INITIAL OPERATIONAL EXPERIENCE OF AN LHC INJECTION KICKER MAGNET UPGRADED FOR HL-LHC *

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Abstract

The intensity of the HL-LHC beam will be twice that of the LHC. Hence, an upgrade of the LHC injection kickers (MKIs) is necessary for HL-LHC to avoid excessive beam induced heating of the MKIs. In addition, any newly installed MKI magnet would limit HL-LHC operation for a few hundred hours due to dynamic vacuum activity. Extensive studies have been carried out to identify solutions to address these problems and they have been implemented in an upgraded LHC injection kicker magnet (MKI Cool): the first MKI Cool was installed in the LHC during the 2022-23 Year End Technical Stop. Magnet heating has been reduced by redistributing a significant portion of the beam induced power deposition from the ferrite yoke to a ferrite loaded RF Damper, which is not at pulsed high voltage, and by water cooling of the damper. Furthermore, a surface coating, to mitigate dynamic vacuum activity, has been applied. This paper discusses the upgrades, presents results from the initial operational experience, and compares the predicted and 'measured' beam induced power deposition.

INTRODUCTION

The Large Hadron Collider (LHC) is equipped with two injection kicker (MKI) systems for deflecting the incoming particle beams onto the LHC's equilibrium orbits. The injected beam is deflected by four MKI magnets at each of Point 2 (MKI2) and Point 8 (MKI8) [1]. The magnets are named "A" through "D": "D" is the first to see injected beam.

The MKIs have a large amount of ferrite close to the beam to ensure that the pulsed magnetic field has the required homogeneity and magnitude: hence, the yoke is susceptible to beam induced heating [2]. The MKIs were upgraded during Long Shutdown 1 (LS1), which ended in 2015, to reduce their beam induced heating [2] and improve high voltage (HV) behaviour [3]: the MKIs are expected to operate without beam induced heating limitations during run III [4]. However, in preparation for the High Luminosity (HL) LHC, the MKIs need to be upgraded to withstand the increasing bunch intensities and thus the higher beam induced heating [5]. This involves reducing the total beam induced power deposition in the MKIs, and redistributing a significant portion of the remaining losses to an RF damper. This RF damper will be water cooled: hence the upgraded kicker magnet is referred to as MKI Cool.

The MKIs yokes are shielded in part by metallic screen conductors in the aperture, to provide a path for the beam image current [6–8]. In the MKIs a ~3 m long alumina tube provides mechanical support and electrical insulation for these conductors [3]. Measurements show that the alumina has a maximum Secondary Electron Yield, SEY, (δ_{max}) of 9 [9], and can thus result in significant electron cloud (ECloud).

ELECTRON CLOUD

Dynamic vacuum activity, due to ECloud, occurs in and nearby the MKIs. Conditioning of surfaces reduces ECloud, but further conditioning is often required when beam parameters (e.g. bunch spacing, length and intensity) are pushed [10, 11]. Voltage is induced on the screen conductors (up to 30 kV) during field rise and fall [3]. 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 5x10^{-8} mbar [12]. 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 significant dynamic pressure both in the upgraded MKI8D tank and interconnects to both MKI8C and the adjacent superconducting quadrupole (Q5) [12]. 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 [12].

To prevent an MKI magnet significantly limiting LHC operation, e.g. in the event it is necessary to exchange a magnet during a Run, the SEY of the surface of the alumina tube facing the beam must be greatly reduced. Hence, Cr_2O_3 coating is applied to the inside of the alumina tube, by magnetron sputtering, by Polyteknik [13]. During YETS 2022-23 the MKI8D was replaced with the first MKI Cool: this MKI had the inner surface of its alumina tube Cr_2O_3 coated. Two alumina witness samples were coated together with the alumina tube. The measured δ_{max} of the coating on the witness samples was in the range 1.6 to 2.1 [14]. Bombarding the surface with 1.4×10^{-2} C/mm^2 of 250 eV electrons reduced the measured δ_{max} from 2.1 to 1.2 [14].

