OPERATIONAL EXPERIENCE OF THE UPGRADED LHC INJECTION KICKER MAGNETS

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Abstract

During Run 1 of the LHC the injection kicker magnets caused occasional operational delays due to beam induced heating with high bunch intensity and short bunch lengths. In addition, sometimes there were also sporadic issues with microscopic unidentified falling objects, vacuum activity and electrical flashover of the injection kickers. An extensive program of studies was launched and significant upgrades were carried out during long shutdown 1. These upgrades include a new design of a beam screen to both reduce the beam coupling impedance of the kicker magnet, and to significantly reduce the electric field associated with the screen conductors, hence decreasing the probability of electrical breakdown in this region. In addition new cleaning procedures were implemented and equipment adjacent to the injection kickers and various vacuum components were modified. This paper presents operational experience of the injection kicker magnets during Run 2 of the LHC and assesses the effectiveness of the various upgrades.

INTRODUCTION

The Large Hadron Collider (LHC) is equipped with injection kicker (MKI) systems for deflecting the incoming particle beams onto the accelerator's equilibrium orbits. Two counter-rotating beams circulate in two horizontally separated beam pipes. Each beam pipe is filled by 12 consecutive injections, at 450 GeV. The total deflection provided by the four MKI kicker systems, per injection point, is 0.85 mrad, requiring an integrated field strength of 1.3 T·m. Reflections and flat top ripple of the field pulse is less than ±0.5 %.

KICKER MAGNET

General

Each MKI system has a high bandwidth and is impedance ($Z=5\ \Omega$) matched to meet the stringent pulse response requirements. A system consists of a multi-cell Pulse Forming Network (PFN) and a 33-cell travelling wave kicker magnet [1], connected by a matched transmission line and terminated by a matched resistor: Fig. 1 gives the basic schematic.

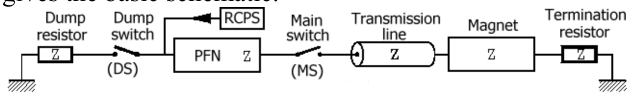

Figure 1: Schematic circuit of a MKI kicker system.

The PFN design voltage is 60 kV and, allowing for overshoot, the magnet design voltage is 35 kV. There are four MKI magnets at each injection point, called P2 and P8. Following an optimization of the transfer lines, the operating PFN voltages for injection were reduced, during August 2015, from 49.6 kV to 48.5 kV at P2 and from 51.3 kV to 50.2 kV at P8.

Design

Each cell of the kicker magnets consists of a U-core ferrite between two high voltage (HV) conducting plates: two ceramic capacitors are sandwiched between the HV plate and a plate connected to ground [1].

During Run 1 of the LHC bunch intensity, together with the large number of bunches, caused significant heating of the magnet ferrite yoke due to its beam coupling impedance [2]. To limit the longitudinal beam coupling impedance, while allowing a fast magnetic field rise-time, an extruded ceramic tube (99.7% alumina) with screen conductors lodged in its inner wall is placed within the aperture of the magnet [3]. The conductors, which provide a path for the image current of the beam, are connected to the standard LHC vacuum chamber at one end and are capacitively coupled to it at the other end.

Voltage is induced on a screen conductor mainly by mutual coupling with the cell inductance. Hence the voltages, at the open end of the screen conductors, show a positive peak during field rise and a negative peak during field fall: the positive peak is about twice the magnitude of the negative peak. The maximum voltage (~30 kV) occurs for conductors adjacent to the HV busbar (Fig. 2).

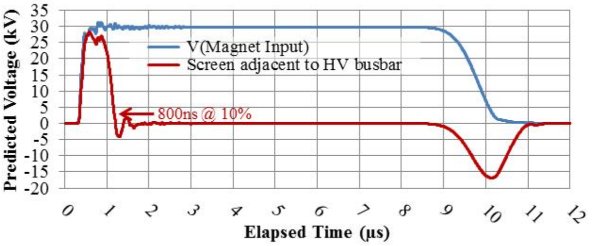

Figure 2: Magnet voltage and voltage of one screen conductor, for 60 kV PFN voltage.

