ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPMP027

UPDATE ON BEAM TRANSFER LINE DESIGN FOR THE SPS BEAM DUMP FACILITY

J. Bauche, Y. Dutheil, M.A. Fraser, B. Goddard, C. Hessler, J. Kurdej,
L.A. Dougherty, V. Kain, J. Uythoven, F.M. Velotti
CERN, Geneva, Switzerland

Abstract

The SPS Beam Dump Facility (BDF) being studied as part of the Physics Beyond Colliders (PBC) CERN project has recently reached an important milestone with the completion of the comprehensive feasibility study. The BDF is a proposed fixed target facility to be installed in the SPS North Area, to accommodate experiments such as SHiP (Search for Hidden Particles), which is most notably aiming at studying hidden sector particles. This experiment requires a high intensity slowly extracted 400 GeV proton beam with 4×10^{13} protons per 1 s spill to achieve 4×10^{19} protons on target per year. The extraction and transport scheme will make use of the first 600 m of the existing North Area extraction line. This contribution presents the status of the design work of the new transfer line and discusses the challenges identified. Aperture studies and failure scenarios are treated and the results discussed. In particular, interlock systems aiming at protecting critical components against the uncontrolled loss of the high energy proton beam are considered. We also present the latest results and implications of the design of a new laminated Lambertson splitter magnet to provide fast switching between the current North Area experiments and the BDF.

INTRODUCTION

The Physics Beyond Colliders initiative is an ongoing study to identify critical physics topics that could fully benefit from CERN accelerator infrastructure and expertise. One of the projects currently investigated is the search for dark matter on the SHiP experiment. The associated project to build this experiment at CERN and provide it with unique beam characteristics is referred to as the Beam Dump Facility [1].

As the SHiP detector targets the direct observation of extremely rare events, it will require a large flux of high energy particles. This will be provided by slowly extracted proton beam from the SPS at an energy of 400 GeV. This has been routinely done at CERN since the 70’s in the Prevessin North Area but this project poses new challenges in terms of intensity and efficiency. To achieve the SHiP objectives a new beamline and experimental complex branching off the existing North Area facility is foreseen. This facility will receive 1 s long spills of 4×10^{13} protons at 400 GeV and every 7.2 s [2]. This will result in an instantaneous beam power of up to 2.5 MW that requires careful design of the facility to safely transport the beam.

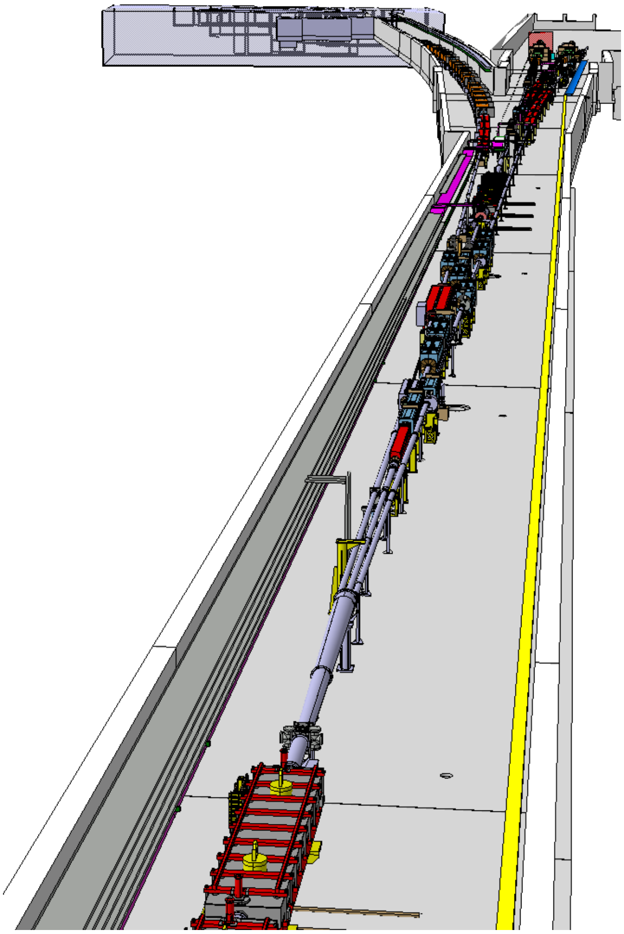


Figure 1: Beamline view of the BDF engineering model with the splitter at the bottom, the new line branching off to the left and the existing targets in the upper right.

