COOLING OF THE LHC INJECTION KICKER MAGNET FERRITE YOKE: MEASUREMENTS AND FUTURE PROPOSALS

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Abstract

LHC operation with high intensity beam, stable for many hours, resulted in significant heating of the ferrite yoke of the LHC Injection Kicker Magnets. For one kicker magnet the ferrite yoke approached its Curie temperature. As a result of a long thermal time-constant the yoke can require several hours to cool sufficiently to allow re-injection of beam, thus limiting the running efficiency of the LHC. The beam screen, which screens the ferrite yoke from wakefields, has been upgraded to limit ferrite heating. In addition it is important to improve the cooling of the ferrite yoke: one method is to increase the internal emissivity of the cylindrical vacuum tank, in which the kicker magnet is installed. This paper describes a method developed for measuring the emissivity of the inside of the tanks, which has been benchmarked against measurements of the ferrite yoke temperature during heat treatment in an oven and transient thermal simulations. Conclusions are drawn regarding an ion bombardment technique evaluated for improving emissivity without degrading vacuum properties. In addition initial concepts for improved cooling are presented.

INTRODUCTION

The Large Hadron Collider (LHC) is equipped with injection kicker (MKI) systems, each with four kicker magnets, 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 total deflection from 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 beam emittance blow-up [1].

MKI MAGNET

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 lodged in its inner wall is placed within the aperture of the magnet [2]. 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. Prior to Long Shutdown 1 (LS1) the MKIs generally had 15 screen conductors installed [2]. For one MKI magnet which limited LHC operation, the screen conductors were found not to be straight, but had a 90 degree twist over their length: based on impedance measurements the beam induced power deposition in this MKI was ~160 W/m, compared to ~70 W/m for a magnet with 15 straight conductors [3]. During LS1 the number of screen conductors is being increased to 24 [4, 5]: despite the enhanced beam intensity post LS1, the increased number of screen conductors is expected to limit the beam induced power deposition to ~50 W/m; hence, heating of the ferrite yoke of the MKIs is not expected to limit LHC operation. However, improved cooling of the ferrite yoke will likely be required in the long term - as the LHC beam parameters will be further pushed - in order to cope with an expected power deposition of ~200 W/m [3].

Each MKI kicker is a 33-cell travelling wave magnet [1], connected by matched transmission lines to a pulse forming network and terminated by a matched resistor. A cell consists of a U-core ferrite between two HV conducting plates, and two ceramic capacitors sandwiched between a HV plate and a plate connected to ground [4].

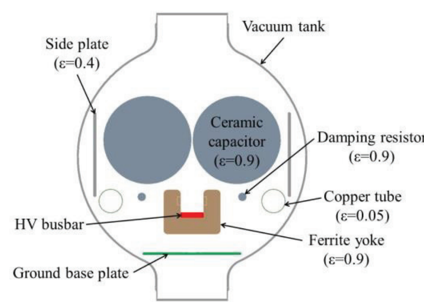

Figure 1: simplified schematic cross-section of an MKI kicker magnet.

An MKI magnet is installed in a vacuum tank (Fig. 1): cooling of the ferrite yoke is dominated by both direct and indirect thermal radiation between the yoke and vacuum tank. The yoke's ferrite has a high emissivity ($\varepsilon \simeq 0.9$ [4]). On the other hand the tanks (3,414 mm long, 540 mm diameter) housing the MKI magnets are reused from the LEP accelerator: they were utilized for 300 kV electrostatic separators and were thus electro-polished on the inner surface. The electro-polishing process, although good for achieving high vacuum, results in low emissivity, and hence poor radiative cooling of the MKI ferrite yoke.

Assessment of each tank's emissivity is of paramount importance for determining thermal performance. Previous attempts to measure the emissivity of the inside of the vacuum tank, using an infra-red (IR) lamp and an IR camera, gave inconsistencies and a wide range of values: thus a new method has been developed.

ISBN 978-3-95450-132-8

TANK EMISSIVITY

Measurement of Emissivity

A reliable measurement method is required, in order to both (i) confirm ANSYS simulations showing that poor emissivity of the inside of the MKI tank is a major contributor to the inefficient cooling of the ferrite yoke [4], and (ii) determine the effectiveness of employing various treatments to increase the emissivity. The method developed uses an MKI ceramic tube which is heated up using four nickel-chrome (NiCr) conductors on its inner wall. The 2.56 m long ceramic tube is installed in an MKI vacuum tank and pumped down to a pressure where convection is negligible (see below). The emissivity measurement is carried out with the tank installed in a temperature regulated room.

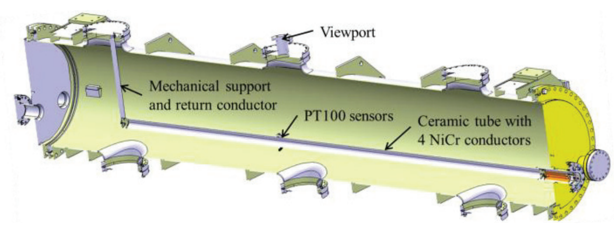

Figure 2: setup to measure emissivity of an MKI tank.

