OPERATIONAL EXPERIENCE OF THE UPGRADED LHC INJECTION KICKER MAGNETS DURING RUN 2 AND FUTURE PLANS

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Abstract

During Run 1 of the LHC, one of the injection kicker magnets caused occasional operational delays due to beam induced heating with high bunch intensity and short bunch lengths. In addition, there were also sporadic issues with 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 (LS 1). These upgrades included a new design of beam screen to reduce both beam coupling impedance of the kicker magnet and to the electric field associated with the screen conductors, hence decreasing the probability of electrical breakdown in this region. This paper presents operational experience of the injection kicker magnets during the first years of Run 2 of the LHC, including a discussion of faults and kicker magnet issues that limited LHC operation. In addition, in light of these issues, plans for further upgrades are briefly discussed.

INTRODUCTION

The Large Hadron Collider (LHC) is equipped with two injection kicker (MKI) systems, MKI2 and MKI8, for deflecting the incoming particle beams onto the LHC's equilibrium orbits [1]. Counter-rotating beams circulate in two horizontally separated pipes. Each beam pipe is filled by 12 consecutive injections, at 450 GeV. Both MKI2 and MKI8 comprise four systems, named A through D: D is the first to see injected beam. The total deflection by an MKI system is 0.85 mrad, requiring an integrated field strength of 1.3 T·m. To limit beam emittance blow-up due to injection oscillations, reflections and flat top ripple of the field pulse must be less than ±0.5%.

A low impedance (5 Ω) and carefully matched high bandwidth system meets the stringent pulse response requirements. An MKI kicker system consists of a multi-cell Pulse Forming Network (PFN) and a multi-cell travelling wave kicker magnet [2], connected by a matched transmission line and terminated by a matched resistor (TMR). Each travelling wave magnet has 33 cells. A cell consists of a U-core NiZn ferrite sandwiched between high voltage (HV) plates: ceramic capacitors are sandwiched between each HV plate and a plate connected to ground (Fig. 1). The magnets are operated in vacuum of ~10^{-11} mbar. The complete magnet is baked out at 300°C before HV conditioning and tests.

BEAM INDUCED HEATING

With high bunch intensity and short bunch lengths, integrated over many hours of a good physics fill, the impedance of the magnet ferrite yoke can lead to significant beam induced heating. To limit longitudinal beam coupling impedance, while allowing a fast magnetic field rise-time, an alumina tube with screen conductors lodged in its inner wall is placed within the aperture of the magnet [2]. 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. There is a set of toroidal ferrite rings mounted around each end of the alumina tube, outside of the aperture of the magnet (Fig. 1), whose original purpose was to damp low-frequency resonances [3]. Each set of nine toroids utilizes two types of NiZn ferrite [4].

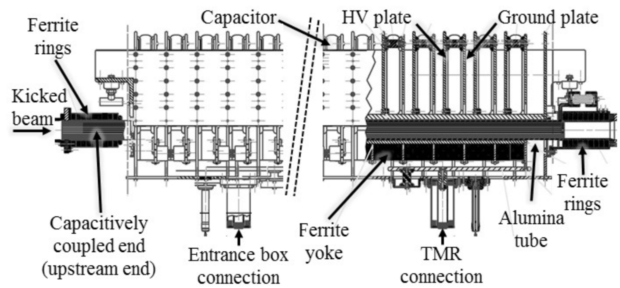

Figure 1: MKI kicker magnet.

During Run 2 the measured temperatures at the upstream (capacitively coupled) end of the MKI magnets have been consistently higher than those measured at the downstream end [5]. CST Particle Studio [6] has been used to study beam coupling impedance and the predictions are in general agreement with observations: the longitudinal distribution of volume losses of the post-LS1 kicker magnets is non-uniform. The ferrite rings at the capacitively coupled end of the structure experience more than 25% of the total power deposition, for a structure that has relatively little volume [7]. The power deposition in the yoke is predominantly at the upstream end of the magnet: the first cell, at the upstream end, experiences ~9% of the total power deposition [8].

