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BEAM OPTICS STUDIES FOR BDF AND FOR TESTS OF A PROTOTYPE TARGET

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Abstract

Within the framework of the Physics Beyond Collider project a new fixed target facility at the SPS North Area, the so-called Beam Dump Facility (BDF), is under study. BDF requires a high intensity slowly extracted 400 GeV proton beam with 4e13 protons per 1 s spill to achieve 4e19 protons on target per year. This results in an exceptionally high average beam power of 355 kW on the target, which is a major challenge. To validate the target design, a test of a prototype target is planned for 2018 at an existing North Area beam line. A large part of this beam line is in common with the future BDF beam line with comparable beam characteristics and several measurement campaigns were performed in 2017 to study the optics of the line in preparation for the test. The intrinsic characteristics of the slow extraction process make the precise characterisation of the beam reaching the target particularly challenging. This paper presents beam and lattice characterisation methods and associated measurement results.

INTRODUCTION

The Physics Beyond Colliders study [1] aims at exploiting the full scientific potential of CERN's accelerator complex through projects, which are complementary to the LHC or other possible future colliders like CLIC or FCC. Within this framework, a new fixed target facility at the SPS North Area, the so-called Beam Dump Facility (BDF) [2], is being studied. Beam dump means in this context a target, which absorbs most of the incident protons and contains most of the cascade generated by primary beam interactions. In the initial phase, it is planned that the facility accommodates the Search for Hidden Particles experiment (SHiP) [3], which aims at studying hidden sector particles in the MeV-GeV range [4].

BDF requires a high intensity slowly extracted 400 GeV proton beam with 4e13 protons per 1 s spill. An overview of the parameters of the present beam to the North Area and the future beam to BDF is shown in Table 1. It is foreseen to deliver a total number of 4e19 protons to the BDF target per year, which is approximately four times as high as presently sent to the North Area. This imposes radiation protection issues, since accelerator equipment – mainly the electro-static septa – would be severely activated. Therefore, a reduction of the beam losses during the slow extraction process is mandatory and extensive investigations on the optimization of the slow extraction are on-going [5].

After extraction, the beam is transported via the 600 m long TT20 transfer line towards the North Area up to the location of the first splitter magnet (MSSB1). MSSB1 is an assembly of three Lambertson septa, which splits the present North Area beam into two, sending beam towards the T2/T4 and T6 targets. For BDF these magnets will be replaced by a new laminated design, which allows additionally a deflection of the entire beam to the left towards the BDF target on a cycle-by-cycle basis. The beam will then be transported in a 400 m long new transfer line to the BDF target. The design of the transfer line for BDF is presented in detail in Ref. [6].

Table 1: Beam Parameters

Parameter	North Area	BDF
Energy	400 GeV	400 GeV
Momentum spread	±1.5e-3	±1.5e-3
Horizontal emittance (norm.)	15.0 µm	15.0 µm
Vertical emittance (norm.)	5.0 µm	5.0 µm
Total beam intensity	up to 4E13 p	4e13 p
Spill length	4. 8 – 9.6 s	1.0 s
Cycle length	26.4 s	7.2 s

The high beam intensity results in an exceptionally high average beam power of 355 kW on the target, which is a major challenge for the target design. To withstand the high thermo-mechanical loads, a large beam size of 8 mm (1σ) and a circular beam dilution on the target is required. In order to validate the design of the BDF target a test of a prototype target with beam is planned for 2018 at the TT25 North Area beam line upstream the existing T6 target [7]. The beam optics for this target test and measurements to validate this optics are discussed in this paper.

BEAM OPTICS

The aim of the target test is to study the properties and behaviour of the test target under beam conditions as close as possible to those expected at the BDF. A beam dilution is not possible at the foreseen location with the available equipment. This means using BDF spill and cycle length and a beam intensity and beam radius as large as possible. To achieve a maximum beam intensity on the test target the beam needs to be completely deflected in MSSB1 towards TT25, similar but in the opposite direction planned for BDF. Therefore, the new optics for the BDF beam line [6] will be used up to the splitter and matched then in TT25 to the maximum possible beam size at the test target, which is 3 mm (1σ radius) due to aperture limitations in the existing beam line.

