ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC11

CORRELATING START-OF-RAMP LOSSES WITH BEAM OBSERVABLES AT FLAT-BOTTOM IN THE LHC

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Abstract

Power limitations are expected at injection energy for the main Radio Frequency (RF) system due to the doubled bunch intensity in the High Luminosity (HL-) Large Hadron Collider (LHC) era. One way to overcome these power limitations is to reduce the capture voltage. The smaller RF bucket, however, leads to increased beam losses at the start of the ramp. In practice, these beam losses, which contain both capture and flat-bottom losses, can trigger beam dumps if any of the Beam Loss Monitor (BLM) thresholds are reached. In this contribution, the correlation between start-of-ramp beam loss and beam observables before the ramp is investigated by analysing Beam Current Transformer (BCT) measurements from physics fills. Estimates of how the maximum ratio to BLM dump threshold scales with longitudinal losses are also made. The aim is to make predictions for operation at higher bunch intensities on the basis of these correlations in view of the intensity ramp up for the HL-LHC era.

INTRODUCTION

At injection energy, de-bunched particles outside the RF separatrix in the longitudinal phase space move asynchronously around the ring. At the start of the ramp, part of the particles drifting at higher energies might be recaptured; all other de-bunched particles eventually hit aperture limitations as their relative energy decreases. As the particles left behind deviate from the design orbit, the losses will increase rapidly at the ring locations with higher dispersion, such as interaction region (IR) 3. Beam losses are therefore expected to be higher at the BLMs positioned downstream the off-momentum cleaning collimators in IR3 [1, 2]. Although some losses occur on the betatron collimators in IR7 as well, due to the non-zero dispersion, the losses observed in IR3, i.e. those mainly originating from the longitudinal plane, are the main focus of this contribution.

The losses at the start of the ramp can originate from two main sources, immediate capture losses and flat-bottom losses. Capture losses are particles that do not end up inside the LHC RF buckets after the beam is injected from the Super Proton Synchrotron (SPS), and the initial injection transients are overcome. Flat-bottom losses are particles that are driven out of the buckets during LHC filling and preparation for the ramp, which typically takes an hour. As the bunches stay at injection energy, effects such as intra-beam scattering [3], RF phase noise [4] and beam phase loop transients at every injection lead to longitudinal emittance blow-up. Due to these effects, halo particles close to the separatrix are slowly pushed outside the buckets.

The target bunch intensity of 2.3×10^{11} protons per bunch (p/b) for the HL-LHC [5] is estimated to require a capture voltage of 7.9 MV [6]. For this voltage and bunch intensity, with the beam-loading transients, the estimated peak power exceeds the presently installed RF power, which by design is 300 kW per klystron [7]. Fine-tuning the voltage with respect to losses and RF power demand will be essential for operation during the HL-LHC era.

In this contribution, results from the 2022 and 2023 LHC runs are shown. Projections are also made for 1.9×10^{11} p/b, which is the highest bunch intensity the LHC RF system can capture without any modifications for 72-bunch trains.

BUNCH-BY-BUNCH LOSSES DURING FLAT-BOTTOM

In the LHC, the intensity for every 25 ns bunch slot is measured by the fast beam current transformer (FBCT) [8], and the total intensity in each ring is measured by the direct current (DC) BCT. The DC BCT gives a very accurate measurement of the total intensity circulating in each ring, but does not resolve where the intensity is located along the circumference. For this analysis, the bunch intensity, $N_b^{(i)}$ of bunch i was found by scaling the FBCT measurement with the DC BCT measurement injection-by-injection according to

$$N_b^{(i)} = \frac{N_{\mathrm{DC}}}{\hat{N}_{\mathrm{fast}}} N_{\mathrm{fast}}^{(i)} . \quad (1)$$

Here, N_{DC} is the total intensity of the bunch train as measured by the DC BCT at injection, $\hat{N}_{\mathrm{fast}}$ is the total intensity of the bunch train measured by the FBCT at injection, and $N_{\mathrm{fast}}^{(i)}$ the intensity of bunch i measured by the FBCT. The batch intensity, as measured from the DC BCT, is obtained from the derivative of the DC BCT signal and by summing the first few values of the derivative after the injection.

