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BEAM INDUCED POWER DEPOSITION IN CERN SPS INJECTION KICKERS*

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Abstract

The SPS injection kicker magnets (MKP) were developed in the 1970's, before beam power deposition was considered an issue and before any advanced tools for analysing beam coupling impedance were available in their current form. These magnets are very lossy from a beam impedance perspective, and the beam induced power deposition is highly non-uniform. This is expected to be an issue during SPS operation with the higher intensity beams needed in the future for HL-LHC. There is an existing design, with serigraphy, that will mitigate the heating issues, which is presently being implemented on a prototype for test and measurement. Models have been developed to aid in predicting the safe operating regions until the upgraded MKPs are installed in the SPS: these are reported herein. A novel measurement technique is also presented to confirm the non-uniform power deposition in the ferrite yoke. Beam coupling impedance, power deposition, field rise time and field uniformity data are also presented for an upgraded, prototype, MKP.

INTRODUCTION

In CERN's Super Proton Synchrotron (SPS), a fast Kicker system (MKP) is used for injection of the beam into the accelerator [1]. Two different types of the MKP are used, 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 conductors. The two apertures are used to both meet optics requirements and provide the required deflection, within the constraints of available length and voltage and current demands on the pulse generators. The MKP magnets are transmission line type, constructed of multiple cells and operated in machine vacuum: the MKP-L has 22 cells.

The measured temperature rise of the MKP-L is a factor of ~3 higher than for the MKP-S: this is attributable to the relatively high beam coupling impedance of the MKP-L. The higher temperature has generally not been an issue, thanks to the sufficiently low beam intensities in the SPS but, in the advent of High Luminosity LHC, high beam induced heating is expected in the ferrite yoke of the MKP-L, which could result in its Curie point being reached. There is an existing design that mitigates the high heat load, in the MKP-L, which uses serigraphy [2, 3], which is planned to be installed in the SPS once it is available. Until then, however, the MKP-L needs to operate with higher beam intensities. Hence, extensive work has been carried out to develop accurate models of beam induced heating in the MKP-L, to aid in predicting safe operating regions until the upgrade is installed. However, the techniques developed are also applicable for generally modelling of beam induced heating in accelerator components.

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MODELLING BEAM INDUCED HEATING

The method of modelling the beam induced heating is based on the combination of electromagnetic simulations using CST [4] and thermal simulations [5] in ANSYS [6]. Although CST has functionality for thermal simulations, the need for a second software tool comes from the more diverse functionality that ANSYS can offer.

The broadband losses that kicker magnets typically manifest make the CST wakefield solver suitable for beam impedance and power deposition simulations. Figure 1 shows real impedance for the MKP-L kicker magnet, with and without serigraphy: the measured and predicted real impedances are in general in good agreement. The serigraphy consists of five silver fingers on each of two alumina plates, three fingers from one end of the plate and two from the other [2, 3]: the two sets of fingers are capacitively coupled together.

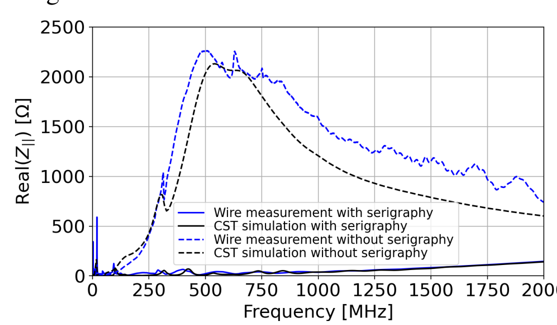

Figure 1: Predicted and measured real impedance, for the MKP-L, with and without serigraphy.

Figure 2 shows the normalized power deposition in the MKP-L magnet versus frequency, derived from predictions of the real beam coupling impedance (Fig. 1) and the beam spectrum with 3 ns bunch length (BL): a significant portion of the beam induced power deposition occurs between 250 MHz and 500 MHz. The results are post processed to be compatible for import into ANSYS, where they act as a heat source. This heat source can be scaled and varied in time to reflect power inputs corresponding to different beam intensities and bunch lengths, which makes the thermal modelling of actual accelerator runs realistic.