In the original design the alumina tube had 24 nickel-chrome (80/20) conductors, each 0.7 mm × 2.7 mm with rounded corners, inserted into slots [1]. In the original version installed in the LHC, nine conductors closest to the HV busbar were removed to reduce the maximum electric field by 20%. With this arrangement no surface flashover was observed up to 49 kV PFN voltage [3]. However removing screen conductors increased beam impedance and thus heating of the ferrite yoke [2].

Extensive 3D electromagnetic simulations have been carried out, using the code TOSCA, to study electric fields on the surface of the alumina tube. The predictions, in conjunction with operational experience, were used to determine a safe upper operating limit for the electric field [4]. A new design, at the capacitively coupled end of the beam screen (Fig. 3), allowing 24 screen conductors to be used, was implemented in all eight MKI magnets during Long Shutdown 1 (LS1) [5, 6].

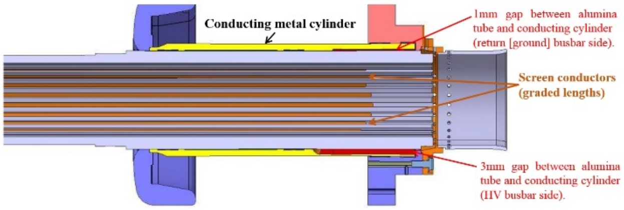

Figure 3: Cross-section of the beam screen for the MKI implemented during LS1.

EXPERIENCE FROM RUN 2 OF THE LHC

High Voltage Behaviour

In addition to normal operation of the MKI kicker systems, during which beam is injected into the LHC, there is a “SoftStart” (SS) mode: a SS is used when there is no beam in the LHC and no beam is being injected. A SS was originally foreseen to ensure the kicker magnets are properly HV reconditioned, prior to injection: during a normal/extended SS, the PFN voltage is ramped to between 3 kV and 4 kV above the injection value.

During 2012 there were a total of ~6×10^5 pulses, for the kicker magnets with 15 screen conductors, and 4 flashovers. Three of these breakdowns occurred during normal operation (51.3 kV PFN) and the 4th was during a SS (53.3 kV PFN). These 4 breakdowns correspond to a breakdown rate of ~7×10^{-6} per pulse. During the third Technical Stop of 2012 (TS3), in September 2012, one MKI magnet was exchanged for a 19 screen conductor version, which gave a significantly higher breakdown rate in the LHC of ~2×10^{-4} per pulse.

During 2015 there was a total of ~6.2×10^5 pulses, for the 8 MKI kicker magnets and 5 flashovers, corresponding to a breakdown rate of ~8×10^{-6} per pulse. These 5 flashovers all occurred during a SS and at PFN voltages between 50.8 kV and 52.7 kV: only 1 breakdown was at 51.3 kV or less (compared to 3 at 51.3 kV during 2012). A breakdown rate of ~8×10^{-6} is very similar to the rate observed during Run 1, with only 15 screen conductors.

Heating of Ferrite Yoke

Beam-induced heating, due to high circulating beam current, can lead to a significant temperature of the MKI ferrite yoke. During Run 1 of the LHC one non-conforming MKI, which had a 90 degree twist in its beam screen, occasionally approached the ferrite Curie temperature [2]. During LS1 all the MKIs were upgraded to have 24 screen conductors (Fig. 3): beam coupling impedance measurements show that the expected beam induced power deposition would be decreased by a factor of 2 to 3, relative to a conforming magnet with 15 screen conductors, for post-LS1 operation [6].

To improve the measurement of the ferrite yoke temperature, during LS1 the temperature probes (PT100s) were moved from the end-plates of the magnets to the side-plates. One probe is towards the upstream end of the magnet and the other is near to the downstream end.

In addition, in an attempt to improve cooling of the ferrite yoke, the inside of the vacuum tank was pre-treated by ion bombardment: this was to increase the emissivity (~0.14 pre-LS1) [5]. However, although the ion bombardment increased the emissivity of sample stainless steel plates from 0.14 to 0.6, there was not any increase of the emissivity of the vacuum tank – probably because the power used was controlled to limit the tank temperature to 380˚C, to protect vacuum flanges, during treatment [7].

