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OPTICS REMATCHING BETWEEN TT24 AND P42 PRIMARY BEAM LINES WITHIN THE HI-ECN3 STUDY PROJECT AT CERN

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Abstract

The High Intensity ECN3 (HI-ECN3) study project aims to increase the intensity of the proton beam delivered to a new experimental facility housed in the ECN3 underground cavern in CERN's North Area up to ~ 4×10^{13} ppp (protons per pulse) and up to ~ 4×10^{19} POT (protons on target) per year. The increase necessitates upgrades of the primary beam transfer lines coming from SPS directly to the new Target Complex upstream of ECN3. In this work we describe the modifications to the primary beam line optics that allow the transfer of the beam to the HI-ECN3 facility in two scenarios: shared (beam is split between the three existing production targets) and dedicated (beam goes directly to the target serving ECN3). An optimization study is presented to reduce the sensitivity of the beam optics to errors and minimize the effects of the beam's interaction with material when transiting the existing target area between TT24 and P42, whilst respecting the different constraints needed to share the beam between ECN3 and the rest of the North Area and permit a vertical trajectory bump around the target serving EHN1.

INTRODUCTION

At present, the North Area [1] operates with a single SFTPRO-type (proton beam for the fixed-target programme at the CERN Super Proton Synchrotron ring) cycle that is utilized and shared among all experimental and test-beam users as part of routine operations (black lines in Fig. 1). The HI-ECN3 project aims to upgrade the transfer lines between SPS and ECN3 in order to deliver a high intensity (~ 4×10^{13} ppp) proton beam to the fixed target of the recently approved SHiP [2] experiment. Beam delivery to ECN3 starts from slow-extraction of particles from the SPS ring using Constant Optics Slow Extraction technique [3]. After extraction the beam is being split at the end of both TT21 and TT22 lines, hits the T4 target in the end of TT24 line and finally is delivered to T10 target through P4 and P42 lines [4]. In future it is planned to implement a dedicated cycle specifically designed to transfer high-intensity beams to ECN3 (red line in Fig. 1). On this dedicated cycle protons will bypass the beam splitters and T4 target station via a closed vertical magnetic bump.

The proposed dedicated beam delivery scenario requires the operation of certain beamlines in Pulse-by-Pulse Modulation (PPM) mode, whereby the magnets can pulse with different settings depending on the cycle played. This is crucial for seamlessly switching the optics between dedicated ECN3 cycles and standard STFPRO cycles for EHN1 and EHN2 within an SPS supercycle. Currently, most of TT21-TT24 meets these criteria, with the exception of QSLD.2201 and the dipole magnets surrounding T4 target that cannot be pulsed due to their solid iron yokes. Vertically bypassing the T4 target using a magnetic bump offers a solution, enabling the continued operation of the MTN dipole magnets in T4 in DC mode with minor drawbacks.

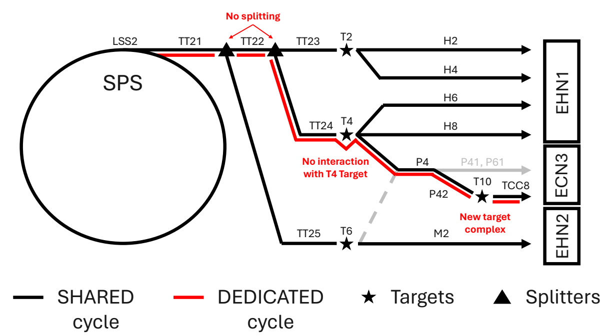

Figure 1: CERN North Area operation scenarios.

While the solid MDX magnets could potentially be replaced by laminated counterparts during the next long shutdown (LS3), and a suitable optics solution has been found for the non-laminated QSL in P4, a complete re-engineering of the control system is already in work and scheduled until LS3. Implementing the beam lines in the LHC Software Architecture (LSA) data-based control system [5] will be fully compatible with PPM operation. However, achieving full PPM operation of these beamlines may only be possible after LS4, once the power converter consolidation of the most downstream beamlines is completed. Taking into account the PPM constraints in P42 mentioned above, optimized settings of TT24 and P42 lines have to be defined to fulfill operational requirements of both SFTPRO and ECN3 dedicated cycles until LS4. Optics for a future dedicated cycle, including bump around T4 target, was developed in 2022-2023 by the ECN3 Task Force [6]. In this paper we use these settings as a reference case for further improvements in the line optics. For efficient beam delivery on shared cycle before achieving full PPM operation we keep settings in P42 similar to that of dedicated cycle, but the upstream optics is matched at T4 centre to P42 conditions using TT24 line quadrupoles.

MODIFICATIONS IN TCC2

One of the main points of interest for optics optimisation in TT24 and P42 is TCC2, where T4 target and mobile dump collimators XTAX.X0430018 and XTAX.X0430020

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are located. The target consists of 2 mm thick and 160 mm wide Be sheets of different length (40 mm, 100 mm, 180 mm, 300 mm and 500 mm) that are distributed vertically with 40 mm gap between them [7].

