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LHC injection losses for tighter collimator settings in view of HE-LHC

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1 Introduction

In view of the smaller physical apertures of Nb3Sn magnets for the HE-LHC study [1, 2], a machine study was performed in the LHC to tighten correspondingly the ring and injection protection collimators and measure the change in loss behaviour. The smaller physical apertures will result in significantly smaller normalised apertures than what is presently available in the LHC. This report will address the question of whether Hilumi beam types can be injected with tight collimator settings. The results presented in this study will show the measured injection losses as a function of collimator setting with the preliminary attempts to extrapolate to higher injected intensities. This extrapolation will enable limitations of the collimator settings to be identified.

2 Measurements and analysis

The measurements took place on 13^{th} September, 2018, between the hours of `9:00` and `18:00` on beam 2 (beam 1 was used for another parallel MD). The measurement steps are shown in Fig. 1 where the purple line denotes the transfer line collimators (TCDI) gaps, the brown and green dots show the losses on these collimators and their shower on the most representative ring beam loss monitor `BLMQI.07R8.B2E10_MQM`, respectively. Injections were performed with both single pilot bunches, single nominal bunches, and trains of nominal bunches for a range of different collimator settings. A summary of the collimator settings used for the different beam types are shown in Tables 1–3.

During the study there were a number of issues with the injector chain resulting in some lost time between fills. After a successful injection, a loss map was obtained by blowing up the bunch emittance before dumping the bunch. Loss maps were not performed for the bunch trains, and the trains of 12 or 48 bunches were left circulating around the ring whilst the collimator gaps were reduced. The loss pattern in the beam 2 injection region is shown Fig. 2, where the beam direction is from right to left. The highest red bar is the Q7

Time	TCP	TCSG	TCDI
08:50	5.7	6.7	5.0
09:07	5.0	6.0	5.0
09:13	5.0	6.0	4.5
09:16	4.5	4.5	4.5
13:10	4.0	5.0	3.0
13.11	3.0	4.0	3.0

Table 1: Collimator settings for the pilot bunch.

Time	TCP	TCSG	TCDI
13:25	3.0	4.0	3.0
13:35	4.0	5.0	4.0
13:43	5.0	6.0	4.0
13:45	5.0	6.0	5.0

Table 2: Collimator settings for the nominal intensity bunch.

Time	TCP	TCSG	TCDI
15:24	5.7	6.7	5.0
15:29	5.0	6.0	4.0
15:34	4.0	5.0	4.0
15:46*	4.0	5.0	3.0
15:55	4.0	5.0	3.5
16.03	3.5	4.5	3.5
16.04	5.7	6.7	5.0
16.31^{+}	4.5	5.5	4.0

Table 3: Collimator settings for the bunch trains. * Beam dump due to 104% of threshold BLMQI and 103% TCP.C6R7. + significant portion of the BLM threshold reached: 31% BLMQI.B2E10.MQM and 44% TCP.C6R7.B2.

