UPGRADING THE SPS FAST EXTRACTION KICKER SYSTEMS FOR HL-LHC*

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Abstract

The CERN SPS has two fast extraction systems, each consisting of travelling wave kicker magnets (MKEs). The beam induced heating in the ferrite yoke of these magnets was historically kept to an acceptable level by implementing water cooling of the kicker magnets: in addition serigraphy was applied on the surfaces of the ferrite yoke facing the beam. Nevertheless, high intensity beams needed in the future for HL-LHC will significantly increase the beam induced heating, potentially raising the MKE ferrite yoke temperature to its Curie point. Hence detailed studies of longitudinal beam coupling impedance were carried out to identify simple but effective methods of further reducing beam induced power deposition. Based on the results of these studies, and in the framework of the LHC Injectors Upgrade (LIU) project, an upgraded MKE kicker magnet was installed during the 2015-2016 shutdown. This paper reports and compares results of predictions, laboratory measurements, temperature measurements during SPS operation, and machine development studies. Measurements of both dynamic pressure rise in the upgraded magnet and Secondary Electron Yield, on samples, are also reported.

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]. There are two extraction kicker systems called MKE4 and MKE6: these systems extract beam to be injected into the LHC in anti-clockwise and clockwise directions, respectively.

The SPS provides intense proton beams for the LHC. The intense beam can result in significant power deposition in the ferrite yoke of the kicker magnets. If the temperature of the ferrite yoke exceeds the Curie point, of ~125°C, the ferrite temporarily loses its magnetic properties – which would prevent the extraction of beam from the SPS. Furthermore, the ferrite has a thermal time-constant of many hours and hence takes a significant time to cool down.

In the early 2000's, the MKE kicker magnets were equipped with water-cooled aluminium nitride plates which are in good thermal contact with the ferrites [2, 3]. Tests in the SPS showed that the observed kick strength starts to diminish when the temperature, measured at the position of a PT100 sensor, is 80°C. The water cooling allows the MKE to operate with approximately twice the beam induced power deposition [2].

Starting in 2010, the MKE kicker magnets were 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 [4, 5].

A massive improvement program of the LHC injector chain is being conducted under the LHC Injectors Upgrade (LIU) project [6]. The LIU project aims at increasing the intensity/brightness in the injectors in order to match the HL-LHC requirements. The increased beam intensity, by more than a factor of two, will result in a further significant increase in power deposition in the MKEs which, unless other precautions are taken, could raise the ferrite temperature above the Curie point.

MKE SYSTEM

General

Each MKE magnet cell is constructed from a C-shaped ferrite, sandwiched between two high voltage (HV) metallic plates. There are two types of magnets: the L-type has an aperture of 147.7 mm by 35 mm and the S-type aperture is 135 mm by 32 mm: the larger dimension is the distance between the HV and return busbars. 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. Each MKE is a transmission line type magnet, constructed of seven cells, and is housed in a vacuum tank. The simplified electrical schematic of a cell 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.

Figure 1: MKE kicker magnet with silver serigraphy on the aperture side surface of a ferrite (inter-digital comb structure with 20 mm spacing between adjacent edges).

As mentioned above, the ferrite of the yoke is indirectly cooled using water [2, 3]. In addition, in order to ensure that the ferrite remains below its Curie temperature, silver serigraphy is applied on the aperture side surface surfaces of the ferrite facing the beam (Fig. 1) [4]. Each finger, prior to modifications which started during a Technical Stop (TS) in December 2015, had a length of 200 mm. The spacing between adjacent edges of the fingers is 20 mm.

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Beam Induced Heating

The 25 ns bunch spacing, which is the baseline for High-Luminosity LHC (HL-LHC), has spectral lines spaced by 40 MHz. A bunch spacing of 50 ns, which was also under consideration several years ago, has spectral lines spaced by 20 MHz [7]. The normal bunch intensities, for 25 ns beam, are presently $1.1\text{x}10^{11}$ protons per bunch (ppb), and will increase to $2.3\text{x}10^{11}$ ppb, for HL-LHC type beam, at flattop: at SPS injection the intensity will be $2.6\text{x}10^{11}$ ppb.

