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IMPEDANCE AND THERMAL STUDIES OF THE LHC INJECTION KICKER MAGNET UPGRADE

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Abstract

The bunch intensities of High Luminosity (HL) LHC are predicted to lead to heating of the ferrite yokes of the LHC injection kicker magnets (MKI), in their current configuration, to their Curie temperature. Hence, the MKIs are being upgraded to meet the requirements of HL-LHC, which is planned to start in the mid-2020s. The upgraded design features an RF damping ferrite loaded structure, at the upstream end of each magnet, which will absorb a large portion of the beam induced power deposition of the magnet. The ferrite damper is cooled via a copper sleeve, brazed to the ferrite, and a set of water pipes. The thermal contact conductance (TCC) between ferrite and copper is very important, as are the properties of the ferrite. In this paper, we present measurements of the TCC and ferrite properties. This data is used to predict temperatures during operation of the LHC. In addition, a measurement and prediction is shown for the longitudinal impedance of the magnet. The models developed in this study will be benchmarked during run III of the LHC.

INTRODUCTION

The LHC injection kicker magnets (MKI) were upgraded during Long Shutdown I, that ended in 2015, to reduce their beam induced heating [1] and improve high voltage (HV) behaviour [2]: the MKIs are expected to operate without beam induced heating issues during the upcoming run III. In preparation for the High Luminosity (HL) LHC, however, the MKIs need to be upgraded to withstand the increasing bunch intensities and thus the increased beam induced heating [3]. The upgrade involves reducing the total beam induced power deposition in the MKIs, and redistributing a significant portion of these losses to an RF damper. This RF damper will be water cooled: hence the upgraded kicker magnet is referred to as MKI Cool.

The problem of beam induced heating is of particular interest in accelerator devices containing lossy materials that are directly exposed to the electromagnetic fields of high intensity particle beams [4]. The dielectric and magnetic losses due to electromagnetic interaction in such devices can, in some cases, be substantial and can lead to significant beam induced heating. In the case of a typical transmission line kicker magnet, there is normally a large amount of exposed lossy materials. The magnetic yoke, typically ferrite, has in general high relative permeability and magnetic losses. These ferrites are located close to the beam to produce the required pulse magnetic field with a reasonable magnitude of current, which makes them especially exposed to heating from the particle beam. The ferrites can be shielded in part by metallic screen conductors in the aperture, to provide a path for the beam image current: in the MKI Cool an alumina tube provides mechanical support and electrical insulation for these conductors [2]. Stringent rise time specifications require that the screen conductors are capacitively coupled to a grounded metallic cylinder at one end of the tube (the upstream end is chosen) while the other end is directly grounded.

Ferrite magnetic properties are sensitive to high temperatures and relative permeability will approach unity when the ferrites reach their *Curie temperature* [5]. Hence, at this temperature, the kicker magnet cannot adequately deflect injected beam. Furthermore, the heating can cause thermal gradients and expansion which in severe cases can crack the ferrite due to mechanical stress [6]. Thus, high rates and amounts of heating could compromise the functionality of the kickers magnets if other mitigating measures are not taken.

RF DAMPER

Overview and Manufacturing

It is not feasible to cool the ferrite yoke of the MKIs since they are at pulsed HV. Hence, to limit the heat deposition in the yokes, an RF damper has been developed. The damper consists of a ferrite loaded structure, at the upstream end of the magnet, that is designed to reduce total beam induced power dissipation and move dissipation away from the yoke and into the damper itself instead. The damper and its location in the context of the full magnet is shown in Fig. 1. More details on the electromagnetic design of the damper are published in [7].

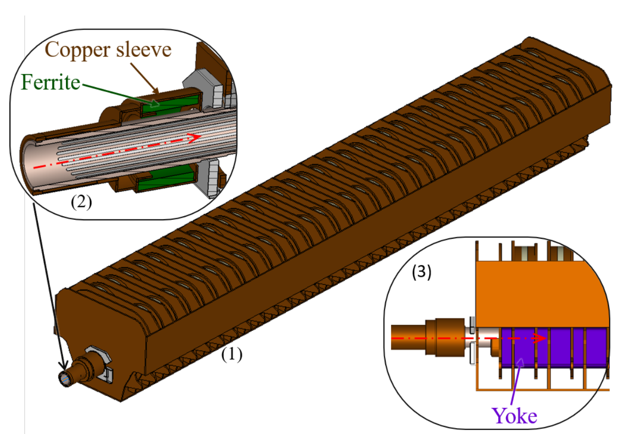

Figure 1: (1) The kicker magnet in its entirety, with the damper located on the left hand side. (2) Cross section of the damper (cooling pipes not shown). The red arrow indicates the direction of the beam. (3) External side view of the damper.

