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STUDIES TOWARDS THE NEW BEAM SCREEN SYSTEM OF THE LHC INJECTION KICKER MAGNET FOR HL-LHC OPERATION*

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Abstract

Although no heating issues were observed in the Large Hadron Collider's (LHC) injection kicker magnets (MKIs) during Run 2, simulations suggest that for operation with the high intensity beams of the High Luminosity LHC (HL-LHC) project, the magnet's ferrite yokes will reach their Curie temperature, thus leading to long turnaround times before a new beam can be safely injected into the machine. To safely enter the HL-LHC era, a campaign to redesign the kicker's beam screen was launched. An improved beam-screen has already been implemented in an upgraded MKI, that was installed in the LHC tunnel in the Year End Technical Stop (YETS) 17/18, and has been successfully tested during 2018 operation. However, the improved design alone is not expected to be enough for HL-LHC operation, and further modifications are required. In this work, the approach to the design from an electromagnetic point of view is presented and different considered options are reported, emphasising the final design of the new beam screen system that is currently being implemented.

INTRODUCTION

Although the design of the LHC injection kicker magnets (MKIs) after Long Shutdown 1 (LS1) [1] did not lead to heating issues that could limit the LHC operation during Run 2, simulations suggest that for operation with beam parameters of the High-Luminosity LHC (HL-LHC) project [2], the ferrite yokes will reach their Curie temperatures (T_C) [3]. Consequently, their magnetic properties will be affected and injection into a stable LHC orbit may not be possible. Waiting for the magnets to cool down would lead to unacceptably long turnaround times and therefore a campaign was launched to modify the MKI's beam screen system to ensure sufficiently low temperatures when operated with HL-LHC beams.

During the YETS 17/18 an upgraded MKI was installed in the LHC tunnel at point 8 (MKI8D) [4]. Among other improvements, the new kicker featured a modified beam screen that aimed to reduce the total induced RF heating while at the same time relocating it from the ferrite yokes to 9 upstream-side (beam input) ferrite rings, initially placed around the alumina tube outside the magnet aperture to damp low frequency modes [5]. Operational experience during 2018 has demonstrated that the upgraded magnet is exhibiting significantly lower temperatures than any of the other seven currently installed magnets [6]. However, simulations suggest that the improvements provided by the modified design alone will not be sufficient for HL-LHC operation [3]. Although the RF power that is directly dissipated in the magnet's yokes is expected to be significantly reduced, the ferrite rings are expected to reach high temperatures and heat would be transferred to the yokes through radiation and conduction [3]. These predictions were made assuming constant beam parameters (steady state simulations) and that the ferrites maintain their damping properties even above their T_C. The latter assumption implies that, in the simulation models, ferrites do not cease to dissipate RF power and thus their temperatures are constantly increasing to even higher values; as demonstrated in [7], such an assumption is unphysical. In a more realistic scenario, the rings would loose their damping properties once their T_C is reached, leading to the degradation of the magnet's longitudinal impedance and in turn to more power being dissipated in the yokes. The analysis of such a dynamic phenomenon was too complex to be addressed with the existing tools and the level of uncertainty of any approximate model would be considerable. Instead, a more conservative approach was adopted allowing the ferrites to maintain their magnetic properties even above T_C. However, for an acceptable design, all ferrites were required to remain below their respective T_C.

Ultimately, to achieve relocation of the dissipated power and to ensure proper functionality of all ferrites with HL-LHC beams, additional measures had to be taken. In particular, it was decided that the new beam screen system will consist of (i) a suitably chosen and properly placed lossy material (RF load) to dissipate the coupled RF power before it reached the yokes and (ii) an active cooling mechanism in the vicinity of the load to maintain it at acceptably low temperatures.

THE RF LOAD AND ITS HOUSING

Based on the existing experience and successful operation of the upgraded magnet, it was decided that a tubular ferrite placed around the upstream end of the alumina tube will be used as an RF load, in place of the 9 rings. CMD10 from National Magnetics [8] fulfilled all set criteria, discussed in [9]. Contrary to the current designs, a single ferrite block is used to facilitate heat transfer within the load by avoiding inevitable small gaps between adjacent ferrite rings that would impair the effectiveness of the cooling mechanism [3].