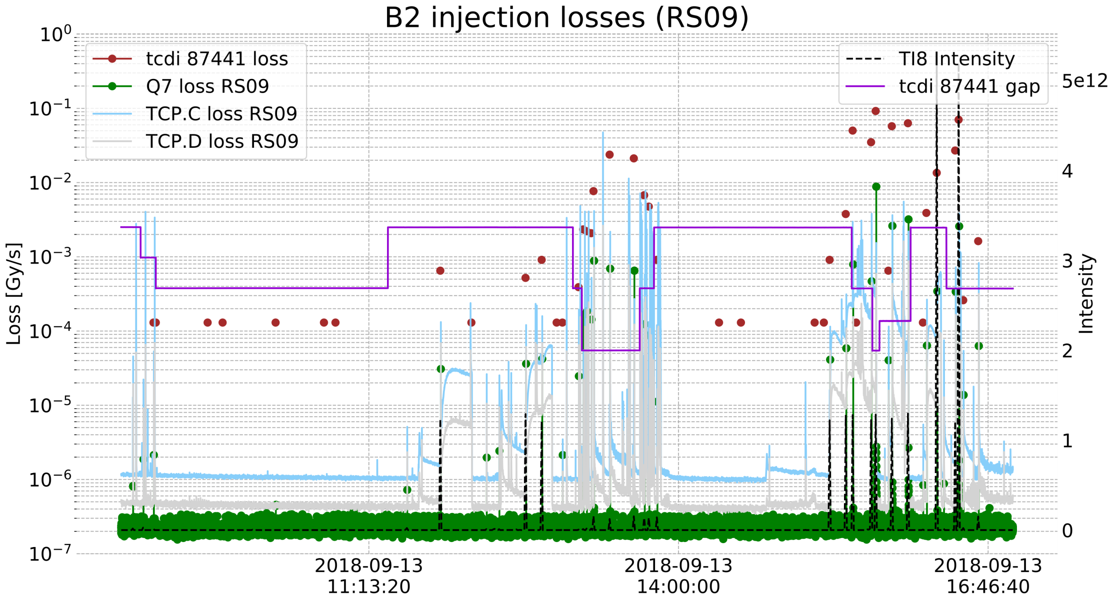


Figure 1: Measurement steps with different TCDI gaps and injected intensities.

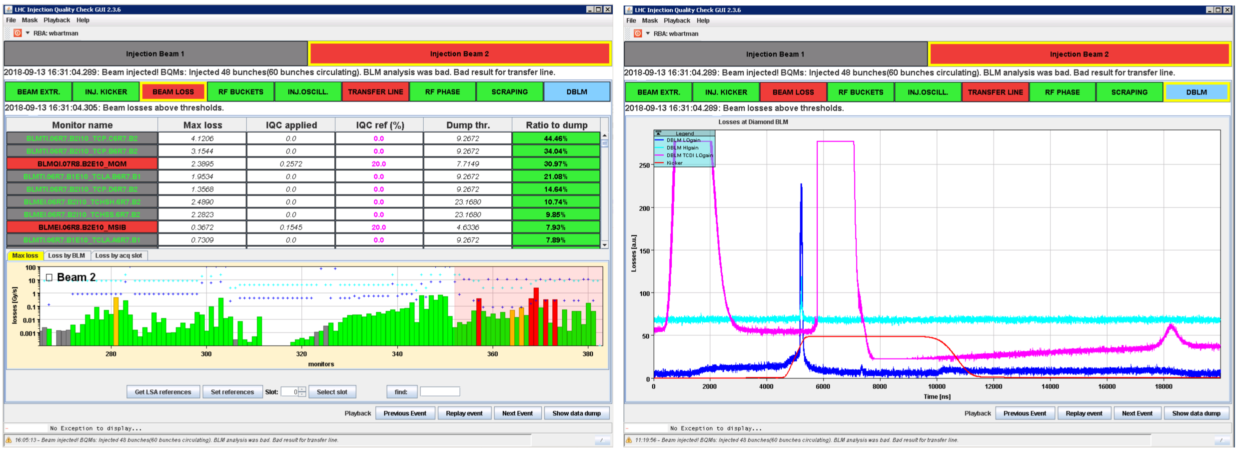
monitor as mentioned above, the absolute highest loss levels are on primary collimators in IP7. This is most likely due to a high level of satellites in front of the train to be injected which is miskicked by the rising edge of the injection kicker, see bottom of Fig. 2, and lost at primary collimators presenting the closest aperture downstream. The loss level at the primary collimators reaches 13 % of dump threshold for nominal collimator settings, which is high compared to usual operational losses below 10 % for injection of 144 bunch trains. Thus, losses from satellites contributed with a significant constant loss level during these measurements which needs to be considered when extrapolating to higher intensity injections. There is a clear correlation of losses measured in the transfer lines and in the ring. The losses in the transfer line impact on normal conducting magnets protected by masks and therefore are much less critical than losses impacting the superconducting magnets in the ring. Due to the clear correlation of both loss types, in the following only the ring losses denoted as Q7 are shown.

