CERN-ACC-2015-0010

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Upgrades to the LHC Injection and Beam Dumping Systems for the HL-LHC Project

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CERN-ACC-2015-0010
20/01/2015

Keywords: LHC, HL-LHC

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Presented at IPAC14, 15-20 June, Dresden, Germany

Geneva, Switzerland
January 2015

UPGRADES TO THE LHC INJECTION AND BEAM DUMPING SYSTEMS FOR THE HL-LHC PROJECT

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Abstract

The HL-LHC project will push the performance of the LHC injection and beam dumping systems towards new limits. This paper describes the systems affected and presents the new beam parameters for these systems. It also describes the studies to be performed to determine which sub-components of these systems need to be upgraded to fulfil the new HL-LHC requirements. The results from the preliminary upgrade studies for the injection absorbers TDI are presented.

INTRODUCTION

The High Luminosity LHC project foresees a tenfold increase of the delivered luminosity to the main experiments by increasing the beam intensity, reducing the beam emittance and by further reducing the beam size at the interaction points [1, 2]. Higher beam intensity and reduction of emittance find their source in the injector chain and are part of the LHC Injector Upgrade programme (LIU) [3]. The LIU project envisages completion during Long Shutdown 2 (LS2), which is planned for 2018 – 2019. The main changes to the LHC to obtain the HL-LHC parameters are foreseen to take place in Long Shutdown 3 (LS3), planned for 2023 – 2025. A comparison of the beam parameters for the LHC and HL-LHC is given in table 1. Injection is taken place at a beam energy of 450 GeV with batches of 288 bunches up to a total of 2808 circulating bunches. Full nominal energy of the LHC is 7 TeV.

Table 1: LHC and HL-LHC beam parameters.

	Normalised emittance [μm]	I bunch [p/b]	Energy [GeV]
LHC nominal	3.75	$1.15 \cdot 10^{11}$	7000
HL-LHC	2.50	$2.20 \cdot 10^{11}$	7000
HL-LHC	2.08	$2.32 \cdot 10^{11}$	450
LIU-Standard	1.88	$2.00 \cdot 10^{11}$	450
LIU-BCMS	1.37	$2.00 \cdot 10^{11}$	450

This paper identifies the elements of the injection and beam dumping systems which require modifications in the context of the HL-LHC project. Changes to protection elements of the injection system are planned to be implemented during LS2, following the upgrades of the injector chain. Upgrades to both the injection kicker magnets and the beam dumping system will take place in LS3.

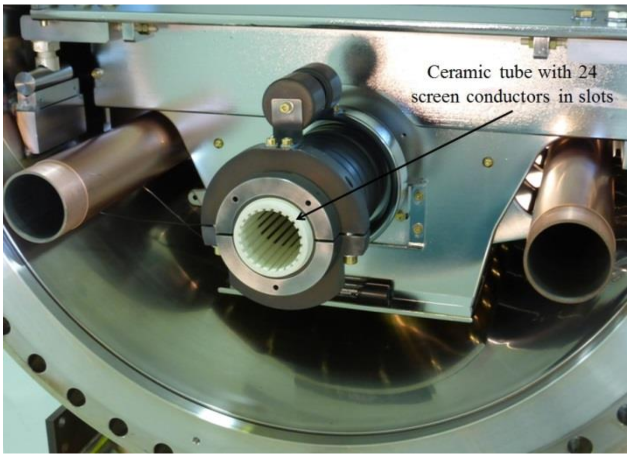

Figure 1: upgraded MKI, in its vacuum tank.

INJECTION SYSTEM

The LHC Injection Kickers, MKI

To limit the longitudinal beam coupling impedance of the injection kicker magnets MKI [4], while allowing a fast magnetic field rise-time, a ceramic tube (99.7% alumina) with screen conductors on its inner wall is placed within the aperture of the magnet [5]. In the original design the extruded ceramic tube had 24 nickel-chrome (80/20) conductors, inserted into slots [5]. In the version installed in the LHC prior to Long Shutdown 1 (LS1) the nine conductors closest to the HV busbar were removed to reduce the maximum electric field by 20%. With this arrangement no surface flashover was observed up to 49 kV PFN voltage [5]. However removing screen conductors increased the beam impedance and thus heating of the MKI ferrite yoke [6]. During LS1 the MKIs have been upgraded to have 24 screen conductors (Fig. 1): the new design reduces the beam induced power deposition by a factor of between 2 and 4 [6], for given beam parameters, and decreases the maximum surface electric field associated with the screen conductors by ~40% [5].

