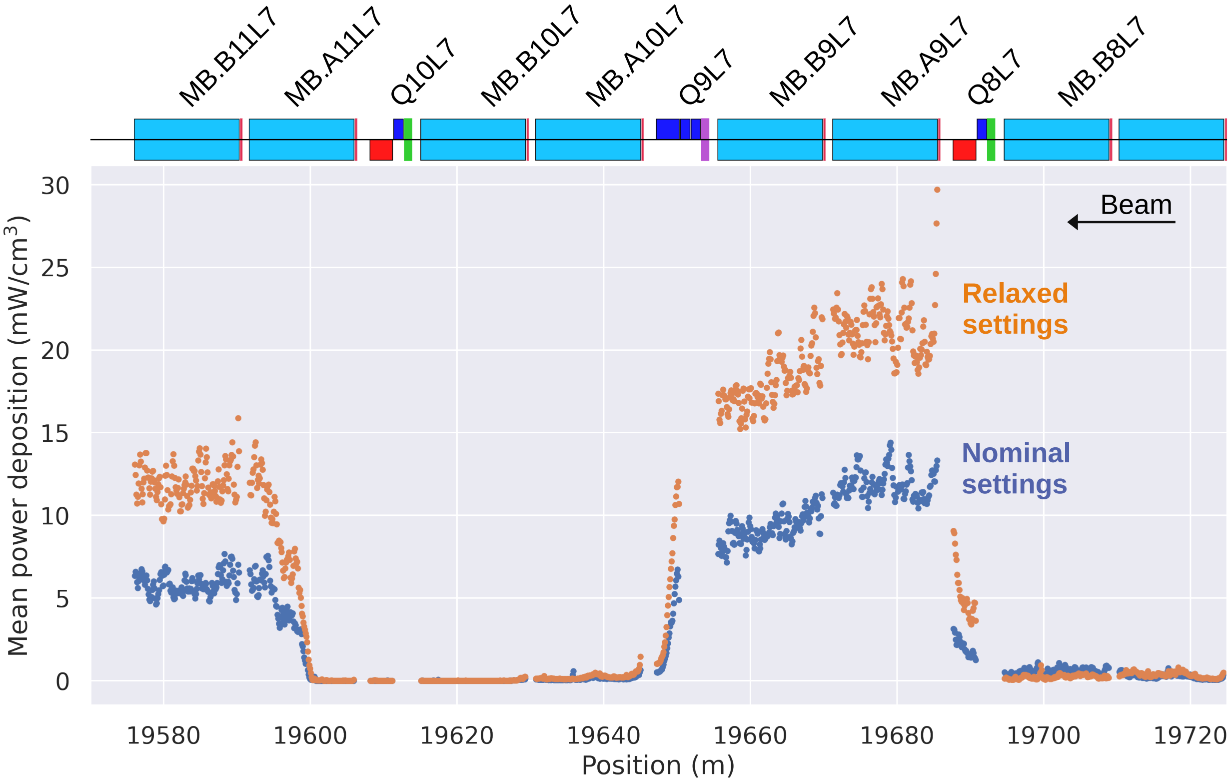


Figure 2: FLUKA simulation of the power deposition from collimation losses in the B2H plane, in the DS downstream of the betatron collimation region with nominal collimator settings (blue) and relaxed settings (orange). The assumed beam loss rate in the primary collimators is 946 kW. The dipole with the highest power deposition is MB.A9L7 in both cases. This is the same magnet that was quenched in the heavy-ion quench test carried out in 2015.

Table 2: Nominal and relaxed collimator settings used in the quench test. Injection protection (TCLI, TDI) and physics debris collimators (TCL, TCLD in IR2) were in parking positions. We marked the secondary collimators in IR7 in bold; they are the only collimators for which nominal and relaxed settings are not identical.

Family	**Region**	**Nominal** $[\sigma]$	**Relaxed** $[\sigma]$
TCP	IR7	5	5
TCSG/TCSPM	**IR7**	**6.5**	**8.5**
TCLA	IR7	10	10
TCP	IR3	15	15
TCSG	IR3	18	18
TCLA	IR3	20	20
TCDQ	IR6	7.3	7.3
TCSP	IR6	7.3	7.3
TCT	IR2	37	37
TCT	IR1/IR5/IR8	18	18

Target dipole

Following the simulation results of the power deposition shown in Fig. 2, the magnet with the highest quench risk is the superconducting dipole magnet MB.A9L7. It is the same dipole that was quenched during the heavy-ion collimation quench test in 2015 [9]. Note that the highest losses would occur at the front face of the dipole with relaxed settings. Although this first loss peak, reaching levels of $30\,\mathrm{mW\,cm^{-3}}$, was not considered when the PPD was calculated, in case a quench had been achieved, it would have been difficult to reconstruct from where the quench originated and how representative the intensity limit derived from the test would be for HL-LHC. However, changing collimator settings to modify the longitudinal pattern of power deposition is not a straightforward task. Among numerous settings studied in simulations, the relaxed settings discussed before were considered the most suitable for the test. In this context we highlight that the PPD of $24\,\mathrm{mW\,cm^{-3}}$ discussed previously, refers to the peak power deposition expected along the magnet length, not at the front face. Therefore, not observing a quench with the relaxed collimator settings would still deliver tangible information on the achievable HL-LHC intensities.

Filling scheme

The experience gained in previous collimation quench tests showed that the loss rates required for such tests are difficult to achieve. BLM thresholds must be relaxed to allow for the high beam loss rates aimed at the MD. If the circulating beam is lost, the turnover time to have a new beam at flat top ready for a quench attempt is approximately two hours. In the past, quench tests have been performed with several individual bunches plus some bunch trains that would allow for one single quench attempt. In the event of low injector availability, this can lead to significant delays that jeopardize the success of the test.

To improve the efficiency of this MD, we designed a filling pattern that would accommodate enough beam intensity so that two quench attempts could be performed per fill. This choice was considered unproblematic in terms of machine safety. The approach turned out to be crucial to the success of the test. In the estimation of the required beam intensity per quench attempt, the following three components, derived from the intended loss-time profile were crucial:

1. Increase of loss rate from 0 MW to 1 MW over 15 s: To have enough intensity to ramp the losses from 0 MW to 1 MW over 15 s, a total of 7.5 MJ of stored beam energy must be available.

2. Constant loss rate of 1 MW over 10 s: Maintaining losses at the aimed high level of 1 MW requires a stored beam energy of 10 MJ.

3. Margin: The endeavour of controlling beam loss is highly challenging, and the response of beam loss to a change in ADT blowup gain is non-linear. If deviations from the ideal beam loss time profile occur, there must be enough beam intensity to compensate for it. We estimate a few MJ as sufficient to provide this buffer. Another factor that leads us to require some margin is the fact that roughly 2×10^{10} charges per bunch have to be left intact so that the interlocked BPMs can still measure the position of the bunch. Otherwise, a dump would be triggered, which would obstruct our approach of carrying out two quench attempts. Considering the nominal bunch intensity of 1.4×10^{11} charges, this means that only 86 % of the intensity can be used for the quench attempt.

We decided to employ five trains of 36 bunches per train with an intensity of 1.4×10^{11} protons per bunch for each quench attempt, corresponding to a stored beam energy of approximately 27.5 MJ, which was deemed sufficient considering the requirements mentioned above.

A dedicated filling scheme `Quench_test_2022` was prepared for the MD, illustrated in Figs. 3 and 12 (in the Appendix), providing:

(a) *One train of 12 bunches* to provide a reference trajectory for the injection of the next bunch trains.

(b) *Three nominal bunches* to test the ADT excitation gain time profile.

(c) *Two batches of 180 bunches (*5×36 *bunches)* for two quench attempts per fill. The distance between the two batches was maximised to avoid crosstalk when excited by one batch using the ADT (avoid interaction with the ADT residual field).

(d) *Three trains of 36 bunches* for testing the ADT excitation gain time profile. Initially, it was foreseen that individual nominal bunches would be injected into these slots. During the MD, it was observed that the emittance (measured with the beam synchrotron radiation telescope, BSRT) of individual bunches was different from that of the bunches in a train. To probe the ADT time profile with bunches as representative as possible of the batches used for the quench attempt, three single trains of 36 bunches would be injected, instead of individual bunches. This change of plan was agreed upon with the machine protection team.

