LBDS AND INJECTION SYSTEM

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ABSTRACT

The most critical failure scenarios for LHC machine protection concern the injection and dump systems. In view of operation at higher energy and intensity and in light of the experience gained during Run 1, several upgrades were put in place to further enhance the reliability of these systems. Changes were applied both to the protection elements and the kickers (magnets, related electronics, powering systems and interlock logic). The effective performance of the injection and extraction systems and the impact on operation and machine availability are reviewed with respect to forecasts. Extrapolations to operation at 7 TeV and further increased intensity are drawn.

INTRODUCTION

A general description of the LHC injection and Beam Dump System (LBDS) is given together with the main consolidation and upgrade activities which were performed during the Long Shutdown 1 (LS1). The results of the LBDS reliability runs are presented. Performance in 2015 is reviewed, compared with Run 1 and extrapolations are made for operation until the end of Run 2. Needed improvements for Run 3 and the HL-LHC era are described.

INJECTION SYSTEM

Beams are transferred from the SPS through two Transfer Lines (TI2 and TI8) and injected in the LHC in the straight sections just upstream of ALICE and LHCb experiments (IR2 and IR8). The LHC injection system [1] consists of a series of five horizontal septa (MSI) and four vertical kickers (MKI) which deflect the beam onto the LHC closed orbit. Several protection elements are installed in the TLs (TCDI) and in the injection region (TDI, TCLIA, TCLIB, TCDD and TCLIM) to intercept mis-steered beams and shield the machine aperture.

INJECTION KICKERS: MKI

MKIs are 2.7 m long fast pulsed magnets which give a total deflection of 0.85 mrad, corresponding to an integrated field of 1.3 T·m. The beam screens consist in ceramic tubes which can carry up to 24 screen conductors. One end of each conductor is connected to ground while the other end is capacitively coupled to the ground. The screen conductors shield the ferrite yoke from the high intensity beams and thus minimise beam induced heating. On the other hand they can enhance the probability of having an electrical breakdown and thus degrade the high voltage performance of the kickers.

At the beginning of Run 1, all the MKIs were equipped with only 15 conductors to reduce the risk of flashovers [2]. When operating the LHC with 1380 bunches of $1.5{\cdot}10^{11}$ protons in 2012, injection was inhibited, in a few occasions, for more than one hour due to the heating of one MKI in point 8 (MKI8D). An interlock exists which prevents injection when the temperature is above a defined threshold since the magnetic properties of the ferrite change when the Curie temperature is reached (∼120 °C). A chamber with 19 screen conductors was installed at this magnet during the third Technical Stop (TS3) and the heating problem was solved. Still a non negligible rate of flashovers occurred at MKI8D and could be ascribed to the higher radial field due to the increased number of screen conductors.

The instantaneous and integrated pressure at the MKIs are constantly monitored and interlocked (software interlock, SIS). A pressure rise in the kicker tank and near the capacitively coupled end of the beam screen, increases in fact the probability of an electrical breakdown when pulsing the magnet. MKI sublimation is periodically performed (either during the TS or in the shadow of other interventions) to restore the integrated pressure conditions. Significant pressure rises, induced by the electron-cloud activity, were observed during the scrubbing periods in Run 1. The SIS interlock had to be increased in steps to allow accumulating enough intensity for the scrubbing [3]. An extended soft start (SS) was performed at each step to check the MKI functionality.

MKIs were also hotspots for the Unidentified Falling Objects (UFO); this was ascribed to macro particles originating from the ceramic beam screens [4].

LS1 Activities

The main purpose of the LS1 consolidation works on the MKI was to improve the High Voltage (HV) performance (i.e. minimize the number of flashovers at the screen conductors) and reduce beam induced heating, pressure rise, e-cloud activity and UFO rate [5].

In order to reduce the heating without compromising the high voltage performance of the MKIs , all the beam screens were upgraded by installing the full set of 24 conductors with graded lengths. The last 20 mm of the external metallisation of the ceramic tube was removed to reduce the radial electric field. A conducting metal cylinder was installed at the end of the chambers, with a 1 - 3 mm gap, to provide the missing path for the image current.

An attempt was made to enhance the MKI vacuum tank emissivity (to reduce the ferrite temperature) through ion bombardment but no evident improvement was observed. An ameliorate cleaning procedure was adopted to reduce the UFOs generated by the ceramic chambers. NEG coating and cartridges were implemented at several elements (cold-warm transitions, bellows close to the MKIs, MKI interconnects , bypass tubes, BTV and BPTX) to reduce e-cloud induced vacuum activity.

