Electron cloud studies for the LHC TDI and HL-LHC TDIS

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Abstract

The LHC injection protection absorber (TDI) is designed to protect the machine in case of injection kicker malfunctioning. During the operation it was observed that electron cloud can build up inside the TDI chamber especially for certain openings of movable jaws. Numerical studies were done to estimate the electron flux on the internal surfaces of the device for the present TDI and the future segmented injection protection absorber (TDIS) foreseen for the HL-LHC. Different configurations of the devices as well as possible coating options to reduce electron multipacting are discussed in this report. The results presented here will be used by the vacuum team to quantify the detrimental effect of the electron cloud on the vacuum pressure.
1 Introduction

The LHC injection protection absorber (TDI) is a critical machine protection element which is designed to intercept the beam in case of injection kicker malfunctions and timing errors. There are two TDI devices in the LHC, one located in the cell 4L2 (beam 1 injection region), and another one in the cell 4R8. Both devices are installed in the experimental common regions, where the two beams circulate in the same chamber. The current LHC TDI has two movable absorber jaws, which are 4.185 m long, and two beam screens as shown on the CST [1] model in Figure 1.

Figure 1: Transverse cut of the TDI with the two movable jaws on top and bottom part and the two beam screens on left and right (CST model by B. Salvant).

During operation, in terms of machine protection, TDI performed as expected in all cases of injection failures, both when the injected beam was grazing along the jaws or when it had a direct impact on the TDI jaws. However, the device has suffered from vacuum issues observed when retracting the jaws after the beam injection as well as heating and other issues [2–4].

For the future High Luminosity LHC upgrade (HL-LHC) a new segmented injection protection absorber (TDIS) was designed with a beam screen on one side and three pairs of short movable absorbing blocks to allow for a simpler alignment of the device. The TDIS model is shown in Figure 2. The jaws in the first two segments will be made of graphite, whereas the jaws in tank three will be metallic with a section in aluminum coated with titanium and a section in copper. The electron cloud (e-cloud) formation in the present TDI and in the future TDIS was studied by means of PyECLoud build-up simulations [6]. The results presented in this report will be used as input for the dynamic pressure simulations by the vacuum team.

2 Electron cloud simulation setup

The main beam parameters used in the simulations are listed in Table 1. The nominal LHC beam parameters are used for the TDI while the HL-LHC beam parameters (very close to those presented in [7]) are used for the TDIS.
To reach the saturation of the e-cloud buildup it was sufficient to simulate two trains of 288 bunches. All results presented in the following are re-scaled to the total number of 2748 bunches.

To correctly model the presence of two counter-rotating beams in the same chamber, we simulate different slices along the device, accounting for different arrival times of the two beams and for variations of the transverse sizes. The transverse positions of the beams in TDI and TDIS are chosen to be the ones in the middle of the devices while their divergence is neglected. With the 25 ns bunch spacing, the delay between the arrival times of bunches of the two beams was

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**Table 1: Simulation parameters for the proton beams**

<table>
<thead>
<tr>
<th>Device</th>
<th>TDI</th>
<th>TDIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy, GeV</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>Bunch population, p/bunch</td>
<td>$1.1 \times 10^{11}$</td>
<td>$2.2 \times 10^{11}$</td>
</tr>
<tr>
<td>RMS bunch length (Gaussian), m</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>Bunch spacing, ns</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Normalized transverse emittance, µm</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Optics</td>
<td>runII 2016</td>
<td>HL-LHC v1.2</td>
</tr>
</tbody>
</table>

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Figure 2: TDIS model with indicated materials at the jaw surface (top) and a 3D representation of a single tank (bottom) (from [5]).
scanned from -12.5 ns to +12.5 ns, depending on the distance from the locations of the long-range encounters (LREs), i.e. the locations at which bunches of the two counter-rotating beams pass simultaneously. The results of the simulations discussed in this report are obtained for the devices installed at Point 2, however, due to the symmetry in the LHC layout, the same results are applicable for the absorbers at Point 8.

2.1 Assumptions and simplifications

In the simulations of the e-cloud buildup the following assumptions and simplifications were made for both the TDI and the TDIS models.

TDI

The TDI jaws have a step-out structure from 96 mm to 112 mm jaw width shown in Figure 1. This step was omitted and jaws of intermediate width of 102 mm were used in the model. This is not expected to have a major impact on the multipacting process. The TDI chamber profile used in the e-cloud buildup simulations is shown in Figure 3 where the dots indicate the positions of the two beams. Simulations were performed for delays ranging from -12.5 to +12.5 ns. For simplicity the SEY parameter was considered uniform, for the entire surface and was scanned in the range from 1.0 to 1.6. Since the TDI has retractable jaws, the possible configurations were scanned with half-gaps ranging between 1 and 50 mm.

