ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPAF021

IDENTIFICATION AND REMOVAL OF SPS APERTURE LIMITATIONS

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Abstract

The CERN SPS (Super Proton Synchrotron) serves as LHC injector and provides beam for the North Area fixed target experiments. Since the 2016 run automated local aperture scans have been performed with the main focus on the vertical plane where limitations typically arise due to the flat vacuum chambers in most SPS elements. For LHC beams the aperture limitations with the present low integer tune optics also occur at locations with large dispersion. Aperture measurements in the horizontal plane using a variety of techniques were performed and showed surprising results, which could partially explain the unexpected losses of high intensity LHC beams at the SPS flat bottom. In this paper, reference measurements from 2016 are compared with the ones taken at the beginning of the run in 2017. Several aperture restrictions in the vertical plane could be found and cured, and a potential systematic restriction in the horizontal plane has been identified. The results of the measurements and the origin of the restrictions are presented in this paper, and the outlook for partial mitigation is discussed.

INTRODUCTION

The Super Proton Synchrotron (SPS) at CERN delivers beam to the North Area fixed-target experiments using resonant slow extraction. It serves also as LHC injector and provides beam to the HiradMat [1] and AWAKE [2] facilities. The proton beams for fixed target physics are injected on the so-called Q26 optics at a momentum of 14 GeV/c and need to cross transition at $\gamma_t = 23.2$ in the early part of the acceleration to the 400 GeV/c extraction momentum.

The dipole magnets are equipped with flat vacuum chambers such that the acceptance in the vertical plane is smaller than in the horizontal plane by design and is critical for fixed target beams. The requested intensities for fixed-target physics range from 3 to 4×10^{13} protons per cycle with typically 3300 cycles per day. Due to the high intensity and high duty cycle of the fixed-target beams, beam loss in the SPS has to be kept as low as possible to limit activation of the ring.

For all single and multi-bunch LHC-type beams (destination LHC, HiRadMat, AWAKE) the SPS is operated with the lower transition energy optics Q20 [3] ($\gamma_t = 18$) for beam stability reasons. The beams are injected above transition energy at a momentum of 25.92 GeV/c. Figure 1 shows the comparison of the horizontal dispersion function for Q26 and Q20. The peak dispersion reaches ≈ 8 m in Q20 wrt to 4 m in Q26. The minimum beta function is also slightly larger in Q20. For LHC beams the critical parameter in terms of aperture is momentum acceptance. With high intensity beams of $\approx 2 \times 10^{11}$ protons per bunch and 288 bunches

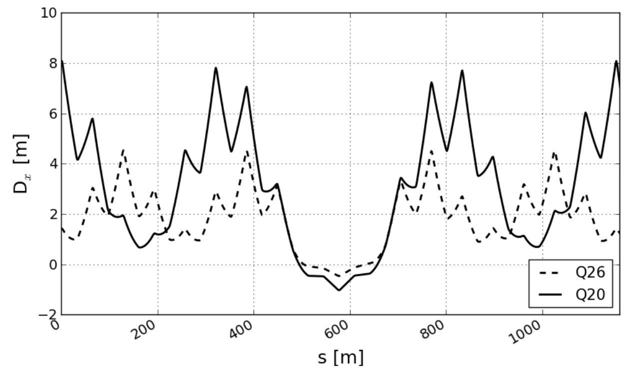

Figure 1: Comparison of dispersion function in optics Q26 and Q20 for one sextant in the SPS.

roughly 15 % of the beam are lost at the momentum aperture at low energy.

Automatic local aperture scans are carried out every start-up and before the end of each run. The applied technique which is based on optimized bump scans is described in [4]. In the following the results of vertical and horizontal aperture scans carried out during the 2017 SPS run and beginning of 2018 will be presented.

