SPS Beam Dump Facility

COMPREHENSIVE OVERVIEW

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Abstract

The proposed Beam Dump Facility (BDF) is foreseen to be located at the North Area of the SPS. It is designed to be able to serve both beam dump like and fixed target experiments. The SPS and the new facility would offer unique possibilities to enter a new era of exploration at the intensity frontier. Possible options include searches for very weakly interacting particles predicted by Hidden Sector models, and flavour physics measurements. The SPS BDF team has performed in-depth studies and prototyping for all critical aspects of the facility design. The feasibility study has demonstrated that, with suitable modifications, the SPS can deliver the beam required for the proposed Search for Hidden Particles (SHiP) experiment at the BDF with the required characteristics and with acceptable losses. The study has proven the feasibility of the robust high-power target housed in a dedicated target complex, and completed the initial design of the primary beam transfer line. Civil engineering, integration, safety and radiation protection studies have also been completed.

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1 Context and motivation

The proposed Beam Dump Facility is foreseen to be located at the North Area of the SPS. It is designed to be able to serve both beam dump like and fixed target experiments. Beam dump in this context implies a target which aims at provoking hard interactions of all of the incident protons and the containment of most of the associated cascade. In the first instance, exploitation of the facility, in beam dump mode, is envisaged to be for the Search for Hidden Particle (SHiP) experiment.

Several recently proposed experiments [1] highlight that the SPS operating in beam-dump mode or in fixed-target mode would be an excellent way to go beyond the current SPS program and enter a new era of physics studies at the intensity frontier. These studies would complement the exploration of the high-energy frontier at the Large Hadron Collider (LHC) after 2026. Papers have been submitted [2, 3, 4] to demonstrate the unique potential in searches for particles predicted by Hidden Sector models and in flavour physics measurements.

The multi-user design and full exploitation of the SPS accelerator with its present performance could allow the delivery of an annual yield of up to 4×10^{19} protons on target with a beam momentum of 400 GeV/c while respecting the beam requirements of the HL-LHC, and while maintaining the operation of the existing SPS beam facilities. Currently, CERN has no experimental facility which is compatible with this beam power. The consolidation and upgrades of the CERN injector complex and the continued operation of the SPS with the unique combination of the high-intensity proton beam and slow beam extraction, motivates the construction of a new high-intensity experimental facility which is capable of fully exploiting its capacity in parallel to the operation of the HL-LHC. CERN's North Area has a large area next to the SPS beam transfer lines which is for the most part free of structures and underground galleries, and which could accommodate the proposed facility. In addition, the facility may be designed with future extensions in mind. On a longer time scale, the possible future large-scale programs at CERN could also pave the way for upgrading the facility to take advantage of new or upgraded injectors.

Following a first evaluation of the required facility in 2014-2016 [5, 6, 7], the CERN management launched a Comprehensive Design Study over three years[8, 9]. The study team has executed an in-depth feasibility study of proton delivery to target, the target complex, and the underground experimental area, including prototyping of key sub-systems and evaluations of the radiological aspects and safety. A first iteration of detailed integration and civil engineering (CE) studies have been performed in order to produce a realistic schedule and cost. As a complement to the physics and detector proposals, this document summarises the results of the studies, and presents an overview of the proposed facility.

2 Objectives

The lack of firm hints to the mass scale of new particles calls for a concerted effort by direct searches and precision measurements. At the same time the absence of new particles is not necessarily due to their high scale of masses but could equivalently be due to their weak scale of couplings with the Standard Model particles. This motivates investing in an ambitious complementary programme to investigate the possibility of a light Hidden Sector coupled to the Standard Model.

Beam dump experiments are potentially superior to collider experiments in the sensitivity to GeV-scale hidden particles having luminosities several orders of magnitude larger than those at colliders. The large forward boost for light states, gives good acceptance despite the smaller angular coverage and allows efficient use of filters against background between the target and the detector, making the beam-dump configuration ideal to search for new particles with long lifetimes.

