TDI - PAST OBSERVATIONS AND IMPROVEMENTS FOR 2016

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Abstract

In Run 1, the LHC injection absorbers (TDIs) were affected by several anomalies including structural damage of the beam screens and elastic deformations of the jaws due to heating during fills. Other issues became apparent in 2015, like excessive vacuum spikes, which gave rise to several beam dumps, as well as quality issues affecting the hBN absorber blocks. This paper briefly summarizes past observations and issues like impedance, and describes the modifications which have been implemented in LS1 and the YETS 2015/2016. In addition, the expected implications and improvements for operation in 2016 are discussed.

INTRODUCTION

The LHC injection regions in IR2 and IR8 accommodate a system of beam-intercepting devices and masks to protect machine components in case of MKI malfunctions and timing errors. The main element of the protection system is the TDI [1], a movable two-sided absorber installed at a phase advance of 75–95° from the MKIs. The TDI jaws are 4.185 m long and accommodate different absorber blocks. In order to sufficiently protect the LHC during injection but also allow for some operational margin, the TDI jaws are maintained at a half gap of 6.8σ which corresponds to a jaw opening of approximately 7.6 mm [2]. Several injection failures with beam impact on the TDIs occurred in Run 1 and in 2015. The different events are summarized in Table 1. In a few cases, beams were grazing along the jaws after being deflected with non-nominal MKI strength. This in turn led to a quench of downstream magnets owing to secondary showers escaping through the TDI gap [3]. For such failure events, magnet quenches are unavoidable and were considered acceptable when designing the injection protection system [1,4,5].

In all injection incidents, the TDIs performed as anticipated. The TDIs however exhibited several other anomalies during operation in Run 1 and 2015, some of them affecting availability or limiting operation. New TDIs are being designed for HL era, however the present TDIs are foreseen to be operational until LS2. Several modifications have been carried out on the existing TDIs to improve their performance and to add more instrumentation. Following a brief recap of the main issues encountered in Run 1 and the modifications carried out in LS1 (2013–2014), this paper summarizes the main observations and limitations from 2015 and the changes implemented in the YETS 2015/2016. In addition, the paper discusses the expected improvements for 2016 and provides a brief outlook on the foreseen TDI upgrade in LS2.

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Table 1: LHC injection failures in Run 1 and Run 2 (up to 2015) with beam impact on the TDIs in IR2 and IR8. In most of the cases, injected bunch trains were not kicked and impacted on the TDI with a large impact parameter (ip).

Date	Beam	MKI failure	TDI impact	Lost bunches
2010				
23/10	1/inj.	not firing	large ip	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

RECAP OF ISSUES IN RUN 1 AND MODIFICATIONS IN LS1

In Run 1, the TDIs were affected by several issues like structural damage of the beam screens, thermal drifts of jaw positions, and bad vacuum quality [6–8]. Many of the issues were likely caused by beam-induced RF heating [9–11]. As a consequence several related hardware changes were foreseen in LS1, however some of them had to be discarded or delayed due to manufacturing issues [11–14]. Some of these modifications (like a Cu coating on absorber blocks for reducing the resistive wall impedance of the jaws) were eventually carried out in the YETS 2015/2016. A brief overview of the main observations in Run 1 and related hardware changes carried out in LS1 is given in the following.

Observations and issues in Run 1

The TDIs installed in the machine in Run 1 acommodated blocks of hexagonal boron nitride (hBN, 18×15.7 cm), aluminium (1×60 cm) and CuBe (1×70 cm). With increasing beam intensity in 2011, the LVDT position sensors started

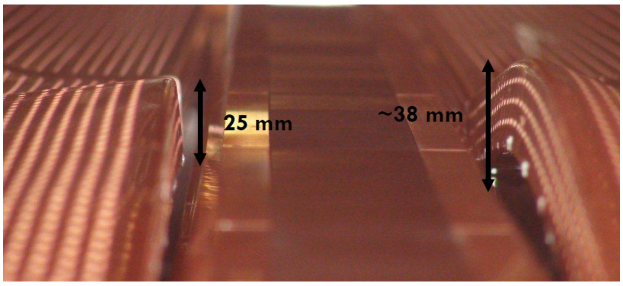

Figure 1: Deformation of copper beam screens observed in Run 1. The photo depicts the screen of the TDI.4R8. Deformations were also observed in the TDI.4L2.