In addition to the development of the simulation methods and peripheral infrastructure that is necessary (post processing scripts etc), the models also require special attention:

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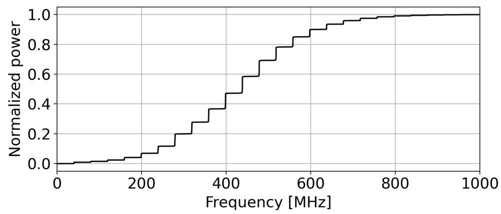

Figure 2: Frequency versus normalized power in the MKP-L. Beam parameters: 72 protons per bunch, 4 bunches, 25 ns spacing, 3 ns BL, no serigraphy.

geometry and material parameters are critical aspects of a representative model. When a device is in vacuum, one of the most uncertain aspects of the model are the thermal contacts between parts [5,7]: these are in practice very difficult to evaluate. Hence, the thermal contacts have been determined empirically through comparison of simulations with temperature measurements of the magnet while it was operating in the SPS. This simulation also incorporates a power input that varies in time, to better represent the actual beam intensity, acceleration, burn-off, etc.

POWER DISTRIBUTION

The beam induced power is not necessarily distributed uniformly inside the ferrite [8] and, hence, there might be 'hot spots' and significant temperature gradients. Such a region is of particular interest since it may be at a higher risk of mechanical cracking. There are indications of non-linear heating in the MKP-L, Fig. 3 shows an example, where the upstream end of the magnet appears to be heating up more rapidly than the downstream - in agreement with CST and thermal simulations: however, note the limited resolution of the downstream temperature measurement.

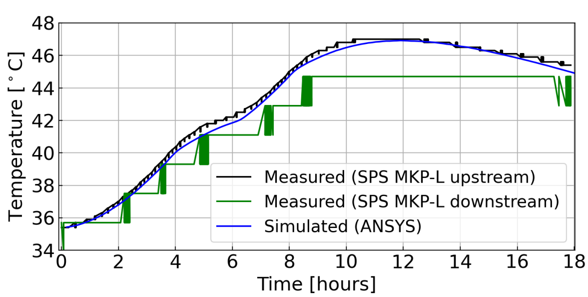

Figure 3: Simulated and measured temperatures.

Figure 4 shows the predicted longitudinal power distribution in the ferrite yoke of the MKP-L: each of the 22 ferrite yokes can be distinguished. It is clear that the upstream end of the yoke (far left), due to the higher power deposition, would heat-up more than the downstream end. This indicates that the operation of an unserigraphed MKP-L might be limited by the localized heating at the upstream end. To confirm the non-linear power deposition, a new type of measurement was devised. Similar to how beam coupling impedance measurements are made, using a coaxial wire [9], a network analyzer is connected to the two ends of a wire that is in the aperture of the device under test. The novel part is to also connect the electrical circuit of the magnet to the network analyzer, and in this way measure the device as a four port network. Hence, we can determine whether the fields from the 'beam' couple more strongly in to the electrical circuit at one end of the magnet than the other.

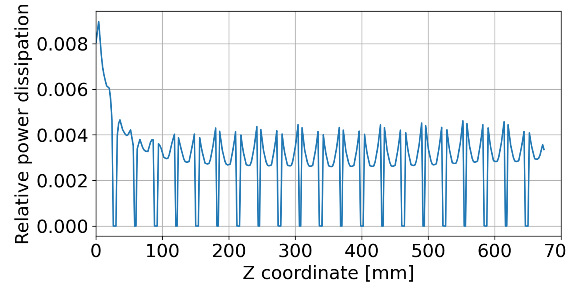

Figure 4: Predicted longitudinal power distribution in ferrite.