The detailed specification of the BDF is, in the first instance, mainly driven by the SHiP experiment. SHiP has been optimised to search for light long-lived particles produced in decays of charm and beauty hadrons and radiative processes, and consists of two complementary apparatuses which are sensitive to both decay of hidden particles and scattering signatures of light dark matter. The combination of the intensity and the energy of the SPS proton beam allows the production of a very large yield of the processes potentially capable of giving rise to the different Hidden Sector particles. During five years of operation with 4×10^{19} protons on a high-density target per year, it is expected to produce $\mathcal{O}(10^{18})$ charmed hadrons and more than 10^{21} photons above 100 MeV. In addition, it has been found that the 400 GeV/c proton beam at the SPS provides a good compromise between the large yield of heavy hadrons and photons, and a manageable background. Furthermore, the unique feature of slow extraction of a de-bunched beam on a timescale of around a second allows a tight control of combinatorial background.

The new beam-dump facility would also allow the performance of unprecedented measurements with tau neutrinos. Five years of operation on SHiP's target at 400 GeV would yield $\mathcal{O}(10^{16})$ tau and anti-tau neutrinos. The first direct observation of the anti-tau neutrino and the measurement of tau neutrino and anti-tau neutrino cross-sections are among the goals of the SHiP experiment. As charm hadron decays are also a source of electron and muon neutrinos, it will also be possible to study neutrino-induced charm production from all flavours with a data-set which is more than one order of magnitude larger than those collected by previous experiments, solely performed with muon neutrino interactions.

The BDF beam-line offers a potential opportunity to host and operate in parallel an experiment [3] to search for lepton flavour violation and rare decays with the very large production of tau leptons and D mesons. Intercepting about 2% of the intensity delivered to SHiP with a thin target, the experiment would have access to about 8×10^{13} tau leptons and 10^{16} D^0 and D_s meson decays.

In the medium term, extensions of the long-lived particle search programme at the BDF is possible with a large volume light dark matter and neutrino scattering detector located downstream of the SHiP detector. Assuming the same angular acceptance and a liquid argon target, the equivalent mass to the current proposal with a 10 tonne scattering target of lead at 30 m from the target, would be $\sim$ 450 tonne detector at 120 m.

In the longer term, beyond 2035, depending on the future large-scale project at CERN after the HL-LHC, upgraded or new injectors could open a new search region. Continued operation of the SPS leaves several options open for the BDF depending on the development of the physics landscape. Findings at SHiP could motivate continued operation with protons to further establish or measure properties of new particles, but also potentially operation with electrons. An upgrade of the SPS to a superconducting machine at 0.9–1.3 TeV in conjunction with an upgrade of the slow extraction and the transfer lines, could open a new mass window in the searches for weakly coupled particles. Alternatively, with a reconfigured target system the facility could also host a kaon physics experiment in the future, such as the proposed experiment KLEVER[4] which aims at making a measurement of the branching ratio for the $K_L \to \pi^0 \nu \overline{\nu}$ decay.

3 Overview of the BDF facility

The BDF relies on slow extraction of protons from the SPS, from an upgraded extraction channel in Long Straight Section 2 (LSS2). After about 600 m of the present TT20 transfer line, a new splitter/switch magnet system, which will maintain compatibility with the existing NA operation, will deflect the beam into a dedicated new transfer line. The new line will be connected by a modified junction cavern to the existing tunnel. The beam is dumped on a high power target housed in a purpose-built, heavily shielded, target complex. Behind the target, a muon shield is followed by an experimental hall. To meet the specific requirements of SHiP, the BDF design aims at a slow extraction over 1 s, with 4×10^{13} protons swept onto a dense target. The scope of the facility studies includes these elements plus the associated CE and service infrastructure. The proposed location and overall layout of the facility is shown in Fig. 1. A description of the key features of the new facility and a brief overview of the progress made by the study on the technical aspects follows.

