CHARACTERISATION OF THE OPTICS OF THE TT24 AND P42 BEAMLINES IN THE CERN SPS NORTH AREA

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Abstract

400 GeV protons extracted from the CERN SPS are transported to the T4 target via the TT20 transfer line. The P42 beamline then transports the protons that did not interact in the T4 target to the T10 target. During operation in 2021 and 2022, higher than expected beam losses were measured, in addition to the increased beam spot size that had previously been observed. It was previously suspected that the optics between TT24 and P42 might not be well matched but due to a lack of instrumentation this was not confirmed. The recent installation of additional beam profile monitors (BSG) in the P42 beamline has allowed the present optics to be evaluated for the first time. In addition, magnet response functions have been re-measured and updated. A kick response study was performed using corrector dipoles to kick the beam with the subsequent displacement measured on the BSGs. The dependence between the kick and the beam position was used to fit a MADX optics model of TT24 and P42. Quadrupole scans were then performed to determine the initial conditions of the model. These results are presented in this paper.

INTRODUCTION

The Physics Beyond Colliders (PBC) project was setup in 2016 to explore ways to exploit the full physics potential of CERN's facilities and accelerator complex [1]. One major proposal to emerge from PBC is to install a higher intensity experimental facility in the existing ECN3 cavern, presently hosting the NA62 kaon experiment [2]. A task-force was established to investigate the feasibility of the new facility, known as HI-ECN3 [3]. Three experiments were proposed to be housed in HI-ECN3 [4], with the Search for Hidden Particles experiment (SHiP) selected in 2024 [5].

SHiP requires a proton beam with very different properties to NA62, which may necessitate changes to the present optics in the beamlines transporting protons from the SPS to ECN3, TT20 and P42. Implementing optics changes will require good knowledge of the existing optics and initial conditions.

OPTICS STATUS

For nominal operation, the beam in TT20 is split by two sets of septa magnets, so-called splitters, sharing the beam between the three NA targets [6]. Protons heading towards ECN3 pass through both splitters. Following the second splitter, the protons are transported through TT24 to the T4 target, then through P42 to the T10 target. To reduce beam loss induced activation of equipment, a dedicated beam delivery scenario for HI-ECN3 has been conceived where the beam is transported un-split through the splitters and bypasses the T4 target [3].

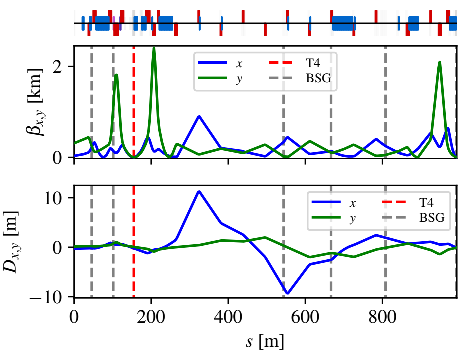

Figure 1: Dedicated optics through TT24 and P42.

The optics for the dedicated beam in TT24-P42 are shown in Fig. 1. Presently the optics in P42 are unchanged from the split optics. For maximum secondary production, there is a strong vertical focus at T4 and a strong focus in both planes at T10. The focuses necessitate the expansion of β_y to ~2 km in the regions upstream and downstream of the targets. These regions are thus sensitive to optics errors. The horizontal dispersion is dominated by large horizontal bends in P42 and grows to a magnitude of ~10 m. During commissioning, quadrupoles Q1 and Q2 in P42 are tuned to match the beam spot on T10. Changes to the optics, reducing the sensitivity and decreasing the magnitude of dispersion have been proposed [7]. Additionally new power converters are to be installed during Long Shutdown (LS) 4, allowing pulsed operation of different optics between cycles.

Following LS2, substantial issues were observed with beam transport in P42 [8]. The source was eventually found to be scattering on a broken vacuum chamber, which has since been removed. Although the beam quality is now adequate for the rest of the NA62 experimental run, the issues motivated a study of the TT20 and P42 optics. Kick response (KR) scans were done in TT20 for both split and dedicated optics using secondary emission monitor grids (BSG) to record beam profiles [9, 10], showing a substantial difference between the MADX model and the real optics in TT24. Quad scans were performed in TT24, with the beam size at T4 measured using a BBS wire scanner [11]. Again large discrepancies between the model and data were seen.