Figure 4 shows bunch intensity, bunch length and measured temperature for conforming MKI magnets, as a function of elapsed time, for a fill during both 2012 and 2015: the 2012/2015 data is for a magnet with 15/24 screen conductors. There is similar initial bunch intensity and bunch length for both fills however, as a result of synchrotron radiation, the bunch length reduces significantly during the 2015 fill: a shorter bunch length is expected to increase heating [8]. Nevertheless the maximum rate of increase of the measured temperature is 1.5˚C/hour for the 2012 fill and 0.5˚C/hour for the 2015 fill, confirming that the screening of the ferrite yoke is a factor of ~3 better with 24 screen conductors.

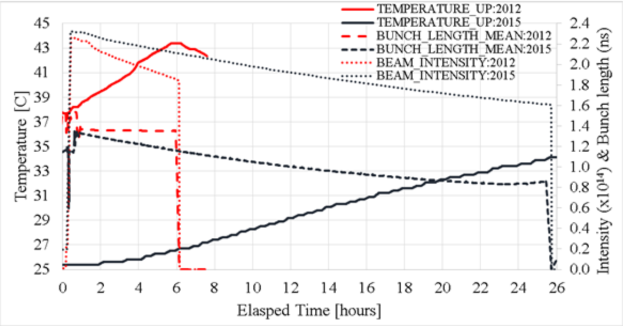

Figure 4: Bunch intensity, bunch length and measured temperature for conforming magnets, as a function of elapsed time, for a fill during both 2012 and 2015.

The highest measured temperature during Run 2, of ~50˚C, occurred during fill #4569 (Nov. 2-3, 2015), with 2244 bunches and a total of 2.65×10^{14} protons (1.18×10^{11} protons per bunch (ppb)). Thermal simulations show that 50˚C side-plate, steady-state, corresponds to a maximum ferrite temperature of 75˚C (Fig. 5), which is well below the ferrite Curie temperature of 120˚C. A SS is run after each high intensity physics fill. The data from the SS data is analysed to determine whether part or all of the ferrite yoke is above the Curie temperature [9]: the analysis confirmed that the ~50˚C measured corresponds to a ferrite yoke temperature below the Curie point.

Post LS1 the PT100 at the upstream end of each MKI gives a higher measurement than for the downstream end. This observation is consistent with recent simulations which indicate that the beam induced power deposition is significantly higher at the upstream end [10].

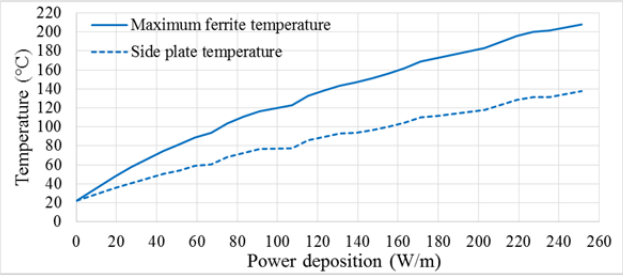

Figure 5: Side-plate and maximum ferrite temperature, for steady-state operation with bake-out jackets installed on the magnet vacuum tank, versus power deposition.

During 2016 it is planned to fill the LHC with a maximum of 2748 bunches and ~1.2 x10^{11} ppb [8] which, for the same bunch length as 2015, would increase power deposition by ~55%. MKI heating is not expected to limit 2016 operation: however to prevent excessive heating of several LHC equipments, it may be necessary to limit the minimum bunch length to ~1 ns.

Electron-Cloud

Significant pressure rise, due to electron-cloud, occurs in and nearby the MKIs and may increase the probability of electrical breakdown in the magnet and surface flashover on the alumina tube. Thus, during LS1, adjacent equipment and vacuum components were modified to reduce the pressure rise with high-intensity operation.