The MKI2D and MKI8D were replaced during YETS 2016-17 and YETS 2022-23, respectively. Figure 1 shows a comparison of the P_n of the Q5-MKI2D interconnect during 2017 and the Q5-MKI8D interconnect during 2023, for 25 ns bunch spacing. The P_n of the MKI8D-Q5 interconnect reduced significantly more rapidly than that of the Q5-MKI2D interconnect. Rapid conditioning was also observed for the MKI8D-Q5 interconnect during 2018, following the replacement of the MKI8D with a version with a Cr_2O_3 coated

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alumina tube during YETS 2017-18 [15]. The Q5-MKI8D pressure is historically between a factor of ~3 (2012, 2015 and 2017) and ~12 (2016) higher than Q5-MKI2D [15]. This factor has not been observed after the MKI8D alumina tube is coated with Cr_2O_3: hence, this is attributed to the Cr_2O_3 coating of the MKI8D alumina tube.

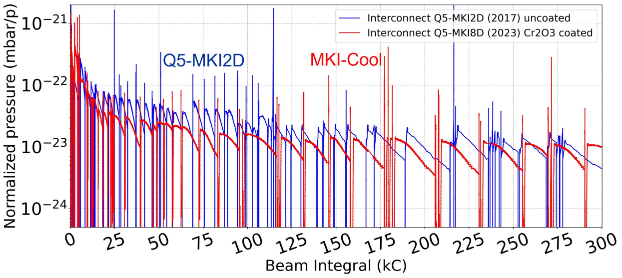

Figure 1: P_n, versus integral of beam current, on Q5 side of both MKI2D (during 2017) and MKI8D (during 2023): 25 ns bunch spacing. MKI2D and MKI8D were replaced during YETS 2016-17 and YETS 2022-23, respectively.

BEAM INDUCED HEATING

RF Damper

It is not feasible to directly cool the ferrite yokes of the MKIs since they are in vacuum and at pulsed HV. Hence, to limit heat deposition in the yokes, an RF damper has been developed (Fig. 2). The damper consists of a ferrite loaded structure, mounted around the outside of the alumina tube at the upstream end of the magnet, outside of the aperture: the damper reduces total beam induced power deposition and also moves power from the yoke and into itself. Details of the electromagnetic design of the damper are given in [16].

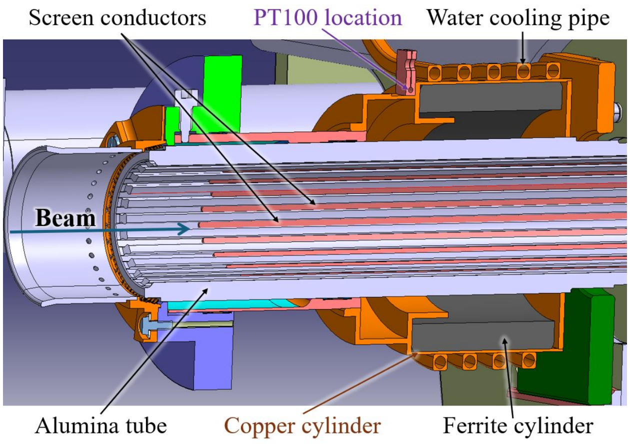

Figure 2: Cross section of water cooled RF damper, developed for MKI Cool kicker magnets

The damper is designed to dissipate a major portion of the overall beam induced losses in the MKI, estimated in simulations to be >90 % of the total losses [17]: hence, the ferrite in the damper is subject to significant heating. The ferrite chosen for the damper is CMD10, which has a Curie temperature of ~250°C [18]. The CMD10 should remain below its Curie temperature as it will otherwise temporarily lose its magnetic properties and consequently its damping function [19]. To mitigate the risk of the CMD10 heating beyond its Curie temperature, it has a copper cylinder, brazed to the ferrite cylinder, and a set of water cooling pipes on the outer diameter of the copper cylinder [20]. Additionally, the maximum temperature of the ferrite must be limited as it could otherwise crack due to temperature gradients causing internal mechanical stress [20]. The datasheet thermal conductivity of the ferrite is 3.5-5 W/(m·K). Thermal simulations indicate that cracking of the ferrite could occur at 100°C: this corresponds to a thermal contact conductance (TCC) of 1000 W/(m^2·K), between the ferrite and copper cylinders, with a power deposition of 365 W [21].

