

# OPERATIONAL EXPERIENCE OF A PROTOTYPE LHC INJECTION KICKER MAGNET WITH A LOW SEY COATING AND REDISTRIBUTED POWER DEPOSITION\*

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## Abstract

In the event that it is necessary to exchange an LHC injection kicker magnet (MKI), the newly installed kicker magnet would limit operation for a few hundred hours due to dynamic vacuum. A surface coating with a low secondary electron yield, applied to the inner surface of an alumina tube to reduce dynamic vacuum activity without increasing the probability of Unidentified Falling Objects, and which is compatible with the high voltage environment, was included in an upgraded MKI installed in the LHC during the 2017-18 Year End Technical Stop. In addition, this MKI included an upgrade to relocate a significant portion of beam induced power from the yoke to a “damping element”: this element is not at pulsed high voltage. The effectiveness of the upgrades has been demonstrated during LHC operation, hence a future version will include water cooling of the “damping element”. This paper reviews dynamic vacuum around the MKIs and summarizes operational experience of the upgraded MKI.

## INTRODUCTION

The Large Hadron Collider (LHC) is equipped with two injection kicker (MKI) systems, MKI2 and MKI8, for deflecting incoming particle beams onto the LHC’s equilibrium orbits [1]. Counter-rotating beams circulate in two horizontally separated pipes. Both MKI2 and MKI8 comprise four systems, named “A” through “D”: “D” is the first to see injected beam. On the “D” side of the injection kicker magnets there is a superconducting quadrupole, known as “Q5”.

With high bunch intensity and short bunch lengths, integrated over many hours of a physics fill, the beam coupling 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, a ~3 m long 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 around each end of the alumina tube, outside of the aperture of the magnet, whose original purpose was to damp low-frequency resonances [3]. Measurements show that the alumina has a maximum Secondary Electron Yield, SEY, ( $\delta_{max}$ ) of 9 [4], and can thus result in significant electron cloud (ECloud).

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## ELECTRON CLOUD

Dynamic vacuum activity, due to ECloud, occurs in and nearby the MKIs: the predominant gas desorbed from surfaces is H<sub>2</sub>. Conditioning of surfaces reduces ECloud, but further conditioning is often required when beam parameters (e.g. bunch spacing, length and intensity) are pushed [5, 6]. Voltage is induced on the screen conductors during field rise (to 30 kV) and fall. High pressure, at the capacitively coupled end, can result in breakdown/flashover: hence an interlock prevents injection when the pressure is above threshold. The thresholds, for the MKI interconnects, are typically set to  $5 \times 10^{-8}$  mbar [7]. During 2012 it was necessary to replace an MKI, during a Technical Stop, which was exhibiting electrical breakdowns. The high SEY of the virgin alumina tube resulted in high dynamic pressure both in the upgraded MKI8D tank and interconnects to both MKI8C and Q5. A figure of merit for the dynamic pressure is the normalized pressure ( $P_n$ ): this is the measured pressure divided by the number of circulating protons (p). The highest  $P_n$  occurred in interconnect Q5-MKI8D, followed by interconnect MKI8D-MKI8C. Initially it was necessary to keep the beam current low to maintain the pressure below the interlock thresholds. It required ~280 hours, with 50 ns spaced beam bunches, to achieve a  $P_n$ , in the MKI8D tank, similar to the pre-TS3 level [7]: the integral of the beam current, during this time, corresponds to a charge of 24 C. Nevertheless,  $P_n$  for Q5-MKI8D remained a factor of ~3 above Q5-MKI2D.

All the MKIs were upgraded during Long Shutdown 1 (LS1) to have a beam screen with 24 (instead of 15) conductors [8]: the alumina tubes were also replaced with new tubes, still of 99.7% alumina. In addition, 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<sub>2</sub> (prior to LS1, ion pumps provided a nominal 30 l/s for H<sub>2</sub>). Fig. 1 shows  $P_n$ , Post-LS1: the X-axis is the integral of beam current, which allows comparison of  $P_n$  for different periods of time. The reduction in  $P_n$  by a factor of ~5 between ~2 C and ~4 C (Fig. 1) corresponds to 50 ns spaced beam bunches, rather than 25 ns spacing. The upper envelopes of the  $P_n$  curves are relatively flat from ~20 C of beam current. Although Fig. 1 only shows the MKI8D-MKI8C interconnect between MKIs, the other 5 interconnects between magnets have a  $P_n$  very similar to this trace. By 20 C, the MKI8D-MKI8C has a  $P_n$  a factor of 4 to 5 below Q5-MKI2D, which is itself a factor of 3 below Q5-MKI8D.

