HARDWARE LIMITATIONS AT INJECTION

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Abstract

Hardware limitations due to the intercepting devices in the SPS, the SPS-to-LHC transfer lines and the LHC will be briefly reviewed with potential operation beam in mind for 2018. Heating issues in the LHC injection kicker magnet (MKI) are also a possible future limiting factor for LHC's availability. Prior to LS1 one of the MKIs occasionally exhibited high temperatures leading to significant turnaround times before beam could be safely re-injected. After a successful impedance mitigation campaign during LS1, the MKI temperature has been below the Curie point and did not limit LHC availability: simulations suggest that they will remain fully operational with nominal Run 2 beam parameters. To investigate intensity limits in view of the 2018 run, different filling scenarios have been considered. A prototype MKI magnet, scheduled for installation during YETS 2017/2018, is upgraded to reduce dynamic vacuum activity and relocate beam induced losses within the magnet. The main design changes are outlined and the corresponding thermal behaviour and intensity limits are discussed.

INJECTION PROTECTION LIMITS

Hardware limitations assuring safe operation of the protecting devices of the SPS-to-LHC transfer system, have been thoroughly discussed in [1]. After the successful replacement of the SPS internal dump (TIDVG) the current limitation comes from the attenuation factor provided by the injection septum protection collimator (TCDI). Material damage tests, reported in [2], have set the acceptable brightness level to 288 bunches of 1.7×10^{11} protons and $3.5\mu m$ normalised emittance. Therefore the beam parameters of any operational scenario (subscript op) and the corresponding ones of the ultimate case (subscript ult) must satisfy the condition

$$\frac{I_{op} M_{op}}{\epsilon^n_{op}} \leq \frac{I_{ult} M_{ult}}{\epsilon^n_{ult}} \qquad (1)$$

where M is the number of injected bunches, ϵ^n the normalised emittance and I the bunch intensity.

To investigate possible brightness limitations in 2018, two filling schemes were considered, namely the BCMS and BCS schemes, assuming bunch intensities of 1.3×10^{11} and 1.4×10^{11} protons. For the emittances achieved thus far in the SPS [3,4], 4 BCMS batches of 1.3×10^{11} can be safely injected into the LHC, wheareas injecting 4 BCS batches the beam brightness levels will be close to the limit. Moreover, if the maximum achievable values are considered, then in both cases operation is limited to 3 batches per injection. Finally, pushing the bunch intensity to 1.4×10^{11} protons, both

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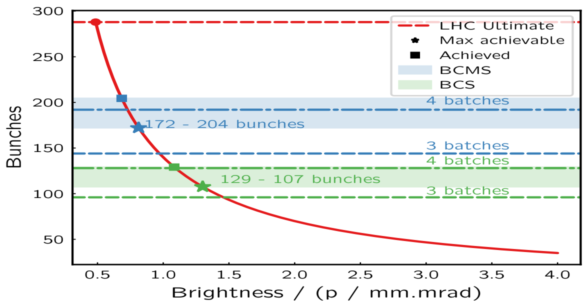
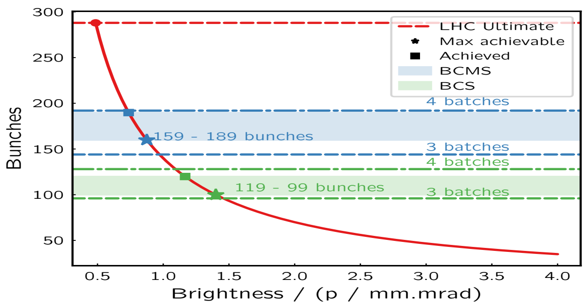


(a)



(b)

Figure 1: Maximum number of bunches as a function of bunch brightness for (a) 1.3×10^{11} and (b) 1.4×10^{11} protons per bunch.

with the currently achieved and with the maximum achievable emittance values, operation is limited to 3 batches per injection. The above conclusions are concisely summarized in Fig.1.

MKI BEAM INDUCED HEATING

High temperatures in the ferrite yokes of the MKIs can also potentially limit LHC's performance. Once the yokes have exceeded their Curie temperature (T_c), their magnetic permeability is significantly decreased leading to a misinjected beam that may damage neighbouring equipment. Therefore, in the absence of active cooling in the magnet, long turnaround times may be necessary to ensure sufficiently low temperatures in the yokes.

Temperatures in 2017

To monitor the reached temperatures, two thermal probes (PT100s) are currently installed per end of each kicker magnet (4 kickers per injection point). In agreement with simulation predictions, the upstream end probes are showing consistently higher temperatures than the downstream ones and therefore are of primary concern. Nonetheless, since the ferrite yokes are pulsed at high voltage (HV) during op-

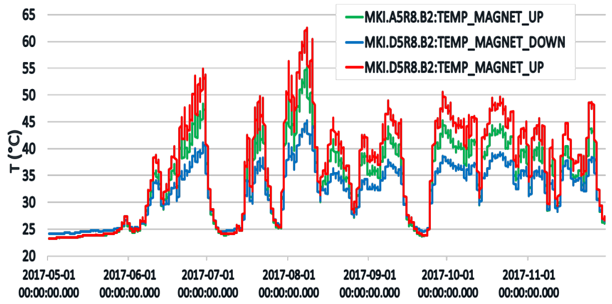


Figure 2: Measured temperatures in the three hottest MKI magnets during 2017.

