INFLUENCE OF CONDUCTING SERIGRAPHY UPON FIELD PULSE SHAPE OF THE SPS EXTRACTION KICKER SYSTEMS

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Abstract

Fast pulsed magnets with ferrite yokes are used for beam extraction from the CERN SPS accelerator. These kickers are transmission line type magnets with a rectangular shaped aperture through which the beam circulates. Unless special precautions are taken, the beam impedance of the yoke can provoke significant induced heating, especially for high intensity beams. Previous upgrades of the SPS extraction kicker magnets have included silver fingers serigraphed on the surfaces of the ferrites facing the beam, to help shield the ferrite yoke from circulating beam. Beam based measurements of the extracted beam indicated that the serigraphy may influence the shape of the field pulse, causing it to slightly increase in magnitude during the "flat-top". Hence theoretical studies have been carried out to determine whether the serigraphy influences the field pulse: these studies are reported in this paper.

INTRODUCTION

The CERN Super Proton Synchrotron (SPS) contains two kicker systems, MKE4 and MKE6. MKE4 and MKE6 extract beam to be injected into the LHC in anti-clockwise and clockwise directions, respectively. In the early 2000's, MKE4 was upgraded in preparation for the LHC and also to permit fast extraction to the CNGS neutrino facility [1]. For extraction towards LHC only one extraction per SPS-cycle, with a usable flat-top length of up to 7.8 µs, is required: since only one third of the SPS ring is filled there are no severe restrictions on the field rise-time nor fall-time, however, the flat-top ripple requirements are challenging (±0.5%). For extraction to CNGS the required field rise-time and fall-time (2% to 98%) was 1.1 µs.

Starting in 2010, the MKE4 kicker magnets have been upgraded to reduce their longitudinal beam coupling impedance, and hence the beam induced heating of the ferrite yoke. The reduction in beam impedance is achieved by serigraphing silver fingers on the surfaces of the ferrite facing the beam [2]. A comparison of beam based measurements of the MKE4 deflection field before, during and after the impedance upgrade suggests that the serigraphy causes an increase in magnitude of the field during the "flat-top" of the field pulse. Hence a detailed finite element model of an MKE kicker magnet has been simulated, with the software OPERA2D, to predict the effect of the serigraphy upon the magnetic field.

MKE SYSTEM

General

The MKE magnets are transmission line type magnets with rectangular shaped apertures. The MKE4 system, prior to December 2015, consisted of five kicker magnets, each terminated with a matched resistor. Each MKE4 magnet is impedance (Z=10 Ω) matched with its Pulse Forming Network (PFN) to meet the specification for low ripple. A magnet consists of seven ferrite cells separated by high voltage plates and is housed in a vacuum tank. The simplified electrical schematic of a cell of the magnet is a π-network consisting of a series inductor, whose value is defined by the dimensions of the aperture of the kicker magnet, and a capacitance to ground at each end of the inductor. The MKE kicker magnets were designed and built in the 1970's: in order to achieve the relatively high cell capacitance, the available technology required that each capacitance to ground was housed in a metallic box mounted externally on the magnet vacuum tank.

Design

Each MKE magnet cell is constructed from a C-shaped ferrite, sandwiched between metallic plates. There are two types of magnets: the L-type has an aperture 147.7 mm by 35 mm and the S-type aperture is 135 mm by 32 mm. Prior to December 2015, the MKE4 system had three L-type and two S-type magnets. Each cell, for both magnet types, has a length of 238 mm, a nominal inductance of 1242 nH and a nominal cell capacitance of 12.42 nF: a ~5 Ω resistance, in series with the capacitance, provides damping of ripple.

The ferrite of the yoke is indirectly cooled using water [3]. In addition, in order to ensure that the ferrite remains below its Curie temperature, with high-intensity beams, silver serigraphy is applied on the aperture side surface surfaces of the ferrite facing the beam (Fig. 1) [2].

Figure 1: MKE kicker magnet with silver serigraphy on the aperture side surface of a ferrite.

