ANALYSIS OF FERRITE HEATING OF THE LHC INJECTION KICKERS AND PROPOSALS FOR FUTURE REDUCTION OF TEMPERATURE

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Abstract

The two LHC injection kicker magnet (MKI) systems must produce a kick of 1.3 T.m with a flat top 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 the magnets: the screen consists of a ceramic tube with conductors on the inner wall. The conductors provide a path for the image current of the high intensity LHC beam and screen the ferrite against wake fields. The conductors initially used gave adequately low beam coupling impedance however screen conductor discharges occurred during pulsing of the magnet; hence an alternative design with fewer screen conductors was implemented to meet the often conflicting requirements for low beam coupling impedance, fast magnetic field rise-time and good high voltage behaviour. During 2011 the LHC was operated with high intensity beam, coasting for many hours at a time, resulting in heating of the ferrite yoke of the MKIs. This paper presents an analysis of thermal measurement data and an extrapolation of the heating for future operation; in addition means are discussed for reducing ferrite heating and improving cooling.

INTRODUCTION

The Large Hadron Collider (LHC) is equipped with injection kicker (MKI) systems for deflecting the incoming particle beams onto the accelerator's circular trajectory. Two counter-rotating beams circulate in two horizontally separated beam pipes. Each beam pipe is filled by 12 batches of protons injected, at 450 GeV, successively on the machine circumference. Injection is carried out in the horizontal plane by a septum magnet followed by a vertical fast pulsed kicker system [1].

The beam to be injected approaches the kicker at an angle of 0.85 mrad, requiring a total kick of 1.3 T.m per system for deflection onto the central machine orbit. 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

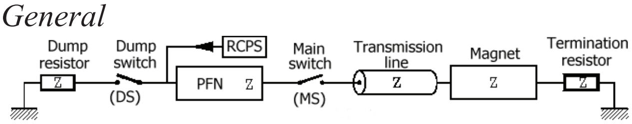

Figure 1: Schematic circuit of kicker system.

A low impedance (Z = 5 Ω) and carefully matched high bandwidth system meets the stringent pulse response requirements. The system (Fig. 1) 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).

Design

The travelling wave magnet consists of 33 cells [2]. 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. 2). The nominal inductance and capacitance per cell are 101 nH and 4.04 nF, respectively. The magnets are operated in vacuum of ~10^{-11} mbar. The complete magnet is baked out at 300°C before HV conditioning and tests.

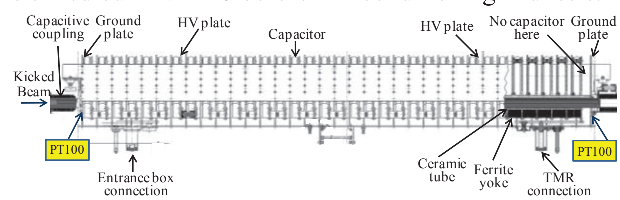

Figure 2: MKI kicker magnet.

With LHC beam, which has high peak current, the impedance of the ferrite yoke can provoke significant beam induced heating. To limit 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. 2).

In an early design the extruded ceramic tube had 24 nickel-chrome (80/20) conductors, each 0.7 mm x 2.7 mm with radiused corners, inserted into slots [3]: in the current version, nine conductors closest to the HV busbar are removed (Fig. 6, left) to avoid electrical discharge. However removing these has the undesirable effect of increasing beam impedance [3, 4].

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 (Fig. 2). The first ground plate, at the kicked beam upstream end, is connected to the adjacent HV plate via two ceramic capacitors (Fig. 2); these capacitors also provide a path for thermal conduction to the end ground plate. However, at the kicked beam downstream end, there are no ceramic capacitors between the last ground plate and the adjacent HV plate. This asymmetry between the PT100s results in a difference in measured temperature between the two ends of the magnet. In addition, since the magnet is under vacuum, there is a problem of obtaining good thermal contact with the PT100s.

Measured Temperature During LHC Operation

The LHC has been operated with high intensity beam, coasting for many hours at a time, resulting in heating of the ferrite yoke of the MKIs. Fig. 3 shows measured temperature for 7 MKIs during October 2011: the PT100s in magnet MKI2 D were not connected. The PT100 which registered the highest maximum temperature is plotted for each MKI: the legend is arranged in descending order of maximum temperatures. MKI8 D and MKI8 B measured maximum temperatures of 68˚C and 58˚C, respectively: the other magnet temperatures are clustered together and have a maximum of approximately 45˚C.