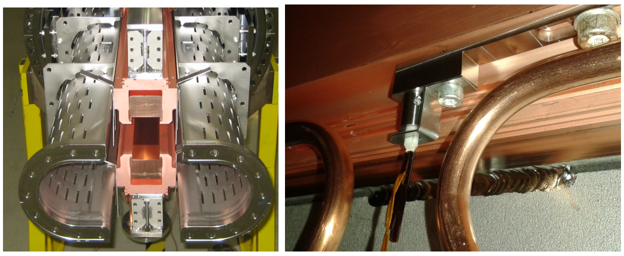

Figure 2: New reinforced beam screens (left) and temperature sensors (right) installed in LS1. Photos courtesy of A. Perillo Marcone and I. Lamas Garcia.

Figure 3: Issues with coatings in LS1: damaged Ti/NEG/Cu/NEG coating on hBN block due to hBN outgassing during bakeout (left) and discolored copper coating on beam screens due to Cl contamination (right). Photos courtesy of M. Taborelli and A. Perillo Marcone.

to measure drifts of the TDI jaw positions in the presence of beam (up to ~200 μm), which indicated a thermal expansion of the jaws during fills [7]. The drifts typically reverted in periods without beam when the jaws had time to cool down. Both TDIs were equally affected and the issues persisted throughout 2012. Interlock limits on the jaw positions had to be adjusted multiple times in order to prevent unnecessary dumps or not to delay subsequent injections. Owing to a flexible junction on one of the motorization axes, the drifts could however not be unambiguously correlated with the actual jaw deformation [7, 14].

In the winter stop 2011/2012, the copper beam screens of both TDIs were found deformed, with local elevations of almost 4 cm in the TDI.4R8 (see Fig. 1) [6]. A possible cause of the deformations is beam-induced RF heating, but other aspects may have contributed as well. For example, the sliding contacts were found blocked and the copper was found to have softened after bakeout. In the original TDI design (as described in the LHC design report [15]), the screens would have been foreseen to be made of Cu-coated stainless steel and not of copper [6].

In 2011 and 2012, the TDIs were also affected by outgassing issues [8]. The vacuum behaviour was typically worse in the TDI.4L2, in particular the baseline pressure was about one order of magnitude higher in the TDI.4L2 (2×10^{-9} mbar in 2012) as compared to the TDI.4R8 (few 10^{-10} mbar). Starting from mid-2012, the outgassing of the TDI.4L2 became progressively worse; for most of the fills, the pressure steadily increased during the first hours into stable beams, typically reaching a few 10^{-8} mbar. In conjunction with an equally bad vacuum pressure observed in the neighbouring 800 mm chamber, the pressure levels in the TDI gave rise to severe background issues in ALICE.

Modifications in LS1

Several hardware modifications were carried out in LS1 in order to address issues encountered in Run 1 [11–14]. In particular, the original copper beam screens were replaced by new reinforced stainless steel screens with an increased wall thickness of 6 mm (see Fig. 2). In addition, the RF contacts between the two beam screen halves were substituted by a more robust flange made of stainless steel. New sliding contacts were introduced, based on ceramic spheres, which improved the sliding of the screens in case of thermal expansion and therefore reduced the risk of similar problems as encountered with the original pin-based design. To allow for a better monitoring of the heat load, several PT100 temperature probes, as shown in Fig. 2, were installed on the lower jaw and the beam screens. In addition, the ion pumping system was consolidated with NEG cartridges and the TDIs were sectorized with vacuum valves [16].

Owing to manufacturing difficulties and time constraints, some of the modifications originally foreseen for LS1 had to be discarded or delayed [12–14, 17]. This included a sandwich of new coatings on top of the Ti-coated hBN blocks, consisting of a 2 μm Cu layer to reduce resistive heating and a 1 μm NEG coating to reduce the secondary electron yield (SEY). The coating sandwich however peeled off after a bakeout cycle at 300°C as the strong outgassing of the hBN blocks damaged the NEG irreversibly [14, 17] (see Fig. 3). The NEG coating was therefore discarded and the implementation of the Cu coating was delayed to the YETS 2015/2016 (for 2015 operation, the hBN blocks were hence left with the 5 μm Ti coating already present in Run 1). Likewise, the originally foreseen NEG coatings on the aluminium blocks, CuBe blocks and beam screens (in all cases for SEY reduction) could not be implemented due to the same reason. The aluminium blocks were instead coated with Ti, whereas the CuBe blocks were left uncoated. Suppressing the NEG coatings on the CuBe blocks and the screens was eventually considered justified as electron cloud-related effects were likely not the main cause of problems faced in Run 1 [17]. Issues were also encountered when applying a Cu plating on the beam screens owing to the geometry

Figure 4: Cracked hBN blocks after thermal treatment in vacuum at 800°C. Material projections are visible on the block surface.

which hindered a proper removal of Cl from the previous Ni plating process [13] (see Fig. 3). As a consequence, the Cu coating was removed from the screens and the screens were left uncoated. The impact on impedance was estimated to be acceptable [11].

