STUDIES OF IMPEDANCE-RELATED IMPROVEMENTS OF THE SPS INJECTION KICKER SYSTEM

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Abstract

The injection kicker system for the SPS consists of sixteen magnets housed in a total of four vacuum tanks. The kicker magnets in one tank have recently limited operation of the SPS with high-intensity beam: this is due to both beam induced heating in the ferrite yoke of the kicker magnets and abnormally high pressure in the vacuum tank. Furthermore, operation with the higher intensity beams needed in the future for HL-LHC is expected to exacerbate these problems. Hence studies of the longitudinal beam coupling impedance of the kicker magnets have been carried out to investigate effective methods to shield the ferrite yoke from the circulating beam. The shielding must not compromise the field quality or high voltage behaviour of the kicker magnets and should not significantly reduce the beam aperture: results of these studies, together with measurements, are presented. In addition, an analysis to identify the causes of abnormal outgassing are presented.

INTRODUCTION

In CERN's Super Proton Synchrotron (SPS), fast Kicker systems are used for injection and extraction of the beam into and from the accelerator [1]. For the injection kicker (MKP) two different types exist, namely MKP-S and MKP-L. The MKP-S has an aperture of 100 mm wide by 61 mm high and the MKP-L aperture is 141.5 mm wide by 54 mm high: the width is the distance between the high voltage (HV) and return busbars. The two apertures are used to both meet optics requirements and provide the required deflection, within the constraints of available length and demands on the pulse generators. The MKP magnets are transmission line type, constructed of multiple cells. Each cell consists of a C-core ferrite between two high voltage (HV) metallic plates: ground plates interleave between the HV plates to provide the required capacitance.

During 2015 operation with high intensity beams (scrubbing) the MKP-L kicker magnet heated up significantly: the measured temperature rise is a factor of ~5 higher than for the MKP-S. The larger beam induced power deposition in the MKP-L is due to its relatively high beam coupling impedance, which results from the reduced height of the aperture (the legs of the ferrite are closer to the circulating beam) and the greater aperture width, compared to the MKP-S. The temperature rise in the MKP-L ferrite yoke results in increased outgassing of the ferrite and hence a relatively high pressure (Fig. 1) – which increases the probability of electrical breakdown.

The MKP-L tank was replaced during the Christmas shutdown of 2014-2015. The replacement MKP-L was upgraded to have temperature sensors and so called transition plates, which electrically connect the beam-pipe to the end ground plates of the magnet – the plates significantly reduce RF coupling into the vacuum tank and losses in the ferrite yoke. The temperature is measured on the return busbar and hence the temperature of the ferrite yoke will be different to this.

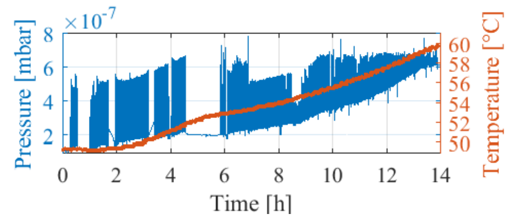

Figure 1: Measured temperature and pressure in the MKP-L tank, during a 25 ns scrubbing run from 19/06/2015.

OPERATIONAL EXPERIENCE

Pressure Versus Temperature

The measurements shown in Fig. 1 are for a scrubbing run with 25 ns bunch spacing, up to $2x10^{11}$ protons per bunch, injected, and 288 bunches total. The purpose of a scrubbing run is to condition equipment which is close to the beam, by decreasing the Secondary Electron Yield (SEY) of surfaces, and therefore reducing or eliminating fast pressure rise due to beam. Figure 1 shows a measured temperature rise of ~10°C during the ~14 hour scrubbing run, and a pressure of up to $7x10^{-7}$ mbar for a significant time. A high pressure increases the probability of an electrical flashover during pulsing (i.e. during injection). In addition, the temperature of the ferrite must remain below the Curie temperature so that injected beam is not mis-kicked.

The influence of temperature upon pressure has been obtained by noting the pressure when there is no fast vacuum activity, e.g. between 5 and 5.5 hours in Fig. 1: this has been carried out over intervals of several months, starting from March 2015 (Fig. 2).

