# OPERATIONAL FEEDBACK AND ANALYSIS OF CURRENT AND FUTURE DESIGNS OF THE INJECTION PROTECTION ABSORBERS IN THE LARGE HADRON COLLIDER AT CERN

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## Abstract

Two injection protection absorbers, so-called TDIs (**T**arget **D**ump **I**njection), are installed close to **I**nteraction **P**oints IP2 and IP8 of the **L**arge **H**adron **C**ollider (LHC) right downstream of the injection kicker magnets (MKI). Malfunction or timing errors in the latter lead to wrong steering of the beam, which must then be intercepted by the TDI to avoid downstream equipment (which includes superconducting magnets) damage. In recent years, the MKI failures during operation have brought to light opportunities for improvement of the TDI. The upgrade of this absorber, so-called TDIS (where "S" stands for segmented), is conceived as part of the **H**igh **L**uminosity-**LHC** (**HL-LHC**) project and those operational issues are taken into account for its design. The present document describes not only the aspects related to the current TDI performance and their impact in its successor's design but also the key modifications to cope with the stronger requirements associated to the higher luminosity goal.

## INTRODUCTION

The TDI is intended for downstream equipment protection in case of injection kicker magnets failure. As shown in the Fig. 1, it consists of several absorbing blocks split in two sub-assemblies known as jaws (a) that can be vertically and independently displaced inside a vacuum chamber (b). The jaws are powered by four external electric motors (c) whilst the necessary vacuum level is achieved by means of four ionic pumps (d). Another main component of the system is a stainless steel RF beam screen (e) necessary to mitigate the electromagnetic interference induced by the beam.
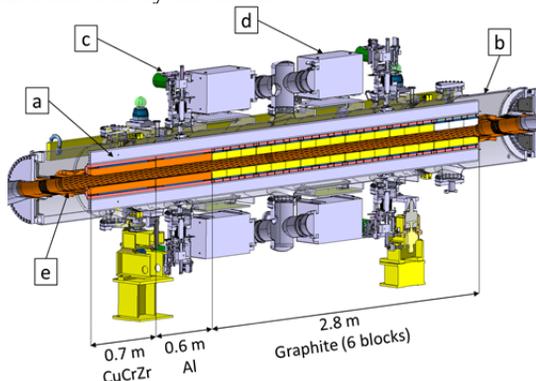


Figure 1: Current TDI design [1].

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Although the present TDI has provided the required machine protection in all cases of injection failure arisen during the last years (Table 1), some issues were reported in terms of vacuum and structural behaviour [2, 3].

Table 1: History of LHC Injection Failures with Beam Impact on the TDIs [2, 3].

| Date | Beam | MKI failure | TDI impact | Lost bunches |
|------|------|------|------|------|
| 2010 | | | large impact | |
| 23/10 | 1/inj. | not firing | parameter | 32 |
| 2011 | | | | |
| 18/04 | 2/inj. | flashover | grazing | 36 |
| 23/04 | 1/inj. | not firing | large ip | 36 |
| 27/04 | 2/inj. | not firing | large ip | 72 |
| 28/07 | 1/inj. | erratic | large ip | 144 |
| 28/07 | 1/circ. | erratic | grazing | 176 |
| 2012 | | | | |
| 26/03 | 2/inj. | erratic | large ip | 1 |
| 30/11 | 2/inj. | B1 MKI fired | large ip | 20 (BCMS*) |
| 12/12 | 1/inj. | timing error | large ip | 48 (BCMS) |
| 15/04 | 2/inj. | flashover | grazing | 108 |
| 2015 | | | | |
| 28/07 | 1/inj. | not firing | large ip | 144 |
| 2016 | | | | |
| 02/09 | 1/inj. | erratic | grazing | ~170 |
| 24/11 | 2/inj. | not firing | large ip | 28 (Pb) |

\***B**atch **C**ompression, bunch **M**erging and **S**plitting

On the other hand, the target of increasing the beam luminosity of the LHC up to a factor of 10 (HL-LHC), implies a more intense beam injected into the accelerator (Table 2). Hence, an MKI failure would result in more beam power deposited in the different components of the TDIS. This gives rise to stronger thermal shocks that the constitutive materials must withstand without suffering permanent deformation or other alterations of their properties.

