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SPS INJECTION KICKER SYSTEM: 2023 OPERATIONAL EXPERIENCE AND UPGRADE PROPOSALS FOR HIGH-LUMINOSITY LHC

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Abstract

The SPS injection kicker system comprises twelve MKP-S (small aperture) modules and four MKP-L (large aperture) modules. An upgraded MKP-L magnet was installed in the SPS, during December 2022, in view of the higher beam intensity needed in the future for High-Luminosity-LHC. The upgrades have significantly reduced the beam coupling impedance and consequent beam induced heating. The improved performance is due to a new beam screen, consisting of silver fingers painted on an alumina chamber, inserted in each magnet's aperture. Additionally, a surface coating on the chamber's inner surface reduces its secondary electron yield and hence dynamic vacuum activity. The effectiveness of these upgrades was demonstrated during the 2023 operation. This paper provides an in-depth exploration of the initial year of operational experience with the upgraded MKP-L, giving a comparative analysis of dynamic vacuum and beam induced heating with the MKP-S modules. An alternative approach for upgrading the MKP-S modules, to reduce their temperature, is also proposed.

INTRODUCTION

The SPS injection system includes four vacuum tanks containing kicker magnet modules: two tanks with five MKP-S modules each, one with two MKP-S modules, and one with four MKP-L modules. MKP-S and MKP-L characteristic impedance are respectively 16.7 Ω, and 12.5 Ω.

Prior to YETS 2022-23, the MKP-L, due to its larger aperture, exhibited higher beam coupling impedance than the MKP-S. This higher impedance led to stronger interactions with the beam, resulting in high beam-induced power loss. Consequently, this induced heating, combined with a rise in pressure due to both outgassing of the ferrite and electron-cloud effects, posed limitations during the SPS scrubbing as well as for the achievement of HL-LHC beam intensities [1].

To address these limitations, a low beam impedance MKP-L was designed and installed. This new design includes a beam screen to shield the ferrite from beam wakefields, thereby mitigating the high heat load. This beam screen consists of silver fingers painted on the inner surface of a U-shaped alumina chamber, creating a conductive path for the beam's image current [2–4]. To decrease alumina's inherently high Secondary Electron Yield (SEY), Cr_2O_3 coating was applied on the inner surface of the chamber facing the beam. This coating, applied via magnetron sputtering by Polyteknik [5], reduces the maximum SEY from ~9 to ~1.4, the lowest value measured on coated witness samples conditioned with beam [6]. Additionally, the ends of each chamber were coated with amorphous Carbon at CERN to eliminate high-voltage weaknesses likely caused by high SEY and consequent gas desorption [7].

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2023 OPERATIONAL EXPERIENCE

The temperature of the MKP magnets is monitored using PT100 sensors installed on the side plates of selected modules. All MKP-L modules are equipped with these temperature sensors, whereas only two sensors are installed in the first MKP-S tank, with five modules. PT100 sensors cannot be mounted directly on the ferrite yokes since these are pulsed at high voltage. Therefore, the measured temperature does not reflect the true temperature of the ferrite, which may be higher. In 2022, the temperature rise recorded for the MKP-L modules was up to four times higher than that of the MKP-S modules. To avoid potential damage to the MKP-L modules from excessive heat, their measured (side plate) temperatures were limited to 70°C [1]. This precaution, despite limiting scrubbing [8], was necessary to reduce the risk of electrical breakdown during pulsing, especially as the static pressure reached levels as high as $5x10^{-7}$ mbar [1].

Significant improvement following the low-impedance upgrade was evident during the entire 2023 operational beam run: the temperature rise of the MKP-L was only 28% of that of the MKP-S, i.e. ~14 times lower than in 2022, as shown in Fig. 1. The maximum temperature achieved in the MKP-L modules during this period was 36.5°C.

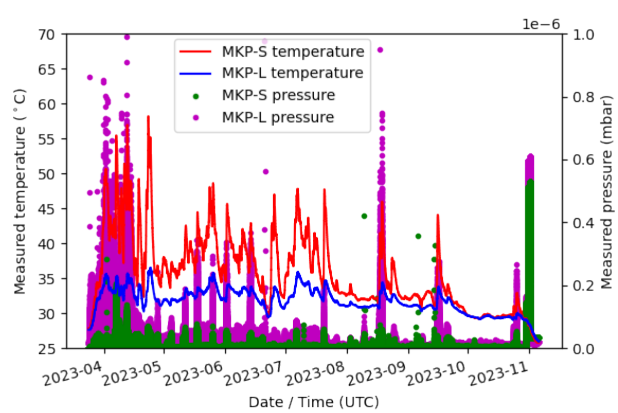

Figure 1: Temperature and pressure measurements, from 24/3/2023 to 5/11/2023, for an MKP-S and a low-impedance MKP-L module.