Figure 5 shows the measured transmission to the upstream and downstream circuit connectors: the coupling is significantly higher at the upstream end from ~220 MHz. Figure 2 shows that the highest power is predicted to be dissipated in the MKP-L from ~220 MHz. Although not unambiguous, since it is not an absolute measurement of coupled power, the results agree with the predicted skewed power distribution.

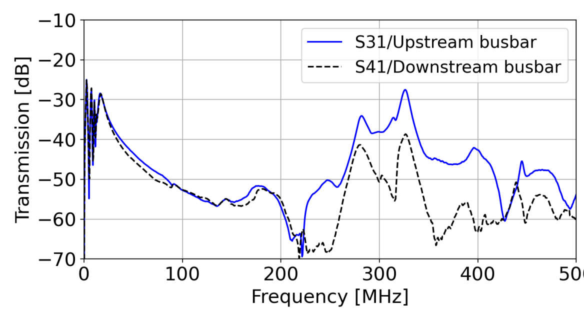

Figure 5: Four port measurement: power transmission to the upstream and downstream circuit connectors.

MAGNETIC FIELD

Predicted Field Homogeneity

Simulations were carried out, using Opera-2d [10], to evaluate the influence of the serigraphy upon magnetic field homogeneity in the aperture. These were frequency domain simulations: an equivalent circuit will be fitted to the Opera-2d predictions [11] and time domain simulations, which will include the transmission line nature of the MKP magnet, will be carried out using PSpice [12]. The MKP-L magnets are symmetrical around the x-axis: advantage is taken of this in the Opera-2d simulations (Fig. 6). The electrical resistivity of the conductors (Fig. 6, red regions) and serigraphy were modelled as $1.71 \times 10^{-6}\,\Omega\cdot$m and $2.64 \times 10^{-8}\,\Omega\cdot$m, respectively. The relative permeability of the ferrite yoke (Fig. 6, blue region) is modelled as 1640.

Figures 6(a), (b) and (c) show the predicted magnetic field homogeneity in the aperture, for 40 μm thick serigraphy, at 10 kHz, 100 kHz and 1 MHz, respectively. The field is normalized with reference to the magnetic flux density at the nominal beam centre (x = 75.75 mm, y = 0.0 mm): the white regions are outside of the specified ±2% homogeneity.

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The solid and dashed black lines show the required beam aperture, for the entrance and exit of the MKP-L system (4 magnets), respectively [13]. As a result of eddy currents, the homogeneity near to the serigraphy is degraded at higher frequencies: hence the ±2% homogeneity is not achieved locally (Fig. 6(c)). The concerned regions are small and will only influence the start of the flattop of the field pulse [14]: nevertheless, means of reducing the inhomogeneity are under study. These mitigating measures include reducing the width of the serigraphy finger above and below the beam centre and have this finger commence at the beam exit end of the magnet: however, the beam coupling impedance will need to be verified.