LAYOUT AND BEAM TRANSPORT

Slow extracted beam from the SPS is transported towards the Prevessin site, in the Transfer Tunnel (TT) 20. The BDF beam will follow the same path for the first 600 m of the TT20 line. The new beamline then branches off the existing channel at the level of the first Lambertson splitter. Figure 1 shows the new line branching towards the BDF target and beyond, the SHiP detector. Starting at the tunnel branching off towards the left, all downstream structures will have to be built.

Figure 2 shows the synoptic and Twiss parameters of the beam transport for the BDF, from the SPS to the target. The evolution of the beta function along the line can be split into three sections. In the first 150 m large values in the beta function are needed to match the beam parameters to the rest of the line, a regular FODO lattice. In the middle part, up to around s = 800 m, the beta function follows a regular FODO pattern. There, the vertical dispersion function grows to large values as the beam is transported from the SPS level to near the ground level at s = 600 m. The last part of the line is characterised by large optical functions in both planes as the beam size on the target needs to be at least 8 mm in both planes. Anything smaller would cause the target material too much stress and induce unacceptable plastic deformation of its material [3].

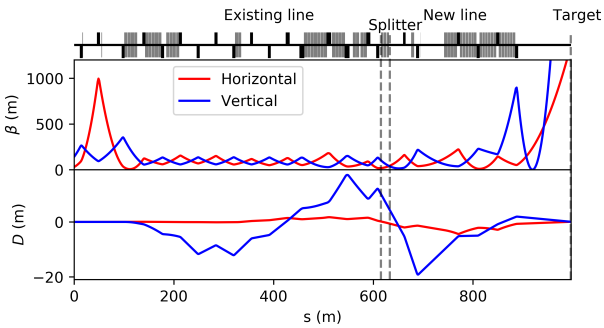


Figure 2: Synoptic and optical functions along the transfer line from the SPS to the BDF target. Dipoles are represented as grey bars while quadrupoles use black squares above the centreline for focusing, and below for defocusing function.

New Splitter

Ongoing nominal operation of the North Area involves the transverse splitting of the beam using Lamberston DC magnets [4], in two locations, in order to simultaneously deliver beam to 3 targets. Although the beam intended for the BDF will not be split, its trajectory branches off the existing line at the first splitter. Interleaved operation of the BDF and existing lines will require a reversal of the field in the first splitter, within at most 1 s. This is not possible with the current devices as their solid cores would generate strong Eddy currents. A new laminated core design is therefore being investigated.

As the original design cannot be directly converted into a laminated version, joint efforts between magnet and beam dynamics experts aim at identifying the best feasible splitter design. In particular, magnet experts are investigating the mechanical processes capable of producing lamination with the smallest possible septum thickness while beam dynamics experts study the feasibility of different splitting schemes and their associated efficiencies.

Integration

As the new beamline branches off the existing ones at the first splitter, that region is particularly crowded with up to 3 beamlines and their equipment side by side. Figure 3 shows a small volume of the engineering model of the new line. This integration work is of critical importance as the positioning of the new devices has, in some cases, to be done with only a few millimetres of margin.