In December 2016 the MKE4 installation was reconfigured to have only four kicker magnets, connected electrically in series, powered by a single PFN and terminated in a short-circuit [4]. Beam coupling impedance measurements carried out in the lab show that terminating an MKE magnet in a short-circuit, rather than with a 10 Ω matched impedance, elongates the "tail", on the real part of the beam coupling impedance, following a resonance, in the frequency range of ~50 MHz to 70 MHz (Fig. 2). Power deposition calculations, based on the measured real impedance and a representative SPS beam spectrum, show that the short-circuit termination increases power deposition by ~16%. A comparison of the average temperature of the MKE4 magnets (resistively terminated) and the MKE6 (short-circuit termination), during June 2015, showed that the temperature rise in the short-circuit magnets was 17% higher than the resistively terminated magnets, consistent with the results of the beam coupling impedance measurements in the lab.

The expected power deposition in a resistively terminated MKE magnet, with HL-LHC type beam, is ~1400 W: for a short-circuit installation this would increase to ~1650 W. A power deposition of 1650 W per magnet is expected to result in a ferrite yoke temperature very close to the Curie point of 125°C, and could thus limit extraction to the LHC.

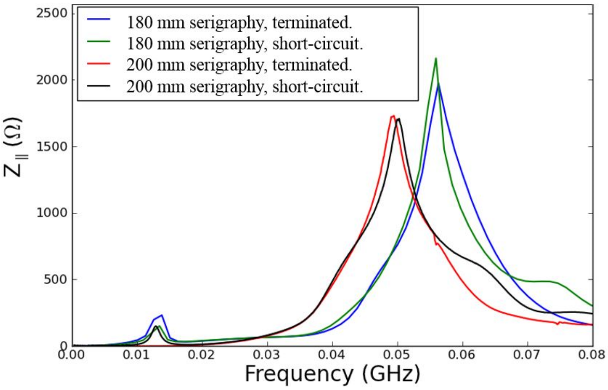

Figure 2: Measured real part of beam coupling impedance for a MKE magnets with 180 mm or 200 mm serigraphy.

CST simulations, for an MKE magnet with 200 mm long serigraphy, predict a high impedance resonance at 44 MHz: the frequency of the peak is a function of the length of the serigraphy [8]. The Q-factor of this high impedance resonance results in considerable beam induced power deposition, in the ferrite yoke: the power loss at 44 MHz, for 25 ns bunch spacing, is 70% of the total predicted power deposition in an MKE-L magnet. Figure 3 shows predicted power deposition as a function of the frequency of the high impedance resonance, in the frequency range 30 MHz to 70 MHz. Figure 3 shows that for 25 ns beam, the predicted power loss due to the high impedance resonance is minimized, in the plotted frequency range, at ~56 MHz: however the corresponding power loss for 50 ns bunch spacing is relatively high. In order to keep the option for operating with 50 ns bunch spacing, a compromise is to choose a 180 mm length of serigraphy, which results in an impedance peak of ~49 MHz (Fig. 3). Reducing the serigraphy length from 200 mm to 180 mm results in a considerable reduction in beam induced heating:

- Based on CST predictions for real impedance the reduction in power deposition is 50% and 30%, for 25 ns and 50 ns bunch spacing, respectively;
- Based on lab measurements of real impedance (Fig. 2) the reduction in power deposition is 20% and 15%, for 25 ns and 50 ns bunch spacing, respectively.