The relative loss in intensity, $l^{(i)}$ of bunch i, injected into the LHC until the ramp is given by

$$l^{(i)} = \frac{N_{\mathrm{fast,inj}}^{(i)} - N_{\mathrm{fast,sor}}^{(i)}}{N_{\mathrm{fast,inj}}^{(i)}} , \quad (2)$$

with the subscript “inj” denoting the FBCT intensity at injection and “sor” at the start of the ramp. The absolute intensity loss, $\Delta N_b^{(i)}$, is then given as $\Delta N_b^{(i)} = N_b^{(i)} l^{(i)}$ for bunch i. Note that $\Delta N_b^{(i)}$ is a combination of the beam lost from the

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bucket but still circulating in the ring and the particles lost from the ring. The latter is denoted as L_{fb}. In this contribution l is used for the bunch intensity loss and L is used for total beam loss.

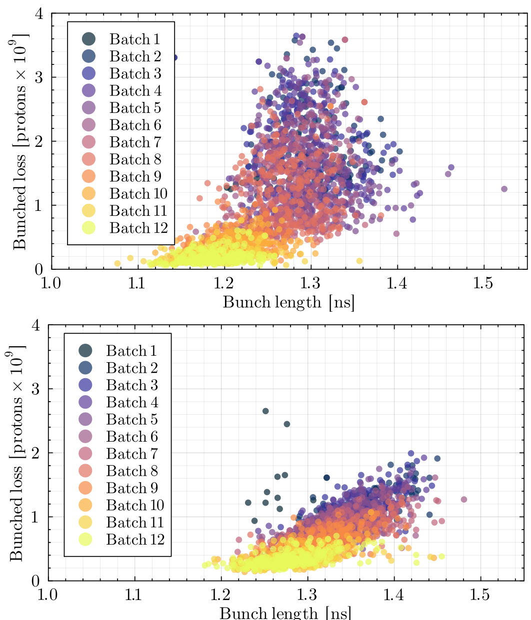

Figure 1: Decrease in bunch intensity, $\Delta N_b^{(i)}$, as a function of the bunch length at the start of the ramp in beam 1 (top) and beam 2 (bottom). The data was taken from fill 9068.

The absolute bunched intensity loss was extracted from logged data for all LHC physics fills in 2022 and 2023 which were accelerated. Figure 1 show $\Delta N_b^{(i)}$ as a function of bunch length at the start of the ramp for beam 1 (B1) (top) and beam 2 (B2) (bottom). The plotted data is taken from fill 9068, which was considered representative for the 2023 run. The plot shows that $\Delta N_b^{(i)}$ is larger in B1 than in B2 on average. Furthermore, there is a correlation between bunch length and $\Delta N_b^{(i)}$ for B2. This correlation is not as prominent in B1, which might point towards a significant loss contribution from transverse effects. Furthermore, one can see that even though $\Delta N_b^{(i)}$ is higher for B1, the bunches are shorter than in B2. Both the increase in bunch length and the increase in loss is greater for the bunch trains that have been in the machine for longer (low batch index), since these bunches had a longer time to blow up.

ESTIMATING OFF-POSITION BEAM

As already mentioned, the DC BCT measures the total intensity in the ring. Finding the difference between the total injected intensity into the LHC, by summing N_{DC} for every injection, and the total intensity before the ramp one can estimate L_{fb}. The difference between the total bunched intensity loss and the total intensity loss from each injection to start of ramp,

$$N_{\mathrm{off}} = \sum_i \Delta N_b^{(i)} - L_{\mathrm{fb}}\,, \qquad (3)$$

should be the total beam circulating in the ring outside the bunches, which is the so-called off-position beam N_{off}. Note here that the off-position beam is a combination of the off-momentum beam and other particles which are not in their desired RF buckets. Figure 2 summarizes the losses at the start of the ramp L_{sor}, seen in IR3, as a function of off-position beam for LHC fills in 2022 and 2023. The start-of-ramp loss is estimated based on the signal of the BLM downstream of the primary collimator for each beam in IR3 with an integration window of 655 ms (running sum, RS8), which is then re-scaled and saved in Gy/s. The data is logged at 1 Hz by taking the maximum value of the running sum within the 1 s period. There are 12 different RSs ranging from 40 μs to 84 s [9] and, if any running sum of any monitor of the BLM system exceeds its threshold, the BLM system triggers an abort sending the beam to the dump. The RS8 data was chosen because, from operational experience, it has been the most limiting. This data is then converted into p/s via a scaling factor [10, 11] and integrated over the first 20 GeV of the LHC ramp to estimate the final loss value. Note that integration of the RS8 data will have the effect of overestimating the losses since the maximum value is logged. From Fig. 2, one can see that there is a clear correlation for both beams between the off-position beam and the loss estimated at the start of the ramp.