Performance and Availability

The number of flashovers and erratics per year is shown in Fig. 1 for the MKIs in IR2 and IR8. These failures can occur both during nominal operation (with beam) and during the SS (without beam). During nominal operation either the injected (sparks when pulsing) or the circulating (erratics) beam can be mis-kicked by the MKIs and hit the TDI jaws. This can cause the quench of several magnets in the IR and in the downstream arc. A few hours are needed to recover from the quench and go back into operation. In Run 1, a clear improvement was observed for MKI2: the number of failures went down from 14 (50% with beam, see Table 1) in 2010 to zero in 2012. A peak of faults with beam (70%) was registered for MKI8 in 2012. This was mainly due the installation of the MKI8D with 19 screen conductors during TS3. The gained experience allowed to upgrade the ceramic chambers design as described above. The total number of faults decreased by a factor of two in 2015 and all of them happened during the SS when pulsing the magnets with a 1.4 kV higher voltage than nominal.

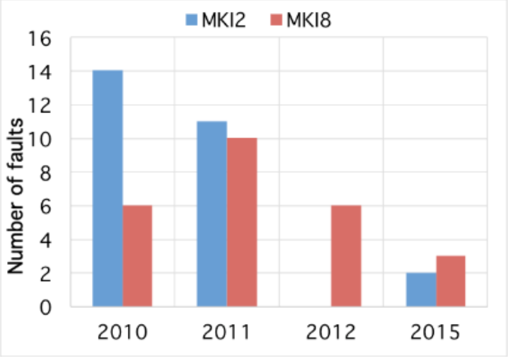

Figure 1: Number of faults per year for the MKIs in IR2 and IR8.

Table 1: Percentage of failures which occurred during nominal operation with beam and during SS without beam.

	MKI2		MKI8	
	beam	no beam	beam	no beam
2010	50%	50%	50%	50%
2011	27%	73%	33%	67%
2012	-	-	70%	30%
2015	0%	100%	0%	100%

Looking at the global MKI performance and availability (hardware and control wise), 22 faults were recorded by the Accelerator Fault Tracking (AFT) tool. In four cases an access was required (for the BETS-AGK reconnection, to fix an oil leakage, replace a fuse and exchange an heater module) causing a cumulative downtime of 9 h : 45 min (total LHC downtime in 2015 > 1800 h). Eight faults prevented injection (recovering from sparks during SS, vacuum spikes, etc.) for 6 h : 38 min in total.

Almost all failures were correctly detected and understood through the BETS and IQC analysis. A fault appeared twice (on October 28^{th} and December 12^{th} 2015) on the MKI2 RCPS monitoring (a new diagnostics software on the MKI resonant power supply) after the replacement of a Terminating Dump Resistor (TDR). It is not fully understood if this was a real fault or due to noise. The TDR was replaced, the cables were checked and further investigations are ongoing.

Beam Induced Heating

MKI beam induced heating did not cause any stop or delay in operation during 2015. The temperature interlock threshold was gradually increased over the year and the MKI rise time linearity (indicating the reaching of the Curie temperature) was regularly checked with a SS.

Vacuum and e-cloud

A pressure rise in the cold-warm transition at the interconnect on the Q5 quadrupole and the MKI8D occasionally limited operation also during the 2015 scrubbing runs [6] and when reaching 2244 stored bunches [7]. The possibility of rotating the MKI8D by 180° to expose the grounded end, which is less sensitive to high pressure, to Q5 is being evaluated. This intervention cannot be performed before the next EYETS and the effect of this change has to be carefully analysed and documented. Another option could be improving the efficiency of the anti e-cloud solenoids and the scrubbing at this critical location. Raising the SIS limit also during nominal operation could enhance the number of breakdowns; this would affect the LHC operation and could increase the risk of damaging the magnet itself.