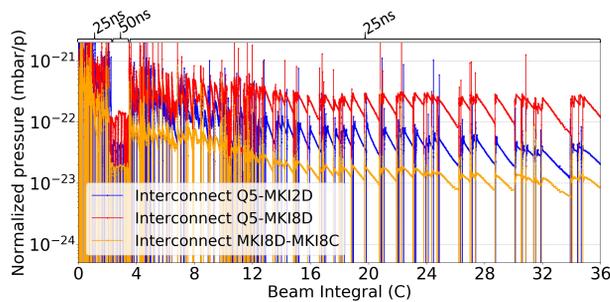


Figure 1:  $P_n$ , versus integral of beam current, 1/6/2015 to 10/10/2015: all MKI alumina tubes replaced during LS1.

During mid-2016 ECloud resulted in a factor of  $\sim 20$  rise in pressure in most MKI8 interconnects. However, ECloud in the alumina tube of MKI8D resulted in a dynamic pressure rise, measured in the Q5-MKI8D interconnect i.e. at the capacitively coupled end of the MKI8D where HV is induced on the screen conductors, being a factor of up to  $\sim 1000$  [9]. In addition, during TS3 (Nov. 2016), it was necessary to replace magnet MKI2D. Hence, although ECloud around MKI2D had not limited injection during Run 2, the alumina tube in the new MKI2D had not experienced proton beam and would require conditioning with beam after the Extended Year End TS (EYETS). Hence, during the EYETS starting Dec. 2016, a NEG cartridge, of 400 l/s for  $H_2$ , was integrated in each of the Q5-MKI8D and Q5-MKI2D vacuum sectors. Analysis of the  $P_n$  in the interconnects, before and after the EYETS, and comparison with other interconnects, shows that these upgrades locally decreased  $P_n$  by a factor of 4 to 5.

Figure 2 shows a comparison of the  $P_n$  of the Q5-MKI2D and Q5-MKI8D interconnects during 2017, for 25 ns bunch spacing. As mentioned above, MKI2D was exchanged during EYETS 2016-17, whereas Q5-MKI8D had been installed in the LHC since the restart in early 2015. The newly installed MKI2D initially had a  $P_n$ , for Q5-MKI2D, a factor of 2-3 higher than Q5-MKI8D. The MKI2D alumina tube conditioned so that Q5-MKI2D had a similar  $P_n$  to the Q5-MKI8D by 10 C. The Q5-MKI2D  $P_n$  continued to reduce between 10 C and 40 C, however the Q5-MKI8D did not. Hence, from  $\sim 40$  C the Q5-MKI2D had a  $P_n$  a factor of  $\sim 3$  lower than the Q5-MKI8D – historically the Q5-MKI8D has a  $P_n$  between 3 and 12 times higher than Q5-MKI2D.

On the 4th of September 2017 the LHC beam was changed to the so-called "8b4e" beam ("8 bunches" and "4 empty (slots)"), instead of a continuous train of bunches spaced by 25 ns. This irregular beam pattern suppresses the formation of EClouds compared to the standard beam, however there is a lower number of bunches in the LHC due to the empty bunch slots. While the LHC operated with up to 2556 bunches in July 2017, operation with "8b4e" limited the number of bunches to  $\sim 1920$  [10]. Fig. 2 shows that when the 8b4e beam was introduced, the  $P_n$  in both the Q5-MKI2D and Q5-MKI8D interconnects reduced by a factor of  $\sim 3$ .