OBSERVATIONS AND OPERATIONAL LIMITATIONS IN 2015

Several new issues became apparent after the restart of the LHC in 2015. This concerned in particular the hBN blocks, which were found to fail at much lower temperatures than specified by the manufacturer. In addition, excessive vacuum spikes were observed in the TDI.4R8 during injections. This section summarizes the main issues and resulting limitations encountered in 2015 and presents preliminary findings of inspections carried out in the YETS 2015/2016.

Quality issues with hBN blocks

In spring 2015, major quality issues affecting the hBN blocks became apparent during thermal treatment of the

Table 2: Maximum number of batches/bunches (N_{bt}^{max}/N_{bn}^{max}) per LHC injection in 2015. The limits were imposed due to hBN quality issues.

Beam type	I_b (p/b)	ϵ_n (μm·rad)	N_{bt}^{max}	N_{bn}^{max}
Std 25 ns	1.2×10^{11}	2.6	2	144
BCMS 25 ns	1.3×10^{11}	1.3	2	96
50 ns	1.2×10^{11}	1.5	3	108

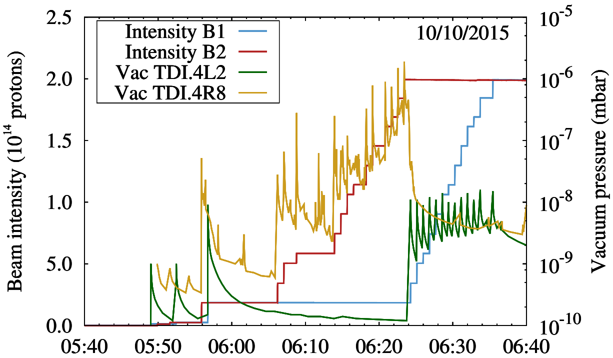

Figure 5: Typical vacuum pressure spikes in the TDIs (VGPB.4L2.231.X.PR and VGPB.4R8.231.X.PR) during injection for a regular physics fill in 2015. Spikes were orders of magnitude higher in the TDI.4R8 than in the TDI.4L2. The number of bunches per injection was 144.

blocks for the spare TDIs [18]. To achieve a better cleanliness before coating, new procedures were applied involving a high-temperature bakeout cycle under vacuum. Previous treatments were carried out at lower temperature (400 °C in air and vacuum). About 20% of the blocks were found cracked after a thermal treatment at 800 °C, and about 50% failed after a cycle at 1000 °C (see Fig. 4). These findings were in contradition to the material specifications of the manufacturer which state a maximum use temperature of 1150 °C in inert atmosphere. The faulty behaviour can likely be attributed to a non-conformity in the manufacturing process. Remains of unreacted binder material (B_2O_3), with a melting point of around 450 °C, were found inside the blocks. No clear correlation with a single batch of blocks could be determined.

As a consequence of these findings, limits on the maximum intensity per injection had to be imposed for the 2015 run in order to prevent the risk of damaging the blocks in the machine or polluting the machine vacuum [18, 19]. Depending on the brightness of beams, the number of batches transferred from the SPS was restricted such that the peak temperature in the hBN blocks would remain below 400 °C in the event of an injection failure. At the same time, the pulse length of the LHC injection kickers had to be adjusted in order to equally limit the number of bunches onto the TDI in case the MKIs would accidentally kick the stored beam. Table 2 summarizes the beam parameters for different beam types and the resulting intensity limitations applied in 2015. Owing to these limitations, injections for regular physics fills with standard 25 nsec beams were restricted to 144 bunches (instead of 288 bunches). This increased the overall time spent at injection and, in addition, required an adjustment of the filling pattern [19].