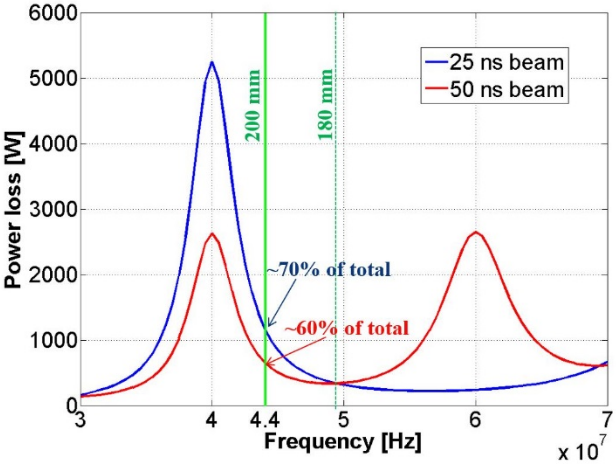

Figure 3: Predicted power loss due to the high impedance resonance as a function of frequency.

In December 2016, when the MKE4 kicker system was reconfigured to consist of four series connected, short-circuit terminated, magnets - one of these magnets (an MKE-S) was replaced with one with 180 mm long serigraphy [4]: the serigraphy was shortened by carefully scraping off the last 20 mm. All the other three magnets in MKE4, and all three in MKE6, had 200 mm long serigraphy.

At the end of March 2016 a so-called scrubbing run was performed, with high-intensity 25 ns beam, over a forty-eight hour period. The single magnet with 180 mm serigraphy had the lowest temperature rise of all seven MKE magnet's over this period. The temperature rise of the MKE with 180 mm serigraphy was 46% lower than the average temperature rise of the other six MKE magnets: this is consistent with the expectation from CST simulations.

At the end of June 2016 a machine development study was performed with 50 ns beam, over an eight hour period. Again the single magnet with 180 mm serigraphy had the lowest temperature rise of all seven MKE magnets over this period. The temperature rise of the MKE with 180 mm serigraphy was 23% lower than the average temperature rise of the other six MKE magnets: this is again consistent with the expectation from CST simulations.

Secondary Electron Yield

The scrubbing run at the end of March 2016 (see above) resulted in high dynamic pressure (Fig. 4), due to electron cloud, probably in the aperture of the ferrite of the newly installed MKE4 kicker magnet. The dynamic pressure inside the tanks of other MKE magnets, which had not been recently replaced, was typically at least a factor of five below the newly installed MKE4. It is not clear if the high dynamic pressures was due to the ferrite of the upgraded MKE being exposed to air or the scraping off of the serigraphy.

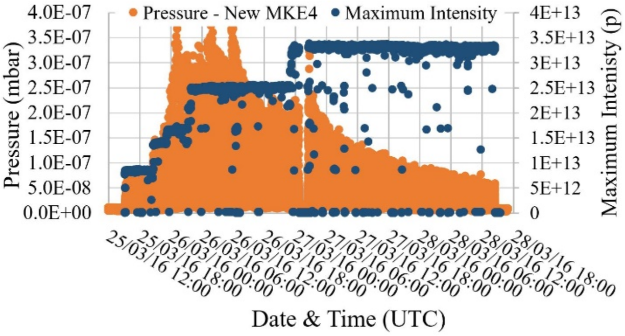

Figure 4: Maximum beam intensity, for 25 ns beam, and dynamic pressure rise measured in the tank of the newly installed MKE4, S-type magnet, with 180 mm serigraphy.

Simulations of electron cloud for 25 ns beam with 1.2×10^{11} ppb show an electron-cloud threshold, for an MKE-S magnet, of 1.85. For an MKE-L magnet the predicted threshold, for 25 ns beam, is 1.8 for 1.2×10^{11} ppb and 1.7 for LIU beam parameters.

