MKP-L IMPEDANCE MITIGATION AND EXPECTATIONS FOR MKP-S IN THE CERN-SPS

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Abstract

Beam coupling impedance mitigation is key in preventing intensity limitations due to beam stability issues, heating and sparking. In this framework, a very good example is the optimization of the SPS kickers beam-coupling impedance for beam-induced heating mitigation. After the optimization of the SPS extraction kickers, the SPS injection kickers became the next bottleneck for high intensity operation. This system is composed of three MKP-S tanks and one MKP-L tank. To accommodate LIU beam intensities, it was necessary to mitigate the beam induced heating of the MKP-L, using a shielding concept briefly reviewed in this paper. Moreover, temperature data from the 2023 run are analyzed to qualify the accuracy of the models and assess the effectiveness of the impedance mitigation. Finally, the expected limitations from the MKP-S, foreseen to become the next bottleneck in terms of beam induced heating, are discussed.

INTRODUCTION

The beam coupling impedance describes how a particle beam interacts with an accelerator component. As the beam passes through the accelerator, it generates electromagnetic fields that can impact its stability and induce power to be dissipated on the accelerator wall [1] causing heating of specific devices. For instance, in ferrite kicker magnets, this heating can risk damage or malfunction if not addressed during the design phase. Historically, beam coupling impedance was not systematically considered in accelerator component design due to typically forgiving beam performance requirements. Consequently, the original SPS ferrite-loaded kicker design was not optimized for beam-induced heating.

For example, due to heating issues [2], the original design of the SPS extraction kickers (MKEs) had to be modified [3]. Serigraphy, which introduces a parallel impedance, was applied directly to the ferrite. Proper engineering of this serigraphy significantly reduced the beam coupling impedance across a broad frequency range without affecting kicker rise time or High Voltage (HV) performance [3–8]. Following the SPS extraction kicker optimization [9], the SPS injection kicker (MKP-L) became the primary bottleneck for CERN-SPS beam induced heating [10].

MKP-L BEAM-INDUCED HEATING MITIGATION

The SPS injection kicker system is composed of four tanks (three MKP-S and one MKP-L tank): the MKP-L tank contains four modules [11]. The MKP-L, due to the wider aperture, has a higher impedance than the MKP-S at lower frequency. This causes a stronger interaction with the beam spectrum and hence higher beam induced power loss [12, 13].

The need to mitigate the MKP-L beam induced power loss in order to accommodate HL-LHC beam intensities was identified already in 2013 and reported in [14]. Consequently, potential solutions to mitigate the beam induced heating were investigated. Based also on the SPS extraction kicker experience, a design with silver fingers was developed. However, due to the shorter length of the MKP-L ferrite cells, 31 mm in comparison with 235 mm, applying the fingers directly on an MKP-L ferrite, as done for the MKEs, was not a viable solution. It was found that significantly longer fingers, extending over several cells, would be needed to efficiently shield the impedance. This was achieved by applying silver fingers on the beam side of ceramic (Al_2O_3) plates, with the fingers connected to the module end ground plates, to ensure isolation from the ferrite and HV plates. Figure 1 shows a sketch of the concept.

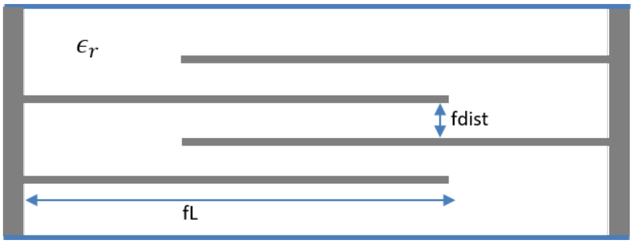

Figure 1: Sketch of the silver fingers applied to Al_2O_3 with electrical permittivity ϵ_r: 'fL' indicates the finger length, and 'fdist' represents the finger separation. The resonance frequency resulting from the serigraphy increases as 'fdist' increases (smaller capacitance) and decreases as the finger length 'fL' increases (higher inductance).

