“WHAT YOU GET” INJECTION AND DUMP SYSTEM

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Abstract

The performance of the LHC injection and extraction systems and the main problems encountered during 2012 operation are described. Special attention is dedicated to the stability of the transfer lines, steering frequency, sensitivity to beam and machine changes, injection protection collimators setup and the consequent impact on operation and possible machine protection issues. The improvements foreseen for operation with injection of up to 288 bunches after LS1 in terms of stability, availability and safety are explored. The modifications foreseen to strengthen the reliability of the LHC Beam Dumping System and the new TCDQ hardware for operation at 6.5 TeV with high intensity beams are introduced.

INTRODUCTION

Following the 2011-2012 winter stop the reference trajectories in the LHC Transfer Lines (TL) were re-established on March 25^{th}. The TL collimators (TCDI) were centred around the new reference and initially set to $\pm 4.5\ \sigma$ (nominal beam size) aperture. The “golden” trajectory, defined in March, remained valid for the full year of operation (r.m.s. deviation from reference < 0.2 mm for TI 2 and < 0.4 mm for TI 8 in both planes), also for injections with 288 bunches spaced by 25 ns. However, the need for transfer line steering became more frequent and lengthy towards the end of the run, in particular when moving to the SPS Q20 optics [1] (once/twice per week until the end of September, every 1-2 days in October and November). Observations and TL stability studies performed to explain the reason for the described degradation are presented.

Several issues, mainly caused by beam induced heating and frequent cycling, were encountered at the TDI both in IR 2 and IR 8. After the main failures the position of the TDI with respect to the beam had to be re-checked and validated. This required on average a shift of eight hours each time. The correct positioning of the TDI is vital to protect the machine in case of failures of the injection kickers (MKI) which happened several times during the year, as shown in the following. An intense consolidation campaign, involving the MKIs and TDIs, is foreseen for LS1: for both elements new beam screens will be installed, the TDIs will be completely dismounted and re-assembled with new parts as replacement, spares will be produced and the possibility of adding a thin layer of copper to reduce the heat load at the jaws is considered [2]. A new TDI design is under study and will be ready for operation after LS2.

The LHC Beam Dumping System (LBDS) [3] performance was excellent: the total downtime induced by the LBDS was about 14 hours and no asynchronous dump with beam occurred during the entire run. Nevertheless critical weaknesses were discovered in the powering logic of the system. Mitigation measures were put in place during the year and important improvements are foreseen for LS1 to allow safe operation at 6.5 TeV.

TRANSFER LINES

Ideally, the steering of the lines to the reference trajectory should minimise losses at the TCDI and injection oscillations at the same time. Large injection oscillations were the main reason for the repeated steering, while the setup procedure was slowed down by the difficulty in reducing the losses in the LHC injection region. The injection losses come from two main sources:

- Cross-talks induced by losses at the TCDI due to high tail population or mis-steering in the collimators region (transverse losses);
- Losses from de-bunched or un-captured beam from the SPS and/or in the LHC (longitudinal losses).

Only the first kind of losses can be mitigated with the TL steering while it has no effect on the longitudinal losses. Previous studies [4] showed that the Beam Loss Monitors (BLM) in the injection region can give an indication on the origin of the injection losses: high signals at the BLMs located close to the quadrupoles Q7 and Q8 indicate losses from the TL, while losses at the TDI injection protection collimator and downstream of it are mainly due to uncaptured beam. ln May the TCDIs were opened to $\pm 5\ \sigma$ to be less sensitive to injection losses induced by shot-to-shot trajectory jitter (losses reduced by a factor of 4, the validation tests were performed with the collimators at $\pm 5\ \sigma$ [4]). A detailed analysis showed that the injection losses recorded towards the end of the run were mainly longitudinal; this explained the reason for the lengthy and inefficiency of the steering. The Injection Quality Check (IQC) application will be upgraded to clearly indicate when TL steering is need to reduce injection losses (highlighting Beam Position Monitors (BPM) in the collimators region