Integration in the System

Different options for the integration of the RF load into the existing system were examined and simulated with CST [10]. Due to a strict timeline, the grounded metallic cylinder that overlaps with the screen conductors and provides capacitive

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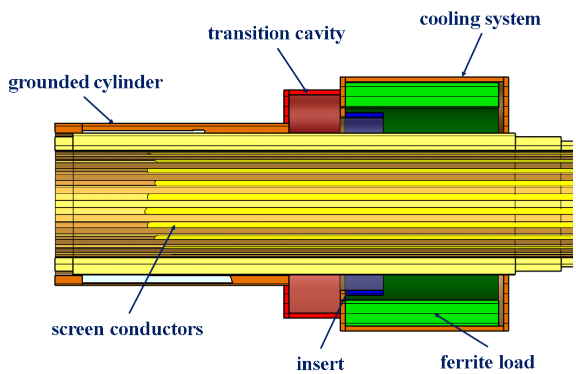

Figure 1: Schematic of the MKI beam screen system.

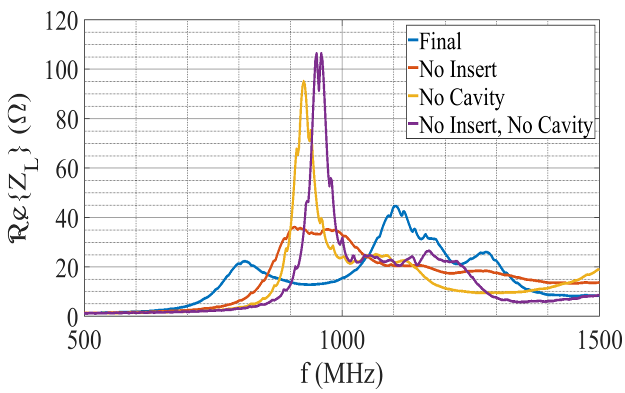

Figure 2: RLI for different integration options of the RF load to the existing MKI design.

coupling to the ground for the beam image currents, could not be redesigned. Therefore, the overlap length between the cylinder and the screen conductors, that strongly affects the MKI longitudinal impedance, remained at ~56 mm, as implemented in the upgraded MKI8D magnet [5].

As shown in Fig. 2, if the load is directly connected to the grounded cylinder, i.e. without the transition cavity, a relatively strong resonance in the real part of the longitudinal impedance (RLI) is observed. This behaviour is attributed to the mismatch between the load and the coaxial structure that precedes it, formed by the metallic cylinder and the screen conductors, and to which the RF power carried by the beam is initially coupled. The resulting reflections increase the time needed to dissipate the coupled power, thus increasing its Q-factor. To improve the matching, an additional 20 mm-long, hollow cylindrical transition cavity of 43 mm radius was introduced between the grounded cylinder and the load, as it is schematically shown in Fig. 1. Although the expected total losses for all the models presented in Fig. 2 is ~156 W, it was considered preferable to avoid strong resonances as losses may increase in case they hit a beam harmonic. For the presented power loss estimations, 2748 equidistant and equi-populated Gaussian bunches of 2.2×10^{11} protons and 1 ns bunch length ($4\,\sigma$), are assumed and the standard power loss formula is used without additional scaling [11]; neglecting side-band harmonics, due to gaps in the filling pattern, is expected to influence predicted power deposition by less than 1% [12].