![Figure 3: TDI geometry as simulated in PyECLOUD with the positions of the two circulating beams.](image)

TDIS

The TDIS absorber is designed to be about 4.7 m long and is built of three tanks 1.56 m long each. The gaps between the segments are not taken into account in the simulated model. Simulations were performed for delays ranging from -12.5 to +12.5 ns assuming uniform secondary electron yield (SEY) parameter ranging from 1.0 to 1.6 as well
as assuming the realistic nonuniform materials in the TDIS chamber. The different surfaces inside the TDIS chamber will be referred to as the back plate, the jaws, the side of jaws and the flat and round parts of the beam screen as indicated in Figure 4.

3 Single beam versus two beams

It is important to correctly model the e-cloud in the presence of two beams in the same chamber. A set of simulations was performed to establish the effect of each beam separately. Figure 5 shows the electron current in the TDI chamber with 40 mm half-gap when only beam 1 or beam 2 is present and when both beams are circulating. For the latter case, we consider a location at the LRE and a location in between LREs. With beam 2 alone no multipacting takes place due to the fact that the beam trajectory is shifted away from the jaws. With beam 1 alone the multipacting occurs for SEY above 1.2. When simulating the two beams together the
delay in the arrival time plays a big role and the multipacting threshold can again be very different. In particular, in Figure 5 we can observe that the multipacting is not always stronger in the presence of two beams compared to the single beam case.

4  E-cloud simulations with uniform SEY

Both the TDI and the TDIS have movable absorbing jaws. A scan of the half-gap between the jaws was performed in the range from 1 mm to 50 mm. It shows that the e-cloud is stronger for larger gaps.

E-cloud simulations with two counter-rotating beams with different delays between the beams provide the longitudinal profile of the e-cloud along the device. Figure 6 shows the electron current at the LRE in the TDI and in the TDIS as a function of the gap for \( SEY = 1.4 \). The current is increasing when opening the jaws. In the TDIS the maximum is observed when the half-gap reaches \( \sim 40 \) mm. The full set of longitudinal profiles for different gaps can be found in Appendices A and B for the TDI and the TDIS respectively.

Figures 7 and 8 show the longitudinal distributions of electron current along the TDI and the TDIS for the maximum simulated half-gap of 50 mm and for different SEY values. For the case of the TDIS the current and the heat load increase with the distance from the LRE, exhibiting a behavior which is opposite to the case of the TDI. This opposite behavior could be the result of the different simulated bunch population (\( 1.1 \times 10^{11} \) p/bunch for the TDI and \( 2.2 \times 10^{11} \) p/bunch for the TDIS) or of the different chamber geometry.

To differentiate between the two effects a reduced set of simulations (coarser delay scan) was performed for the TDI device with the HL-LHC bunch population of \( 2.2 \times 10^{11} \) p/bunch. The results are presented in Figure 9 and show that the different dependence of the e-cloud on the distance from the LRE is indeed de-

![Figure 6: Electron current at the LRE depending on the half-gap size in the TDI and TDIS for the uniform SEY 1.4.](image)
termined by the different bunch population. The total electron current and heat load versus half-gap for different SEY (uniform over the chamber) are shown in Figures 10 and 11 for the TDI and the TDIS respectively. The multipacting is stronger for larger gaps in both devices, however, in the TDI no multipacting occurs for half-gaps smaller than 20 mm while in the TDIS multipacting takes place for small gaps and large SEY values.

Figure 7: Longitudinal profile of the electron current in the TDI for the 50 mm half-gap and different SEY (uniform over the chamber). The bunch population of the two beams is set to $1.1 \times 10^{11}$ p/bunch. The total current and heat load for each SEY is indicated in the legend. The positions of LREs are marked with dashed lines.

Figure 8: Longitudinal profile of the electron current in the TDIS for the 50 mm half-gap and different SEY (uniform over the chamber). The bunch population of the two beams is set to $2.2 \times 10^{11}$ p/bunch. The total current and heat load for each SEY is indicated in the legend. The positions of LREs are marked with dashed lines.
Figure 9: Longitudinal profile of electron current in the TDI for the 50 mm half-gap and different uniform SEY. The bunch population of the two beams is set to $2.2 \times 10^{11}$ p/bunch. The total current and heat load for each SEY is indicated in the legend. The positions of LREs are marked with dashed lines.