UFOs

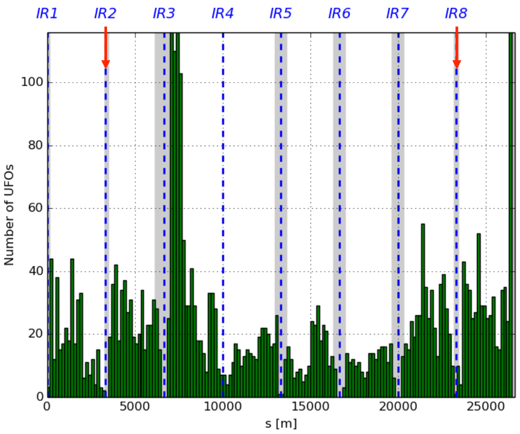

Figure 2: UFO location during operation at 6.5 TeV. The MKI positions are indicated by two red arrows; no UFO was recorded at those locations in 2015.

With the improved cleaning procedure, which was implemented during LS1 for the ceramic tubes, the MKIs virtually vanished from the UFO statistics at 6.5 TeV as shown in Fig. 2.

TDI

The TDI is installed at 90° phase advance from the MKI to intercept the beam in case of kicker failures. It is constituted by two 4.2 m long jaws, each made of three different materials: hBN (2.8 m), Al (0.6 m) and CuBe (0.8 m) following the beam direction. During Run 1, the TDIs in IR2 and IR8 suffered from beam induced RF heating and outgassing. The jaw position sensors (LVDT) drifted by up to ~100 μm because of the deformation caused by the heating and high vacuum spikes were recorded when operating with high intensity beams. A correlation between the LVDT drifts and the jaw sagitta could not be defined. Moreover, the Cu beam screens were found deformed and some sliding contacts blocked.

LS1 Activities

A reinforced beam screen, made of stainless steel, was installed in LS1 and improved sliding contacts, with ceramic spheres, were also implemented [8]. The mechanism for the jaw displacement was fully refurbished. Additional temperature sensors were installed on the lower jaw and on the beam screen. NEG cartridges were integrated and Ti coating was applied on the Al block to reduce the secondary emission yield (SEY).

The TDI gap was monitored by the BETS in a completely independent way with respect to the standard collimation interlock logic.

Performance

A non-conformity was found after the bake-out treatment of the hBN blocks. This limited the maximum number of injected bunches at the time for the full 2015 run (i.e. 144 nominal 25 ns bunches). Signatures of beam induced heating were still detected through the LVDT drifts. A significant pressure rise was observed during injections and spurious spikes appeared as well during the fills with fully retracted jaws. The TDI in IR8 proved to be much more critical from the impedance, heating and vacuum point of view (see Fig. 3) Visual inspection of the jaws during the past YETS showed that the Ti coating was degraded especially for the TDI in point 8. Blisters in the Cu coating of the jaw clumps were also visible. More details can be found in [8] [9].

Upgrade for 2016

During the YETS, the hBN blocks were replaced by Graphite R4550, with a 2 μm Cu coating; no intensity limitation is expected for the rest of Run 2. An interferometric system, which monitors the gap between the jaws, was installed and should allow a direct measurement of any heating induced jaw deformation.

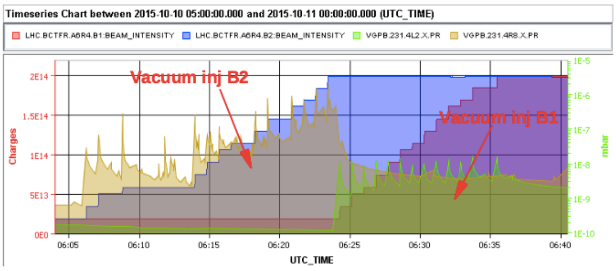

Figure 3: Stored beam intensity and pressure at the TDIs in IR2 and IR8; clear spikes appear at each injection and are about a factor of two higher for Beam 2.

LBDS

A system of fifteen fast kickers (MKD) and fifteen steel septum magnets (MSD) per beam is used to extract the beam from the LHC towards the dump lines [10]. The extracted beam is painted on the dump block (TDE), which is located ~750 m from IP6, by mean of ten dilution kickers MKB (four horizontal and six vertical). Protection elements are located just upstream of the septa (TCDS) and the superconducting quadrupole (Q4) to intercept the beam in case of an asynchronous beam dump (MKDs firing outside the beam free abort gap).

