AUTOMATIC LOCAL APERTURE MEASUREMENTS IN THE SPS

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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. It is equipped with flat vacuum chambers to accommodate the large horizontal beam size required during transition crossing and slow extraction. At low energy, the vertical acceptance becomes critical with high intensity large emittance fixed target beams. Optimizing the vertical available aperture is a key ingredient to optimize transmission and reduce activation around the ring. Aperture measurements are routinely carried out after each shutdown. Global vertical aperture measurements are followed by detailed bump scans at the locations with the loss peaks. During the 2016 run a tool was developed to provide an automated local aperture scan around the entire ring. This allowed to establish detailed reference measurements of the vertical aperture and identify directly the SPS aperture bottlenecks. The methodology applied for the scans will be briefly described in this paper and the analysis discussed. Finally, the 2016 SPS measured vertical aperture will be presented and compared to the results obtained with the previous method.

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 at a momentum of 14 GeV/c and need to cross transition in the early part of the acceleration to the 400 GeV/c extraction momentum. 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.

The shape of the vacuum chambers follows the beam size variation around the ring circumference and the aperture with the flat vacuum chambers in the dipole magnets is optimised to accommodate the horizontal beam size during transition crossing and slow extraction. By design the acceptance in the vertical plane is smaller than in the horizontal plane. At low energy any further reduction of the vertical aperture due to orbit and misalignments directly translates into increased losses. The SPS vertical aperture bottleneck is expected to be at the TIDVG internal beam dump (vertical aperture of 42 mm).

The ≈ 7 km circumference SPS has a regular FODO lattice with one long straight section (LSS) per sextant. The SPS FODO cell consists of a focussing main quadrupole followed by two main dipoles of type MBA, then two main dipoles of type MBB and the defocusing main quadrupole followed by two MBBs and finally two main dipoles of type MBA. The MBB has a gap height of 48.5 mm and the MBA dipole of 34.5 mm. There are 18 cells per sextant. With the fixed-target beam optics, the phase advance per cell in the horizontal and vertical plane is close to 90 degrees. The QF short straight sections contain a horizontal dipole corrector magnet and beam position monitor (BPM) and the QD short straight sections a dipole corrector and BPM in the vertical plane.

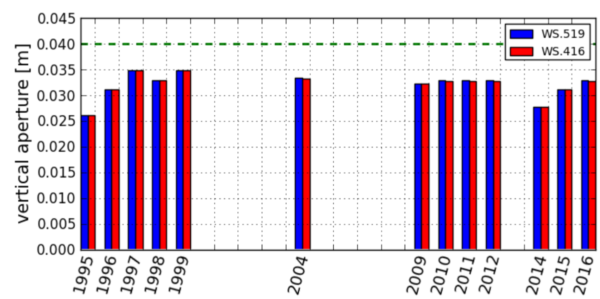

Figure 1: Result of global aperture measurement in the vertical plane with wire scanners 416 and 519 for the different SPS runs scaled by the beta function to the location of the internal beam dump TIDVG. The dashed green line indicates the aperture at the TIDVG minus 2 mm to account for the misalignment.

Global Aperture Measurements

The vertical acceptance of the SPS varies from year to year due to several reasons such as changes in the machine alignment and installation of new equipment. As part of the yearly start-up procedure the vertical aperture is assessed with the traditional global aperture measurement technique. Low intensity fixed target beam at 14 GeV/c is excited with the tune kicker, left to filament and fill the aperture. The vertical SPS wire scanner is then used to measure the beam profile, that has been cut at the restrictions around the machine. The full width of the beam profile corresponds to the vertical aperture limit of the machine scaled to the beta function at the wire scanner location. Figure 1 shows the results of these measurements for the different SPS runs measured with two different wire scanners. The results are scaled to the TIDVG location by the beta function. The aperture varies between 27 to 35 mm, compared to the TIDVG aperture of ≈ 42 mm. Both wire scanners give similar results, but the available aperture is consistently significantly smaller than the theoretical value.

The global aperture measurement technique has the advantage of being fast and simple. Unfortunately the bottleneck locations cannot always be resolved with this technique as the coverage and resolution of the SPS beam loss monitor system is insufficient. To overcome this limitation, an additional aperture measurement technique was put in operation

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during the SPS run of 2016 - the automatic local aperture measurement.

AUTOMATIC LOCAL APERTURE MEASUREMENTS

The automatic local aperture measurement tool is based on applying three-corrector-bumps at all quadrupole locations around the SPS. The bump amplitudes are increased linarely during the measurement period and the evolution of the beam intensity in the SPS is recorded. The amplitude is either increased from 0 mm to the maximum corresponding to the corrector circuit current limit or decreased from 0 mm to the minimum.