For Beam 1 only (a) was injected, to keep the time required for injection to a minimum.

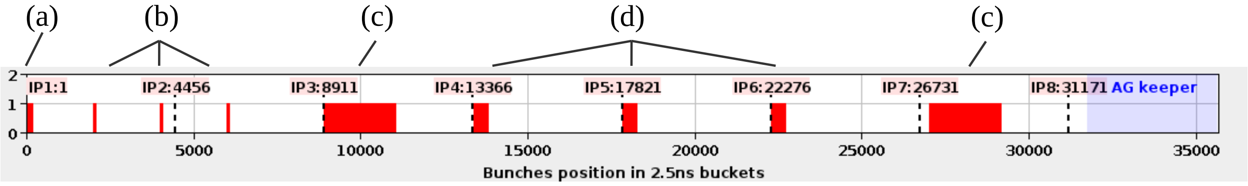


Figure 3: Beam 2 filling scheme used in the MD.

BLM thresholds

The BLM threshold strategy for IR7 in regular operation allows for a primary beam power load of 200 kW for 20 s (RS11) and a beam power load of 40 kW for a maximum of 80 s (RS12) [15]. To account for the required loss rate of 1 MW, the BLM thresholds needed to be increased. Based on the BLM signals measured during the qualification loss maps with nominal and relaxed settings, discussed earlier in this chapter, updated BLM thresholds were derived. More concretely, scaling factors were derived for different families of BLMs and running sums, including different safety margins to account for uncertainties in the estimation of the scaling factor. The threshold changes concern, most notably, IR7 and downstream regions, but also IR6. Details are given in the dedicated ECR [15].

2.2 Operational aspects

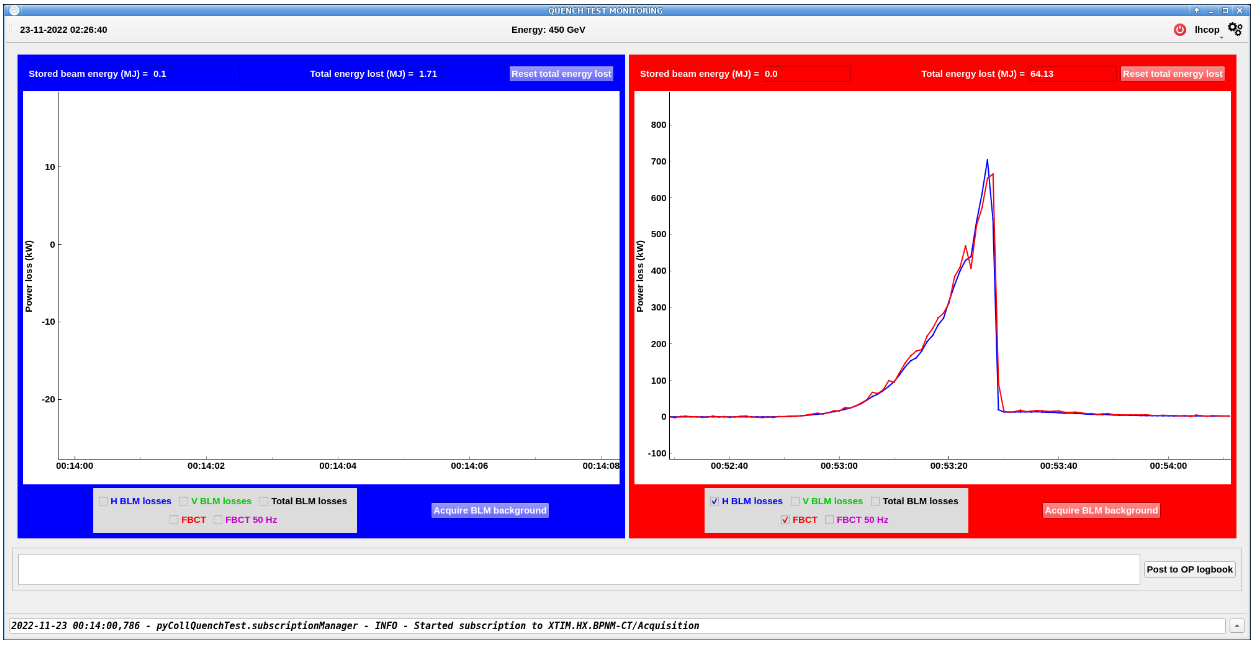
Transverse damper

The required settings of the transverse damper, particularly the time profile of the excitation gain, are difficult to prepare. For this MD, we attempted to simulate the beam loss rate in particle tracking simulations to estimate the required gain-time profile. However, the excitation gain-time profiles derived with this approach did not turn out to reproduce the loss-time profile expected from the simulations. Tangible information on this matter is not available without further studies. Our current hypothesis considers the lack of knowledge of the transverse beam shape (Gaussian vs. non-Gaussian distribution), as well as assumptions on transverse emittance, as the main drivers for the observed discrepancies.

Nevertheless, expert software was already available before the test, to tailor the excitation gain time profile to our needs in the CCC.

Live loss monitoring (OP)

A dedicated software application was prepared for the quench test (D. Mirarchi), which allowed us to monitor the rate of beam loss as a function of time. The figure is calculated on the basis of either the BCT signals or the calibrated BLM signal. It turned out to be crucial for the success of the experiment because it allowed the ADT excitation gain function to be tailored based on the loss rates observed with test bunches. A screenshot of the application showing the usage in the MD is shown in Fig. 4.



23-11-2022 02:26:40

Energy: 450 GeV

Stored beam energy (MJ) = 0.1

Total energy lost (MJ) = 1.71

Stored beam energy (MJ) = 0.0

Total energy lost (MJ) = 64.13

```
2022-11-23 00:14:00,786 - pyCollQuenchTest.subscriptionManager - INFO - Started subscription to XTIM.HX.BPNM-CT/Acquisition
```

Figure 4: Beam loss monitoring application developed for the quench test. On the right-hand side, the primary power loss is shown at the second quench attempt.

Beam process for relaxed settings

In the preparation of the MD, a dedicated beam process was prepared to open the limits and drive the secondary collimators in IR7 to relaxed settings. The name of the beam process is `RAMP-SQUEEZE-6.8TeV-ATS-1.3m_V1@1275_[END]_QuenchTest`. Note that only the secondary IR7 collimators for B2 are changed, and B1 is unaffected.

A screenshot showing the configuration of the beam process in LSA is shown in Fig. 5.