Thermal simulations have been carried out to confirm that the calculated power losses for Run 2 result in the temperatures measured during LHC operation. To compare the results with the measurements it must be taken into account that the PT100 temperature sensors for the yoke are located on a side plate of each magnet. There is good agreement between measured and predicted side-plate temperatures [9], validating the power loss calculations and the thermal model:

- Maximum measured side-plate temperature during Run 2 is 57˚C, at the upstream end of MKI8D [fill #5069, $1.25\text{x}10^{11}$ ppb (protons per bunch), 2076 bunches, 25.5 hrs stable beam];

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- Steady-state thermal simulations show that 57˚C corresponds to a temperature, in the first cell at the upstream end, of ~80˚C and a total power deposition of almost 100 W in the magnet.

Scaling total power deposition linearly with the number of bunches, to the nominal 2808 bunches, and assuming 1.25×10^{11} ppb, the total expected power is almost 150 W. The corresponding predicted temperature, in the first cell at the upstream end, is 107˚C and an expected side-plate temperature, at the upstream end, is 77˚C. The 107˚C is below the Curie temperature (125˚C), hence no issues with MKI heating are foreseen during Run 2. Jackets are installed on each magnet for the bake-out [4] and are presently left on. If necessary, to improve heat transfer, the jackets could be removed: this would reduce the highest temperature rise in the ferrite yoke, by ~7% [9].

Beam Induced Heating: Future Plans

For Run 3 operation, with High Luminosity (HL) LHC type beams, the power deposition in the MKIs is expected to be a factor of ~4 greater than for LHC: this would be unacceptably high unless measures are taken. Hence means of reducing heating of the yoke [8] and efficiently removing heat from the magnet [9] are being studied.

ELECTRON CLOUD

Significant pressure rise, due to electron-cloud, occurs in and nearby the MKIs: the predominant gas desorbed from surfaces is H_2. Conditioning of surfaces reduces electron-cloud, and thus dynamic pressure rise, but further conditioning is often required when beam parameters (e.g. bunch spacing, length and intensity) are pushed.

Voltage is induced on the screen conductors during field rise (to 30 kV) and fall (to −17 kV). High pressure, at the capacitively coupled end, can result in breakdown/flashover – hence an interlock (SIS) prevents injection when the pressure is above threshold. The SIS thresholds, for the MKI interconnects, are 5×10^{-8} mbar. During LS1, the vacuum systems on the interconnects between MKI magnets were upgraded: (a) interconnects were NEG coated; (b) a NEG cartridge was integrated to give a nominal pumping speed of 400 l/s for H_2 (prior to LS1, ion pumps provided a nominal 30 l/s for H_2).

The alumina tube of each MKI has a Secondary Electron Yield (SEY) of ~9 when first installed and, together with metallic surfaces facing the beam, requires conditioning with beam. During mid-2016 electron cloud resulted in a factor of ~20 rise in pressure in most MKI8 interconnects: the dynamic pressure rise in the MKI tanks was a factor of ~10. However, electron cloud in the alumina tube of MKI8D resulted in a dynamic pressure rise, measured in the MKI8D-Q5 interconnect, adjacent to MKI8D but outside of the four magnets, being a factor of ~1000: this pressure rise is at the capacitively coupled end of the MKI8D, i.e. where HV is induced. Hence, to avoid flashover, there is an SIS threshold on this interconnect pressure, which is historically set to 6×10^{-8} mbar. Figure 2 shows the pressure in the MKI8D-Q5 interconnect, and beam 2 intensity during June 2016.

Figure 3 shows pressure normalized to the number of protons, for 25 ns bunch spacing, for interconnect MKI8C-MKI8D, tank MKI8D, and interconnect MKI8D-Q5, from 24 June to 27 June, 2016. Beam 2 intensity is also shown.

The first fill shown in Fig. 3 had 72 batches per injection (bpi), 1.11×10^{11} ppb and 2040 bunches. Three injections where missing from beam 2 due to the MKI8D-Q5 threshold exceeding 6×10^{-8} mbar. The second long fill shown in Fig. 3 had 96 bpi (2 x 48 batches, each batch separated by 250 ns), 1.18×10^{11} ppb and 2076 bunches. The third long fill shown in Fig. 3 had 96 bpi (2 x 48 batches, each batch separated by 250 ns), 1.23×10^{11} ppb and 2076 bunches. The 20% lower normalized pressure for the last two long fills, in comparison with the first fill, is due to the 250 ns gap, in the train, between the two injected 48 bunch batches, reducing electron cloud.