Table 2: Injected Beam Parameters

| Variable | LHC | HL-LHC |
|------|------|------|
| Proton energy [GeV] | 450 | 450 |
| # protons/bunch [-] | $1.2 \cdot 10^{11}$ | $2.3 \cdot 10^{11}$ |
| # bunches/pulse [-] | 288 | 320 |
| # protons/pulse [-] | $3.5 \cdot 10^{13}$ | $7.4 \cdot 10^{13}$ |

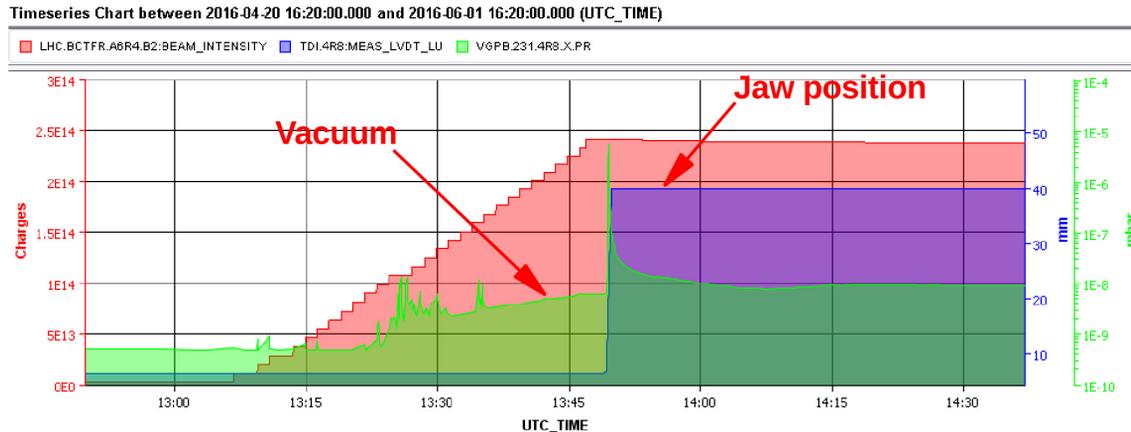## CURRENT TDI OPERATION

### Vacuum Aspects



Figure 2: TDI pressure spike observed in IP8 after injection phase, when high intensity beam circulates under large jaws retraction [2].

In its latest status, the TDI has suffered from vacuum issues observed when retracting the jaws after beam injection into the LHC. This displacement is required to allow enough gap for the circulating beams thus preventing any undesired impedance effects or interaction with the absorbing blocks after the end of the injection process. The chart of Fig. 2 reveals a pressure spike close to $10^{-5}$ mbar (which could cause closure of adjacent sector valves) inside the chamber when the jaws are moved away. Despite an operational solution was found by parking the jaws at 40 mm [4], the relationship between jaws retraction and pressure increase (which could be related with impedance, RF heating and/or electron cloud phenomena) is currently under investigation. Recent simulations suggest that, in the initial stages of operation, with high intensity beams, significant electron cloud is generated from the copper coating when the jaws are at parking position. Retracting the jaws progressively during beam commissioning and for different fills as intensity increases would allow for a more gradual conditioning of the materials, generating a milder impact on the vacuum pressure [5].

In spite of this specific anomaly, in general terms the vacuum performance of the equipment has been enhanced over previous years by changing the primary absorbing block material to Cu-coated graphite instead of Ti-coated boron nitride (hBN). Such improvement can be justified by a lower outgassing rate, better thermomechanical performance and higher electrical conductivity in the second configuration.

### Device Setting-Up

A proper alignment of the jaws with respect to the beam is crucial to enable the interception of mis-steered beams without interfering with well-steered ones.

The supporting mechanism of the TDI jaws tolerates a certain tilting angle ($\alpha$ in Fig. 3). Based on operational

feedback this angle can reach up to 760 µrad, and considering a length of nearly 4.2 meters of the aforementioned jaws, there can be an offset of more than 3 mm between both ends (upstream and downstream) of the jaw. This offset has to be measured and compensated during the alignment procedure, which lengthens the setting-up duration.
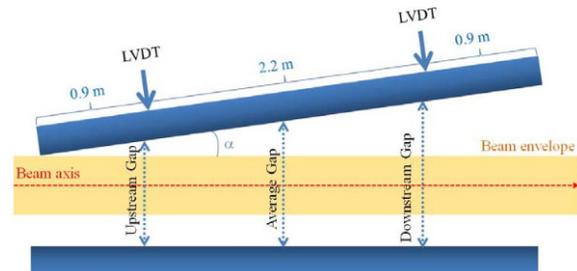


Figure 3: Jaws-beam relative position [6].

Additionally, beam induced RF heating leads to certain elastic deformation of the jaws (effect observed indirectly by the drift shown by LVDT - linear variable differential transformers - readings) detrimental for the function and that cannot be countered by the initial alignment [7].