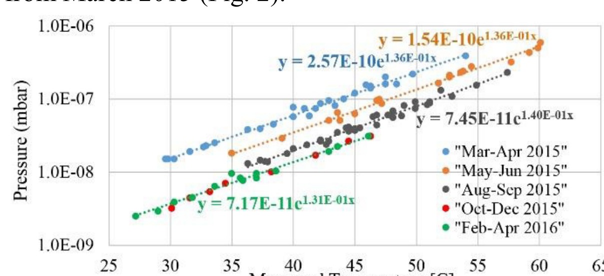

Figure 2: Pressure versus measured temperature, for MKP-L, without circulating beam.

Figure 2 shows that for a given measured temperature, there has been a reduction in pressure by a factor of 4-5

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between Mar.-Apr. 2015 and Feb.-Apr. 2016. Thus a measured temperature of 50˚C, without beam, would be expected to give a pressure of 2.3x10^{-7} mbar during March 2015 and 5x10^{-8} mbar during April 2016.

Based on the curve-fits shown in Fig. 2, the pressure data shown in Fig. 1, for June 2015, has been corrected for temperature rise above 30˚C: the resultant curve is shown in Fig. 3 (green trace). During the cooldown from 60˚C measured, the green trace goes slightly negative, possibly indicating that operation at an elevated temperature has helped to reduce outgassing.

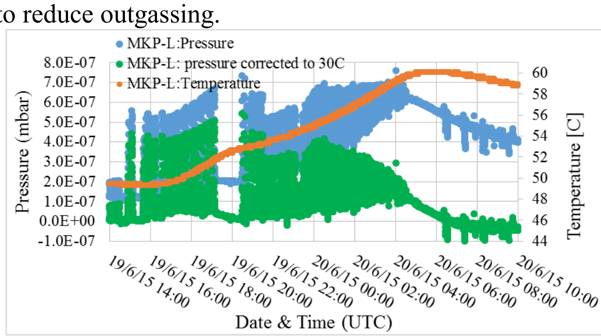

Figure 3: Measured temperature and pressure in tank MKP-L and pressure corrected to 30˚C (25 ns scrubbing).

Pressure and Intensity

Figure 4 shows the pressure corrected for temperature rise above 30˚C, for the 25 ns scrubbing run of June 2015, together with beam intensity. In general, the fast pressure rise and beam intensity curves have the same shape, indicating that the corrected pressure rise is attributable to multipacting: methods of reducing multipacting in kicker magnets are being considered [2]. The normalized pressure, corrected to 30˚C measured, is ~1x10^{-20} mbar/proton. A similar analysis for 25 ns scrubbing during March 2016 gives a normalized pressure of ~4x10^{-21} mbar/proton: thus the normalized pressure has reduced by a factor of ~2.5 since June 2015, as a result of conditioning.

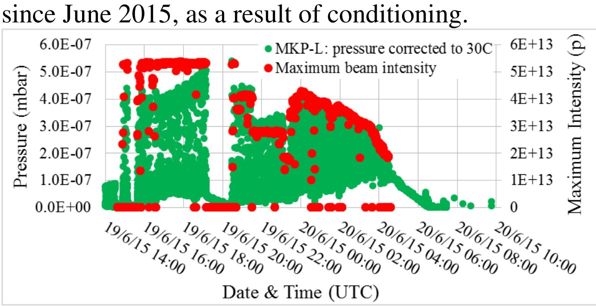

Figure 4: Pressure corrected to 30˚C, for MKP-L, and maximum beam intensity (25 ns scrubbing).

POWER DEPOSITION CALCULATION

Both simulations and measurements are used to assess the beam coupling impedance of equipment, including the kicker magnets. The temperature rise is proportional to the beam induced power deposition (ΔW) which is calculated from:

$$\Delta W = (f_0 e N_{beam})^2 \sum_{p=-\infty}^{p=\infty} \left(|\Lambda(p\omega_0)|^2 Re\left[Z_{||}(p\omega_0)\right]\right).$$

Where $Z_{||}$ is the longitudinal impedance, e is the charge of an accelerated particle, N_{beam} is the intensity of the whole particle beam and Λ is the beam spectrum rotating with the revolution frequency $f_0 = \omega_0/2\pi$. The beam induced power deposition is dependent upon both the real part of the beam coupling impedance and the spectrum of the beam. Thus, for given beam parameters, in order to reduce the temperature rise, the real part of the beam impedance must be decreased. For the power loss calculations, a bunch in the SPS is generally assumed to have a Gaussian distribution. The 25 ns/50 ns bunch spacing thus has a spectrum with 40 MHz/20 MHz lines weighted by a Gaussian distribution: this leads to significant spectral components up to ~700 MHz. Thus the impedance should be known up to this frequency.

