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LHC Heavy-Ion Collimation Quench Test at 6.37Z TeV

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Summary

This note summarizes the collimation quench test MD with $^{208}Pb^{82+}$ beams at 6.37 Z TeV in which a quench of a dipole magnet in the dispersion suppressor (DS) downstream of the betatron collimation region (IR7) was achieved. The aim of the test was to experimentally validate the quench limit at 6.37 Z TeV in this region by inducing high losses at the LHC collimation system and quench the magnet with the collimation debris mainly lost at the IR7 DS. This was also the first test with heavy-ions in which the transverse damper (ADT) could be used to induce these losses over extended periods of time (approximately 10-15s) while previous tests used tune resonance crossing methods in which the beam loss is less controllable and faster. The quench was achieved at a beam loss rate of 15 kW. The note summarizes the measurement strategy, technical realization, the test results and implications for future heavy-ion operation.

1 Introduction

In 2015, the LHC heavy-ion programme with $^{208}Pb^{82+}$ beams reached a total stored beam energy of $\approx$ 9.51 MJ, which is beyond the value of 3.81 MJ foreseen in the LHC design phase [1]. An even further increase to 18.0 MJ is envisaged based on an upgrade of the LHC injector chain [2]. An inevitable consequence is the rising likelihood for beam-induced quenches of the superconducting LHC magnets operated at 1.9 K due to collimation losses. The LHC collimation system that protects the machine from uncontrolled beam loss is less efficient for heavy-ion beams than for proton beams. Especially the magnets in the dispersion suppressor region downstream of the betatron cleaning system in IR7 are exposed

Table 1: Machine and beam parameters for the MD.

Date	13.12.2015
Start Time	17:00h
End Time (quench)	22:08h
Fill Numbers	4722 & 4723
Energy (Fill 4723)	6.37Z TeV
Optics	Injection Optics
TCP Half Gap	5.5 σ

to a significant fraction of the collimation debris and may quench if the losses become too high.

Beam losses during the operational cycle cannot be avoided. For a given collimation cleaning efficiency, this means that the quench limit imposes an upper boundary for the possible reach in terms of total stored beam energy. The knowledge of the quench limit allows to evaluate this intensity limitation and gives essential input for the study of upgrade scenarios.

In a previous heavy-ion quench test at 3.5 Z TeV carried out in 2011 [3], tune resonance crossing was used as a method to generate the beam losses. A peak loss rate of 150 kW was reached over 75 ms and no quench was achieved. In the quench test presented in this MD, the loss scenario is different because the DS magnets were exposed to continuous losses over 14 s. Given the different nature of the loss scenarios studied, the results of the two quench test can not be directly compared.

The MD was carried out the 13.12.2015 from 17:00h until 22:08h. Tab. 1 summarizes the main machine and beam parameters for the quench test. The beam energy and intensity (Beam 2) during the MD are shown in Fig. 1.

2 Preparation

2.1 Definition of Target Primary Loss Rates for the MD

The quench test MD was carried out by generating losses in the horizontal plane of Beam 2 (B2). The collimation debris is lost in the IR7 DS immediately after its generation, thus the optics in the remaining IRs are irrelevant for the experiment. Therefore, the quench test was carried out with injection optics. The applied collimator settings in IR7 were identical to the settings used in physics operation.

The qualification loss map for the horizontal plane of B2 measured in the commissioning phase of the 2015 heavy-ion run is shown in Fig. 2. The highest BLM signal at the cold LHC magnets is measured at BLMQI.09L7.B2I10_MQ with a cleaning inefficiency of $\eta = 1.65 \times 10^{-2}$. The BLM monitor factor at this location was set to 0.499, hence the BLM thresholds were set to values 1.5 times above the loss signal at which a quench is expected