Numerical studies of the errors in MADX suggested that the transfer function (TF), between current and field gradient

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in the QNL and QTL magnets installed in TT20 was the leading error source. The magnets are similar in design and the currents were set with the same TF in the LSA database [12]. Due to the age of the magnets, only limited documentation was available. Therefore, in 2023, the integrated field gradient of the QNL [13] and QTL [14] magnets as a function of current was re-measured, shown in Fig. 2. The integrated field was similar for both magnets, with a maximum discrepancy of 0.38%. However, the TF used to set the magnets in LSA was very different. The difference grows as the magnet becomes saturated, with a maximum discrepancy of 3.5% and 3.9% respectively. It should be noted that QNL magnets in P42 were set using a different TF (QNN), based on measurements taken in 2014. The QNN TF shows good agreement to the 2023 measurements to ~400 A. The TF for the other quadrupole type in TT20 (QTA) has not yet been re-measured, although this is planned for 2024.

It was not possible to perform further optics measurements at T4 and in P42 due a lack of suitable instrumentation. Therefore, in 2023 three new BSGs were installed in P42 with an existing BSG moved [15]. The present locations of all BSGs in TT24-P42 are shown in Fig. 1.

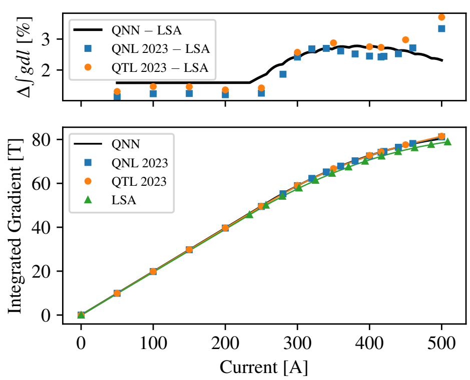

Figure 2: Measured integrated gradient of QNL and QTL magnets, the QNN TF and the TF present in LSA vs. I.

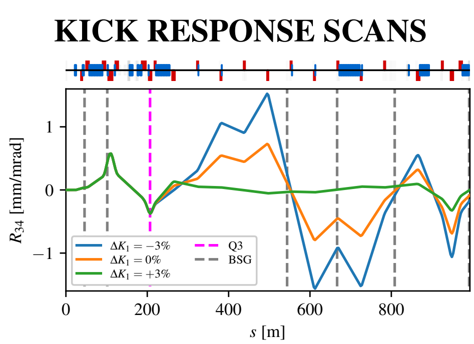

Figure 3: R_{34} calculated in MADX vs. distance s from corrector MDLV.2401 for deviations on Q3 strength of ±3%.

Kick response scans using the BSGs were performed to measure the optics of TT24-P42. Correctors were used to induce small angular kicks to the beam, displacing the beam on the BSGs, shown in Fig. 3. The displacements can be used to calculate the values of R_{12} and R_{34} between the corrector and each grid. Small changes in K_1 at key quadrupoles can cause large changes to the matrix elements.

Each horizontal and vertical corrector in TT24-P42 was scanned by ±10 µrad. A Gaussian fit was done to each beam profile. Faulty or broken signal channels in the BSGs were removed before fitting. R_{12} and R_{34} were calculated from the movement of the beam centroid as a function of angle. Due to time constraints and a low repetition rate, only single shots were taken for each measurement. The initial MADX model was set using the nominal strengths in TT24, with the P42 QNL magnets set by converting the current to K_1 using the QNN TF. The vertical BSG at 389 m could not be used for this test as the beam profile was too large relative to the grid to give accurate centroids. To increase the data used in the minimisation, multiple measurements for each corrector were taken, with quadrupoles in P42 changed to vary the optics. Although the optimisation was performed fitting to all sets of optics simultaneously, only plots of the nominal optics are shown here.