Figure 10: Total electron current versus half-gap in the TDI (left) and the TDIS (right) for different SEY values.

Figure 11: Total heat load versus half-gap in the TDI (left) and the TDIS (right) for different SEY values.
5 e-cloud with nonuniform SEY in the TDIS

5.1 Effect of a-C coating of the metallic jaws

By design the TDIS will have three segments in separate tanks, allowing for better alignment of the device with respect to the beam. The absorbing blocks in the first two tanks will be made of graphite, which has low SEY, close to 1.0. The jaws in tank three, instead, will be made of blocks of metal alloys (Ti6Al4V 965 mm long and CuCrZr 600 mm long), which is much less favorable from the e-cloud point of view. To account for the presence of materials with different properties a set of simulations with nonuniform SEY was performed. For the metallic parts we assume a $SEY = 1.6$, corresponding to the partially conditioned surface. Following the same consideration, the rest of the chamber is also assumed to have a SEY of 1.6. Figure 12 shows the SEY distribution in the TDIS chamber along the three tanks. This model will be hereafter called the uncoated SEY model.

Since the jaws in tank three are metallic, multipacting can occur and a large number of electrons can accumulate in the chamber. For this reason the possibility of coating the jaws in tank three (J3) with amorphous Carbon (a-C) was considered. For these coated surfaces we assume $SEY = 1.0$ as for the graphite jaws, as shown in Figure 13. The rest of the chamber, i.e. the back plate, the sides of jaws and the beam screen, are again simulated with a SEY of 1.6. The model described above will be hereafter called the coated J3 model.

A comparison of the longitudinal electron current profiles for the uncoated SEY model with the coated J3 model is shown in Figure 14. The uncoated model shows a significant increase in the electron current density near the coated jaws, while the coated model shows a reduction in the current density. This indicates that the coating is effective in reducing the e-cloud effects in the TDIS.
Figure 13: SEY distribution in the TDIS with a-C coating on the jaws in tank three (the coated J3 model) (3D model provided by Luca Gentini).

Figure 14: Contributions to the total electron current from different surfaces in the chamber (as marked in Figure 4) for the uncoated SEY model (left) and the coated J3 model (right).

and for the coated J3 models is shown in Figure 14 for a jaw half-gap of 40 mm (worst-case scenario, see Figure 6). Different colors mark contributions from different surfaces of the chamber. The effect of the coating the jaws in tank three is clearly visible. The gain in electron current is however only about 65 mA, as
electrons mainly build up from the surface of the beam screen in both cases. The portion of electrons impacting on the surface of the beam screen, including round and flat parts, constitutes more than half of the total number of electrons and is not changing significantly between the uncoated SEY and the coated J3 models.

5.2 Effect of a-C coating of the beam screen

Based on the results of the simulations with the two models discussed earlier we have explored the possibility of reducing the contribution from beam screen surface. For this purpose, the e-cloud in the TDIS was simulated assuming a-C coating on the beam screen. We consider two options:

- a-C coating of the beam screen, hereafter called the coated BS model (see Figure 15)
- a-C coating of the beam screen and of the jaws in tank three, hereafter called the coated J3+BS model (see Figure 16)

![Diagram](image)

Figure 15: SEY distribution in the TDIS with a-C coating on the beam screen (the coated BS model) (3D model provided by Luca Gentini).

The contribution of the different surfaces to the electron current in the two cases is shown in Figure 17. With a-C coating of the beam screen alone, the electron current can be reduced by one order of magnitude compared to the cases with uncoated beam screen and the multipacting occurs only in tank three where the metallic jaws are located. By coating also the jaws in tank three together with the beam screen, the e-cloud can be completely suppressed. The total heat load
Figure 16: SEY distribution in the TDIS with a-C coating on the beam screen and jaws in tank three (the coated J3+BS model) (3D model provided by Luca Gentini).

Figure 17: Contributions to the total electron current from different surfaces in the chamber (as marked in Figure 4) for the coated BS model (left) and the coated J3+BS model (right).
Figure 18: Total electron current (left) and heat load (right) versus half-gap in the TDIS for the different SEY scenarios.

and electron current versus half-gap for the different SEY scenarios are shown in Figure 18.

Based on these results the present design of the TDIS includes the a-C coating of the beam screen and the metallic blocks, in order to achieve a full suppression of the e-cloud formation [8].

