THERMAL ANALYSIS OF 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 coming from the injector chain. Operation with high intensity beams for many hours can lead to significant beam induced heating of the ferrite yokes of the MKIs. When the ferrite exceeds the Curie temperature of 125°C it loses its magnetic properties, preventing further injection until the ferrite cools down, potentially causing a delay of several hours. Hence important upgrades of the beam-screen were implemented after Run 1 of LHC. However, the High-Luminosity (HL) LHC will be operated with significantly higher intensity beams and hence additional measures are required to limit the ferrite temperature. These magnets operate under ultra-high vacuum conditions: convection is negligible and, as a result of low emissivity of the inside of the vacuum tanks, thermal radiation is limited. A detailed study of the thermal behaviour of these magnets is reported and compared with measurements. In addition several options to improve cooling of the ferrites are presented and analysed.

INTRODUCTION

The LHC injection kicker magnets (MKIs) deflect the incoming beam onto the LHC's equilibrium orbits [1]. To deflect the incoming particle beam, these magnets are pulsed at high voltage and current, creating a magnetic field pulse. The field lines are guided using a NiZn ferrite yoke. Although the MKIs only pulse 12 times to fill the LHC, the high intensity beam circulates through the aperture of these magnets constantly for many hours. This leads to significant beam induced heating in the ferrite yokes. If the Curie temperature (~125°C) is reached, the yoke will lose its ferromagnetic properties and the beam will be mis-injected, which can cause quenches of downstream superconducting magnets. In the future the HL-LHC will be operated with significantly higher intensity beams [2], so additional measures are required to avoid heating of the ferrite yokes above the Curie point. Furthermore, because of the ultra-high vacuum (UHV), convection is negligible and, as a result of low emissivity of the inside of the vacuum tanks, thermal radiation is limited [1]. A numerical model has been created to study the thermal behaviour of the MKI magnets. The purpose is to identify solutions to reduce the effect of beam induced heating.

THERMAL MODEL

A finite element model has been created using ANSYS [3]. The complexity of the MKI magnets is remarkable: there are many components with complex geometries. An MKI magnet has both side-to-side symmetry, in the longitudinal axis, and a periodic structure: each MKI is composed of 33 repeated cells. A cell consists of a U-core ferrite yoke between two HV conducting plates, and two ceramic capacitors sandwiched between a HV plate and a plate connected to ground [4]. Different models of an MKI have been analysed to identify a reasonable trade-off between accuracy and computational cost.

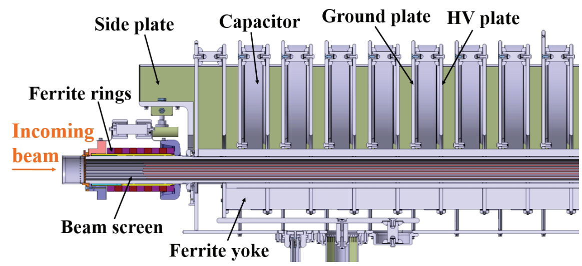

Figure 1: Model of the upstream end of an MKI magnet.

To simplify the model, advantage can be taken of the side-to-side symmetry in the longitudinal axis. The first models were 2D, taking advantage of the periodic structure [4]. However, recent studies indicate that the power is deposited in a non-uniform manner along the longitudinal axis: it is deposited mostly in the upstream end of the magnet, in the ferrite rings located at the beam entrance and in the first two ferrite yokes. From the 3^{rd} to the 33^{rd} ferrite yokes, the power deposition is close-to-uniform and of relatively low magnitude [5,6]. In order to determine how many cells should be modelled, to obtain accurate predictions, simulations with up to 15 cells have been performed - these simulations allow one to see from which cell the longitudinal heat transfer can be considered adiabatic. For the thermal predictions presented in this paper the power distributions detailed in [6] have been modelled: it is concluded that 10 cells are sufficient, as the temperature difference between the 10^{th} and the 11^{th} ferrite yokes is less than 2%.

VALIDATION

The numerical model has been validated by simulating the calculated power for several operational fills of LHC: the predicted temperatures are then compared with measured temperatures in one of the installed MKIs. To compare these temperature it must be taken into account that the PT100 sensors are not installed directly on the ferrite yoke, since it is pulsed to high voltage. The two PT100's for the yoke are located on a side plate: there is one PT100 towards each of the upstream and downstream ends, located at the position of the third yoke from each end of the magnet. In addition there is a PT100 associated with each set of ferrite rings, located on a clamp in contact with the rings (Fig. 2).

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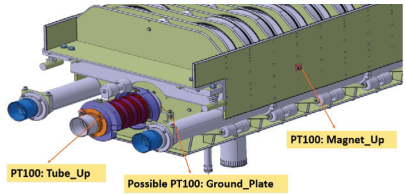

Figure 2: PT100 at the upstream end.

The time dependent values of the power depositions calculated for each of the upstream ferrite rings and each of the first 10 yokes, for a specific fill during LHC operation (in this case from 02-07-2016 00:57hrs to 03-07-2016 15:21hrs), are modelled with ANSYS. The results are shown in Fig. 3.