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In March 2023, a rapid conditioning of the coated surfaces was observed [1], when the dynamic pressure halved in ~12 hours with a constant beam current. Furthermore, the normalized pressure continued to decline, dropping from $3.5{\times}10^{-21}$ mbar/p to $6{\rm x}10^{-22}$ mbar/p over approximately ~3.5 months. The static pressure of the MKP-L, which is influenced by temperature, decreased from $0.4{\times}10^{-7}$ mbar to $0.15{\times}10^{-7}$ mbar during this period [9].

MKP-S Behaviour and Limitations

Following the low-impedance upgrade of the MKP-L, this magnet was no longer a limitation and beam intensity and scrubbing duty cycle could both be increased. As a result, in April 2023, the MKP-S modules recorded a peak temperature of 58.3°C, experiencing a maximum temperature rise of 30.7°C, in evident contrast to the 8.9°C rise observed in the MKP-L and a marked deviation from the trends observed in the previous year.

To ensure that the beam injected into the SPS is not miskicked due to the ferrite yoke exceeding its Curie temperature and to preserve magnet integrity, a Software Interlock System (SIS) is employed. This system monitors the side-plate temperatures and inhibits injection if these temperatures surpass predefined thresholds. Given the unprecedented rise in temperatures, a threshold was set for the MKP-S at 60°C during the 2023 run, with plans to adjust it based on further analysis and operational experience. Consequently, the 2023 scrubbing operation was tailored to keep the heating of the MKP-S modules below critical thresholds.

Capacitive pickups (CPUs) are installed on the high voltage busbars at the input and output of some MKP modules, providing temporal data for the input and output voltage waveform. The delay time of a module, measured between the rising edges of the pulse, is proportional to the square root of a magnet cell's inductance. Hence, any abrupt reduction in the delay time would indicate that one or more cells have reached Curie temperature.

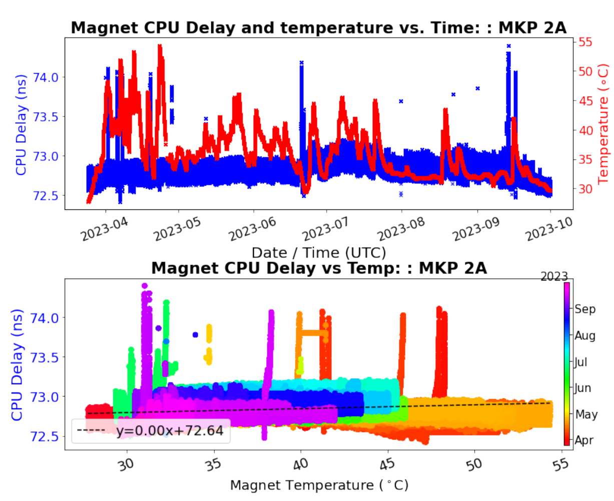

Figure 2: Delay of one MKP-S module as a function of time (top image) and temperature (bottom image).

Throughout the operational run, there was no significant reduction in delay for any MKP modules equipped with CPUs (Fig. 2), indicating that the magnet yokes always remained below their Curie temperature. An increase in the measured delay was only observed during high-voltage magnet conditioning (occasional peaks in Fig. 2): these are unrelated to the modules inductance, but are due to imprecise evaluations occurring when the magnet is pulsed.

Prior to the YETS 2022/23, effective conditioning of the MKP-S ferrite with beam was limited by the high temperatures in the MKP-L modules. Following the MKP-L upgrade, an increase of the MKP-S temperature and hence static pressure was observed in the first month of operation: the static pressure subsequently showed a gradual decline. This trend indicates a progressive enhancement in the conditioning of the ferrite of the MKP-S (Fig. 3).

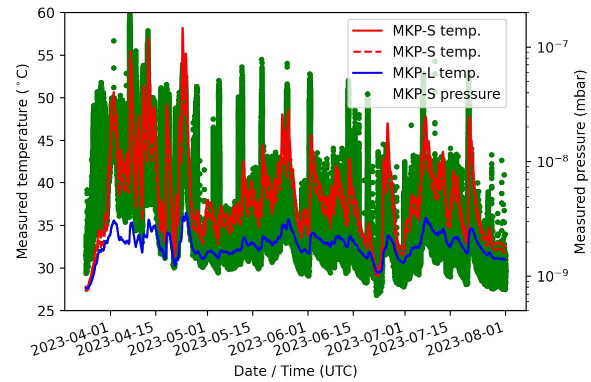

Figure 3: Temperature and pressure measurements, from 24/03/2023 to 01/08/2023, for an MKP-S and a new MKP-L module.