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The new optics for the target test have been simulated with MAD-X [8] and they differ significantly from the standard optics in TT20/TT25 (Fig. 1), for which a very large vertical beam size at the splitter is required, yielding beta function of almost 25 km. For the new optics, the beta function at the splitter is only a few hundred metres and the maximum around 1600 m (Fig. 2). In the central FODO section, a regular oscillation pattern with small betatron amplitudes is present. The dispersion has been matched to zero at the test target, but reaches large values of 25 m at the splitter in the vertical plane.

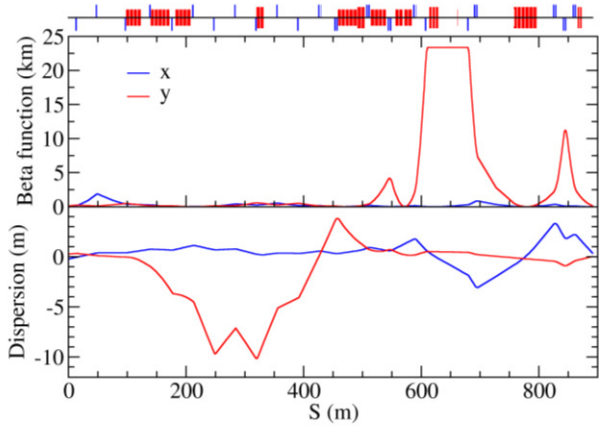

Figure 1: Standard optics of TT20/TT25 beam line.

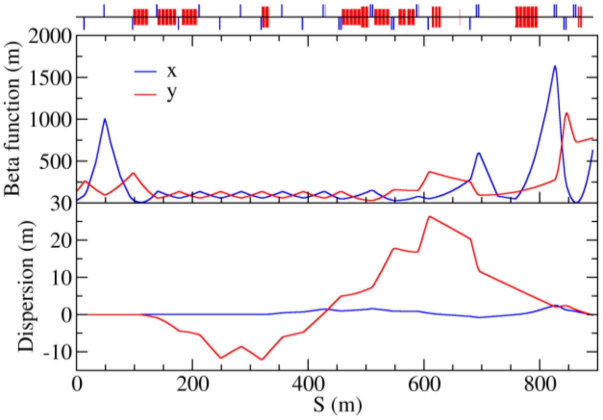

Figure 2: Optics for prototype target test in TT20/TT25.

The beam size at the target has been chosen so that the 6-sigma beam envelope computed according

$$\Sigma = n_\sigma k_\beta \sqrt{\beta\varepsilon} + \left|k_\beta D \frac{\Delta p}{p}\right| + co\sqrt{\frac{\beta}{\beta_{max}}}$$

still fits into the physical aperture. With $n_\sigma = 6$ being the number of sigma of the betatron beam size, $k_\beta = 1.1$ the beta beating factor, $co = 5$ mm the maximum deviation from the reference trajectory and β, ε, D and $\Delta p/p$ the beta function, emittance, dispersion and momentum spread. The total momentum spread is a uniform distribution with the width ±1.5e-3, however, there is some correlation between the momentum and the temporal position within the spill, since the tune is swept through the tune spread of the beam during the chromatic 3rd order resonant slow extraction process. To compensate the dispersive shift of the trajectory caused by the momentum sweep the magnets are trimmed in the beam line during the spill. Therefore, the effective momentum spread, which determines the dispersive component of the beam size, is lower and has been assumed to be 1e-4. The computed beam envelope is shown in Fig. 3 together with the physical aperture. It is obvious that the beam envelope just fits into the aperture near the target and therefore a 3 mm 1-sigma beam size is the maximum achievable beam size.

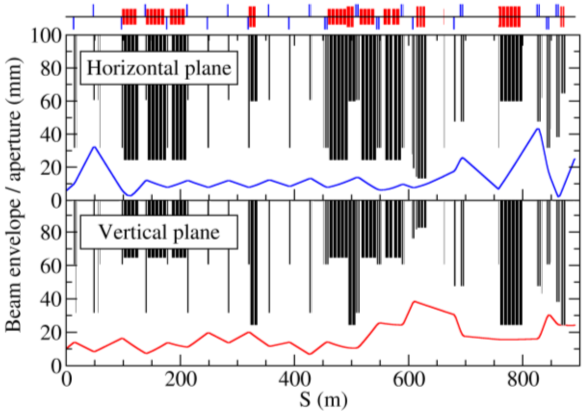

Figure 3: 6-sigma beam envelope and physical aperture for prototype target test in TT20/TT25.

