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CERN SPS DILUTION KICKER VACUUM PRESSURE BEHAVIOUR UNDER UNPRECEDENTED BEAM BRIGHTNESS

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Abstract

The Super Proton Synchrotron (SPS) is the second largest synchrotron at CERN and produces high-brightness beams for the Large Hadron Collider (LHC). Recently, the dilution kicker (MKDH) of the SPS beam dump system (SBDS) has demonstrated unanticipated behaviour under high beam brightness conditions. During the 2022 and 2023 beam commissioning, the MKDH, which is routinely pulsed at high voltage, was subjected to intensities of up to 288 bunches of 2×10^{11} protons per bunch and bunch lengths as low as 1.5 ns. Under these conditions, all the SPS kickers and septa exhibited a rapid vacuum pressure rise and a significant temperature increase with the MKDH playing the dominant effect in restricting the maximum line density that can be attained. This paper presents the results of the collected data, emphasizes the dependence on beam parameters, and introduces a probabilistic model to illustrate the effect of MKDH conditioning observed to forecast the pressure behaviour. Finally, potential countermeasures and outlook are discussed.

INTRODUCTION

The CERN Super Proton Synchrotron (SPS) serves as the final acceleration stage for the LHC beams. Protons are accelerated from 26 GeV to 450 GeV before being delivered to the LHC through two distinct extraction systems. Within the framework of the LHC Injectors Upgrade (LIU) program, the SPS underwent several modifications, including the introduction of a new internal dump system. This updated dump system was conceived to facilitate the internal disposal of 25 ns beams with intensities up to 2.3×10^{11} p/b, accommodating a maximum of 320 bunches with potential emittances as low as 1.37 mm mrad [1].

Relocating the SBDS to Long Straight Section (LSS) 5 from LSS1 necessitated the incorporation of an additional vertical kicker (MKDV) and the development of a completely new absorber block to handle the augmented brightness. The existing dilution system, denoted as MKDH and comprising three 1.6 m tanks, remained unchanged but was relocated to the new dump position. This system's primary function is to diminish the particle density at the absorber block's front face.

The MKDH kickers are constructed using laminated steel plates and are available in two variants, differentiated by their lamination thickness. They possess a magnetic length of 1.256 m and are designed to achieve a magnetic field strength up to 1.5 T.

Following the resumption of operations after Long Shutdown (LS) 2, during which the SBDS received its upgrade, the LHC-type beam intensities were progressively increased during specialised measurement sessions. A notable observation was that as the intensity per bunch increased and the bunch length reduced, the vacuum pressure at the MKDH rose rapidly at every cycle, and in many cases went beyond the limit allowed for the safe operation of the kicker system, stopping machine operation.

Although this phenomenon has been noted in earlier instances with different kickers [2], it has yet to be replicated in simulations. The observed threshold effects related to both the intensity per bunch and bunch length remain unexplained by current models. A comparable behaviour was documented at RHIC [3], but one must exercise caution when drawing parallels due to significant disparities in beam type and energy.

This paper provides a comprehensive review of the observations gathered pre and post the SBDS upgrade. We delve into the specifics of the beam parameters recorded in the SPS and the corresponding response of the MKDH. Lastly, we outline the conditioning rate and detail the peak parameters achieved.

OBSERVATIONS PRE-LS2

The LHC demands a beam consisting of up to 288 bunches with a spacing of 25 ns, organised into 4 batches, or 6 batches

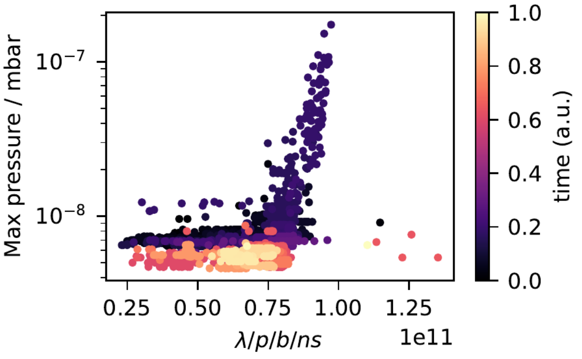

Figure 1: Maximum vacuum pressure recorded among all MKDH tanks as a function of the line density at 450 GeV for 72 bunches. The relative time with respect to the beginning of the year 2023 is shown as colour code.