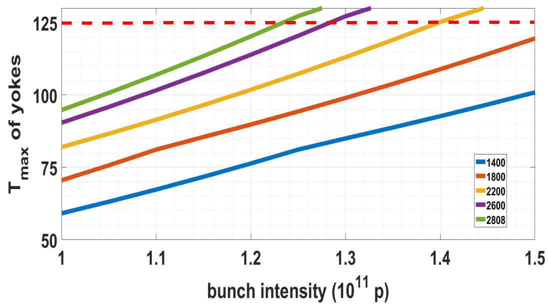
eration, the probes are placed at neighbouring locations at ground potential, thus providing only indirect temperature measurements. The temperatures of the two hottest MKI's during 2017 are shown in Fig.2. In the same graph, the temperature difference between the upstream and downstream ends of the magnet is also presented.

Due to the criticality of the yoke temperatures on the performance of the MKI, and thus on the safety of the LHC, an interlock is activated when measured temperatures exceed pre-set SIS (Software Interlock System) thresholds, defined separately for each of the 8 magnets. Initially, the thresholds were set to values that, by experience and early simulations, ensured good operation of the kickers and are being adapted ever since. Once they are exceeded during operation, a Soft Start is run following the beam dump, whose analysis can determine the status of the yokes. According to the outcome of the analysis, either the thresholds are increased, in case the ferrites are below their T_c, or LHC operation is stalled until the MKIs have cooled down sufficiently. In 2017 the analysis was to a big extent automated and an operator can determine the status of the yokes within a few minutes.

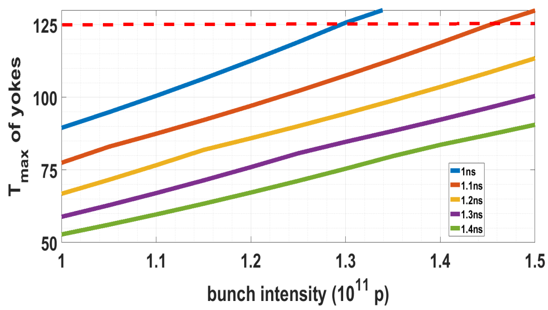
During 2017 the MKI temperatures have not limited LHC's availability. However, the SIS thresholds of the MKI8D magnet, the one constantly exhibiting the highest temperatures, have been exceeded twice in August, when the peak values for the year were reached. Although concerns were raised at the time, excess of the thresholds does not imply per se that the MKI yokes are above their T_c. Instead, it indicates that temperatures higher than before have been reached, on a specific magnet, and further analysis is required to evaluate the status of its yokes.

Intensity margins for Run 2

To investigate intensity limitations due to heating of the MKI yokes in future LHC operation, an analysis combining electromagnetic and thermal simulations was performed. The bunch intensity, the total number of bunches and the bunch length are the main beam parameters that determine the RF power loss and consequently the produced heating. Due to the a priori unknown duration of a fill, a steady state approach was adopted as a worst case scenario [5], assuming constant peak bunch intensity and bunch length throughout the fill. Although the approach may seem conservative, validation of the model is currently ongoing and the predicted numbers need to be treated with caution. Operational experience in 2018 with the upgraded magnet (see next section) will be of significant importance in the validation process.



(a)



(b)

Figure 3: Maximum MKI yoke temperature dependence on bunch intensity for (a) 1ns bunches and different number of bunches (b) 2556 bunches and different bunch lengths. The dashed line indicates the Curie temperature of the MKI ferrite yoke (T_c = 125°C).

To estimate the expected temperatures for the various scenarios and beam parameters using the steady state approach, Figs.3a and 3b show the maximum temperature of the hottest yoke as a function of the bunch intensity, for different number of bunches and bunch lengths respectively, while keeping the other parameter fixed to 1ns and 2556 bunches. For the rest of Run 2, the BCMS filling scheme is most likely to be used for which the nominal number of bunches is 2556 [4]. From Fig.3a it is suggested that for 1ns bunch length, the bunch intensity can marginally go up to 1.3×10^{11} protons, while increasing the bunch length to 1.1ns can potentially allow for bunch intensities even up to 1.4×10^{11} protons. Therefore it can be concluded that for the rest of Run 2 the MKI temperatures are not expected to be a limitation for LHC's availability, and at the same time there is still some margin towards higher bunch intensities.

UPGRADED MKI

What is new?