The first, third and fifth fingers are connected electrically to the high voltage (HV) plate at the far end of a ferrite: the second and fourth fingers are connected electrically to the HV plate at the near end of a ferrite (Fig. 1). Each finger, prior to modifications starting in December 2015, had a length of 200 mm [4]. The spacing between the adjacent edges of the fingers is 20 mm, with the middle finger positioned 5 mm to the right of the centre of the circulating beam. The thickness of the silver serigraphy is specified to be 30 µm. The present serigraphy application procedure involves painting the silver on the ferrite with a roller, with the aid of a mask: hence, the thickness cannot be guaranteed.

BEAM BASED MEASUREMENTS

The MKE4 deflection waveform has been measured with an LHC single bunch pilot beam, by varying the kick delay and recording the position on the beam position monitor screens. The transfer function between the position on a screen and the strength of the deflecting field is determined by keeping the delay fixed, so that the bunch is approximately in the centre of the flat-top, and varying the PFN voltage by a known amount. Thus a variation in the flat-top deflection can be mapped back to an effective PFN voltage and a deflection angle relative to the nominal. Figure 2 shows waveform scans for MKE4 during 2009, 2011 and 2014. In 2009 none of the MKE4 magnets had serigraphy: the deflection is within the ±0.5% specification for more than the required 7.8 µs.

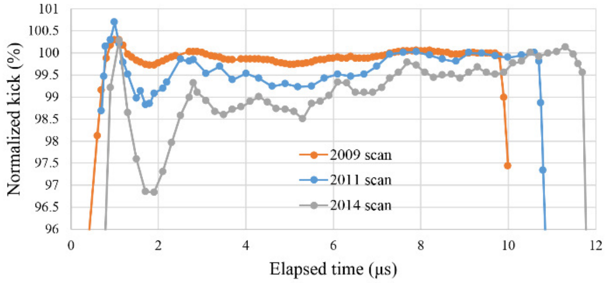

Figure 2: Waveform scan for MKE4 system, 2009 (no serigraphy), 2011 (two magnets serigraphed) and 2014 (all five magnets serigraphed).

During December 2010 two of the five MKE4 magnets were exchanged for ones that had serigraphy. Another waveform scan was carried out during October 2011 and is shown in Fig. 2: in addition to ripple there is an increase in field during the flat-top.

During December 2011 two unserigraphed MKE4 magnets were exchanged for serigraphed ones. In April 2013 the remaining unserigraphed magnet, an L-type, was exchanged for a serigraphed one. The grey curve in Fig. 2 shows a waveform scan for 2014 (all 5 magnets serigraphed): this waveform is ~1% below nominal at 2.5 µs after the start of the flat-top, and generally increases in magnitude over the next 9 µs. The above observations were the motivation for studies of the effect of serigraphy on the shape of the flat-top.

MKE MODEL AND PREDICTIONS

Model

As a baseline for the theoretical studies, thicknesses of serigraphy of 30 µm, as per the specifications, 100 µm and 200 µm have been simulated to determine the effect of the thickness upon the flat-top field.

A cross-section of an S-type magnet aperture, including the serigraphed fingers on the surface of the ferrite leg facing the beam, has been modelled in Opera2D. Due to symmetry only the upper half of the magnet has been simulated. Since the magnet is far from saturating non-linear effects from the ferrite have been neglected. The S-type magnet was chosen to be modelled since it has the smallest aperture and hence the effect of the serigraphy, upon the beam, is expected to be more significant than in the L-type.

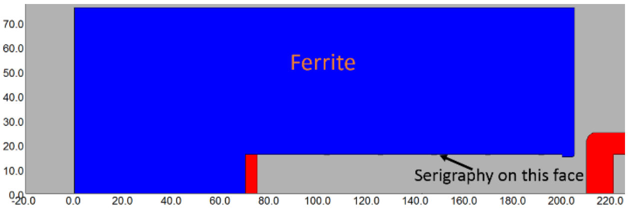

Figure 3: Cross-section of MKE-S magnet: symmetry is utilized so only half the magnet is simulated (dark blue – ferrite; red – busbars and serigraphy).