Details about the first version of the impedance shielding of the MKP-L can be found in [15]. This initial beam coupling impedance mitigation solution was successfully verified with bench measurements [13]. Unfortunately, this first version was not a good solution at high voltage [16]. After several investigations, the connection of the fingers to the HV end-plates was chosen as the best solution [16]. As previously mentioned, the serigraphy leads to a significant reduction of the broadband impedance. However, resonances are introduced in the low frequency range. The design of the shielding has been optimized, with the HV constraints in mind [16], to place the dangerous impedance resonance as far as possible from the 40 MHz, 25 ns, beam spectrum line maximizing also the distance from 8b4e additional lines.

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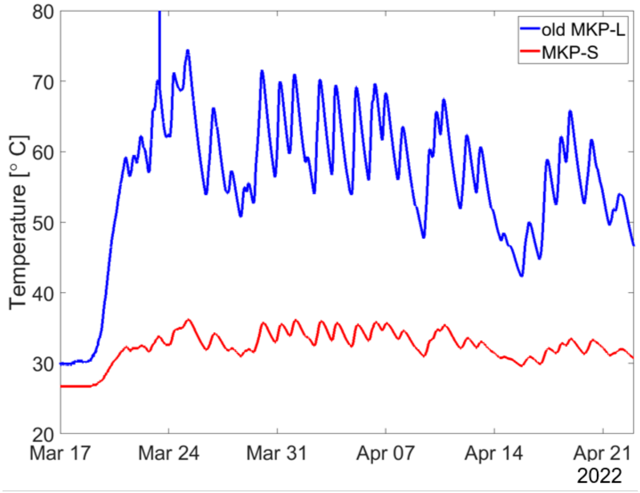


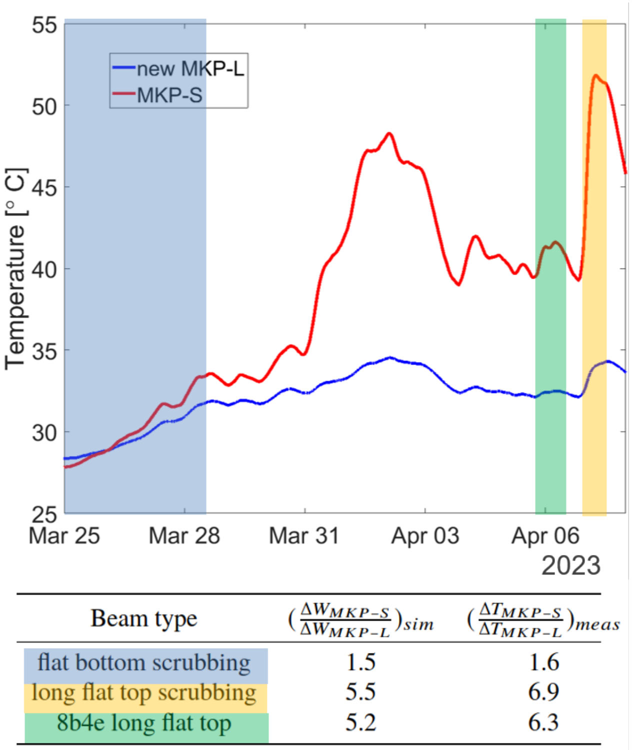
Figure 2: Measured temperatures on MKP-L and MKP-S before and after MKP-L impedance shielding.

Once the MKP-L design was optimized for both HV behaviour and impedance, and verified on a prototype module, all four modules were assembled [17]. The beam coupling impedance of the fully assembled MKP-L was measured and found in good agreement with the simulation model [13].