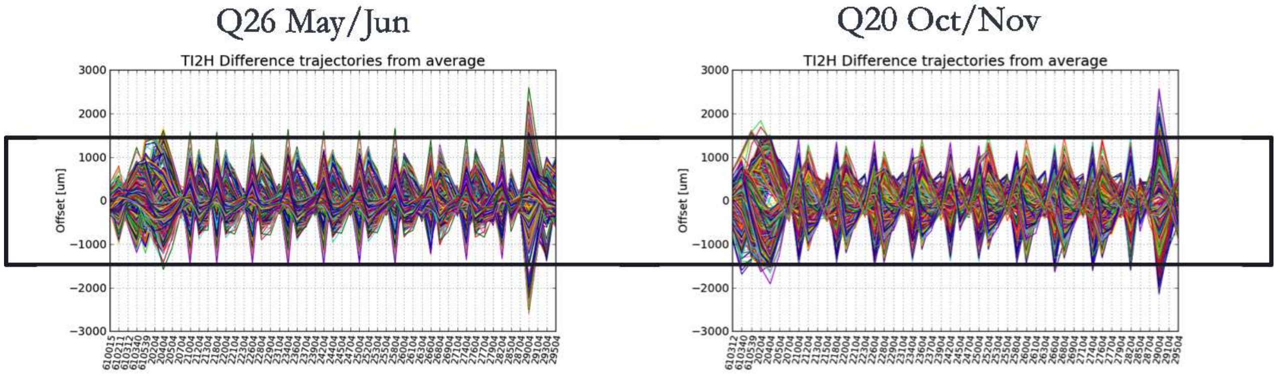

Figure 1: TI 2 uncorrected horizontal trajectories for 144 bunches injection in May/June (Q26 period, left) and in October/November (Q20 period, right).

and BLMs pointing to losses from the TL plus revision of the warning thresholds).

The steering of the lines is performed with a train of six nominal bunches. During the LHC re-commissioning period studies were carried out to define the best position of the six bunches on the waveform of the SPS extraction kicker (MKE), to be representative for the nominal injection of 144 bunches (50 ns bunch spacing) [5]. A discrepancy between the six and the 144 bunches trajectory was observed towards the end of the run. The corrections for the steering had to be calculated on the 144 bunches trajectory and, for safety reasons, any correction had to be followed by a six bunches injection. This required a frequent change of the beam in the SPS and had a relevant impact on the time spent for the injection setup. The reason for this discrepancy is not yet understood.

Stability Studies

Dedicated studies were performed to investigate the reason for the frequent drift of the lines and the resulting requirements for steering when moving to the Q20 optics. The uncorrected trajectories for the injections with 144 bunches were compared for two months of operation with the Q20 and Q26 optics. A Model Independent Analysis (MIA) was used to define the strongest Eigenmodes of the oscillations observed and to identify the most probable source of shot-to-shot variations. Two main sources of instability were identified:

- Current ripple in the SPS extraction septum (MSE) [5];
- Orbit variations in the SPS.

Only a negligible worsening of the trajectory variations was observed for the Q20 optics (Fig. 1). The MSE currents were changed by 5-8% to match the Q20 optics but the ripple remained at the same level as for Q26. The orbit variations in the SPS were monitored only for the Q20 optics; it is therefore impossible to say if any worsening was introduced. No clear conclusions could be drawn from these studies; a campaign of orbit measurements in the SPS with the Q26 optics should be performed.

Losses from De-bunched and Un-captured Beam

The LHC was operated, for three short periods (Q20 optics), with an enhanced level of 25 ns satellites to produce collisions with the main bunches in ALICE. The injection losses at the TDI (longitudinal losses) doubled only during the last two runs with satellites (red zones in Fig. 2). Moreover, for Beam 1, these losses remained higher than for the Q26 optics (before MD3, Fig. 1), even after removing the satellites' enhancement. Further elements (i.e.

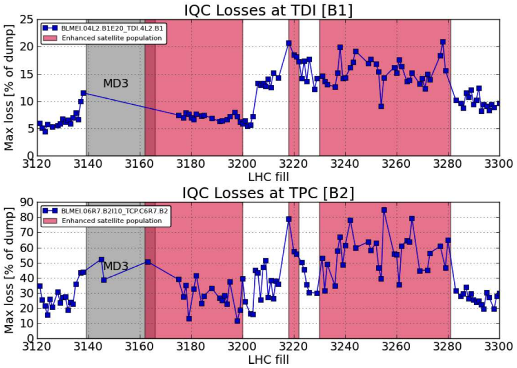

Figure 2: Maximum injection losses (in % with respect to the BLM dump thresholds) at the TDI during operations with (in red) and without satellites enhancement are plotted for several fills, for Beam 1 (top) and Beam 2 (bottom).

batch-by-batch blowup, injection cleaning, etc.) must have contributed to the increased rate of de-bunched and uncaptured beam but it was not possible to disentangle the different contributions and understand the reason for the observed degradation.

Two beam dumps (fill number 3278 and 3281) were induced by the losses recorded by the LHCb Beam Conditions Monitor (BCM) at injection. These losses were due to the presence of two unwanted 50 ns bunches at the end of the 144 bunches train. The trailing bunches were removed by shortening the pulse length of the PS extraction kicker and no new similar dump re-occurred.