The ring loss data is plotted as a function of TCDI gap in Fig. 4. Even though the emittance of single bunches and 48 bunch trains with 1.5 μm and 12 bunch trains with 2.6 μm differ significantly, the tail cut assuming a Gaussian distribution changes for the tightest TCDI setting only by $5{\cdot}10^{-4}$, see Fig. 3. This difference is negligible compared to normalized loss levels varying by up to 40 % for the same collimator setting.

The measurements from 48 b trains were scaled up to a full LHC batch (6 batches of 48 b trains of same bunch intensity) and to a full Hilumi batch (6 batches of 48 b trains with increased bunch intensity).

2.1 Measurement of the losses in IR7.

In addition to the losses at the `TCDI`, the losses on the primary collimators in IR7 of the LHC were also analysed at the various collimator settings. Figure 5 shows the losses on the



2018-09-13 16:31:04.289: Beam injected! BQMs: Injected 48 bunches(60 bunches circulating). BLM analysis was bad. Bad result for transfer line.

2018-09-13 16:31:04.305: Beam losses above thresholds.

Monitor name	Max loss	IQC applied	IQC ref (%)	Dump thr.	Ratio to dump
BLMTI.06R7.B2I10_TCP.C6R7.B2	4.1206	0.0	0.0	9.2672	44.46%
BLMTI.06R7.B2I10_TCP.B6R7.B2	3.1544	0.0	0.0	9.2672	34.04%
BLMQI.07R8.B2E10_MQM	2.3895	0.2572	20.0	7.7149	30.97%
BLMTI.06R7.B1E10_TCLA.B6R7.B1	1.9534	0.0	0.0	9.2672	21.08%
BLMTI.06R7.B2I10_TCP.D6R7.B2	1.3568	0.0	0.0	9.2672	14.64%
BLMEI.06R7.B2I10_TCHSH.6R7.B2	2.4890	0.0	0.0	23.1680	10.74%
BLMEI.06R7.B2I10_TCHSS.6R7.B2	2.2823	0.0	0.0	23.1680	9.85%
BLMEI.06R8.B2E10_MSIB	0.3672	0.1545	20.0	4.6336	7.93%
BLMTI.06R7.B1E10_TCLA.A6R7.B1	0.7309	0.0	0.0	9.2672	7.89%

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16:05:13 - Beam injected! BQMs: Injected 48 bunches(60 bunches circulating). BLM analysis was bad. Bad result for transfer line.

2018-09-13 16:31:04.289: Beam injected! BQMs: Injected 48 bunches(60 bunches circulating). BLM analysis was bad. Bad result for transfer line.

2018-09-13 16:31:04.289: Beam losses above thresholds.

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11:19:56 - Beam injected! BQMs: Injected 48 bunches(60 bunches circulating). BLM analysis was bad. Bad result for transfer line.

Figure 2: Beam 2 injection region losses (left) and satellites (right) for a 48 bunch train injection at 4 σ TCDI setting.

