BEAM COUPLING IMPEDANCE OF THE NEW BEAM SCREEN OF THE LHC INJECTION KICKER MAGNETS

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Abstract

The LHC injection kicker magnets experienced significant beam induced heating of the ferrite yoke, with high beam currents circulating for many hours, during operation of the LHC in 2011 and 2012. The causes of this beam induced heating were studied in depth and an improved beam screen implemented to reduce the impedance. Results of measurements and simulations of the new beam screen design are presented in this paper: these are used to predict power loss for operation after long shutdown 1 and for proposed HL-LHC operational parameters.

INTRODUCTION

The injection kicker magnets (MKIs) are fast pulsed transmission line kicker magnets, with a ceramic tube inserted into the ferrite yoke: this supports a number of screen conductors, designed to provide a good conducting path for the image currents of the circulating beam. One end of the screen is directly connected to the beam pipe whilst the other is capacitively coupled to the beam pipe in order to preserve the fast field rise time of the magnet. The initial design foresaw using 24 equally spaced screen conductors, however poor HV performance necessitated that the 9 closest to the HV busbar be removed, leaving a large section of the ferrite yoke unscreened. During the 2011 and 2012 runs of the LHC, high temperatures were observed in several devices in the LHC, including the MKIs [1], which was attributed to beam induced heating. This heating was observed to raise the temperature of the ferrite yoke of one of the MKIs close to its Curie point during fills, thereby necessitating waiting times of several hours for the ferrite to cool before safe injection could be carried out [1]. A magnet with an improved beam screen was inserted during technical stop 3 (TS3) (September 12), replacing the MKI8D which was measured to have the highest temperature [2]; the replacement magnet was subsequently shown to have the lowest temperature of all injection kickers in the LHC.

Building on this success a new design has been proposed to satisfy competing needs of low rates of electrical breakdown, during magnet pulsing, and a low beam coupling impedance to reduce the power lost into the structure by wakefields; in addition to meeting strict requirements for magnet operation for field rise time and flat top ripple [3].

NEW BEAM SCREEN DESIGN

The new screen involves a redesign of the capacitively coupled end of the beam screen to reduce the electrical field, due to the induced potentials on the screen conductors during magnet pulsing. This reduced electric field decreases the possibility of surface breakdown on the internal face of the ceramic tube allowing additional screen conductors to be inserted, where previously they had been removed due to being located in regions of high electric field, providing complete screening of the ferrite yoke of the magnet. See [4] for more information on behaviour relating to surface flashover.

IMPEDANCE MEASUREMENTS

In order to observe the effect of manufacturing tolerances between kicker magnets, and as part of the campaign to characterise the impedance of all devices placed into the LHC, each of the MKIs with the new beam screen has its longitudinal beam coupling impedance measured following assembly. These measurements are carried out using the resonant coaxial wire method [5], a measurement technique that turns the device under test (DUT) into a coaxial resonator with a weak external coupling. This permits very sensitive measurements of the impedance of the DUT to be made at the expense of poor frequency resolution. The real component of the longitudinal beam coupling impedance of an example of the new design, as well as for an MKI before LS1 (with 15 screen conductors), and the MKI8D before TS3 (a twist existed in the ceramic tube exposition).

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A comparison of the beam coupling impedance for each method is shown in Fig. 5. The frequency domain data for the time domain gated measurement is processed to give a beam coupling impedance: it can be seen that there is a large DC offset, caused by the loss of transmitted energy by the gating of the signal. The resistively matched measurements give good results below \( \approx 500 \text{ MHz} \) but the residual mismatch in the system (characteristic impedance of \( Z_{DUT} \approx 270 \text{ } \Omega \)) was matched using a carbon film resistor of \( 220 \text{ } \Omega \) which caused large oscillations which mask the true impedance. It can be seen that although the gated and matched network measurements give useful information, particularly the presence of lower frequency impedance, the absolute magnitude is not necessarily meaningful.

**POWER LOSS**

To determine the temperatures reached during operation of the MKI under various operational conditions of the LHC it is necessary to calculate the power lost by the beam into the MKIs due to beam-rise-wakefield interactions. Assuming \( M \) equi-spaced, equal populated bunches in a circular machine, power loss is calculated using Eqn. 1, where \( f_0 \) is the revolution frequency, \( \omega_0 = 2 \pi f_0 \), \( e \) is the charge of an electron, \( N_b \) is the number of particles per bunch, \( \lambda(\omega) \) is the beam current spectrum, and \( \text{Re}(z_{||}(\omega)) \) is the real component of the longitudinal beam coupling impedance. \( \lambda(\omega) \) is highly dependent on the bunch profile, especially the bunch length \( t_b \). The bunch separation is defined by \( \tau_{sep} \).

\[
P_{loss} = 2 (f_0 e M N_b)^2 \sum_{n=-\infty}^{\infty} \left| \lambda(p M \omega_0) \right|^2 \text{Re}(z_{||}(p M \omega_0))
\]

(1)

The power losses are calculated assuming the parameters shown in Table 1, representing the LHC operational parameters before long shutdown 1 (LS1), after LS1 and covering two upgrade paths for High-Luminosity LHC (HL-LHC) using 50ns or 25ns bunch spacing. The power loss for 15 screen conductors (as most MKIs prior to LS1) and with the new design with 24 screen conductors (as all MKIs will have post-LS1) is shown in Table 2. The new beam screen design will dramatically reduce the power lost into the MKIs, from 68 W pre-LS1 to between 34-52 W.

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after LS1 - a reduction of 20-50%. A range is given due to the variation between the MKIs with the new design. The proposed HL-LHC parameters, with a higher beam current, will cause the power loss to increase significantly again - such that the power loss even exceeds the power loss experienced by the MKI8D before TS3 (∼160 W) - indicating that heating may become a problem again if steps aren’t taken to remedy the situation [7].

**FUTURE PLANS**

Given the possibility of further heating problems in the MKIs under HL-LHC parameters, even with the new beam screen design, efforts are being made to increase the rate of power evacuation from the ferrite yoke by improving the ability of the magnet to radiate heat [7]. In addition it’s being considered how to further reduce the beam-induced power loss to the structure. If the ferrite yoke is well screened (as it is with the new beam screen design) the resonant impedance and beam-induced heating, demonstrating that there will be a substantially lower power loss into the magnets after LS1 is finished. The source of the high temperatures of MKI8D was found to be due to a twist in the ceramic tube, causing a power loss of ∼160 W, compared to 68 W for most magnets. Calculations for HL-LHC predict that heating of the device may again become a problem and solutions are discussed with preliminary results shown. In addition some comments on different beam impedance measurement methods are given relating to their use on low beam coupling impedance devices, including benefits and drawbacks in this situation.

**REFERENCES**

3. M.J. Barnes et al., Upgrade of the LHC Injection Kicker Magnets, IPAC’13, Shanghai, China, MOPWA030.