The low impedance MKP-L has been installed in the SPS during the Year-End Technical Stop (YETS) 2022–2023. In very good agreement with the predictions, the new MKP-L heating has been dramatically reduced and is now significantly lower than MKP-S heating (see Fig. 2). As an example, Fig. 3 shows temperature data analyzed during the scrubbing run 2023 and the relative comparison of the expected power loss ratio and the measured temperature gradient ratio. In agreement with the expectations, the temperature gradient ratio between MKP-S and MKP-L significantly increases during flat top scrubbing due to the reduction of the bunch length. It is also worth mentioning that, during the long flat top scrubbing, there is a high rate of change of temperature for the MKP-S, which now becomes the next bottleneck in terms of beam induced heating. Long flat top scrubbing had to be adapted to allow MKP-S cooldown.

EXPECTATIONS FOR THE MKP-S

The expectations for the MKP-S kicker are paramount, especially in light of the recent optimization efforts directed towards mitigating SPS beam-induced heating limitations by reducing the beam coupling impedance of the MKP-L. With the MKP-L now exhibiting significantly lower heating, the MKP-S kicker emerges as the device pacing the scrubbing and maybe operation in terms of beam-induced heating within the SPS kickers. In this context, several key considerations come to the forefront. One key question to address is whether we can apply the MKP-L impedance shielding concept to the MKP-S. Beam coupling impedance simulations have been conducted to evaluate the impact of implementing the MKP-L shielding concept on the MKP-S. As illustrated in Fig. 4, the shielding mechanism is expected to be highly effective for the MKP-S as well. Similarly to the MKP-L case a significant reduction of the broadband impedance is observed. In its original version, the MKP-L shielding applied to the MKP-S kicker would introduce resonances close to the 40 MHz and 80 MHz spectrum lines (which are the two main amplitude lines of the 25 ns beam). Like the MKP-L case, the design can be optimized by adjusting the



Beam type	$(\frac{\Delta W_{MKP-S}}{\Delta W_{MKP-L}})_{sim}$	$(\frac{\Delta T_{MKP-S}}{\Delta T_{MKP-L}})_{meas}$
flat bottom scrubbing	1.5	1.6
long flat top scrubbing	5.5	6.9
8b4e long flat top	5.2	6.3

Figure 3: The temperature evolution of MKP-L and MKP-S during the 2023 scrubbing run. Highlighted are the temperature data points used for comparing with the expected power loss ratio, with flat bottom scrubbing in blue, 8b4e in green, and long flat top scrubbing in orange.

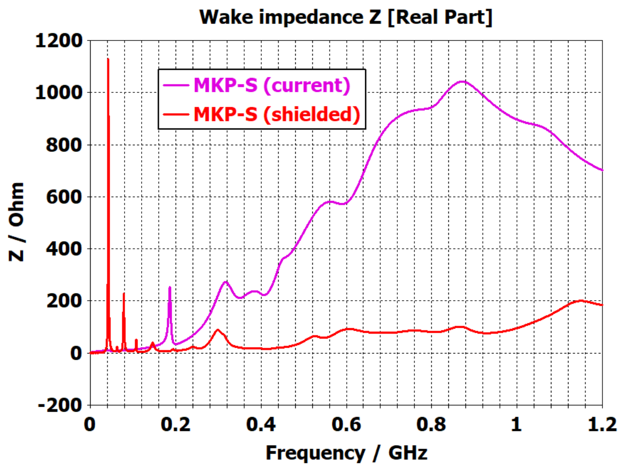


Figure 4: Simulated real part of the longitudinal beam coupling impedance of an MKP-S module, both unshielded (current) and shielded (with the option used for the MKP-L).

finger lengths. Figure 5 shows the expected impedance of a MKP-S module for various lengths of finger #2 and finger #4: these are the fingers connected at the input end of the kicker magnet. In all cases, the broadband impedance is similar and significantly smaller than the current MKP-S impedance. On the other hand, the low frequency resonances are shifted to a higher frequency with shorter fingers due to reduced inductance. This allows for the optimization of beam induced power loss. In contrast to the MKP-L case, this optimization requires shortening the serigraphy, which is not expected to be detrimental to the high-voltage (HV) requirements.

Figure 6 depicts the beam-induced power loss for the shielded (current) MKP-L and both the unshielded (current) and shielded MKP-S, normalized to the current MKP-S. The anticipated beam-induced power loss for the shielded MKP-S is expected to closely approach that of the new MKP-L.