The mechanical aperture at a given location corresponds to the bump amplitude, where the intensity drops to zero as the entire beam is scraped off. A typical intensity evolution during a bump scan is plotted in Fig. 2. This method is independent of the transverse beam distribution, that can vary from shot to shot, but requires sufficient corrector strength.

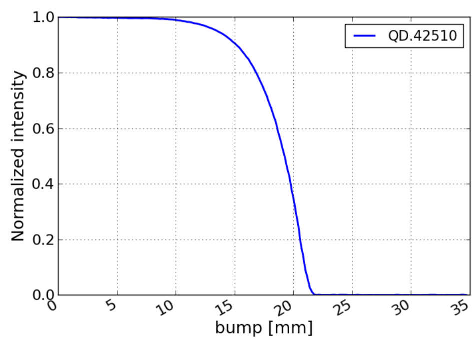

Figure 2: Intensity evolution during the scan of the amplitude of a three-corrector bump at location of QD.42510.

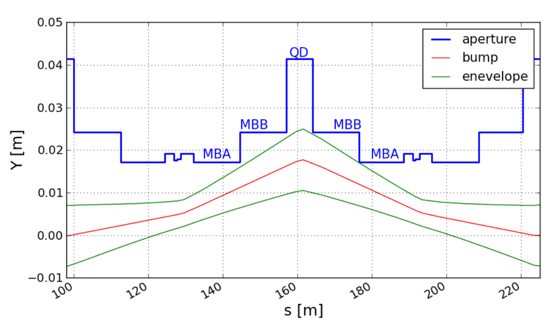

Figure 3: Mechanical aperture in the FODO cell of the SPS in the vertical plane with three-corrector bump and beam envelope. The bump will touch the aperture at the MBA to MBB or QD to MBB transition before reaching the QD aperture.

Limitations

The SPS orbit corrector magnets are limited to ±3.5 A. For proton fixed-target beams, injected at 14 GeV/c and optics Q26, the maximum possible three-corrector-bump amplitude is thus ± 35 mm. This is sufficient for the vertical plane to probe the mechanical aperture, but not for the horizontal one given the vacuum chamber dimensions.

The other limitation arises from the fact that the three-corrector-bumps span two SPS FODO cells and the mechanical aperture changes along a cell. In fact the bump as used during the scan does not probe the aperture of the defocusing quadrupole QD, but of the transitions from the QD to MBB vacuum chamber or from the MBB to MBA type of main dipoles as indicated in Fig. 3. In the current implementation of the tool the location of potential aperture bottlenecks that are found during the aperture scans cannot be better localised than to the region comprising the half cell upstream and downstream of the QD. The option to apply asymmetric bumps with four correctors to further localise the aperture restriction could be made available in an upgraded version of the local aperture measurement tool.

RESULTS

The above introduced aperture measurement technique was developed, tested and finally deployed during the SPS run 2016. Low intensity 2 μs long MTE [3] beam of an intensity of $2-3\times10^{11}$ protons was used in a test cycle with a 3.6 s long 14 GeV/c plateau. The locations of all 108 defocussing quadrupoles of the SPS were scanned in positive and negative direction. Each scan was repeated 3 times for statistics. The error bars in the plots only contain the statistical errors.

The CERN accelerator control system provided all building blocks required for the automatic aperture scan. The YASP steering program includes an automatic bump scan routine. YASP relies on the LHC software architecture (LSA) framework [4] which allows to configure knobs, i.e. bumps, to be applied in a user defined manner over time. An additional JAVA application had to be prepared to record the beam intensity measurement through the cycle and associate the data with the bump amplitude and the bump location name.

Two measurement series were carried out towards the end of the run in 2016, one on 18^{th} of October and the second one on 22^{nd} of November. The aperture was analysed as total aperture per location by combining the result of the positive and negative scan to be independent of the actual orbit on the test cycle. The total aperture measured at the different QD locations for the two scans is shown in the upper plot of Fig. 4. At the locations were no measurement point is indicated, the aperture was either never reached or the quality of the measurement was inadequate. In the long straight sections of every sextant, the QDs of half cells 17 and 19 are not neighboured by dipoles. Thus the aperture is larger than elsewhere and the correctors there are not strong enough to reach the mechanical aperture of the QD chamber itself. The exception is LSS1 where the SPS internal beam dump TIDVG is installed. The aperture at location QDA.11910 is much reduced because of it. Table 1 summarises the

