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Pb ions collimator losses in IR7 DS and quench test at 3.5 Z TeV

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Summary

A Machine Development study session was held on December 6th, 2011 to test BLM quench thresholds in the IR7 dispersion suppressor (DS) for lead ion operation in the LHC at 3.5 Z TeV. High loss rates were artificially produced in the machine to allow full qualification of ion leakage with as realistic as possible loss distributions. Any potential collimation-related intensity limit imposed by a magnet quench was explored in parallel, to provide input for potential future collimation upgrade scenarios.

1. Introduction and motivation

The main motivation for performing a quench test with lead ion beams in the LHC was to verify predicted ion intensity limitations with realistic loss distributions and provide important information on performance limits and potential future collimation upgrade scenarios.

In a first MD carried out in May 2011 with proton beams, a loss power of 500kW was achieved during 1 s on the IR7 primary collimators using beam 2. No quench was observed in the dispersion suppressor. This result confirmed the operational thresholds in the cold DS magnets and gave a lower limit for the maximum leakage of single diffractive losses into the IR7 DS [1]. Furthermore it showed that for 3.5 TeV proton operation there are no collimation-related intensity limits expected in the LHC.

Based on the proton quench test MD results, and making certain assumptions on similarities of behavior between protons and ions, an estimate of the ultimate intensity limit for lead ion operation was made [2] using the formula:

$$\eta N_{MAX} = \tau R_q$$

where η is the highest local cleaning inefficiency, N_{MAX} the maximum beam intensity, τ the minimum lifetime for steady state losses, and R_q the lower quench limit. The minimum lifetime for steady state losses was derived from Pb ions data to be $\tau = 3600\,\mathrm{s}$, and the worst measured inefficiency value of $\eta = 0.045$ was assumed for a conservative approach.

In the assumption that the main performance limitation is in the DSs of the cleaning insertions (and not due to luminosity debris in the Interaction regions) and using these numbers, one reaches an expected performance limit for ion beams of $1.7\text{x}10^{11}$ ions (~4 times the nominal ion intensity) at 3.5 Z TeV, and of $3.2\text{x}10^{10}$ ions (or 80% of the nominal ion intensity)

extrapolating to 7 Z TeV. These numbers assume a minimum beam lifetime independent of beam energy and intensity, identical cleaning inefficiency and scale down the lower quench limit by a factor of 2.5 for dependence on the magnet current.
Moving from protons to ions, for an equivalent beam loss in the DS of the order of 100W, a factor of 100 reduction in the primary beam loss on the TCPs was assumed in in order to account for the proven difference in collimation inefficiency. Thus the 500kW beam loss limit measured for protons was reduced to a 5kW limit in the case of ions (in the design assumptions), equivalent to the loss of 1E8 ions (8.9E9 charges) at 3.5 Z TeV in 1 s.
An independent validation of the assumed lower DS quench limit came from the analysis of ion loss maps measured during the ion run setup in November 2010. Here two cases were identified for worst collimation efficiency:

1) a vertical loss map with Beam1 taken on 07/11/2010, where 4.88E9 charges were lost (nearly half of a bunch).
2) a horizontal loss map with Beam2 taken on 08/11/2010, where 8.89E9 charges were lost (about one full bunch).

Already for the normal run setup at 3.5 Z TeV in 2010, it was thus proven that the power equivalent of ~1E10 charges could be safely dumped on the primary collimators in IR7 without quenching a magnet in the DS (corresponding to the loss of one full bunch in two bunches beam operation).
The performance of the heavy-ion injector chain has recently indicated that substantially higher than nominal intensities could be within reach. This justified an interest to better investigate and understand any possible collimation-related intensity limits. Considering however the large error bars and important assumptions made in the above extrapolation of ion intensity limits, better reliability in the prediction could only be achieved with dedicated quench test measurements with ion beams. Hence the motivation for this MD test, whose results are presented in this note.