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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: 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 [8]. The ferrite should remain below its Curie temperature as it will otherwise temporarily loose its magnetic properties and consequently its damping function [5]. To mitigate the risk of the ferrite damper heating beyond its Curie Temperature, it has been fitted with a set of water cooling pipes on its outer diameter [6]. However, care must be taken to limit the maximum temperature of the ferrite as it could otherwise crack due to temperature gradients causing internal mechanical stress [6].

The damper structure requires a special manufacturing process, as the ferrite cylinder needs to be brazed to the copper sleeve and the cooling pipes brazed to the sleeve [6]. It is crucial that a good thermal bond is formed between these components as the heat exchange needs to be efficient. Making a good 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 thermal contact conductance (TCC) [6].

High Voltage Compatibility

During HV conditioning of the prototype MKI Cool there were some HV flashovers, several of which were at the upstream end of the magnet, in the vicinity of the RF damper. There was concern that during field rise time, which results in positive HV being induced on the screen conductors [2], electron emission from metallic pieces at ground potential could result in multipacting and thus a surface breakdown, along the outside of the alumina tube, to the HV busbar of the magnet. Thus, several modifications were made in the upstream region, including replacing a metallic support ring for the alumina tube with a macor [9] ring and a redesign of part of the RF damper. The copper end-cap of the RF damper, was originally designed to have an inside diameter only slightly greater than the outside diameter of the alumina tube. This caused a relatively high electric field during field rise and fall: to mitigate this issue, the end-cap inside diameter was increased (Fig. 2). CST [10] simulations show that increasing this diameter does not have a significant influence on the longitudinal beam coupling impedance, at beam harmonics of 40 MHz, below ~1 GHz [11].

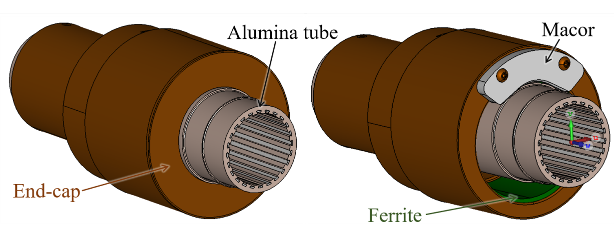

Figure 2: RF damper before (left) and after (right) modifications.

Thermal Model

Understanding the temperature magnitude and distribution in the ferrites is key to addressing the problems of reaching the ferrite Curie temperature as well as thermally induced stress and mechanical failures. It is possible to model the entire process of beam induced heating using electromagnetic and thermal simulations [12]. Nevertheless, the accuracy of predictions are limited by available data, e.g. for ferrite properties and the TCC between ferrite and copper sleeve of the RF damper.

To adequately model the beam induced heating, it is important to have a good understanding of the electrical as well as the thermomechanical properties of the ferrite material, which is where most of the beam induced heating will occur. The electromagnetic properties have previously been presented in [5]. Figure 3 shows minimum and maximum measurements of the thermomechanical properties of isostatically pressed CMD10, for 3 samples, conducted by the CERN Mechanical and Materials Engineering (MME) group. Thermomechanical data can be incorporated, including their temperature dependency, into a thermal modeling tool such as ANSYS [13].

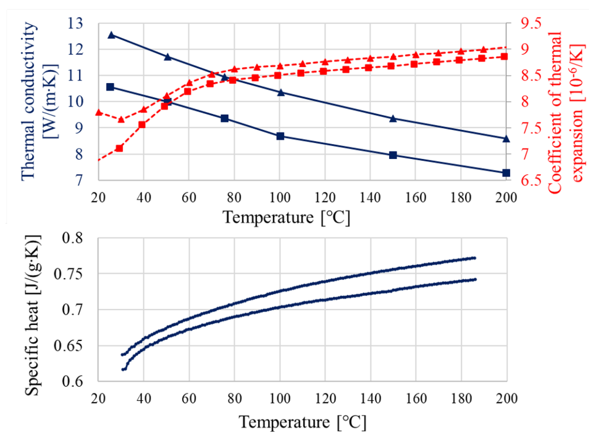

Figure 3: Min. and max. of measured thermomechanical material properties of isostatically pressed CMD10 ferrite: thermal expansion is measured for heating of samples.