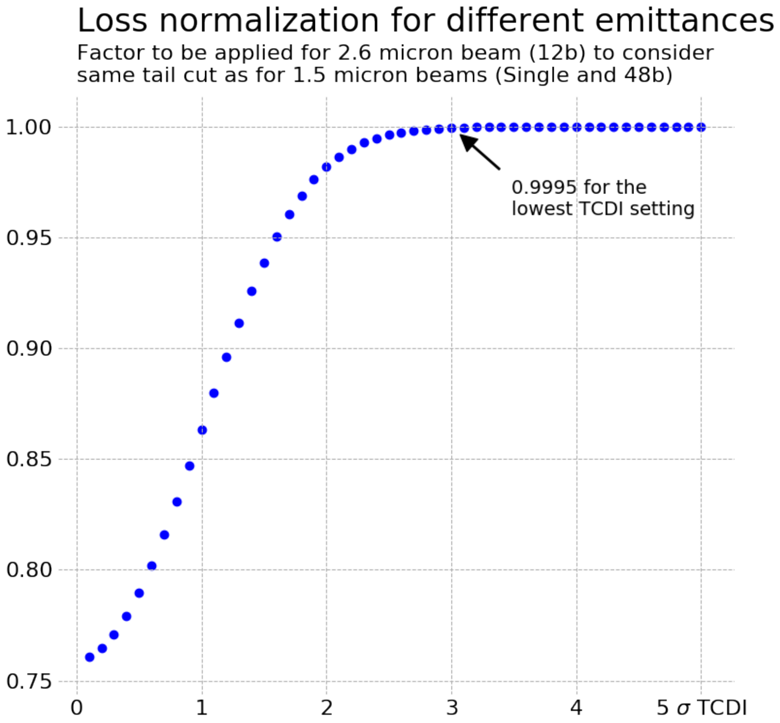

Figure 3: Loss correction factor to account for different tail cut of injected beams. This is relevant if losses from different beam types are compared and extrapolated.

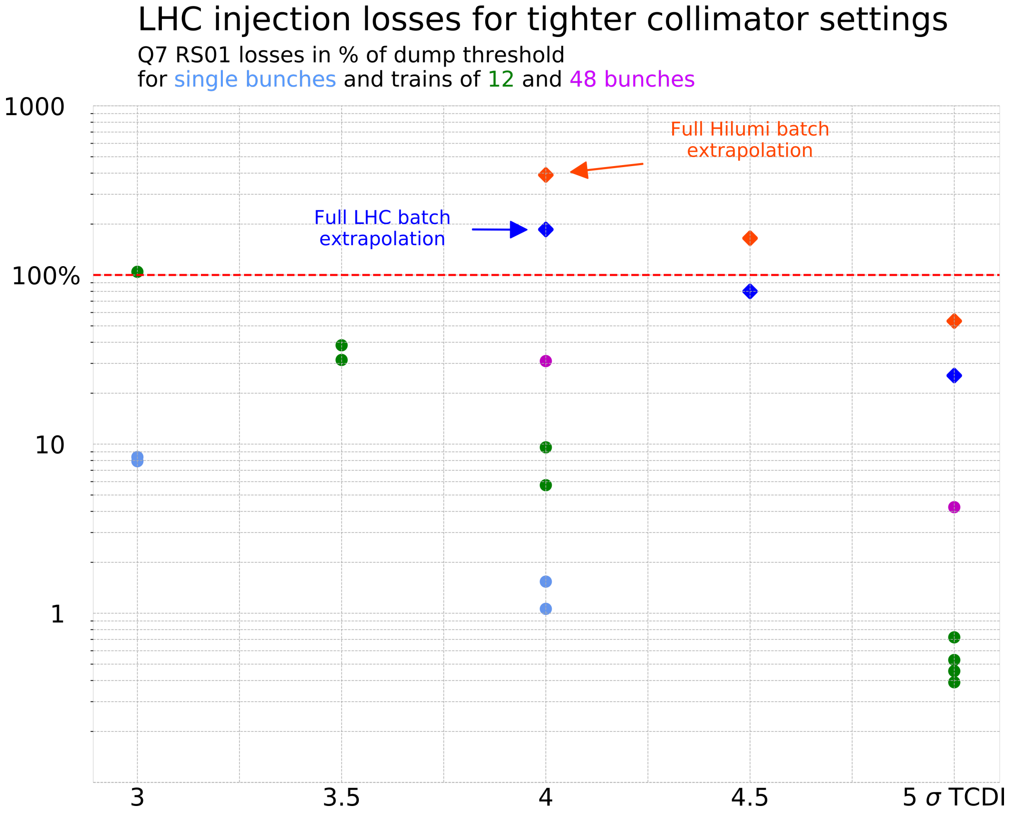

Figure 4: LHC injection losses for different gap settings of the transfer line collimators TCDI. Data points for beams of different intensities are shown in circles, extrapolation of these data points to full LHC and Hilumi batches are shown as diamonds.