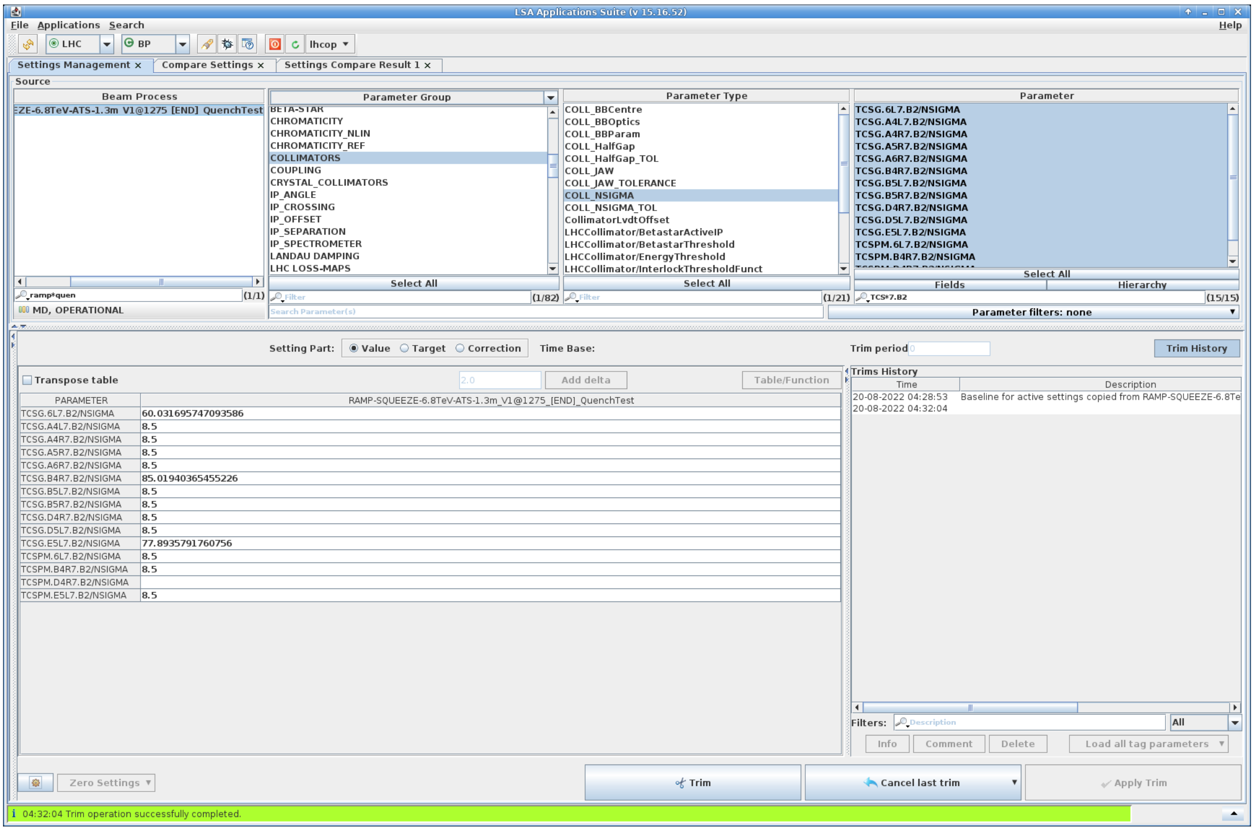
3 Execution of the experiment

In this section, we summarise the execution of the experiment, starting with a brief chronological overview, and then concluding with some general remarks and describing some observations made with individual subsystems.

3.1 Chronology

The MD started on 22.11.2022 at 20:00 h after the previous MD on the 2023 optics was completed. The MD ended around 7:00 the next morning when the changes to the BLM settings were reverted. An overview of the quench test is shown in terms of beam intensity and energy in Fig. 6. We started the experiment preparation by adjusting the BLM thresholds, a process that took less than an hour. In preparation of ADT excitation, the gain for the ADT feedback was reduced from 0.04 to 0.02, making excitation more efficient.

Once these changes were applied, we started injecting some nominal bunches to test the ADT at injection energy. These tests demonstrated that the time profile of beam loss could



Beam Process: ZE-6.8TeV-ATS-1.3m_V1@1275_[END]_QuenchTest

ramp*quen (1/1)

MD, OPERATIONAL

(1/82)

(1/21)

TCS*7.B2 (15/15)

Setting Part: ● Value ○ Target ○ Correction

Time Base:

Trim period 0

☐ Transpose table

2.0

PARAMETER	RAMP-SQUEEZE-6.8TeV-ATS-1.3m_V1@1275_[END]_QuenchTest
TCSG.6L7.B2/NSIGMA	60.031695747093586
TCSG.A4L7.B2/NSIGMA	8.5
TCSG.A4R7.B2/NSIGMA	8.5
TCSG.A5R7.B2/NSIGMA	8.5
TCSG.A6R7.B2/NSIGMA	8.5
TCSG.B4R7.B2/NSIGMA	85.01940365455226
TCSG.B5L7.B2/NSIGMA	8.5
TCSG.B5R7.B2/NSIGMA	8.5
TCSG.D4R7.B2/NSIGMA	8.5
TCSG.D5L7.B2/NSIGMA	8.5
TCSG.E5L7.B2/NSIGMA	77.8935791760756
TCSPM.6L7.B2/NSIGMA	8.5
TCSPM.B4R7.B2/NSIGMA	8.5
TCSPM.D4R7.B2/NSIGMA	
TCSPM.E5L7.B2/NSIGMA	8.5

Trims History

Time	Description
20-08-2022 04:28:53	Baseline for active settings copied from RAMP-SQUEEZE-6.8Te
20-08-2022 04:32:04	

Filters: Description All

04:32:04 Trim operation successfully completed.

Figure 5: Screenshot from LSA with the beam process to drive the secondary IR7 collimators to relaxed settings in the MD.

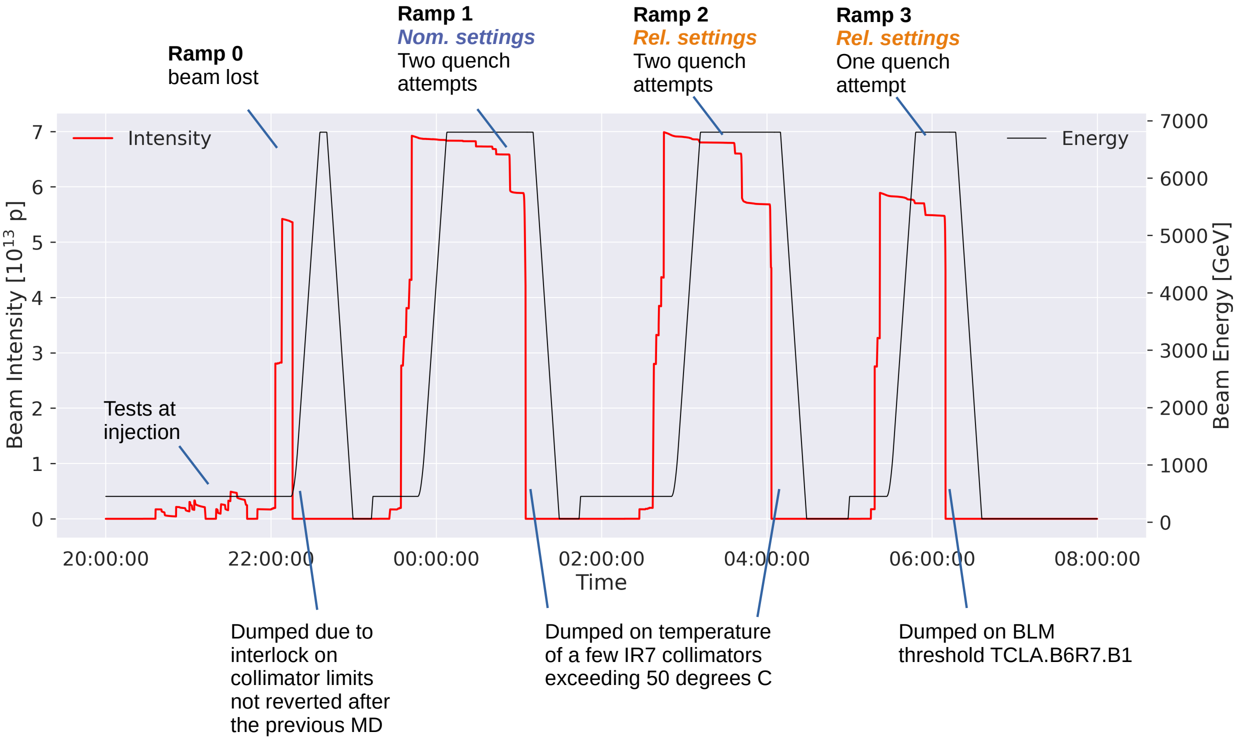


Figure 6: Overview of the quench test: beam intensity (red) and beam energy (black).

be controlled very efficiently by applying a time-dependent excitation gain factor. Although not representative of the excitation at top energy, the experience gained in these tests turned out to be useful in the quench attempts at top energy, in which an excellent control of the loss rate evolution was achieved.

After completion of these tests, we proceeded to inject the beam for the first ramp using the filling scheme discussed above. During this ramp, the beam was dumped by the interlock system because the energy limits of the TCT jaw positions were not reset to the nominal settings after the previous MD. In Fig. 6, this ramp is denominated *Ramp 0*.

To alleviate the problem, the beam process for the combined ramp and squeeze was reverted to the nominal 2022 configuration, so that from now on the correct nominal energy limits would be applied. After completing the ramp-down, the next beam was injected following the exact same procedure as before. This ramp was successful and the top energy was reached shortly before midnight. We denominate this ramp as *Ramp 1*. The nominal collimator settings were maintained. We tested the excitation gain of the ADT with nominal bunches and a train of 36 bunches, reaching loss levels of 200 kW.

In the following, we describe all quench attempts. An overview of the achieved primary beam loss rates is given in Fig. 10 with a discussion of the analysis method given in the next section.