Figure 4 shows a comparison of static and dynamic pressure for MKP-S during April and July 2023, under high beam intensity conditions (288 bunches accelerated to 450 GeV). In April, the normalized dynamic pressure was $1{\times}10^{-21}$ mbar/p with a beam intensity of $1.8{\times}10^{11}$ ppb (protons per bunch) and a relatively high static pressure. By July, the normalized dynamic pressure had decreased to $5{\times}10^{-22}$ mbar/p with higher beam intensities of $2.1{\times}10^{11}$ ppb, accompanied by a reduced static pressure. This significant reduction in pressure over time indicates effective beam conditioning of MKP-S, suggesting that it will continue to improve with further operation.

MKP-S POTENTIAL IMPROVEMENTS

During the 2024 operation run, HL-LHC target intensity beam parameters ($2.3{\times}10^{11}$ ppb, 288 bunches, 1.65 ns at 450 GeV) have been achieved in the SPS [10]. However, following the upgrade of the MKP-L, the MKP-S emerged as a potential constraint for achieving long-duration circulating beam of such intensities. Hence, several mitigation strategies are under evaluation to reduce the beam-induced heating of the MKP-S. It should be noted that since a typical LHC fill and preparation usually takes no more than 2 hours, MKP-S heating is unlikely to limit normal physics operations with 25 ns beams.

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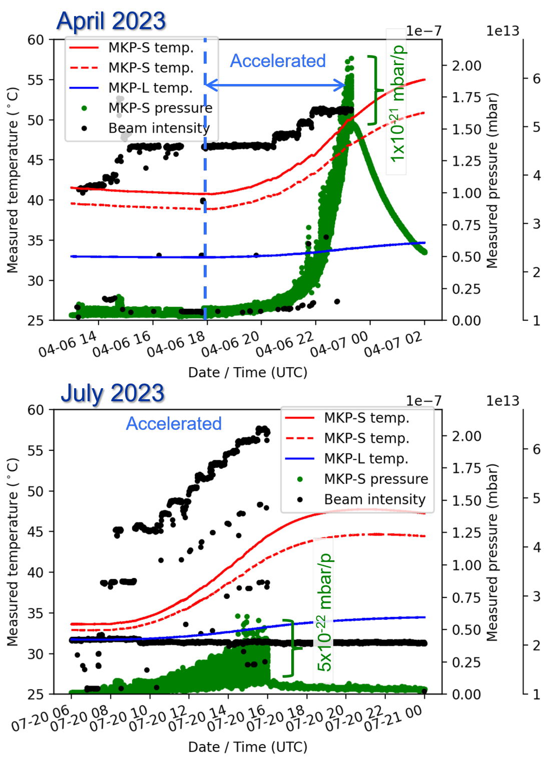

Figure 4: Beam intensity and MKP-S temperature and pressure measurements in April 2023 (top image) and July 2023 (bottom image).

Hardware Solutions

Preliminary simulation studies have tested the feasibility and effectiveness of incorporating an MKP-L-like impedance shielding into MKP-S modules [11]. These studies suggest that a significant reduction in broadband impedance could be achieved. However, further detailed analysis is required to optimize the design and ensure that the silver fingers do not excite resonant modes that could couple with the beam. Moreover, an evaluation of the available beam aperture is necessary to accommodate these changes.

If beam aperture constraints exist, the possibility of replacing MKP-S modules with larger aperture versions, similar to MKP-L, might be considered. However, this would necessitate the use of shorter modules and/or with higher characteristic impedance than the MKP-L, to achieve the faster rise time requirements of the MKP-S, potentially leading to additional electrical stress due to higher voltage requirements.

An alternative approach could involve a completely new magnet design that keeps the circulating beam outside the aperture, so-called "open-C", and as considered at one time for the SPS extraction kicker magnets [12]. This design would result in higher inductance because it necessitates moving the return busbar further from the aperture, requiring more current to achieve the desired beam deflection.

A less drastic modification could involve implementing a cooling system on the side plates, to remove the heat through thermal conduction, and/or increasing the thermal emissivity of the inside of the vacuum tank e.g. using a method described in [13].

Beam Offset

Beam offset studies have demonstrated that the beam-induced power loss varies considerably with the beam's horizontal position in the aperture of the MKP kicker magnet, significantly decreasing when the beam is shifted towards the ground conductor [14]. Beam induced heating could be reduced by a factor ~2, by introducing a beam offset of 22 mm toward the ground conductor (Fig. 5).

In the 2024 operational run, a ~17 mm offset was effectively implemented using the existing SPS injection bump [10]. This solution, necessitating ten hours of stable beam conditions for a thorough evaluation, proved to effectively mitigate heating, confirming the theoretical expectations [14]. However, this can only be implemented at flat bottom energy, due to limited SPS corrector strength at higher energy, where the most significant heating occurs. Hence, such adjustment may not be enough to provide the required power loss reduction and complementary solutions, such as magnets re-alignment with an horizontal offset, could be implemented. A feasibility study on the required MKP-S magnets offset is currently in progress, examining both mechanical aspects and beam dynamics implications.

