BEAM INDUCED FERRITE HEATING OF THE LHC INJECTION KICKERS AND PROPOSALS FOR IMPROVED COOLING

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Abstract

The two LHC injection kicker systems produce an integrated field strength of 1.3 T·m with a flattop duration variable up to 7860 ns, and rise and fall times of less than 900 ns and 3000 ns, respectively. A beam screen is placed in the aperture of each magnet, which consists of a ceramic tube with conductors in the inner wall. The conductors provide a path for the beam image current and screen the ferrite yoke against wakefields. Recent LHC operation, with high intensity beam stable for many hours, resulted in significant heating of both the ferrite yoke and beam impedance reduction ferrites. For one kicker magnet the ferrite yoke approached its Curie temperature. As a result of a long thermal time-constant the ferrite yoke can require several hours to cool sufficiently to allow re-injection of beam, thus limiting the running efficiency of the LHC. Thermal measurement data has been analysed, a thermal model developed and emissivity measurements carried out. Various measures to improve the ferrite cooling have been simulated, including an improved emissivity of the vacuum tank and active cooling on the outside of the tank.

INTRODUCTION

The Large Hadron Collider (LHC) is equipped with two injection kicker (MKI) systems for deflecting the incoming particle beams onto the accelerator's equilibrium orbits. Counter-rotating beams circulate in two horizontally separated beam pipes. Each beam pipe is filled by 12 consecutive injections, at 450 GeV. The injected beam is first deflected in the horizontal plane by a series of septum magnets followed by a vertical deflection by four MKI systems [1]. The total deflection by the four MKI magnets is 0.85 mrad, requiring an integrated field strength of 1.3 T·m. Reflections and flat top ripple of the field pulse must be less than ±0.5%, a demanding requirement, to limit the beam emittance blow-up due to injection oscillations.

KICKER MAGNET

General

A low impedance (5 Ω) and carefully matched high bandwidth system meets the stringent pulse response requirements. An MKI kicker system consists of a multi-cell PFN and a multi-cell travelling wave kicker magnet [2], connected by a matched transmission line and terminated by a matched termination resistor (TMR). Each travelling wave magnet has 33 cells. A cell consists of a U-core ferrite sandwiched between HV conducting plates: two ceramic capacitors are sandwiched between a HV plate and a plate connected to ground (Fig. 1). The magnets are operated in vacuum of ~10^{-11} mbar. The complete magnet is baked out at 300°C before HV conditioning and tests.

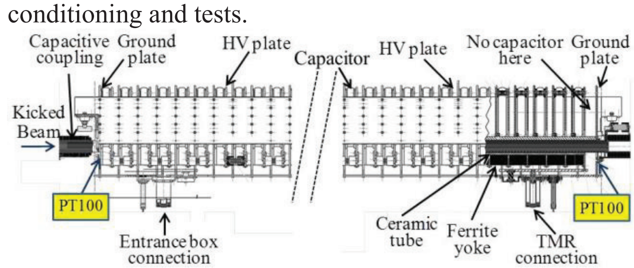

Figure 1: MKI kicker magnet.

Ferrite Yoke Temperature

With high LHC beam currents, integrated over the several hours of a good physics fill, the impedance of the magnet ferrite yoke can lead to significant beam induced heating. To limit longitudinal beam coupling impedance, while allowing a fast magnetic field rise-time, a ceramic tube with screen conductors on its inner wall is placed within the aperture of the magnet [3]. The conductors, which provide a path for the image current of the beam, are connected to the standard LHC vacuum chamber at one end and are capacitively coupled to it at the other end (Fig. 1).

The temperature of the ferrite yoke is measured indirectly using two PT100 temperature sensors, connected to a ground plate at each end of the magnet [3]. However, since the magnet is under vacuum, and as a result of indirect and non-ideal thermal contact between the PT100s and the ferrites of the magnet, the temperature indicated by a PT100 may be significantly less than the real yoke temperature.

Either 8C11 or CMD5005 ferrite is used for the MKI yoke: the data sheets for these ferrites show that the initial permeability starts to reduce for temperatures above ~100˚C. In addition to reducing the strength of the magnetic field, a decrease in the inductance of an MKI results in a decrease in the rise-time of the current in the TMR as well as a reduction in the propagation delay through the magnet. By pulsing the MKI magnets without beam, the rise-time of the current in the TMR is measured [3]. In addition a new diagnostic allows the delay of the magnet to be measured. These measurements allow the deduction as to whether or not the ferrite yoke is approaching/above the Curie temperature.

As a result of low emissivity of the inside of the MKI vacuum tanks the time-constants for the measured ferrite cool-down are relatively long (in the range 22 hours to 38 hours) which can result in delays of several hours before beam can be re-injected.