EVOLUTION OF VERTICAL APERTURE IN THE SPS

In [4] the first results of local vertical aperture scans from the 2016 SPS run were presented. At the beginning of the 2017 run, the aperture scan was repeated and the 2016 bottlenecks were confirmed in cells 107, 133, 331 and 423. An additional severe restriction was found in 511. Figure 2 shows the total measured aperture at all QD locations for the beginning of the year 2017, the end of 2017 and beginning of 2018 scaled to the location of the transition from dipole type MBA to MBB within the FODO cell where the aperture bottleneck is expected. The aperture restrictions in 511 and 133 were repaired in the course of 2017. The problem at 511 was due to non-conform RF fingers [5]. The restriction in cell 133 was only removed when MBA.13370 was exchanged during the technical stop in July 2017. During the winter shutdown 2017-18 all other remaining bottlenecks were examined and repaired where possible. The 2018 scan (green curve in Fig. 2) revealed that only the aperture restriction in 423 had however been cured with the interventions during the stop.

Another important result of the measurements since 2016 is that the SPS mechanical aperture is remarkably stable and the result of the now well established aperture measurement technique is reproducible from year to year.

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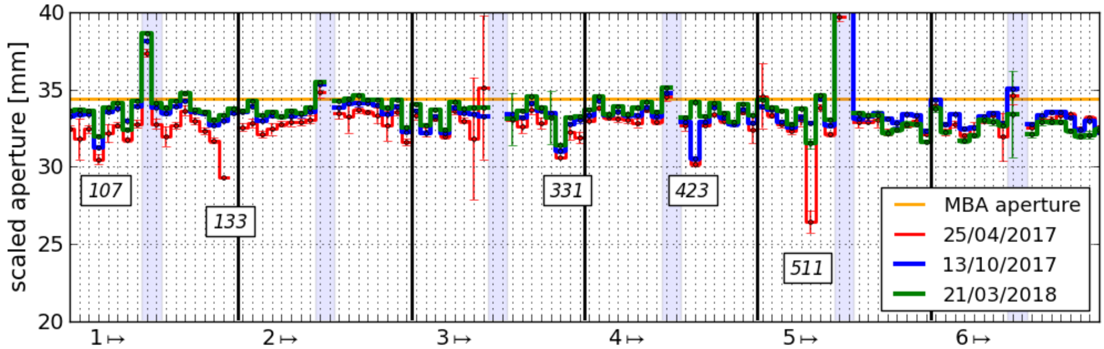

Figure 2: Total vertical aperture measured at all defocusing quadrupole locations at the beginning of the 2017 run in red, end of the 2017 run in blue and beginning of the 2018 run in green scaled to the location of MBB-MBA transition where the aperture bottleneck is to be expected. The numbers 1 - 6 on the bottom of the plot indicate the corresponding sextant. The shaded areas correspond to the long straight sections (LSS). The aperture of the MBA vacuum chamber is also indicated.

HORIZONTAL APERTURE IN THE SPS

For the Q20 optics the horizontal aperture limitation in the SPS is expected to be at or in the vicinity of the defocussing quadrupoles. A measurement of the global momentum aperture with LHC beam at injection energy revealed that less aperture is available for negative momentum offset than for positive one, see Fig. 3. To find the origin of the asymmetric restriction in the horizontal plane, the mechanical aperture in the horizontal plane was scanned at every QD around the ring (except the areas of the long straight sections with large aperture but also sensitive equipment) with the automatic bump scan technique as used for the vertical scans.

To have sufficient corrector strength, low intensity fixed target beam of $\approx 5 \times 10^{11}$ at 14 GeV/c was used with Q26 optics. Four-corrector bumps were applied at the different QD locations in the positive and negative direction. Figure 4 shows an example of such a bump and the surrounding horizontal aperture. The maximum possible amplitude at the QD in this bump configuration, optics and energy is 40 mm compared to $r = 42$ mm aperture in the QD short straight section vacuum chamber.

In addition, the orbit was recorded at the start of the measurement campaign to correct the obtained aperture values accordingly and derive the aperture available towards the inside and outside of the machine instead of only quoting the total aperture as for the vertical aperture results earlier.

