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PRELIMINARY DESIGN OF A COOLING SYSTEM FOR THE LHC INJECTION KICKER MAGNETS *

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Abstract

The CERN Large Hadron Collider (LHC) is equipped with two fast pulsed magnet systems (MKIs) that inject particle beams from the injector chain. Future operation for High Luminosity LHC (HL-LHC) with high intensity beams will cause heating of the ferrite yokes of the MKIs beyond their Curie temperature, preventing injection until the yokes cool down. Beam coupling impedance studies show that it is possible to move a substantial portion of the beam induced power deposition from the upstream ferrite yokes, which are the yokes with the highest power deposition, to ferrite rings located at the upstream end of the magnet. Thermal predictions show that this power redistribution, combined with the installation of a cooling system around the rings, will maintain the temperatures of all the yokes and ferrite rings below their Curie point. Since the rings are not pulsed to high voltage, whereas the ferrite yokes are, the installation of a cooling system is feasible around the rings. The proposed design of the cooling system will be tested to ensure good performance before its installation on the MKIs. The details of the simulations and the design process are reported.

INTRODUCTION

The LHC injection kicker systems (MKIs) deflect the incoming beam onto the LHC's equilibrium orbits. The MKIs are composed of 33 cells: In each cell there is a U-core ferrite yoke between two high voltage conducting plates, and two ceramic capacitors sandwiched between a HV plate and a plate connected to ground [1]. A beam screen is used to shield the ferrite yokes from the beam [2]. To ensure good operation of the MKI magnets, the temperature of the ferrite yokes must not exceed their Curie point, which is ~125 °C for the 8C11 [3] or CMD5005 [4] ferrite used. In order to estimate the temperatures for different LHC operating scenarios, detailed thermal analyses have been performed with a numerical model created in ANSYS [5]. The power is deposited in a non-uniform way along the longitudinal axis and is mostly in the upstream (beam entrance) end of the magnet, in the ferrite rings located at the entrance and in the first ferrite yokes [6, 7]. For this reason the model can be simplified to reduce computational time and the magnet is represented only up to the 10th cell [8]. The model was validated by comparing ANSYS predictions with temperature measurements of MKIs during LHC operation: they are in good agreement [8].

For the current period of operation (Run 2) no thermal issues are expected. However, for future operation with high intensity beams [9] the temperature of the yokes will exceed the Curie point if no further measures are taken [8]. Hence various options have been studied, such as increasing the thermal emissivity of the vacuum tank [8, 10] or removing bake-out jackets [8]: these have been discarded because the reduction of the temperatures is insufficient. Another option is to cool the ferrite yokes by attaching cold plates [11]: this has also been discarded due to the mechanical complexity [8]. Recent efforts have focused on moving the beam induced power deposition out of the ferrite yokes, by deliberately concentrating the losses in the upstream ferrite rings. The rings are not at pulsed high voltage, hence the installation of a cooling system is less complicated than for the yokes.

RUN 2 TEMPERATURES

CST [12] simulations show that redistributing the beam induced power deposition, from the yoke to the upstream ferrite rings, can be achieved by modifying the geometry of a metal cylinder inside the upstream ferrite rings, which increases the interaction of the rings with the beam [13]. In order to verify the predicted redistribution, modifications have been implemented in an upgraded MKI installed in the LHC during the 2017-18 Year End Technical Stop (YETS) [13, 14].

Figure 1 shows the predicted temperatures, during Run 2, for the post-LS1 [15] and the upgraded magnet. Bake-out jackets are not included in the simulations. For the upgraded magnet, the temperatures of all ferrites will be below their Curie points. However, the predicted temperature of the first yoke of the post-LS1 magnets is 126°C. Although all post-LS1 magnets are nominally the same, and would hence be expected to have the same power deposition, beam impedance measurements show a spread in expected beam induced power deposition: the "worst-case" power loss is ~50% above the "best-case". The expected "worst-case" magnet (MKI8D) had the highest measured temperature during 2017 operation: this is the magnet that was replaced with the upgraded MKI during the YETS. The second highest temperature measurement (MKI8A), during 2017 LHC oper-

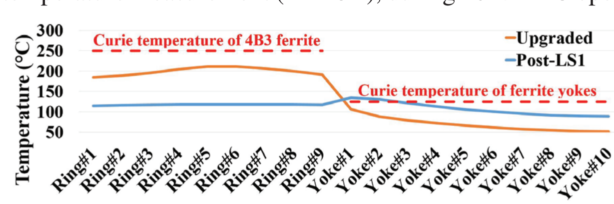

Figure 1: Expected temperatures for a "worst-case" post-LS1 and upgraded magnet during Run 2.

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ation, had a temperature rise 15% below MKI8D. Hence, the yoke-temperatures for the post-LS1 magnets are expected to be below those shown in Fig. 1, and no issues are expected. In addition, these thermal predictions assume steady-state conditions, i.e. no reduction of beam intensity during a physics fill. Due to the high thermal inertia of the yokes and the limited duration of the LHC fills, this maximum value is not expected to be reached.

