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UPDATED SIMULATION STUDIES OF DAMAGE LIMIT OF LHC TERTIARY COLLIMATORS*

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Abstract

The tertiary collimators (TCTs) in the LHC, installed in front of the experiments, in standard operation intercept fractions of 10^{-3} halo particles. However, they risk to be hit by high-intensity primary beams in case of asynchronous beam dump. TCT damage thresholds were initially inferred from results of destructive tests on a TCT jaw, supported by numerical simulations, assuming simplified impact scenarios with one single bunch hitting the jaw with a given impact parameter. In this paper, more realistic failure conditions, including a train of bunches and taking into account the full collimation hierarchy, are used to derive updated damage limits. The results are used to update the margins in the collimation hierarchy and could thus potentially have an influence on the LHC performance.

INTRODUCTION

During the first run in 2010-2013, the Large Hadron Collider (LHC) [1] was successfully operated at energies up to 4 TeV and at stored energies of 146 MJ with proton beams [2]. In 2015, the operation will resume after a long shutdown at an energy of 6.5 TeV, with the aim of achieving 7 TeV in the future. Further upgrades of luminosity are foreseen within the High-Luminosity LHC (HL-LHC) project, by increasing the beam intensity, reducing the beam emittance and decreasing β^* at the Interaction Points (IPs).

Given the destructive potential of such energetic beams, a multi-stage collimation system [3] must ensure efficient beam halo cleaning, prevent the superconducting magnets quench and protect the machine in case of beam failures. The investigation of the consequences of the LHC beam impacts in case of single turn beam losses on the tertiary collimators, which are made of a tungsten heavy alloy (Inermet180) and not robust enough to intercept large beam intensities, close to the IPs is fundamental to ensure machine protection and has also consequences on the luminosity performance [3, 4].

The LHC filling scheme has a gap of about 3 μs without beam, to allow the 15 extraction kicker magnets (MKDs) to rise up to full field during a standard beam dump. Nevertheless, faults could lead to an asynchronous beam dump, where the MKDs trigger is not synchronised with the abort gap. The worst scenario is represented by the spontaneous misfiring of one kicker module, followed by the re-triggerig of all the others, the so-called *single module pre-firing* [5]: due to the slowest rising time up to the total kicker field that is required for the extraction of the beam in Point 6 (IP6), several bunches may receive an intermediate kick and be sent directly to sensitive equipment, as machine aperture and non-robust collimators. During the operation at low β*, the next aperture bottleneck downstream of the dump protections in IR6 might be the TCTs at the interaction points [6]. It is therefore important to understand safe limits for the present TCTs, which have their active parts made of Inermet180.

In the past, first damage estimates for tungsten collimators were calculated through advanced simulations [7]. One single bunch with variable intensity impacting the TCT jaw at a fixed impact parameter was considered. The distribution of the energy density deposited by the protons provided inputs for complex wave propagation calculations to reproduce the dynamic responses in the impacted structure of the collimator. These thresholds have been updated in light of recent beam tests at the CERN HiRadMat facility [8, 9].

A new simulation setup is now available that introduces an initial step of particle tracking simulations to study a more realistic scenario of failure and impacts on the TCTs. After introducing the improved simulation chain used for this study, on overview of the most relevant scenarios for the LHC will be given, followed by simulation setup for the case of tertiary collimators hit by protons scattered out from IR6 collimators (for this reason labelled as "secondary protons" from now on, to be distinguished from particles hitting directly the TCT, called instead "primary protons") in the nominal 7 TeV optics for Beam 2. To conclude, results and new damage limits will be presented for this case.

THE SIMULATION CHAIN

Particle Tracking with SixTrack

Particle tracking simulations were performed using a modified version of the SixTrack collimator routine [10–12]. A single MKD module pre-fire was simulated for a train of LHC protons at 7 TeV with the full collimation system in place. The real 25 ns beam time structure was considered accounting for bunch spacing between consecutive impacts: each of them receives a different kick angle according to the rising of the kicker field. Thus, fractions of several bunches will impact on the TCT jaw.

SixTrack simulations were done for a perfect machine, without errors on optics, apertures and collimators. Possible errors are accounted for by scanning TCT positions around their nominal settings, down to apertures of IR6 protection devices. Only the TCT settings in the low-β* insertions IR1 and IR5 were modified, since these would be the most exposed locations in case of a dump failure of Beam 1 and Beam 2, respectively. The coordinates of the particles in SixTrack that experience inelastic interaction inside the TCTs provide inputs for full shower simulations.

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FLUKA Energy Density Maps

The Monte-Carlo particle transport code FLUKA [13, 14] is used for the simulation of secondary particles (showers) generated by the impact of the primary beam on the TCT jaw. The collimator geometry is shown in Fig. 1.