25 NS SCRUBBING RUN

A scrubbing run with 25 ns beam was carried out just before the Technical Stop 4 (TS4). The trajectories in the TLs were steered with respect to the "golden" reference defined for the 50 ns beams allowing a straightforward injection of up to 288 bunches with low injection losses (maximum loss in percentage from dump threshold:15.3 % for Beam 1 and 10.8 % for Beam 2). As expected, the losses from the TLs scaled linearly with the injected intensity while the longitudinal losses remained almost unchanged. Several consecutive injections of trains of 288 bunches were performed with maximum losses of $\sim$50 % of the dump threshold for both beams.

Several mitigations were put in place to reduce the sensitivity to injection losses at a number of BLMs in the LHC injection region (including the TDI): implementation of RC electronic delays at the BLMs [4] (sensitivity reduced by up to a factor 180) and TCDI relaxed apertures ($\pm 5\ \sigma$ instead of $\pm 4.5\ \sigma$). Ideally, all the electronic delays at the BLMs should be removed and the TCDIs should be set at nominal aperture to provide a better protection and allow more margin for orbit variations in the LHC. Alternative solutions have to be put in place for a safe operation after LS1 without being limited by the injection losses. The BLM team is evaluating the option of substituting the critical BLMs with Little Ionisation Chambers (LICs) which are less sensitive and have a wider dynamic range.

TDI HARDWARE PROBLEMS

TDI in IR8

Two spurious glitches occurred on the Right-Upstream (RU) end-switch of the TDI lower jaw when moving to parking position before the start of the energy ramp. As a consequence of the glitch, the switch was activated and the RU motor stopped while the motor at the other corner (Right-Downstream, RD) continued moving; this introduced a tilt of up to 22 mrad at the jaw and a suspected plastic deformation. The jaw position controller revealed the fault and reacted correctly: the collimator went into a "warning" state without triggering any beam dump (in one occasion the beam was dumped by the losses induced by the RU corner moving into the beam). As a follow-up of these accidents, the control module of the RU switch was exchanged and the TDI beam based alignment was re-checked and validated. An additional interlock was implemented to limit the maximum tilt of the jaw to 5 mrad. A task was added in the LHC operational sequencer, before the start of the energy ramp, to check the TDI position with respect to the settings and eventually stop operations in case of anomalies.

During the 25 ns scrubbing run the interplay between the beam induced heating and the frequent cycling of the jaw from injection to parking position (to reduce the heat load at the jaw) caused a mechanical degradation of the motorisation system and the blockage of the upstream axis of the upper jaw. The current of the motor was increased to augment the motor torque; the full motorisation system of the faulty axis will be replaced during TS4.

TDI in IR2

The LVDT position sensor used for the controls of the upstream corner of the TDI upper jaw (LU) in IR2 broke. The controls were moved to the second LVTD, normally used for redundancy, and the position and energy interlock thresholds were re-setup around the new LVDT readings. This introduced an offset of $\sim$200 μm between the settings and the LVDT readouts.

Figure 3: Picture of the unscrewed "goupille" which caused the fall of the TDI upper jaw in IR 2.

The LU side of the TDI jaw fell across the beam axis onto the lower jaw because of the failure of a "goupille" (Fig. 3) when moving from parking to injection position; no beam was in the machine at the time of the accident. The jaw was put back into the correct position and the system was consolidated. Both jaws were re-aligned and no significant change was measured with respect to the previous settings. An additional offset of $\sim$100 μm was introduced between settings and readings and the LU corner approached the inner position interlock limit. This, plus a further slow mechanical drift of the LU corner, brought the LVDT beyond the inner dump limit and blocked the jaw (as by design). A new beam based alignment was required to compensate the mechanical drift and new positions and thresholds were defined. A total offset of 530 μm persisted between settings and readings.

MKI ERRATICS AND FLASHOVERS

The TDIs provide the only protection in case of MKI failure. Normally the MKIs have a pulse length of $\sim$8 μs to fit the full train of 144 or 288 injected bunches (depending on the bunch spacing) on the waveform flattop. Three main types of failures can occur:

- A flashover during injection: the pulse length is reduced so that part of the beam is mis-kicked and hits the;
- A Main Switch (MS) erratic: the circulating beam is kicked towards the lower jaw of the TDI;
- MKIs do not pulse when injecting beam (timing issues, previous erratic).