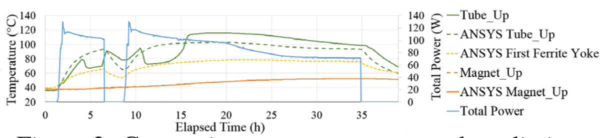

Figure 3: Comparison: measurements and predictions.

In Fig. 3, Magnet_Up and Tube_Up correspond to the measured temperatures, at the upstream end of the magnet, on the side plate and by the ferrite rings, respectively: both are for the magnet named MKI8D. The temperatures for the side plate show very good agreement between measurements and predictions: the curves are overlapped.

For the temperature of the clamp next to the ferrite rings (Tube_Up), there is some discrepancy between measurements and predictions: this may be partially due to uncertainty about the value of the thermal contact resistance between the rings and the clamp, which is very difficult to estimate. However the measured temperature Tube_Up (Fig. 3, continuous green line) shows several rapid changes: these are most likely not realistic for the ferrite rings and the cause is currently under study: one theory is that this might be related to a loss in thermal contact between the ferrite rings and the clamp, due to different thermal expansion. Similar behaviour has been observed for the measured upstream ferrite ring temperatures of all the MKI magnets.

Optimum Location of PT100 Sensors

Calculation of the power deposition in the ferrites presents uncertainties [5, 6]. Thus, good agreement between the measured temperatures and thermal predictions also helps to validate the power deposition. Ideally the PT100 sensors should be located in positions with a high sensitivity to the ferrite temperatures, where changes in yoke temperature result in reasonable changes in the measured temperature.

In order to evaluate the quality of the present locations of the PT100s, the same transient simulation used for the validation of the model (Fig. 3) has been re-run with 25% increased power depositions, and the bake-out jackets that cover the tanks have not been included. The predicted temperature of the first yoke increases by 11%. Fig. 4 shows that the temperature on the side plate has increased by only 4%: hence the present PT100 location on the side-plate is not optimum. Whereas the first Ground Plate (Fig. 2) temperature,

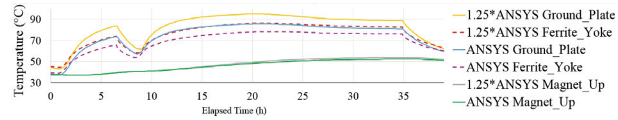

Figure 4: Power input 25% higher and no bake-out jackets.

close to the beam aperture increases by 14%. It is planned to install a prototype MKI, with several upgrades [7] at the end of 2017. Moving a side-plate PT100, to the first ground plate, is under consideration: however, since design changes, to reduce power deposition in the yoke, are planned [6], if the PT100 is moved, the quantitative comparison to other MKIs is lost.

FERRITE YOKE TEMPERATURE

Potentially the most accurate way to predict ferrite yoke temperatures is to run a transient thermal simulation with the power data calculated for a specific fill, as was done for the validation of the model (Fig. 3). However, typical transient simulations require several days of CPU time and, in addition, maximum temperatures are dependent upon initial conditions which are themselves influenced by previous fills. A simpler and more pessimistic approach is to consider steady-state conditions. Fig. 5 shows the relationship between the steady-state power and the temperature of the ferrite yoke and rings.

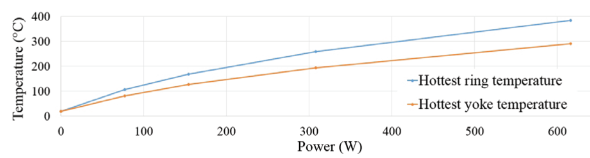

Figure 5: Relationship between steady-state power and maximum temperature of the ferrite yoke and rings.

For estimating ferrite temperature, there are several approaches to choosing a representative steady-state power. Using the above validation fill as an example, the temperature of the 1^{st} ferrite yoke, at the end of the cycle, is 78°C (Fig. 3, yellow dashed line). The peak power deposition of the fill (120 W) would give a steady-state yoke temperature of 109°C (Fig. 5). This is a very pessimistic result because this power is only present at the start of the cycle and then reduces due to a decrease in beam intensity. In addition, due to the long thermal-time constant (~20 hours) of the MKIs, many hours are needed to reach steady-state conditions. Alternatively, the average power of the fill (91 W) would give a steady-state yoke temperature of 91°C (Fig. 5).

Predicted Temperatures for Future Operation

Based on the long fill of July 2016 (Fig. 3), and scaling the number of bunches to 2808, the maximum temperature expected during Run 2 is 107°C [7], which is below the Curie point. The predictions presented in this paper for HL-LHC are carried out for 25% more power deposition than expected: this is to give a safety margin. The temperature of the hottest ferrite yoke, for different operation scenarios, can be estimated using Fig. 5: for future operation of HL-LHC,

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the expected temperature is 291°C, well above the Curie point. However the power (616 W) corresponds to the peak power expected, which is a very pessimistic approach as it has been commented.