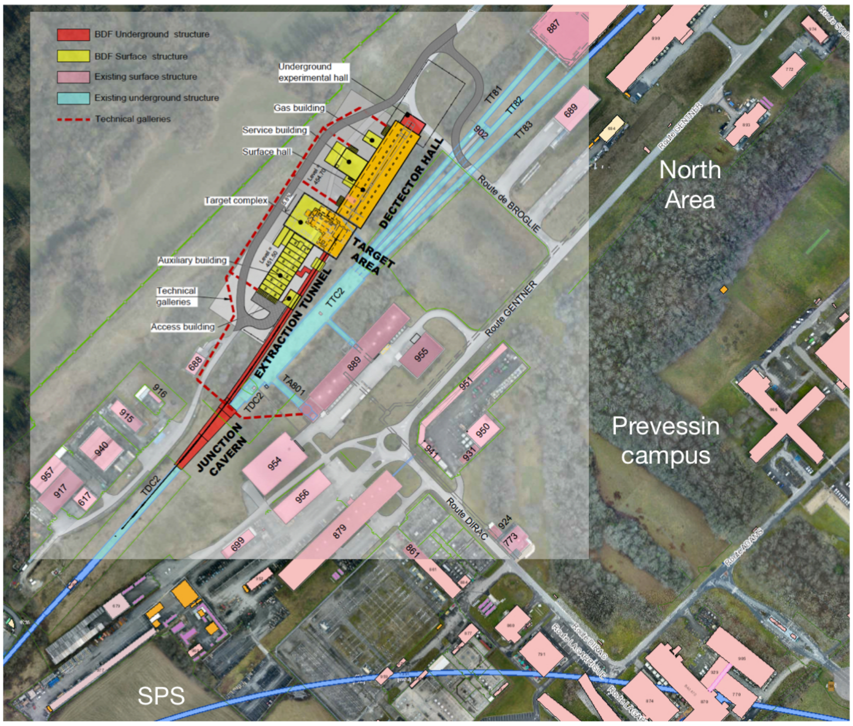

Fig. 1: Overview of the proposed implementation of the BDF at the SPS North Area at the CERN Prévessin campus.

3.1 Extraction from SPS

Third-integer slow extraction of 400 GeV/c protons from the SPS is well established. A few percent of beam losses on the septum wires is intrinsic to the process and results in machine activation, reduces component lifetime and places severe limitations on personnel access and maintenance. Significant operational effort already goes into minimising these losses and ensuring a high quality, uniform spill. The proton intensity on target (PoT) requested by SHiP poses significant challenges [10] and improvements will need to come from a combination of lower beam loss per extracted proton, reduced activation per lost proton, and improved or remote interventions. The most effective solution is to reduce the beam loss per extracted proton, since this also reduces the radiation dose to cables and high voltage feedthroughs. A factor of four reduction is needed.

Methods to reduce the losses concerning the extraction process, hardware and controls have been developed and tested in 2018, both with a SHiP cycle and the longer NA cycle.

The Q-sweep method used for slow extraction in the SPS since its construction has been replaced by a new type of Constant Optics Slow Extraction (COSE), where the optics are kept constant in normalised strength while the whole machine momentum is ramped. COSE has several advantages over the Q-sweep, since it keeps the orbit and separatrix angle at the electrostatic septum (ZS) fixed through the spill. Since mid-2018 COSE has been systematically deployed for NA operation.

For loss reduction, both passive scatterers and bent silicon crystals have been developed and tested as diffusers to locally reduce the proton density at the ZS wires. For the passive diffuser [11], a 240 μm wide, 30 mm long array of Ta wires achieved a loss reduction of 15%, consistent with an effective ZS width of 500 – 600 μm. For the bent silicon crystal [12] a 780 μm width and 2.5 mm long crystal with a large channelling angle of 150 μrad gave a loss reduction of slightly over 40%, again consistent with a ZS width of around 500 μm. Both diffuser types were tested for 12 hour periods with the full beam intensity of 3×10^{13} protons per spill, and demonstrated that ZS shadowing was stable and reproducible.