Despite the upgrades to the MKI, during LS1, the expected beam induced power deposition for 25 ns HL-LHC beam is in the range of 125 to 190 W/m [6] which, unless steps are taken, would increase the temperature of the ferrite beyond the Curie point and thus limit injection into the HL-LHC. Several possible means of mitigating this are being studied, including; (i) reducing further the beam induced power deposition [6]; (ii) improved cooling of the ferrite yoke [7]; and (iii) a ferrite with a higher Curie temperature.

An MKI with 15 screen conductors which, due to the ferrite temperature approaching the Curie point, occasionally limited the ability to inject into the LHC, was replaced with a 19 screen conductor version during September 2012 [8]. However the new ceramic tube, together with metallic surfaces facing the beam (e.g. screen conductors), of the replacement MKI, had a high secondary electron yield (SEY), of 6 to 7, and required ~250 hours, with beam, to condition to a normalized pressure similar to the pre-replacement level [8].

For HL-LHC, a coating of either amorphous carbon (aC) or Cr_2O_3 is under investigation in order to reduce SEY of the ceramic tube to below 1.4 [9]. An aC coating, of ~200 nm thickness, has been successfully applied to the inside diameter of a 48 cm long ceramic tube: this will soon be high voltage tested [5]. Industry has provided samples of Cr_2O_3 coated ceramics: measurements have shown that some of these have a maximum SEY of ~2, but can be conditioned to below 1.4. A method of applying a uniform Cr_2O_3 coating to the inside diameter of a ~3 m ceramic tube is currently being developed in industry: the coating will initially be applied to a 48 cm ceramic tube and subsequently high voltage tested.

Injection Absorber TDI

In the case of any failure of the MKI injection kickers the miskicked injected beam or any accidentally kicked stored beam will be intercepted by the injection absorber TDI and auxiliary absorbers TCLI. The TDI has to provide sufficient attenuation of the miskicked beam to protect the downstream super-conducting elements (the separation dipole D1 and the triplet quadrupoles) just in front of the collision points at the experiments. In case of the impact of a full injection batch, these downstream elements should not be damaged; however, a quench of these magnets cannot be excluded. For the injection protection calculations the assumed injection beam parameters are summarised in Table 1, for the different injector configurations. The low emittance options, so called LIU - BCMS beam in Table 1, is the most demanding for the absorber material if impacting at 1σ beam size distance from the absorber edge. Material studies for this failure case are presented below.

Candidate Materials for TDI Absorber Blocks

Candidate materials with the capabilities to withstand intense particle beams for relatively short time (7.8 μs), starting from room temperature and reaching temperatures up to 1400 °C, have been studied. For the material selection, criteria of thermal shock resistance were applied in the form of:

$$R_T = \frac{\sigma_T(1-\nu)}{CTE \cdot E}$$

where, σ_T – Fracture Stress of material, ν – Poisson's ratio, E – Elastic Modulus, and CTE – Coefficient of Thermal Expansion.

From a material property perspective, this translates into identifying materials with the following properties:

- Density lower than 2 g/cm^3
- Relatively low value of Elastic Modulus
- Low coefficient of thermal expansion
- Strength of material as high as possible
- High specific heat

The materials considered for further simulation are [10]:

- Graphite R4550 (R_T= 523)
- Boron Nitride H5000 (R_T=42)
- Carbon Fibre reinforced Carbon (CFC) (R_T=217)

Graphite R4550 is a very well-known material and easily available, however the tensile stress limit is too low for the foreseen use (see below). Boron Nitride has excellent material properties but at low temperatures only. Carbon Fibre reinforced Carbon (CFC) is anisotropic: it has excellent material properties but only in two dimensions and there are large error bars on the material properties.