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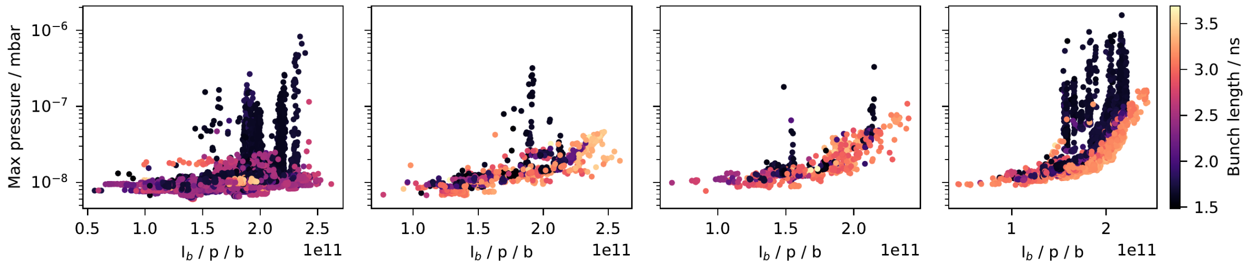

Figure 2: Maximum vacuum pressure recorded among all MKDH tanks as a function of the mean intensity per bunch measured at flat top in 2023, for different number of batches. The mean bunch length is shown as colour code. In each plot, the parameters shown are grouped by number of batches, starting at 1 (left) and ending at 4 (right).

when featuring a BCMS production scheme [4] (48 bunches). The acceptable bunch length for the LHC RF system is 1.65 ns. In 2008, during the preparation of LHC-type beams, the MKDV exhibited a rapid and significant increase in vacuum pressure. This increase was found to be exponentially related to both the intensity per bunch in the SPS and the bunch length of individual bunches. This pressure surge could be mitigated by conditioning the MKDV through the circulation of high-intensity beams. An exponential decrease in vacuum pressure was observed after just a few hours of consistent operation with unchanged beam parameters.

Over the years, the intensity per bunch in the SPS saw a consistent uptrend, attaining approximately 1.2×10^{11} p/b in 2017. In Fig. 1, the pressure measured at the MKDH kickers is plotted against the circulating mean line density ($\lambda = I_b/\sigma_L$), when up to 72 bunches were accelerated to 450 GeV. The colour-coding indicates the specific periods during which measurements were taken. After the kickers' exposure to high-intensity beams, the pressure increase is diminished for equivalent line densities. This shows the beam's conditioning effect on the MKDH's vacuum pressure rise.

OBSERVATIONS POST-LS2

The objective for HL-LHC is to attain a peak of 2.3×10^{11} p/b with a bunch length of 1.65 ns, culminating in a total of 288 bunches at an energy of 450 GeV in the SPS [5]. The entire machine requires conditioning to withstand such high intensities, and particularly critical components such as kickers, septa, and RF cavities are the most stressed during this procedure.

In the first two years after recommencing operations, the conditioning rate was hampered by one of the injection kickers, MKP-L. Its elevated longitudinal beam coupling impedance caused the MKP-L to reach its operational limits much more rapidly than other components, effectively constraining the time allotted for conditioning. However, during the annual maintenance window between 2022 and 2023, the MKP-L was replaced with a low-impedance variant [6]. This modification resulted in a substantial enhancement in the maximal integrated intensity the SPS could handle.

In this heightened operational state, the MKDH began to exhibit rapid pressure increase when the line density approached unprecedented levels within the SPS. As depicted in Fig. 2, this pressure surge demonstrates a distinct threshold effect, influenced by both intensity per bunch and bunch length, and the response varies depending on the number of batches. Intriguingly, the data suggests that minor adjustments in beam parameters can instigate a substantial alteration in pressure surges. To further refine the data and diminish uncertainties, it might be beneficial to employ more descriptive statistics beyond merely the mean to assess functional dependencies.

CONDITIONING EVOLUTION WITH 288 BUNCHES

After the replacement of the MKP-L, the conditioning of the MKDH in 2023 proceeded steadily and efficiently. One key change that facilitated this conditioning rate was the introduction of cycles with an extended flat top, although only reaching an energy of 400 GeV. Notably, conditioning seemed to be solely influenced by the bunch length and intensity per bunch, and was not energy-dependent. The extended flat top (4.8 s compared to the standard 0.5 s) resulted in prolonged high-pressure duration in the MKDH compared to routine operations. This adjustment ensured a more optimal use of machine time.

Figure 3 portrays the progression of optimal beam parameters over specified time intervals for 288 bunches. The relevant time interval was only considered when the line density in the SPS was within a 10% range of its maximum recorded value. Specifically:

$$t : \text{cycle where } \left|\frac{\lambda}{\lambda_{max}}\right| \le 0.1, \qquad (1)$$

where λ_{max} represents the highest line density achieved up to that point, and λ indicates the current line density. Using this metric for representing the temporal evolution, the 2023 increase in line density within the SPS appears almost monotonic. This relationship can be utilised to deduce the conditioning rate based on time and beam parameters.