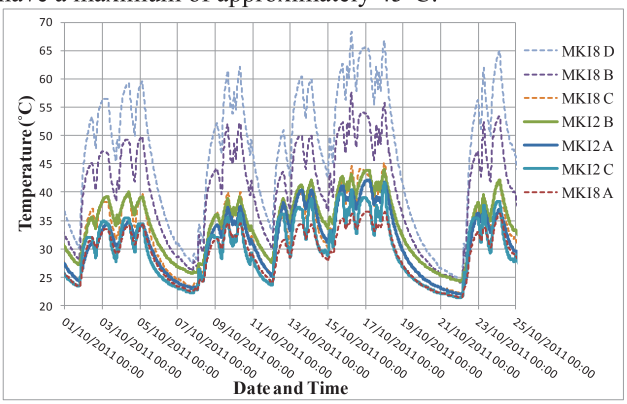

Figure 3: MKI kicker magnet measured temperatures.

The permeability of the ferrite yoke is dependent upon its 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. Detailed PSpice simulations of the kicker system show that a 1 % reduction in the inductance of an MKI results in a decrease in the rise-time (5 % to 95 %) of the current in the TMR (Fig. 1) by ~0.7 ns; there is also a decrease in the propagation delay through the magnet of ~3.8 ns. The waveform of the TMR is continuously measured and analyzed however, prior to January 2012, the electrical delay of the kicker magnets was not measured with precision during routine operation.

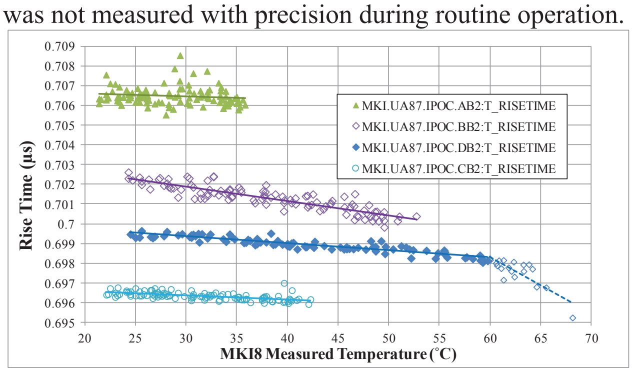

Figure 4: Rise-time of MKI8 TMR waveforms versus measured temperature, averaged for 7 pulses, during a SS.

In addition to normal operation of the MKI kicker systems, during which beam is injected into the LHC, there is a "SoftStart" (SS) mode: this mode is used when there is no beam in the LHC and no beam is being injected. SS was originally foreseen to ensure the kicker magnets are properly HV conditioned, prior to injection, but is now also used to determine the rise-time of the current in the TMR: Fig. 4 shows the measured rise-time, for SS operation, as a function of measured temperature for MKI8, during October 2011.

MKI8 A, B and C show a linear reduction of rise-time for increasing temperature: this is attributable to the temperature coefficient of the ceramic capacitors (approx. −800 ppm/°C). MKI8D shows a linear reduction in rise time up to ~60°C: above ~60°C the rate of reduction increases. Thus a measured temperature of 60°C is thought to correspond to a ferrite yoke temperature, near to the beam aperture, of ~100°C. The thermal time-constant for the measured ferrite cool down is relatively long: 25 hours for MKI8D (Fig. 3).

Extrapolation of Measured Temperature

A simple empirical model of ferrite heating and cooling, based on observations with different beam intensities during 2011, has been used to forecast future MKI heating and the duration of waiting time, for the ferrite to cool down to below the Curie temperature, for injection. Assuming that the hottest magnet ferrite should not exceed 62°C (measured), for injection and that the yoke reaches steady-state before the beam is dumped:

- for $1.7x10^{11}$ protons/bunch, 50 ns bunch spacing and 1380 bunches, peak measured temperature would be 70°C with ~4.5 hours to cool to 62°C;
- for $1.15x10^{11}$ protons/bunch, 25 ns bunch spacing and 2808 bunches, peak measured temperature would be 69°C with ~4 hours to cool to 62°C;
- for $4x10^{11}$ protons/bunch, 50 ns bunch spacing and 1380 bunches, peak measured temperature would be 100°C with 15 hours to cool to 62°C.

The extrapolated temperatures and cool down times, for higher intensity operation, would limit availability of the LHC. Thus alternative MKI designs will be required for the future to permit good availability of the LHC.

ALTERNATIVE DESIGNS

Ferrite Curie Temperature

Ferrite with a Curie temperature 50°C greater than that presently used for the yoke would permit high-intensity beam operation with better availability. The effect upon vacuum, in the kicker magnet tank, has been evaluated by plotting pressure versus measured temperature, during the period of October 18^{th} to 22^{nd} 2011, when there was no beam and the ferrites were cooling down (Fig. 3).

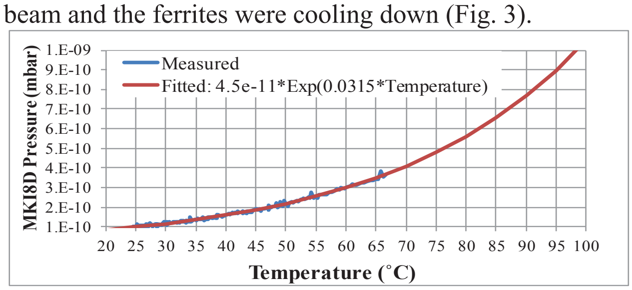

Figure 5: MKI8D pressure versus measured temperature, during the period of October 18^{th} to 22^{nd} 2011, without beam, together with a fitted curve.

