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MITIGATION OF LOSSES AT INJECTION PROTECTION DEVICES IN THE CERN LHC

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Abstract

During loss maps performed with beam at injection energy in the LHC to validate collimation settings, with the high octupole and chromaticity settings used for multi-train operation, large beam losses were observed at an injection protection device (TDIS). Although these losses did not present a threat to machine operation or protection, mitigating them is of high importance to reduce the local radiologial-activation. Various strategies were developed to mitigate these losses, such as octupole setting optimization at constant Landau damping and vertical tune reduction. Further optimization of collimator settings is also considered. Results of experimental tests and first simulations are reported here together with considerations for the future.

INTRODUCTION

The TDIS is a dump/absorber aimed at protecting downstream LHC equipment during the injection phase. Since the LHC stores two counter-rotating beams, two of these devices are installed in the machine at the injection points in the Insertion Region (IR) 2 and 8 for Beam 1 and 2, respectively. The TDIS consists of two vertically movable jaws, with two counter-rotating beams circulating: the injected beam that is passing between the jaws and the circulating one traversing the device in a RF-screen [1]. During the injection phase the jaws are inserted symmetrically with respect to the injected beam reference orbit. The TDIS settings in sigma are just above the secondary collimators (TCS), which are retracted 1 σ from the primary collimators (TCP), as shown in Table 1. After the injection phase is completed, the jaws are completely open.

Table 1: IR7 and injection collimator settings during the injection phase in beam σ with and emittance of $\epsilon = 3.5\,\mu$m.

	Half Gap [σ]
TCP	5.7
TCS	6.7
TDIS	6.8

During 2022, off-momentum and on-momentum loss maps were performed with large Landau octupoles (MO) and chromaticity (Q') settings for the first time, revealing large losses at the TDIS [2]. The strong octupoles and chromaticities are needed to damp coherent beam instabilities driven by electron clouds in operation [3, 4]. The scans of these losses versus Q' and MO strength are presented in

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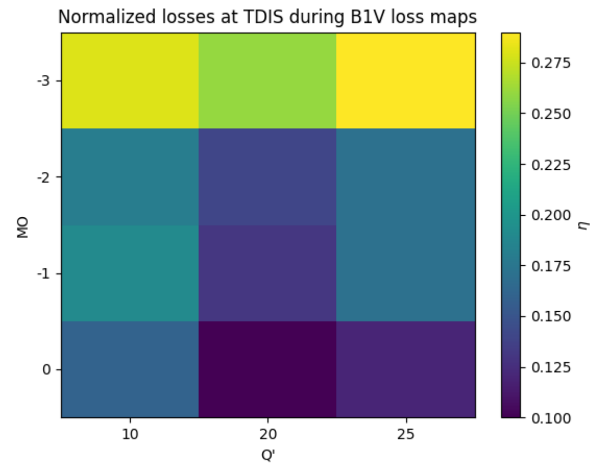

Figure 1: Losses at the TDIS normalized to the TCP losses versus chromaticity and octupole settings for vertical betatron loss maps with low bunch intensity.

Figs. 1 and 2. For the negative off-momentum loss maps, these normalized losses reach a value of 1, implying a break in the collimator hierarchy. No particular issue was observed during horizontal or positive off-momentum loss maps. To study the source of the unwanted losses, loss maps were performed with an optimized octupolar knob and with a reduced vertical tune. The results of which are presented below along with discussions for the next steps.

LOSS MAPS

Loss maps are performed in the LHC to validate the collimation settings in terms of cleaning efficiency and machine protection. Transverse loss maps are performed by blowing up the horizontal or the vertical emittance. For the off-momentum loss maps, the beam energy is increased or decreased by changing the RF frequency by ±300 Hz ($\delta p/p = \pm 0.0021$).