A separate technique of loss reduction by separatrix folding [13] was also tested successfully.

The extraction sextupoles which govern the speed of diffusion across the ZS wires were increased in strength to reduce the particle density and losses, while octupole fields slow the diffusion speed at higher amplitude to avoid increased losses on the ZS cathodes. In beam tests this method also reduced the losses by slightly over 40%. Importantly, it was successfully tested in combination with the crystal ZS shadowing. The combination of the two methods gave a loss reduction of slightly more than a factor three.

The alignment of the five ZS anodes is a crucial factor in the overall beam loss, since it determines both the absolute beam loss and the potential gain from the shadowing methods. The control of the alignment was improved to a resolution of below 50 μm, while numerical optimisers were simulated and deployed to align the five anodes to the extracted beam. The alignment time (with 9 degrees of freedom) was reduced from 8 hours to 40 minutes.

3.2 Transfer lines, switching and dilution

The location of the BDF target complex allows the re-use of about 600 m of the present transfer line TT20, which is already operated with slow-extracted beam at 400 GeV/c. After the upgraded switch/splitter element, a new 380 m long section of beam line (TT90) is required to deliver the beam to the target.

The powering scheme for the TT20 transfer line will remain largely unchanged. The design of TT90 uses 23 standard bending magnets at a field of up to 1.9 T in a FODO structure to ensure adequate separation between the new and existing beam lines, and to minimise the longitudinal extent of the CE works in the new junction region. Six standard focusing quadrupole magnets provide flexibility and tunability of the beam spot size and dispersion at the proton target. The line optics have been finalised with the completion of trajectory correction and aperture studies, and the parameter feasibility at the target has been demonstrated with the use of existing magnet designs.

The transfer line design replaces the three existing splitter magnets by laminated versions with dual functionality: either splitting the beam destined for the NA targets as today; or deflecting the entire beam into TT90 for transport to the BDF target. For the BDF beam sent to TT90, the entire beam will be steered through the switch/splitter aperture without losses. This solution maintains full compatibility with the present NA operation.

The present splitter magnet is an in-vacuum Lambertson septum with a yoke machined from solid iron, with the coil based on a water-cooled lead of copper with an insulation of compacted MgO powder. For the new magnets a laminated yoke is required to perform the polarity switch between SPS cycles in about 2 s.

A magnetic and mechanical design has been made and the magnet performance simulated, complicated by the details of the possible mechanical errors and effect on the beam losses. Prototyping of the laminated yoke design is underway to evaluate the feasibility of the very tight mechanical tolerances required to maintain low beam losses. MgO coils will provide the required radiation resistance. Procurement of parts for the construction of a short magnet prototype will start in early 2019.

The beam dilution sweep will be implemented with two sets of two orthogonal kicker magnets with Lissajous powering functions to produce a circular sweep at $4\,\mathrm{Hz}$. With a free drift length for the beam of about $120\,\mathrm{m}$ and a bending angle of $0.5\,\mathrm{mrad}$ per plane, the sweep radius will be $50\,\mathrm{mm}$. Since the survival of the proton target relies critically on the beam dilution, the SPS beam will be interlocked with the beam dilution system and the instantaneous loss rate at the target. New concepts for interlocking of the slow extraction have been developed.

A straightforward reconfiguration of the existing beam elements in the BDF extraction channel would allow the accommodation of the drift space required to implement the in-line target and experimental zone for the tau lepton flavour experiment.