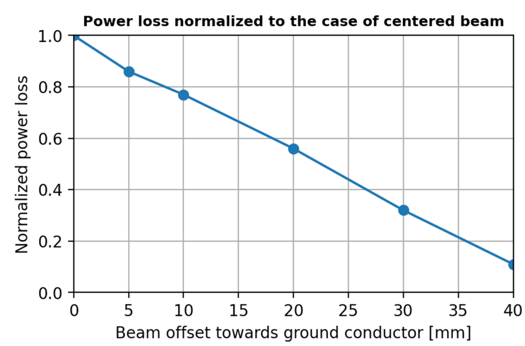

Figure 5: Simulated normalized power loss as function of beam offset towards return conductor in an MKP-S module [14].

CONCLUSION

The MKP-L system's performance in 2023 confirmed the success of its low-impedance upgrade, significantly reducing beam-induced heating and enhancing beam conditioning, thereby lowering both static and dynamic pressures.

The conditioning of the MKP-S, which had been constrained by the MKP-L before the YETS 22/23, exhibited substantial improvement in 2023, likely aided by significant ferrite outgassing. However, the significant temperature rise in MKP-S limited the duty cycle of the 2023 scrubbing run and posed potential risks to magnet integrity.

Given the potential limitations of MKP-S for long-duration circulating beams of higher intensities, various mitigation strategies are being examined, with some initial findings outlined in this paper.

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REFERENCES

[1] M. J. Barnes *et al.*, "Operational experience of a low beam coupling impedance injection kicker magnet for the CERN SPS ring", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 4352–4355. doi:10.18429/JACoW-IPAC2023-THPA164

[2] M. J. Barnes *et al.*, "Studies of impedance-related improvements of the SPS injection kicker system", in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 3611–3614. doi:10.18429/JACoW-IPAC2016-THPMW030

[3] M. J. Barnes, O. Bjorkqvist, and K. Kodama, "Beam induced power deposition in CERN SPS injection kickers", in *Proc. IPAC'21* Campinas, Brazil, May 2021, pp. 3490–3493. doi:10.18429/JACoW-IPAC2021-WEPAB342

[4] C. Zannini, M. Barnes, M. Diaz, L. Ducimetière, D. Standen, G. Rumolo, P. Trubacova, "Beam-induced heating mitigation of the SPS kickers: a crucial upgrade to move towards HL-LHC beam intensities", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 3486–3489. doi:10.18429/JACoW-IPAC2023-WEPL157

[5] Polyteknik AS, DK-9750 Oestervrå, Denmark, http://www.polyteknik.com/.

[6] M. J. Barnes *et al.*, "Operational experience of a prototype LHC injection kicker magnet with a low SEY coating and redistributed power deposition", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 3974–3977. doi:10.18429/JACoW-IPAC2019-THPRB072

[7] M. J. Barnes *et al.*, "Mitigation of high voltage breakdown of the beam screen of a CERN injection kicker magnet", in *Proc. EAPPC'22*, Seoul, South Korea, Sep. 2022, pp. 286–289. https://www.eappc-beams2022.org/main/su_paper_pp.htm

[8] V. Kain *et al.*, "Achievements and performance prospects of the upgraded LHC injectors", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 1610–1615. doi:10.18429/JACoW-IPAC2022-WEIYGD1

[9] M. Barnes, "Low impedance MKP-L conditioning and observations on MKP-S", presented at SPS kickers high intensity conditioning, Geneva, Switzerland, Aug. 2023.

[10] C. Zannini, I. Mases Sole "Transverse beam stability and MKP-S heating test", presented at SPS MPC #59, Geneva, Switzerland, Apr. 2024. https://indico.cern.ch/event/1398867/contributions/5891519/attachments/2833883/4952258/SPS_MPC_2024_04_09.pdf

[11] C. Zannini *et al.*, "MKP-L impedance mitigation and expectations for MKP-S in the CERN-SPS", in *Proc. HB'23*, Geneva, Switzerland, Oct. 2023, pp. 466-469. doi:10.18429/JACoW-HB2023-THBP11

[12] LIU-SPS Open 'C' Core MKE Extraction Kicker Review. https://indico.cern.ch/event/233229/overview

[13] L. Vega Cid, "Thermal modelling, conception and design of a cooling system for the LHC injection kicker magnets towards high luminosity operation", CERN-THESIS-2020-415, https://cds.cern.ch/record/2825339/.

[14] M. S. Beck, "Simulation, measurement and mitigation of the beam induced power loss in the SPS injection kickers", CERN-THESIS-2015-374, M.S. thesis, KIT, 2015.