Subsequently to the studies reported in [20], thermomechanical properties of the isostatically pressed CMD10 were carried out by the CERN Mechanical and Materials Engineering (MME) group. The CMD10 had a measured thermal conductivity of 8.7-10.2 W/(m·K) at 100°C, in comparison to the datasheet value of 3.5-5 W/(m·K) [17]. A thermal conductivity better than the datasheet value may allow the specified TCC, between ferrite and copper cylinder, to be relaxed: studies are ongoing to assess this.

Achieving a good thermal joint between a metal and a ceramic material is non-trivial and special attention has been dedicated to this to minimize the amount of voids between the two surfaces and thus maximize the TCC [20, 22]. Transient thermal measurements are carried out to assess the TCC, at several points around the circumference of the ferrite, and ensure that the lowest measured value is adequate [17, 23]. The RF damper installed in the first MKI Cool had a measured TCC of >3000 W/(m^2·K) [24].

In the long-term the four kicker magnets in each of Point 2 and Point 8 will be water cooled, in parallel, from a demineralised water circuit in the LHC tunnel. The nominal water velocity is 1.5 m/s per magnet, to avoid erosion of the pipes, and the nominal flow rate is 1.4 l/minute per magnet. The flow is turbulent to ensure a good transfer of the heat. Historically, simulations underestimated temperatures observed in the MKI magnet during operation: to compensate for this discrepancy, power loss estimates are scaled-up by a factor of 2.5 before being used as input in thermal simulations [21]. The total beam induced power deposition, for HL-LHC ultimate beam parameters, is ~365 W per magnet, including the factor of 2.5 [21]. Assuming all the 365 W is extracted by the cooling circuit, a rise in temperature of 3.6°C, between the inlet and outlet of the cooling circuit, will occur [21].

Observations in the LHC

PT100 temperature sensors are installed on each MKI kicker magnet: these cannot be installed on the ferrite yoke, since it is at pulsed HV. Hence, two PT100's are located on a side plate, at ground potential. One of these PT100's is at the upstream end at the position of the third ferrite yoke [25].

Figure 3 shows measured temperatures of the MKI sideplates, at the upstream end, during LHC operation from

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April to July 2023. The MKI Cool exhibited a maximum temperature rise of 7°C, in comparison to a maximum rise of 40°C for the other MKIs. Thus, the measured upstream temperature rise of the MKI Cool is less than 20% of the other post-LS1 designs. For HL-LHC ultimate beam parameters, the beam induced power will be a factor of <5 greater than for Fig. 3: hence, no heating issues are expected for the MKI Cool design during HL-LHC operation.

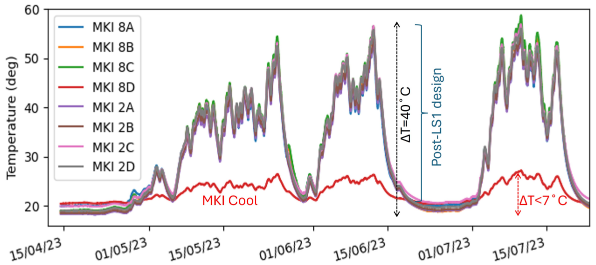

Figure 3: Measured temperatures of MKI side-plates, at upstream end, during LHC operation from April through to July 2023. The MKI8D is the MKI Cool (red trace).