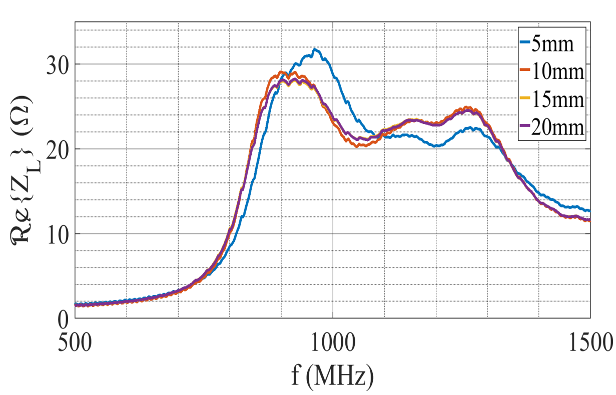

Figure 3: Effect of the radial thicknesses of the RF load on the MKI's RLI.

Load Dimensions

The radial thickness of the load was a critical parameter for the thermal performance of the system. Due to its ease of implementation and high expected effectiveness, it was decided that an active water-cooling system will be installed around the outer surface of the ferrite load in contact the metal cylinder that will house the load, as indicated in Fig. 1 [3]. However, heat in the load is expected to be generated in its inner side, i.e. where the load first interacts with the coupled RF field. Therefore, to ensure high heat extraction rates its thickness needed to be minimized due to the low thermal conductivity of ferrites. Since a thickness of 5 mm would offer limited mechanical strength to the load and, as shown in Fig. 3, thicknesses above 10 mm offered no significant improvement in the RLI, the radial thickness of the load was chosen to be 10 mm.

At the same time, a trade-off for the inner radius of the load was looked for, to ensure the effective functionality of the load while preventing thermal energy being transferred to the alumina tube and avoiding close proximity to surfaces that could damage the ferrite. A 60 mm-long ferrite tube of inner radius of 38 mm and a radial thickness of 10 mm was considered a good compromise for low total dissipated RF power, sufficient heat extraction efficiency, good mechanical stability as well as manufacturing feasibility.

Power Loss De-localisation

The structural integrity of the ferrite load is of significant importance and must be ensured under all operating conditions. Due to the expected high temperature differences between the inner and outer sides of the load, thermal stresses may lead to cracks that could jeopardize its proper functionality. Aiming to avoid high concentrations of dissipated power at one end of the load, an additional metallic cylindrical insert was introduced inside the ferrite tube, as shown in Fig. 1. Due to temporal constraints, an optimization of the parameters of the insert was not possible and an intermediate length of 15 mm was considered an acceptable choice. As it is shown in Fig. 4, the insert allowed for

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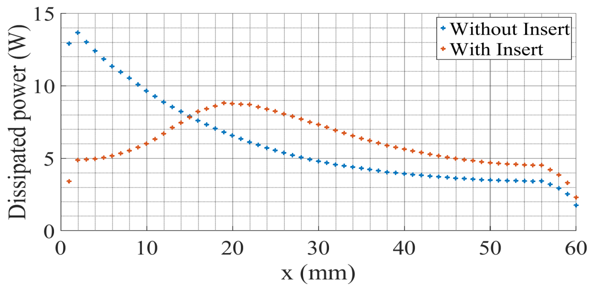

Figure 4: Expected distribution of the dissipated power along the RF load without (blue) and with (orange) the insert.

Table 1: Design parameters of the new design of the beam screen system of the MKI magnet.

Parameter	Value
Type of ferrite	CMD10
Load length	60 mm
Load radial thickness	10 mm
Load inner radius	38 mm
Transition Cavity Length	20 mm
Transition Cavity Radius	43 mm
Insert Length	15 mm

a smoother distribution of the dissipated power along the length of the load, which in turn decreased the temperature differences to acceptable levels [3]. The RLI of the final design of the new MKI beam screen system, is shown in Fig. 2, and all discussed parameters are summarized in Table 1.

OTHER MODIFICATIONS

In order to reduce the expected temperature gradients in the ferrite tube, a uniform RF power dissipation would be the optimal solution. The left hand of Fig. 5 shows the post-LS1 design of the upstream end of the beam screen: for HV reasons the screen conductors are reduced in length towards the HV busbar (bottom) and adjacent conductors are staggered in length [13]. The overlap between the screen conductors and vacuum is ~20 mm. The vacuum gap is 3 mm adjacent to the HV busbar and 1 mm at the top [1]. This asymmetrically design results in RF power being asymmetrically dissipated in the azimuthal direction, as shown in Fig. 6.