Vacuum spikes in the TDI.4R8

In 2015, excessive vacuum spikes were observed in the TDI.4R8 during injections, typically resulting in a significant vacuum pressure build-up when filling for scrubbing or for physics (see Fig. 5). The abnormal vacuum behaviour became apparent during the first scrubbing period in June, when the machine was filled for the first time with higher intensities after LS1, i.e. with several hundreds of bunches. No conditioning was observed throughout the year. The pressure build-up at injection became progressively worse in summer and autumn owing to the increasing number of bunches per fill, and hence the increasing number of injections. For many of the fills, the spikes reached a few 10^{-6} mbar up to a few10^{-5} mbar for the last batches injected into Ring 2. Several times the beams were dumped and the vacuum valves next to the TDI closed as the pressure spikes exceeded the interlock limit on nearby vacuum gauges (at least 2 gauges need to exceed the interlock limit in order that the beams are dumped). To improve availability, the interlock limits were increased in several steps throughout the year, from initially 2×10^{-6} mbar to 1×10^{-5} mbar in early November. Spurious pressure spikes were also observed in between injections, as well as at flat top with the jaws being in parking position. The spikes at flat top were typically smaller than the ones at injection. To determine the cause of the abnormal vacuum behaviour, x-ray inspections of the TDI.4R8 were carried out in the first technical stop in 2015, however no obvious non-conformities were found [20]. Vacuum spikes occurred also in the TDI.4L2 (when injecting into Ring 1), however they typically remained below a few 10^{-8} mbar (see Fig. 5). Apart from the spikes, the vacuum pressure of the TDI.4R8 did not show any anomalies. In particular, the baseline pressure in absence of beam was similar as in 2012 (few 10^{-10} mbar).

Impedance and RF heating

Besides the vacuum spikes, also other differences were observed between the TDI.4R8 and the TDI.4L2 in the 2015 run. Measurements with beam showed that the transverse impedance was four times higher for the TDI.4R8. In addition, the synchronous phase shift and hence the power loss was found to be a factor two higher [21]. The latter observation was consistent with PT100 readings, which indicated somewhat higher temperatures for the TDI.4R8 as compared to the TDI.4L2. However, the temperature readings exhibited some anomalies due to electromagnetic coupling between the PT100 probes and the beam through high-order modes. Hence, the comparison of temperature readings was not always conclusive. As in Run 1, thermal drifts of jaw positions were measured by the LVDTs on both TDIs. Unlike the observations above, the drifts were however not much different between the two TDIs and were comparable to the drifts measured in 2011 and 2012.

Inspections of the TDIs in the YETS 2015/2016

Both TDIs installed in the machine in 2015 were replaced with the spare TDIs in the YETS 2015/2016. First inspections of the TDI.4R8 after removal from the machine showed that the Ti coating on the hBN blocks had substantially degraded across large surface areas (see Fig. 6) [22]. In addition, blisters were found in the Cu coating of the aluminium

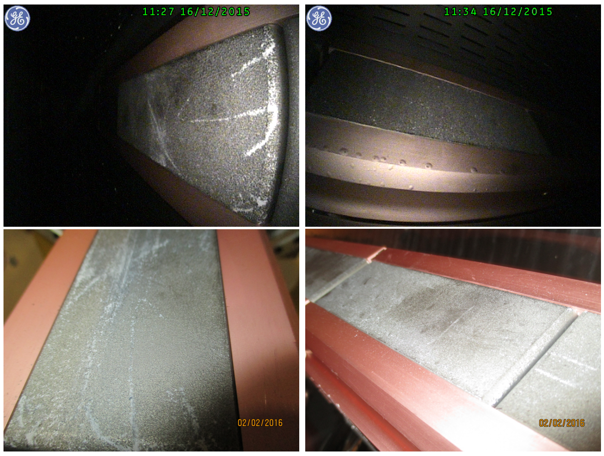

Figure 6: Degraded Ti coating on the hBN blocks of the TDI.4R8 installed in the machine in 2015. The two upper pictures are images from a first endoscopy inspection carried out in the YETS 2015/2016, whereas the two bottom pictures show the TDI jaws after they have been removed from the tank. Photos courtesy of A. Perillo Marcone and I. Lamas Garcia.

frame (see top right photo in Fig. 6). The Ti coating on the hBN blocks of the TDI.4L2 also showed some signs of degradation, but much less severe than for the TDI.4R8 [22]. The reason for the coating degradation is unclear. Measurements of the longitudinal and transverse impedance with a stretched wire confirmed the differences between the two TDIs observed in operation [23]. The TDI.4R8 was found to have a higher broadband impedance at every gap [23]. A correlation with the increased level of coating degradation in the TDI.4R8 seems likely, but more investigations are needed to confirm this assumption [23].