An upgraded MKI was installed in the LHC tunnel during the YETS 17/18 [6]. The new magnet has a Cr_2O_3 coating

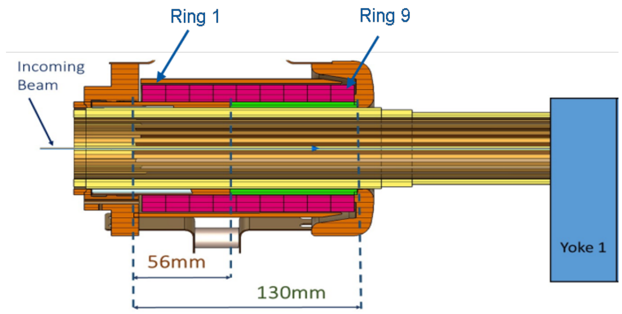


Figure 4

Figure 5: Simplified schematic of the MKI beam screen for the existing (130mm) and the upgraded magnet (56mm).

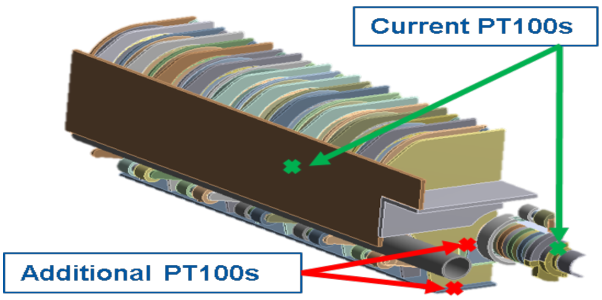


Figure 6

Figure 7: improved instrumentation of the upgraded MKI.

on the inner part of the ceramic tube that is placed along its length and serves as a support to the NiCr conducting wires that shield the particle beam from the ferrite yoke. Due to its higher surface conductivity, compared to Al_2O_3, it is expected that the coating will improve the HV behaviour of the kicker leading to a reduction of flashovers and an increase in the dielectric breakdown voltage. At the same time, the coating is foreseen to provide a significant reduction of the secondary electron yield (SEY) of the ceramic tube, which will subsequently improve the dynamic vacuum pressure of the magnet.

In addition, the beam screen design is altered compared to the one implemented in the existing magnets [7]. The new design is expected to reduce the produced RF losses while at the same time relocating them to more easily cooled areas. The proposed change is a crucial part of the baseline design of the kicker for HL-LHC operation. Therefore, operational experience with LHC type beams will be of paramount importance in the validation process of the followed approach. Lastly, the upgraded kicker will be equipped with two additional PT100's in optimized locations, as shown in Fig.6, to improve the accuracy of the evaluation of the model.

The upgraded magnet was installed in IP8 and replaced the existing MKI8D module. This choice was made because MKI8D has been consistently exhibiting with the highest measured temperatures and dynamic vacuum pressure.

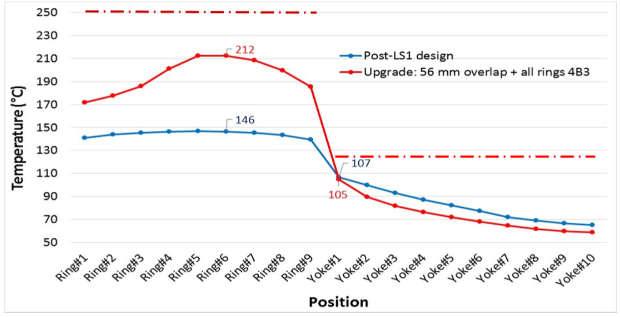


Figure 8: Predicted maximum temperatures for critical components of the MKI for the current (blue) and the upgraded (red) design. The Curie temperature of each component is depicted in dotted lines.

Predicted temperatures

A similar thermal analysis was carried out to estimate the temperatures that the new kicker would reach when long fill times are assumed. The results, shown in Fig.8, indicate that all the yokes will remain below their T_c when operated with nominal Run 2 beams.

However, in the new design, the nine ferrite rings that are placed at the upstream end of the magnet are heating significantly more than in the current design. To assess its influence on the vacuum pressure, an outgassing analysis was subsequently performed. It was shown that the resulting difference would be negligible and the vacuum pressure will not be jeopardized, possibly due to the small volume of the rings.

CONCLUSIONS

The main hardware limitations at injection for 2018 were reviewed. The main protection system limitation comes from the attenuation provided by the septum collimator (TCDI) and it is expected to limit the allowed injected BCMS batches to 4 when operating with $N_b = 1.3 \times 10^{11}$ and to 3 when the bunch intensity is increased to 1.4×10^{11} protons. For the BCS scheme and for both intensity values, only 3 batches are allowed.

As far as the LHC injection kickers are concerned, during 2017 the temperatures of the MKIs have not limited LHC's availability. Although SIS thresholds were exceeded twice, following an established and standard procedure it was concluded that the yoke's T_c had not been exceeded and operation could have continued uninterrupted. According to simulations, the MKIs are expected to operate safely with the proposed beams for 2018 and some intensity margins are also possible.

An upgraded kicker was installed in YETS 17/18. The upgrades are expected to lead to improved HV and vacuum behaviour of the kicker while at the same time reducing the RF losses. Thermal simulations also suggest that neither the upgraded magnet will limit LHC's availability during 2018.

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