2. BLM quench thresholds

In a collimation loss-induced quench test, the risk to dump at undesired locations before reaching maximum loss rates at the DS must be avoided in order to make the test meaningful. This can only be done by increasing the BLM thresholds in a way that makes sure that the DSs become the real limiting factor, as expected from simulations. The BLM thresholds configuration used during beam tests is described in detail in the note [3] that was approved by the machine protection panel as a prerequisite for the execution of the tests. This approach was successfully established for the proton quench test [4].
The choice of BLM thresholds was based on the analysis of the loss maps performed to validate the cleaning system at flat-top (before the start of the betatron squeeze). Only tertiary collimators in the experimental regions move during squeeze and collision processes, with little effect on the local cleaning in the DSs of IR7. A quench test after the squeeze would however require more preparatory work to change BLM thresholds in the experimental regions to avoid additional loss locations.

The new thresholds are based on the limiting BLMs found during two horizontal loss maps with ions in the 2011 run (1Hz losses). The changes are done in a way to keep the number of manipulations as low and as simple as possible, in order to reduce the probability of manipulation errors. The monitors have either the Monitor Factor (MF) increased or the master threshold changed (never both). For the two monitors BLMQI.09R7.B1E10_MQ and BLMQI.09L7.B2I10_MQ, the master thresholds are changed for the 3.5 TeV energy levels only. The short Running Sums – RSs- stay unchanged, where RS09 needs to be increased by a factor 12. The rest of the monitors affected can be handled by increasing the Monitor factor (see table below). Monitor factor changes affect of course all energy levels and all integration times. After the end of the MD, all applied changes were fully reverted.

3. Machine configuration and collimation settings

The DS quench test was performed at 3.5 TeV with un-squeezed beam ("flat-top"). The machine configuration was the nominal one used for physics fills. In particular, crossing angles and beam separation as well as collimator settings were not modified. The flat-top collimator settings in units of the betatron beam size in the collimator plane, σ, listed in Tab. 2. The beam tests were performed with trains of nominal bunches. High beam losses were achieved by crossing the third-order resonance with the horizontal tune, as it is done in standard loss maps. In order to maximise loss rates, the transverse damper was switched OFF before the tunes were changed. Before starting the loss maps, the horizontal, Qh, and vertical, Qv, tunes are inverted to bring Qh close to the third order resonance.

4. Beam tests strategy

A staged approach was adopted during the MD. The first fill was used for calibrating loss rates: the beam intensity was chosen such as to give a leakage in the DS comparable to the assumed quench limit. Then in the following fill, the intensity was ramped up by a factor of 3 to go beyond the quench limit. Two horizontal loss maps measured during the 2011 run, worst cases for collimation efficiency for beam1 and 2 respectively, were analysed to derive the scaling factors for beam intensity to be applied in the quench test. The two loss maps were taken with an initial intensity of 2 bunches, in a machine configuration with squeezed optics and separated beams. For both cases the highest leakage in the cold aperture was compared to the set BLM dump thresholds and the scaling factor was applied to the initial number of bunches to find the beam intensity that, in the assumption of constant and reproducible beam loss rates, would yield losses comparable to the quench limit (x3 the BLM dump thresholds). This analysis was carried out considering only the 1.3s integration running sums.

For example, the B1 horizontal loss map in Fig.1 shows a peak loss rate of ~ 6.3E9 charges/s, equivalent to a primary loss of 3.5kW. The highest leakage in the cold aperture, normalised to the losses on the TCPs, reaches a value of 2.4% on Q9R7. The highest ratio of beam loss to the currently applied BLM dump thresholds in the cold aperture amounts to 51.5% (fig.2). Hence to reach the assumed quench limit (a factor of 3 higher than the assumed BLM dump threshold), one needs to rescale the initial beam intensity used for this loss map by a factor of 3x1/0.515~6, or in other words inject 12 bunches (up to 1.6E11 charges) to achieve a loss rate of about 3.8E10 charges/s. For the second fill, it was proposed to step the intensity up to a factor of 3 higher than the quench limit equivalent, and hence increase the number of injected bunches by a factor 18 to a total of 36 (4.8E11 charges), for an equivalent loss rate of 1.13e11 charges/s.