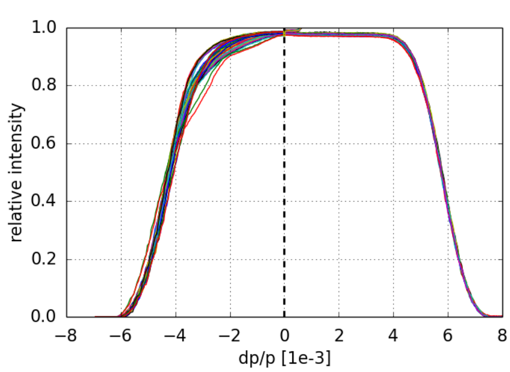

Figure 3: Normalized beam intensity evolution as a function of programmed momentum offset at 26 GeV/c for Q20.

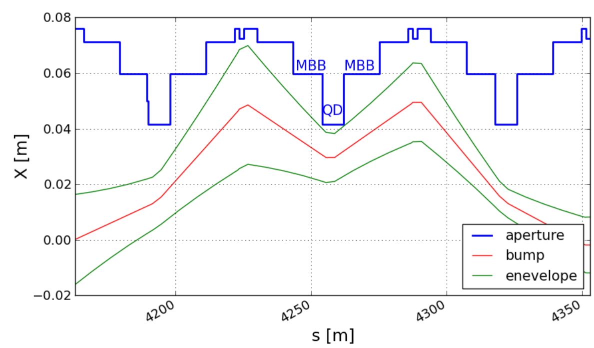

Figure 4: Mechanical aperture in the SPS FODO cells in the horizontal plane with four-corrector bump and beam envelope in the Q26 optics. The bump will touch the aperture of the vacuum chamber in the QD short straight section first before reaching the aperture elsewhere in the FODO cell.

Results

Figure 5 shows the results of the aperture measurements in the horizontal plane corrected for the orbit on the measurement cycle. The red curve gives the results at the various QD locations towards the inside of the machine and the blue curve towards the outside. The inner aperture was found to be systematically at least $\approx$ 5 mm smaller than the one towards the outside. Using this data and compiling the available aperture based on the Q20 optics information and assuming typical LHC high intensity parameters of a normalized emittance of $\varepsilon = 2\,\mu$m, 2-mm orbit error and a momentum spread of $\delta p/p = 1.5$ ‰(rms), results in only 3.8 σ available aperture towards the inside. The aperture towards the outside corresponds to 4.9 σ with these assumptions.

The limited horizontal aperture explains the observed reduction of transmission for LHC beams with larger transverse emittances [6]. The aperture data can also be used

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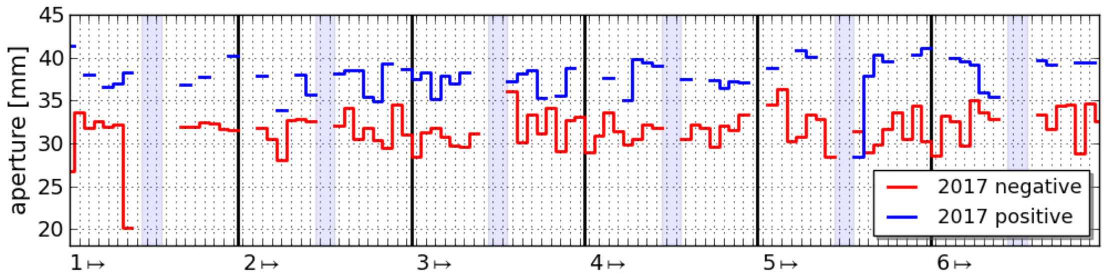

Figure 5: Horizontal aperture at QD locations: the red curve is the mechanical aperture towards the inside of the machine and the blue curve towards the outside from the theoretical beam axis. The numbers 1 - 6 on the bottom of the plot indicate the number of the corresponding sextant. The shaded areas correspond to the LSS.