## DESIGN UPGRADE OF TDIS VS TDI

The TDIS design proposes significant modifications with respect to the current TDI. First of all, the future device features a segmented design with three modules (Fig. 4) instead of one. One of the advantages of having various modules is the use of independent shorter jaws less prone to bending under their own weight or due to RF heating. In this way, a better flatness is achievable all along the jaws. Furthermore, each jaw can be vertically aligned independently so, overall, the setting-up stage is expected to be eased.
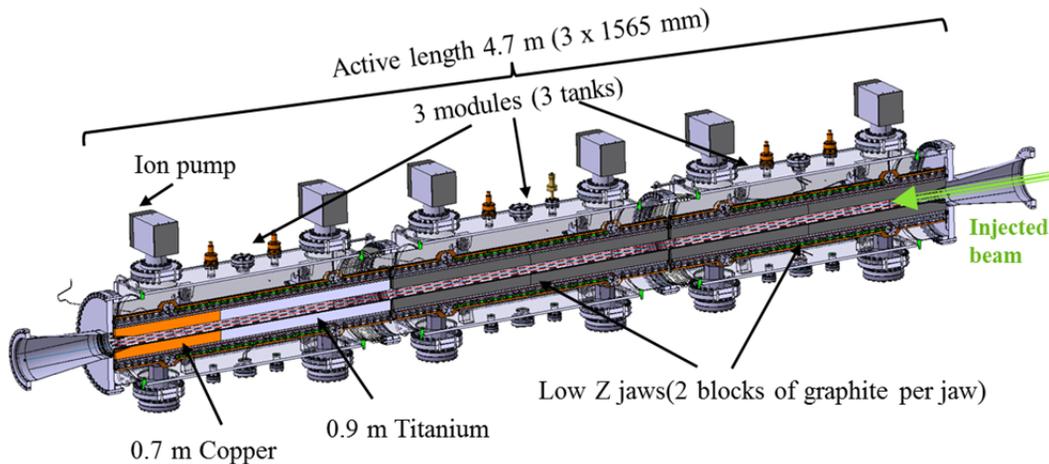
Figure 4: TDI upgrade (TDIS) design [1].

The jaw structure has also been deeply modified and inspired on the design of collimators jaws. The cross-section views of both TDI and TDIS jaws displayed side by side in Fig. 5 evidence major changes in the cooling system, the clamping of absorbing blocks and stiffening elements.
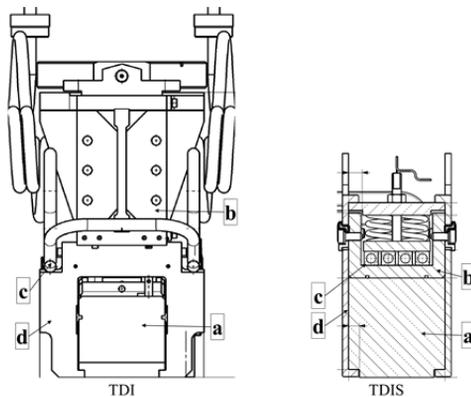


Figure 5: TDI and TDIS jaws cross-section views.

Conducted thermo-mechanical simulations indicate that the absorbing blocks (element (a) in the Fig. 5), stiffener (b) and cooling pipes (c) are the most sensitive elements against beam impacts [8]. The first of them are sensitive especially in case of grazing events, when graphite (primary absorber material) could experience a sudden temperature increase above 1300 °C over a small area. The graphite mechanical robustness against the arisen stresses are assessed by means of the Christensen criterion [9], a failure theory well adapted for brittle materials. According to it, the stresses produced in graphite are equivalent to 76% of the maximum allowable value, suggesting that a sufficient safety margin is available.

Concerning the stiffener, the particle shower developed as consequence of the beam impact against the primary absorbing blocks also produces a strong thermal shock. Numerous iterations have been carried out to find the most suitable geometry and material. Besides a high thermal shock resistance, a high density is also desirable for this component to shield the cooling pipes from indi-rect beam impact. Moreover, a good thermal conductivity is as well necessary since the stiffener acts as interface between cooling pipes and absorbing blocks (subjected to beam induced heating). Lastly, ultra-high vacuum compatibility is mandatory for all components. Overall, the best candidate material was found to be the Titanium-Zirconium-Molybdenum alloy (TZM), which features a density of 10.2 $g/cm^3$ and thermal conductivity of 126 W/K-m at room temperature. The stiffener made out of this material will be submitted to peak temperatures of 230 °C and maximum von Mises stresses close to 450 MPa, whereas its yield strength exceeds 560 MPa.

## CONCLUSIONS

The upgrade of the LHC aiming at a 10 times higher integrated luminosity brings new challenges not only for the accelerator itself but also for the whole injection system. As part of the injection protection equipment, the current TDI must be upgraded as well, since the more challenging conditions of a beam impact would exceed its absorption capacity.

The current design status of the new injection protection absorber TDIS is based on multiple studies that support the compliance with the operational and performance requirements of the HL-LHC. Key elements such as the jaws and the motorizations have been improved to ensure stability during its entire lifespan. Even after repeated worst-case failures of the MKI kickers, all are expected to remain operational and without functional degradation.

Impedance-wise the presence of RF fingers between jaws and RF beam screen as well as the reduction of the vacuum chamber volume render a positive effect. These are both important ingredients to reduce the presence of resonant modes in the structure [10].

## ACKNOWLEDGEMENT

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