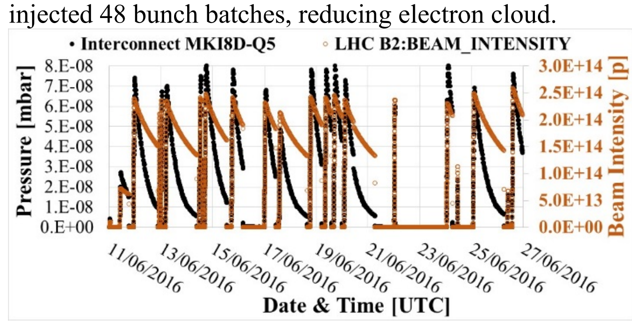

Figure 2: pressure in the MKI8D-Q5 interconnect, and beam 2 intensity during June 2016.

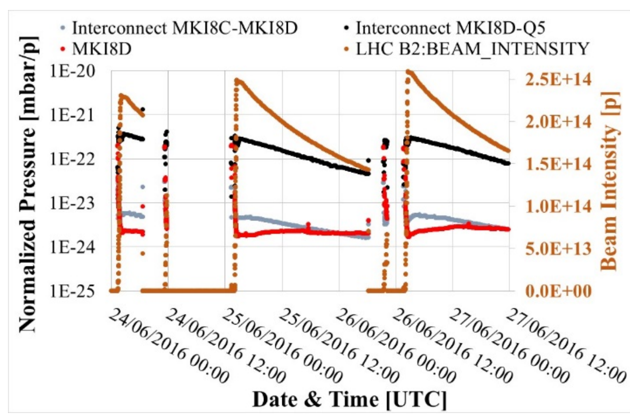

Figure 3: pressure normalized to the number of protons for: interconnect MKI8C-MKI8D, tank MKI8D, and interconnect MKI8D-Q5. Beam 2 intensity is also shown.

During the Extended Year End TS (EYETS), from Dec. 2016, two NEG cartridges, of 400 l/s each for H_2, were integrated in the vacuum sector between MKI8D and Q5. The upgrade locally increases the pumping speed and hence is expected to maintain the dynamic pressure, in this interconnect, below 5×10^{-8} mbar, up to the nominal, 2808, 25 ns bunches.

During TS3, Nov. 2016, it was necessary to replace magnet MKI2D (see below). Hence, although electron cloud around MKI2D has not limited injection during Run 2, the alumina tube in the new MKI2D will not have seen high intensity proton beam and will require conditioning after the EYETS. To assist the conditioning, two new NEG cartridges, of 400 l/s each, have also been integrated in the vacuum sector between MKI2D and Q5. However, despite the upgrade to this vacuum sector, the dynamic pressure in the MKI2D-Q5 interconnect is expected to initially limit intensity of LHC beam 1.

Electron Cloud: Future Plans

For the longer term a coating of Cr_2O_3, applied to the inside of the alumina tube by magnetron sputtering, is a promising means of eliminating electron cloud. Measurements show that naked, high-purity, alumina has a maximum SEY (δ_{max}) of ~9. A Cr_2O_3 coating, applied by magnetron sputtering by Polyteknik [10], reduces δ_{max} to approximately 2.3: bombarding the surface with electrons further reduces δ_{max} to less than 1.4 (Fig. 4).

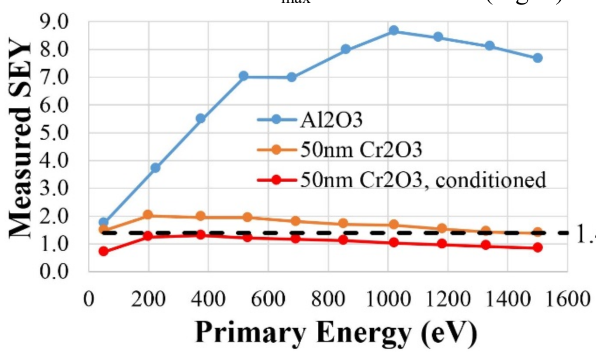

Figure 4: Measured SEY of high purity alumina and alumina with a 50 nm Cr_2O_3 coating: bombarding Cr_2O_3 with electrons reduces δ_{max} to below 1.4 [Measurements courtesy of E. Garcia-Tabares Valdivieso and H. Neupert].