Cooling at the centre of the ceramic tube is mainly by thermal radiation to the MKI tank and thus the temperature of the ceramic tube is strongly dependent upon the emissivity of the inner wall of the tank. The four NiCr conductors are heated by passing a total current of ~30 A and the voltage is measured at the input to the tank: the power is ~140 W/m along the length of the tube. The ceramic tube is permitted to reach a steady-state temperature (~2 hours): the temperature near to the centre of the ceramic tube is measured using PT100s, clamped to the tube, and also by using an IR camera through a Zinc Selenide IR window [6]. The emissivity of the inner wall of the tank (ε_2) is calculated from the following formula for infinitely long concentric cylinders [7]:

$$Q_{12} = \frac{A_1 \cdot \sigma \cdot \left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{1-\varepsilon_2}{\varepsilon_2}\left(\frac{r_1}{r_2}\right)} \qquad (1)$$

where Q_{12} is radiated power (W); A_1 is the surface area of the ceramic tube radiating power (m^2); r_1 is the outer radius of the ceramic tube (m); r_2 is the inner radius of the tank (m); T_1 is the steady-state temperature of the ceramic tube (K); T_2 is the steady-state temperature of the tank (K), ε_1 is the emissivity of the ceramic tube (0.88 [4]) and σ is the Stefan-Boltzmann constant.

The temperature T_2 is measured on the outer surface of the 5 mm thick tank, manufactured from SS304L: the actual temperature on the inner surface of the tank is calculated to be negligibly higher.

ANSYS 2D simulations have also been carried out to verify the emissivity of the inner wall of the vacuum tank calculated from eqn. (1): the predictions show that the actual (non-concentric) location of the ceramic tube has negligible effect and hence equation 1 can be used. To date, the above measurement technique has been used on eight electro-polished MKI vacuum tanks and the range of emissivities is 0.12 to 0.15 [6].

Convection is considered negligible once the free mean path (λ) of the molecules inside the tank is greater than or equal to the characteristic length of the tank volume [8]:

$$p = \frac{k_B T}{\pi d^2 \lambda \sqrt{2}} \qquad (2)$$

where p is pressure in the tank (Pa); k_B is the Boltzmann constant; T is temperature inside the tank (K) and d is diameter of the molecule of interest (e.g. $3.7 \cdot 10^{-10}$ m for oxygen). The characteristic length of the volume of the tank is defined as the ratio of the volume to the surface area, and is equal to ~0.14 m for the MKI vacuum tank.

For the emissivity measurements, eqn. 2 gives a pressure of 0.012 Pa (i.e. $1.2 \cdot 10^{-4}$ mbar) at ambient temperature. However, when the measurements are made, the MKI tanks do not have vacuum gauges installed; therefore, vacuum is measured close to the pump and after a vacuum valve (measured values range from $1 \cdot 10^{-5}$ to $1 \cdot 10^{-7}$ mbar). Pressure in the tank is expected to be higher than that measured by a factor ≤5 [9]. In order to determine the system's sensitivity to convection, a measurement has also been performed, where the vacuum valve was closed - thus the tank was not pumped - for a period of 40 minutes. The steady-state temperature (~150˚C, compared to ~90˚C at ambient pressure) was not influenced by the increase in pressure, thus showing consistency of the no-convection hypothesis. In a second test, the vacuum valve was closed for a period of 3 hours: when the valve was re-opened the pressure had increased by 2 orders of magnitude, to $2 \cdot 10^{-4}$ mbar, causing a reduction in the measured temperature by 3˚C.

Transient Simulation of Oven Bake-out

The complete MKI magnet is baked out, in an oven, to ~300°C: the bake-out permits the MKIs to achieve vacuum of ~10^{-11} mbar. In order to confirm both the thermal model of the MKI and the value of the emissivity of the inside of the MKI tank, as determined from the above measurement method, temperature data is recorded during the oven bake-out and compared with predictions from ANSYS, 2D, transient thermal simulations.

Prior to LS1 the two PT100 sensors, used for measuring the temperature of the MKI ferrite yoke, were installed on the end ground plates of the magnet. However, these locations were not ideal for thermal evaluation as they were a significant distance from the ferrite yoke and could also be influenced by nearby components [4]. Therefore, during LS1, they have been moved to a side-plate of the MKI magnet (Fig. 1): 2D ANSYS simulations, for radiative cooling of the ferrite, show that the side plates have a steady-state temperature approximately equal to the average of the ferrite and tank temperatures: this information will be used to set thermal interlocks [10] for post LS1 operation in the LHC. The temperature of the side-plate, as well as the tank

ISBN 978-3-95450-132-8

temperature, is logged during the bake-out. The tank temperature is used as an input to ANSYS simulations: the simulations are run for various emissivities of the inside of the tank and the predicted side-plate temperature compared with measurements. Figure 3 shows measured tank temperature, and both predicted and measured side-plate temperature for tank emissivities of 0.14 and 0.2.