In order to prevent an MKI magnet significantly limiting LHC operation, in the event it is necessary to exchange a

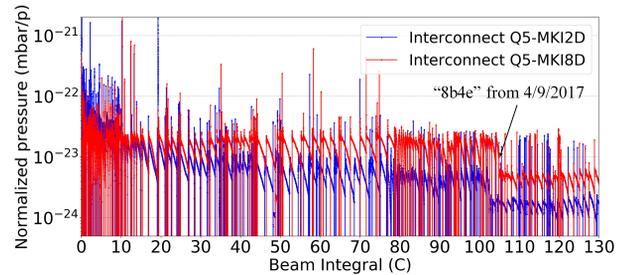


Figure 2:  $P_n$ , versus integral of beam current, 29/4/2017 to 01/10/2017, on Q5 side of both MKI2D (newly installed) and MKI8D (installed since LS1): 25 ns bunch spacing.

magnet during a Run, the SEY of the surface of the alumina tube facing the beam must be greatly reduced. Several methods have been tested for achieving this: the most promising is to apply a  $Cr_2O_3$  coating, to the inside of the alumina tube, by magnetron sputtering. Measurements show that such a coating reduces the  $\delta_{max}$  to 2.3 or less: bombarding the surface with electrons further reduces  $\delta_{max}$  to less than 1.4 [9]. During YETS 2017-18 the MKI8D was replaced with a new MKI: this MKI had the inner surface of its alumina tube coated with  $Cr_2O_3$ , by Polyteknik [11]. Two alumina witness samples were coated together with the alumina tube. The measured  $\delta_{max}$  of the witness samples was in the range 1.3 to 1.5: bombarding the surface with electrons had little influence upon the measured  $\delta_{max}$  [4].

Figure 3 shows a comparison of the  $P_n$ , for 25 ns bunch spacing, of the Q5-MKI2D during 2017, immediately following its exchange, and Q5-MKI8D during 2018, immediately following its exchange. In addition, both of these kicker magnets have upgraded pumping in the interconnection to the Q5 quadrupole. The  $P_n$  in the Q5-MKI2D (2017) and Q5-MKI8D (2018) interconnects start at a similar level for the naked and coated  $Cr_2O_3$  tubes: the reason for this is not understood as, based on laboratory measurements of SEY [9], the coated tube was expected to start at a lower  $P_n$ . Nevertheless, by an integral of 4 C the  $P_n$  in the interconnects either side of both magnets has dropped by  $\sim 2$  orders of magnitude, and the coated tube has lower  $P_n$  than the uncoated tube. The Q5-MKI8D pressure is historically between a factor of  $\sim 3$  (2012, 2015 and 2017) and  $\sim 12$  (2016) higher than Q5-MKI2D. This factor has not been observed anymore after YETS 2017/18 – no other vacuum changes have been made in this sector: hence, this is thought to be attributable

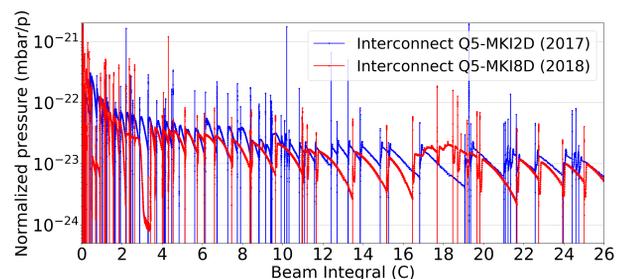


Figure 3:  $P_n$ , versus integral of beam current for Q5-MKI2D, from 29/4/2017, and Q5-MKI8D from 30/3/2018, following their exchange: 25 ns bunch spacing.

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to the Cr<sub>2</sub>O<sub>3</sub> coating of the MKI8D alumina tube. Following the exchange of MKI8D there were some alignment issues, which were solved: simulations show that any historical misalignment, of a few millimetres, would not explain a higher  $P_n$  [12].

Pre-LS1 Unidentified Falling Objects (UFOs) occurred all around the LHC, however many events were around the MKIs [13, 14]. Extensive studies identified MKI UFOs as most likely being macro particles, which originated from the alumina tube when the screen conductors are installed in the slots [14]. Alumina tubes of all MKIs upgraded during LS1 underwent extensive cleaning with high pressure nitrogen: post-LS1, the MKIs no longer show up on the UFO statistics. Similar cleaning was carried out for the Cr<sub>2</sub>O<sub>3</sub> coated alumina tube. Two to three UFOs were observed at both MKI2 and MKI8 during 2017: all were well below threshold for dumping the beam. Similarly, only two to three UFOs were observed at MKI8 during 2018, also all well below dump threshold [15]. Hence, there was no statistically significant change in UFOs at MKI8 from 2017 to 2018, confirming that the Cr<sub>2</sub>O<sub>3</sub> does not result in an increase of UFOs.