Figure 3 shows the bunch tune footprint corresponding to a vertical loss map, where colors are schematically used for different relative energy deviations ($\delta p/p$) within the bunch. Some particles reach the $3Q_y$ and $4Q_x$ resonances which could cause phase-space deformations breaking the collimation hierarchy and increasing the losses in the TDIS.

Figure 4 shows the model horizontal and vertical tunes versus $\delta p/p$ representing the evolution of the tunes during off-momentum loss maps. For the negative off-momentum loss maps, the vertical tune reaches $2Q_x - 2Q_y$ and the

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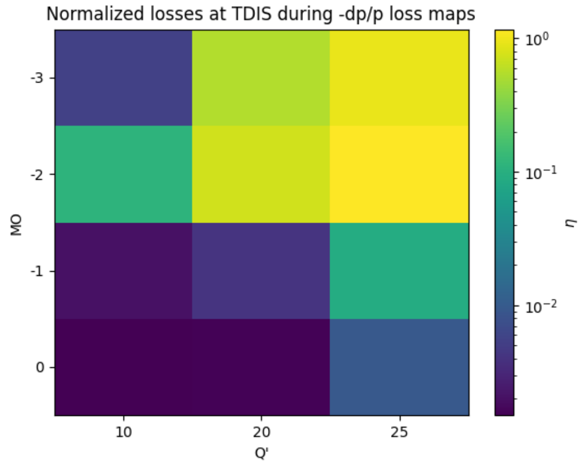

Figure 2: Losses at the TDIS normalized to the TCP losses versus chromaticity and octupole settings for negative off-momentum loss maps with low bunch intensity.

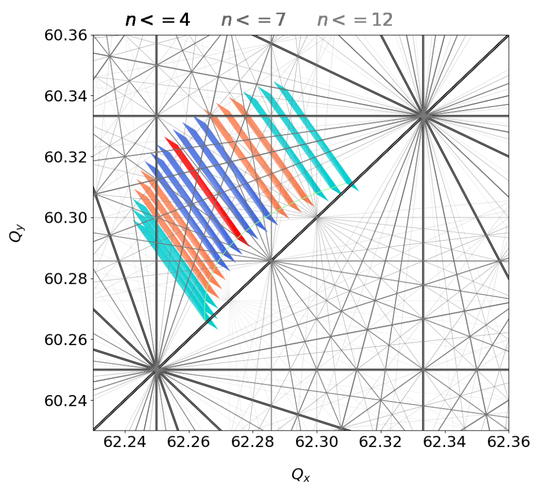

Figure 3: Schematic view of the tune footprint during a vertical loss map where the vertical beam size is blown up to reach collimator gaps at about 6 σ, MO=-3 and $Q' = 25$. The different colors correspond to different $\delta p/p$ for a full range of $\pm 3\sigma_\delta$, with $\sigma_\delta = 3 \times 10^{-4}$ and red being $\delta p/p = 0$. n stands for the order of the resonance.

$4Q_y$ resonances which could cause the collimator hierarchy breaking.

During 2022, only a very limited set of experiments could be performed to further investigate the source of the TDIS losses. To this aim, two new configurations were conceived, using a new octupole knob and reducing the vertical tune.

New Octupole Knob

The Landau octupoles strongly drive the resonances $2Q_x - 2Q_y$, $4Q_x$ and $4Q_y$. These resonances deform the transverse phase space of the particles in a way that could

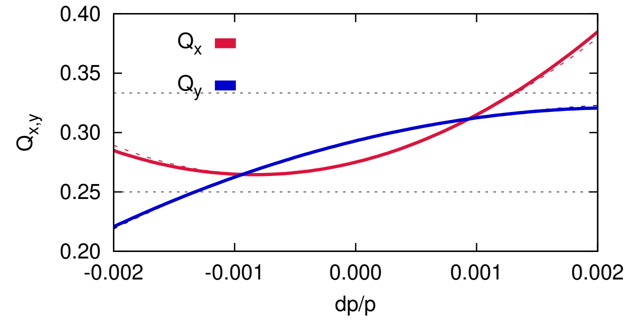

Figure 4: Tunes versus relative energy deviation. Third and fourth order resonances are shown with horizontal dotted lines.

