UPGRADES TO THE SPS-TO-LHC TRANSFER LINE BEAM STOPPERS FOR THE LHC HIGH-LUMINOSITY ERA

V. Kain, R. Esposito, M. A. Fraser, B. Goddard, M. Meddahi, A. Perillo Marcone,
G. Steele, F. Velotti, CERN, Geneva, Switzerland

Abstract

Each of the 3 km long transfer lines between the SPS and the LHC is equipped with two beam stoppers (TEDs), one at the beginning of the line and one close to the LHC injection point, which need to absorb the full transferred beam. The beam stoppers are used for setting up the SPS extractions and transfer lines with beam without having to inject into the LHC. Energy deposition and thermo-mechanical simulations have, however, shown that the TEDs will not be robust enough to safely absorb the high intensity beams foreseen for the high-luminosity LHC era. This paper will summarize the simulation results and limitations for upgrading the beam stoppers. An outline of the hardware upgrade strategy for the TEDs together with modifications to the SPS extraction interlock system to enforce intensity limitations for beam on the beam stoppers will be given.

INTRODUCTION

Two 3 km long transfer lines are used to fill the two rings of the Large Hadron Collider (LHC) from the Super Proton Synchrotron (SPS) at CERN, TT60/TI2 for LHC beam 1 and TT40/TI8 for LHC beam 2. To set up and study the SPS fast extraction systems and transfer lines, two TED (Target Extraction Dump) beam stoppers are installed in each line. One is located about 100 m downstream of the SPS extraction point and the second one about 200 m upstream of the LHC injection point, see Fig. 3 for the transfer line TT40/TI8. The TEDs are 4.3 m long devices consisting of a material sandwich of a Ø80 mm graphite cylinder 2.9 m long housed in a Ø80/158 mm aluminium blind tube 3.5 m long, which itself is fitted into a Ø160/310 mm copper blind tube, see Fig. 1. This core is then surrounded by cast iron shielding. A TED installed in a transfer line is shown in the photo of Fig. 2. These devices sit on rails together with a y-shaped vacuum chamber and can be moved in and out of the beam line. They are in air. The beam has to traverse a thin window to impact the front face of one of these beam dumps. All LHC transfer line TEDs have the same design except the one in the zone TT60, which has an older design [1]. Another set of beam stoppers installed in the lines as safety devices are moved in during personnel access. These so-called TBSEs should never be impacted by beam. The TBSE has the same design as the TED concerning the core, but it is not equipped with the lateral cast iron shielding. The TBSEs in the LHC transfer line TI8 and the line TT41 are indicated as well on Fig. 3.

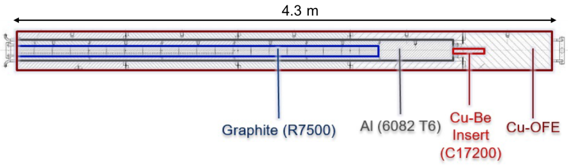

Figure 1: A schematic drawing of the core of the LHC transfer line TEDs. The different materials of the sandwich structure are indicated.

Figure 2: A photo of the TED installed in LHC transfer line TT40. Only the Ti window on the front face of the graphite core as well as the cast iron shielding are visible.

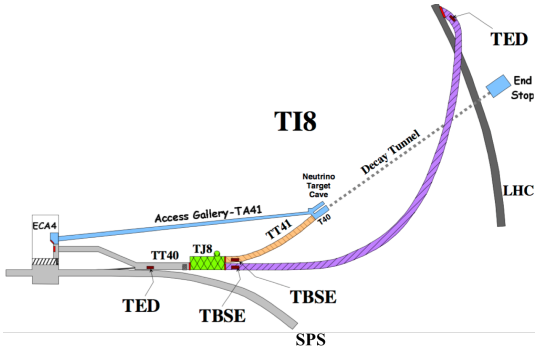

Figure 3: Two beam stoppers (TED) are located in the transfer line for LHC beam 2 from the SPS through TT40 and TI8. The TBSE has a similar design as the TED core and acts as a safety element. It is moved into the beam line only if there is access to zone. The drawing also shows the transfer line TT41 which is used for the experiment AWAKE [2].

The LHC transfer line TEDs have been designed to absorb and withstand ultimate LHC intensities at 450 GeV [1] with 288 bunches spaced by 25 ns in steady state with an extraction every 16.8 s. After the high luminosity upgrade the LHC will require beams from the injectors with a brightness much increased with respect to the nominal or even ultimate LHC intensities. These parameters will only be achievable after substantial upgrades in the LHC injectors themselves [3].

The beam characteristics after the LHC Injector Upgrade (LIU), of the LHC ultimate as well as the currently available standard beam are summarized in Table 1.

