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LONGITUDINAL IMPEDANCE ANALYSIS OF AN UPGRADED LHC INJECTION KICKER MAGNET*

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Abstract

Prior to Long Shutdown 1 (LS1) one of the LHC injection kickers (MKIs) occasionally exhibited high temperatures leading to significant turnaround times. 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. However, for HL-LHC operation the MKI yokes are expected to exceed their Curie temperatures after long physics runs. To ensure uninterrupted future HL-LHC operation, a modified beam screen design, relocating some of the heat load to more easily cooled parts, and a suitable cooling system are under development as the current baseline for the HL-LHC upgrade of the MKIs. An upgraded beam screen providing such relocation has been designed, simulated and compared to the existing model. To validate simulations, two longitudinal beam coupling impedance measurement techniques have been used and the results are compared to predictions. The modified beam screen was implemented in an upgraded MKI installed in the LHC during the Year End Technical Stop (YETS) 2017/18.

INTRODUCTION

During LS1, the beam screen of the MKIs was upgraded from 15 to a full complement of 24 screen conductors [1]. A set of 24 NiCr conducting wires are placed on the inner wall of a slotted alumina tube, providing a conducting path for the beam image currents, thus shielding the ferrite yokes from the electromagnetic (e/m) field of the circulating beam. To avoid eddy currents that would increase the rise time of the pulsed field, the screen conductors are not grounded at both ends of the magnet. Instead, they are capacitively coupled to a grounded metallic cylinder at the upstream (beam entrance) end and connected to the local ground at the downstream end. To reduce the probability of flashovers on the inner surface of the alumina tube, the lengths of the wires were optimised and a vacuum gap was introduced between the outside of the alumina tube and the external grounded cylinder, at the upstream end [2]. Finally, a set of nine ferrite rings, Ferroxcube types 4B3 and 4M2 [3], are used alternately, to damp low frequency, $\lambda/4$-modes that can develop along the open ended screen conductors; these are placed at each end of the alumina tube, outside the magnet.

For HL-LHC the beam intensity will be twice that of the nominal LHC intensity and thus the beam induced power deposition will increase by a factor of ~4. According to simulations, the MKI yokes will exceed their T_C [4] and as a result long turnaround times would be necessary before a new beam could be safely injected. Therefore, measures need to be taken to reduce the yoke temperatures, hence ensuring high machine availability and continuous luminosity production.

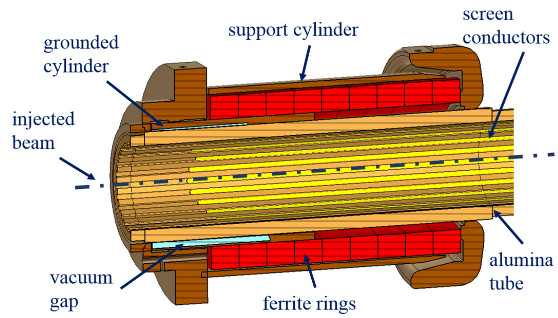

Figure 1: Details of the existing MKI beam screen.

NEW BEAM SCREEN DESIGN

According to reference [5], reducing the overlap length between the beam screen conductors and the external grounded cylinder, which provides the capacitive coupling at the upstream end of the magnet, will shift the resonant modes of the MKI real longitudinal impedance (RLI) to higher frequencies. Assuming a Gaussian longitudinal bunch profile, the envelope of the beam power spectrum follows a Gaussian decay with increasing frequency. Therefore, a reduction of the overlap length would lead to a reduction of the beam induced losses in the magnet. In addition, the new beam screen design allows for a more efficient damping of the coupled RF beam power in the upstream ferrite rings, thus providing better e/m shielding of the ferrite yokes [6]. As a result, higher temperatures are expected in the ferrite rings. Hence, in the new design all nine rings at the upstream end of the magnet are of the type 4B3 due to its higher T_C (250 °C compared to 200 °C for the 4M2).

An upgraded MKI kicker magnet was installed in the LHC during the YETS 2017-18. The primary purpose is to validate, with beam, the Cr_2O_3 coating applied to the inner surface of the alumina tube [7]. Due to its higher surface conductivity compared to the ceramic tube [8], the Cr_2O_3 is not expected to have a negative effect on impedance. It was highly desirable to use the opportunity to also implement the new design for the beam screen and validate the predicted redistribution of power deposition from the upstream ferrite yoke to the upstream ferrite rings of the MKI. Hence, when implementing the proposed new beam screen design, temporal constraints had to be taken into consideration in order to meet the installation deadlines.