CST SIMULATION MODEL

To predict the impedance of the MKP magnet, simulations have been carried out using CST Particle Studio and subsequently verified by measurements. A spare MKP-S magnet was available for measurements, and thus the MKP-S was initially simulated to verify the CST model. The verified model has then been used as the basis for the MKP-L model.

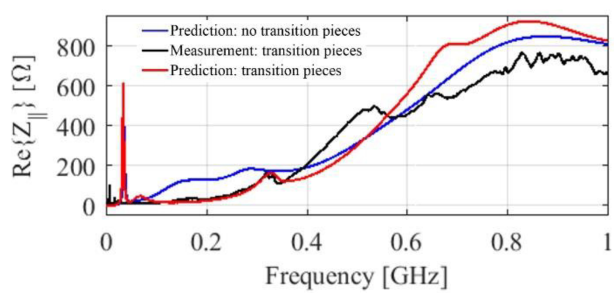

Figure 5: Comparison of MKP-S impedance simulations for two magnet models and impedance measurements.

The initial CST model of the MKP-S has been presented in [3-4]. As shown in Fig. 5 without transition pieces modelled the predictions had a significant discrepancy compared to the measurements with transitions pieces, over the first 400 MHz. Adding these transitions pieces to the model results in the red impedance curve in Fig. 5: for the first 400 MHz the simulated impedance of the updated model is in good agreement with measurements. The peak at 34 MHz occurs due to a TEM-mode in the simulations of the kicker magnet [5].

IMPEDANCE REDUCTION OF MKP-L

Offsetting the Magnet Relative to the Beam

The circulating beam is nominally in the centre of the aperture of the MKP magnets. The longitudinal impedance of these magnets can be reduced by offsetting the magnet such that the beam is closer to the ground busbar, allowing more beam image current to flow in this busbar. The maximum offset, for beam optic reasons, is 30 mm: CST simulations show that this offset would reduce the power deposition by ~30%, for high luminosity LHC. However, 30 mm offset could result in mis-injected beam hitting the kicker magnet – hence this option is not considered further.

Serigraphy

Serigraphy can be used to reduce the real impedance of a kicker magnet [6]: a silver paste is used to create a coupler structure, to shield the ferrite yoke from the beam. Current induced by the beam can flow on the serigraphy and hence the wakefields penetrating the ferrite are reduced in magnitude. The technique has already been successfully used on the extraction kickers of the SPS [6]. Serigraphy for the MKP kickers can reduce the real impedance of the kicker. However, to achieve sufficient coupling, the serigraphy fingers must extend over a significant portion of the length of the yoke (Fig. 6). Thus the serigraphy must cross the MKP-L HV plates sandwiching the ferrite cores: hence an insulation must be introduced between the magnet and the serigraphy. In reality it is expected that the serigraphy would be applied to alumina plates [2], however for the initial CST simulations vacuum was modelled.

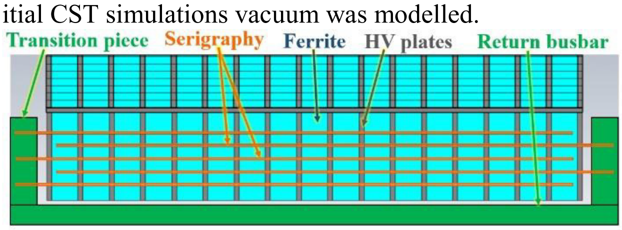

Figure 6: Longitudinal serigraphy for MKP-S kicker.