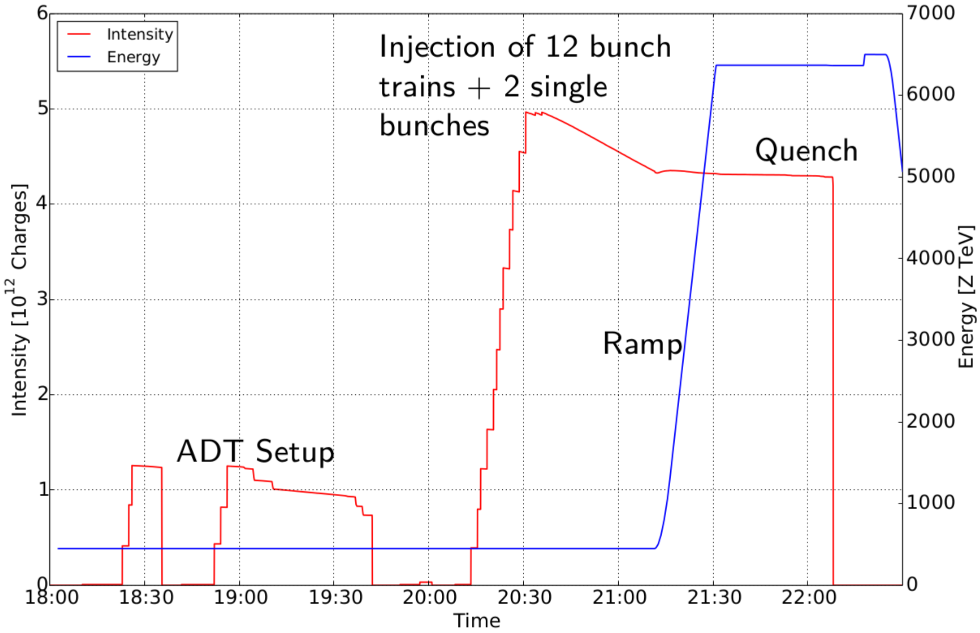

Figure 1: Energy and stored beam intensity during the heavy-ion collimation quench test.

for UFO events. The peak BLM signal from the qualification loss map B_m normalized by the BLM signal equivalent to the assumed quench limit for UFO events B_q is given by

$$B_m/B_q = 9.1 \times 10^{-3}\,. \tag{1}$$

From the peak intensity drop measured by the beam current transformers (BCT) at the loss map measurement, the total beam loss power P_l at the TCP yields:

$$P_l = 123 \text{ W}. \tag{2}$$

Thus, to reach the BLM signal equivalent to the assumed quench limit for UFO events, a power loss of

$$P = 13.5 \text{ kW} \tag{3}$$

is required. For the different loss scenario of collimation losses, this power loss can not be expected to be the quench limit. We prepared for a maximum loss rate of 100 kW which allowed for a sufficient margin to probe the quench limit without endangering the primary collimator (TCP). For heavy-ions, the latter is particularly exposed, because the energy deposition from ionization losses at the collimator surface is about ten times larger than for the same number of proton charges at the equivalent energy [4].

2.2 Modification of BLM Thresholds

Based upon the qualification loss map, we determined the BLM thresholds which have to be changed in order to allow for losses of 100 kW without triggering a beam dump. The BLM