3.3 Production target/dump

The BDF/SHiP target can be considered as a beam dump, as it has to safely absorb the full 400 GeV/c SPS primary beam every 7.2 s. The target is required to maximise the production of charm and beauty hadrons, and to maximise the re-absorption of pions and kaons, which implies a high-Z material with a short nuclear interaction length, contrary to a neutrino-producing target. The high deposited power is the most challenging aspect, with up to 355 kW average power deposited on target and 2.56 MW over the 1 s spill. To produce sufficient dilution of the energy density in the target, the slow extraction needs to be combined with a beam spot of at least 8 mm root-mean square in both planes and a $300\,\mathrm{mm}$ long sweep of the beam over the target surface.

Detailed energy deposition and thermo-mechanical design studies have been performed. The required performance may be achieved with a longitudinally segmented hybrid target consisting of blocks of four nuclear interaction lengths (58 cm) of titanium-zirconium doped molybdenum alloy (TZM, density 10.22 $\mathrm{g/cm^3}$) in the core of the proton shower followed by six nuclear interaction lengths (58 cm) of pure tungsten (density 19.3 $\mathrm{g/cm^3}$).

A medium-density material is required in the first half of the target to reduce the energy density and resulting thermal-induced stresses. The thickness of each block and location of each cooling slot has been optimised to provide uniform energy deposition and sufficient energy extraction. The blocks are interleaved with 5 mm wide slots for water cooling. Tantalum alloy cladding of the TZM and the tungsten blocks - by means of diffusion bonding via Hot Isostatic Pressing - will prevent corrosion and erosion of the core material by the high water flow rate. The design limits the peak power density in the target to below 850 $\mathrm{J/cm^3}$/spill and compressive stresses to below 130 MPa.

The target blocks will be assembled in a double-walled helium vessel. The inner vessel will enforce the high-flow 35 $\mathrm{m^3/h}$ water circulation between the proton target blocks at 20 bar to avoid water boiling. The outer vessel acts as a safety hull to contain hypothetical leaks, and is filled with He gas to prevent corrosion.

A prototype target built to the BDF/SHiP design was installed and tested with beam in TCC2 in 2018. Lower intensity 1 s spills of 4×10^{12} protons without dilution sweep was used to achieve stress levels comparable to the final target. The prototype was successfully operated with beam for over 14 h, accumulating 2.4×10^{16} PoT. Online measurements of strains and temperature on instrumented target blocks showed a very good agreement with simulation. In 2019 the target blocks will be disassembled and analyzed in a dedicated facility to quantify the target material behaviour under irradiation conditions.

3.4 Target complex

The target will be subject to severe radiological constraints, and will be located in a shielded bunker around 15 metres below ground level. Remote handling for manipulation of the target and surrounding shielding will be mandatory due to the high residual dose rates expected after operation. The target complex has been designed to house the target and its shielding in a helium vessel, along with the cooling, ventilation and helium purification services below ground level. The SPS beam will enter the surrounding helium vessel through a removable beam window, then pass through a collimator which serves to protect the target and adjacent equipment from misalignment of the incident SPS beam and to protect the equipment in the extraction tunnel from particles (essentially neutrons generated by the target) travelling backwards relative to the incident beam.

The target will be surrounded by approximately 3700 tonnes of cast iron and steel shielding (part of it water-cooled to dissipate the deposited power) with outer dimensions of around $6.8 \times 7.9 \times 11.2\,\mathrm{m^3}$ (the so-called bunker/hadron absorber) to reduce the prompt dose rate during operation and the residual dose rate around the target during shutdown. The target and its surrounding shielding will be housed in the vessel containing gaseous helium slightly above atmospheric pressure in order to reduce air activation and reduce the radiation accelerated corrosion of the target and surrounding equipment. The design allows for removal and temporary storage of the target and shielding blocks in the cool-down area below ground level and includes dedicated shielded pits for storage of the highest dose rate equipment.

In 2018 the target complex design has been developed in detail with full definition of the handling and remote handling operations required throughout the life of the facility. This work demonstrated the feasibility of the construction, operation, maintenance of the BDF target complex along with decommissioning of the key elements. The remote handling of highly activated radioactive objects, such as target, beam window, collimator, shielding blocks and magnetic coil, along with their connection and disconnection within the target complex building were studied in detail, including foreseen remote handling operations such as target exchange as well as unforeseen operations needed to recover from failures or damage to equipment.