Table 1: LIU Beam Parameters in the SPS at 450 GeV [3]. BCMS stands for the beam production scheme "Batch Compression, Bunch Merging and Splitting". N_b is the number of bunches.

	$p^+/bunch$	ε $[\mu m]$	brightness $[\frac{10^{11}}{\mu m}]$	N_b
Standard	1.2×10^{11}	2.6	0.46	288
Ultimate	1.7×10^{11}	3.5	0.49	288
HL-LHC	2.32×10^{11}	2.1	1.1	288
BCMS LIU	2.0×10^{11}	1.3	1.54	288

The TED's Role in the SPS Extraction Interlocking System

The LHC intensities extracted from the SPS are about a factor 20 above equipment damage limit for ultimate intensities. Machine protection is therefore a major concern for the SPS-to-LHC transfer which involves fast extraction and injection kickers. All equipment involved with the transfer as well as the LHC equipment is monitored and only if all parameters are within pre-defined tolerance windows the SPS extraction interlock system gives the green light for the extraction kickers to fire. The position of the TED beam stoppers, i.e. whether they are in or out of beam, is used to condition the extraction interlocking matrix. In case a TED is in the beam line, the status of all equipment downstream of the TED is ignored for the extraction permit. For example, if the TED in TT40 is in beam for the line TT40/TI8 as in Fig. 3, the equipment in TI8 as well as in the LHC can be faulty without stopping SPS extraction tests. This feature is essential to decouple the setting-up of the SPS extractions and transfer lines from the LHC status during the beam commissioning phase. This logic is true for any intensity in the SPS.

So-called Beam Interlock Controllers (BICs) are used to locally gather the interlocking information from the different equipment in the lines [4]. The TEDs are also monitored. Extraction is not allowed in case the TEDs are moving. The simplified equation defining the LHC beam 2 extraction permit used in the so-called extraction master BIC with emphasise on the role of the TEDs can be summarized as

$$\mathrm{BIC}_{TT40} \wedge \{\mathrm{TED}_{TT40} \vee [\mathrm{BIC}_{TI8} \wedge (\mathrm{TED}_{TI8} \vee \mathrm{BIC}_{LHC})]\} \tag{1}$$

where TED_{TT40} and TED_{TI8} are *true* if the TEDs are in beam. (Note that in reality the different parts of the lines are equipped with several BICs plus beam flags to further condition LHC injection. The real equation is more complicated [5].)

Mode of Operation of the TEDs in the Transfer Lines

The upstream TEDs in TT60 for LHC beam 1 and TT40 for LHC beam 2, are used to set up the extraction from the SPS. Most of this is done with very low intensity (5×10^9 to 1×10^{11} protons). As the useful part of the kicker pulse is rather short, i.e. only about 8 μs, correct synchronisation of beam and kicker pulse is vital. The 25 ns batch has a length of 7.8 μs. The final verification of the synchronisation is done by extracting a full 25 ns batch consisting of 288 bunches onto the upstream TEDs. The downstream TEDs are never used with high intensity. The maximum intensity so far was about 1×10^{11} in single bunches. All TEDs are mainly used with beam during the beam commissioning period at the beginning of the year and rarely after the extractions and transfer are fully commissioned.

RESULTS OF THERMO-MECHANICAL SIMULATIONS OF TEDS WITH LIU BEAM PARAMETERS

Energy deposition simulations were carried out with the code FLUKA for the TED.610321, as it will have the smallest beam size in the future with LIU optics. The beta functions after the upgrade will be $\beta_x = 56.57$ m and $\beta_y = 75.23$ m.

The peak temperatures for the different materials for the different beam scenarios in steady state with a shot every 21.6 s are summarized in Table 2. The higher the brightness of the beam, the higher is the peak temperature in the different materials.

Table 2: Peak Temperatures in the Different TED Materials in Steady State. The HL-LHC beam with 144 bunches will create similar peak temperatures as the standard beam currently used for the LHC with 288 bunches.