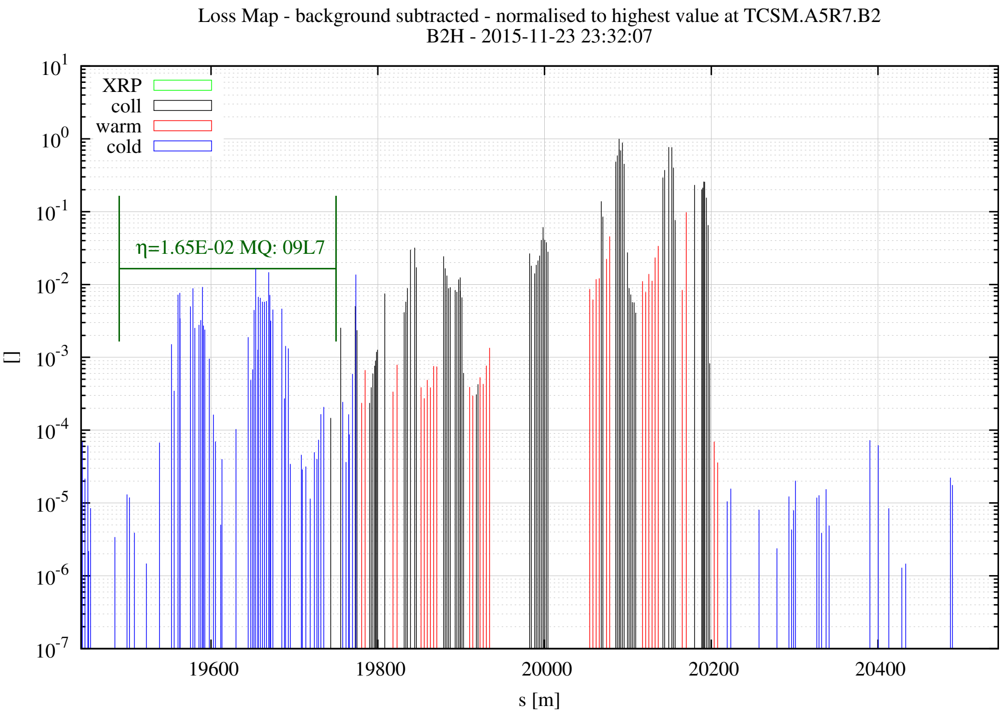

Figure 2: Qualification loss map measured in the heavy-ion commissioning phase of 2015 at flat top with nominal collimator settings. The figure shows the BLM signals for RS09 with 1.3s integration time normalized by the highest signal.

signals measured in the qualification loss map were normalized to the BLM threshold and re-scaled for the scenario of 100 kW power load to identify the thresholds which have to be modified.

The affected BLMs are mainly located at cold magnets in IR7 and dedicated integration times for selected collimators. In order to keep the changes simple and allow for slight modifications during the experiments, the decision was taken to increase the master table by a factor of 10 at BLMs of cold magnets and maintain the monitor factors unchanged.

The full set of changes to BLM thresholds used in the quench test are summarized in [5].

2.3 Setup of the Transverse Damper

The loss rates for the quench test require simultaneous excitation of a large number of ion bunches. One ion bunch of 10^{10} charges with an ion energy of 6.37 Z TeV carries an energy of 10 kJ. Including a safety margin, assuming that only 70% of the bunch can be lost (to avoid triggering an interlock because the intensity per bunch drops below 3×10^{10}), the required number of bunches for continuous losses over 10s is about 1.4 bunches/kW.

For the attempted peak power loss of 100 kW, the required number of bunches is thus

$$n_B^{\min} = 140\,, \tag{4}$$

or approximately 6 bunch trains of 24 ion bunches. To have enough margin during the test it was decided to expand the ADT window into two independent windows, both large enough to cover eight bunch trains of 24 bunches.

After the adjustment of the excitation window, a small number of bunch trains was injected and the ADT was optimized at injection energy to flatten the power loss profile (see Fig. 3).

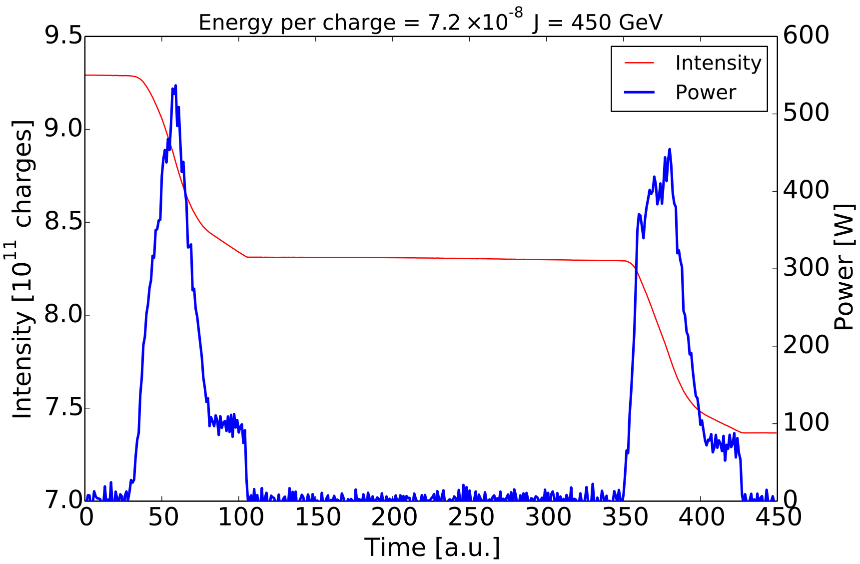

Figure 3: Intensity and power loss profile for two subsequent excitations during the adjustment of the ADT to flatten the loss profile.