To verify the thermal distribution, and hence the predicted power depositions, two additional temperature sensors (PT100s) are installed in the upgraded magnet in locations with a high sensitivity to power deposition [8] (Fig. 2). Table 1 shows predicted "worst-case" temperatures, for Run 2, at the locations where the PT100s are placed.

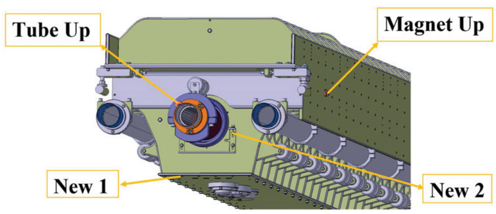

Figure 2: PT100 locations in upgraded magnet.

Table 1: Predicted Temperatures of Upgraded Magnet Run 2

Location	*Magnet Up*	*Tube Up*	*New 1*	*New 2*
Temperature (°C)	67	167	106	120

COOLING THE FERRITE RINGS

Figure 3 shows predicted temperatures for the upgraded magnet without any cooling (blue curve), for HL-LHC operation. Although the power deposition in the first yoke is decreased by a factor of 20.5 with respect to post-LS1, the temperatures of the first 5 yokes exceed their Curie point. This is caused by the high power deposition in the rings [13] which is transmitted by conduction and radiation. To analyse their influence upon the yokes temperature, Figure 3 shows a prediction (brown curve) for a theoretical case where power deposition is modelled only in the yokes and not in the rings. The low temperatures obtained in the yokes confirm that the high temperatures in the blue curve are caused by the power in the rings. Hence, a cooling system must be installed around the rings to evacuate their heat.

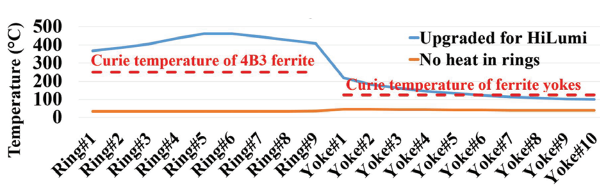

Figure 3: High Luminosity predictions for upgraded magnet.

Design Limitations

Different ways of cooling the rings have been thoroughly studied and a design based on loops of water cooled pipes has been selected. However, there are limitations that add complexity to the design: The magnets are in ultra high vacuum (UHV). Thus, all materials used must be UHV compatible. Vacuum acceptance tests must be done for any material that has not been qualified for use in the LHC, which is time consuming [16]. For this reason, it is preferable to use materials that have been already tested [17]. Another important limitation is that no water-to-vacuum joints are allowed due to the risk of leakage [18]. Hence, the joint between the cooling pipes and the LHC demineralised water circuit [19] must be made outside the vacuum tank. In addition, for achieving the UHV, the magnets are baked-out at 315°C before installation in the LHC [14]. Hence the choice of materials for components, of the cooling system, that will be in contact with the ferrite rings is important: high thermal stresses, due to different thermal expansion coefficients, must be avoided. Therefore structural analysis is carried out to verify that the thermal stress generated is below the yield strength of all the components. Furthermore, the temperature gradient between the internal surface of the ferrite ring, where most of the power deposition is concentrated, and the external surface, where the cooling system is located, can cause internal stresses which might crack the rings.

Proposed Cooling System

Taking into consideration all the mentioned limitations, the water cooling system shown in Fig. 4 is proposed. The nine ferrite rings are replaced by one ferrite cylinder: The feasibility of this is under study, as the rings are manufactured by sintering and dimensions are limited [20]. A copper cylinder will be placed around the ferrite ring, and cooling pipes will be attached to it.

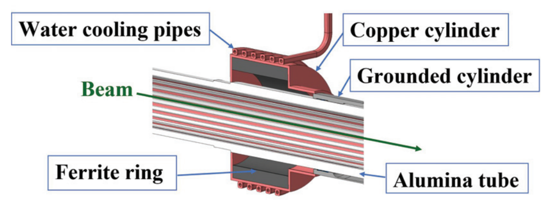

Figure 4: Proposed cooling system for the ferrite rings.

Analytical Model

In order to choose properly the dimensions of the cooling system, and identify the parameters that are key to achieve an efficient heat extraction, an analytical model is presented:

$$Q = (T_{ring} - T_{water})/R_{th} \tag{1}$$

where Q is the heat loss in the rings (W), T_{water} is the average temperature of the water in the cooling pipes [19], T_{ring} is the temperature of the internal surface of the ring where the heat is mainly deposited, and R_{th} is the total thermal resistance (K/W) to the cooling circuit. An important objective is to obtain a value of R_{th} which results in the ferrite temperature being an acceptable value, including a safety margin. The following sections describe the parameters that contribute to the the value of R_{th}. A more detailed study including equations and numerical results will be reported in a future paper.