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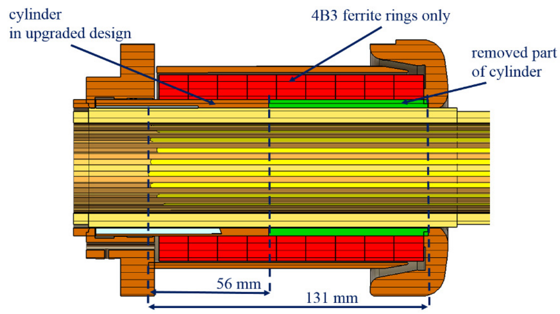

Figure 2: Changes in the upgraded MKI beam screen.

Due to the strict timetable, and in order to achieve a shorter overlap, the existing metallic cylinder was reduced in length, rather than a new one being designed and manufactured. The minimum cylinder length that could be achieved without any additional changes in its design was determined to be 81 mm, i.e. 75 mm shorter than the existing one. This led to a new overlap length of 56 mm with respect to the longest screen conductor. An outer cylinder was also introduced to provide mechanical support to the ferrite rings at the upstream end. Details of the upgraded beam screen design are shown in Fig. 1, while the main changes compared to the post-LS1 design are highlighted in Fig. 2.

Impedance Simulations

To optimize the performance of the new beam screen, impedance simulations were performed using CST Particle Studio [9]. As shown in Fig. 3, and in agreement with the physical argument presented above, the resonant modes are shifted higher in the frequency spectrum thus leading to reduced RF losses in the kicker magnet. Specifically, in the current (post-LS1) design the first resonant mode appears at ~390 MHz while in the new design it is shifted close to 980 MHz. Assuming equidistant (25 ns) and equi-populated Gaussian bunches with nominal Run 2 beam parameters, 1.15×10^{11} protons per bunch, 2808 bunches and 1 ns bunch length, the proposed design is expected to reduce the generated RF losses, derived from the predicted RLI, from 51 W to 37 W; a reduction of approximately 28%.

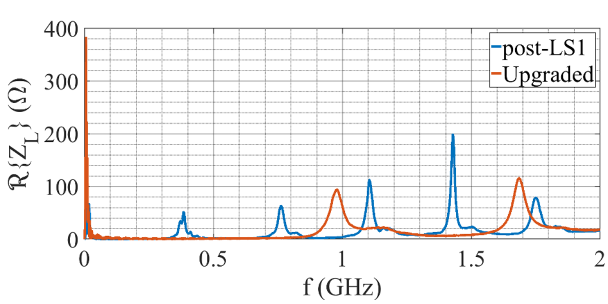

Figure 3: Predicted RLI for the post-LS1 and upgraded MKI beam screens.

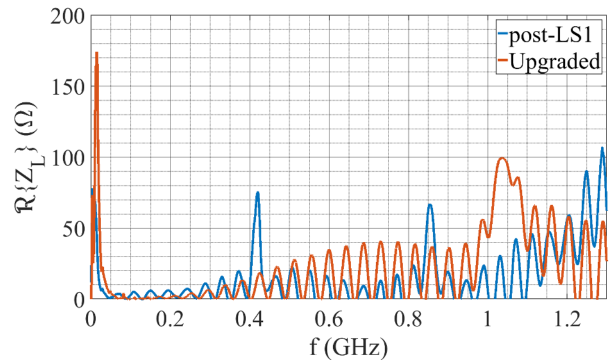

Figure 4: RLI measurements using the classical wire method.

Impedance Measurements

To validate the simulation models two types of impedance bench measurements were carried out. As a first step, the classical wire method [10] was used, which offers good frequency resolution. However, matching is required over the whole frequency range of interest which is achieved with low inductance carbon resistors.

Measurement results, of the classic wire method, for both beam screen designs are shown in Fig. 4. The oscillatory behaviour of the signal for high frequencies, is attributed to the mismatch of the 50 Ω Vector Network Analyzer (VNA) cables to the ~270 Ω transmission line, formed by the MKI screen conductors and the wire that is stretched through the magnet aperture. This mismatch is caused by the frequency dependent behaviour of the 220 Ω matching resistor. Nonetheless, the impedance resonant modes, expected from simulations, can be identified. For the post-LS1 design, the first mode appears at 420 MHz while for the upgraded design it is located at 1.03 GHz, in close agreement with the simulation results. Data are presented only for frequencies up to 1.2 GHz, because for higher frequencies the mismatch strongly dominates the measured signal.