The power loss was monitored in real time during the experiment by means of the new online display, developed for the proton collimation quench test which took place before [6].

2.4 BCT Logging

Before the quench test, the logging of the fast BCT data was activated, which allows a more precise analysis of the intensity and thus power evolution. The logged data is thus available with 50Hz instead of the default 1Hz resolution.

3 MD Plan and Realization

The planned fills for the MD are summarized in Tab. 2 together with the two fills which took place. The schedule foresaw an initial setup at injection energy to adjust the ADT and to perform test excitations (fill 1). Then three ramps to attempt the quench were foreseen. In the second fill, the loss rate was intended to be 13.5 kW to continue with 50 kW in fill 3 and 100 kW in fill 4 if no quench was attained before.

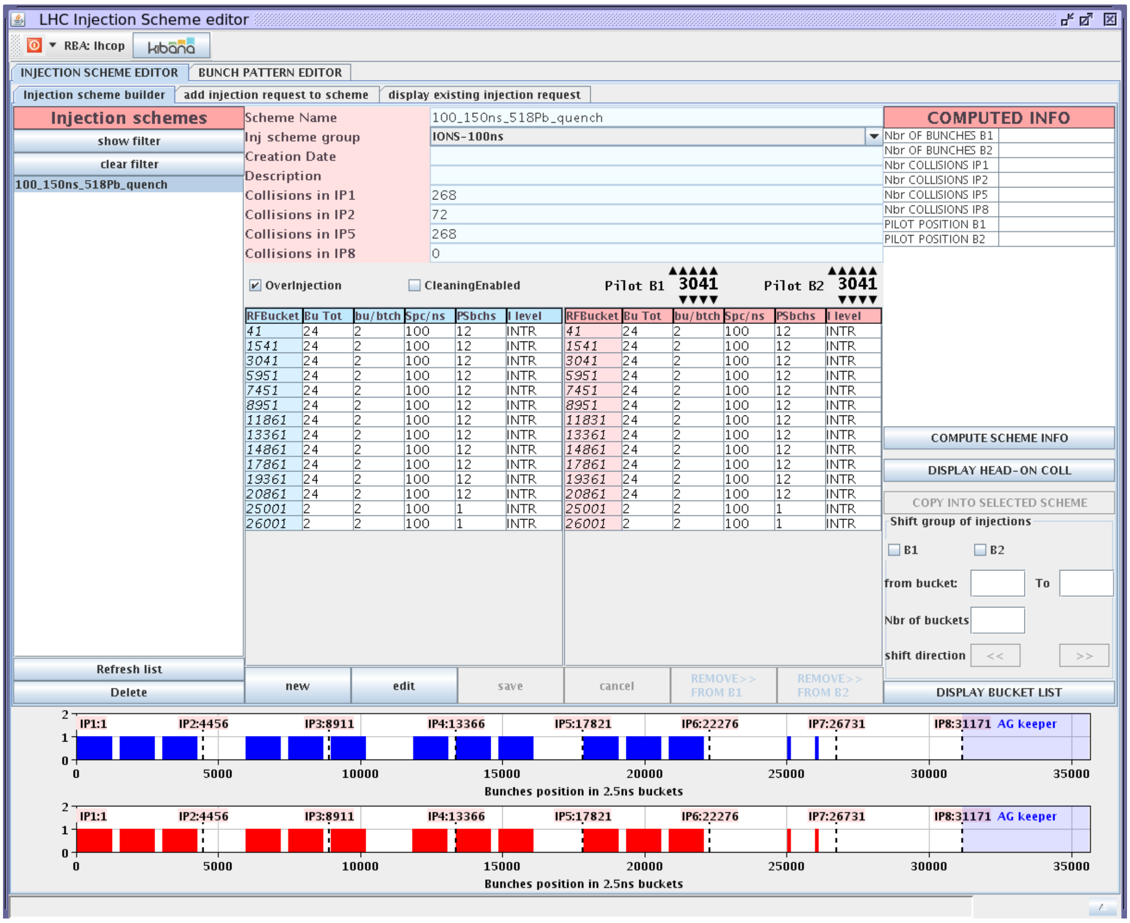

Figure 4: Filling scheme employed in the MD; the scheme includes 12 bunch trains of 24 bunches for the quench test and 2 individual bunches for ADT tests at flat top.

