OPERATIONAL LIMITS FROM INTERCEPTING DEVICES

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ABSTRACT

LHC operation in 2016 was limited by the constraints on the maximum allowed intensity in the SPS due to the vacuum leak at the internal dump. The present baseline foresees the replacement of the TIDVG with a new upgraded hardware during the upcoming EYETS. This would allow providing nominal 25 ns to the LHC as well as beams with a brightness well beyond design. Nevertheless, the consequences of an accidental impact of such beams on the intercepting devices in the SPS-to-LHC transfer lines and in the LHC injection regions have to be carefully evaluated. At the same time potential dangers related to faults during the extraction of high intensity beams at top energy have to be taken into account. The survival of all the protection elements and the downstream machine components have to be insured for every operational scenario. Past and present assumptions on possible failure scenarios, their likelihood and effects are reviewed together with the estimated damage limits. Potential intensity and performance limitations are therefore derived for the 2017 Run in view of the specific beams available.

2017 OPERATIONAL SCENARIOS

At present, the SPS can produce beams with intensity and brightness higher than the LHC design parameters (1.15×10^{11} ppb and 3.5 mm mrad nrmalised emittance) as shown in Table 1.

Table 1: Achievable beam parameters in the SPS.

	ppb [10^{11}]	**Norm. emittance [mm mrad]**	**# bunches**
25 ns	1.3	2.7-2.8	288
BCMS	1.3	1.4	288
80 bunches	1.2	2.8	240-320

A vacuum leak was identified inside the SPS internal dump (TIDVG) shielding and this reduced the maximum allowed beam intensity in 2016 to 96 LHC BCMS bunches or 2.2×10^{13} protons per pulse for the Fixed Target (FT) beams. The present baseline is to replace the TIDVG during the EYETS with a new upgraded design [1]; this would allow to remove the past limitation and provide high intensity and high brightness beams to the LHC (see Table 1). In case of delay in the new TIDVG production, either the present dump will be kept in the tunnel or will be replaced by a refurbished one and operation will be accordingly limited.

KEY ASSUMPTIONS

Several beam stoppers and collimators are installed in the SPS, the SPS-to-LHC Transfer Lines (TL) and in the LHC ring (see next session). All these equipment were designed for operation with LHC ultimates beams (i.e. 1.7×10^{11} ppb and 3.5 mm mrad normalised emittance), they have to withstand possible direct beam impacts and provide enough attenuation to prevent the damage of the downstream machine components. Materials and geometries were decided based on FLUKA and ANSYS calculations, to assess the energy density profiles and the stress and strain distribution, plus beam tests. In particular, a so called "damage test" was performed in 2004 in the TT41 beam line and allowed to declare as safe a beam intensity corresponding to 2×10^{12} protons ($\sim$1 mm radius spot size) [2]. An attenuation factor A [3] can be calculated from:

$$\frac{I_{after}}{\varepsilon_{after}} = \frac{1}{A} \cdot \frac{I_{beam}}{\varepsilon_{beam}} \tag{1}$$

where the ratio between the beam intensity (I_{after} and I_{beam}) and the normalised emittance (ε_{after} and ε_{beam}) defines the beam brightness before (right term) and after (left term) the impact of the beam against an intercepting device. The brightness of the impacting beam, for ultimate intensity, has to be attenuated by a factor $A \simeq 20$ to be reduced below the safe limit, with the conservative assumption of a negligible emittance blow up (or equivalently that the beam spot size at some downstream location is comparable to that of the original impacting beam).

INTERCEPTING DEVICES FOR $\leq$ 450 GEV BEAMS

The main intercepting devices installed in the SPS are:

- The SPS internal dumps: TBSJ (26 GeV), TIDH (28 GeV) and TIDVG (450 GeV),
- The TL beam dumps TED (450 GeV) and stoppers for personnel safety TBSE (450 GeV),
- The SPS betatron and momentum scrapers TIDP (450 GeV),
- The SPS extraction septa protection elements TPSG (450 GeV)

Collimators are then placed at the end of the TL (TCDIs) to protect the injection septum (MSI) and the LHC aperture from mis-extracted beams from the SPS. These objects are space by 30° in phase advance to provide the best phase space coverage while minimising the number of needed jaws. Finally the TDI, which is installed in the LHC injection regions at 90° phase advance from the injection kickers (MKI), protects the LHC aperture in case of MKI failures affecting the injected and/or circulating beam.