	C [°C]	Al [°C]	Cu-Be [°C]	CuOFE [°C]
Standard [288]	625.1	182.6	190.3	73.6
HL-LHC [144]	672.1	180.1	185.6	71.8
HL-LHC [288]	1162.1	315.6	333.5	123.1
BCMS LIU [144]	757.0	152.8	164.1	65.1
BCMS LIU [288]	1317.1	278.6	294.6	109.9

There is still sufficient margin to the melting temperatures for all materials. The FLUKA results were then used as input to ANSYS simulations to investigate the stresses due to the high temperature gradients as well as shock waves generated with this intense and short beam pulses. The resulting stresses were compared to the strengths of the materials found in literature and datasheets of suppliers. As an extreme case, simulations were also carried out with beam parameters even more severe than the LIU target parameters, assuming 288 bunches with 2.32×10^{11} protons per bunch and an emittance of only 1.3 μm. The strains for the metallic part of the TED core under these conditions are all acceptable and are summarized in Table 3. The situation for the graphite part is more critical. The Stassi factor [6] was used as safety criterion. Due to the uncertainties on material properties and simulation errors, the applied criterion was that the Stassi factor had to be smaller than 0.6. In an ideal situation with no uncertainties a Stassi factor of below 1 would be sufficient. Table 4 summarises the results for the target beam parameters of BCMS and HL-LHC. Especially for the LIU BCMS case, integrity of the graphite part after impact cannot be guaranteed. Also, the HL-LHC case would be above the agreed Stassi factor of 0.6. The stresses in graphite become however acceptable if the number of bunches is reduced to 144 for HL-LHC and LIU BCMS beams. Also, for the extreme case again of 2.32×10^{11} protons per bunch in 1.3 μm emittance and 144 bunches this is true. The simulation results for this case are summarized in Table 5.

Table 3: The Resulting Strain in the Different Metallic Parts of the TED Core for an Impact of 288 Bunches with 2.32×10^{11} Protons per Bunch and 1.3 μm

material	eq. plastic strain [%]	eq. total strain [%]
Al	0.33	0.66
Cu-Be	0.27	0.3
CuOFE	0.43	0.44

Table 4: Stresses in graphite for impact of different beam types with 288 bunches. The tensile strength of the used graphite type is 35 MPa. The resulting Stassi factor is too high. It should be below 0.6.

	max. tensile stress	max. Stassi factor
HL-LHC	27 MPa	0.75
LIU BCMS	30 MPa	0.9

Table 5: Stresses in graphite with extreme beam parameters of 2.32×10^{11} protons in 1.3 μm with 144 bunches. The tensile strength of the used graphite type is 35 MPa.

	max. tensile stress	max. Stassi factor
graphite	19 MPa	0.56

NEW OPERATIONAL AND MACHINE PROTECTION STRATEGY WITH LHC BEAM ON TEDS POST LIU

Given the limited flexibility in the transfer lines to change the optics and increase the beam sizes at the TEDs, the limited number of alternatives for graphite and the associated cost, a new design of the LHC transfer line stoppers was discarded. The maximum intensity to be extracted with TED in beam will however be reduced to I_{TED} equal to 144 HL-LHC bunches consisting of 2.32×10^{11} protons per bunch. This will be implemented by modifying the TED interlocking strategy. Instead of only interlocking if the TEDs are moving, extraction will also be inhibited if the TED is in beam and the intensity in the SPS is above I_{TED}. An additional beam flag will have to be generated by the SPS Safe Machine Parameter System (SMP) [7] from two redundant beam current measurements. The flag will read *true* for a beam intensity in the SPS below I_{TED} and *false* otherwise. The beam flag distributed by the SMP will be used in the interlocking logic of the transfer line TEDs. The extraction master BIC equation will not be modified. Operational flexibility will also not be impacted by this strategy choice. To verify the synchronisation of the extraction kicker pulse and extracted beam, 50 ns beam can be used instead of 25 ns beam. In this way the same batch length can be achieved with half the number of bunches.

In addition the TED in TT60 that is of an older design will have to be replaced by one of the latest design. Most probably a spare TED will be used for that purpose. There is no operational scenario to extract high intensity onto the downstream TEDs.

SUMMARY

The TED beam stoppers in the transfer lines were originally designed for beams up to ultimate brightness. The brightness required for the LHC high luminosity project will however be more than twice this. These beams will be the result of the LHC Injector Upgrade (LIU) project. Thermo-mechanical simulations showed that the graphite part of the TED core will very likely not survive beam impact with so-called LIU BCMS beams. The simulations also showed that extracting 144 bunches on the TEDs with LIU beam parameters would however still be acceptable. It was therefore decided to not upgrade the TEDs and/or find an alternative optics with larger beam sizes at the TED front faces, but to reduce the maximum allowed intensity with TEDs in the beam line. The maximum intensity on the TEDs will be interlocked by creating an additional beam flag in the SPS Safe Machine Parameter System. The beam flag will be used in the TED's surveillance that is input to the extraction interlock system. Extraction will be inhibited in case of an intensity higher than $144 \times 2.32 \times 10^{11}$ bunches and TED in the beam line. Setting-up quality will not be compromised. The TEDs are only used for setting-up and beam commissioning. All necessary tests can be done with 144 LIU bunches only.

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