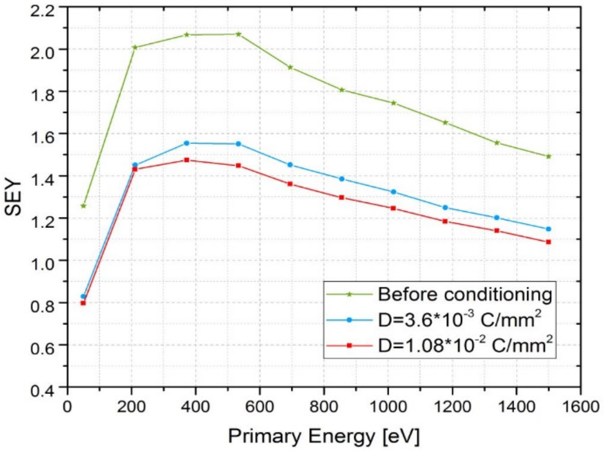

Figure 5: SEY measurements, on samples of CMD5005 ferrite, as a function of primary energy: SEY before and after conditioning is shown.

Secondary Electron Yield (SEY) measurements were carried out on samples of CMD5005 ferrite (Fig. 5). The maximum SEY (δ_{max}) is ~2.1, and bombarding the surface with electrons reduced the δ_{max} to ~1.5. Samples magnetron sputtered with Cr_2O_3 condition, in the lab, to have δ_{max} less than 1.4 [9], with the same electron dose as shown in Fig. 5. Thus, long-term, Cr_2O_3 coating of ferrite may be beneficial for reducing electron cloud in the MKE kicker magnets.

SEY measurements were also carried out on a sample of ferrite which had the silver serigraphy paint applied, cured, and then scraped off. The results were similar to those shown in Fig. 5. In addition SEY measurements were carried out on the silver paint: the results are shown in Fig. 6. The δ_{max} is ~1.7, which is close to the electron cloud threshold: bombarding the surface with electrons reduces δ_{max}.

The initial SEY measured for the ferrite is above the electron-cloud threshold for 25 ns beam. However Figs. 5 and 6 show that the ferrite and silver paint condition, in the lab, when bombarded with electrons. Hence conditioning can be expected to occur in the SPS, during machine operation. Conditioning can be observed in Fig. 4: there is a factor of four reduction of pressure, for a given beam intensity, during the last ~30 hours of the scrubbing.

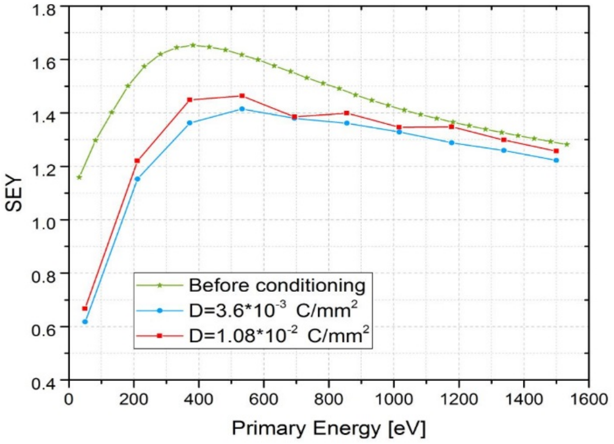

Figure 6: SEY measurements, on silver paint, as a function of primary energy: SEY before and after conditioning is shown.

CONCLUSION

Detailed studies have been carried out, in the framework of the LIU project, to reduce the beam induced heating of the SPS extraction kicker magnets: this is essential for operation with HL-LHC type beams. CST simulations indicate that the optimum serigraphy length is 180 mm, rather than the original 200 mm. Measurements, during SPS operation, on an MKE upgraded to have 180 mm long serigraphy agree with predictions: magnet temperature rise is halved with 25 ns beam and reduced by one-fifth for 50 ns beam. The reduced power deposition is expected to result in reliable operation with HL-LHC type beams. Hence the remaining three magnets of MKE4 were upgraded during the TS which started in December 2016: MKE6 will be upgraded during the TS which starts in December 2017. SEY measurements on both ferrite and silver paint show that the SEY reduces, in the lab, when bombarded with electrons: this is consistent with conditioning with beam, of an upgraded MKE magnet, observed in the SPS.

ACKNOWLEDGEMENT

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