Quench Attempt 1 (QA1)

In the first quench attempt, the losses increased more slowly than anticipated. However, with increasing losses, we observed that we approached the BLM thresholds of unmaskable

BLMs in IR7, especially for the short integration times. We stopped excitation in order to avoid a beam dump when we reached 91 % of the BLM threshold (for integration time 40 µs at the TCLA.B6R7.B1). The quench-test application showed a power load of approximately 700 kW at the end of the excitation. No quenching occurred. Thanks to having stopped the excitation early enough, we had the second batch at our disposal, allowing us to attempt a second excitation.

Quench Attempt 2 (QA2)

For the second quench attempt, we tried to circumvent the problem encountered in the first attempt by increasing the beam loss at a slower rate than before, to keep the BLM signal for shorter integration times under control. With this attempt, the temperature interlock at several collimators triggered a beam dump. The latter is set to 50 °C. The temperature evolution at the B2 skew primary collimator in IR7, just downstream of the horizontal primary collimator, is shown in Fig. 7. The temperature increase during the two quench attempts is clearly visible. From the quench-test application, we could conclude that the dump was initiated at a loss rate of approximately 500 kW. No quenching occurred.

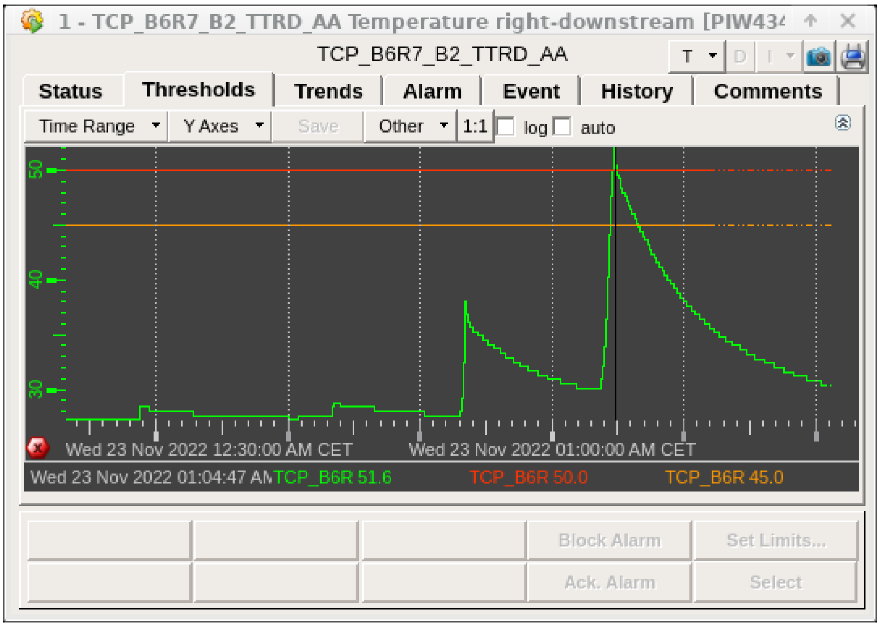


Figure 7: Temperature reading of TCP.B6R7.B2 during the first fill. The red horizontal line shows the dump threshold.

This experience already indicated that the target loss rate would be difficult to reach: If the beam loss increase were slow enough to not trigger a beam dump based on the short BLM running sums, a dump would be triggered because the time needed to increase the loss rate to the target level would lead to a collimator heating. The same is true vice versa. We reiterate that the fact that the loss rate increase could be controlled in such a precise way underscores the excellent control of the ADT.

During the preparation of the next ramp, we follow up on the machine protection checklist to apply the relaxed collimator gaps. It is shown for reference in the Appendix. It was concluded that all items to check were satisfactory so that we could proceed with the relaxed collimator settings for the next quench attempts.

Quench Attempt 3 and 4 (QA3 and QA4)

After the second ramp (*Ramp 2*), we reached top energy at 03:11h. We proceeded to run the beam process to open the energy limits and the gap of the secondary collimators for B2. At roughly 3:22h we completed the check of the collimator gaps and confirmed that they were correctly driven to the target settings.

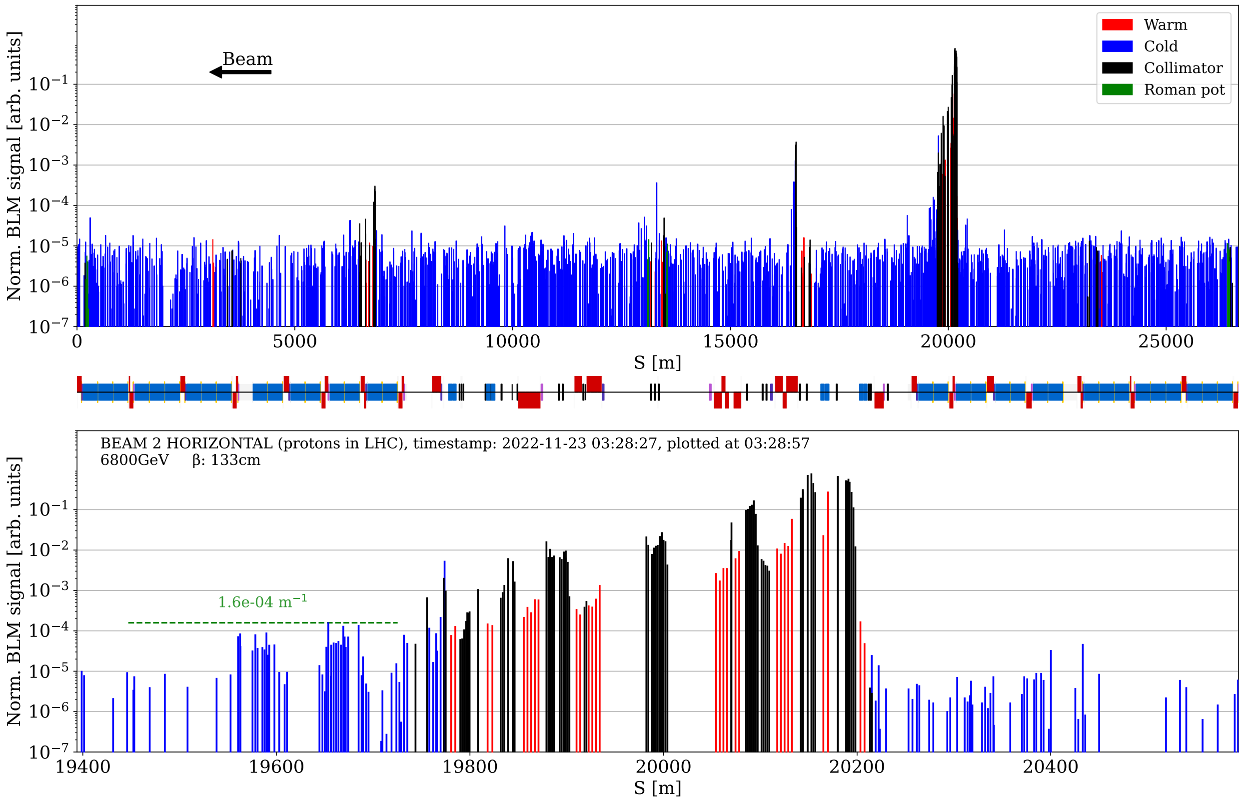


Figure 8: B2H loss map measured during the quench test with relaxed collimator settings, under conditions similar to the loss map measurements used for qualification.

A reference loss map was measured (03:28:47) and is shown in Fig. 8. The cleaning inefficiency measured in this loss map reached roughly $1.6 \times 10^{-4}\,\mathrm{m}^{-1}$, slightly higher than the cleaning inefficiency measured in the preparation of the test. This finding confirmed that the cleaning performance is indeed reduced by roughly 60 %, and the order of magnitude of collimation cleaning degradation that we aimed for was reached. This loss map also served as confirmation that no unusual loss patterns and/or loss locations were visible before attempting to induce very high loss rates. No potential problems were identified for machine safety when evaluating the loss map. We proceeded to prepare the first quench attempt in this fill.

After testing the ADT excitation gain time profile on a single train of 36 bunches, reaching approximately 100 kW, we attempted the first excitation of 180 bunches. This quench attempt (03:41:00h) resulted in a primary beam loss of roughly 500 kW to 600 kW without quenching. In a second attempt (04:02:00), roughly 500 kW was reached, and then the loss rate decreased to levels of 200 kW, when the beam was dumped by the collimator temperature interlock. Also here, a quench was not observed.