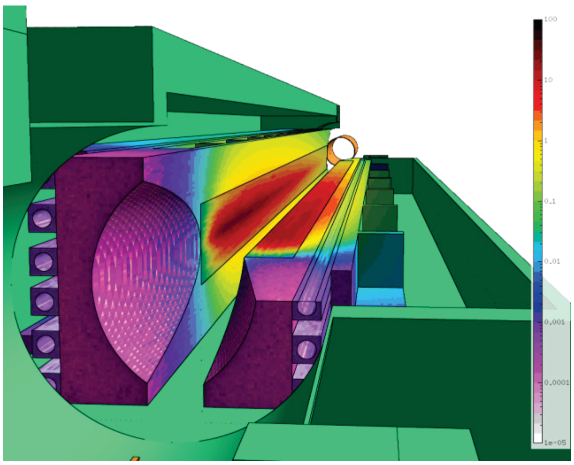

Figure 1: Geometry of a tertiary collimator jaw modelled by FLUKA. A coarse mesh is used to discretize the full jaw and a finer one for each single tungsten block. The colors refer to the energy density deposited in the jaw.

The energy deposited by the protons inside the TCTs, expressed in GeV/cm^3, is simulated for each bunch: the higher the material density, the higher the stopping power of the target and the energy deposited by the beam.

Hydrocode for Wave Propagation Studies

When matter is hit by highly energetic beams, phenomena such as change of density, changes of phase and explosions can occur. Hydrocodes are highly non-linear finite element tools, extensively used to reproduce shock wave formation and propagation due to very short and energetic particle impacts on a structure.

The calculation of the damage limits for TCTs were performed with Autodyn [15] starting from the maps of energy distribution provided by FLUKA. The evolution of pressure inside the jaw is computed based on the equation of state of Intermet180 [16, 17] as a function of material density and temperature. The Johnson-Cook strength model [16, 17] and the Minimum Hydrostatic Pressure model [16, 18] were used to simulate the plastic deformation up to the bulk failure of material and determine its thresholds..

OVERVIEW OF RELEVANT CASES

Both beams and different machine optics were simulated. In all cases the so-called 2σ retraction collimator settings were used (see Table 5 in [19]). A scan over several TCT settings to allow the comparison of the number of impacting protons with the previous estimates of damage (see Fig. 2) was performed using SixTrack: if TCT half gap is smaller than the retraction of the TCSG in IP6, it is not sufficiently shadowed by the dump protections and may experience primary beam losses. More opened TCT settings, instead, guarantee a more efficient protection: mainly particles already scattered out from the TCSG will then impact on it.

From this preliminary analysis, few relevant cases summarized in Table 1 were selected to be followed up with studies at high statistics. They differ by the total number of impacts, the impact distribution and the contribution given by primary and secondary protons to the impacts.

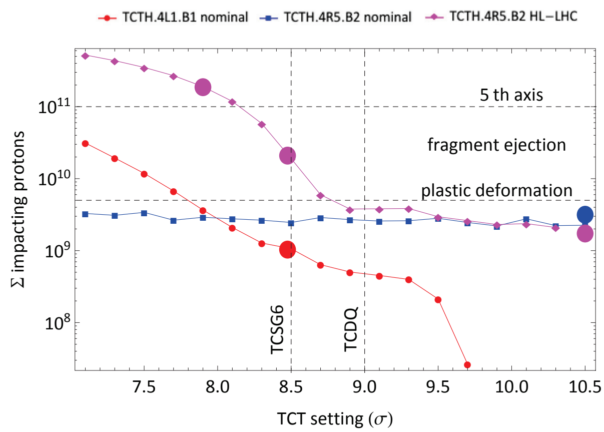

Figure 2: Losses at TCTs as function of collimator retraction for different beam optics. Previous damage thresholds [7] are added for comparison. The bigger markers correspond to the scenarios selected for high statistics simulations.

Table 1: Summary of Relevant Scenarios Considered for Simulation Studies

n.	Beam	Optics	β^* [cm]	TCT halfgap [σ]
Case 1	B1	Nominal 7 TeV	55	8.5
Case 2	B2	Nominal 7 TeV	55	10.5
Case 3	B2	HL-LHC	15	10.5
Case 4	B2	HL-LHC	15	8.5
Case 5	B2	HL-LHC	15	7.9

Between the scenarios listed in Table 1, we focused first on Case 2, since machine and optics parameters are similar to what is expected for the LHC restart in 2015. As shown in Fig. 2, in this case, the losses are dominated by secondary protons, regardless of the collimator settings: a good phase advance (180°) between the MKD and the TCT, indeed, guarantees that the TCT is extremely unlikely to be hit by primary beam. In Fig. 2 the level of losses reached in the TCTs lies still below even though very close to the appearance of plastic deformation limit calculated for primary protons impact.

The immediate goal of studying this scenario is to understand if tertiary collimators keep this safe margin also at nominal settings (big blue marker in Fig. 2) when they are hit by secondary protons.