A set of samples has been sputtered with 50 nm of Cr_2O_3 and installed in a setup in the CERN SPS, during the EYETS, for tests with beam.

MKI FLASHOVERS

Prior to injecting beam into the LHC, in order to re-qualify the MKIs, a short conditioning (SoftStart (SS)) is carried out during which the PFN voltage is ramped up to 8% above the nominal injection voltage. During 2016 (2015) the statistics for MKI flashovers were:

- 4 (5) during "SoftStarts" [~80% of total pulses];
- 3 (0) with injected beam [~20% of total pulses].

There was a disproportionate number of flashovers with high-intensity beam during 2016, in comparison with 2015: this suggests a deconditioning effect of the high-intensity beam upon the alumina. A Cr_2O_3 coating is expected to reduce or eliminate this deconditioning.

MKI2D HIGH IMPEDANCE CONTACT

In Oct. 2016 a high impedance contact, characterized by the magnet not initially carrying current, developed at the input end of the MKI2D magnet. The dashed curves in Fig. 5 shows currents for magnet MKI2C and solid curves for MKI2D: these two sets of curves should be more or less identical. The MKI2D was exchanged during TS3.

An inspection of the removed magnet showed damage and erosion of a high current contact at the magnet input. However the removed MKI2D magnet had experienced two power-cuts during bake-outs, during LS1. These power-cuts may have resulted in excessive mechanical stress on the contact, due to the tank cooling more rapidly than the magnet – hence giving significant, transient, thermally induced, difference in length between the tank and magnet: this is under study.

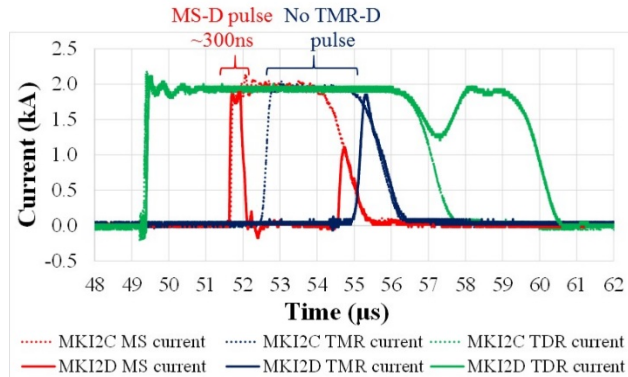

Figure 5: First pulse of a SS (at 20 kV): dashed curves are magnet MKI2C, solid curves are for MKI2D.

MKI ERRATIC TURN-ON

One Main Switch (MS) thyratron erratic (spontaneous turn-on), during resonant charging of the PFN, occurred in September 2016: there were 876 circulating bunches in the LHC, of which 210 were miskicked. Since November 2014 there has been a total, for the two MKI systems, of ~1.4 million MS thyratron pulses. During 2015: 18% of the pulses were for injection; 82% of the pulses were during SS's; almost 60% of the total of the pulses were at or above the nominal injection voltage. There has been a total of three erratics (all on MSs): two during SSs, both at voltages >2 kV above nominal. The erratic in September 2016 was the only one that occurred below nominal voltage.

The observed probability of a MS erratic during injection is ~1.6×10^{-5} per injection. The probability of an erratic occurring is dependent upon the magnitude of the reservoir voltage of the thyratron: hence, during the EYETS, the reservoir voltage of each thyratron was verified.

CONCLUSION

No heating issues are expected for the MKIs during Run 2, with the nominal number of bunches. However, for operation with HL-LHC type beams, methods of reducing heating of the ferrite yoke [8] and efficiently removing heat from the magnet [9] are essential and are being studied. Dynamic pressure rise, due to electron cloud in the MKI8D alumina tube, limited injection of beam 2 during 2016: an upgrade to the vacuum system during the EYETS is expected to solve this issue. Longer term a coating of Cr_2O_3, applied to the inside of the alumina tube by magnetron sputtering, is a promising means of eliminating electron cloud and further reducing electrical flashover in the alumina tube. It is planned to install a prototype MKI, with reduced power deposition

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and a Cr_2O_3 coated alumina tube, during the Year End TS 2017-18. In addition it is currently planned to install cooling systems during LS2.

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