Table 1: Available aperture in the horizontal plane for different optics based on the aperture measurement at defocusing quadrupoles around the ring, assuming 2 mm orbit error, $\varepsilon = 2\,\mu$m emittance and 1.5×10^{-3} momentum spread (rms).

optics	**dp/p acceptance** $[10^{-3}]$	**apeture** $[\sigma]$
Q20	-5.9 / +7.6	-3.8 / +4.9
Q22	-7.3 / +9.0	-4.8 / +5.8
Q26	-13 / +17	-8.3 / +10.5

to calculate the available momentum aperture in terms of momentum offset dp/p. The result is -5.9 to 7.6 ‰, which confirms what was measured in the global momentum aperture scan in Fig. 3. The main results are summarized in Table 1, where the measured data is translated into available aperture for the optics Q20 and Q26 as well as the intermediate γ_t optics Q22 for comparison [7]. With Q26 no aperture limitation is expected for the assumed beam parameters. Q22 would result in roughly 1 σ more aperture.

ORIGIN OF ASYMMETRIC HORIZONTAL APERTURE

The origin of the asymmetric horizontal aperture at the QD locations is a flange with an eccentric bellow between the elliptical MBB vacuum chamber and the round QD vacuum chamber, see Fig. 6. The center of the MBB vacuum chamber is aligned towards the outside by 4.5 mm at the magnet extremities to compensate for the beam sagita in the center of the magnet. The flange provides the translation from the off-axis MBB vacuum chamber to the on-beam-axis QD vacuum chamber, but the flange's center is aligned with the center of the MBB chamber. Roughly 5 mm of aperture are missing on the inside of the flange.

The losses with high intensity LHC beams at low energy are most likely due to uncaptured beam from injection or losses out of the bucket on the injection flat bottom [8, 9]. An increased momentum aperture will give more flexibility to optimize transmission with RF voltage. The Q26 optics with higher momentum acceptance is however not an option due to insufficient beam stability for the intensity required for future LHC beams. For the upgrade of the SPS as part of the LHC injector upgrade (LIU [10]) it is hence foreseen to change the flange design between the MBB and the QD short straight section at the 25 most critical locations with the highest dispersion in the Q20 optics and the smallest mechanical aperture. The list of locations is given in [11].

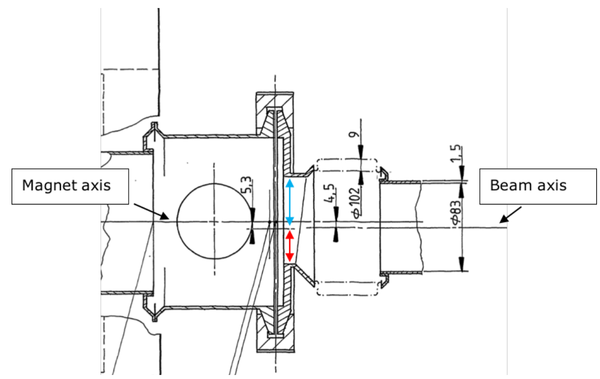

Figure 6: Drawing of topview of the QD drift flange which provides the translation of the off-beam-axis vacuum chamber of the MBB on the left to the on-axis vacuum chamber of the QD on the right hand side. Roughly 5 mm of aperture are missing on the inside of the flange.

SUMMARY

The vertical aperture is measured routinely at all defocusing quadrupoles in the SPS since end of 2016. The measurements are remarkably reproducible. Based on these results several vertical aperture restrictions could be removed during machine stops.

For the first time aperture measurements were also carried out in the horizontal plane at the locations of defocusing quadrupoles to understand the high losses on momentum aperture for high intensity LHC beams in Q20 optics. A systematic reduction of the aperture towards the inside of the machine was found which was traced back to the flanges with eccentric bellow used between the MBB and QD vacuum chambers. A modified design for these flanges will be installed during the next long shutdown at the 25 most critical QD locations with the largest dispersion in Q20 and smallest mechanical aperture.

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