LS1 Activities

Several upgrades were put in place for the LBDS in order to increase reliability (reduce the rate of spontaneous MKD triggers), safety and resistance to radiation [11]. All the MKD and MKB switches were upgraded by installing HV insulators between the HV generators (GTO) and the return plexiglas RODs. This was done to mitigate the problem observed during Run 1 of sparks induced by insulator charging and air ionisation. The MKD GTO electronics was replaced with components which are less sensitive to Single Event Burnouts (SEB). The voltage of the power trigger unit (PTU) was increased to further reduce the sensitivity to radiation. Moreover shielding was installed in the cable ducts between the LHC tunnel and the MKD generator gallery to limit the fluency of electromagnetic showers mainly due to beam scattering at the TCDQ.

Further improvements concerned the power distribution architecture and the Trigger Synchronisation Unit (TSU) which is now fully redundant and equipped with an internal surveillance. A direct connection was created between the LBDS retriggering system and the BIS. This insures that, in case of problem with the Triggering Synchronisation and Distribution System (TSDS), the beam is dumped even if asynchronously with respect to the RF system. The two missing MKBV vere installed in the dump line to accomplish the nominal painting on the TDE. The control SW was upgraded to follow the migration to FESA3 and in view of operation at 6.5 TeV.

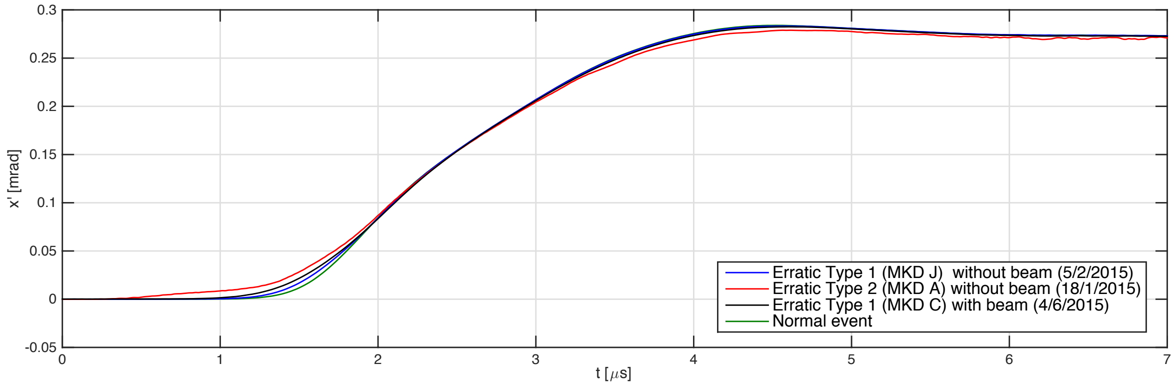

Figure 4: MKD waveform, in terms of beam kicks (x'), for nominal (green curve) and asynchronous beam dumps of Type 1 (blue and black curves) and Type 2 (red curve).

MKD Reliability Runs

Several weeks were dedicated to the MKD reliability runs to assess the fulfilment of the required performance. Tests were performed to check the voltage and the control functions inside the generators. HV tests consisted in:

- Dynamic measurements of the waveforms of the internal current transformer at different energies;
- Sparking rate when operating the MKD in DC mode at 6.5 TeV and 7.1 TeV for 48 h;
- Ramp tests ($\sim$5 days) by powering the MKDs as during an operational LHC cycle but with a ramp up to 7.1 TeV and a 90 min flattop.

A large rate of erratics was recorded at the MDK switches during the HV tests. Three asynchronous beam dumps per beam per year are expected while an average of one and four erratics per generator per day were measured for Beam 1 and Beam 2 respectively (see Table 2). A new type of erratic (Type 2) was found which is characterised by a faster rise-time than the standard Type 1 ($< 2.5\ \mu s$ instead of $2.6\ \mu s$, see Fig. 4). This corresponds to a higher number of bunches impacting the TCDQ and thus a higher dose.

Table 2: Number of erratics which occurred at the different MKD generators during the sparking tests. Gen D for Beam 2 presents a high number of events since it was heavily tested to understand the cause of the problem. The two types of erratics differ in the rise-time speed of the MKD waveform as shown in Fig. 4

Beam 1		Beam 2	
Type 1	Type 2	Type 1	Tye 2
Gen H - 8×		Gen D - 25×	Gen G - 1×
Gen O - 4×		Gen B - 3×	Gen N - 1×
		Gen J - 3×	Gen A - 1×
		Gen N - 2×	
		Gen A - 3×	

Investigations showed that, in general, the generators which suffered from a high erratic rate presented also a higher sparking activity. A clear correlation between dust presence inside the generators and spark rate was also found. Endoscopic inspections and an accurate cleaning of the dust inside the generators was performed in LS1 and repeated during the YETS. Some perforated panels, for PTU cooling, were replaced with non-perforated ones to avoid dust pollution. These mitigations allow a reliable operation at 6.5 TeV with a number of asynchronous beam according to specifications. An increased number of erratics (to be defined) has to be accounted for operation at higher energy with the present design of the MKD switches. Several modifications will be put in place during LS 2 for operation at 7 TeV.