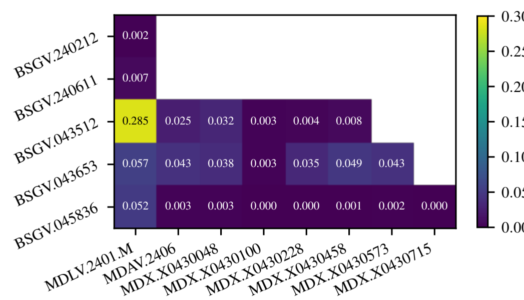

Figure 4: Absolute difference in R_{34} between the measurements and MADX for each corrector and downstream BSG without optics changes, $\Sigma|\Delta R_{34}| = 0.70$ mm/mrad.

The absolute differences between R_{34} between the model and measurements are shown in Fig. 4. The largest differences between the data and MADX are for corrector MDLV.2401, at the start of TT24. R_{34} for the other vertical corrector in TT24, MDAV.2406, located 3 m upstream of QTAD.2407 where $\beta_y \sim 1.8$ km, is relatively similar to the MADX. The same is true for the vertical correctors in P42. The absolute difference for all correctors is small at BSG.045836 due to the strong focus at T10. In the horizontal axis, the differences between R_{12} are small, with the largest discrepancy, 0.05 mm/mrad, coming from MDLH.2409, ~ 35 m upstream of T4. The total difference of R_{12} and R_{34} is 0.12 mm/mrad and 0.70 mm/mrad respectively. The difference between the MADX and measurements suggest that the leading cause of an optics mismatch is in TT24, where it is known that the QNL and QTL magnets are set incorrectly. Additionally, the vertical plane appears to be more sensitive to optical errors due to the large beta function.

An optimisation of all TT24-P42 quadrupole strengths was performed using `Py-BOBYQA` [16] minimising the absolute difference in R_{12} and R_{34}. The absolute difference in R_{34} following the optimisation is shown in Fig 5. The total difference in R_{12} did not change, but the difference between and R_{34} was reduced to 0.28 mm/mrad. The strengths of all magnets were changed by ≤ 0.5% apart from QTAD.2407 which was increased by 1.2%. The relative improvement was larger for correctors in TT24 than in P42. For some correctors and grids the agreement could not be further improved, even when only targeting that grid in the minimisation, which may be due to an as yet not understood systematic error.

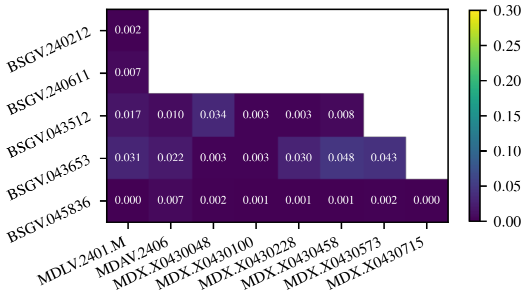

Figure 5: Absolute difference in R_{34} between the measurements and MADX following optimisation, with the nominal machine settings, $\Sigma|\Delta R_{34}| = 0.28$ mm/mrad.

As the MADX settings of the P42 QNLs, set with the QNN TF, showed good agreement to data, the TT24 QNL and QTL magnets were also set by converting the current to K_1 using the QNN TF. An optimisation was then done varying QTAD.2407 only. Again $|\Delta R_{12}|$ did not improve. However, the absolute difference in R_{34} was reduced to 0.31 mm/mrad by increasing the QTAD.2407 strength by 2.4%. Additionally by optimising Q3 in P42 and QTAD.2407, both with large β_y, it is possible to reduce $|\Delta R_{34}|$ to 0.28 mm/mrad with changes of K_1 and -0.4% and 2% respectively. As only one corrector produced large differences to the model, KR scans with correctors further upstream should be done. In 2024 it is planned to do KR scans with the QTL and QNL magnets in TT24 set with the new TF. The QTA magnet measurements will also be compared to this analysis.