Quench Attempt 5

The last fill was prepared with the primary goal of reaching higher loss rates than with the last two quench attempts. Injection and ramp were performed without incident and once at flat top, we opened the secondary collimators to attempt a last excitation with the relaxed collimator settings. The experience of the previous four quench attempts made us aware of the tight constraints imposed by the temperature and BLM interlocks, making it very difficult to reach the target loss rate without triggering a beam dump. It should be noted that some limiting BLMs were unmaskable and the threshold was set to the electronic limit, so further relaxation of the threshold was not possible.

We decided to move forward with a last quench attempt without manually interrupting the ADT excitation if BLM thresholds or temperature interlock thresholds were approached. In this approach, we saw the best chances of reaching the highest possible loss rate, even though triggering a beam dump would be inevitable. After testing the excitation scheme with a train of 36 bunches, we proceeded to the last quench attempt of the MD at 06:08:50h. The approach turned out to be effective: According to the quench test monitoring tool, we reached a beam loss rate of roughly 650 kW to 700 kW with relaxed collimator settings.

After the MD

The MD was completed by reverting the BLM thresholds to the nominal ones. On the collimator side, no changes were needed.

3.2 General remarks and observations

Efficiency: The MD benefited from a very good availability of the LHC and its injectors, leading to a low turnover time. All subsystems were very well prepared, so the implementation of settings and hardware performance in the MD were flawless. Only one unnecessary dump was triggered as a residual of settings from a previous MD - the time lost could be compensated without any issues.

Constraints: As discussed above, the target loss rate could not be achieved due to constraining interlocks. Possible implications for achievable HL-LHC beam lifetimes should be evaluated and considered in the future.

BLM signals with high beam loss rates: The measured BLM signal at the end of QA5 is shown in Fig. 9. It is clearly visible that the noise level of the signals measured in the left and right arc regions of IR7 dropped drastically (see also the bottom right of Fig. 9). The reason for this behaviour is the powering scheme of the BLMs. Preliminary analyses have shown that the ratios of signals measured at different BLMs changed throughout excitation. For example, the location at which the highest BLM signal is measured changes throughout the excitation from TCSM.A6R7.B2 to TCHSV.6R7.B2. This is shown in the bottom left plot of Fig. 9. It is currently unclear whether this behaviour is a physical effect or an artefact

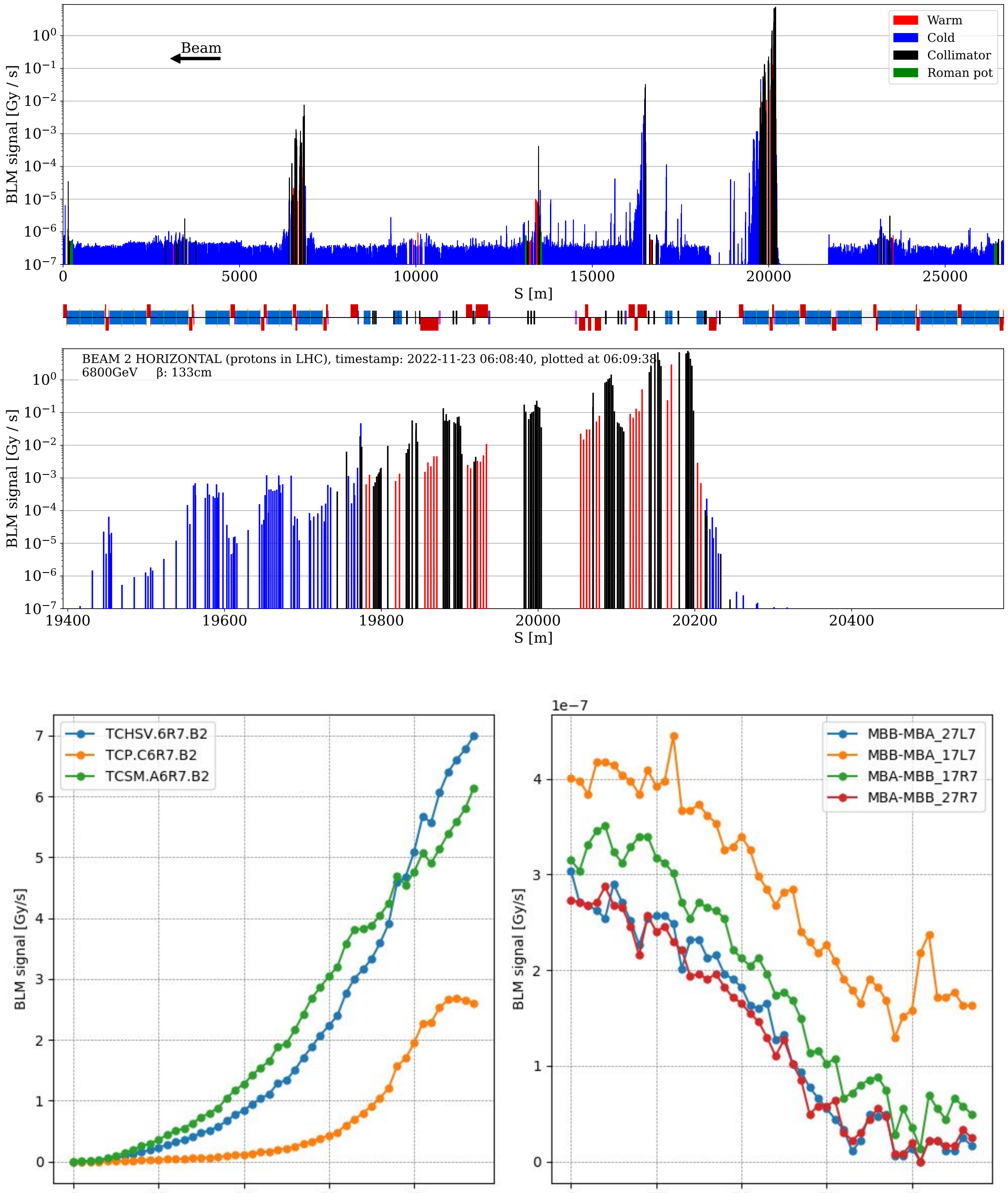


Figure 9: Top: Measured BLM signal (absolute) during the fifth quench attempt, one second before the beam dump. The data show RS09. Bottom left: BLM signals in IR7 during the last quench attempt. Blue and green curves show the highest recorded BLM signals: it is clearly visible that the location with the highest BLM signal changes during excitation (after roughly 30 s to 40 s). Bottom right: BLM signals recorded in the left and right arc regions of IR7 (regions with low loss levels). All signals drop throughout the excitation, and after 30 s to 40 s, some stay constant at very low levels. Currently, it is not clear whether there is a link that causes the timely coincidence between these observations.

of the voltage drain suffered by the BLM system in this high-loss regime. More studies will be necessary.

4 Analysis

In this section, we analyse the loss rate achieved in the MD and derive estimates for the PPD reached in the DS magnet coils.