Two prototype dampers were constructed: the first was manufactured before the brazing technique was perfected and was known to have a significant quantity of voids in the brazing [6]. To better model the heat exchange we developed a method for estimating the TCC value between the critical contact surfaces of the copper sleeve and the ferrite cylinder. The assembled damper is heated to a homogeneous temperature and subsequently cold water is run through the cooling pipes and the cool-down transient on the inside of the ferrite cylinder is recorded using a thermal camera. Neglecting radiation and convectional cooling (without cooling water, measured cooling rates are orders of magnitude slower) and modelling measured thermal conductivities (Fig. 3), we are able to estimate the thermal contact between the ferrite and the copper by comparing these measurements with thermal simulations of the same transient: the simulated TCC value was tuned until good agreement is achieved with measure-

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ments. A large set of these measurements were made on the two prototype dampers, at different points on the inside circumference of the ferrite, to assess the difference in the TCC (Fig. 4). The first prototype damper had a worst-case TCC of ~200 W/(m^2·K), significantly worse than the second version which had a best case TCC of ~10 kW/(m^2·K). The average TCC, for all the measurements on both prototypes, is 600 W/(m^2·K).

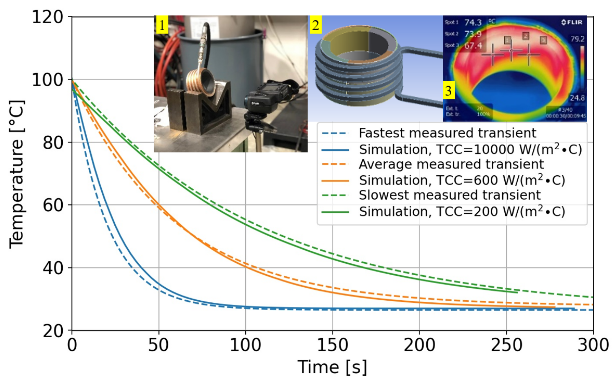

Figure 4: Measured cooling transients and corresponding simulations of the damper: TCC is tuned to agree with the measurement. (1) Measurement setup, (2) ANSYS simulation model, and (3) A thermal camera measurement.

BEAM INDUCED HEATING MODEL

The thermal model described in the previous section is only a part of understanding the heating that occurs in the kicker magnets with beam circulating in the LHC. To obtain the complete picture, we combine wakefield simulations in CST Particle Studio [10] with thermal models of the magnet in ANSYS [13], a method that is described in more detail in [12]. The real part of the longitudinal impedance is combined with the spectrum of the beam to determine the beam induced power deposition [14].

A resonant wire measurement [15] has been carried out on the MKI Cool: the predicted and measured real longitudinal beam coupling impedance are shown in Fig. 5. There is reasonable agreement; although, above 800 MHz, the impedance resonances occur at higher frequency than in the predictions. Nevertheless, the CST model is considered to be reasonable and is likely to produce reliable results for the power loss distribution, which is important as this cannot realistically be evaluated with measurements.

Transient thermal simulations of the damper show that the measured thermal conductivity of the CMD10 ferrite, of ~9 W/(m·K) at 90 °C (Fig. 3), significantly reduces the temperature difference between the inside and outside radii of the ferrite cylinder, hence reducing the mechanical stress, in comparison with the datasheet conductivity of 3.5-5 W/(m·K). In Fig. 6 the predicted peak temperature of the ferrite damper is plotted against time. In some previous thermal models of the MKIs, it has been observed that a scaling factor of the total input power of 2.5 has been required

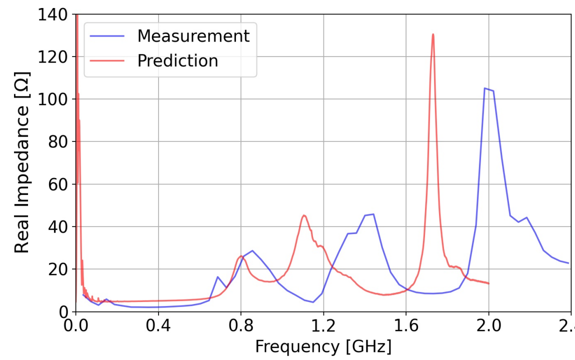

Figure 5: Predicted and measured real longitudinal beam coupling impedance of the MKI Cool.

to match the predicted and measured temperatures [6]. Although this has not been the case for the most recent models of the MKI Cool, in Fig. 6 we show the effect of different scaling factors on the peak temperature. The factor "x 1.0" corresponds to a total beam induced power of 112 W for the magnet: 90% of this occurs in the damper. The 112 W is calculated for a beam of 2.2×10^{11} protons per bunch, 2748 bunches and 1 ns bunch length. Even with a scaling factor of 2.5 (x 2.5 in Fig. 6) the peak, steady-state, temperature in the ferrite of the damper is ~72 °C, for cooling water of 22 °C. The 72 °C is below the critical value of 100 °C identified in [6]. However, the critical value is based on generic data for the ultimate tensile and compressive strength [6]: these data are presently being measured by CERN MME.