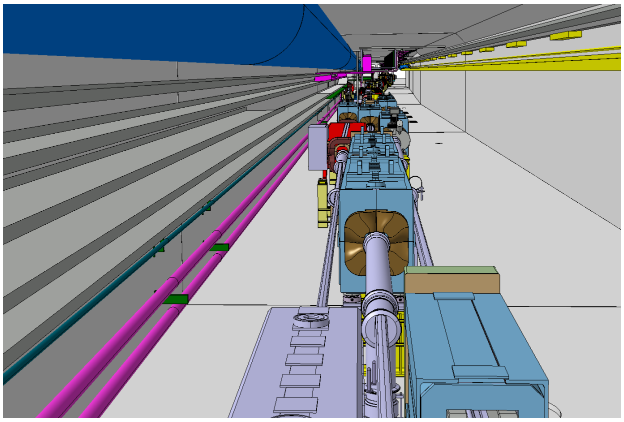


Figure 3: Beamline view of the BDF engineering model downstream of the first splitter and towards the end of the line.

This work is done in close collaboration between integration and beam dynamics experts. In particular, the horizontal beam size and aperture restrictions in the area downstream of the first splitter are shown Fig. 4. In this representation the splitter aperture is curved since the reference trajectory is curved in the field region of the Lambertson septum but does not present particular difficulties in terms of aperture. Downstream, a first challenge was met at the first quadrupole of the BDF line. The optics design of the line required a quadrupole downstream of the splitter, at around s = 650 m or at the bottom of the model Fig. 3. However, the usual type of quadrupole used in the North Area, showed in blue-green in Fig. 3, would have overlapped with the existing lines. Therefore, another quadrupole with smaller transverse dimensions but smaller aperture, which was previously used elsewhere at CERN, has been proposed and validated using both beam dynamics and 3D engineering modelling.

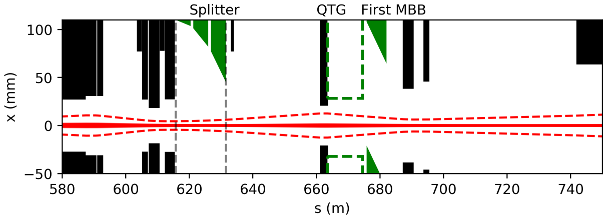


Figure 4: Horizontal beam size along the line around the first splitter with specific aperture restrictions showed in green.

Figure 3 also shows all the miscellaneous systems around the beamline itself such as the cable trays on the left and the air duct in the ceiling.

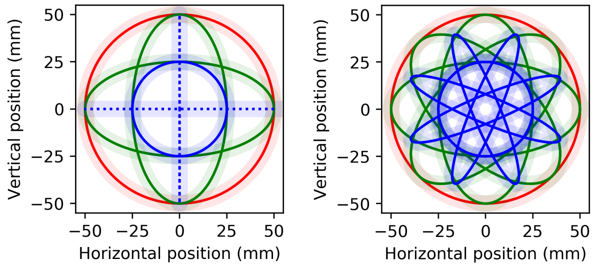
Dilution System

Further downstream we encounter another specific system. In order to reduce the local maximum energy density deposited onto the target to acceptable levels, the beam has to be diluted beyond what is possible by increasing the beam size. This will be done using 4 magnets 100 m upstream the target, capable of deflecting the proton beam by 500 µrad to create a circular pattern of radius 50 mm sweeping at 4 Hz on the target.

Using an existing magnet design 4 magnets will have to be used to achieve the required maximum deviation. Furthermore, a preliminary study on the power supply choice shows that each magnet will have to be powered independently due to the somewhat high voltage required to drive those dipoles at 4 Hz.

Due to the particularly high energy of the beam, it has been established that a failure of the dilution system could lead to plastic deformation of the target material [3,5]. Such an event would require a replacement of the target taking months at best. This system is therefore considered critical and its failure scenarios need to be anticipated. One aspect of this study is to list the possible system failures and study their effects on the dilution pattern and the target.

Since it was established the 4 magnets will have independent circuits, it opens an original solution to generate the circular dilution pattern on the target. If the obvious choice is to orient 2 magnets at 0 rad and 2 at /2 rad, it is also possible to orient all 4 magnets along a different direction (0, $\pi/4$, $\pi/2$ and $3\pi/4$). The former scheme we refer to as the $\pi/2$ while the later we call the $\pi/4$ scheme. Those two schemes differ fundamentally in case of the simultaneous failure of 2 out of 4 circuits. Figure 5 shows the different possible dilution patterns on the target. Note that a two-circuit system would create the red and dotted blue patterns in Fig. 5a.