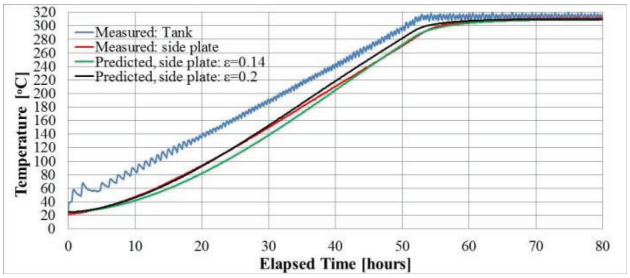

Figure 3: measured and predicted temperatures for bake-out of an MKI magnet.

Over the first ~30 hours of the bake-out the measured temperature of the side-plates correlates well with that predicted for a simulated emissivity of 0.2 for the inside of the tank. Between 30 and 60 hours of elapsed time the measured temperature of the side-plates correlates well with the predicted temperature for an emissivity of 0.14 (measured value) for the MKI tank. The reason(s) for the small discrepancy is not yet understood.

FUTURE PROPOSALS FOR HEAT REMOVAL FROM THE FERRITE YOKE

Increasing Tank Emissivity

ANSYS 2D simulations have been carried out for a power deposition of 250 W/m, i.e. 25% above the worst-case presently foreseen. The predicted ferrite temperature is ~250°C, for a low emissivity tank with no additional cooling: increasing the emissivity of the bottom half of the inside of the tank to 0.6 and using forced air cooling on the outside of the tank reduces the predicted ferrite temperature to ~150°C.

Ion bombardment, in an atmosphere of Argon and Oxygen, increased the emissivity of a sample of SS304L to 0.6 [4]. However applying the same technique to the MKI vacuum tanks, with a coaxial internal anode, did not result in a significant increase in the emissivity, even when treated for up to 10 hours: the reason for this is not yet understood, but may be due to the tank temperature being limited to 380˚C, during the treatment, to avoid damage to welds and vacuum flanges.

Other treatments for the inside of the tank are being considered, including carbon coating: tests on samples of SS304L show that a carbon coating of 2.5 µm thickness can increase the emissivity to over 0.6 [11].

Improved Cooling

The side and base plates of the magnet act as "radiation shields" between the capacitors and tank, and between the ferrite and tanks, respectively (Fig. 1). The "shields", even if they have an emissivity of 1 on both sides, significantly reduce the thermal flux that can be radiated [7], for given temperatures of the capacitors, ferrite yoke and tank. Thus, studies have been carried out regarding minimizing the surface area of these plates: removing the ground base plate reduces the predicted ferrite temperature to ~135°C.

In parallel with improving the emissivity of the tank, a cooling system has been studied for decreasing the temperature of the ferrite yoke. ANSYS 2D simulations show that a good thermal solution is to incorporate cooling channels in the MKI high voltage busbar, which is adjacent to the lower surface of the ferrite yoke (Fig. 1): predictions indicate a reduction in ferrite temperature to ~100°C.

ACKNOWLEDGMENT

The authors acknowledge the careful work of the vacuum team. In addition the authors acknowledge the help of the Electronics and Controls team, in particular R.A. Barlow and G. Florian, for their work in setting up the data logging systems.

REFERENCES

[1] M.J. Barnes, L. Ducimetière, N. Garrel, G.D. Wait "The LHC Injection Kicker Magnet", PAC'03, Portland, May 2003, p.1162, http://www.JACoW.org
[2] M.J. Barnes, F. Caspers, L. Ducimetière, N. Garrel, T. Kroyer, "The Beam Screen for the LHC Injection Kicker Magnets", PAC'06, Edinburgh, June 2006, p. 1508, http://www.JACoW.org
[3] H. Day, M.J. Barnes, F. Caspers, E. Metral, B. Salvant, "Beam Coupling Impedance of the New Beam Screen of the LHC Injection Kicker Magnets", Proc. of this conference, TUPRI030.
[4] M.J. Barnes et al., "Beam Induced Ferrite Heating of the LHC Injection Kickers and Proposals for Improved Cooling", IPAC'13, Shanghai, May 2013, p. 732, http://www.JACoW.org
[5] M.J. Barnes et al., "High Voltage Performance of the Beam Screen of the LHC Injection Kicker Magnets", Proc. of this conference, MOPME074.
[6] Z. Sobiech, "Cooling of LHC Injection Kicker Magnets Ferrite Yoke: Measurements and Future Proposals", Master Thesis, University of Technology and Life Sciences, Bydgoszcz, March 2014.
[7] T.L. Bergman A.S. Lavine, F.P. Incropera, D.P. Dewitt, Fundamentals of Heat and Mass Transfer, 7th edition, J. Wiley and Sons, Chapter 13.
[8] TV Team, "Tower 1 and 3 TV Chamber – Vacuum Profile Report", April 2005, glast.pi.infn.it/database/scripts/newsrv/NCRAnnex/Annex1_to_NCR_FM_INFN_PI_459.doc
[9] G. Bregliozzi, Private Communication, 31/01/2014.
[10] M.J. Barnes et al., "Upgrade of the LHC Injection Kicker Magnets", Proc. of IPAC'13, Shanghai, May 2013, p. 729, http://www.JACoW.org
[11] S. Jakobsen, Private Communication, 14/01/2014.