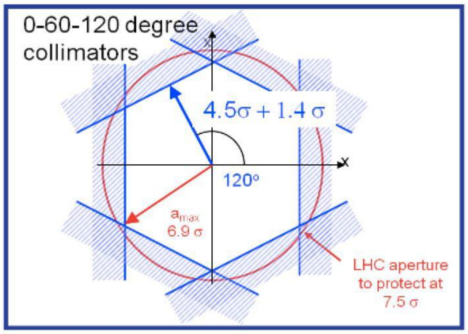

Figure 1: Phase space coverage provided by the TCDIs installed in the SPS-to-LHC TL.

INTENSITY LIMITATIONS BEFORE LS2

After the TIDVG replacement, all the SPS intercepting devices will be ready for operation with the maximum achievable intensity and brightness[1]. The TDI underwent several upgrades and the present design, consisting of 4.2 m long jaws composed of blocks of graphite followed by high Z materials (CuCrZr), is compatible with operation with high brightness beams [4]. Instead, according to the actual knowledge on damage limits, due to the extremely small spot size at certain collimators (down to $\sigma_x = 247\ \mu$m and $\sigma_y = 473\ \mu$m), the 1.2 m long graphite jaws of the TCDIs would not survive an impact of more than 240 BCMS bunches. Moreover the provided attenuation is a factor of two too low for BCMS beams (twice higher brightness than ultimate LHC beams) and the TCDIs could provide the adequate protection only for up to 144 bunches.

Are we too conservative?

Lately the question if the assumed constraints for the TCDI attenuation were too strict was risen. The design of the full system was based on the principle that in case of any possible, even unknown, failure and consequent impact of the "transmitted beam" (scattered primary protons from the TCDIs) on the MSI and/or the LHC aperture no damage would have been caused. Two main aspects have to be considered to answer this question:

- The actual knowledge of the damage limits,
- The typology and likelihood of the failure scenarios which could determine a beam impact on the MSI/LHC aperture and the consequent effective energy deposition.

HiRadMat tests are foreseen for next year and should allow to improve the damage limit knowledge for different materials including the coils of the superconducting magnets. Several layers of protection, mainly based on hardware and software interlocks, exist to prevent mis-extraction and mis-transfer of the beams from the SPS towards the LHC. In particular, Fast Extraction Interlock (FEI) combined with Fast Current Change Monitors (FMCM) and Beam energy Tracking System (BETS) provide protection against the failure of critical extraction and transfer line magnet circuits. In case of fault of one of these systems the extracted beam would hit the TCDIs, which are set at 5 σ, with a grazing or quasi-grazing impact (0 σ and 1 σ impact parameter respectively). Double failures are excluded but would translate in a large impact parameter if reaching the TCDIs, depending on where the failure occured in the line. An erratic or asynchronous firing of the SPS extraction kicker (MKE) would sweep and dilute the beam on the different TCDIs. On the other hand, an internal breakdown of the MKE when pulsing could still extract the full beam on one TCDI with a fixed impact parameter (between grazing and ~7 σ, i.e. up to 12 σ amplitude oscillations in the TLs). Even if the recent reconfiguration with short-circuit terminations reduced the MKE voltage and thus the risk of flashover [5], this eventuality cannot be completely excluded. Finally a beam with an energy up to ±0.6% different with respect to the nominal one could be extracted on the dispersive orbit and hit the TCDI sitting at the highest dispersion location. Also in this case, depending on the energy offset, the impact parameter could vary from grazing up to ~5 σ.

The estimated LHC arc aperture at injection is 11.2 σ and local bottlenecks exist which correspond to 10.8 σ and 11.0 σ in IR6 and IR7 for Beam 1 and Beam 2 respectively. Assuming that one of the mentioned failures occurs, that the beam intercepts only one TCDI and "enough" beam goes through the MSI (0°-180° phase advance between the intercepted TCDI and the MSI), then the LHC aperture could be hit and possibly damaged. In case of quasi-grazing impact, a maximum amplitude of 8.4 σ (considering a maximum escaping amplitude of 7.4 σ due to a non perfect phase coverage and to TCDI positioning errors) can be reached so that the probability of hitting the machine aperture is quite low (the effect of local orbit bump should not be neglected). On the other hand, even if unlikely, failures corresponding to larger oscillations could occur and dedicated tracking and FLUKA studies have to be performed to quantify the actual amount of beam which would impact the machine and the consequent local energy deposition. The worst possible failure scenario should be identified to decide if the constraints on the minimum required attenuation provided by the TCDIs could be relaxed. Moreover the gain in peak Luminosity has to be carefully weighted with respect the potential risk of injecting more than 144 BCMS bunches.

LIMITATIONS AT TOP ENERGY

The risk of damaging the protection elements installed in the dump region in case of failure at 6.5 TeV of the extraction (MKD) and/or dilution (MKB) kickers was also evaluated.