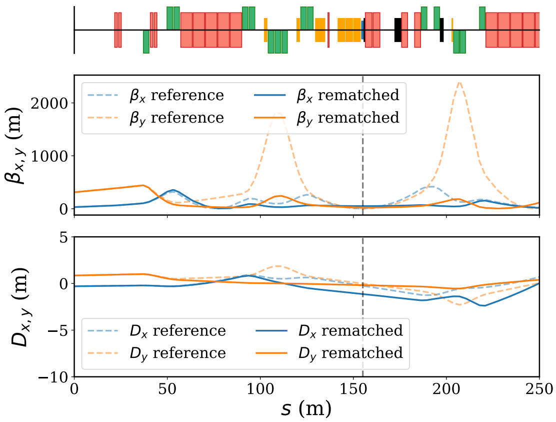

Figure 2: Comparison of rematched (solid lines) and reference (dashed lines) optics in TT24 and P42 lines near T4 target. Location of the target centre is shown with the black dashed line.

There are two constraints for the beam size in this region. Firstly, the vertical beam size must be small enough to have a reasonable number of the protons interacting with the target and generate secondary particles for EHN1. Presently, the thickness of the target sheet is a factor of 10 times larger than the vertical RMS size (σ_y). For the high intensity operation mode we decided to relax this constraint and limit the beam size at the target to ≈ 0.5 mm, which allows to fit $2\sigma_y$ within a sheet thickness.

Secondly, a relaxed beam size at the T4 target allows to reduce the strengths of the final focus quadrupoles in TT24 and the sensitivity to errors. On the other hand, a larger beta function at the T4 target will increase the emittance growth induced from the beam's interaction with the material in the target station. The impact on beam loss of the rematched optics will need to be further evaluated, but the high intensity beam will not interact with the T4 target and the XTAX collimator will help collimate particles scattered to large amplitude.

Figure 2 shows the rematched optics in TCC2 with the vertical beta function significantly reduced in the quadrupoles at either sides of the target. The performed optimisation takes into account the constraints mentioned above. Comparing to the reference case (dashed lines), the beam size was significantly reduced near QTAD.240900, QNL.X0430054 and XTAX. Optics modifications allowed to reduce the beam size at XTAX by ≈ 0.58 mm (21%) and 0.65 mm (81%) in the horizontal and vertical planes, respectively. The phase advance from T4 target to the XTAX is ≈ 21° and 44° in the horizontal and vertical planes, respectively.

The vertical trajectory bypass of the T4 target is provided by three correctors (MDLV.240209, MCXCA.x0430048 and the recently installed MNPA30) and was rematched for the

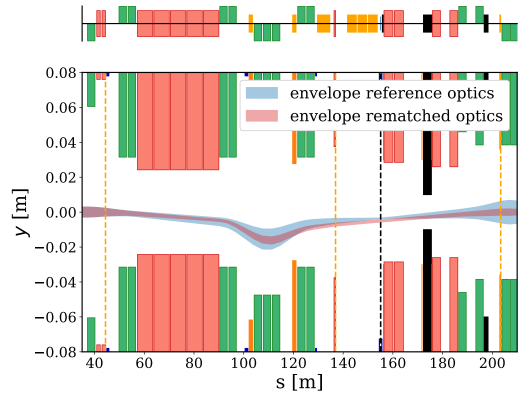

Figure 3: Beam envelopes for reference (blue area) and rematched optics (red area) near T4 target. The T4 centre and the bump magnet positions are shown with black and orange dashed lines, respectively.

new optics (Fig. 3) by shifting the beam vertical position at T4 by 1.5 mm downwards (from -3.5 mm). This modification prevents losses at the target for the beam with a larger size with respect to the reference optics. Changes in the strengths of the correctors are shown in Table 1. Although the modified bypass requires to reverse the polarity of MNPA30, integrated strength of all of the correctors is relatively low and lies within the limits of the equipment.

Table 1: Settings of the T4 Bump Correctors

Corrector	**Integrated strength**	$[T \cdot m]$
	Reference	Rematched
MDLV.240209	0.0947	0.1027
MNPA30	0.0926	-0.1032
MCXCA.X0430048	0.0592	0.0838

MATCHING TO FODO SECTION IN P42

A large part of the P42 beam line between QNL.X0430111 and QNL.X0430710 is a periodic FODO lattice. The rematching in the upstream part of the line changed the conditions at the beginning of this FODO section; quadrupoles QSL.X0430033 - QNL.X0430111 were used to match back to the reference optics (Fig. 4). However, absolute peak values of the dispersion function reach ≈ 10 m in the beginning and the middle of the section that makes the beam size comparable with the apertures of the quadrupoles at these locations. Further work will be needed to improve the matching to the FODO whilst at the same time reducing the maximum excursion of the horizontal dispersion function.