QUADRUPOLE SCANS

As the KR scans showed that the P42 optics matched the model well, quad scans were performed for the dedicated beam to determine the beam parameters at T4. Each quadrupole was scanned and beam profiles were measured on the BSGs. The parameters at T4 in MADX were then optimised to fit all data taken. The dispersion at each BSG was calculated by looking at the position of the beam centroid vs. time. The momentum of the extracted beam is linear with time, causing a sweep in position of the beam centroid. The dispersion can be calculated from the ratio of the change in position vs. the change in momentum over the same time. Measurements of the SPS beam during the test showed that the momentum change over the extraction was $\pm 1 \times 10^{-3}$.

An example of the comparison between data and the MADX model, before and after optimisation is shown in Fig. 6. The optimisation minimises the absolute difference between each data point in all of the scans, weighted by the uncertainty, to the MADX model. The dispersion was first optimised, then $\varepsilon_{x,y}$, $\beta_{x,y}$ and $\alpha_{x,y}$ to the beam sizes.

The optics following the optimisation are shown in Fig. 7. There are substantial differences between the nominal optics and the optimised model. In both x and y the beam focus is

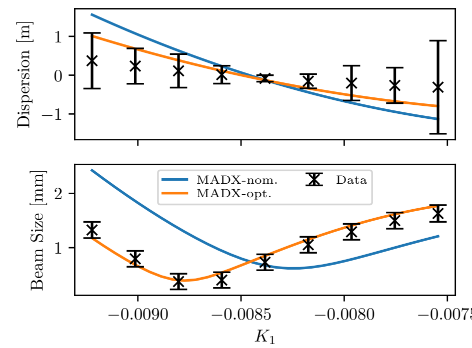

Figure 6: Vertical beam size and dispersion measured at BSG.043653 as Q13 was scanned.

upstream of T4 with $\alpha = -2.17$ and $\alpha_y = -2.28$ at T4. In the horizontal plane, β_x is larger than the nominal model throughout and grows to ~ 3 km at 170 m, which may lead to losses. The vertical beam is larger at Q3 and in the large horizontal bend at 520 m. However, it is smaller in the final focus. The dispersion is relatively similar to the nominal model. At T10, the beam size is relatively similar to the nominal optics. It should be noted that the conditions at T4 are close to those calculated in MADX when the TT24 QNLs and QTLs are set with the QNN TF and QTAD.2407 is set from the KR data, although they are not identical. The same is not true if the strengths are taken from the KR optimisation of all T24-P42 magnets.

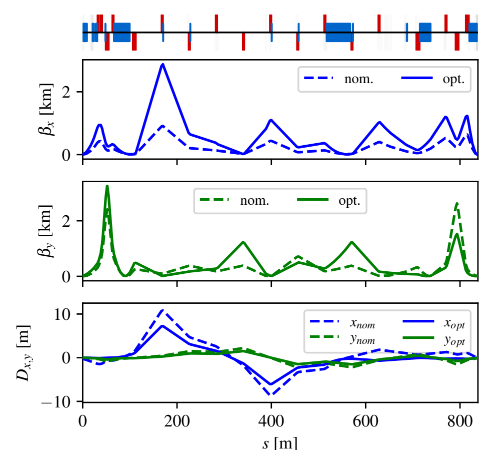

Figure 7: Nominal P42 optics and optics calculated using the beam parameters at T4 from the quad scan optimisation.

CONCLUSIONS

Optics studies performed on TT24 and P42 have demonstrated significant sensitivity to errors. The KR study demonstrated that P42 can be accurately set with the new QNL and QTL TF, but that TT24 is presently set incorrectly. The KR study also suggest that further magnetic measurements need to be done, particularly for the QTAs. The quad scans performed suggest that the beam is mismatched at T4. Further work should be done to analyse the data from these scans before definite conclusions can be drawn, however, it appears to be consistent with the KR study. Additional optics measurements will be taken with the new TF implemented in TT24 to complement these studies.

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