CURRENT AND FUTURE BEAM THERMAL BEHAVIOUR OF THE LHC INJECTION KICKER MAGNET

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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. Significant upgrades were carried out to the injection kicker magnets during long shutdown 1, including a new design of beam screen to reduce the beam induced heating. Nevertheless these kicker magnets may limit the performance of HL-LHC unless additional mitigating measures are taken. Hence extensive simulations have been carried out to predict the distribution of the beam induced power deposition within the magnet and detailed thermal analyses carried out to predict the temperature profiles. To benchmark the simulations the predicted temperatures are compared with observables in the LHC. This paper reports on observations of the thermal behaviour of the magnet during Run 2 of the LHC, with 25 ns beam. In addition the measurement data is used to extrapolate temperature rise for the beam parameters expected for high-luminosity LHC.

INTRODUCTION

The injection kicker magnets (MKIs) are fast pulsed transmission line kicker magnets, which have a ceramic tube inserted into the aperture of the ferrite yoke: this supports a number of screen conductors, designed to provide a good conducting path for the image currents of the circulating beam. One end of the screen is directly connected to the beam pipe whilst the other is capacitively coupled to the beam pipe in order to preserve the fast field rise time of the magnet. Beam-induced heating, due to high circulating beam current, leads to high temperatures being observed in devices in the LHC, including the MKIs [1]. In one non-conforming MKI this lead to problems as the temperature of the ferrite yoke occassionally approached its Curie temperature (≈120 °C) necessitating 2-3 hours waiting time between fills [2]. Substantial work has been done to reduce the power deposited by reducing the beam coupling impedance of the device - a revised beam screen was implemented on all magnets during long shutdown 1 (LS1) which has reduced the power loss to a safe level for Run 2 of the LHC [3].

The planned high luminousity upgrade of the LHC (called HL-LHC or Hi-Lumi LHC) proposes doubling of the beam current in the LHC under current nominal parameters [4] - this is predicted to lead again to a four fold increase in the power loss to all devices in the LHC unless counter-measures are taken. To this end, further improvements to the beam screen have been studied in order to both reduce the power loss into the magnet and control the location of power loss to maintain magnet performance without long cool down periods between fills. Building on the previous success a new design has been proposed to satisfy competing needs of low rates of electrical breakdown, during magnet pulsing, and a low beam coupling impedance to reduce the power lost into the structure by wakefields; in addition to meet strict requirements for magnet operation for field rise time and flat top ripple [5].

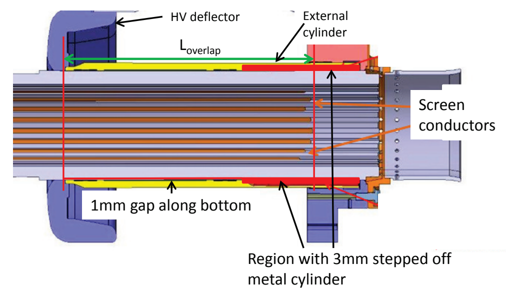

Figure 1: Cross-section of the proposed beam screen for the MKI under HL-LHC conditions.

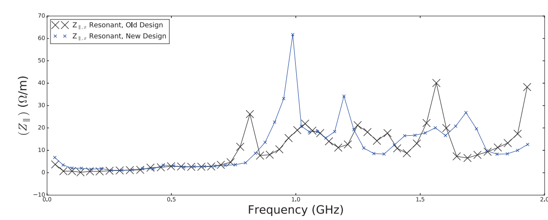

Figure 2: Real component of the longitudinal impedance for the post-LS1 ("old") and proposed post-LS2 ("new") MKI beam screens.

BEAM COUPLING IMPEDANCE

Following previous studies of the MKI impedance [3], a series of prototype tubes were constructed for the MKI to

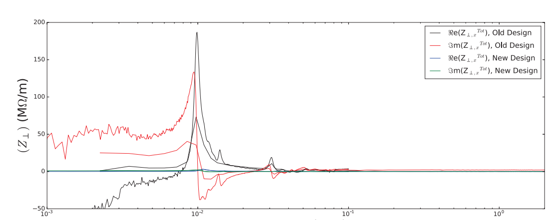

Figure 3: Total horizontal impedance for the post-LS1 ("old") and proposed post-LS2 ("new") MKI beam screens.

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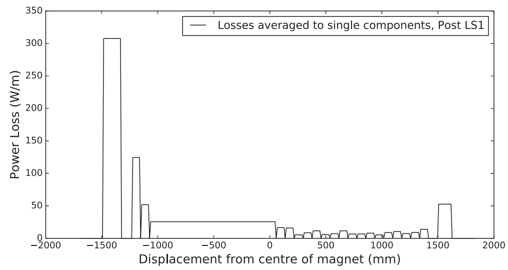

Figure 4: Power loss distribution for a post-LS1 MKI.

