WP14 in a nutshell – Injection & Dumping systems

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**Technologies:** High precision Assembling and manufacturing technologies, Raw Materials, Others, Electrical Equipment, electronics and instrumentation for accelerators

The beam transfer into the LHC is as well as the dumping system needs to be upgraded due to the new beam parameters, injected intensity and brightness foreseen for the HL-LHC project.

**HL-LHC High Luminosity LHC Project WP 14 - Injection & Dumping systems**

**WP 14 - Injection & Dumping systems - Injection system**
- TDIS - Beam absorber for injection
- TCDD - D1 Injection protection mask
- TCLIA and TCLIB – Injection protection collimators
- MKI - Injection kicker mask

**WP 14 - Injection & Dumping systems - Dumping system**
- TCDS - Beam dumping system absorber
- MKB - Beam dumping dilution kickers

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Fig. 1 - 3D view of the new TDIS to be installed on the LHC

Fig. 2 - 3D detailed view of the new TDIS.
Fig. 3 - 3D model of the interconnection between tanks.

Fig. 4 - Injector kicker mask (MKI) design.

Fig. 4 - Existing LHC Dump
GENERAL PARAMETERS

The beam transfer into the LHC is achieved by the two long transfer lines TI2 and TI8, together with the septum and injection kicker systems, plus associated machine protection systems to ensure protection of the LHC elements in case of a mis-steered beam. The LHC is filled by approximately 10 injections per beam. The foreseen increase in injected intensity and brightness for the HL-LHC means that the protection functionality of the beam-intercepting devices needs upgrading. In addition, the higher beam current significantly increases the beam-induced power deposited in many elements, including the injection kicker magnets in the LHC ring. The beam dumping system is also based on DC septa and fast kickers, with various beam intercepting protection devices including the beam dump block. Again, the significant change in the beam parameters for the HL-LHC implies redesign of several of the dump system devices, because of the increased energy deposition in the case of direct impact, but also because of increased radiation background that could affect the reliability of this key machine protection system.

INJECTION SYSTEMS

The high injected beam intensity and energy mean that precautions must be taken against damage and quenches, by means of collimators placed close to the beam in the injection regions. The beam to be injected passes through five horizontally deflecting steel septum magnets (MSI) with a total deflection of 12 mrad, and four vertically deflecting kickers (MKI) with a nominal total kick strength of 0.85 mrad. Uncontrolled beam loss resulting from errors (missing, partial, badly synchronized, or wrong kick strength) in the MKI could result in serious damage to downstream equipment in the LHC injection regions, in particular the superconducting separation dipole D1, the triplet quadrupole magnets near the ALICE or LHCb experiments, or in the arcs of the LHC machine itself. Damaging detector components, in particular those close to the beam pipe, with excessive showers generated by lost protons, is also possible.

INJECTION SYSTEMS - PRIMARY INJECTION ABSORBERS - TDIS

The presently installed TDI is a movable two-sided vertical absorber. Its purpose is to protect machine elements in case of MKI malfunctions and to intercept low-intensity bunches during set-up or commissioning of the injection system. Protection must be provided both in case of mis-deflections of the injected beam due to MKI faults as well as in case of accidental kicks of the stored beam due to MKI timing errors. The protection objectives should be met for any impact condition, including cases where beams are swept over the aperture (beam affected by MKI rise or fall time) or where a full batch is grazing the TDI jaw due to a non-nominal MKI kick strength. The largest energy deposition in downstream magnets and the highest stresses in the absorber blocks themselves are expected for small impact parameters, which could occur in the case of a high voltage breakdown in one magnet during injection.

The new TDIS will comprise three shorter absorbers most likely accommodated in separate tanks. The jaws of the three TDIS modules will all be identical except for the active absorber material. For robustness reasons, the two upstream modules will accommodate low-Z absorber blocks. The baseline is to use the same grade of Graphite as in the present transfer line collimators (SIGRAFINE® R4550, 1.83 g/cm3), the final decision of the material is pending further material tests. The third module is foreseen to host higher-Z absorber materials to enhance to partially absorb and efficiently attenuate the particle showers from the low density absorber blocks upstream. The final choice of materials for this module is subject to further studies. The active absorber length of each jaw will be 1.5 m. The new TDISs will be approximately at the same position as the present TDI, as they need to be at 90° betatron phase advance relative to the MKIs. The total length including vacuum transition chambers will be the same as the present TDI, i.e. not requiring any modification of nearby vacuum equipment.

The correct positioning of the TDIS is a vital element of the machine protection system during injection. A beam energy tracking system (BETS) is foreseen to guarantee the correct position at injection energy. For a
multi-module TDIS system the correct alignment with beam between the different modules will be very important. The jaws of the third module need to be slightly retracted compared to the upstream jaws to avoid direct beam impact on the higher-Z absorber blocks.