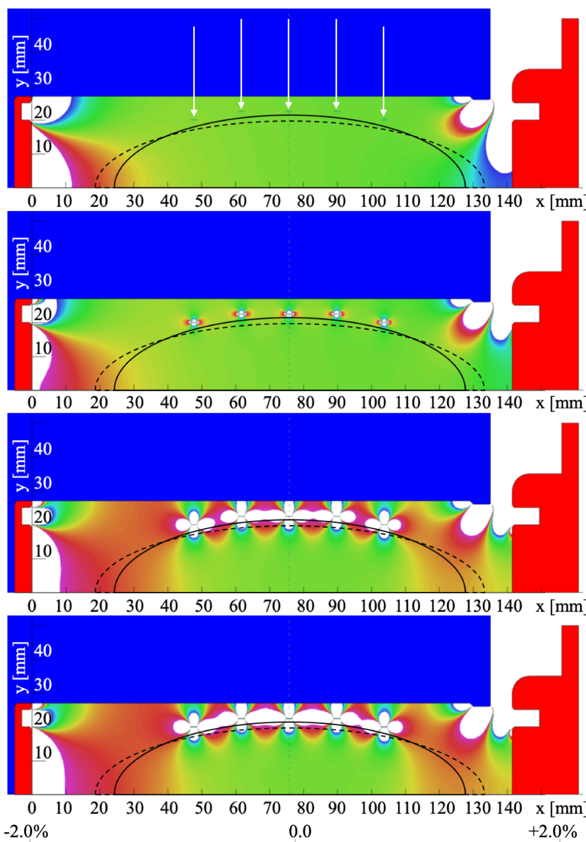

Figure 6: Predicted magnetic field homogeneity in the aperture. With 40 µm serigraphy: (a), (b) and (c) are for 10 kHz, 100 kHz and 1 MHz, respectively. (d) is for 80 µm thick serigraphy, at 1 MHz. The arrows show the positions of the serigraphy. The solid and dashed black lines show the required beam aperture, for the entrance and exit of the MKP-L system (4 magnets), respectively. The legend, at the bottom, gives the colour coding for the field homogeneity.

Figure 6 also shows that there is a small further degradation if the serigraphy is 80 µm thick (Fig. 6(d)), rather than the nominal 40 µm (Fig. 6(c)), at 1 MHz . However, once the prototype serigraphed alumina plates were available, the thickness of the serigraphy was measured mechanically and was in the range 20 µm to 30 µm. The end-to-end resistance of each serigraphy finger was also measured, and based on this and the manufactures specified resistance/□, the thickness is in the range of 15 µm to 20 µm. Thus, the field homogeneity should be better than shown in Fig. 6(c). CST simulations show that, for the nominal electrical conductivity of the serigraphy, adequate shielding of the ferrite from the beam is expected, even for thicknesses of 1 µm [15].

Measured Field

Measurements of field in the beam centre of the aperture have been carried out. The field probe, which consists of 2 parallel strips of copper, was adapted from another project [16]. The output of the probe was connected to an analogue integrator with a measured time-constant of 7.41 µs and the resultant signal recorded using a digital oscilloscope. The output of the integrator, corrected for droop due to the relatively fast time-constant, is shown in Fig. 7, with and without serigraphy in the aperture. The serigraphy reduces the magnitude of the field by less than 0.75% over the initial ~300 ns of the field flat-top. The small increase in field after ~400 ns is thought to be due to decaying eddy currents in the copper strips of the probe, thus allowing additional field to penetrate into the copper and, hence, increasing the effective cross-sectional area of the probe: it is planned to study this effect with Opera-2d.

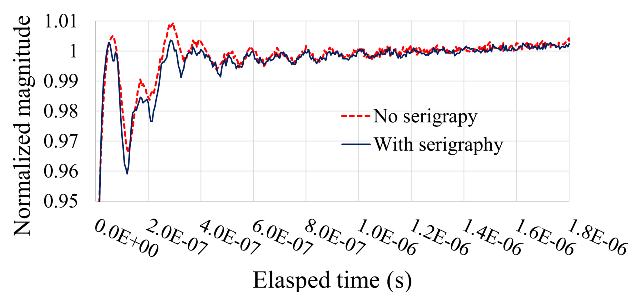

Figure 7: Measured field flattop with and without serigraphy.

CONCLUSION

A thermal model of the MKP-L has been tuned to allow for thermal contacts between ferrite and high voltage capacitance plates. This model will permit more accurate studies of the MKP-L, while waiting for a serigraphed version to be installed in the SPS, and will permit thermal limitations to be assessed for different SPS operating scenarios. Nonlinear longitudinal power dissipation has been predicted in the ferrite yoke and this seems to be confirmed using a novel beam coupling impedance measurement. Predictions for field homogeneity in the aperture show that the serigraphy fingers have a local influence at higher frequencies. Measurements of the field in the beam centre of the aperture show that serigraphy reduces the magnitude of the field by less than 0.75% over the initial ~300 ns of the field flat-top.

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