Table 1: Parameters computed based on the start-of-ramp losses, L_{sor} in IR3. The average fraction of dump threshold is denoted as R_{dump}.

Parameter	Unit	Beam 1	Beam 2
$L_{\mathrm{sor}}/N_{\mathrm{off}}$	[%]	54.9 ± 3.2	57.0 ± 2.5
L^0_{sor}	$[\mathrm{p} \times 10^{10}]$	-8.4 ± 3.2	-17.1 ± 2.8
$R_{\mathrm{dump}}/L_{\mathrm{sor}}$	$[\%/(\mathrm{p} \times 10^{11})]$	3.8 ± 0.2	7.1 ± 0.4

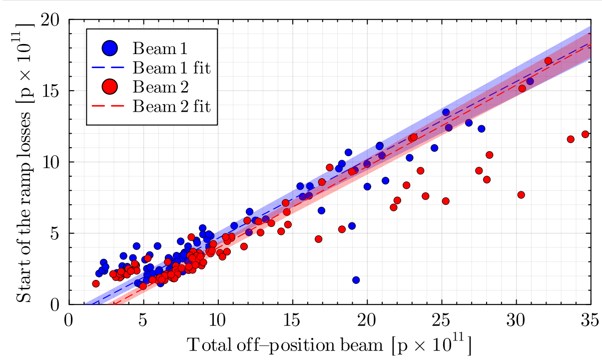

Figure 2: Start-of-ramp losses as a function of total off-position beam before the start of the ramp.

Figure 2 shows that the fill-by-fill spread in N_{off} increases for fills which had a higher L_{sor}. As start-of-ramp losses are expected to be limiting in the HL-LHC, linear fits were performed on the data points along the main diagonal in order to study the worst case scenario. The resulting values from the fits are found in Table 1. The percentage of N_{off} converted into losses in IR3 at the start of the ramp seem to be the same for both beams. The constant term of the fit, L^0_{sor}, could be interpreted as giving the maximum amount

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Table 2: Projections for higher intensities based on operational experience in 2022 and 2023. The values given for 1.6×10^{11} p/b are based on measurements, while the other are estimated.

Bunch intensity	Voltage	Beam 1		Beam 2	
		L_{sor}	R_{dump}	L_{sor}	R_{dump}
1.6×10^{11} p/b	5 MV	$(3.8 \pm 2.5) \times 10^{11}$ p	(18 ± 16) %	$(3.7 \pm 2.3) \times 10^{11}$ p	(34 ± 26) %
1.9×10^{11} p/b	5 MV	$(8.29 \pm 0.63) \times 10^{11}$ p	(31.6 ± 2.4) %	$(13.07 \pm 0.7) \times 10^{11}$ p	(93.2 ± 5.0) %
1.9×10^{11} p/b	7 MV	$(3.44 \pm 0.41) \times 10^{11}$ p	(13.1 ± 1.6) %	$(3.48 \pm 0.36) \times 10^{11}$ p	(24.8 ± 2.6) %

of N_{off} without having any L_{sor} when divided by the factor L_{sor}/N_{off}. The uncertainty for this term is comparable to the value itself and could come from many different factors, e.g. a small difference in abort gap cleaning efficiency.