There is also a PT100 installed adjacent to the upstream ferrite rings of each MKI: this PT100 is held in a clamp. For the MKI Cool the clamp is brazed to the copper cylinder of the RF damper (Fig. 2). For the other MKIs the clamp is brazed to a metallic cylinder which mechanically supports the ferrite rings, but is not brazed to the rings: this can result in poor thermal contact with the ferrite during periods of rapid heating or cooling, so does not necessarily give a proper measurement of ring temperature. Figure 4 shows the measured temperatures of MKI ferrite rings, for all MKIs except MKI8D, and the temperature of the copper cylinder for MKI8D, at the upstream end, during LHC operation from April through to July 2023. The MKI Cool exhibited a measured temperature rise of only ~2% of the other MKIs.

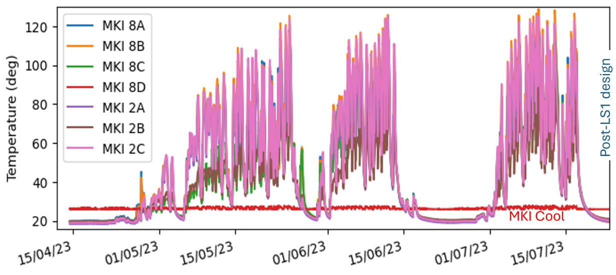

Figure 4: Measured temperatures of MKI ferrite rings (all MKIs except MKI8D) and copper cylinder for MKI8D, at upstream end, during LHC operation from April through to July 2023. The MKI8D is the MKI Cool (red trace).

In addition, the MKI Cool has PT100's installed on the input and output of the water cooling circuit, close to the magnet vacuum tank. The thermal time-constant of the RF damper is relatively short (~1 min) [26], hence short-term properties of beam can be considered [27].

During the period 12-14 July 2023 there was relatively high intensity beam circulating in the LHC (up to 2464 bunches of $1.6{\times}10^{11}$ protons per bunch and 1.3 ns bunch length ($4\,\sigma$)): the power deposition in the MKI Cool is estimated, from the predicted real impedance, to be 91 W, including the factor of 2.5. Assuming 90% of this power is in the RF damper, this corresponds to 82 W.

The measured flow-rate and temperatures of the inlet and outlet water have been used to determine the beam induced power deposition in the damper: a worst-case is estimated by assuming that there is no temperature difference between the inlet water and the RF damper, giving a range of 50 W to 60 W [27]. This estimate also assumes that there is no temperature difference between the water at the output of the RF damper and the sensor at the output, situated just outside the vacuum tank: however, in reality, there is expected to be a difference [27].

An alternative approach is to use the copper cylinder and inlet water temperatures together with the flow-rate. There is expected to be a difference between the copper cylinder temperature and average water temperature of 2.1°C, with the 4 turn cooling pipe and 365W power deposition [21]. Again assuming that there is no temperature difference between the inlet water and the RF damper, the range of power deposition is estimated to be 74 W to 82 W [27]. The corresponding temperature difference between the water at the output of the RF damper and the sensor at the output is estimated to be in the range 0.27°C to 0.22°C, respectively. This method of estimating the power deposition is considered more representative [27].

CONCLUSION

In preparation for the HL-LHC, an MKI has been upgraded to withstand the higher bunch intensities and thus the increased beam induced heating. The upgraded kicker, MKI Cool, has reduced total beam induced power deposition, and a significant portion of the remaining losses are moved to a water cooled RF damper. The beam induced power deposition in the RF damper, during LHC operation, is inline with expectations. Operation with high intensity beam shows that the upstream measured temperature rise of the MKI Cool is less than 20% of the post-LS1 MKI versions: hence, no heating issues are expected for the MKI Cool with HL-LHC ultimate beam parameters. In addition, the MKI Cool alumina tube has been coated with Cr_2O_3 to mitigate dynamic vacuum activity: the coated tube demonstrates relatively rapid conditioning with beam. These observations validate the design of the MKI Cool: the design improves machine availability, and allows for the full HL-LHC potential.

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