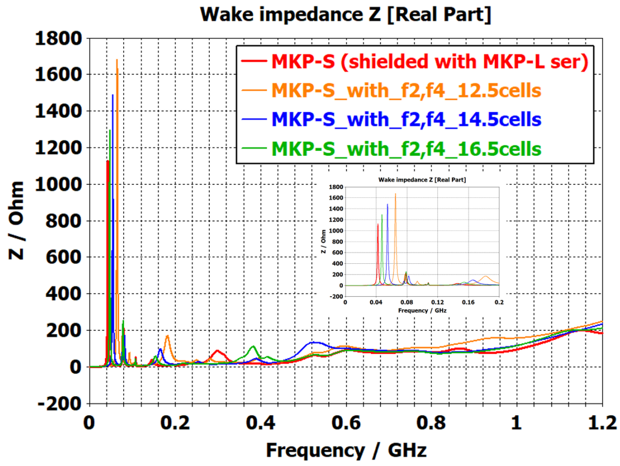


Figure 5: Simulated real part of the longitudinal beam coupling impedance for a shielded MKP-S module with various finger lengths. Additionally, a zoomed-in view of the low-frequency behavior is provided to better illustrate the frequency shift of the resonances with finger length.

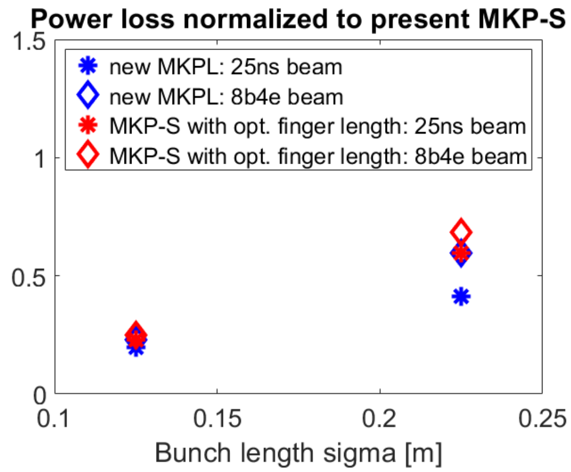


Figure 6: Expected beam induced power loss on the MKP-L (25 ns beam) and on the shielded MKP-S (8b4e and 25 ns beam), normalized to the current MKP-S power loss.

A crucial aspect to consider is the MKP-S power loss dependency on the horizontal beam position. Due to the relatively small horizontal aperture of the MKP-S, the beam-induced power loss strongly depends on the beam's position and diminishes when the beam is moved towards the ground conductor. If compatible with aperture requirements, this would represent a relatively straightforward solution for reducing power loss. Preliminary data suggests that introducing a beam offset of 10 mm can result in a substantial 30% reduction in MKP-S power loss [15].

CONCLUSIONS

Beam-induced heating strongly affects the ferrite-loaded kickers in the SPS. Following the optimization of the SPS extraction kickers, the bottleneck shifted to the SPS injection kickers. Notably, the MKP-L modules exhibited more pronounced beam-induced heating than the MKP-S, primarily due to their larger aperture dimensions. In order to achieve and reliably operate the higher beam intensities required by LIU, it became important to mitigate the beam-induced heating in these kickers. We briefly discussed the beam coupling impedance shielding solution applied to the MKP-L device. The 2023 temperature data for the new MKP-L modules have confirmed the effectiveness of the mitigation implemented for beam-induced heating.

Furthermore, we explored the applicability of the MKP-L impedance shielding concept to the MKP-S modules. Simulations suggest that the MKP-L shielding concept will be effective also for the MKP-S. Alternatively, one could introduce a horizontal beam offset of at least 10 mm towards the ground conductor. Both solutions would need to be compatible with aperture requirements and would facilitate scrubbing runs and operation in the coming years. Water cooling of the MKP-S side plates is also being considered.

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