During the HV conditioning processes of the MKI8D, installed during EYETS 2017/18, there were not any flashovers that could be attributed to the surface of the Cr<sub>2</sub>O<sub>3</sub> coated alumina tube [4]. During operation with beam, there were initially some fast vacuum spikes during pulsing: however, these "conditioned away", and analysis showed that these likely occurred within the magnet vacuum tank and were not associated with the beam screen.

## BEAM INDUCED HEATING

Prior to LS1 one of the MKIs occasionally exhibited high temperatures leading to significant turnaround times [7]. After a successful impedance mitigation campaign during LS1, the MKI ferrite yokes have remained below their Curie point and have not limited LHC's availability [9]. However, for HL-LHC operation the yokes are expected to reach their Curie temperatures during long physics runs, unless mitigating measures are taken. To ensure reliable future HL-LHC operation, an upgraded beam screen, relocating beam induced power deposition from the yoke to the upstream ferrite rings, was designed and incorporated in the MKI8D installed in the LHC during the YETS 2017-18 [16]. Fig. 4 shows temperature measured at the upstream end of a side-plate of each MKI magnet. The upgraded MKI has

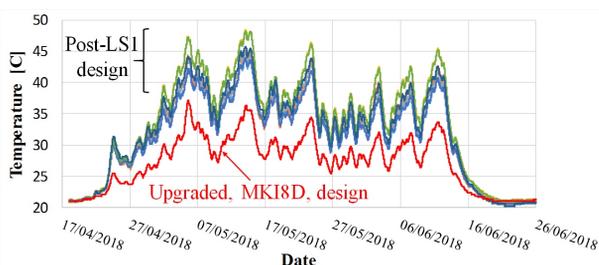


Figure 4: Temperature measured on the MKI magnets side-plate, at the capacitively coupled end of the MKIs.

a significantly lower side-plate temperature than those of the Post-LS1 MKIs: thus validating the concept for moving power deposition from the upstream end ferrite yoke.

## Future Plans for Beam Induced Heating

A final iteration of the beam screen will be installed in an "MKI Cool" kicker magnet, which will be installed in the LHC during LS2, for final validation with beam, before launching the upgrade of the full MKI series. The MKI Cool design has, in addition to the Cr<sub>2</sub>O<sub>3</sub> coated alumina tube, more power deposition relocated from the yoke to an upstream ferrite tube [17]. A copper sleeve will be brazed to the ferrite tube (Fig. 5): the brazing gives good thermal conduction. Studies show that, following this relocation, an active water cooling system for the ferrite rings is sufficient to keep the temperature of the full magnet well below 100°C even with HL-LHC beams [18]. Initial brazing tests are very promising and show a 90% covering of braze at the interface between ferrite tube and copper sleeve [18].

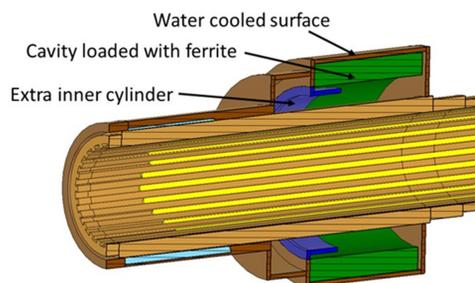


Figure 5: Simplified schematic of the upstream end of the beam screen to be implemented in the "MKI Cool", to be installed during LS2.

## CONCLUSION

An upgraded MKI kicker magnet was installed in the LHC during the YETS 2017/18. The primary goal was to validate the Cr<sub>2</sub>O<sub>3</sub> coating, applied by magnetron sputtering to the inside of the alumina tube. This coating did not influence the initial  $P_n$ , following beam injection. However, the  $P_n$  in Q5-MKI8D was a factor of 3 to 12 less than that observed for the previous MKI, with an uncoated tube, in the same location. The upgraded MKI also had losses relocated from the ferrite yoke to the upstream ferrite rings: as expected, this magnet had the lowest measured temperature rise, thus confirming the efficacy of this change. During LS2, an "MKI Cool" will be installed for validation with beam, before the series is upgraded. The MKI Cool relocates additional losses from the yoke to an upstream ferrite tube. The ferrite tube will be water cooled: predictions show that the all the ferrites will remain significantly below their Curie temperature even with HL-LHC beam.

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