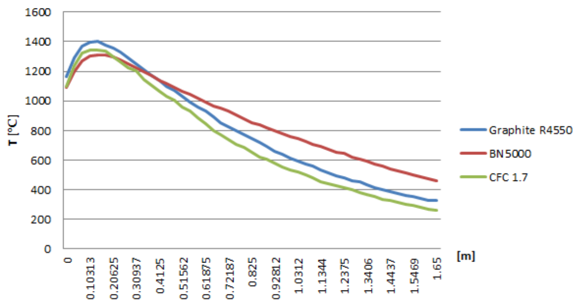

Figure 2: Temperature distribution along the block length for LIU-BCMS beam (1 σ scenario, 288 bunches).

Results of Numerical Simulations for the TDI

The TDI temperature profile after impact of the LIU-BCMS beams at 1 σ distance from the absorber edge, is shown in Fig. 2 for the three materials presented above. The peak temperatures reached, up to 1400 °C, pose no problem to any of the three materials. However, the large temperature gradients, as shown in Fig. 3 for graphite R4550, lead to important stresses in the material.

The evaluation of the thermal load has been performed with the Monte-Carlo code FLUKA and the energy deposition maps used as input to thermo-structural studies via ANSYS [11]. Two techniques were used in order to evaluate the maximum stresses: strong coupling analysis, (solving simultaneously the transient thermal and structural), and the weak coupling analysis.

For the various materials a different equivalent stress criterion was used. The relevant robustness criterion for Graphite and BN5000 is the Mohr-Coulomb criterion, resulting in the Safety Factor:

$$S.F. = \left[\frac{\sigma_1}{\sigma_{Tensile\ limit}} + \frac{\sigma_3}{\sigma_{compressive\ limit}}\right]^{-1}$$

For CFC the maximum and minimum principal tensile stress criterion is used:

$$T.S. = \left[\frac{\sigma_{Tensile\ limit}}{\sigma_1}\right]$$

where σ_1 is the maximum principal stress at a given point in the material and σ_3 the minimum principal stress. For

CFC materials, the strength is highly dependent on the direction considered and the principal stress directions vary locally. For these two reasons the most conservative limit was adopted for CFC, as there is no direction with reduced load due to a particle sweep, like for some other absorbers.

For the material to survive a certain stress load, the safety factor S.F and T.S. have to be larger than 1. Results of simulations, as shown in Table 2, indicate the possibility of structural failure in all three of the candidates in the case of LIU-BCMS beam parameters. Values of ultimate strength of materials were obtained from tensile, compressive and 3-point bending tests without considering dynamic load. Further material tests are ongoing, to investigate material behaviour under thermal shock conditions, in order to obtain more realistic strength limits of materials as well as their mechanisms of failure.

At the moment graphite seems to be the best compromise for the TDI in terms of manufacturing issues and ratio between tensile strength and maximum tensile stress. Latest calculations show that the S.F. would be just above 1 in the case of 1 σ impact of the larger but more intense HL-LHC beams.

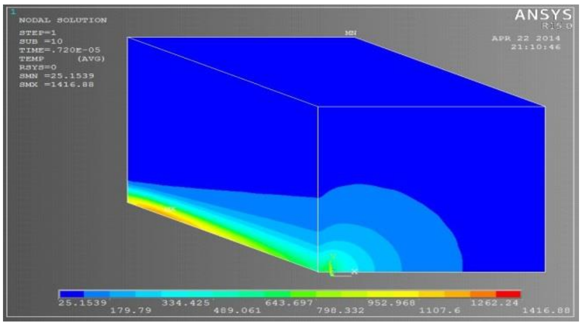

Figure 3: Temperature profile of Graphite R4550.

Table 2: Summary of Thermo-Structural behaviour for the different TDI material candidates

Material	Density $[g/cm^3]$	Mohr – Coulomb S.F.	Max T [°C]	T.S. [MPa]
BN5000	1.92	0.46	1311	3/11
R4550	1.83	0.9	1400	29/32
CFC	1.70	-	1370	12.8/20

Other Injection Absorbers

Additional movable injection absorbers, TCLIA and TCLIB, are located downstream of the TDI, after the interaction point, following the separation dipoles and in front of the Q6 quadrupole, to cover the phase space in case of injection losses. The present TCLI collimators are 1.0 m long graphite jaws. They will need to be re-evaluated taking into account the HL-LHC beams and optics. The design issues here are, besides the robustness, the beam impedance heating of the two-in-one design.