The components and raw materials required for the manufacturing of the TDIS have been already purchased since this equipment will be installed during LS2. The assembly of all components (Vacuum vessels, platines, jaws, RF screens, craddles, etc.) and the installation in the tunnel will be carried out in-house.

SUPPLEMENTARY SHIELDING OF D1 COILS - TCDD/TCDDM
The superconducting D1 separation dipole (See WP3) is located just downstream of the TDIS. The largest energy deposition in the D1 coils can be expected if bunches impact close to the edge of the leading TDIS absorber block or if they graze along the jaws since secondary particle showers can escape through the TDIS gap. During the design of the present TDI, it was found necessary to add a complementary mask in order to prevent damage to the D1 coils for such accident scenarios. The masks, called TCDD in IR2 and TCDDM in IR8, are 1 m long Cu blocks, which are movable in IR2 to provide enough aperture for the ALICE ZDC detector during data taking. The TCDDs have a rectangular opening (70 x 42 mm²), which is smaller than the inner diameter of the D1 coils (80 cm). Although some reduction of the energy density in the D1 coils can be achieved with these measures, it is more efficient to complement the present TCDD/TCDDM with another mask-like protection element inside the insulation vacuum of the D1 cryostat (TCDDXM). This solution offers the advantage of intercepting shower particles closer to the magnet and would not affect the present machine aperture. Made of a heavy material to optimize its protection efficiency (e.g. tungsten alloy or steel), such a mask could be placed upstream of the cold mass endcap, tightly enclosing the cold bore which protrudes from the D1 cold mass assembly.

The mask for the D1 will be manufactured and assembly during LS2.

INJECTION SYSTEMS – INJECTION PROTECTION COLLIMATOR – TCLIA & TCLIB
Two auxiliary collimators, TCLIA and TCLIB, are installed at a phase advance of nx180°±20° from the TDIS. They are vertical collimators, made up of 1 m long graphite jaws (R4550 for the TCLIA and 2D C-C AC 150 K for the TCLIB) and have the purpose of enhancing the protection provided in the event of phase advance errors between the MKI and the TDIS. No modification of these protection devices is foreseen, except for a small increase of the TCLIA jaw stroke in order to improve the angular acceptance of the ALICE ZDC. Besides this minor modification, the TCLIA is foreseen to be moved by about 1.8 m towards the IP to further increase the ZDC acceptance.

No procurement is foreseen for TCLIA and TCLIB.

INJECTION SYSTEMS - INJECTION KICKER MAGNET - MKI
The injection kicker magnets MKI installed in IR2 and IR8, deflect the injected beam vertically onto the LHC closed orbits. If the ferrites of the injection kicker magnets reach a temperature above their Curie temperature their magnetic properties are temporarily compromised and the beam cannot be injected. Reducing beam-induced heating, additional cooling, and/or ferrites with a higher Curie temperature would avoid waiting periods without beam before the beam can be injected into the LHC. A reduced magnetic field from the injection kickers is also a machine protection risk, possibly leading to quenches of downstream magnets. A prototype MKI magnet with reduced power deposition at the capacitively coupled end of the ferrite yoke and additional cooling will be developed for HL-LHC. In addition different ferrite types are being considered. A ferrite such as CMD10, which has a higher Curie temperature presently used for the MKI yoke, would permit high intensity beam operation with better availability. However, operating at higher yoke temperatures will result in a higher pressure in the vacuum tank, which may result in an increased electrical breakdown and surface flashover rate. Further optimization of the capacitive coupled end of the beam screen is being made.
to further decrease beam coupling impedance and reduce the electric field strength in this area, and so the likelihood of surface flashovers.

Electron cloud in the ceramic tube results in a pressure increase, which may result in an increased electrical breakdown and surface flashover rate. A low SEY coating, such as Cr2O3 or Laser Engineered Surface Structure (LESS) could eliminate multipactoring, and thus the related pressure rise, permitting more reliable operation of the injection kickers. Thus, research and development of special coatings and LESS for the inner surface of the ceramic tube is being carried out, and it is planned to modify the inner surface of the ceramic tube of the prototype MKI.

After a comprehensive study programme, the macro particles causing beam losses around the MKIs were identified as fragments originating from the ceramic tube inside the MKI magnets. Thus, the ceramic tube of MKI8D installed during a Technical Stop was subjected to improved cleaning, which included iterations of flushing of the inside of the tube with N2 at 10 bar and dust sampling, until no significant further reduction of macro particles was noted. Before TS3, MKI8D exhibited the highest rate of beam–dust particle interactions of all MKIs in P8; the replacement MKI8D, in operation after TS3, exhibited the lowest rate. Extensive additional cleaning was carried out on the ceramic tubes of all eight MKI magnets installed during LS1: in 2015 the MKIs have vanished completely from the UFO statistics at 6.5 TeV compared to 2012, which validates the new preparation procedures for the MKI beam screen.