MKD and MKB Performance

The number of asynchronous beam dumps per year which occurred during Run 1 and in 2015 are presented in Fig. 5. In 2015 there was only one MKD erratic; this proved the effectiveness of the cleaning campaign which was carried out to remove the dust from the generators. Only a few bunches were in the machine and none of them saw the MKD rising edge; the beam was cleanly extracted. The failing switch

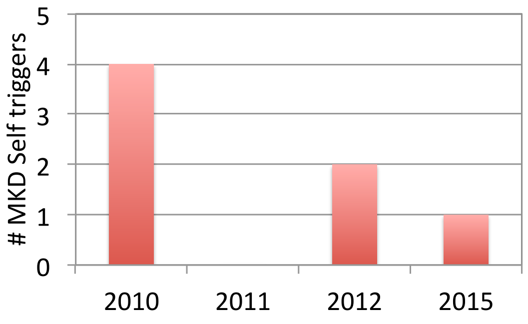

Figure 5: Number of asynchronous beam dumps per year. Two occurred at 7 TeV (2010) and 4 TeV (2012), one event happened at 3.5, 5 (2010) and 6.5 TeV (2015). In only two cases (3.5 and 6.5 TeV) there was beam in the machine.

was exchanged and in total the intervention and revalidation took about 17 h. An MKD generator was replaced at the end of TS1, in the shadow of a cryogenics problem, due to a broken pickup.

Past studies allowed to estimate that 8 ± 2 internal LBDS failures per year, which would have triggered a dump, had to be expected. This agrees very well with the total 29 false dumps recorded during Run 1. A decreasing trend was observed (from 14 in 2010 to 5 in 2012) showing a clear improvement of the LBDS reliability. Five internal dump requests, all due to erratics in the same MKB generator, happened in 2015. The generator was replaced in October 2015 causing a downtime of 10 h : 26 min. All faults were correctly diagnosed and understood (XPOC, IPOC and BETS). There are plans to improve the IPOC triggering in order to be able to capture also MKB erratics.

R2E

As explained above, the MKD electronics was upgraded in LS1 to limit the number of SEB. A target of 0.2 MKD erratics (i.e. asynchronous dumps) per year, induced by SEB, was defined. With the present electronics, 0.1 events per year were expected at 6.5 TeV, assuming a fluency of High Energy Hadrons (HEH) of $5{\cdot}10^4$ cm^{-1}y^{-1}. No SEB was recorded in 2015 and no main limitation is expected also for operation at 7 TeV after having completed the shielding installation.

A large uncertainty characterises the HEH fluency since the assumed value corresponds to one forth of the background at the sea level. Highly sensitive radiation monitors were installed in the dump area for more precise measurements which will allow extrapolation to operation with HL-LHC beams.

TCDQ

The original TCDQ design, which was installed in the machine during Run 1, consisted of a 2-tank system per beam housing a single jaw made of two 3 m long graphite blocks (1.77 g cm^{-3} density). Dynamic stress calculations revealed that this diluter was not robust enough to withstand the energy deposition following an asynchronous beam dump at 7 TeV.

Moreover the possibility of a common mode failure was identified since the control (Motor Drive and Control: MDC) and the surveillance (Position Readout and Survey: PRS) systems were on the same PLC CPU.

LS1 Activities

A third tank was added to the existing two and the TCDQ jaw was lengthened by 50% [12]. The graphite was replaced by Carbon Fiber reinforced Carbon (CFC) with different densities along the blocks (1 m 1.75 g cm^{-3}, 4 m 1.4 g cm^{-3} and 4 m 1.75 g cm^{-3} following the beam direction).

Two functions were deployed in two separate PLCs for the MDC and PRS making the control and survey systems completely independent. The TCDQ position was integrated in the BETS and interlocked to add another layer of protection [11].