To ascertain the conditioning rate and determine the standard error on such estimations, a Monte Carlo Markov Chain

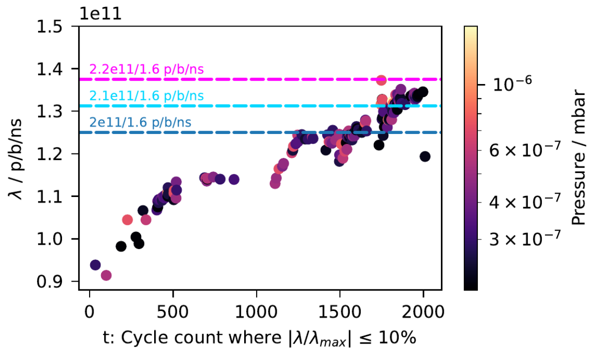

Figure 3: Evolution of maximum line density per cycle as a function of time metric t, as outlined in Eq. 1. The colour code indicates the maximum pressure recorded on the MKDHs.

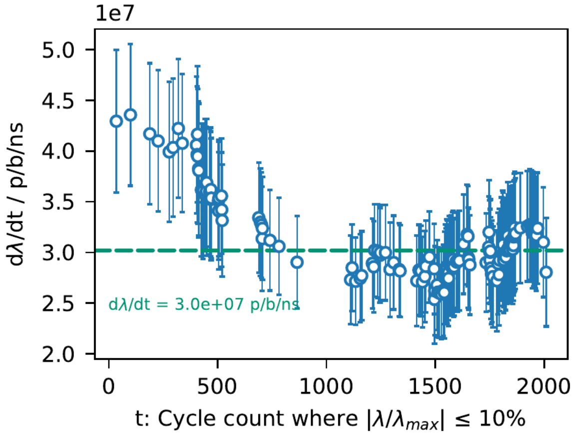

Figure 4: Maximum time variation of the maximum line density per cycle, $\frac{d\lambda}{dy}$ as a function of time variable t. The error bars represent the standard deviation of the estimation.

(MCMC) technique was employed. This method can be used to determine the distribution of possible best linear fits for selected time bins, utilising the maximum likelihood criterion based on available data. Figure 4 presents the conditioning rate as a function of t. An initial rapid conditioning phase is evident, this partially corresponds to the use of the extended flat top cycle. Subsequently, the conditioning rate decelerates, stabilising at $\frac{d\lambda}{dt} = 3 \times 10^7$ p/b/ns/cycle. This implies a potential rise of roughly 0.05×10^{11} p/b over 1.6 ns in 100 cycles, where the line density remains within 10% of its maximum recorded value.

Such rates can provide projections for conditioning durations, particularly if events like a magnet replacement or a vacuum chamber breach in a nearby sector occur. Assuming the initial conditions of the MKDH remain consistent and the SPS operates at approximately 50% efficiency, the time required to progress from 1.0×10^{11} p/b to 2.4×10^{11} p/b at a constant bunch length of 1.6 ns would span approximately 10 slots of 8 h each.

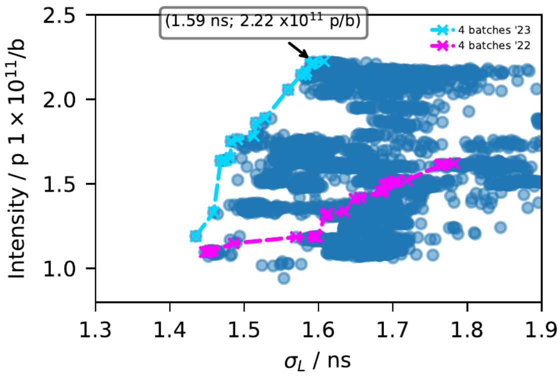

Figure 5: Map of the beam parameters recorded at flat top in the SPS in 2022 and 2023, namely intensity per bunch and bunch length σ_L. In cyan and magenta the pareto front for these two parameters is shown for 2023 and 2022, respectively.

HIGHEST BRIGHTNESS ACHIEVED

The advancements achieved in 2023 markedly surpassed prior efforts. The maximum beam parameters achieved with four batches, each consisting of 72 bunches, were an intensity of 2.22×10^{11} p/b and a bunch length of 1.6 ns (measured using the SPS Beam Quality Monitor). A visual representation of these parameters is provided in Fig. 5. Here, the Pareto front delineates the optimal beam parameters accomplished in both 2022 and 2023.

CONCLUSIONS

The SPS kickers, especially the MKDH, exhibit a pronounced vacuum pressure rise influenced by factors such as intensity per bunch, bunch length, and the number of bunches. The underpinning physical mechanism behind this behaviour remains elusive and does not align with existing models predicated solely on the electron cloud phenomenon. However, it has been observed that the vacuum pressure rise conditions over time, particularly with consistent exposure to certain parameters. This has facilitated the achievement of exceptional brightness levels in the SPS, reaching peaks of 2.22×10^{11} p/b in 1.6 ns for 288 bunches. Notably, a comparable behaviour has been documented in other facilities, yet the uniformity of the underlying physical mechanisms across facilities remains uncertain. To grasp this effect comprehensively and to characterise it fully, both in-situ and laboratory studies are necessary and will be undertaken in the following operational years.

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