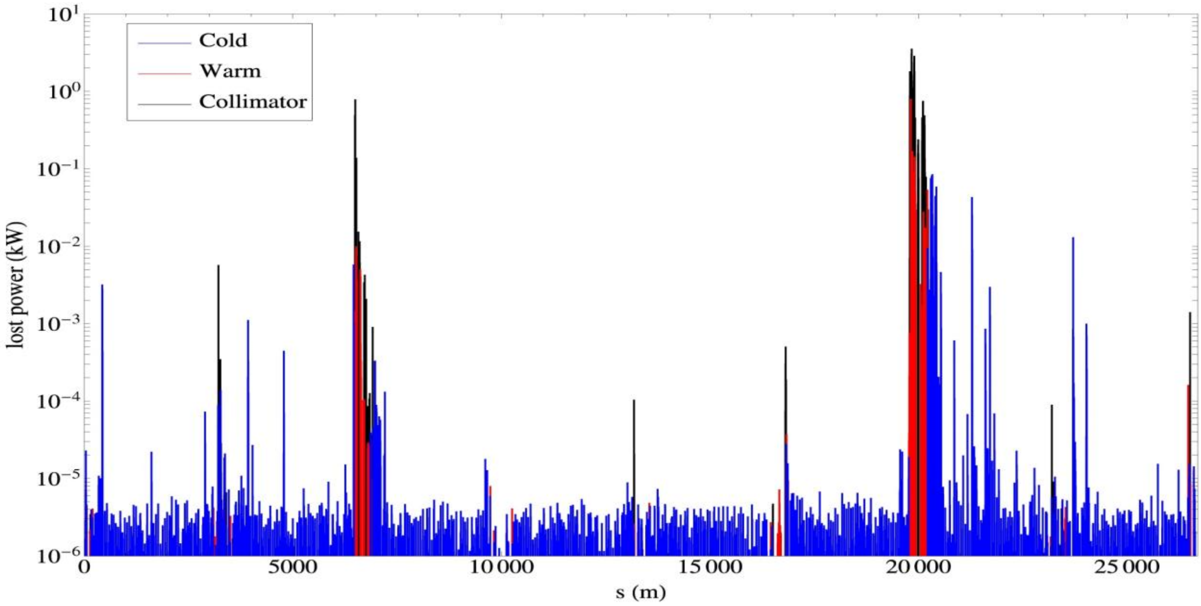

Figure 1 B1 horizontal loss map (normalised to highest primary leakage)