In Table 1 the failures which happened during the 2012 LHC run are summarised. All the problems occurred at the MKIs in IR8 and mainly on MKI8-D. This kicker was exchanged during the Technical Stop 3 (TS3) by a new hardware (MKI8-D* in Table 1, more details in the following) that still experienced three additional flashovers.

In all listed cases the TDI provided the required protection and no damage was provoked to the machine.

No MKI flashovers occurred during the 25 ns scrubbing run, vacuum was continuously monitored and the anti-ecloud solenoids were always kept on.

MKI Heating

When the temperature of the MKI ferrite exceeds the Curie temperature the strength of the kicker reduces [6] and the injected beam could be mis-kicked and induce high losses and a quench of several magnets. For this reason, an interlock exists to inhibit injections if the measured temperature at the MKI is above threshold (Fig 4). At about ten occasions, after a series of long fills, it was required to wait longer than one hour before injecting to allow the cool-down of the MKI8-D kicker. A new hardware, equipped with an increased number of screen conductors (19 instead of 15), was installed during TS3 to reduce the heating [2]. The temperature of the new MKI8-D was amongst the lowest measured temperatures. On the basis of this result, all the MKIs will be upgraded during LS1 to a system with 24 screen conductors (as by design); no delays in operations for kickers cool-down are expected after LS1.

Table 1: List of MKI failures occurred in 2012.

Problem	Magnet	Effect
MS erratic during PFN charging	MKI8-C	1 nominal bunch on TDI
Flashover, 4.4 μs pulse length	MKI8-D	12 inj. bunches correctly kicked
Flashover, 3 μs pulse length	MKI8-D	108 bunches on TDI, quenches, vacuum valves closed, lost cryo conditions
Flashover during UFO MD (anti-ecloud solenoids off)	MKI8-C	MKI pulsing in empty gaps, no beam kicked
Flashover during Q20 inj. test, 1.3 μs plus length	MKI8-D*	No beam extracted from the SPS
Flashover, 6 μs plus length	MKI8-D*	6 inj. bunches correctly kicked
Flashover, 4 μs plus length	MKI8-D*	No beam extracted from the SPS

WRONG TCDI SETTINGS

The transfer lines had to be re-matched to the new SPS optics when moving to Q20 [7]. The change in the β-functions propagated until the end of the TLs in the region where the TCDI collimators are installed. The change was expected to be negligible and not to have a significant impact on the collimator settings but no explicit check was made. The trajectories could be steered to the nominal reference used with the Q26 optics so that a new centering of the TCDIs with respect to the beam was not needed. About 1.5 months after the change to Q20, the β variation at the collimators was quantified and, for two TCDIs (one per line), an half gap of 6.3 σ instead of 5 σ was measured with a consequent loss of protection. The TCDIs were moved to the correct settings and the protection level provided by the system was validated with the beam. Even if the machine was never in a real danger, this event raised a real concern about the possibility of having wrong settings and not being able to detect them except through manual checks. Discussions are ongoing on the possibility to automatically calculating the expected settings from the optics in use (current of the quadrupoles) and compare them with the applied settings to point out potential problems. Moreover, a tool for the automatic setup of the TCDIs is under development and will be ready for operation after LS1. This tool will not

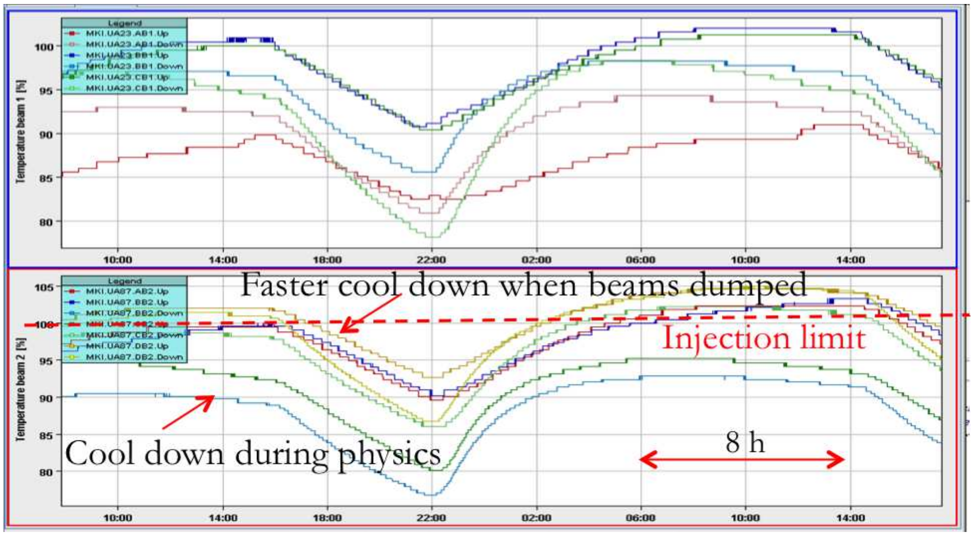

Figure 4: Temperature of the Beam 1 (top) and Beam 2 (bottom) MKIs during the LHC cycle. Injection is inhibited when the temperature is above the Curie limit (dashed red line).

make the setup and validation procedure faster (at least one shift of eight hours per line has to be considered) but will be safer since the settings will be automatically transferred to the “TRIM” application eliminating the human error factor.