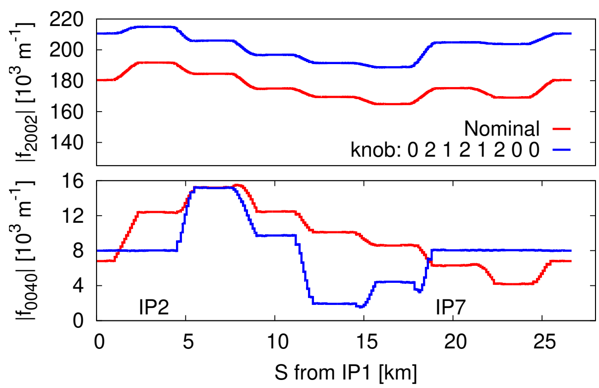

Figure 5: Resonance driving terms f_{2002} (top) and f_{0040} (bottom) for the nominal and the new octupole knob.

allow them to avoid the TCP or TCS yet get lost at the TDIS, thus breaking the collimator hierarchy. The size of this deformation is quantified by the resonance driving terms (RDTs), e.g. f_{2002} for the $2Q_x - 2Q_y$ resonance and f_{0040} for the $4Q_y$, which vary around the ring featuring steps at the locations of the octupoles [5–7]. Towards the end of 2022, it was proposed to use a different powering of the octupoles while keeping the same Landau damping but trying to equalize $|f_{2002}|$ and $|f_{0040}|$ at the TDIS (IR2) and the TCP (IR7). This is achieved by switching off the defocusing octupolar families in arcs 78, 81, and 12 and doubling the strength of the defocusing octupolar families in arcs 23, 45, and 67. The resulting RDTs are shown in Fig. 5. The new octupolar knob reduces the ratios of RDTs at the TDIS and TCP from 1.5 to 1 for $|f_{0040}|$ and from 1.1 to 1.05 for $|f_{2002}|$. Dynamic Aperture (DA) simulations with this new knob show an acceptable level of DA, see Fig. 6, very similar to the nominal configuration. Experiments with this new knob showed a small improvement of the TDIS losses for the vertical loss map, see Table 2, suggesting that these resonances could play a role in the loss mechanism. There was not sufficient time to test this knob for off-momentum loss maps.

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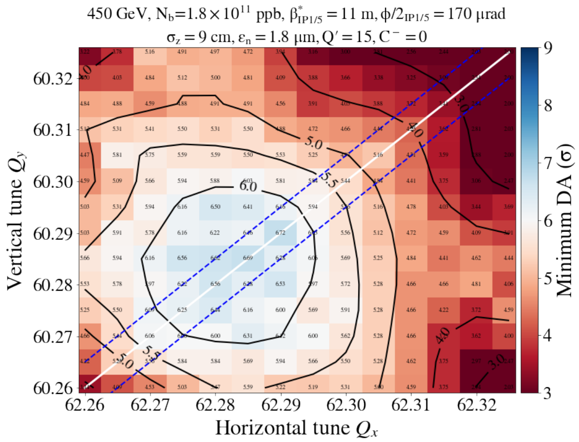

Figure 6: Dynamic aperture versus tunes at injection with the new octupole knob, which is within 0.5 σ from the nominal DA.

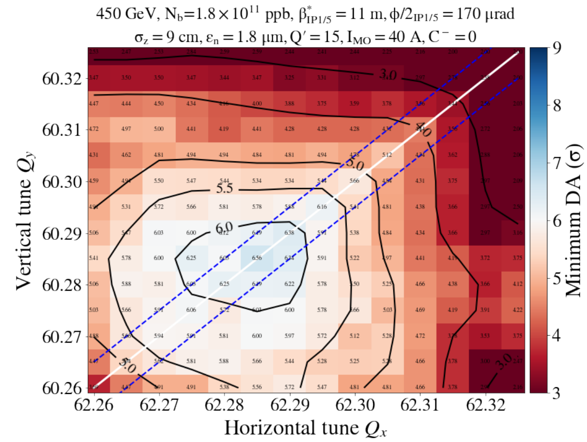

Figure 7: Dynamic aperture versus tunes at injection including an effective model of the $3Q_y$ resonance using MCSSX sextupoles as in Table 3.