COOLING ALTERNATIVES

Increased Thermal Emissivity of the Vacuum Tank

As a result of the low thermal emissivity of the internal surface of the MKI vacuum tanks, cooling of the ferrite yoke by thermal radiation is presently limited [8]. Extensive research has been carried out to find a high emissivity coating which is compatible with ultra-high vacuum, thermal bake-outs and high voltage and does not peel or flake. Several surface finishes have been considered: laser treatment, carbon coating [9], multilayer optical coatings deposited by magnetron sputtering, developed by Polyteknik AS [10], and coatings deposited by thermal spray (plasma spray and flame spray) [11]. However, although increasing the emissivity reduces both the maximum temperature and the thermal time-constant, so that the yokes cool down more rapidly, the temperatures are not reduced enough (for HL-LHC the highest yoke temperature is reduced from 291°C to 176°C, still above the Curie point). Hence other cooling schemes have been studied.

Removal of the Bake-out Jackets

Historically, bake-out jackets are left in place on the MKIs in the LHC tunnel: this is in case there is a need for an in-situ bake-out since there is insufficient space to install them in the tunnel. However the jackets also act to thermally isolate the MKIs vacuum tanks from the local environment. For improving heat extraction from the magnets it is recommended that the jackets are removed: predictions show that the ferrite yoke temperature decreases by 7% for a given power deposition. Alternatively, for a given temperature, the power deposition can be 18% higher without jackets. The following studies, regarding alternative cooling schemes, do not model bake-out jackets. For HL-LHC, the temperature of the hottest yoke would be reduced from 291°C to 267°C.

Cooling of the Ferrite Yokes

One alternative is to cool the ferrite yokes with a cold plate. This plate should be a good thermal conductor but also electrically insulating as the ferrite is at pulsed high voltage. A potential material is Aluminium Nitride [12, 13]. Predictions show that if only the first yoke is cooled like this, its temperature will be reduced from 267°C to 110°C but the subsequent yokes approach the Curie temperature. Hence, it would be necessary to cool down the first and the third ferrite yokes to ensure that all of them remain below the 125°C. However, additional cooling is required for the ferrite rings as their temperatures are otherwise predicted to exceed their Curie point (200°C and 250°C for 4M2 and 4B3, respectively [4]).

Cooling of the Ferrite Rings

Predictions show that, with the beam screen design implemented during LS1, cooling the rings to 15°C is not enough: the ferrite yokes are still above the Curie temperature (Fig. 6, blue continuous line). Hence, there are ongoing studies to reduce the power deposition in the ferrite yokes by decreasing the beam screen overlap length [6]: this would potentially reduce the power deposition in the first ferrite yoke by a factor of 9.5. However, the power in the hottest ring is increased by a factor of 31. Without cooling, the design change reduces the predicted first ferrite yoke temperature from 267°C to 216°C (Fig. 6, orange continuous line). Nevertheless, the high temperature of the first yoke is caused mainly by the heat conducted and radiated from the ferrite rings, where the predicted temperatures are ~500°C. Cooling the rings reduces drastically the temperature of the ferrite yokes too: as shown in Fig. 6 (orange dotted line), if the rings are cooled at 15°C, the maximum temperature of the ferrite yoke is reduced to 41°C, which is well below the Curie temperature. A design of a water cooling system, for the ferrite rings, is currently under development. A prototype will be constructed for testing the performance before its installation in the MKIs in the LHC. Nevertheless the cooling system will be in a pulsed high voltage and UHV environment: hence one must ensure that the risk of liquid leakage into machine vacuum is negligible.

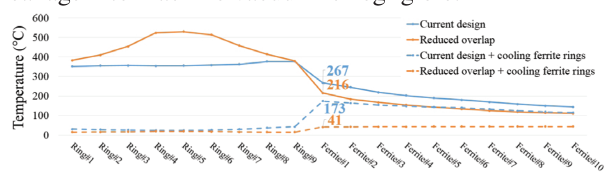

Figure 6: Maximum temperature for two overlaps of beam screen, without and with cooling of ferrite rings.

If the power deposition in the ferrite yokes is not reduced as much as expected, by reducing the overlap length [6], cooling of the rings alone may not be sufficient. Hence direct cooling of the rings combined with a cooling plate for the first ferrite yoke may be required. Considering this case for the present beam screen overlap, the predictions show that all the ferrite yokes are below 107°C.

CONCLUSIONS

A finite element model has been created using ANSYS in order to analyse the thermal behaviour of the MKI magnets: the model has been validated by comparing predictions with temperature measurements of MKIs in the LHC. Predictions show that for HL-LHC the temperature of the yokes will exceed the Curie point if further measures are not taken. Options have been studied to reduce the effect of beam induced heating: by reducing the beam screen overlap length the power deposited in the ferrite yokes can be decreased- for this scenario, installation of a cooling system on the ferrite rings is predicted to maintain all ferrites below their Curie temperature. In case the power reduction is not as high as expected, the first ferrite yoke must be cooled too. Currently a cooling system for the rings is under development.

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