Table 2: Proposed and realized fills for the MD. The quench occurred in the first ramp.

Fill	Bunches	E [Z TeV]	P_{max}[kW]
Planned			
1	8	0.45	≈ 0.1
2	8 + 4×24	6.37	13.5
3	8×24	6.37	50
4	8×24	6.37	100
Realized			
1	3 × 24	0.45	0.6
2	2 + 12×24	6.37	15.0

Besides the bunch trains used for the quenching, some individual bunches were included in the filling scheme of the second fill to allow for test-excitations at small intensities at top energy (see Fig. 4).

In the MD, the decision was taken to inject 12 bunch trains of 24 bunches instead of the 4 bunch trains foreseen for fill 2 due to time constraints. In this fill, the MBB.9L7 quenched at a peak power loss of 15 kW when 6 bunch trains (144 bunches) were excited with an ADT gain of 0.4.

4 Quench Analysis

4.1 Quench Location

The quench occurred at the dipole magnet MBB.9L7.B2. At this location, the BLM signal was highest amongst the BLMs in the cold LHC regions (RS09) with an associated cleaning inefficiency of $\eta = 2.25 \times 10^{-2}$ or a BLM signal of 3.66×10^{-3}Gy/s (see Fig. 5).

4.2 Beam Loss

The beam power loss during the quench can be obtained deriving the fast BCT data with a logging frequency of 50 Hz. The intensity evolution and the corresponding power loss is shown in Fig. 6. The power load increases continuously over 13.6 s until the quench occurs at a power load of

$$P_{\text{quench}} \approx 15\ \text{kW}\,. \tag{5}$$

Note that the beam loss increases at a lower rate than for events in which the beam was dumped by the BLMs in the IR7 DS during nominal operation. In the latter, the losses reach their maximum after 1 s to 2 s. From the BLM signals, the maximum power load on the MBB.9L7 can be estimated as:

$$P_{\text{MBB}} \approx 2.25 \times 10^{-2} \times 15\ \text{kW} \approx 340\ \text{W}\,. \tag{6}$$