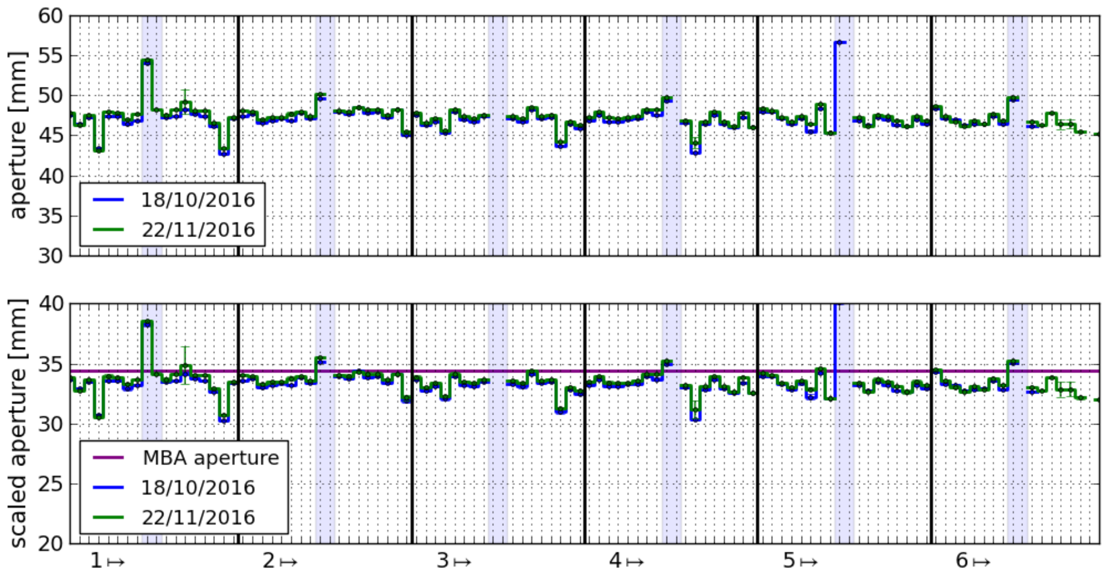

Figure 4: Total aperture measured at all defocusing quadrupole locations on 18^{th} of October in blue and on 22^{nd} of November in green. The numbers 1 - 6 on the bottom of the plot indicate the number of the corresponding sextant. The shaded areas correspond to the LSS. The lower plot shows the aperture measurements scaled to the location of the MBB-MBA transitions. The aperture of the MBA vacuum chamber is also indicated

4 locations found in the scans with the smallest vertical aperture around the ring.

As can be seen from the upper plot of Fig. 4, the aperture measurement is reproducible within typically better than 0.5 mm. Part of the measurement accuracy limitation comes from the noise on the BCT, which is in the order of $\approx 5\times 10^8$ protons. The error bars in the plot do not indicate the error from the BCT resolution. More studies need to be carried out in 2017 to define the systematic error of the new measurement technique.

The consistency of the obtained results was cross-checked by scaling the obtained bump values at the QD locations to the locations of the MBB-to-MBA transitions as indicated in Fig. 3, where the beam loss should occur. Ideally the scaled values should be equal to the MBA aperture at this location. The aperture is however smaller than it should be at almost every location, see Fig. 4 (lower plot).

Table 1: The four locations with the smallest vertical aperture in the SPS in 2016

location	aperture [mm]	error [mm]
QD.13310	43.1	± 0.5
QD.10710	43.3	± 0.2
QD.33110	44.6	± 0.6
QD.42310	45.2	± 0.7

The local aperture measurements suggest that the aperture bottleneck of the SPS is not at the beam dump, but at locations close to QD.10710 and QD.13310. Roughly 4 mm of aperture are missing at these locations. The total aperture measured at location QDA.11910 of 48.2 mm corresponds to $\approx$ 42.5 mm aperture at the center of the internal beam dump TIDVG, but 45.3 mm at the exit of the TIDVG, where the aperture bottle neck is supposed to be located. The theoretical aperture there is 42 mm. This inconsistency will have to be further investigated in 2017.

SUMMARY

Optimising the vertical acceptance in the SPS is fundamental for minimising losses with high intensity fixed-target beams at low energy. An automated tool for measuring the local aperture at all defocusing quadrupoles was developed and tested in 2016. The results show that the vertical aperture bottleneck of the SPS is not at the internal beam dump TIDVG, but in the vicinity of QD.13310 and QD.10710. Also in sextant 3 and 4 bottlenecks were found. A reference measurement for the next SPS runs could be established, that together with the new aperture measurement technique will allow to track the evolution of the SPS aperture in an adequate way.

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