The injection protection system is completed by the fixed absorbers TCDD and TCLIM, positioned just in front of the separation dipole D1 and the quadrupole Q6, respectively. Attenuation calculations, taking into account the new TDI and TCLI, designs will need to be made and most likely the absorbing material of these absorbers will need to be adapted.

BEAM DUMPING SYSTEM

Table 1 also shows the important increase of beam brightness of the full energy HL-LHC beams. The beam dump block TDE has been designed for the so called 'ultimate' LHC beam, which consists of 2808 bunches spaced by 25 ns and a bunch intensity of $1.7{\cdot}10^{11}$ protons per bunch. Depending on the acceptable failure modes of the dilution kicker magnets, and results of detailed FLUKA simulations, the dilution pattern might need to be adapted, by lengthening the sweep, which would require additional dilution magnets.

Absorbers are installed in the beam dump insertion to absorb the beam in case of foreseen timing failures of the extraction kicker magnets. The movable absorber TCDQ has been upgraded during Long Shutdown 1 by increasing the absorber length from 6 m to 9 m and using CFC instead of graphite absorbers. The weaker direction of the CFC is aligned with the particle sweep direction on the TCDQ. The TCDQ is already compatible with HL-LHC beams [12]. The fixed absorber in front of the extraction septa, TCDS, will most likely need to be adapted, which is foreseen for Long Shutdown 3.

CONCLUSIONS

The high brightness of the future HL-LHC beams requires modifications to the injection and beam dumping system of the LHC. Beam impedance reduction of the injection kicker MKI has already taken place during LS1 but additional measures to reduce the MKI temperature are under study for HL-LHC. First tests of a coating for the ceramic chamber, to reduce the SEY, have started.

Initial calculations show that it is difficult to find a suitable material for the injection absorber (TDI) that withstands the impact of 288 bunches of the so called LIU-BCMS beam. HL-LHC parameters at injection are more favourable. The other absorbers that are part of the injection and beam dumping system remain to be studied in more detail.

ACKNOWLEDGMENT

The authors acknowledge the SEY measurements carried out for the MKI by M. Mensi, and thank P. Costa Pinto for the aC coating of the inside of a ceramic tube. All members of the HL-LHC work package 14 are acknowledged for their contribution. The TDI studies profited from the synergies with the LIU TCDI project and their members are gratefully acknowledged.

REFERENCES

[1] L.Rossi, O.Brüning, "High luminosity large Hadron Collider. A description for the European Strategy

Preparation Group, CERN-ATS-2012-236, August 2012.
[2] L.Rossi, "LHC upgrade plans: Options and Strategy", Proceedings IPAC 2011, San Sebastián, Spain, September 2011, page 908, http://www.JACoW.org
[3] K.Hanke, "Status of the LIU project at CERN", these proceedings.
[4] M.J.Barnes, L.Ducimetière, N.Garrel G.D.Wait, "The LHC Injection Kicker Magnet", PAC'03, Portland, May 2003, p.1162, http://www.JACoW.org
[5] M.J.Barnes et al., "High Voltage Performance of the Beam Screen of the LHC Injection Kicker Magnets", proc. of this conference.
[6] H.Day, M.J.Barnes, F.Caspers, E.Metral, B.Salvant, J.Uythoven, "Beam Coupling Impedance of the New Beam Screen of the LHC Injection Kicker Magnets", proc. of this conference.
[7] Z.Sobiech et al., "Cooling of LHC Injection Kicker Magnet Ferrite Yoke: Measurements and Future Proposals", proc. of this conference.
[8] M.J.Barnes et al., "Upgrade of the LHC Injection Kicker Magnets", IPAC'13, Shanghai, May 2013, MOPWA030, http://www.JACoW.org
[9] M.J.Barnes et al., "Reduction of Surface Flashover of the Beam Screen of the LHC Injection Kickers", IPAC'13, Shanghai, May 2013, MOPWA032, http://www.JACoW.org
[10] R.Garoby et al., "LIU technical design report", 2014, to be published. CERN edms 1287889.
[11] Swanson Analysis System, Inc., ANSYS® Academic Research, Release 15.0, http://www.ansys.com.
[12] T.Antonakakis, C.Maglioni, "Upgrade of the TCDQ: a dumping protection system for the LHC", November 2013, sLHC Project Note 0041.