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THERMAL SIMULATIONS

Detailed thermal simulations have been carried out, using the code ANSYS, to study ferrite yoke temperature as a function of power deposition, emissivity (ε) of the inside of the vacuum tank, and external cooling of the vacuum tank. The simulations have been carried out using both 2D and 3D models. The 3D model consists of a single extruded bulk for the ferrite, resulting in a lower maximum ferrite temperature, with respect to reality, mainly because of enhanced axial heat flow. For a total power deposition of 100 W the predicted temperature of the central ferrite is ~8˚C higher than the end ferrite of the yoke. However, in reality, the longitudinal thermal conductivity is less efficient as small (vacuum) gaps are present between cells to allow for expansion during bake-out. On the other hand the 2D simulations consider a slice through the cross-section (Fig. 2): hence they assume no axial heat flow, and are more pessimistic.

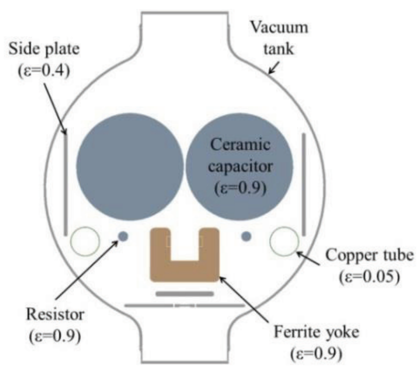

Figure 2: Slice through cross-section of an MKI magnet.

During mid-October 2011, when it was necessary to wait for an MKI to cool-down before re-injecting beam, the estimated beam induced power deposition was 100 W/magnet [4]: assuming, as a worst-case, that this power was all in the ferrite yoke this corresponds to 41 W/m. From the thermal simulations the emissivity of this tank was as low as 0.06. Figure 3 shows the predicted maximum ferrite temperature, for 45.5 W/m power deposition on the inside of the legs of the ferrite yoke, versus emissivity of the inside of the tank. The predicted yoke maximum temperature is proportional to $\varepsilon^{-0.16}$.

Time domain simulations have been carried out to determine the thermal time-constant, for ferrite yoke cool-down, versus tank emissivity. The density and specific heat capacity modelled for the ferrite are 5000 kg/m^3 and 750 J/(kg·K), respectively. An ambient temperature of 22˚C and external convection of 1.9 W/(m^2·K) are used. The predicted time constant, in hours, is also shown in Fig. 3 and is given by $(10/\sqrt{\varepsilon})$. Thus an increased emissivity has the benefit of both reducing the maximum ferrite temperature and the cool-down time-constant.

The inside of the MKI vacuum tanks, to be installed during the 2013-2014 long shutdown one (LS1), are being pre-treated by an ion bombardment technique, in an atmosphere of argon and oxygen [5]. Small stainless steel samples, of SS304L, have a measured post treatment emissivity of up to 0.6. A fully treated tank will soon be received: the ultra-high vacuum (UHV) performance of the tank will be verified and the emissivity measured.

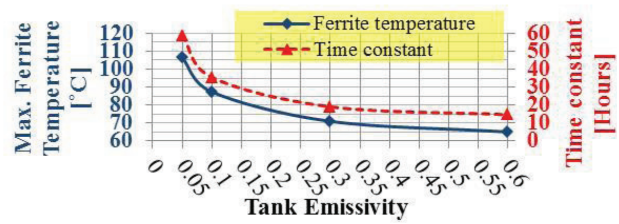

Figure 3: Predicted max. ferrite temperature, for a power deposition of 45.5 W/m, versus tank emissivity. The time-constant for cool-down of the ferrite yoke is also shown.

Figure 4 shows a plot of predicted ferrite temperature versus total power deposition per metre length of ferrite yoke, for various emissivities of the tank and degrees of cooling by convection (α). A standard bake-out jacket for an MKI has an α in the range 1.9-2.9 W/(m^2·K), thus 1.9 W/(m^2·K) is considered pessimistic. An MKI without a bake-out jacket is represented by α=7 W/(m^2·K).

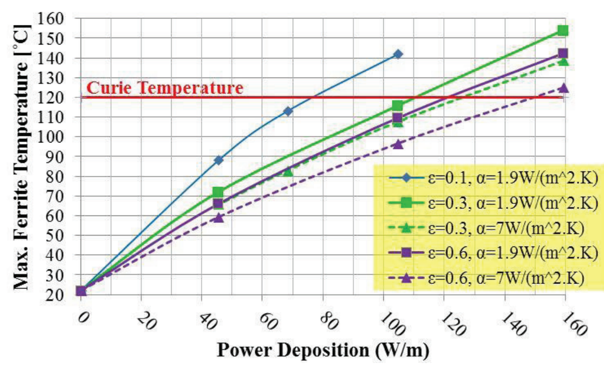

Figure 4: Predicted max. ferrite temperature versus total power deposition per m length of ferrite yoke, for various emissivities of the inside of the tank and convection (α).