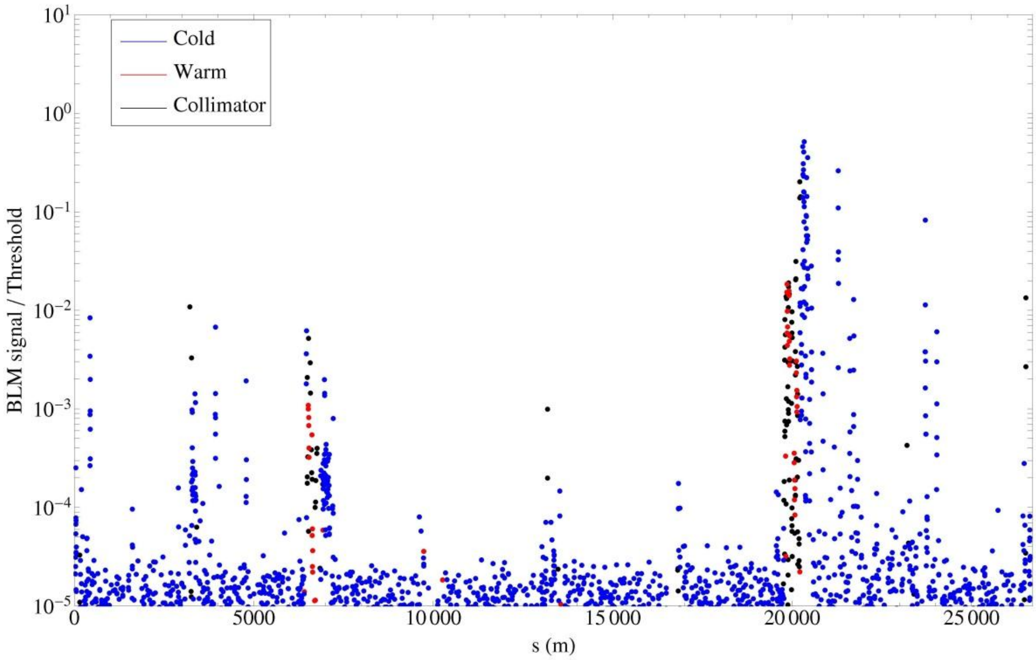

Figure 2 B1 horizontal losses rescaled to the currently applied BLM dump thresholds.

5. Results of beam tests

The summary of achieved parameters in the three ramps performed during the MD is presented in table 1. For each ramp we give the number of bunches and total intensity per beam, the duration of losses before the beam is dumped, and the amount of losses over 1s (max loss spikes), as well as information on the dump (location and BLM integration times).

The first ramp was performed with 20 (24) bunches per beam in Beam1 (2) respectively (for a total intensity of 1.6E11 charges, roughly corresponding to the quench limit in the assumptions made). BLM thresholds were relaxed to MF=1. Beam losses were created by moving the horizontal tune to 0.4, starting with Beam2. A beam dump was triggered due to excessive beam losses in monitor BLMQI.09L7.B2I10_MQ (on the magnet Q9.L7) on short integration windows (10ms RS06, the master thresholds having been changed only on 83ms - and longer - running sums). The total intensity lost amounted to 2E10 charges in 75ms (or equivalently, 2.7E11 charges/s).

Table 1 Summary of the main parameters achieved during the 3 ramps of the MD.

Ramp	I(B1) [charges]	I(B2) [charges]	$(dI/dt)_{max}$ [charges/s]	Δt [ms]	Dump	Magnet
1	1.64e11 (20b)	1.9e11 (24b)	B2: 2.7e11	75	RS06	Q9.L7
2	3.4e11	3.4e11	B2: 2.5e11	100	RS07	Q19.L7
3	3.4e11	3.4e11	B2: 4.9e10	1000	-	-
3	3.4e11	3.4e11	B1: 1.1e11	200	RS07	Q11.R7

For the second fill, BLM thresholds were further relaxed by increasing the monitor factors from 0.1 to 1 (equivalent to raising all thresholds in the dispersion suppressor by a factor of three above the quench level). Since the BLM to quench threshold ratio measured on Q8 during the first fill was 0.57 (see table 2), the beam intensity was doubled to 3x12 bunch trains (or 3.4E11 total number of charges per beam) to reach this upper limit (applying the same loss mechanism, i.e. the same trims to cross the 3rd order resonance). Upon crossing the resonance, a beam dump was triggered by BLMQI.19L7.B2I10_MQ at Q19.L7 for excessive losses on 82ms long running sums. Thresholds had not been changed for monitors placed outside the dispersion suppressor. A total of 2.5E10 charges was lost in 100ms. The ratios of BLM losses (RS06) to assumed quench limit measured 70% at Q8.L7 and 62% at Q9.L7 (placing the upper limit a factor of two above the assumed quench values).