The alumina tube has a high secondary electron yield (up to 10 has been measured) and requires conditioning with beam, together with metallic surfaces facing the beam (e.g. screen conductors). Magnet MKI8D was replaced during 2012 and its alumina tube required ~280 hours, with 50 ns spaced beam, to achieve a normalized pressure similar to the pre-TS3 (~4x10^{-24} mbar/p) level [5]: the reduction in normalized pressure in this tank was greater than 2 orders of magnitude. Post-LS1 with 50 ns beam the normalized pressure is similar to pre-LS1 levels. With 25 ns beam, after almost 400 hours of dedicated scrubbing, the average normalized pressure, in all magnet tanks except MKI8D, is ~9x10^{-24} mbar/p, i.e. a factor of 2 worse than achieved with 50 ns beam pre-TS3: the normalized pressure in MKI8D is a factor of ~4 greater. The normalized pressure in all the MKI magnet interconnects, which were all NEG coated during LS1, is ~6x10^{-23} mbar/p (Fig. 6). The higher pressure in tank MKI8D is a result of a high pressure in the interconnect between this tank and the superconducting quadrupole "Q5", which is ~3.6x10^{-22} mbar/p: the cause of this is under investigation.

UFOs

Pre-LS1 UFOs occurred all around the LHC, however many events were around the MKIs. Extensive studies identified MKI UFOs as most likely being macro particles, of up to 100 μm size, which originated from the alumina tube [11, 12].

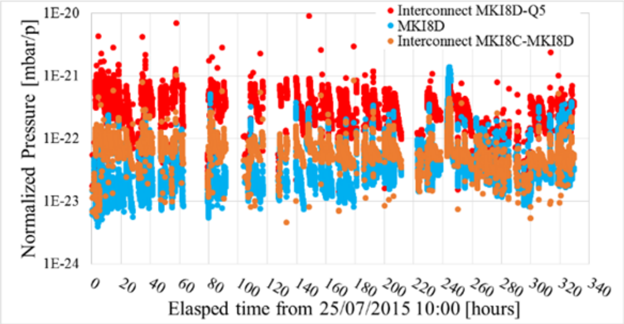

Figure 6: Pressure in tank MKI8D and nearby interconnects, normalized to number of protons (p), 25 ns beam.

Most of the particles have been now shown to be created when the screen conductors are installed in the slots. Thus the alumina tubes of all MKIs upgraded during LS1 underwent extensive cleaning, including (a) inserting 4 screen conductors, at the top of the tube, flushing with dry nitrogen (N_2) at 10 bar at least 4 times, etc. until all screen conductors were in place, then flushing 6 times with 10 bar N_2 into a filter; (b) flushing 10 times with 10 bar N_2 without a filter, followed by 6 flushes with a filter; (c) flushing 20 times with 10 bar N_2 without a filter, followed by 6 flushes with a filter. The three filters were then analysed to determine the approximate number of particles. This cleaning procedure is very effective: post-LS1 the MKIs no longer show up on the UFO statistics. However this might also be partially due to there now being 24 screen conductors installed, which significantly reduces the electric field and thus the probability of charged macro-particles being detached from the alumina tube [12].

LONG TERM OUTLOOK

Other upgrades are being studied for the MKIs in view of HL-LHC: these include methods of reducing power deposition in the ferrite yoke [10], a high Curie temperature ferrite, a high emissivity coating or surface finish for the inside of the vacuum tank, active cooling, and reduction of the SEY of the inside of the alumina tube by either an amorphous carbon coating [13] or an appropriate surface finish.

CONCLUSION

During LS1 all eight installed MKI kicker magnets were upgraded with an improved beam screen to reduce beam induced power deposition, in the ferrite yoke, and decrease electric field associated with the beam screen. Operation with high intensity beam, during Run 2, results in a significantly lower measured rate of temperature rise than during Run 1: despite the additional screen conductors, the statistics for electrical breakdown are similar to Run 1. Furthermore improved cleaning of the alumina tube, together with a full complement of screen conductors, has virtually eliminated MKI UFOs.

Despite the significant upgrades to the MKI magnets, beam induced heating is a real concern for HL-LHC [10], and studies are underway to further reduce beam induced power and to improve the cooling of the ferrite yoke.

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