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Conductive resistance The conductive resistance is the internal resistance to the flow of heat due to thermal conductivity and dimensions. The conductive resistance of the ferrite ring is high due to its low thermal conductivity (4.2 W/m·K) which cannot be changed. Although the thickness of the ring can be reduced, which lowers its thermal resistance, the thickness must also be chosen with the damping properties of the ferrite in mind, as well as the limitations due to the manufacturing process and the brittleness of this material. For the cylinder around the ring, to achieve a low resistance a thin cylinder of copper has been selected as it has a high thermal conductivity.

Contact resistance For components which are in contact, the heat is only conducted through a small fraction of the joint because of the non-flatness and roughness of the contacting surfaces, causing a thermal resistance. This is defined by a parameter called thermal contact conductance (TCC). There is not a single analytical expression for calculating its value but many analytical models exist [21]. In this case Ref. [22] has been used to calculate the TCC between the ferrite ring and the copper cylinder. Calculations show that a high pressure of approximately 5 MPa is needed to achieve a high-conductance: however, there is a risk of cracking the ferrite due to its brittleness, hence this option has been discarded. Brazing could achieve a very low thermal contact resistance between the cylinder and the ring. Brazing is currently being investigated.

Constriction resistance Constriction resistance exists whenever heat flows from one region to another with a narrower cross-sectional area [23], as is the case of the copper cylinder and the cooling pipes. Calculations have been carried out and the value of this resistance is negligible compared to those already mentioned.

Convective resistance Convective resistance represents how efficiently heat is transferred from a solid to a fluid: this is a function of the characteristics of the fluid and the diameter of the pipes. It is important to ensure moderately turbulent water flow and also that the velocity of the fluid is below 1.5 m/s to avoid corrosion of the pipes [24]. The optimum value of the pipe internal diameter is obtained by iterative hydraulic calculations [25]. When the cooling is properly designed the value of this resistance is low compared to those already mentioned.

Numerical Model

A numerical model has been created to analyse the cooling system. The heat is transmitted from the rings to the pipes mainly by conduction. The heat evacuated by radiation is negligible and the influence of the ferrite yokes upon the ring temperature is negligible, for the upgraded magnet, due to the low values of power deposition in the yokes. Figure 3 shows that if no heat was generated in the rings, the yokes and ring temperature would be below 50°C and 30°C, respectively. For this reason, the ANSYS model can be simplified and only the ferrite rings with the cooling system are modeled. To verify this approach , the results of the detailed model (with 10 cells) have been compared to the simplified model and the difference in the ring temperature is only 2%. However, the computation times are highly reduced in the simplified model.

An improvement implemented in the model is an interface between CST, used for the impedance simulations [13], and ANSYS. This allows to import the power dissipation at each mesh point from CST into ANSYS [26]: hence the accuracy of the ANSYS prediction is improved. The distribution of the power in the ferrite rings is shown in Fig. 5.

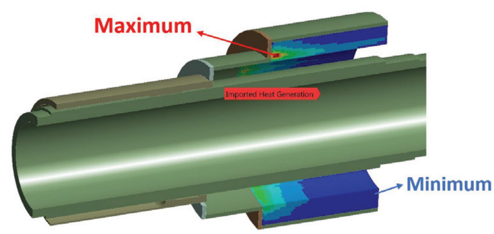

Figure 5: Predicted power density in the ferrite cylinder.

A structural analysis has been done, assuming a ring of 10 mm thickness, to verify that the gradient of temperature will not crack it. The failure criteria that has been used is Christensen [27]: results show that the maximum temperature of the rings should not exceed 100°C. The temperature is highly dependent on the TCC between the rings and the copper cylinder (Fig. 6).

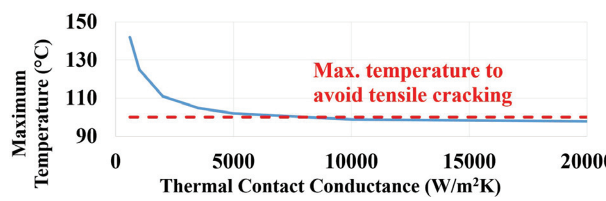

Figure 6: Temperature of the ring vs TCC.

Figure 6 shows that a high conductance bonding (TCC>8000) is needed to ensure a maximum temperature of the ring below 100°C. This can be achieved by methods such as soldering or brazing, which are currently under study. If this condition is fulfilled the cooling system would maintain the yoke and ring temperature below the Curie point for HL-LHC operation without cracking of the ring.

CONCLUSION

The beam induced power deposition has been redistributed from the yokes to the upstream ferrite rings, where the installation of a cooling system is feasible as the rings are not at pulsed high voltage. These modifications have been implemented in an upgraded magnet, installed in the LHC, to verify CST predictions. A design for cooling the ferrite rings, which takes into account the requirements of the UHV system as well as thermally induced stresses in the rings, has been proposed. Preliminary results of a thermo-structural analysis confirm its efficiency. More detailed analyses, including computational fluid dynamics simulations, are planned and a prototype of the cooling system will be built and tested.

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