The beam induced power deposition will be reduced by improved screening of the ferrite yoke from the beam [6, 7]. With a full complement of 24 screen conductors, after LS1, the expected power deposition for operation with 25 ns bunch spacing and 1.15×10^{11} protons/bunch is 12 W/m (30 W/magnet) [6]. Similarly, after the High Luminosity upgrade of the injector chain the deposited power is expected to be 70 W/m (170 W/magnet) [6]. Figure 4 shows that for a vacuum tank emissivity of 0.3, which should be obtainable by ion bombardment, the expected ferrite temperature will be well below the Curie temperature after LS1 (12 W/m).

Figure 4 also shows that for high power depositions, increasing the tank emissivity above 0.3 significantly decreases the ferrite yoke temperature. Furthermore the simulations predict that, with a power deposition of 105 W/m, the tank temperature, with a bake-out jacket, is in the range 45-55˚C: while with α=7 W/(m^2·K) this is reduced to 26-34˚C and the maximum ferrite temperature is decreased by ~13˚C. Thus water cooling of the outside of the vacuum tank may be implemented during LS2. In

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addition water cooling or the side plates, which are nominally at ground potential, is being considered.

MEASUREMENTS & PREDICTIONS

Observation in the LHC

During recent LHC operation the ferrite yoke of one magnet approached its Curie temperature. The ferrite yoke can require several hours to cool sufficiently to allow re-injection of the beam. For a power deposition of 45.5 W/m the predicted temperature drop of the ferrite yoke is ~8% of the temperature rise above ambient when the bake-out jackets are removed: hence the jackets were removed from two MKIs. The measured temperatures reduced by 5.5-7°C for these MKIs: this is ~15% of the measured temperature rise above ambient. Thus if the ferrite is close to its Curie point, the actual reduction in ferrite temperature, from removing the jackets, approaches 15°C. It is not yet understood why the reduction in temperature noted for these MKIs is up to twice the predicted values, but this suggests that the thermal insulation of the jackets is greater than modelled: the effect of increased thermal insulation will be studied.

There has also been unexpected heating of some toroidal ferrites, nine of which are mounted at each end of the ceramic tube, whose purpose is to damp low-frequency resonances [6]. Each set of nine toroids has two types of Ferroxcube NiZn ferrite, namely: 4M2 and 4B3, with a Curie point of 200˚C and 250˚C, respectively. One set of 9 toroids, at the capacitively coupled end of the beam screen (Fig. 1), occasionally reached 193˚C measured; all others remained below 100˚C measured. The source of the heating is still under investigation [6].

The ferrite yoke PT100, near to the capacitively coupled end of the beam screen, measured a temperature rise at the same time as the ferrite toroids increased in temperature: the increase in yoke temperature was ~20% of the toroid temperature rise. A 3D thermal model shows that, as a result of thermal radiation from the toroids, the predicted temperature rise at the position of the yoke PT100 is ~25% of the toroid temperature rise: however very little of the length of the ferrite yoke is actually affected. During LS1 the PT100s, for measuring yoke temperature, will be moved to each end of a side plate (Fig. 2) such that these PT100's are not influenced directly by thermal radiation from the toroids.

Measured Emissivity

Emissivity measurements have been carried out for materials used in the MKI, using an infra-red (IR) camera with a specified spectral range of 7.5-13 µm. The following emissivities have been measured: ferrite 0.92; ceramic capacitor 0.88; ceramic tube 0.87-0.94; "as-rolled" MKI stainless steel side-plate 0.41-0.49; untreated interior of an MKI vacuum tank 0.06-0.13.

The emissivity measurements on the interior of the MKI vacuum tank are particularly difficult to make because of restricted access, the concave shape and poor thermal conductivity. Several methods have been tried, including heating the whole tank and comparing the measurements with an IR camera to those of a thermocouple. Thus a new system has been developed for making measurements: a ceramic tube, with four screen conductors equally spaced around the inner wall, is placed in the tank. A dc current is passed through the four conductors to give a known power dissipation: the tank is under vacuum. It was assumed that convection would be negligible when the mean free path of the molecules inside the tank was equal to the characteristic length of the tank: measurements at low pressures confirm this. Simulations show that the outer surface of the ceramic tube has a reasonably uniform temperature distribution. The temperature of this outer surface, near the centre of the length of the tube, is measured using two PT100s and an IR camera. The IR camera is mounted on a Zinc Selenide viewport, which has a datasheet spectral transmission range of 0.7-15 µm and a transmission of more than 70%. Analysis of the measurement data indicates an emissivity of only 0.13-0.18 for the inside of a treated MKI vacuum tank, and thus the treatment will be repeated with a higher electric field within the tank.

CONCLUSIONS

Predictions from thermal simulations demonstrate that both the temperature of the ferrite yoke and the thermal time-constant for cool-down are reduced by increasing the emissivity of the inside of the MKI vacuum tank. Hence the MKI tanks are being pre-treated by ion bombardment. The goal for the emissivity is >0.3: this, combined with 24 screen conductors and cooling of the outside of the tank, is expected to maintain the temperature of the ferrite yoke below the Curie temperature for all foreseen LHC operation.

ACKNOWLEDGMENT

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