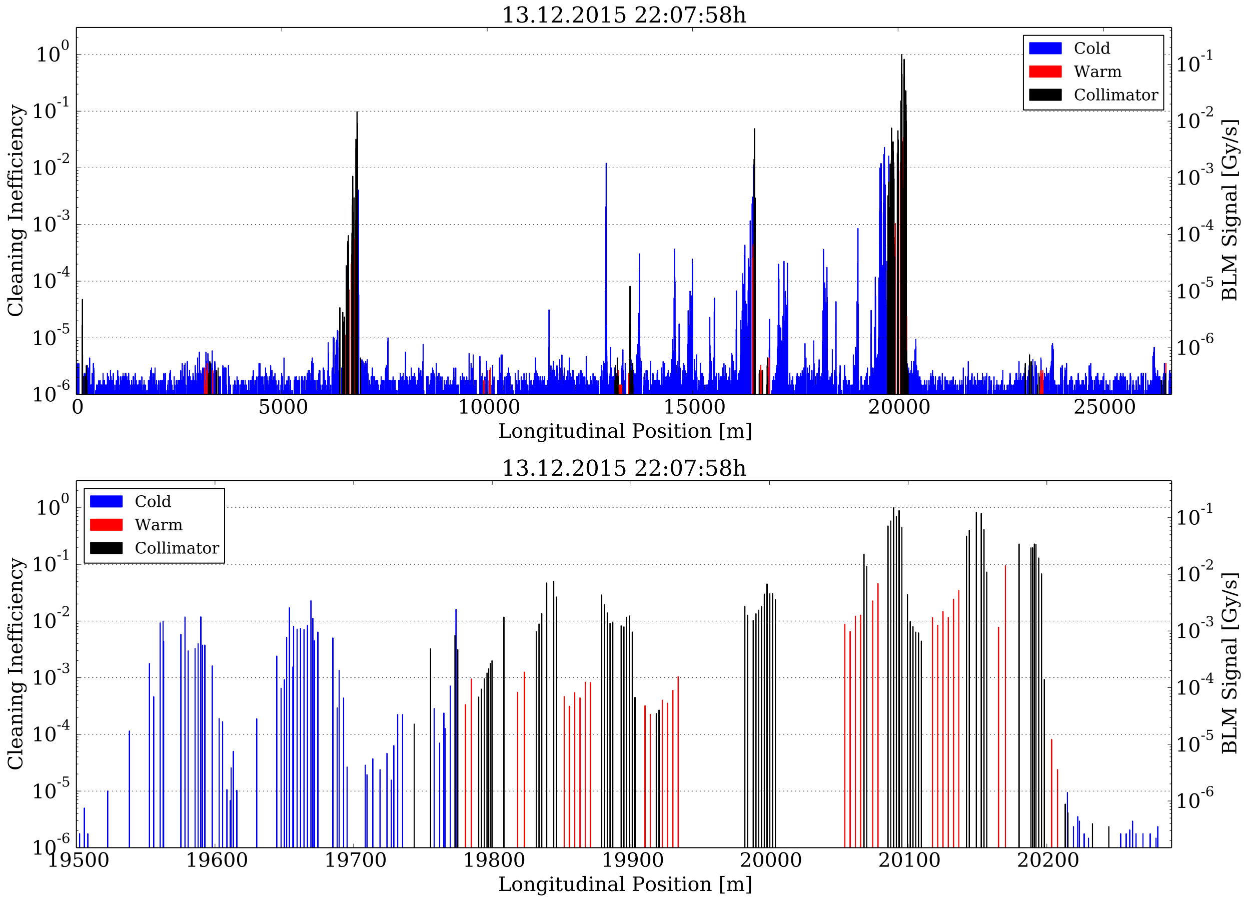

Figure 5: Measured BLM Signals in the LHC (top) and IR7 (bottom) one second before the quench (RS09).

Knowing that the BLM response at the collimators and at the MBB are certainly different, this value should only be regarded as a preliminary estimate until detailed tracking and energy deposition simulations are available.

4.3 BLM Signals at Quench

The BLM signals at the BLMEI.09L7.B2I30_MBB at quench normalized by the operational thresholds in physics operation are shown for different running sums in Fig. 7. The largest BLM signal compared to the threshold is obtained for RS10 where the signal is about 3.5 times the threshold. With RS09 and RS11, the thresholds were exceeded by 60 % and 110 % respectively.

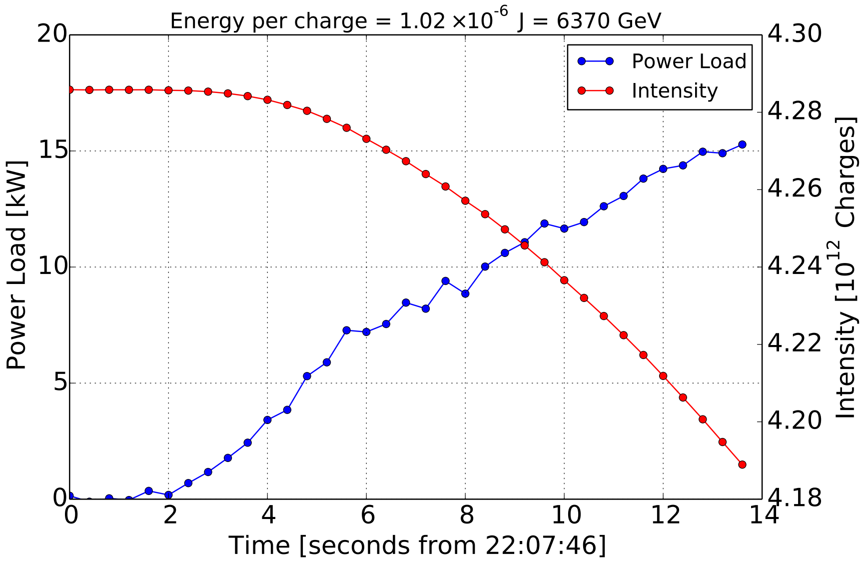

Figure 6: Beam intensity and power loss evolution before the quench. The fast BCT data is smoothened by considering a moving average over 20 data points (i.e. 0.4 s).