4.1 BCT Based Power Load and PPD Estimate

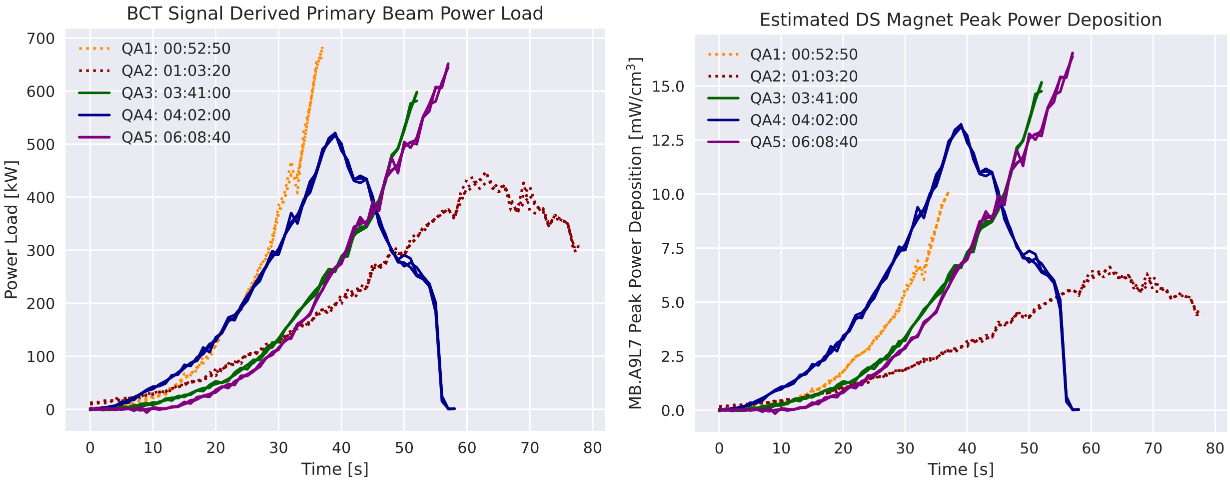


Figure 10: Left: Primary power load for all quench attempts (QA) derived from the BCT signal. The legend shows the time considered as starting time of each excitation (losses increase slowly at the beginning, which is why we used some discretion in assigning the starting point). Solid lines show quench attempts with relaxed collimator settings, and dotted lines show quench attempts with nominal collimator settings. All different recorded BCT signals are shown in the same colour and line style. Right: PPD estimated based on a scaling of the BCT signal derived primary power load, by applying a scaling of the FLUKA simulation result. Line styles carry the same information as in the plot on the left-hand side.

The first approach to estimating the primary power load reached on the basis of the logged data is based on using the BCT signals. For each attempt to quench, we load the BCT signals (BCTDC and BCTFR[1]) from the CERN Accelerator Logging System (NXCALS), which provides the total beam intensity as a function of time. Using the intensity data, we calculate the change in intensity from second to second. Using the known energy per unit charge and the elementary charge, we calculated the energy in Joule lost per second, corresponding to the primary power load in W. The result is shown for all quench attempts in Fig. 10. If the beam were dumped, we would show all data points up to the last second. If we stopped the excitation manually (QA1 and QA3) we show all data points up until the

---

[1] Timber variables: `LHC.BCTFR.A6R4.B2:BEAM_INTENSITY`, `LHC.BCTDC.A6R4.B2:BEAM_INTENSITY`, `LHC.BCTDC.B6R4.B2:BEAM_INTENSITY`, `LHC.BCTFR.B6R4.B2:BEAM_INTENSITY`

loss rate dropped to zero. It is clearly visible how the time profile was changed between the different quench attempts. Note that the second and fourth quench attempts (QA2 and QA4) ended with a dump triggered by the collimator temperature interlocks. It is clearly visible that for these attempts, high loss levels of several hundreds of kW were maintained after the maximum loss level (roughly 420 kW for QA2 and 500 kW for QA4) was reached. Those quench attempts that were not dumped (QA1 and QA3) or dumped by the BLM interlock (QA5) show a continuous increase in beam losses.

4.1.1 Nominal settings

The highest loss rates with **nominal settings** were reached in the first quench attempt. Using the midpoint of the different BCT signals recorded and considering the range maximum and minimum power estimate from the different signals as uncertainty, we obtain the maximum power load reached with nominal settings.

$$P_{\max}^{nom} = (674 \pm 10)\,\mathrm{kW}\,. \tag{1}$$

Using the result of the FLUKA power deposition simulation, showing that at a primary power load of 946 kW, the PPD in the DS magnet coils is roughly 14 mW/cm^3, we can apply a simple scaling to obtain an estimate of the PPD reached in QA1:

$$PPD_{\max}^{\mathrm{nom}} = \frac{(674 \pm 10)\,\mathrm{kW}}{946\,\mathrm{kW}} \times 14\,\mathrm{mW/cm^3} = (10.0 \pm 0.1)\,\mathrm{mW/cm^3}\,. \tag{2}$$

Note that in reality, the uncertainty is greater than what is shown here: The uncertainty in deriving the figure for the PPD from the simulation is unknown.

4.1.2 Relaxed settings

Following the same approach, we obtain the following maximum primary power load in QA5:

$$P_{\max}^{\mathrm{rel}} = (648 \pm 4)\,\mathrm{kW}\,. \tag{3}$$

Using the FLUKA simulation result for the PPD (24 mW/cm^3 for 946 kW primary beam loss) we obtain the following PPD estimate for QA5:

$$PPD_{\max}^{\mathrm{rel}} = \frac{(648 \pm 4)\,\mathrm{kW}}{946\,\mathrm{kW}} \times 24\,\mathrm{mW/cm^3} = (16.4 \pm 0.1)\,\mathrm{mW/cm^3}\,. \tag{4}$$

An important conclusion can be drawn from this figure: considering the fact that no quench was observed during QA5, we can rescale the PPD to the one simulated for the nominal collimator settings and conclude that (at a beam energy of 6.8 TeV), a beam loss of more than 1 MW can be tolerated without quenching ($946\,\mathrm{kW} \times \frac{16.4\,\mathrm{mW/cm^3}}{14\,\mathrm{mW/cm^3}} \approx 1100\,\mathrm{kW}$). To draw conclusions on the risk of quench for HL-LHC, it should be considered that the quench limit at 7 TeV is lower than at 6.8 TeV.

The evolution of the estimated PPD with nominal and relaxed settings for all quench attempts is shown on the right-hand side of Fig. 10.

4.2 BLM Based Power Load and PPD Estimate

The uncertainty estimate derived from the different BCT signals is narrow. To gain a better understanding of the uncertainty we face in the estimate of the primary power load, we study an alternative approach: deriving the primary power load based on the highest BLM signal in the IR7 DS.

It is clear that the ultimate goal of the MD is inducing losses in the IR7 DS. Assuming that the fraction of leakage from the collimation system into the DS remains constant throughout the excitation, there must be a correlation between the primary power load on the TCP and the BLM signal in the IR7 DS. In this section, our aim is to quantify this correlation, calibrating the highest DS BLM signal to the primary power load, and derive the primary power load from the highest BLM signal observed in the excitation. One caveat of using this approach is the sensitivity to potential artefacts in the BLM signals in the high primary beam loss regimes discussed before.

The primary impact depth on the TCP (impact parameter), collimator settings, and chromatic properties of the magnetic lattice downstream of the TCP remain constant throughout the excitation. Therefore, a linear relationship between primary beam loss and BLM signal is intuitively expected.

Consider Fig. 11, in which the measured BLM signal in the DS BLM with the highest signal (BLMAI.09L7.B2I30_MBB) is shown for QA1 and QA5 on the horizontal axis and the primary power load is shown on the vertical axis. The location of the BLM also corresponds to the location with the highest magnet coil power deposition derived in the simulations. The latter was derived using all the BCT signals mentioned above. Considering that three BCT signals were considered, for each second of excitation, three data points are shown.

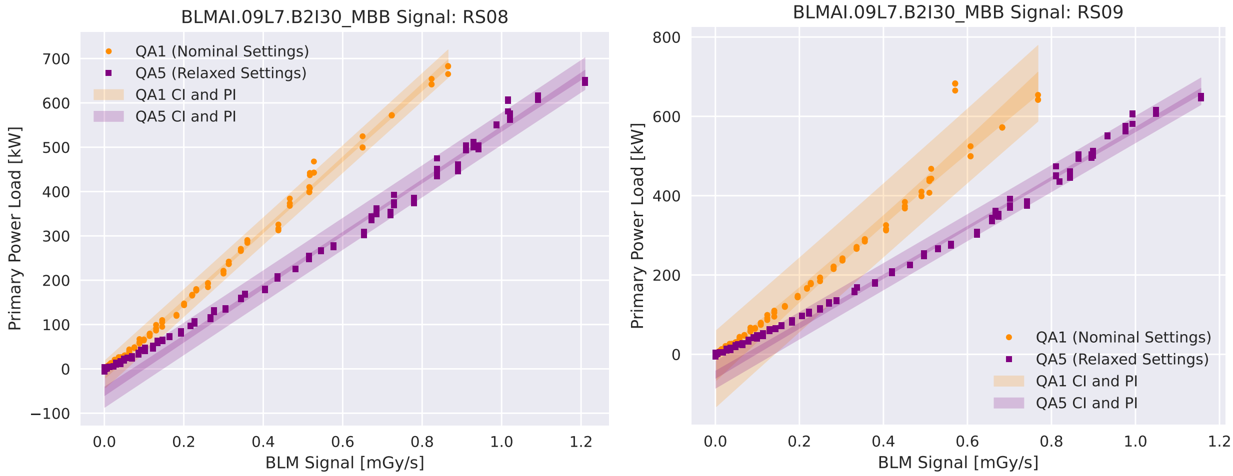


Figure 11: Markers: power load observed in QA1 and QA5 as a function of the BLM signal. Dark-coloured areas: confidence interval of linear regression. Light-coloured areas: prediction interval of linear regression. Left: RS08 (0.3 s). Right: RS09 (1.3 s integration time).