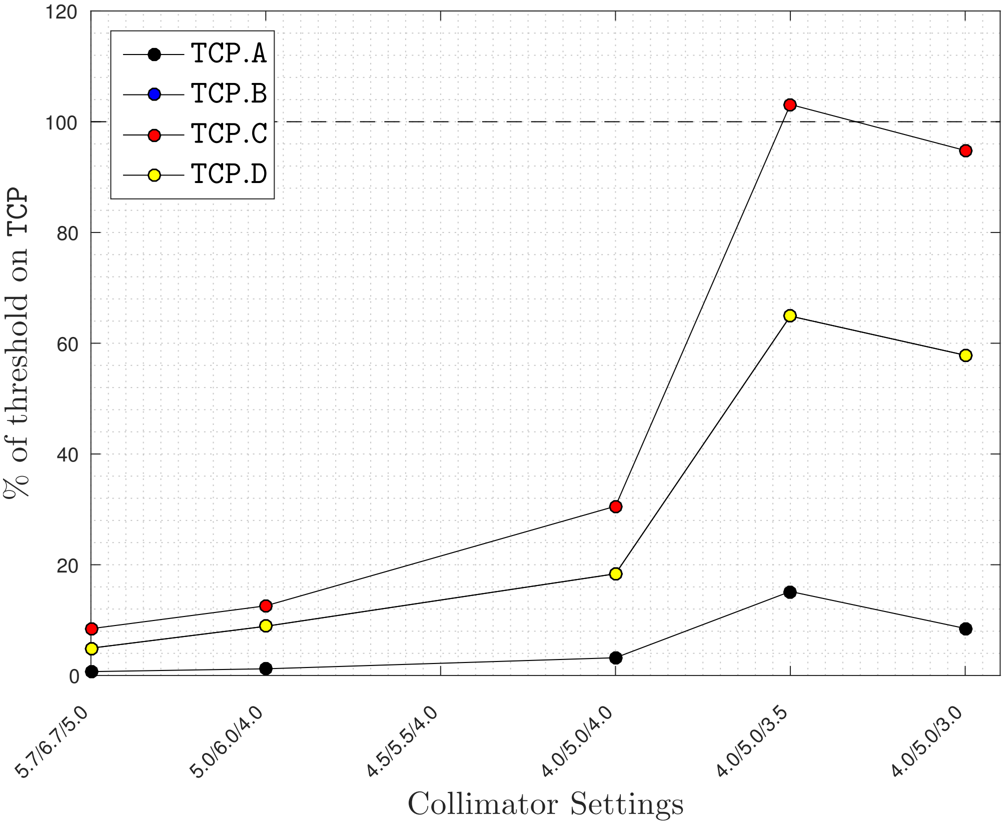

Figure 5: Losses on the primary collimators in IR7 for the 12 bunch trains at various collimator settings given by `TCP/TCSG/TCDI` in units of σ for a beam emittance of 3.5 μm .

primary collimators in IR7 as a function of decreasing collimator gap sizes. The peak losses occur when the primary, secondary and `TCDI` are set to 4.0/5.0/3.5 σ respectively, with the largest losses observed on the `TCP.C` in the horizontal plane. One possible explanation for observing peak losses with the `TCDI` at 3.5 σ on the `TCP.C` is that the TCDI scatters protons that reach IR7.

As previously mentioned in section 2, the loss level at the primary collimators was high for the machine study compared to normal operation, with these losses likely arising due to uncaptured satellites. When extrapolating to higher intensity bunches like those for the HE-LHC or the HL-LHC, the impact from these additional satellites should be subtracted from the scaling to avoid an erroneous calculation. Hence the difference constant can be calculated between machine study and the typical value for nominal operation. This difference value is given by

$$k = \frac{g}{144} \cdot \frac{12}{0.13}, \tag{1}$$

when $g = 0.1$, this gives $k = 0.0641$. This assumes a worse case scenario in which the losses during normal operation are 10%, where in fact they are typically smaller than this. Using this calculation, the losses as a function of collimator settings as shown in figure 7.