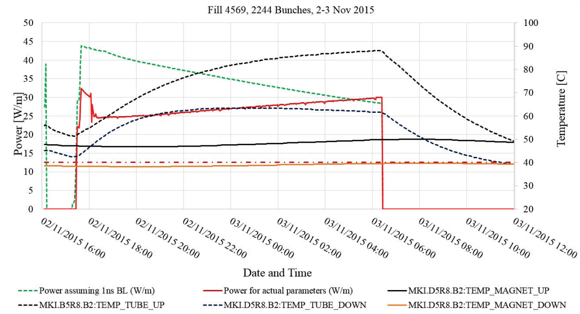

Figure 5: Measured temperature in a MKI during Run 2 operation.

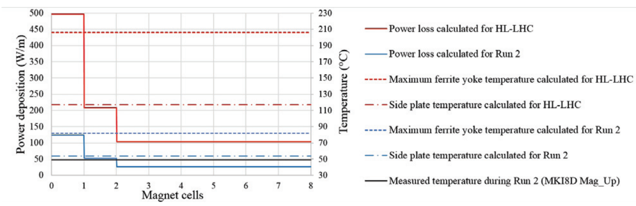

Figure 6: Comparison between predicted and measured temperatures for Run 2 and HL-LHC.

perform measurements of the impedance versus the overlap length; based on the favourable decrease in power loss shown by simulations, this was chosen as the most promising avenue to limit power loss. The results of these measurements confirmed previous recommendations to shorten the length of overlap to 70 mm which will give approximately a 20% reduction in power loss over the current overlap length (117 mm) from 47 W/m to 38 W/m. Further details were presented in [3].

In addition to the reduced overlap length, further alterations to the beam screen have been proposed for HV purposes [6] in order to further reduce the rate of surface flashover during magnet pulsing, shown in Fig. 1. These modifications involve changes which are significant for the beam coupling impedance; a small vacuum gap is introduced around the entire ceramic tube apart from a 90° arc at the top of the cylinder, being a maximum of 1m̃m at the bottom of the tube and tapering to 0 mm on top, see Fig. 1 for illustration.

Recently a further series of impedance measurements focused on transverse impedance, with the overlap length chosen for a prototype MKI ($\approx$ 70 mm). The results for the resonant longitudinal impedance are shown in Fig. 2 and the total transverse impedance in Fig. 3; the transverse impedance is plotted with logarithmic scale to emphasise the low frequency component which is the main contributor to the transverse impedance. Due to the low frequency resolution of the resonant impedance measurement method a peak at 423 MHz isn't visible for the post-LS1 design, which contributes to the majority of power loss with this design. It can be seen that the transverse impedance of the new design is lower than the old design, indicating that there should not be a concern for the new design for the transverse impedance.

POWER LOSS DISTRIBUTION

In addition to reducing the power loss in the MKI and improving heat evacuation from the tank, another strategy to avoid heating the ferrite yoke is to have the power lost in a different, controlled, location in the tank. CST Particle Studio [7] allows the placement of frequency dependent volume loss monitors, compatible with ferrite materials, in the simulation - volume losses are considered as the majority of losses in this system, are lost within ferrites due to magnetic losses (some 48% losses are in ferrite yoke, 27% in the upstream ferrite rings, 25% in metallic surfaces and a marginal quantity in the downstream ferrite rings). For this study the monitors were placed at the resonant frequencies contributing largest to the beam-induced heating - at 420 MHz, 840 MHz, 1240 MHz, 1650 MHz, and 1980 MHz (frequencies are approximate as some configurations cause the frequency to change).

The predicted longitudinal distribution of volume losses of the post-LS1 design is shown in Fig. 4; losses within a component are averaged over the length of the component to give an idea of the relative temperature of different components. It becomes clear that power loss within the structure is non-uniform - the ferrite rings at the capacitively coupled end of the structure see more than 25% of the power loss, for a structure that has very little volume. The loss in the yoke is predominantly in the upstream end of the magnet [8], with losses being negligible in the down-stream half of the magnet. Losses in the down-stream ferrite rings are comparable to that in the ferrite yoke. It should be noted that the magnet

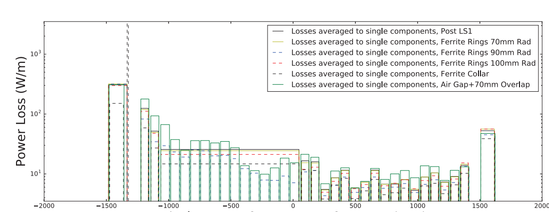

Figure 7: Power loss distribution in a number of configurations of the MKI.