BEAM CHARACTERIZATION

The new optics has been studied in several machine development shifts at the SPS and the beam has been characterized. Beam steering and measurements are challenging in the extraction line to the North Area, since due to the long spill length and the fact that the beam is unbunched no beam pick-ups can be used. Instead, split screens and secondary emission (SEM) grids are used. The spilt screens can only measure the beam position, when the beam is near the center of the beam pipe and partially hits both screens. They are therefore not suitable for e.g. kick response measurements, where deliberately large beam oscillations are excited. The SEM grids used in TT20/TT25 have only a limited resolution of 15 wires and the sizes are optimized for the standard optics. Only a limited number of SEM grids are available along the beam line. There is the lack of suitable SEM grids in the horizontal plane. Therefore, the precision of the beam characterisation measurements is limited.

Beam Size and Dispersion Measurements

To verify the optics and the assumption for the effective momentum spread, the beam size has been measured with the available SEM grids along the line and compared with MAD-X models for different momentum spreads. For a momentum spread of $\Delta p/p$ = 1e-4, the measurement is in reasonable agreement with simulation (Fig. 4). Furthermore, on the SEM grids very close to the expected test target position (BSGH.250611 and BSGV.251009) beam sizes very close to the expected values were measured.

The dispersion has also been measured by shifting $\Delta p/p$ in the SPS in steps of 0.5e-3. The measurements agree well with the model in the first half of the line but there is some discrepancy in the second half (Fig. 4).

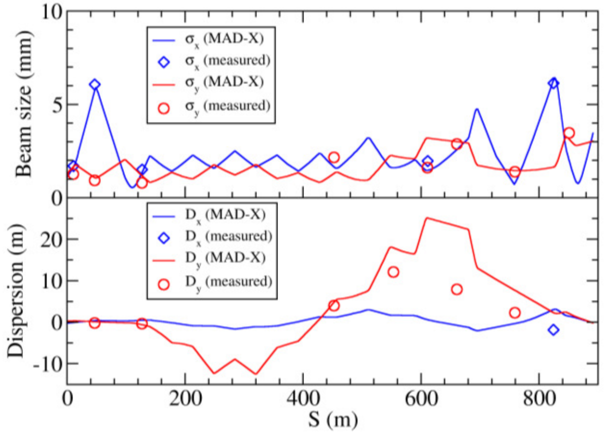

Figure 4: Measurement of the beam size compared with the MAD-X model with $\Delta p/p$ = 1e-4.

Kick Response Measurements

A direct way to verify the optics is to excite transverse oscillations with a corrector magnet at the start of the beam line and record the beam positions on the SEM grids along the line. From these kick response measurements, elements of the transfer matrix can be derived. Figure 5 shows the R21 and R34 matrix elements obtained from the kick response measurements in the horizontal and vertical plane in TT20/TT25 and the matrix elements calculated with MAD-X.

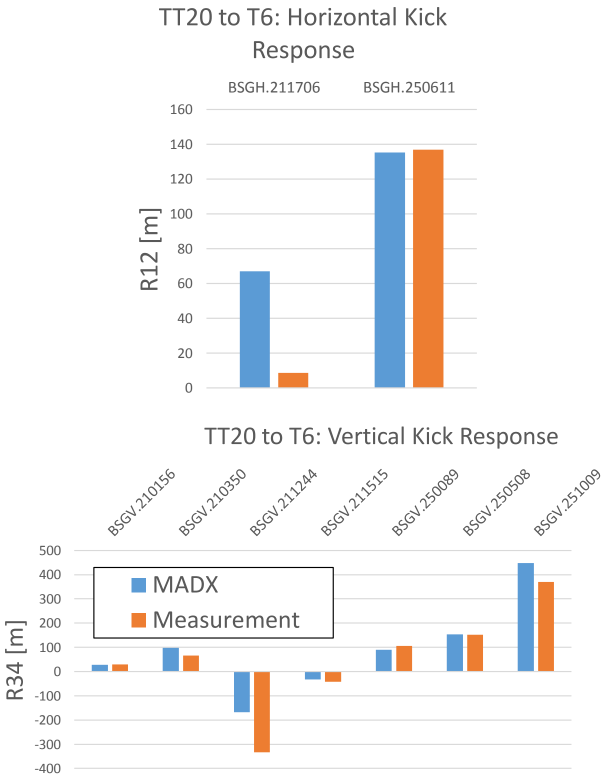

Figure 5: Horizontal and vertical kick response measurement in the TT20/TT25 beam line compared with the MAD-X model.