The study included the conceptual design of lifting, handling and remote handling equipment for the highly activated objects along with the necessary water, helium and electrical connections compatible with the radiation environment and remote handling constraints. These have been integrated in the overall target complex design [14].

3.5 Muon shield

The total flux of muons emerging from the proton target with a momentum larger than 1 GeV/c amounts to $\mathcal{O}(10^{11})$ muons per spill of 4×10^{13} protons. To control the background from random combinations of muons producing fake decay vertices in the detector decay volume, and from muon deep inelastic scattering producing long-lived neutral particles in the surrounding material, and to respect the occupancy limits of the sub-detectors, the muon flux in the detector acceptance must be reduced by at least six orders of magnitude over the shortest possible distance. To this end, a muon shield entirely based on magnetic deflection has been developed [15]. The first section of the muon shield starts within the target complex shielding assembly, one meter downstream of the target, with a magnetic coil which magnetises the hadron stopper made of US1010 steel with a field of 1.6 T over 4.5 m. The rest of the muon shield consists of 6 free-standing magnets, each 5 m long, located in the upstream part of the experimental hall.

3.6 Experimental area

BDF is designed to house a multi-purpose large-scale experimental program using a single beam line and a single main target station. The initial design of the experimental area (Fig. 2) has been dictated to a large extent by the requirements of the SHiP experiment. All phases of the experiment, including assembly, construction and installation, as well as operation, have been taken into consideration. The complex consists of a 120 m long underground experimental hall, centred on the beam axis. In order to reduce background from particle scattering in the walls, the underground hall is 20 m wide along its entire length. A 100 m $\times$ 26 m surface hall is located on top of the underground hall. The installation plan foresees pre-assembly in the surface hall in three principal work zones with the help of a 40 tonne and a 10 tonne crane, in parallel to final assembly in the underground hall using a dual 40 tonne hoist crane and an 80 tonne crane. Three 14.5 m $\times$ 18 m access openings between the surface hall and the underground hall provide direct access to the principal detector installation areas. For shielding purposes each opening would be covered by 18 concrete beams during operation. A 20 m $\times$ 34 m three-storey service building, adjacent to the service hall, houses all services related to the infrastructure and the detector, control room, workshop, labs, and offices.

3.7 Radiation protection

As BDF aims to push the primary proton beam to an average power of up to 355 kW, radiation protection considerations strongly determine the design of the facility. To comply with the applicable CERN radiation protection rules regarding doses to personnel and environmental impact, all relevant radiological aspects were carefully addressed at the design stage. The assessment includes detailed studies of

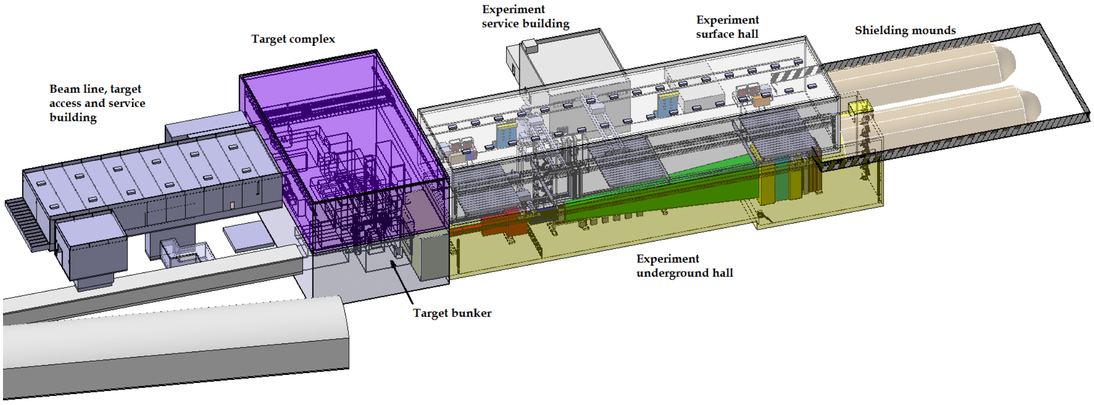

Fig. 2: Overview of the target complex and experimental area.