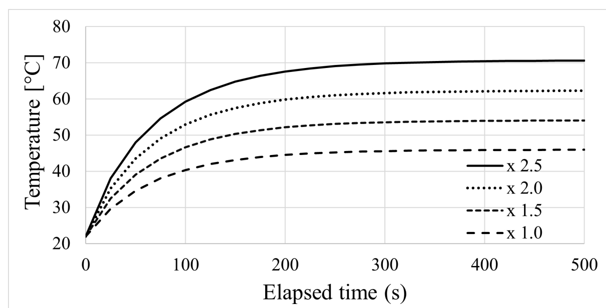

Figure 6: Predicted peak temperatures in the MKI Cool RF damper for different input powers.

CONCLUSIONS

Thermomechanical properties of the ferrite used for the RF damper have been measured and transient measurements carried out to estimate the TCC between the copper sleeve and ferrite of the damper. The predicted beam coupling impedance of the MKI Cool has been verified against a resonant wire measurement. The complete CST and thermal models shows that the maximum temperature of the ferrite of the RF damper should be acceptable with HL-LHC type beams: however, this will be verified following ongoing mechanical measurements of the CMD10 ferrite.

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REFERENCES

[1] H. A. Day, R. M. Jones, M. J. Barnes, F. Caspers, E. Métral, and B. Salvant, "Evaluation of the Beam Coupling Impedance of New Beam Screen Designs for the LHC Injection Kicker Magnets", in *Proc. 3rd Int. Particle Accelerator Conf. (IPAC'12)*, New Orleans, LA, USA, May 2012, paper WEPPR071, pp. 3093–3095.

[2] M. J. Barnes *et al.*, "Reduction of Surface Flashover of the Beam Screen of the LHC Injection Kickers", in *Proc. 4th Int. Particle Accelerator Conf. (IPAC'13)*, Shanghai, China, May 2013, paper MOPWA032, pp. 735–737.

[3] V. Vlachodimitropoulos, M. J. Barnes, L. Ducimetière, L. Vega Cid, and W. J. M. Weterings, "Study of an Improved Beam Screen Design for the LHC Injection Kicker Magnet for HL-LHC", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 3471–3474. doi:10.18429/JACoW-IPAC2017-WEPVA094

[4] B. Salvant *et al.*, "Update on Beam Induced RF Heating in the LHC", in *Proc. 4th Int. Particle Accelerator Conf. (IPAC'13)*, Shanghai, China, May 2013, paper TUPME032, pp. 1646–1648.

[5] A. Chmielinska, M. J. Barnes, F. Caspers, B. K. Popovic, and C. Vollinger, "Measurements of Electromagnetic Properties of Ferrites as a Function of Frequency and Temperature", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 2592–2595. doi:10.18429/JACoW-IPAC2018-WEPMF089

[6] L. V. Cid, A. Abánades, M. J. Barnes, F. Mostchmann, V. Vlachodimitropoulos, and W. Weterings, "Conception and design of a cooling system for the LHC injection kicker magnets", *Nucl. Instrum. Meth. A*, vol. 916, pp. 296-305, 2019. doi:10.1016/j.nima.2018.11.007

[7] V. Vlachodimitropoulos, M. J. Barnes, A. Chmielinska, L. Ducimetière, L. Vega Cid, and W. J. M. Weterings, "Studies Towards the New Beam Screen System of the LHC Injection Kicker Magnet for HL-LHC Operation", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 3982–3985. doi:10.18429/JACoW-IPAC2019-THPRB074

[8] National Magnetics Group, http://www.magneticsgroup.com/

[9] Corning, https://www.corning.com/emea/en/products/advanced-optics/product-materials/specialty-glass-and-glass-ceramics/glass-ceramics/macor.html

[10] Dassault Systems, CST Studio Suite, https://www.3ds.com/products-services/simulia/products/cst-studio-suite/

[11] O. Bjorkqvist, M.J. Barnes, "MKI summary and status", presented at the 45th Impedance Working Group meeting, CERN, Geneva, Switzerland, Jan. 2021.

[12] V. Vlachodimitropoulos, M. J. Barnes, and A. Chmielinska, "Preliminary Results from Validation Measurements of the Longitudinal Power Deposition Model for the LHC Injection Kicker Magnet", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 2636–2639. doi:10.18429/JACoW-IPAC2018-WEPMK005

[13] ANSYS, https://www.ANSYS.com/

[14] H. Day, "Beam Coupling Impedance Reduction Techniques of CERN Kickers and Collimators", Ph.D. thesis, School of Physics and Astronomy, The University of Manchester, Manchester, United Kingdom, CERN-THESIS-2013-083, 2013.

[15] T. Kroyer, E. Gaxiola, and F. Caspers, "Longitudinal and transverse wire measurements for the evaluation of impedance reduction measures on the MKE extraction kickers", CERN, Geneva, Switzerland, Rep. CERN-AB-Note-2007-028, Jan. 2007.