The TCDS and the TCDQ have to intercept the swept beam in case of an asynchronous beam dump or an

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[1] Operation with 320 bunches (Table 1) corresponds to ~10% higher brightness than ultimate LHC beams and is thus considered as acceptable. Nevertheless the impact of lengthening the MKI flattop to accomodate longer trains has to be validated in terms of increased risk of flashovers.

erratic firing of the MKDs. They protect, respectively, the extraction septa (MSD) and the superconducting quadrupole installed immediately after the extraction region (Q4) plus the arc and the collimators in the low-β insertions. Both the TCDS and the TCDQ were built to withstand ultimate intensities knowing that, at top energy, the beam size plays only a marginal role. During the reliability runs performed in 2015 a new type of MKD erratic (Type 2), with a different rise time than a standard one (Type 1), was identified. This translates in a different number of mis-kicked bunches intercepting the TCDQ and a particle density [6], close to the jaw surface, which can be more than a factor of 5 higher than the design assumptions (Fig. 2), depending on the half-gap. Bunches are instead almost uniformly distributed on the TCDS front face independently from the erratic type. The possibility of setting the TCDQ at 7.3 σ is being explored since this would allow reaching a β* of ~30 cm in IP1 and IP5 [7]. The peak dose along the TCDQ jaw was calculated for a Type 2 erratic using BCMS bunches and assuming a half-gap of 7.3 σ and 9.1 σ (2015 setting); in both cases the aperture was reduced by 0.5 σ to take into account possible setup errors (Fig. 3). The resulting stresses at the TCDQ are estimated to be within the damage limits. The highest energy density is expected at the downstream Q5 quadrupole and could reach up to 20-25 J/cm^3. This value seems to be acceptable but the final confirmation will be given by the HiRadMat tests on the damage limits of NbTi coils.

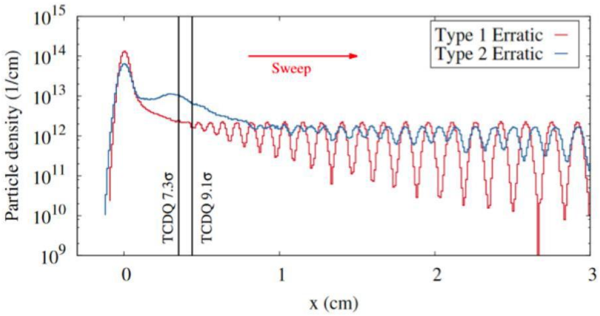

Figure 2: Transverse particle density distribution at the TCDQ location in case of an erratic of Type 1 (red line) and Type 2 (blue line). The positions of the TCDQ jaw corresponding to a half-gap of 7.3 σ (proposed 2017 setting) and 9.1 σ (2015 setting) are also indicated.

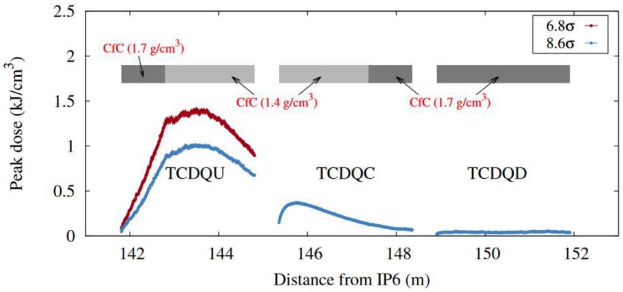

Figure 3: Peak dose along the TCDQ jaw in case of a Type 2 erratic and BCMS bunches. Two different half-gaps are considered and a 0.5 σ margin is removed to take into account possible setup errors.

The survival of the dump block (TDE) and its upstream and downstream windows in case of two horizontal MKBs failing was also considered and no limitation for operation with 2017 achievable beam parameters was found.

CONCLUSIONS

No intensity limitation is expected in the SPS if the new TIDVG dump will be ready and installed during the EYETS. Based on the present knowledge of the damage thresholds, the TCDIs will limit operation to 144 BCMS bunches if the condition of guaranteeing a sufficient beam attenuation, independently from the failure scenario, is maintained. Detailed tracking and FLUKA studies will be performed to identify the worst possible failure scenario and assess the consequences of a beam impact in the injection region (including the MSI) and further downstream in the LHC. The outcome of these studies and an improved knowledge of the damage limits could require a re-evaluation of the present constraints. Particular attention has to be dedicated to insure that the worst case was indeed evaluated, decide if the low probability of such a failure would justify the taken precautions and limits on high brightness beams. Finally the gain in peak Luminosity has to be weighted with the increased risk of damage.

No limitation for high energy operation with 2017 beam parameters and settings (TCDQ,TCDS and TDE).

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