MODIFICATIONS IN THE YETS 2015/16 AND EXPECTATIONS FOR 2016

The TDIs installed in the machine in the YETS 2015/2016 (which were previously the spare TDIs) had been modified in several ways to implement changes originally foreseen in LS1 [24]. This included for example a Cu coating on non-metallic absorber blocks and a jaw gap monitoring system based on interferometry. At the same time the hBN blocks were replaced by Graphite blocks and other minor modifications were carried out. This section summarizes the changes and the expected implications for operation in 2016.

Replacement of absorber block materials

To overcome the limitations arising from the inferior hBN quality, the hBN blocks were replaced with Graphite blocks with a nominal density of 1.83 g/cm^3 (Sigrafine® R4550 SGL Group). The same grade of Graphite has already been used in other devices, both in the transfer lines (TCDIs) and in the LHC rings (e.g. in the TCLIAs and TCDQs, the latter ones being upgraded to R4550 during LS1 [13]). Thermo-mechanical studies showed that this grade of Graphite is robust enough to sustain the impact of 288 bunches with bunch intensities of 1.2×10^{11} protons and a normalized transverse emittance of 2.6 μm·rad [18, 25]. The new blocks therefore allow to lift the limitation adopted in 2015, which allowed only injections of up to 144 standard LHC bunches as shown in Table 2. Likewise, the new blocks allow to lift the limit imposed on the injection of BCMS beams, which was restricted to trains of 96 bunches in 2015. Simulation studies showed that Graphite R4550 is robust enough to sustain the impact of 144 BCMS bunches (1.3×10^{11} protons per bunch) [26], which is the maximum number of bunches for which the existing transfer line collimators (TCDIs) can provide sufficient protection [27].

The new Graphite blocks are also expected to improve both the impedance and the vacuum behaviour of the TDIs. The electrical and thermal conductivity of Graphite is higher than for Ti-coated hBN [28], hence reducing the resistive wall heating generated by the circulating beam (the resistive heat load is further reduced by applying a Cu coating as described below). Outgassing tests of the Graphite R4550 showed that the residual gas remains outside of the LHC vacuum specification due to the porosity of Graphite [29]. However, the total outgassing at room temperature is four times lower than for the previously used hBN [29] and therefore one can expect an improvement compared to Run 1 and 2015.

In addition to the replacement of hBN with Graphite, the downstream CuBe blocks were substituted by new blocks made of another Cu-alloy. It was observed that the CuBe blocks had deformed after being exposed to high temperatures during bakeout. Hence, they were replaced by CuCrZr blocks as this alloy performs better under the expected thermal loads. The new materials (Graphite R4550 and CuCrZr) have similar absorbing properties as the previous ones and will therefore not affect the primary function of the TDI, which is the protection of superconducting magnets and other sensitive elements in the LHC rings.

Coating of Graphite blocks

To reduce the heat load due to the resistive-wall impedance of the TDI, the new Graphite blocks were coated with a 2 μm Cu layer (as originally planned for the hBN blocks in LS1). A flash of Ti was applied below the Cu in order to guarantee a good adherence on the blocks. The Cu-coated Graphite blocks are expected to reduce the resistive power loss to the TDI jaws by a factor 50 compared to the Ti-coated hBN blocks used until 2015 [28] (the reduction is even higher if one compares to hBN blocks with a degraded Ti coating as observed in the TDI.4R8 in 2015). For a circulating beam with 2808 bunches, a bunch intensity of 1.2×10^{11} protons and an rms bunch length of 11.2 cm, the resistive power loss is estimated to be 6 W as compared to 300 W for Ti-coated hBN (both at injection settings) [28]. The reduction of the impedance compared to previous TDIs has been confirmed by measurements on the refurbished TDIs before installation in the tunnel [23].

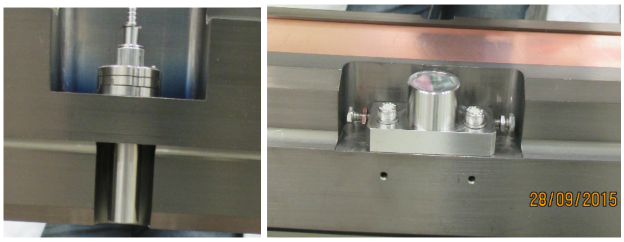

Figure 7: Optical sensor head (left) and retroreflector (right) integrated in the TDI aluminium frame. Photos courtesy of I. Lamas Garcia.