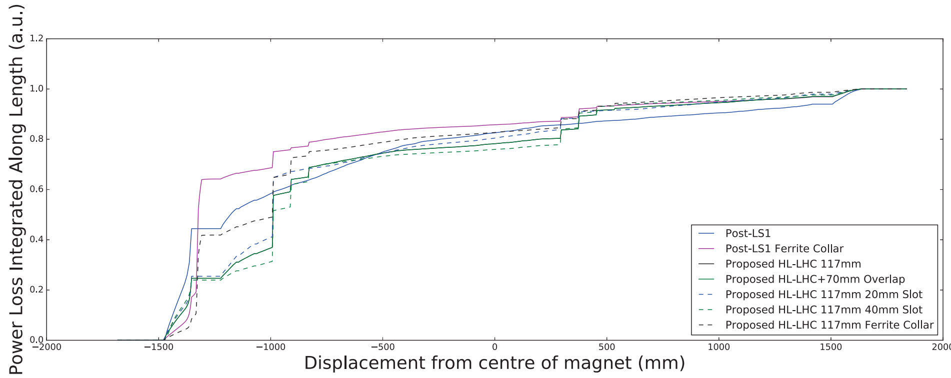

Figure 8: Cumulative power loss in a number of configuration of the MKI.

structure can be seen in the plot - zero volume losses are noted in the location of the HV plates. This distribution of power loss is alluded to in the measurements of temperature during operation [8]: Fig. 5 shows that the upstream ferrite rings becomes substantially hotter than downstream, by up to 25 °C, in line with the expected 6-times larger power loss upstream.

Thermal simulations have been carried out using ANSYS in order to confirm that the calculated power losses for Run 2 (see Fig. 4) correspond to the measured temperatures (see Fig. 5) and also to predict the temperature of the ferrite yoke during HL-LHC operation.

Instead of simulating the whole model (33 cells), just 8 cells have been analysed under steady-state conditions to reduce the complexity of the analysis. To compare the results with the real measurements it must be taken into account that, as the temperature sensors cannot be installed in the aperture of the ferrite yoke, they are located on the side plates. Thus, the MKI8D Mag_Up (see Fig. 6) is measuring the temperature of the side plates at the upstream of this magnet.

The simulations performed for the calculated power loss distribution during Run 2 predict a side plate temperature of 53°C for a measured temperature of 49 °C (see Fig 6): this shows good agreement between measurements and simulations, which validate both the power loss calculations and the thermal model. The maximum predicted ferrite yoke temperature during Run 2 is 81°C which is well below the Curie temperature (120 °C): the predictions are expected to overestimate the temperature as a steady-state ANSYS analysis is performed., Further measures must be taken for the HL-LHC because the ferrite yoke is expected to reach a temperature of 206°C which will limit the operation.

Various methods of reducing the proportion of power loss to the ferrite yoke have been attempted:

- A 3 mm layer of ferrite on the inside of the vacuum tank (not very effective)
- Larger ferrite rings on the capacitive and ground ends (45 mm-100 mm radius)
- A ferrite collar around the ceramic tube, attached to the metal cylinder
- Slots of varying sizes in the metal cylinder to increase coupling to the ferrite rings.

Figure 8 also shows the normalised cumulative power loss for proposed geometries of the HL-LHC design - it can be seen that the addition of the small air gap causes a large change in the distribution, causing more power to be lost in the ferrite yoke. The addition of a ferrite collar causes fewer losses in the ferrite yoke, but not to the level of the Post-LS1 design. Studies of the effect of a thicker collar are ongoing and show promise in further reducing the loss in the yoke. Introducing a slot (of various sizes) in the metallic cylinder have shown little change in the loss distribution apart from a 40 mm slot, but only marginally. It should be noted that the absolute values of these geometries is not equal - relative values are given as there is some uncertainty in the impedance simulations of some of these geometries due to their complexity.

SUMMARY AND FURTHER WORK

A summary of the current studies of power loss in the LHC Injection Kicker Magnets has been presented, focusing on attempts to reduce the power loss and control the location of loss in temperature sensitive components. Coaxial wire measurements have shown that the transverse impedance of the proposed HL-LHC configuration of the MKI should not be higher than the existing configuration, and that simulations have predicted well the beam coupling impedance.

Studies of the power loss distribution have confirmed that the power loss in the MKI is highly non-uniform; the majority of heat loss (almost 25%) is in the ferrite rings at the upstream end, with the majority of the rest in the upstream ferrite yoke or various conductive surfaces. Several ways to further reduce the proportion of power lost in the ferrite yoke have been studied, of which the use of a ferrite collar at the capacitively coupled end is currently the most promising. Further optimisation based on this solution is being pursued.

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