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A curve has been fitted to the measurements to permit extrapolation to higher temperatures (Fig. 5): at 100°C measured the pressure in the tank is expected to be ~3 times greater than for present operation, which would result in an increased and probably unacceptable sparking rate. Hence higher Curie temperature ferrites have not been considered further.

Beam Screen Design

The current generation of ceramic tubes generally has 15 screen conductors installed (Fig. 6, left). A number of alternative designs are under consideration which could allow the full complement of 24 conductors to be installed, and thus reduce beam induced heating by a factor of ~3 [3, 4]. Fig. 6 centre shows a new generation of screen conductor which has a cylinder, with rounded ends, welded on: this will significantly reduce the electric field strength at the capacitively coupled end of the conductors. A ceramic tube has been modified to allow 19 new generation screen conductors to be used in the highest voltage region and 5 unmodified conductors in the lowest voltage region. This will be tested in a kicker magnet this summer. A possible next generation ceramic tube, with closed slots (Fig. 6, right), to prevent electrical breakdown between adjacent conductors, is being prototyped in industry. However, extruding a 3 m long ceramic tube with closed slots is very challenging: in addition beam impedance issues are under study [4].

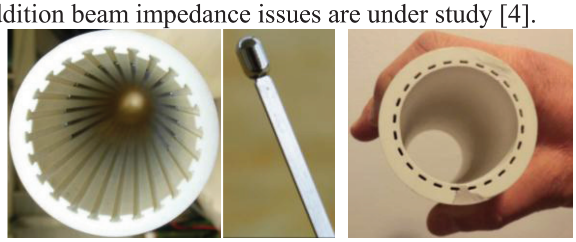

Figure 6: Current generation of ceramic tubes with 15 screen conductors installed (left); new generation screen conductor with rounded end-piece (centre); possible next generation ceramic tube with closed slots (right).

In addition, PSpice simulations have been carried out to assess the effect of metallizing the inside diameter of a MKI ceramic tube with ~1 µm of titanium. The predicted rise time increases from 805 ns for 24 screen conductors, 0.5 % to 99.5 %, to 4.5 µs: this is presently considered an unacceptable increase.

Thermal Considerations

The estimated beam induced power deposition in the ferrite yoke, during mid-October 2011, based on beam coupling impedance measurements and predictions [4] and a measured beam spectrum, is 3.5 W per each of the 33 magnet cells. As a result of the MKI magnet being under vacuum, convection does not contribute to cooling of the ferrite yoke. Many of the parts of the MKI magnet are materials with low thermal conductivity; hence the major contribution to cooling of the yoke is by thermal radiation. The cooling of a body due to thermal radiation can be approximated using the Stefan–Boltzmann law supplemented with a "gray-body" emissivity (≤1). Fig. 7 shows a plot of steady-state temperature of the yoke, for an assumed effective surface area of the ferrite in a cell of 0.05 m^2 and a vacuum tank temperature of 20˚C, versus "gray-body" emissivity: a yoke temperature of 375˚K – which is the temperature at which the ferrite initial permeability starts to reduce – results from an emissivity of 0.1. Subsequently measurements were made on various materials of the MKI, with the following results for emissivities: inside of two tanks 0.07 to 0.13; ferrite 0.92; ceramic capacitor 0.88.

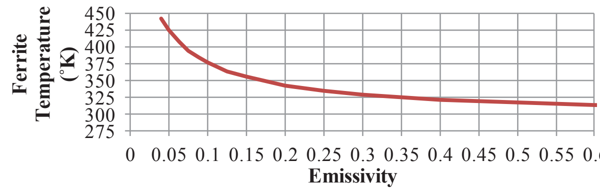

Figure 7: Steady-state temperature of ferrite yoke versus "gray-body" emissivity.

The measured emissivity of the inside of the vacuum tank is in good agreement with the estimated value that would give a ferrite temperature of 100˚C (Fig. 7). In addition Fig. 7 shows that a small difference of the emissivity, either side of 0.1, can have a significant effect upon the ferrite temperature. Thermal simulations have commenced to determine the most important parameters for improving ferrite cooling. Also means of increasing the emissivity of the inside surface of the vacuum tank, without unduly degrading vacuum quality and HV behaviour, e.g. ion bombardment, have commenced.

CONCLUSIONS

During operation of the LHC with high intensity beam, coasting for many hours at a time, the ferrite yoke of one magnet heated to the Curie point. It is undesirable to operate a ferrite, with a higher Curie point, at an increased temperature as higher pressure would result in an elevated risk of electrical breakdown. Various means of reducing beam induced heating, by incorporating more screen conductors, are being considered. In addition improved cooling of the ferrite yoke is being investigated.

ACKNOWLEDGEMENTS

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