The CST predictions for the MKP-S kicker magnet with serigraphy show a relatively low real impedance up to 1 GHz. A predicted resonance peak occurs at ~15 MHz (Fig. 7). Measured real impedance, without and with serigraphy, are also shown in Fig. 7: the measurements of the MKP-S with a serigraphy inlay show a reasonable agreement with the predictions. Below 50 MHz the differences between measurements and simulations can be attributed to the inlay used: the insulation material (PCB for the measurements) influences the frequency of the resonant peak. Ideally the length of the serigraphy will be chosen such that the resonance peak is positioned between two 20 MHz lines of the beam spectrum. Predictions for the MKP-L with serigraphy show that the power deposition can be reduced by a factor of ~3 c.f. no serigraphy.

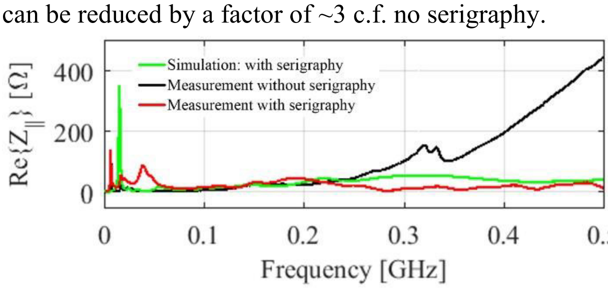

Figure 7: Comparison of simulation of MKP-S with serigraphy, measurement without serigraphy and measurement with serigraphy.

Thermal Model

Beam induced power deposition results in heating of the ferrite yoke. To ensure good performance, the temperature of the yoke must always remain below its Curie temperature, otherwise the beam would be mis-kicked. The MKP-L magnets installed during 2015 have temperature sensors: these cannot be installed in the aperture of the ferrite yoke, where the maximum temperature is reached, but are located on the return busbar. Transient thermal simulations of the MKP-L magnet have been carried out with ANSYS: Fig. 8 shows calculated power deposition in the existing MKP-L magnets, for the 25 ns scrubbing run of June 2015, together with the simplified profile modelled in ANSYS.

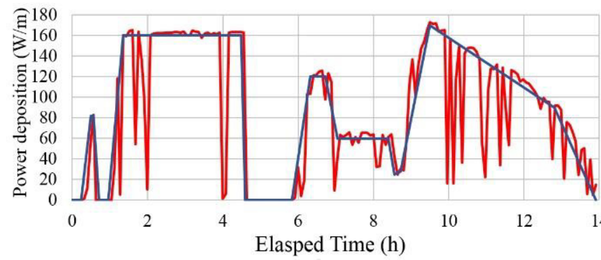

Figure 8: Power deposition for June 2015 25 ns scrubbing (red), and simplified profile for thermal simulations (blue).

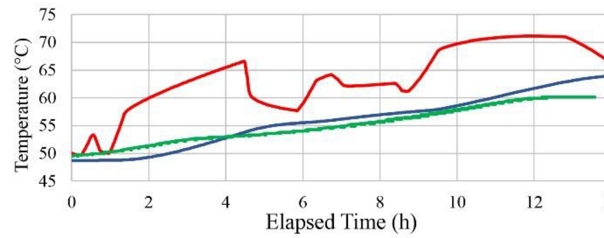

Figure 9: Predicted return busbar temperature (blue), measurements (green) and predicted ferrite temperature (red).

Figure 9 shows predicted and measured temperatures: there is good agreement between predicted (blue) and measured temperature of the ground busbar (green), which gives confidence in the predictions. The slight difference between the curves is probably due to the simplified heating profile modelled, as well as uncertainties in some thermal properties assumed. A ferrite temperature (red) of 71°C, which is well below the Curie temperature (120°C), is predicted for a measured temperature of 60°C. Ongoing studies include prediction of the ferrite temperature for the LHC injectors upgrade, required for reaching the goals of the high luminosity LHC.

CONCLUSION

Following replacement of the MKP-L magnets, at the start of 2015, there has been considerable outgassing in the tank during 25 ns scrubbing. Part of this is attributable to temperature rise due to beam induced heating of the ferrite yoke: this has now reduced by a factor of almost 5. Fast pressure rise seems to be attributable to multipacting – further measurements are required to verify this. The temperature rise can be significantly reduced by installing serigraphy in the aperture: studies will commence soon to determine how to do this while achieving good high voltage behaviour. Thermal predictions show good agreement with measurements, giving confidence in the simulations: predictions will be used to set interlock thresholds.

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