From this initial estimation the minimum plausible operational collimator settings below the threshold can be deduced. For a HE-LHC like bunch with 2.2×10^{11} ppb and $g = 10\%$,

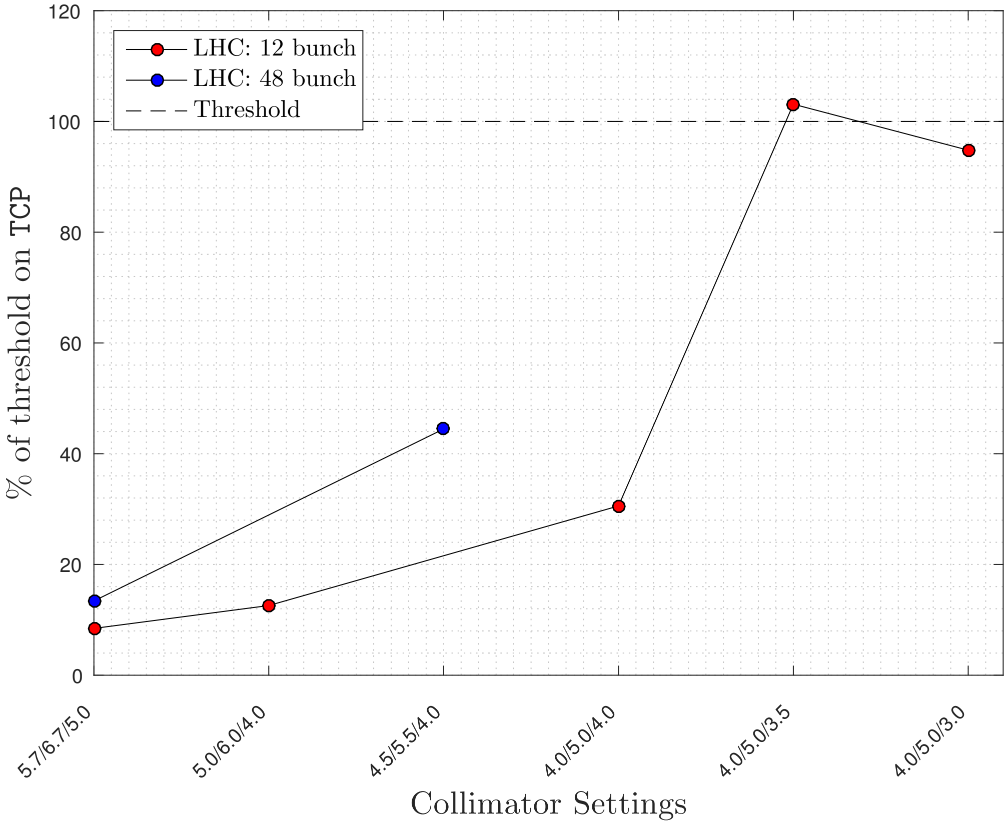

Figure 6: Comparison of the losses on the `TCP.C` for the 12 bunch and 48 bunch train scenarios.