Modification of the series of MKI magnets is not part of the HL-LHC baseline. The necessity of the described changes for the series of magnets depends on the performance of the magnets installed in LS1 and the final beam parameters to be used for the HL-LHC beams (especially the bunch length). The installation of a prototype magnet to test the developed technologies is foreseen during the EYETS in 2017-2018.

**DUMPING SYSTEMS**

The beam in the LHC is aborted or dumped by a dedicated system based on pulsed extraction kickers MKD and DC septum magnets located in the dedicated insertion in LHC point 6, followed by a dilution kicker system MKB, a long drift chamber, and a graphite beam dump absorber block (TDE) kept under N2 gas at atmospheric pressure. The 3 μs rise time of the extraction kicker field is synchronized by a highly reliable timing system to a beam-free abort gap in the circulating bunch pattern. The horizontal and vertical dilution kickers are powered with anti-phase sinusoidal currents in order to paint the bunches onto the TDE with an elliptical shape.

The LHC beam dump block TDE and its entrance window will need to withstand the repeated dumping of high intensity HL-LHC beams. The likelihood of different dilution failures and the consequences for the dump are under study. In case the load on the TDE is found not to be acceptable, the installation of additional dilution kicker magnets on the beam dump lines could be required. This is not part of the baseline.

**DUMPING SYSTEMS - BEAM DUMPING SYSTEM ABSORBER - TCDS**

Several failure modes exist in the synchronization system and in the kicker switches that could lead to an asynchronous dump, in which part of the beam would be swept across the LHC aperture by the rising kicker field. Without dedicated protection devices this would lead to a massive damage of the LHC magnets in IR6 and the downstream arcs 5–6 and 6–7 and, depending on the operational configuration, a number of collimators and possibly experimental triplet magnets. The TCDS is a fixed absorber that protects the downstream extraction septum MSD, and the TCDOQ is a movable absorber that, together with the secondary collimator TCSP, protects the superconducting quadrupole Q4 and further downstream elements, including the arc and the tertiary collimators (TCTs) around the experiments.

The robustness of the present TCDS and the protection of the MSD magnets in the case of an asynchronous beam dump with full intensity HL-LHC beams is being verified, and the absorber material and/or length likely need to be adapted. Any additional length will slightly reduce the aperture for the circulating or extracted beams by a small fraction of a sigma, which should be acceptable. The TCDS upgrade is included in the HL-LHC baseline.
The TCDQ was upgraded in LS1 and a further upgrade is not part of the HL-LHC baseline. The new design, includes an extension of the absorber length from 6 m to 9 m, and the replacement of the higher density graphite absorber material by different grades (1.4 g/cm³ and 1.8 g/cm³) of carbon fibre composites (CfC). The TCSP collimators were upgraded in LS1 with integrated button BPMs in the jaws, which allows for faster and more accurate setup.

The procurement of the TCDS components will be carried out after LS2 (along 2021).

DUMPING SYSTEMS - BEAM DUMPING SYSTEM ABSORBER - MKB

During the several months of reliability running at the end of LS1, the generators of the beam dumping system extraction kickers (MKD) initially showed a large number of erratic triggers due to an increased number of electric breakdowns, compared to LHC Run 1. This was explained by the higher operational voltages required by the higher beam energy of Run 2. The breakdowns were located at regions with large electrical fields at the edges of certain insulators in the generators. Replacing the critical insulators and cleaning of the critical areas in the generator allowed for a reliable operation of the MKD system during the 2015 run at 6.5 TeV. However, operational margins are considered too small for reliable operation at 7.0 TeV in the HL-LHC era. For this reason a redesign of the switch stacks of the MKD generators is ongoing with the aim of keeping the electrical field below 1.5 MV/m in all areas. Replacement of the generator switch stacks is foreseen for LS2. Simultaneously with the upgrade of the MKD switch stacks the control system of the MKD switches will be upgraded. The first part of this upgrade consists of an upgrade of the power trigger system of the main switches. The power triggers are presently rated at a current of 500 A and a dI/dt of 400 A/µs for a voltage of 3.5 kV. The upgraded system will double the current and almost double the dI/dt for a reduced voltage of 3.0 kV. The new parameters are better in line with the specifications of the manufacturer, will increase the lifetime of the GTO switches, result in a shorter rise time and will make the power trigger less sensitive to radiation.

The second part of the control system upgrade consist of an upgrade of the retrigger system which triggers all the extraction and dilution kickers in case of an erratic triggering of an extraction kicker. The present retrigger delay is about 900 ns and the aim is to reduce this to 700 ns, which will reduce the load on the ring elements, in particular the tertiary collimators, in case of an asynchronous dump. At the same time the electronics of the retriggering system which is becoming obsolete will be replaced.