For the third ramp, an extra set of 26 monitors (in cells 11L7, 19L7, 29L7 and 24R5, protecting MQ and MB magnets) had their thresholds increased, with their monitor factors pushed from 0.1 to 0.3 and TCLA.C6L7 was masked. Beam intensity was kept at the same value of 3.4E11 charges per beam. Resonance conditions were approached in a more gentle way, by moving in tune steps of 0.001 from 0.32, in order to perform high loss rates without losing the beam. Peak losses of 1.1E11 and 4.9E10 charges/s were measured on beam1 and beam2 respectively on Q11R7 and Q9.L7. A dump was triggered by beam1 losses on BLMQI.11R7.B2I30_MQ on 82ms integration time window. Losses on MB9.L7 reached 1.6 times the assumed quench limit. A significant temperature increase was measured in a connection cryostat, triggering an alarm. Compared to the results achieved with proton beams in similar quench test studies in the dispersion suppressor, ion losses have been happening on a much faster timescale, down to less than 0.01s. Limiting locations were also different, reaching magnets further down the arc.

Table 2 Ratio of measured BLM signal to assumed quench limit (3x operational BLM dump thresholds) for different integration running sums at limiting locations during the three ramps.

Ramp	Ratio RS02	Ratio RS04	Ratio RS06	Ratio RS07	Ratio RS09
1	MB9.L7: 0.26	MB9.L7: 0.07	Q8.L7: 0.57	Q8.L7: 1.14	MB9.L7: 0.29
2	Q8.L7: 0.08	Q8.L7: 0.16	Q8.L7: 1.66	Q8.L7: 2.35	Q9.L7: 0.49
3	MB9.L7: 0.005	MB9.L7: 0.015	Q8.L7: 0.15	Q8.L7: 1.03	MB9.L7: 1.60
3	Q11.R7: 0.01	Q11.R7: 0.03	Q11.R7: 0.46	Q11.R7: 1.16	Q11.R7: 0.55

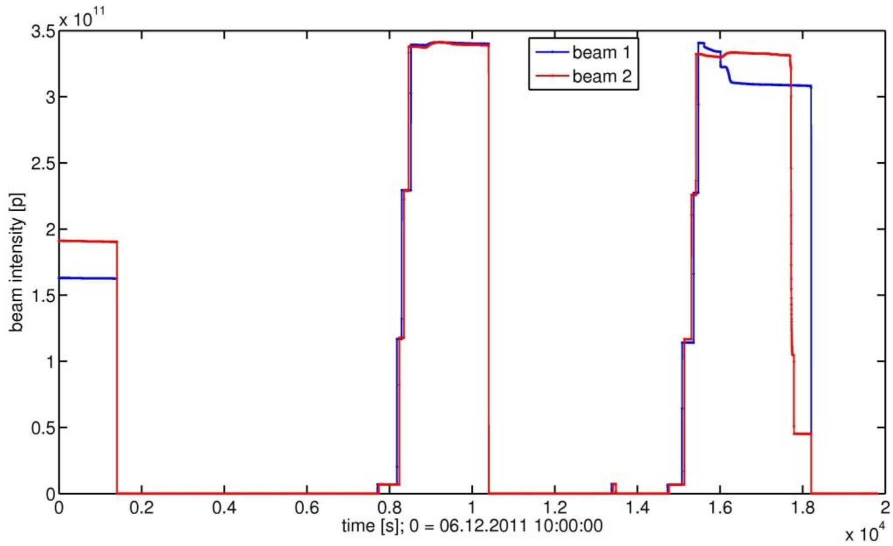

Figure 3 Beam intensity versus time during the three fills of the ion quench test on 06/12/2011.