Table 3: Beam parameters for heavy-ion operation from the LHC Design Report [1], achieved at the 2015 heavy-ion run, foreseen to be achievable for the LIU upgrade and as requested for HL-LHC.

	E [Z TeV]	n_B	I_B [10^7 ions]	E^{tot}_{nom} [MJ]	$E^{\text{tot}}_{\text{max}}$ [MJ]
Design	7.0	592	7	3.81	≤ 10.8
2015	6.37	518	22	9.54	
LIU baseline	7.0	1152	17	18.0	
HL-LHC request	7.0	1248	21	24.1	

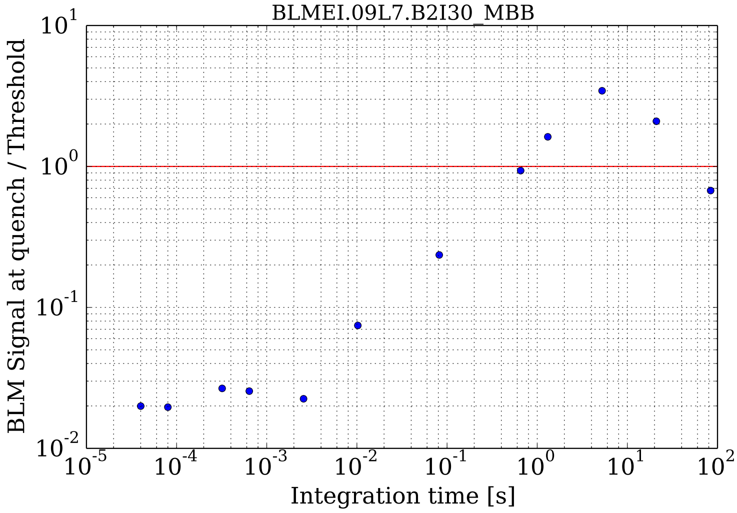

Figure 7: BLM signals at quench normalized to the operational thresholds at BLMEI.09L7.B2I30.

5 Intensity Limitations

The quench limit can be directly related to the maximum intensity allowed to be stored in the machine without quenching. For an assumed beam lifetime of τ =12 min the maximum stored beam energy is given by

$$E_{\mathrm{max}}^{\mathrm{tot}} = P_{\mathrm{quench}} \times \tau = 10.8\,\mathrm{MJ}\,. \tag{7}$$

Note that this value is derived using the experimental quench limit measured in this quench test at 6.37 Z TeV. With the higher magnet currents applied at 7 Z TeV, the quench limit will be lower. Thus far, there is no estimate available for the quench limit at the higher magnet current. Therefore, E_{max} = 10.8 MJ should be considered as an upper boundary for the achievable intensity. The beam parameters for $^{208}Pb^{82+}$ beams foreseen in the LHC design phase, achieved in 2015, foreseen for the LHC injector upgrade (LIU) and requested for HL-LHC are listed in Tab. 3. The beam intensities foreseen for the future are beyond the limit determined by the quench test. The consequences for LHC upgrades have to be studied with dedicated simulations.

6 Summary and Outlook

In this MD, a magnet in the IR7 dispersion suppressor was brought to a quench for the first time caused by collimation losses. The quench occurred at the MBB.9L7 when six trains of 24 bunches of $^{208}Pb^{82+}$ ions at an energy of 6.37 Z TeV were excited. The magnet quenched at a beam loss rate of 15 kW which corresponds to a scaled loss rate of 340 W at the quenched magnet.

At the moment of the quench, the BLM signal for RS10 was 3.5 times the operational threshold. From the obtained quench limit, an approximate estimate of the maximum stored beam energy of 10.8 MJ can be derived, assuming a beam lifetime of 12 minutes. This value is below the stored beam energies foreseen for future heavy-ion operation, which should be taken into account in the discussion of upgrade scenarios.

A more detailed analysis of the experimental result is foreseen with the help of simulations.

Acknowledgments

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