The figure shows that the assumption of a linear relationship is indeed appropriate. We used an ordinary least-squares linear regression model to describe the data. For the estimation of the fit parameters, we use all data points recorded for a primary power load greater than 100 kW. In this way, we ensure the best agreement for regimes with high losses. The confidence and prediction intervals (CI and PI) derived with the model, using a significance level of 0.05, are also shown. It is clearly visible how the PI derived with this approach covers most of the recorded data points, as expected. To derive the highest power load observed throughout QA1 and QA5, we apply the model to the highest BLM signal recorded in each quench attempt.

The prediction interval shown in the figure describes the area in which 95% of new observations would fall, considering the data that was recorded. This means that, according to the model, for a given level of BLM signal, 95% of the recorded primary power loads would fall in this range if additional data points were measured. For the highest BLM signal recorded, we obtain the following PI for QA1:

$$\mathrm{PI}^{0.05}_{\mathrm{QA1}}(\mathrm{RS08}) = [657\,\mathrm{kW}, 674\,\mathrm{kW}]\,, \tag{5}$$

$$\mathrm{PI}^{0.05}_{\mathrm{QA1}}(\mathrm{RS09}) = [587\,\mathrm{kW}, 780\,\mathrm{kW}]\,, \tag{6}$$

and for QA5 with relaxed settings:

$$\mathrm{PI}^{0.05}_{\mathrm{QA5}}(\mathrm{RS08}) = [630\,\mathrm{kW}, 702\,\mathrm{kW}]\,, \tag{7}$$

$$\mathrm{PI}^{0.05}_{\mathrm{QA5}}(\mathrm{RS09}) = [629\,\mathrm{kW}, 697\,\mathrm{kW}]\,. \tag{8}$$

For QA1, the range is comparably broad due to two outliers in the data, visible in Figure 11. Note the remarkable agreement between the estimates from different running sums for QA5. Let us use the minimum and maximum across running sums for a given QA as the lower and upper bounds of the assumed uncertainty, and the midpoint between them as the reported value. We obtain the following maximum primary power loads for QA1 (nominal settings) and QA5 (relaxed settings):

$$P^{\mathrm{nom}}_{\mathrm{max}} = (683 \pm 96)\,\mathrm{kW} \tag{9}$$

$$P^{\mathrm{rel}}_{\mathrm{max}} = (665.5 \pm 36.5)\,\mathrm{kW} \tag{10}$$

It should be noted that the figures derived directly from the BCT signal are within these ranges. This result is not surprising considering the approach chosen. Using the same approach as before, we can estimate the PPD reached in the MD:

$$PPD^{nom}_{\mathrm{max}} = \frac{(683 \pm 96)\,\mathrm{kW}}{946\,\mathrm{kW}} \times 14\,\mathrm{mW/cm^3} = (10.1 \pm 1.4)\,\mathrm{mW/cm^3}\,, \tag{11}$$

with a comparably broad range, due to the outliers mentioned above. With the relaxed settings, a much higher PPD was reached:

$$PPD^{rel}_{\mathrm{max}} = \frac{(665.5 \pm 36.5)\,\mathrm{kW}}{946\,\mathrm{kW}} \times 24\,\mathrm{mW/cm^3} = (16.9 \pm 0.9)\,\mathrm{mW/cm^3}\,. \tag{12}$$

5 Summary and Conclusions

The collimation quench test MD carried out in November 2022 has probed the quench limit of superconducting LHC dipoles with primary beam losses of up to roughly 650 kW. In total five quench attempts were carried out, none of them leading to a quench.

Achieving primary beam losses of 1 MW, initially aimed at, turned out to be very difficult due to interlocks in the BLM signals and the collimator temperature. Although the latter could be relaxed in future tests (within reasonable limits), some limiting BLMs were operated at the electronic limit, making it more difficult to circumvent this issue. Interlocking on the collimator temperature is an artefact of the fact that, with the present BLM thresholds, we can only achieve primary beam losses comparable to the collimation system design with lower losses rates and longer excitation times, which finally deposits much more total power in the collimators.

The BLM system did not trigger any dumps, thanks to the careful preparation of the test and to the excellent control of beam losses: The control of the loss rate with ADT white noise was excellent and allowed one to maximise the reach of the primary loss rate by tailoring the beam loss time profile to the edge of what was reachable with the interlocks in place during the MD.

The offline MD analysis revealed that peak power depositions of $(16.9 \pm 0.4)\,\mathrm{mW/cm^3}$ were reached in the DS magnet coils thanks to the deployment of relaxed collimator settings to artificially worsen the cleaning efficiency. This figure is higher than the expected peak power deposition in HL-LHC at 7 TeV. However, a direct comparison cannot be made because of the reduction of the quench limit when the magnet currents are increased. A detailed assessment of the comparability to the 7 TeV scenario is going to be carried out in the future.

Acknowledgements

We would like to express our gratitude to the colleagues from MP, ABP, MME, MPE, RF, STI, BI, OP for their constant support in the preparation and execution of the MD. We also thank M. Peryt and F. Carra for their availability to support us remotely during the night.

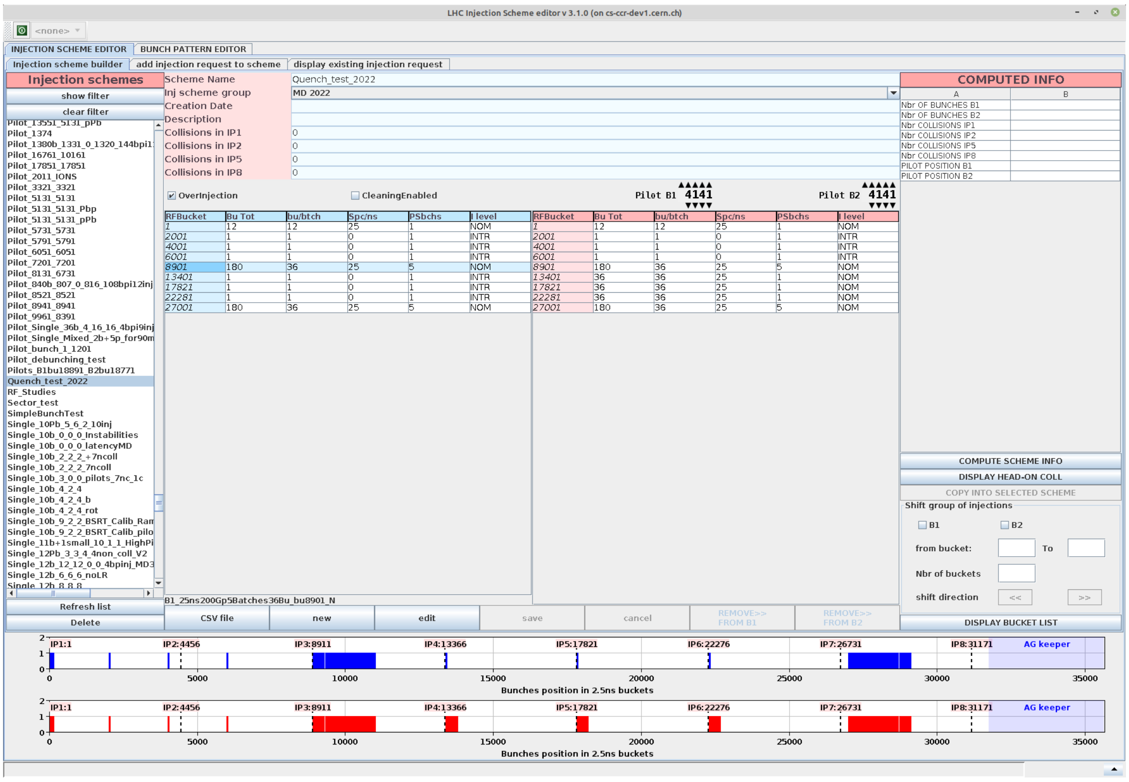
Appendix

Machine protection checklist

The following machine protection checklist was completed before applying the relaxed collimator settings.