the expected prompt and residual dose rates on the various accessible areas of the facility as well as the levels of the stray radiation in the surrounding experimental and public areas. Furthermore, it comprises the evaluation of the risk due to activated air, helium and water and the impact of its release into the environment. Studies on soil activation and radioactive waste zoning were also conducted. All studies were based on extensive simulations using the FLUKA Monte Carlo particle transport code [16, 17].

There was close collaboration between the RP and Target complex teams when optimising the facility from a radiation protection perspective. This allowed the RP constraints during the different stages – construction, operation, maintenance and dismantling – to be fully taken into account. The target complex area is particularly critical due to its high radiation levels and its proximity to the ground level, other experimental facilities, and public areas. Appropriate measures such as heavy shielding, remote handling and dedicated storage for highly activated elements, embedding the target in a helium vessel, etc. were defined on the basis of full FLUKA simulations. Furthermore, tritium out-diffusion experiments were successfully performed during the BDF target prototype test. The results will be important in the continued assessment of the possible environmental impact and mitigation. The final data analysis is ongoing and post-irradiation examination is to come.

The preliminary RP evaluation of the proposed facility showed the general feasibility of the project in terms of exposure of persons to radiation and the radiological impact on the environment.

3.8 Integration

Integration of the beam dump facility from the transfer line to the experimental area has been undertaken. All the infrastructure requirements have been defined, and the locations of structures and the services have been optimised in terms of radiation protection, general safety, accessibility and practicality. The internal layout of the target complex was subjected to a separate study, described in Section 3.4.

The dismantling of the elements in the junction cavern has been examined, and a detailed execution plan with a preliminary dose estimation and sequence of operations in a realistic time-line has been produced taking into account the radiation constraints. The re-installation of the equipment has also been analysed in order to define the activities in line with the ALARA principle.

A detailed integration study of the BDF beam line has been undertaken, considering the handling, maintenance and service requirements, whilst minimising the impact on the existing North Area beam-lines. The transfer tunnel geometry has been optimised, reducing the overall cost of the civil engineering works. The personnel and equipment access to the transfer tunnel has been defined in accordance with radiation protection and safety requirements. The access shaft to install the beam line equipment has been implemented at the optimal location in the access building on top of the transfer tunnel. An auxiliary service building has been developed to house the cooling, ventilation and electrical infrastructure for the

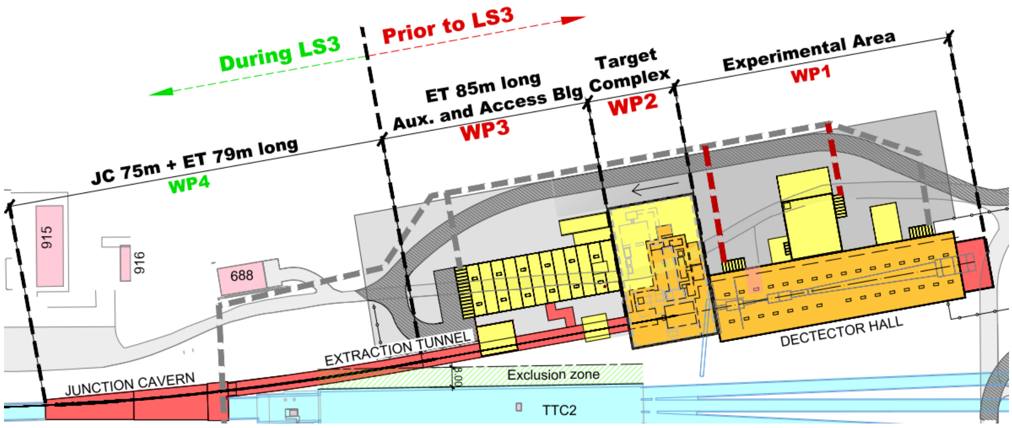

Fig. 3: CE work package breakdown. Underground structures in red; surface structures in yellow; below ground component in orange; existing structures in blue. JC – junction cavern; ET – extraction tunnel.