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DAMAGE LIMITS FOR IMPACTS OF SECONDARY PROTON LEAKAGE

Updated damage thresholds for tungsten were calculated exploiting the full simulation chain for the case of secondary protons hitting the TCTH.4R5.B2 after being out-scattered from IR6 dump protection devices. The average impact parameter over all the simulated bunches as simulated by SixTrack is shown in Fig. 3: the value is about 8 mm.

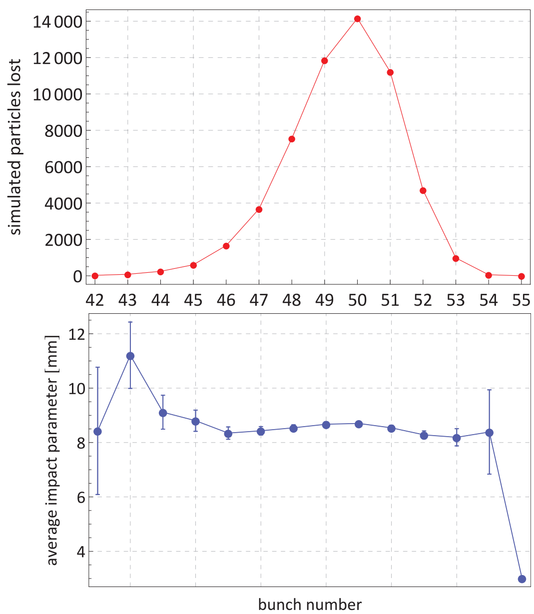

Figure 3: Particle loss bunch by bunch and average impact parameter on TCTH.4R5.B2 left jaw for different bunches for Case 2. In simulation, each bunch contains about 3.2×10^6 macroparticles.

About 10 bunches, the ones that contribute more to the losses in the TCT (red curve in Fig. 3) were then simulated by FLUKA to obtain the distribution of energy deposited by the protons: together they stand for about 98% of the total number of the impacting protons, and the remaining bunches with negligible impacts are not accounted for. The energy maps were loaded in Autodyn by considering for the first time the 25 ns bunch time structure and were weighted according to the number of initial impacts in SixTrack. To optimize the computing time, the effect of the impacts only on the left jaw, which is the most loaded, were performed.

The resulting damage thresholds are listed in Table 2. Note that the estimates refer to the total number of protons impacting on the TCT jaw and not to the original bunch population: the contribution of each bunch to the losses was, indeed, scaled by the fraction of the initial bunch really lost in the jaw. The limits, simulated for secondary protons, are significantly higher than previous estimates calculated for primary ones [7]. The large difference between old and new thresholds in Table 2 is mainly due to different impact distributions on the TCT (as shown in Fig. 4), which come from the different optics and collimator settings and make the tertiary collimator in Case 2 much less exposed to impacts of primary protons.

Table 2: Damage Limits for Tertiary Collimators. Note that the calculation of the old thresholds was based on the assumption that primary protons impact directly on the TCT [7], while the new limits refer to secondary protons impacts only.

Damage	**Old threshold** [p]	**New threshold** [p]	**Gain factor**
Plastic deformation	5×10^9	1.2×10^{11}	~23
W fragment ejection	2×10^{10}	7×10^{11}	~35
Recoverable damage	1×10^{11}	1.1×10^{12}	~11

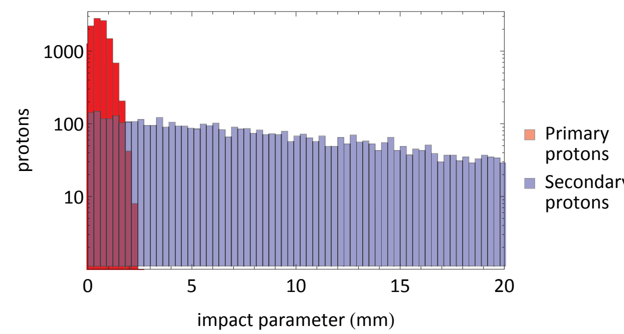

Figure 4: Impact distribution on TCT in case of primary proton impacts (in red), reported in [7] and used to calculate the old thresholds in Table 2, and secondary protons (in blue) simulated in Case 2.

CONCLUSIONS AND FUTURE STUDIES

The calculation of limits of material damage in case of fast beam losses is an important milestone in the framework of robustness studies for the LHC tertiary collimators.

We presented for the first time a new simulation approach based on a 3-steps simulation model, that involves tracking simulations of impacts from 25 ns bunches, energy deposition mapping and simulations of the dynamic material response to pressure waves propagation inside its structure.

First studies are focused on understanding damage limits for the case of diluted secondary protons impacting on TCTs after being out scattered by the dump protection elements. The results for the studied case show damage levels significantly above the old limits calculated for a more pessimistic scenario of primary protons directly impacting on TCTs.

Future studies will address thresholds for primary protons. An intense simulation work is ongoing for selected beam optics and collimator settings in view of different machine upgrades foreseen for the next HL-LHC era.

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