Initially the Opera2D AC solver was used and the inductance of the magnet, as a function of frequency, was derived: this shows a decrease, from DC to 10 MHz, of 0.9% for 30 µm and 1% for 200 µm thick serigraphy. A PSpice model of a kicker magnet, with frequency dependent inductance representing the 200 µm thickness, was analysed (as per [5]). Figure 4 shows the predicted field: the PSpice predictions don't explain the measured slope of the flat-top. However, the inductance calculated is based on total stored energy, in the Opera2D magnet model, and is averaged over the whole model, whereas serigraphy results in regions of inhomogeneous field.

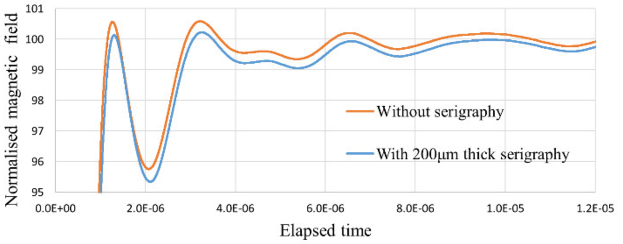

Figure 4: PSpice prediction for normalized magnetic field of an MKE magnet without and with 200 µm serigraphy.

Hence the transient electromagnetic solver of Opera2D was used to understand whether the serigraphy resulted in field inhomogeneity which might explain the slope on the flat-top waveform. Each serigraphed finger is simulated as a separate conductor, in which eddy currents are allowed to flow, but the total current is specified to be 0 A in each finger, i.e. the conductors are "disconnected" at ±infinity. If the fingers were modelled as being connected at ±infinity, eddy currents would circulate between the fingers, considerably extending field rise-time, giving completely unrealistic predictions.

The current in the busbars was modelled as a pulse with 30 ns rise time and 15 µs duration. The Opera2D model does not take into account the capacitors between magnet cells, hence neither the transit time of the pulse through the magnet (~900 ns) nor the cut-off frequency (<2.5 MHz) of a cell is taken into account. However, the theoretical effects of serigraphy upon field inhomogeneity can be studied.

Predictions

The middle finger of the serigraphy is situated 5 mm to the right of the centre of circulating beam. However, just prior to extraction, the beam is bumped 20 mm to the right. The beam envelope has a size of 10 mm in the vertical and 20 mm in the horizontal direction. The closest finger to the centre of the bumped beam is 7 mm to the right and the maximum deviation from the symmetry axis is 5 mm.

Figure 5 shows the field uniformity in the aperture of an S-type magnet without serigraphy, at 30 ns (i.e. the start of the current flat-top). Figure 6 shows the predicted field uniformity for 30 µm thick, silver, serigraphy at elapsed times of 30 ns and 10 µs. The values have been normalized relative to the value of the field at the centre of the bumped beam at 10 µs, for unserigraphed ferrite: the white regions are outside ±1%.

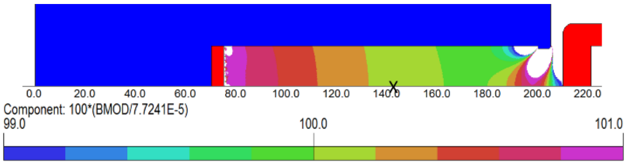

Figure 5: Field uniformity, without serigraphy, at an elapsed time of 30 ns (X is the centre of circulating beam).

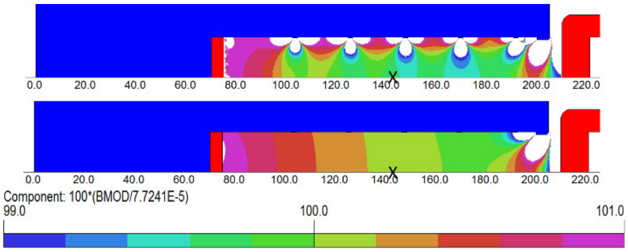

Figure 6: Field uniformity, with 30 µm thick serigraphy, at elapsed times of 30 ns (up) and 10 µs (down). X marks the nominal centre of circulating beam.