Table 2: Beam 1 TDIS losses normalized to the losses of the Beam 1 TCP of IR7 during the experimental loss maps with the new configurations.

	Losses at B1 TDIS [%]			
	On-mom.		**Off-mom.**	
	H	V	$\delta > 0$	$\delta < 0$
Nominal	0.7	48	7.3	200
New octupole knob	0.6	36		
Lower Q_y ($\Delta = -0.005$)		34		
Lower Q_y ($\Delta = -0.01$)		25	2.0	224

Reduction of Vertical Tune

Table 3: Effective settings of IR skew sextupoles in m^{-3} to reproduce the measured $3Q_y$ resonance in Beam 1 in 2022.

Sextuple	**Value**
MCSSX3.R1	$-0.425\,\mathrm{m}^{-3}$
MCSSX3.R5	$-0.425\,\mathrm{m}^{-3}$
MCSSX3.R8	$+0.338\,\mathrm{m}^{-3}$

The impact of the $3Q_y$ resonance on DA is estimated in Fig. 7 by implementing an effective powering of IR sextupoles as in Table 3. A clear reduction in the DA below the 5.7 σ of the TCP half-gap for vertical tunes above 0.29 is observed, indicating that it is possible that the $3Q_y$ resonance affects the cleaning efficiency. Due to time limitations, it was not possible to test the TDIS losses with a correction of the $3Q_y$ resonance, however, it was possible to move the vertical tune away from the $3Q_y$ resonance. As shown in Table 2 lowering Q_y clearly reduced TDIS losses for vertical and positive off-momentum loss maps as expected, due to the reduced overlap of the tune footprint with the resonance. Concerning the negative off-momentum loss map, a degradation is observed that is consistent with the assumption that the $4Q_y$, and maybe also the $2Q_x - 2Q_y$, resonances contribute to the TDIS losses in this case.

SUMMARY & OUTLOOK

Reducing the vertical tune, hence pushing it away from the $3Q_y$ resonance, clearly reduced the TDIS losses in experimental betatronic loss maps. This opens the door to direct mitigation of the TDIS losses by optimizing the working point, possibly in combination with a safety interlock to avoid too large negative energy deviations, during the injection phase. This observation further supports the efforts to find suitable corrections of the $3Q_y$ resonance. Vertical betatronic loss maps with a new configuration of the Landau octupoles, at constant Landau damping, showed a mild improvement in the TDIS losses, suggesting that non-linear resonances as $4Q_y$ and $2Q_x - 2Q_y$ could play a role in the unwanted TDIS losses. Recent simulations with e-cloud suggest that octupolar resonances driven by the Landau octupoles play a key role in the emittance growth [10]. This, along with the TDIS losses, motivated the development of new optics configurations at injection to minimize the $4Q_y$, $2Q_x - 2Q_y$ and $4Q_x$ resonances by optimizing the arc phase advances using MAD-NG [11]. DA simulations with these new optics configurations showed significant improvements in both beams. Therefore, it was decided to implement these operationally in 2023 [12, 13]. Loss map simulations are being developed [14] to allow estimating the TDIS losses. First lifetime measurements in 2023 clearly show an improvement with the new optics configuration [15]. Preliminary loss maps in 2023 reveal significantly lower losses than in 2022 for Beam 1 but comparison to 2022 optics and further tests are still pending [16]. In summary, many alleys are being explored with promising initial results to understand and mitigate the unwanted TDIS losses during the LHC injection phase.

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