1. **Do the collimator LVDTs show nominal readings?**
   The readings were affected by the heating of the collimator and changed by approximately 10 µm. We consider the readings to be okay.

2. **At the display of power losses, are the collimator temperature readings as expected?**
   In the fill with nominal collimator settings, the beams were dumped on the temperature of the TCP at 50 degrees. The reason was the long duration of losses. The observation is understood and the interlock is kept at this low level of 50°. We plan to limit the excitation time with relaxed settings. Okay.



Scheme Name: Quench_test_2022
Inj scheme group: MD 2022
Creation Date:
Description:
Collisions in IP1: 0
Collisions in IP2: 0
Collisions in IP5: 0
Collisions in IP8: 0

☑ OverInjection ☐ CleaningEnabled

Pilot B1 4141

Pilot B2 4141

RFBucket	Bu Tot	bu/btch	Spc/ns	PSbchs	I level
1	12	12	25	1	NOM
2001	1	1	0	1	INTR
4001	1	1	0	1	INTR
6001	1	1	0	1	INTR
8901	180	36	25	5	NOM
13401	1	1	0	1	INTR
17821	1	1	0	1	INTR
22281	1	1	0	1	INTR
27001	180	36	25	5	NOM

RFBucket	Bu Tot	bu/btch	Spc/ns	PSbchs	I level
1	12	12	25	1	NOM
2001	1	1	0	1	INTR
4001	1	1	0	1	INTR
6001	1	1	0	1	INTR
8901	180	36	25	5	NOM
13401	36	36	25	1	NOM
17821	36	36	25	1	NOM
22281	36	36	25	1	NOM
27001	180	36	25	5	NOM

B1_25ns200Gp5Batches36Bu_bu8901_N

Figure 12: Beam 2 filling scheme used in the MD.

3. **Are the beam losses at the primary collimators in MJ as expected?**
   We reached loss levels of 700 kW and independently confirmed this in offline analysis. No surprises were observed. Okay.

4. **Is the loss pattern along the machine as expected?**
   Reduction of BLM readings in arcs 67/78 observed and understood. We conclude that BLM protection is not seriously affected. The other losses in the ring are not suspicious. Okay.

5. **Is the BLM signal to threshold ratio as expected?**
   We approached the BLM thresholds up to 91% when creating losses of 700kW. We conclude that the thresholds are not set too aggressively. Okay.

6. **ADT: Is the power ramp up, flat-top length, and excitation window (bunches) as expected?**
   We observed that only bunches in the excitation window were excited, as expected. The losses were correlated with gain vs. time, as expected. Okay.

7. **QPS: no unexpected behaviour (QPS OK, Post Mortem)?**
   Nothing unusual was identified. Okay.

8. **Is cryogenic in good condition?**
   Following the excitations, the temperature increased as expected and then went back down again. The cryogenics is in a good state.

References

[1] G. Apollinari, I. B. Alonso, O. Bruning, P. Fessia, M. Lamont, L. Rossi, and L. Tavian (editors), *High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report V. 0.1.* CERN Yellow Reports: Monographs. CERN-2017-007-M, CERN, Geneva, Switzerland, 2017.

[2] G. Apollinari, I. B. Alonso, O. Brüning, M. Lamont, and L. Rossi (editors), "High-Luminosity Large Hadron Collider (HL-LHC): Preliminary Design Report," *CERN-2015-005*, 2015.

[3] R. Bruce, A. Marsili, and S. Redaelli, "Cleaning Performance with 11T Dipoles and Local Dispersion Suppressor Collimation at the LHC," *Proceedings of the International Particle Accelerator Conference 2014, Dresden, Germany*, p. 170, 2014.

[4] B. Auchmann, T. Baer, M. Bednarek, G. Bellodi, C. Bracco, R. Bruce, F. Cerutti, V. Chetvertkova, B. Dehning, P. P. Granieri, W. Hofle, E. B. Holzer, A. Lechner, E. Nebot Del Busto, A. Priebe, S. Redaelli, B. Salvachua, M. Sapinski, R. Schmidt, N. Shetty, E. Skordis, M. Solfaroli, J. Steckert, D. Valuch, A. Verweij, J. Wenninger, D. Wollmann, and M. Zerlauth, "Testing beam-induced quench levels of LHC superconducting magnets," *Phys. Rev. ST Accel. Beams*, vol. 18, p. 061002, 2015.

[5] A. Waets *et al.*, "Update on power deposition studies for IR7 DS." Presentation at the LHC Collimation Upgrade Specification Meeting 137, CERN, Geneva, Switzerland, 2021.

[6] R. Assmann, R. Bruce, F. Burkart, M. Cauchi, D. Deboy, B. Dehning, R. Giachino, E. Holzer, L. Lari, A. MacPherson, E. N. del Busto, M. Pojer, A. Priebe, S. Redaelli, A. Rossi, R. Schmidt, M. Sapinski, M. S. Camollocci, R. Suykerbuyk, G. Valentino, J. Uythoven, J. Wenninger, D. Wollmann, and M. Zerlauth, "Collimator losses in the DS of IR7 and quench test at 3.5 TeV," *CERN-ATS-Note-2011-042 MD*, 2011.

[7] B.Salvachua, R.Bruce, M.Cauchi, D.Deboy, W.Hofle, E.B.Holzer, D.Jacquet, L.Lari, E.Nebot, D.Mirarchi, E.Quaranta, S.Redaelli, M.Sapinski, R.Schmidt, G.Valentino, D.Valuch, J.Wenniger, D.Wollmann, and M.Zerlauth, "Collimation quench test with 4 TeV proton beams," *CERN-ACC-NOTE-2014-0036*, 2014.

[8] B. Salvachua, A. Mereghetti, B. Auchmann, R. Bruce, P. Hermes, E. Holzer, D. Jacquet, M. Kalliokoski, D. Mirarchi, S. Redaelli, E. Skordis, G. Valentino, A. Valloni, D. Valuch, D. Wollmann, and M. Zerlauth, "Collimation quench test with 6.5 TeV proton beams," *CERN-ACC-NOTE-2016-0015*, Jan 2016.

[9] P. Hermes, B. Auchmann, R. Bruce, W. Hofle, E. B. Holzer, M. Kalliokoski, G. Kotzian, A. Mereghetti, D. Mirarchi, E. Quaranta, S. Redaelli, B. S. Ferrando, G. Valentino, D. Valuch, D. Wollmann, and M. Zerlauth, "LHC Heavy-Ion Collimation Quench Test at 6.37Z TeV," *CERN-ACC-NOTE-2016-0031*, Mar 2016.

[10] M. Schaumann, R. Alemany, B. Auchmann, C. B. Castro, V. Chetvertkova, R. Giachino, J. Jowett, M. Kalliokoski, A. Lechner, T. Mertens, and L. Ponce, "LHC BFPP Quench Test with Ions (2015)," *CERN-ACC-NOTE-2016-0024*, 2016.

[11] R. Bruce, S. Gilardoni, , and J. M. Jowett, "Effects of ultraperipheral nuclear collisions in the LHC and their alleviation," *Proceedings of the European Particle Accelerator Conf. 2008, Genoa, Italy*, 2008.

[12] W. Hofle, R. Assmann, S. Redaelli, R. Schmidt, D. Valuch, D. Wollmann, and M. Zerlauth, "Controlled transverse blow-up of high-energy proton beams for aperture measurements and loss maps," *Proceedings of IPAC12, New Orleans, Louisiana, USA*, p. 4059, 2012.

[13] R. De Maria *et al.*, "Sixtrack version 5: Status and new developments," in *Proceedings of IPAC 2019, 3200–3203. Melbourne, Australia*, 2019.

[14] "Fluka webite." `https://fluka.cern/`, 2022. Accessed: 2021-11-30.

[15] A. Lechner, B. Salvachua, S. M. Vigo, and M. D'Andrea, "BLM threshold changes for proton collimation quench test 2022 (MD7224)," *LHC-BLM-ECR-0075*, 2022.