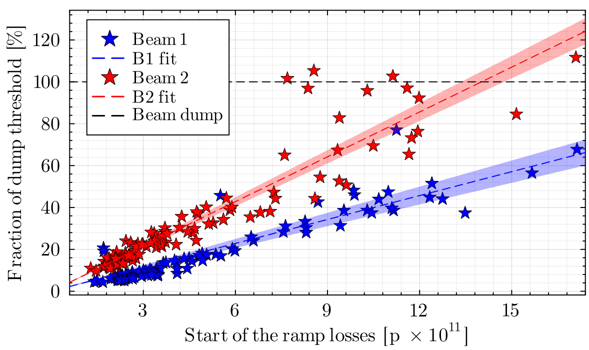

Figure 3: Maximum fraction of the dump threshold in IR3 as a function of the total number of protons lost in IR3 at the start of the ramp.

To make projections for HL-LHC, it is necessary to determine the maximum acceptable loss at the start of the ramp, which is given by the BLM dump thresholds. Figure 3 shows the maximum fraction of the dump threshold of all the BLMs and all running sums in IR3 as a function of losses at the start of the ramp. The same fills as for Fig. 2 were analyzed. Linear fits were performed on the data in Fig. 3 as well, and the resulting fraction of the dump threshold per proton lost can be found in Table 1 (bottom). For the same amount of losses in B1 and B2, the highest faction of dump threshold of the BLMs monitoring B2 is 1.87 times higher than in B1. One of the reasons being that the BLMs are located in different places with respect to the primary collimators, and therefore the particle showers they observe are different. The BLM in B1 having the highest fraction was a mix of BLMTI.05R3.B1I10_TCLA.A5R3.B1 and BLMQI.06R3.B1I10_MQTL. For B2 this was mainly BLMQI.06L3.B2E10_MQTL. Furthermore, the RS corresponding to the data points in Fig. 3 are different for the two beams. For B1 this was mainly RS8 and for B2 RS10.

PROJECTION FOR OPERATION AT HIGHER INTENSITIES

For the first time, in an MD session during the summer of 2023 [12], trains of 72 bunches with 25 ns spacing were injected into the LHC with an average bunch intensity of 1.9×10^{11} p/b. Injections were tested with different RF voltages. Specifically, it was of interest to compare capture with 5 MV, the present operational RF voltage, and 7 MV, which is the maximum voltage maintainable at this intensity. Up to four of these 72-bunch trains were injected before the beam was dumped. These batches were not accelerated due to the excessive time needed for the ramp, so the start-of-ramp losses could not be measured directly.

However, the time evolution of the bunch intensity and the total beam intensity was recorded. It is therefore possible to conduct a similar analysis to what was done for the physics fills, i.e. finding N_{off}. The off-position beam is in principle a function of time, and it should scale with the number of bunches in the ring. Using the correlations found in Table 1, one then obtains the results summarized in Table 2. For these values N_{off} was scaled to 2400 bunches and to an average time of 30 minutes spent at flat-bottom.

As expected, the losses decrease with increasing RF voltage. Furthermore, B2 is consistently closer to the BLM dump threshold than B1, and the threshold is almost within the standard deviation for 1.9×10^{11} p/b with 5 MV in B2. For an RF voltage of 7 MV, however, the fraction-of-dump-threshold level in operation would be similar to that of 2023. If 7 MV is needed for 1.9×10^{11} p/b to avoid regular beam aborts and assuming the required voltage during HL-LHC is 7.9 MV, this will leave little margin for the higher HL-LHC intensity. It is also worth noting that, to obtain N_{off} for the MD data, a linear scaling with time was assumed. This is a simplification of the time behavior of the losses, which will underestimate the start-of-ramp losses.

CONCLUSIONS

Based on operational experience in 2022 and 2023, correlations between off-position beam, the loss at the start of the ramp and the maximum BLM fraction-of-dump-threshold was made. Using these correlations, it was concluded that 7 MV is required to maintain the 2023 operational margin, with respect to the maximum BLM fraction of dump threshold in IR3, for operation with $1.9{\times}10^{11}$ p/b. With the current BLM thresholds in the LHC, this will leave little margin to reduce the RF voltage for the HL era intensities. However, the BLM thresholds are being revisited. The current models are still those of the LHC start-up and require re-evaluation for the HL-LHC.

ACKNOWLEDGEMENTS

Research supported by the HL-LHC project. We thank T. Argyropoulos, I. Karpov, and R. Calaga for helpful discussions and the shift crews of the injectors and the LHC for their help with the measurements.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC11

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