FINAL FOCUS OPTIMISATION

In the end of P42 the beam is tightly focused at the T10 target to serve the NA62 experiment. The future operational scenario implies removing the T10 target to transfer the beam

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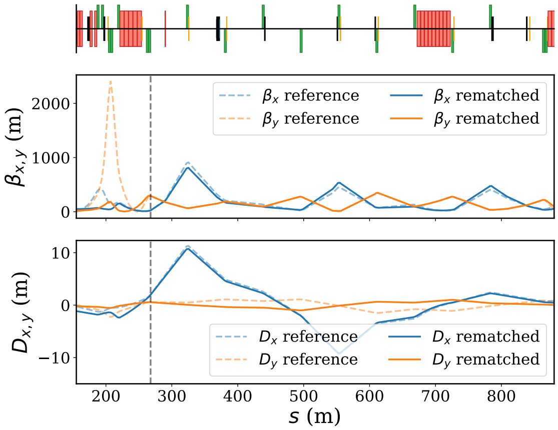

Figure 4: Comparison of rematched (solid lines) and reference (dashed lines) optics in P42 near FODO section. Start of the section is shown with the black dashed line.

to the BDF/SHiP target located more than 100 m further downstream. There will be no such a strict requirement on the beam size at the end of P42, the optics can be rematched to reduce the beam size near the end of P42 to improve the transmission to the target. As an example, the rematching of the optics reduces the peak value of the Twiss beta down to $\approx$ 400 m in both horizontal and vertical planes (Fig. 5). The final focus optics design for BDF/SHiP is ongoing work.

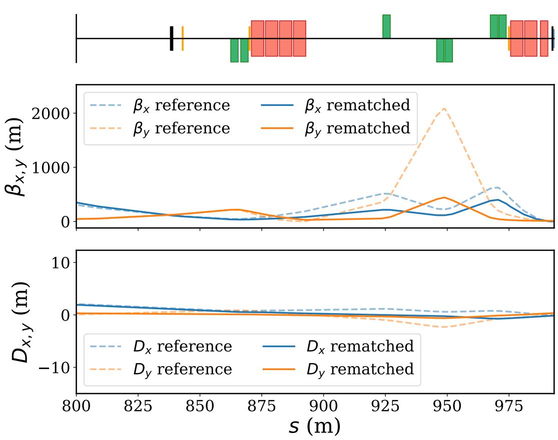

Figure 5: Comparison of rematched (solid lines) and reference (dashed lines) optics in P42 line near T10 target.

OPTICS SENSITIVITY

An error study was performed to understand the sensitivity to optical mismatch from quadrupole gradient errors after having relaxed the constraint on the vertical beam size at the T4 target. For this study we added random errors within $\pm 1\%$ range to each magnet circuit and compared the resulting perturbations of the Twiss beta and dispersion functions ($\Delta\beta_{x,y}$ and $\Delta D_{x,y}$) for both reference and rematched settings. The analysis of the results shows that reference optics is extremely sensitive to variations of strength of several magnets in TT24 and the beginning of P42 [8]. Reducing the beta functions in the regions around T4 and T10 led to a significantly lower sensitivity of the rematched optics in the vertical plane to quadrupole gradient errors (Fig. 6). In particular, Twiss beta function magnitude along the line is highly sensitive to the gradients of the TT24 quadrupoles QTLD.240200, QTLF.240300, QTLF.240400, QTAD.240700 and QTAD.240800, as well as QNL.X0430050, QNL.X0430054 in P42.

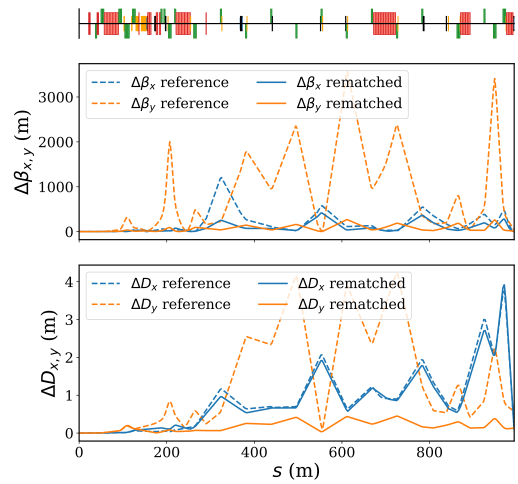

Figure 6: Maximum perturbations of beta functions and dispersion for rematched (solid lines) and reference (dashed lines) optics caused by $\pm 1\%$ errors in quadrupole strengths in TT24 and P42 lines.

CONCLUSIONS AND NEXT STEPS

The optics of the TT24 and P42 lines was rematched to reduce potential beam loss for the future high intensity operational mode and improve the quality of the beam delivered to the ECN3 experimental area housing BDF/SHiP in both shared and dedicated scenarios. The size of the beam at the T4 target was relaxed to significantly reduce the sensitivity of the optics to errors in the quadrupole gradients. There is margin for further improvement as the design of the beam line for BDF/SHiP advances to reduce the beam loss in the transfer lines. In particular, the horizontal dispersion remains relatively high in P42 and further optimisation of the beam line is needed upstream of the FODO section. It is aimed to test the rematched optics during Machine Development sessions this year to demonstrate operation with a larger beam size at T4 and a reduced sensitivity to optical errors, and potentially reduced beam loss.

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