(a) (b)

Figure 5: Possible dilution patterns on the target with all four circuits in red, 3 circuits in green and only two circuits in blue. Figure (a) shows patterns for the $\pi/2$ scheme while the $\pi/4$ possible patterns are shown in (b).

The loss of one circuit generates the same pattern regardless of the scheme. However, in case two circuits fail the $\pi/2$ scheme leads to flat dilution patterns in 33% of cases while the $\pi/4$ scheme only leads to a flattened elliptical pattern, albeit in 66% of cases. In the rest of the cases the pattern resulting from the loss of two circuits is a smaller circle of radius 25 mm.

Careful simulation of the effect of each dilution pattern onto the target showed that the flattened elliptical pattern with the $\pi/4$ scheme was as dangerous as the flat pattern with the $\pi/2$ scheme. Moreover, the smaller circular dilution pattern can be sustained by the target without damage for a single cycle. Therefore, the $\pi/2$ scheme is favoured as, in the event of failure, more likely induces a smaller circular pattern than the $\pi/4$ scheme.

Reliability Study Needs

Beyond the case of the dilution system a comprehensive failure study is necessary. With the large beam power discussed earlier it is not ideal to only rely on radiation monitoring to detect anomalous conditions.

The first aspect is to identify and list failure scenarios. Other than the dilution system failure we have considered the failure of other power supplies in the beam transfer line. Failure of the beam extraction method from the SPS possibly leading to fast extraction of the beam has also been discussed. Listing of failures associated with the SPS control system during operation of the existing North Area and BDF line in consecutive cycles is ongoing.

The second aspect to consider is the failure rate. Although personal safety is absolute, some risk to equipment and devices may be acceptable. This calls for a detailed failure rate assessment of each system in order to associate a probability of occurrence to each failure scenario.

The last step is to consider failure rates in the scope of the whole project to isolate unacceptable failure scenario. Those failure scenarios, which occurrence rate are sometimes impossible to accurately predict, are then met with mitigation measures. For instance, the failure rate of the power supplies considered for the dilution system magnets cannot be certified. Therefore, an independent monitoring system will be implemented to continuously compare the current provided to the requested one and interrupt extraction from the SPS in case an anomaly is detected, quickly enough to protect the BDF target.

CONCLUSION

We have presented several aspects of the beam transfer line being designed for the BDF project. The progress of the study allows us to confirm that the scheme considered is feasible. Some aspects, such as 3D engineering integration are very detailed while others, such as some failure scenario probability remain to be quantified.

As an important milestone for the project, the comprehensive design study will be released in the coming weeks, where not only the beam transfer line but the whole beam production and delivery has been studied. Work will continue towards a conceptual design report to pave the way towards fulfilment of the BDF project.

REFERENCES

[1] 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`

[2] G. De Lellis *et al.*, “Search for Hidden Particles (SHiP): a new experiment proposal”, *Nuclear and Particle Physics*

Proceedings, vol. 263, p. 71-76, 2015. `doi:10.1016/j.nuclphysbps.2015.04.013`

[3] E. Lopez Sola *et al.*, "Design of a high power production target for the Beam Dump Facility at CERN", `arXiv:1904.03074[physics.ins-det]`.

[4] L.R. Evans *et al.*, "The steel septum magnets for beam splitting at the CERN SPS", in *Proc. 6th International Conf. on Magnet Technology (MT-6)*, Bratislava, Slovakia, Aug. 1977, Rep. CERN-SPS-ABT-77-13.

[5] E. Lopez Sola *et al.*, "Beam Dump Facility Target: Design Status and Beam Tests in 2018", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2604–2607. `doi:10.18429/JACoW-IPAC2018-WEPMG002`