To respect the HV constraints in the lower half, two modified configurations were investigated and their schematics are shown in Fig. 5. In both modifications the upper part of the screen conductors is a mirror image of the lower part. The vacuum gap in the first of the two, referred to as "Mod1", is a 59 mm-long tube of 3 mm thickness, whereas in the second, referred to as "Mod2", the upper half vacuum gap is mirror-symmetrical with the bottom part. As shown in Fig. 6 both modifications led to similar azimuthal power dissipation profiles. Their RLI, which is compared to the final design in Fig. 7, gave rise to a dissipated power of 180 W and 167 W, respectively. Thermal simulations suggested that the maximum expected temperatures in the load with the modified designs would be higher and thus the approach was

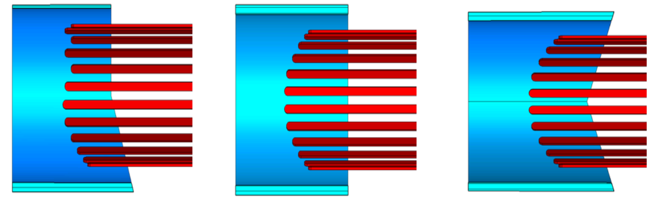
Figure 5: Vacuum gap (blue) and screen conductors (red) for the "Final" (left), "Mod1" (centre) and "Mod2" (right) designs.

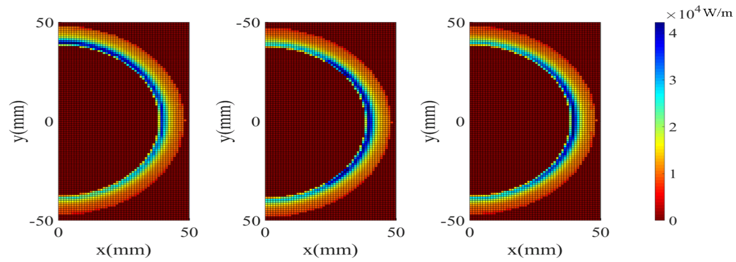

Figure 6: Expected azimuthal distribution of dissipated power in the ferrite load for final (left), Mod1 (centre) and Mod2 (right) designs.

not further pursued [3]. However, provided a HV study can ensure the functionality of a rotationally symmetric configuration of the vacuum gap and the screen conductors, the power loss dissipation in the ferrite is expected to be in turn azimuthally symmetric.

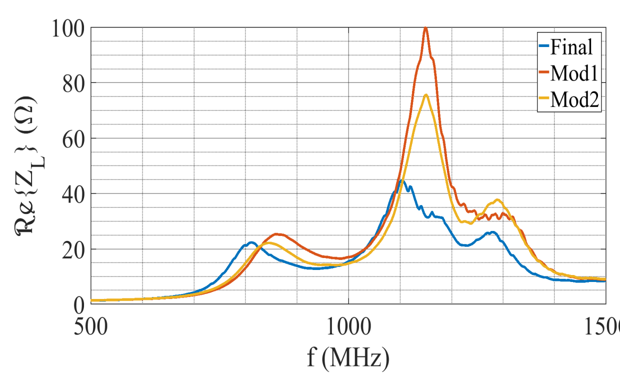

Figure 7: Vacuum gap (cyan) and screen conductors (red) for the "Final" (left), "Mod1" (centre) and "Mod2" (right) designs.

CONCLUSION AND OUTLOOK

In this work studies of the beam screen system of the LHC injection kicker magnet for HL-LHC operation were discussed and the final design was presented. Impedance measurements will be performed on the assembled magnet to validate the results. Provided that good agreement between measurements and simulations has been reached, the new magnet is scheduled for installation in the LHC tunnel during LS2 in order to be tested with LHC beams during Run 3.

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