Despite the non-optimal beam position measurements, the measured and calculated matrix elements in the vertical plane are in reasonable agreement. In the horizontal plane, only two grids were suitable for this measurement and therefore no conclusion on matrix element R12 can be drawn. However, it is unlikely that the measurements agree with theory in one plane and disagree in the other. Therefore, it can be expected that the MAD-X model describes reasonably well the beam optics.

Emittance Measurements

Measurements have been performed to determine the transverse emittance by scanning the strength of quadrupoles and recording the beam size on SEM grids. This is a widely-used method for emittance measurement, however, the conditions in this beam line differ from most other quadrupole scan setups in two aspects:

- The vertical beam profile is Gaussian, but the horizontal beam profile highly non-Gaussian due to the slow extraction process.
- The dispersion in the beam line is non-zero. However, the measurements have been performed within the first 80 m of the beam line, where the dispersion is still small ($|D_x| < 0.5$ m, $|D_y| < 1.5$ m).

The data analysis has therefore not been performed by a classical parabola fit of the observed beam size, but by using the thin tracking module of MAD-X. A realistic simulated distribution was used and parametrized by three scalars allowing the modification of its covariance matrix, commonly called the Twiss parameters in accelerator physics. A fitting procedure adjusted those three parameters to find the modified distribution that fits best the measured beam size as a function of quadrupole strength. Resulting estimation of the geometrical horizontal emittance was $\varepsilon_x = 39$ μm normalized rms using this method and $\varepsilon_x = 37$ μm using a traditional fit of the analytical variation of the beam size as a function of quadrupole strength. This emittance is larger by around a factor 2 from what was assumed from simulation of the slow extraction process. Investigations to explain this discrepancy are ongoing but might be explained by the chromatic extraction scheme or the motion of the separatrix during extraction.

CONCLUSION

The beam optics in the TT20/TT25 transfer line have been adapted for the BDF prototype target test, based on the optics for the new BDF beam line. The beam size on the target has been chosen so that it is as large as possible, but also so that the high intensity beam can still safely be transported along the transfer line.

Despite limitations of the available beam instrumentation, beam characterization measurements showed that the MAD-X model describes reasonably well the reality. For the BDF target test two additional screens will be installed upstream and downstream the test target, which will ensure the precise steering of the beam onto the target and measurement of the beam size.

REFERENCES

[1] Physics Beyond Collider study, `http://pbc.web.cern.ch`

[2] M. Lamont *et al.*, "The SPS Beam Dump Facility", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 2389-2391, `doi:10.18429/JACoW-IPAC2017-TUPVA126`

[3] M. Anelli *et al.* [SHiP Collaboration], "A facility to Search for Hidden Particles (SHiP) at the CERN SPS", CERN, Geneva, Switzerland, Rep. CERN-SPSC-2015-016, Apr. 2015, arXiv:1504.04956 [physics.ins-det].

[4] Sergey Alekhin *et al.*, "A facility to search for hidden particles at the CERN SPS: the SHiP physics case", *Rep. Prog. Phys.* 79 (2016), p. 124201, `doi:10.1088/0034-4885/79/12/124201`

[5] M.A. Fraser *et al.*, "SPS slow extraction losses and activation: Challenges and possibilities for improvement", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 611-614, `doi:10.18429/JACoW-IPAC2017-MOPIK045`

[6] Y. Dutheil *et al.*, "Beam transfer line design to the SPS Beam Dump Facility", presented at IPAC'18, Vancouver, Canada, Apr.-May 2018, paper TUPAF032, this conference.

[7] E. Lopez Sola *et al.*, "Beam Dump Facility target: Design status and beam tests in 2018", presented at IPAC'18, Vancouver, Canada, Apr.-May 2018, paper WEPMG002, this conference.

[8] MAD-X, `http://cern.ch/madx`