6 Summary and conclusions

Simulations of the e-cloud buildup for the TDI and the TDIS absorbers were performed with the PyECLOUD code, studying the dependence on the gap set between the absorbing jaws, for different SEY scenarios. LHC beam parameters were used for the TDI while HL-LHC beam parameters were used for the TDIS.

To account for the fact that the two counter-rotating beams share the same chamber inside the TDI and the TDIS we simulated different slices along the devices, thus looking at different arrival times for the two beams.

The multipacting threshold in the current TDI was found to be very high for small gaps and decreasing when the jaws are opened. In the TDIS, however, multipacting occurs even for small gaps if the SEY is larger than 1.4. The e-cloud builds up mainly from the flat surface of the jaws and of the beam screen. Simulations showed that the electron current and heat load profiles along the device reach a maximum at the locations of LREs in the TDI and at locations far from the LREs in the TDIS. The different bunch populations were found to be responsible for this opposite behavior between the TDI and the TDIS.

Several nonuniform SEY scenarios were simulated for the future TDIS absorber. The graphite jaws do not need any coating as their SEY is intrinsically low. The coating of the metallic jaws in tank three provides a small reduction of the total electron current. In fact, simulations have shown that about half of the total electron current is deposited on the beam screen, thus suggesting the possibility of coating it. Simulations with coated beam screen in the TDIS have shown that the e-cloud can be reduced by one order of magnitude by coating the beam screen.
alone and completely suppressed by coating also the metallic jaws in tank three. Based on these results the present design of the TDIS includes the a-C coating of the beam screen and the metallic blocks. The results presented in this report will be used as input for the dynamic pressure simulations of the devices.

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Appendix A

Longitudinal heat load and electron current profiles in TDI for different gaps

Figures A.1 to A.7 show the longitudinal heat load and electron current profiles in the TDI for different gaps and SEY values (assumed uniform). Highest values of current and heat load are observed at the locations of LREs. Multipacting occurs for half-gaps larger than 20 mm.

Figure A.1: Longitudinal profile of electron current (top) and of the heat load (bottom) in the TDI for 10 mm half-gap.
Figure A.2: Longitudinal profile of electron current (top) and of the heat load (bottom) in the TDI for 20 mm half-gap.

Figure A.3: Longitudinal profile of electron current (top) and of the heat load (bottom) in the TDI for 30 mm half-gap.
Figure A.4: Longitudinal profile of electron current (top) and of the heat load (bottom) in the TDI for 35 mm half-gap.

Figure A.5: Longitudinal profile of electron current (top) and of the heat load (bottom) in the TDI for 40 mm half-gap.
Figure A.6: Longitudinal profile of electron current (top) and of the heat load (bottom) in the TDI for 45 mm half-gap.

Figure A.7: Longitudinal profile of electron current (top) and of the heat load (bottom) in the TDI for 50 mm half-gap.
Appendix B

Longitudinal heat load and electron current profiles in TDIS for different gaps

Figures B.1 to B.9 show the longitudinal heat load and electron current profiles in the TDIS for different gaps and SEY values (assumed uniform). Unlike in the TDI the highest values of electron current and heat load are observed at the locations between the LREs. For high SEY values 1.5-1.6 multipacting occurs even at half-gaps of 4 mm.

Figure B.1: Longitudinal profile of electron current (top) and of the heat load (bottom) in the TDI for 4 mm half-gap.
Figure B.2: Longitudinal profile of electron current (top) and of the heat load (bottom) in the TDI for 8 mm half-gap.

Figure B.3: Longitudinal profile of electron current (top) and of the heat load (bottom) in the TDI for 10 mm half-gap.
Figure B.4: Longitudinal profile of electron current (top) and of the heat load (bottom) in the TDI for 20 mm half-gap.

Figure B.5: Longitudinal profile of electron current (top) and of the heat load (bottom) in the TDI for 30 mm half-gap.
Figure B.6: Longitudinal profile of electron current (top) and of the heat load (bottom) in the TDI for 35 mm half-gap.

Figure B.7: Longitudinal profile of electron current (top) and of the heat load (bottom) in the TDI for 40 mm half-gap.
Figure B.8: Longitudinal profile of electron current (top) and of the heat load (bottom) in the TDI for 45 mm half-gap.

Figure B.9: Longitudinal profile of electron current (top) and of the heat load (bottom) in the TDI for 50 mm half-gap.
Bibliography