The mechanics was upgraded to allow applying a 1 mrad angle to the jaw.

Performance

The improved mechanics allowed a more accurate beam based alignment.

No dump was induced by the TCDQ in 2015 while, during Run 1, several hardware and control issues caused a number of beam dumps (ten only in 2011).

TOWARDS RUN 3 AND HL-LHC

All LHC injection and dump systems are ready for operations with nominal (2808 25 ns bunches of $1.15{\cdot}10^{11}$ protons and 3.75 μm emittance) and ultimate (2808 25 ns bunches of $1.67{\cdot}10^{11}$ protons and 3.75 μm emittance) LHC parameters at 6.5 TeV until the end of Run 2. Due to the high transmission to the downstream magnets, the present TCDIs limit the number of BCMS bunches ($1.3{\cdot}10^{11}$ protons and 1.3 μm emittance) to 144 per injection before LS2. An HW interlock should be implemented as soon as possible to monitor the TDE N_2 pressure and stop operation in case of non-conformities.

For the next operational steps the following upgrades are needed:

Run 3: nominal and ultimate LHC parameters at 7 TeV

During LS 2 the present TDI will be replaced by a new hardware (TDIS, where S stays for “Segmented”) which will be constituted by three modules, each hosting two 1.5 m long jaws. Other improvements will be applied to ameliorate the jaw cooling efficiency and reduce as much as possible the impedance. Also the new 2 m long TCDIs [13] will be installed during LS 2. This will allow to overcome the present limitation for the BCMS beams at injection. Other activities concern the MKI and in particular: the treatment of the ceramic chambers to reduce the SEY, a new design of the capacitively coupled ends to further reduce the flashovers and the coating of the vacuum tank to increase the emissivity.

Only the upgrade of the MKD and MKBH switches is planned for the LBDS before Run 3 while no change will be applied to the protection elements (TCDQ and TCDS) and the dump block (TDE and window). Further studies are needed to define the maximum allowed bunch intensity and brightness at 7 TeV depending on the robustness of these elements and the provided protection to the downstream elements.

HL-LHC

Nominal HL-LHC operation with 25 ns bunches foresees to accumulate up to 2748 bunches of $2.2{\cdot}10^{11}$ protons with an emittance of 2 μm (for BCMS beams: 1968 bunches of $2.3{\cdot}10^{11}$ protons and <2 μm emittance). A significant beam induce heating is expected at the MKI ferrite yoke when operating with such high intensity beams. This could affect the LHC operation by imposing long waiting times to allow the MKI to cool down and recover the nominal magnetic properties. For this reason it is planned to exchange the present ferrite with a new one having a higher Curie temperature during LS3. Other modifications of the injection system concern the installation of an additional mask to protect the D1 dipole and a slight modification of the TCLIA collimator to allow for a larger gap, when opened to parking, in order to increase ALICE crossing angle.

As mentioned before, studies are still ongoing to asses if the dump protection elements are adequate for operation at top energy with high intensity and brightness beams. Required modifications, if any (an additional module and new materials could already be envisaged for the TCDS according to past studies [14]), plus beam and optics constraints will be defined by June 2016. Additional dilution kickers could be needed to reduce the energy density at the window and dump block. Finally, the decision on the need of closing the TCDQ during the squeeze (ATS optics) has to be taken early enough to allow to redesign the BETS and implement an interlock on the $\beta*$. At present no money and manpower are allocated for this purpose.

CONCLUSIONS

The extremely high reliability and safety required for the LHC injection and dump systems could have an impact on the machine availability. Several activities were performed during LS 1 to find the optimum tradeoff between all these aspects. The machine checkout period and the reliability runs proved to play a vital role to identify non-conformities and unexpected faults early enough to react and be ready for operation with beam. 2015 Run showed that some goals were achieved (MKI HV performance, heating and UFO rate, improved TCDQ operational performance, etc.) but non-conformities were also observed (TDI, MKD switches, etc.). Further upgrades were put in place not to limit operation during the rest of Run 2. The number of MKD erratics and the impact on the integrated luminosity in case of operation at 7 TeV, before the replacement of the switches during LS 2, has to be carefully evaluated. Studies are ongoing to define the beam and optics conditions (maximum allowed intensity and brightness) for operation at 7 TeV during Run 3. All the required modification and constraints for the HL-LHC era are being defined and will be finalised by the end of June 2016.

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