It is evident that the field homogeneity at the start of the flat-top, in areas in proximity to the serigraphy, is influenced by the presence of the serigraphy. The eddy currents, in the serigraphy, decay with time and at 10 µs there is no effect. Figure 7 shows the normalized magnetic field at various positions, relative to the nominal centre of bumped beam, for unserigraphed ferrite.

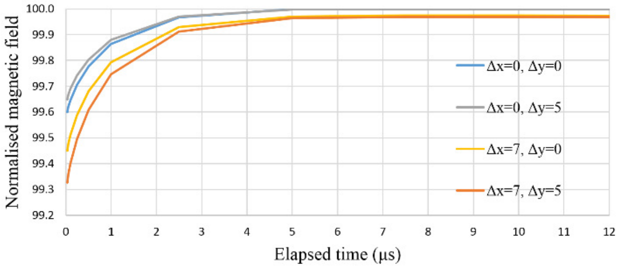

Figure 7: Normalized magnetic field, versus time, at various positions relative to the centre of bumped beam.

Figure 7 shows that for the centre of the bumped beam, the field is 0.4% less than nominal at 30 ns and 0.13% less than nominal at 1 µs. Moving closer to the finger at Δx=7 mm and Δy=5 mm, the inhomogeneity increases to 0.68% at 30 ns and 0.25% at 1 µs.

Previous measurements showed that silver paste applied by painting could be up to 200 µm thick [2]. Serigraphy thicknesses of 100 µm and 200 µm have been modelled to study and compare with the 30 µm case. Figure 8 shows the normalized field, with respect to unserigraphed ferrites, at certain points in the aperture. Thicker serigraphy fingers have an effect upon the maximum inhomogeneity of the field and also increases the time for the decay of the eddy currents.

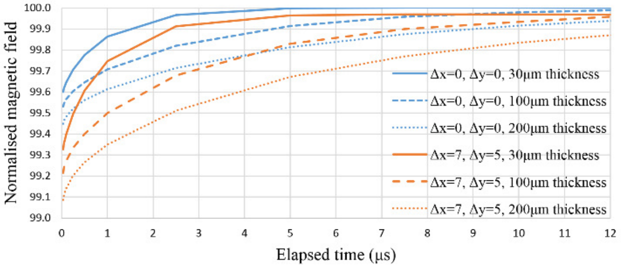

Figure 8: Predicted normalized magnetic field for 30 µm, 100 µm and 200 µm serigraphy thicknesses.

Analysis

The field rise time requirement for the MKE4 system, for CNGS operation, was 1.1 µs [1]. For the first cell of the magnet this means there is ~1 µs for the eddy currents, in the serigraphy, to decay before the field flat-top commences. The only regions significantly affected after 1 µs are those in close proximity to the fingers.

From the results presented above it is clear that, although serigraphy can have an influence upon the field rise time and flat-top, it cannot explain an increase of 1% in magnitude during the pulse as observed in Fig. 2. Even if the serigraphy thickness is 200 µm, it would only have a ~0.5% effect upon the flat-top between 1 µs and 10 µs.

The CNGS experiment is no longer installed. Therefore fast rise-time is not now required for the MKE4 system, and hence the MKE4 system has been simplified to have only four kicker magnets, connected electrically in series, powered by a single PFN and terminated in a short-circuit. The resulting field rise time is ~8 µs, and the PFN has been modified to have more cells to extend the duration of the pulse. Although the MKE4 waveform has not been measured with beam since the system was modified, the field in the kicker magnets now has a relatively long time to reach steady-state, and hence the serigraphy will have less than 0.2% influence upon the flat-top field.

CONCLUSIONS

Eddy currents in the serigraphy can result in field inhomogeneity in the aperture, especially in proximity to the serigraphy. As the eddy currents decay there is an increase in magnitude of the field pulse, towards the nominal value. Nevertheless the nominal, 30 µm, thick serigraphy would explain only a 0.4% increase in kick during a 10 µs flat-top. Thicker serigraphy fingers do increase the time for the field to reach its nominal value. Measurements of the serigraphy thickness, for a randomly chosen ferrite block, are planned.

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