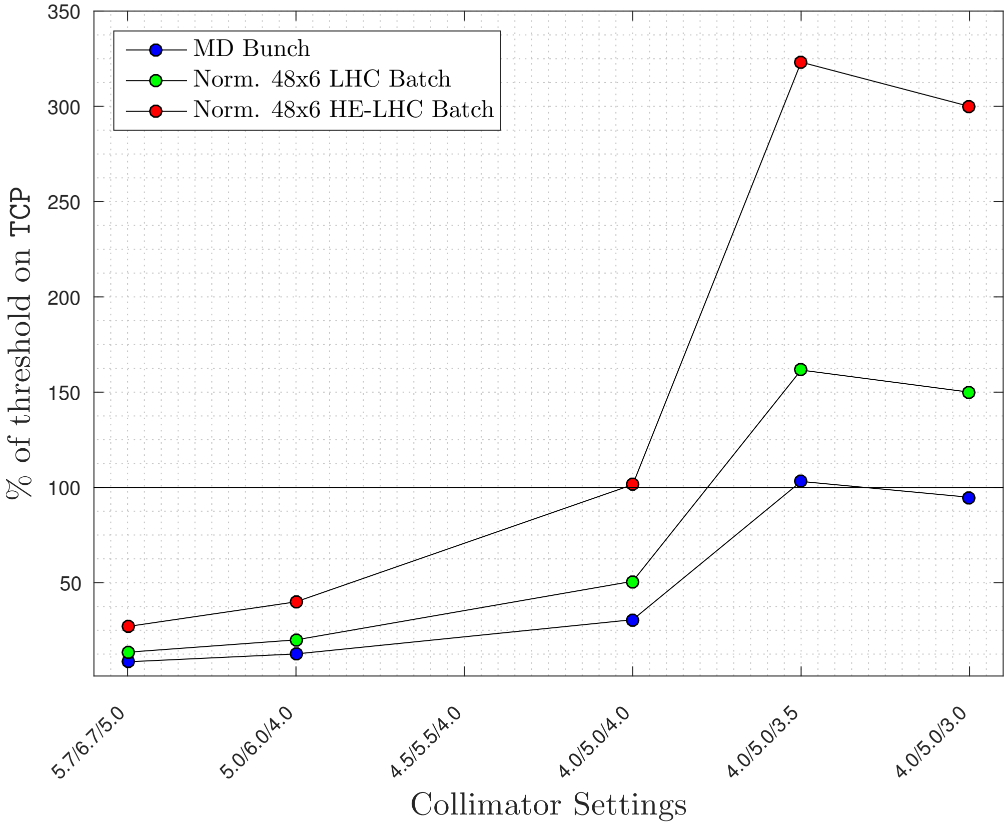

Figure 7: Extrapolation and estimation of the loss threshold for a full batch of LHC and HE-LHC like trains assuming relevant bunch intensities.

the limit is set to 5.0/6.0/4.0. These settings could possibly be reduced further down to 4.5/5.5/4.0, however this is with the existing LHC system. The HE-LHC would use Nb_3Ti as the main superconducting component and this magnet material will behave differently to the NbTi currently employed by the LHC. Hence these limits and would need to be revised for the HE-LHC magnets in the future. In addition, although the estimated values are below the threshold limit, for collimator settings of 5.0/6.0/4.0 and $g = 10\%$, the extrapolated estimated threshold limit is 40%. This is significantly larger when compared to nominal LHC operation which is typically below 10%.

3 Conclusions

What can be observed from the measured data is an increase of transverse losses by about a factor 10 for a reduction of the TCDI gap by 1 σ.

From the extrapolation one can conclude that injection of a full Hilumi batch is already now operable for a 5 σ TCDI opening and envisage-able for 4.5 σ with careful scraping of tails in the SPS and regular transfer line steering. A TCDI opening of 4 σ seems out of range without severe modifications of hardware related to injection trajectory fluctuations. Settings are expressed using a normalized emittance of 3.5 μm following the standard LHC notation. This is 1.5 to 2 times larger than the emittance values measured in these tests.

While the interlock request of certain injection region monitors - including the Q7 monitor used for the analysis - can be temporarily ignored, this cannot be done in general for the full injection region without compromising the protection of the machine.

From the analysis of the losses on the primary collimators in IR7, it can be seen that by reducing the primary collimator gap by 1 σ increases the losses on the TCP.C approximately by a factor of 2.5, however the operational minimum depends on how well the longitudinal losses can be controlled. From this study it can be seen that the TCP losses depend on the TCDI setting and it is not possible to fully decouple the the losses with this MD data. An operational collimator setting with a 4 σ primary opening seems unfeasible with current hardware constraints since a normal batch with a HE-LHC-like beam contributes to 50% of the primary threshold limit.

The analysis here assumes present dump thresholds which are derived for the quench limits of LHC magnets made of NbTi coils. These limits will have to be revised for HE-LHC magnets. Also, a full design of the injection protection system is required to define the required transfer line collimator settings with respect to the tighter physical machine aperture.

References

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[2] A. Abada et al. HE-LHC: The High-Energy Large Hadron Collider. *The European Physical Journal Special Topics*, 228(5):1109, 2019.