LHC BEAM DUMPING SYSTEM

No major operational problems or long downtime were induced by the LBDS. The longest intervention (about eight hours downtime) was caused by the failure and the consequent replacement of a compensation power supply; this required a low level re-calibration of the power supply (gain and offset correction) and the re-validation of the Beam Energy Tracking System (BETS) through two test ramps. Two main weak points were nevertheless identified during the last year of operations:

- Issues with the powering logic of the general purpose crates (lack of redundancy) and unreliability of the WIENER power supplies used within the front-end computer; this caused the conditions (without beam) to generate two asynchronous dumps;
- A common mode failure possibility in the VME +12 V DC power feed line of the TSU crate which, if occurring, would not allow dumping the beam when requested neither synchronously nor asynchronously.

The LBDS cabling and powering logic was re-defined in order to power the Time Synchronisation Unit (TSU) and the Beam Energy Tracking System (BETS) in a fully redundant and independent way. The WIENER power supplies were equipped with additional protection (2 A fast fuses) in order to improve the electrical selectivity in case of failure. An external fast monitoring of the VME +12 V line was implemented which would trigger an asynchronous beam dump to a different way, bypassing the normal triggering lines (which would not work if the VME +12 V line had a short), in case of failures. Finally a slow surveillance of the VME +12 V line has also been added to forbid arming the system if the failure had occurred while the system was not armed. Further consolidation works are foreseen for LS1. The UPS electrical distribution will be modified to make the LBDS powering system completely redundant, the circuit breaker technology will be upgraded; the WIENER crates will be replaced by ELMA crates with internal protection and the two TSUs will be lodged in two different VME crates. The Beam Interlock System (BIS) will be connected to the re-triggering lines. The BIS, after each dump request, will trigger a delayed asynchronous dump as ultimate protection; the impact of the increased probability of asynchronous dump has to be evaluated.

Operation at 6.5 TeV, after LS1, will augment the risk of switch spontaneous firing for the extraction (MKD) and dilution (MKB) kickers. All the MKD and MKB generators of part of the GTO switches will be overhauled to increase reliability and reduce the sensitivity to radiation.

TCDQ Upgrade

The present TCDQ collimator, whose purpose is to provide protection in case of asynchronous beam dumps, will be substituted by an upgraded and more robust system during LS1. The new TCDQ will be constituted by three, instead of two, 3 m long jaws made of Carbon Fibre Compound (CFC) to withstand the nominal energy deposition in case of asynchronous beam dumps at 6.5 TeV with 25 ns beams.

SUMMARY

Clean injections with 144 and 288 bunches (scrubbing run) could be performed using the same reference trajectory during the full 2012 LHC run. No intensity limitations came from injection losses but a solution has to be provided, for operation after LS1, to remove RC filters from the BLMs and operate with the TCDI at their nominal aperture of $\pm 4.5\ \sigma$. TL steering became more frequent and lengthier after moving to Q20 optics but no evident explanation could be found for this worsening (SPS orbit, MSE ripple, losses from de-bunched and un-captured beam, enhanced satellites, injection cleaning, etc.). Clearer references will be implemented in the IQC to give indications for steering and facilitate operation. A tool for automatic setup of the TCDI will become operational after LS1; studies are ongoing to calculate the expected settings from the optics in use, compare them with the applied settings and spot eventual anomalies.

Work will be done on the TDI hardware to reduce the beam induced heating, make the system more robust and avoid the failures which happened during the last run. The TDI provided the needed protection in case of MKI failures (six flashovers and one erratic) and confirmed its vital importance for machine protection.

The beam induced heating at the MKI8-D has been reduced by increasing the number of screen conductors to 19. All kickers will be equipped with 24 screens and no waiting time for cooling is expected after LS1.

Some weak points were identified in the LBDS and the system will be upgraded and made safer for operation at 6.5 TeV. The foreseen changes might increase the probability of asynchronous beam dumps; the impact on operation has to be evaluated.

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