To increase confidence in the results, the resonant method [10] was also used. At the price of limited frequency resolution, determined by the length of the measured device, no matching network is required for this technique and thus

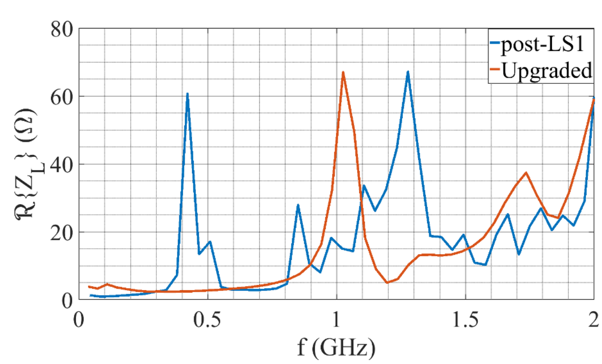

Figure 5: RLI measurements using the resonant method.

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low values of the real part of longitudinal impedances can be determined. The obtained results are presented in Fig. 5: there is very good agreement of the resonant frequencies of the impedance modes to those obtained by the classical method.

Although the resonant modes given by the two measurement techniques, for both designs, appear at the same frequencies, there is still some disagreement with simulation results. Such discrepancies can possibly be related to imperfect modelling of the material characteristics in the simulation. However, the achieved agreement was considered satisfactory to give confidence in the improvements offered by the upgraded beam screen design.

Power Loss Relocation

In addition to power loss reduction, one of the main goals of the MKI beam screen upgrade is to relocate losses away from the ferrite yokes, which are pulsed at HV, to areas where a cooling system can be more easily implemented. As discussed in [6], in addition to the reduction of the generated RF losses, the proposed design is expected to lead to a redistribution of the power deposition along the magnet. Therefore, the model that was developed to estimate the power deposition distribution along the MKI is presented and applied to magnets with a post-LS1 beam screen and the one featuring the upgraded design. To validate the expected redistribution and the adopted approach, a simple bench measurement has been carried out and preliminary results have been reported [6].

Simulations predict that in the upgraded design nearly 90% of the total dissipated power is deposited in the upstream ferrite rings, compared to almost 20% in the post-LS1 design. At the same time the power dissipated in the first yoke was reduced by more than 95%, from 10 W to almost 0.45 W. This power loss relocation is attributable to the fact that in the new design the ferrite rings serve more effectively as an RF load, where power is dissipated before reaching the yokes.

Thermal Behaviour

In [12] beam intensity margins for the rest of Run 2 were discussed. However, improvements in the power loss estimation model presented in [6] suggest that the MKI yokes will exceed their T_C for nominal Run 2 beams [11]. The estimations, however, are derived using a worst case assumption based on power loss estimations using impedance measurement data of the hottest MKI (8D) during 2017 operation [13].

Due to its worse thermal and dynamic vacuum performance compared to the other installed magnets, it was decided that the MKI8D would be the one to be replaced by the upgraded magnet [7]. According to the thermal simulations presented in [11], the new magnet is expected to offer significant thermal improvement by reducing the maximum predicted yoke temperature from 126 °C to 106 °C, when long fill times and no intensity reduction during the fill are assumed. Finally, the replacement of the hottest magnet with one exhibiting improved thermal behaviour suggests that the maximum expected temperatures of the MKIs and the corresponding beam intensity thresholds need to be re-evaluated. Studies to investigate these limits are currently ongoing.

SUMMARY AND FUTURE WORK

An upgraded injection kicker magnet was installed in the LHC during YETS 2017/18. The new magnet featured an alumina tube whose inner surface was coated with Cr_2O_3 and a modified beam screen to reduce the beam induced RF losses and to redistribute them away from the ferrite yokes to more easily cooled locations. In this paper, the new design was discussed, results from impedance simulations were presented and validated using two bench measurements techniques. Finally, the improved thermal behaviour of the upgraded magnet was briefly discussed.

Experience with the upgraded MKI kicker magnet, with LHC beam during the remainder of Run 2, will allow for further validation of both the electromagnetic and thermal models and shall increase confidence in the effectiveness of the design. The latter, to be combined with a cooling system for the ferrite rings, is part of the current baseline for HL-LHC. If the new magnet is proven to comply with predictions, it will have successfully replaced the hottest kicker, that has been used so far as reference for thermal limitations. Hence, studies to investigate new beam intensity thresholds are ongoing.

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