In case the copper coating is slightly compromised during grazing beam impact, the resistive heating is expected not to be worse than in previous years due to the better conductivity of Graphite compared to Ti-coated hBN. Even if the Graphite blocks would not be coated with copper, the power losses due to the resistive wall impedance are expected to be a factor 4 lower compared to present TDIs [28]. Moreover, in case of grazing impact, it is expected that only a small portion of the coated surface would be affected. Hence, a good conductivity can still be provided by the rest of the surface.

Interferometric system

A new jaw gap monitoring system based on interferometers [30] was installed on the refurbished TDIs. The system consists of pairs of sensor heads and retroreflectors, which are integrated into the frames of the two opposite jaws (see Fig. 7). The new system allows for a direct gap measurement and is redundant to the indirect measurement provided by LVDT position readings on the motorization axes of the opposite jaws. Having an independent gap measurement was motivated by the implementation of a new redundant gap interlock for the injection Beam Energy Tracking System (BETS) in LS1 [31, 32]. It is the first time that such an interferometric system is employed in the LHC and its performance under regular operational conditions still has to be evaluated. If the system proves reliable, it would allow overcoming the deficiencies of the LVDT-based gap measurement since a direct account of jaw deformations would be possible.

Other modifications

In addition to the changes described in the previous sections, several minor modifications were carried out on the TDIs installed in the YETS 2015/2016. This included for example a closer attachment of the cooling pipes to the aluminium frame of the jaws. This modification increases the contact between the pipes and the frames and is expected to improve the efficiency of the cooling system. The overall efficiency of the circuit is however still limited due to the general weakness of the circuit design. To monitor the temperature of both jaws, some of the temperature probes were moved from the lower to the upper jaw. Further modifications were implemented aiming at optimising the behaviour and stiffness of the jaw displacement mechanism. Amongst other minor modifications, a more precise mechanical end-stop was implemented, in order to have a more reliable position reference, preventing the uncertainties that arose several times during Run 1 and that cost a few shifts for realignment with beam.

CONCLUSIONS AND OUTLOOK

Several hardware modifications have been carried out on the TDIs in LS1 and the YETS 2015/2016 in order to mitigate operational issues and limitations encountered in Run 1 and at the beginning of Run 2 (2015). As the non-metallic absorber blocks yield the largest contribution to the resistive-wall impedance of the TDIs at injection settings, the new Cu-coated Graphite blocks are expected to significantly reduce the heating of the TDI jaws in 2016 operation as compared to previous years. The modications implemented in the YETS 2015/2016 do however not change high-order modes. This has been confirmed by impedance measurements on the fully assembled TDIs before installation in the tunnel [33]. The modes are distributed from 31 MHz onwards and can heat different locations in the TDIs like the jaws, tank, transitions, Al frame, etc. [33]. The power loss can be of the order of 10-100 W per mode [34], but can potentially be much higher in case of non-conformities. Operation in 2016 will show how high-order modes affect the TDI considering that resistive heating should be much reduced due to the Cu-coated Graphite blocks. Although the performance of the optical gap measurement system still has to be demonstrated under regular operational conditions, the system is expected to provide a better understanding of the actual jaw deformation in case the heating is not entirely suppressed by the new Cu coating.

The two TDIs, which have been removed from the machine in the YETS 2015/2016, are presently subject of careful inspections in order to identify the different performance in 2015 operation and to understand the observed damage to the Ti coating in the TDI.4R8 and a possible relation with the vacuum spikes encountered in 2015. Once the investigations are completed, the two TDIs will be modified to become the new spares. The time needed for these modifications is about 6 months after the YETS, which means that no spares will be available during this period.

A new TDI is being designed within HL-LHC WP14 and is foreseen to be installed in LS2 [35]. The new TDI (called TDIS) will be segmented into three modules, each hosting a pair of jaws with an active length of 1.5 m. The new design features an improved cooling circuit directly embedded into the jaws, which should significantly enhance the cooling efficiency with respect to the present design where the circuit is attached on top of the frame. In addition, several other measures will be implemented in order to reduce as much as possible the impedance. Considering that several design requirements are similar to the existing TDIs (large aperture etc.), operation in 2016 will also provide useful information for the new design.

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