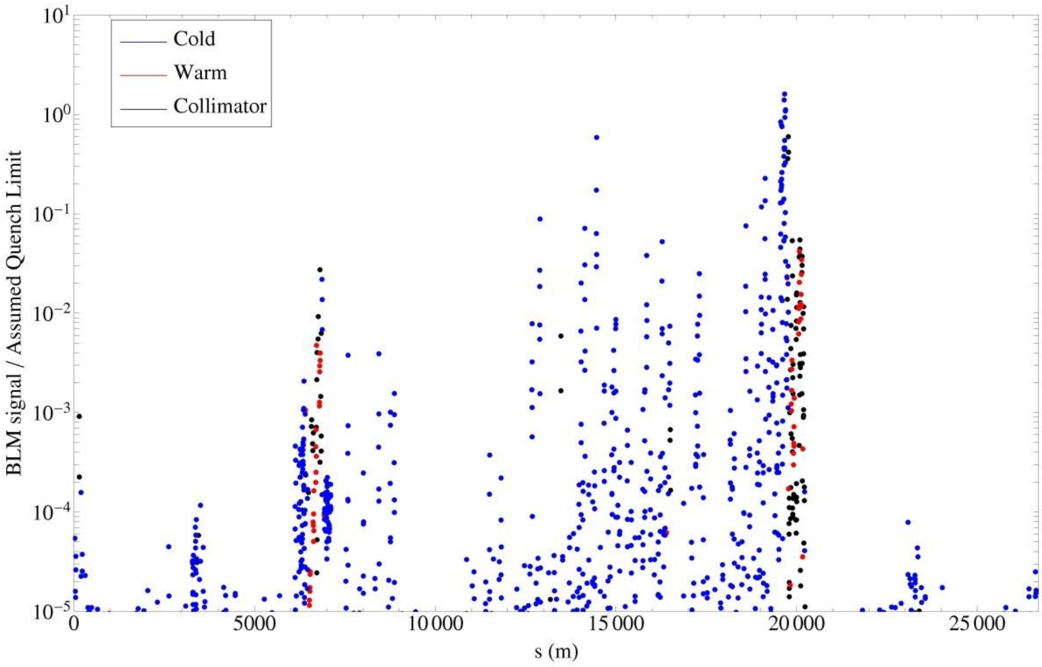

Figure 4 Ratio of the recorded BLM signal to the assumed quench limit for Beam2 losses during ramp#3 of the quench test (on RS09 integration running sum).

6. Preliminary conclusions

In this MD, losses of up to 2.7E11 charges/s were achieved by crossing the horizontal third order resonance at 3.5 TeV. The design loss rate for ions has always been assumed in studies to be 0.22h for a total ion intensity of 4.1E11 ions (3.4E12 charges). Compared to this, the MD results proved a performance improvement of a factor 11.4. Extrapolating to 7 TeV beam energy, the quench limit is expected to decrease by a factor of 4.5, while the deposited energy increases by a factor 2, thus reducing the margin on the performance by 9 to an overall factor 1.3. This could be further increased by taking into account that the measured lifetime of the beam exceeds by a factor 4.5 the estimated value, thus raising the bar on maximum ion intensity to nearly 6 times the design value.

The highest BLM signal observed, in cell 8L7, was about 100 times higher than during ion luminosity runs (cell 10L2) which translates in a margin of 2-5 times the design luminosity at 7TeV.

These numbers should however be used and considered with an appropriate degree of caution. They were derived from the loss rates measured in one particular case (beam2 during the third ramp, on RS09 running sums); since no quench was achieved, the figures derived are on the conservative side.

Extrapolation of the measured losses to the target ’slow’ loss regime is not trivial. On the other hand, the assumed quench limits were exceeded for different integration times without inducing quenches.

A series of important assumptions have been made in the extrapolation exercise at 7 TeV: among them the scaling law for the quench limit with energy and the invariance of the cleaning efficiency and lifetime with the beam energy. Differences in the loss pattern between fast and slow loss cases have not been properly understood yet. In addition, the duration of losses in these tests was limited to 1-2s by the loss mechanism used (3^{rd} order resonance crossing). This is shorter by a factor of 5 than the design assumption of continuous losses during 10s.

Tests should be repeated in 2012 using ADT for controlled beam blow-up. Knowledge of steady-state quench limit in dispersion suppressor is key parameter in the estimate of luminosity reach for ions after LS1.

References

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