transfer tunnel, the target complex and the experimental area. The transfer tunnel's personnel access has also been integrated in the building. The access to the target complex has been established in accordance with requirements from radiation protection requirements.

The integration of the experimental area has been based on a detailed analysis of the implementation of the SHiP detector systems. Structural load conditions, fixed and dynamic, and operational requirements in terms of powering, ventilation, cooling, alignment, vacuum and access scenarios have been evaluated. The experimental underground hall has been dimensioned for the SHiP experiment, and routing of services has been defined.

The experiment surface hall and underground hall provide the required space for the assembly of the SHiP experiment. A first preliminary installation plan, with well-defined transport and handling activities, has been drawn up in collaboration with SHiP. A second surface building adjacent to the surface hall provides the space required for services, control, network, computing and electronics racks. Two escape routes are foreseen for safety reasons, and a specific design of the smoke extraction system has been proposed based on several compartments separated by smoke curtains. A preliminary proposal for the layout of the technical galleries for the overall facility has been produced. A preliminary global beam interlock scheme to provide protection of the equipment and personnel has been drawn up. As a result, the final layout of the facility covers all the requirements in terms of both radiation protection and general safety as well as the functional and operational needs of the facility.

3.9 Civil engineering

The CE works required to implement the BDF have been studied with external consultants. The CE requirements of each part of the facility have been captured and a detailed study carried out to determine feasibility, optimise the form of construction and enable a robust cost estimate to be made.

The major CE elements of work for the project consist of: demolition of 75 m of the existing TDC2 tunnel and construction of the 75 m junction cavern, a 165 m long extraction tunnel, the target complex facility, and the experimental area along with associated support and service buildings, as shown in Fig. 3.

As part of the work carried out, proposals were made on the most appropriate structural form, foundation design and indicative sizing of key structural members. The study has produced a proposed design and an indicative optimised construction sequence and methodology.

An options analysis has been carried out to determine the optimum strategy for the demolition of the junction cavern, as this is the most schedule-critical part of the CE works. This included key constraints and considerations for both CE and RP. Strategies have also been developed to: minimise differential settlement; minimise water ingress/egress for activated areas; incorporate seismic design issues; define best-use of spoil generated by the works; provide infrastructure for access and services.

Although the project presents a number of challenges, the CE studies thus far have revealed no show-stoppers. Some important future investigations have been identified to fully assure the project. In particular, further ground investigations are required to progress towards a definitive CE design.

4 Beam and operational scenarios

The SPS serves several clients in sequence via a repetitive operational sequence (“Supercycle") of a length of a few tens of seconds. Users can include the LHC, AWAKE, HiRadMat and the NA. The NA receives a primary proton beam at 400 GeV/c wherein the full SPS beam is slowly extracted over a flat top of typically several seconds.

The recent maximum slow-extracted proton intensity was about 3.5×10^{13} protons over 4.8 s. This proton flux is transported and shared through two series of splitter magnets onto three primary targets, T2, T4 and T6, from which the NA secondary beam lines are served. Important limitations on the intensities extracted to the NA are the losses inherent to slow extraction and to the splitting process.

The beam and SPS cycle parameters foreseen for SHiP at BDF are shown in Table 1. Of note is the total beam intensity, the relatively short slow extraction spill length, and high beam power on target.

Table 1: Key SPS beam and cycle parameters foreseen for SHiP

Momentum	400 GeV/c
Beam Intensity per cycle	4.2×10^{13}
Beam Intensity on target	4.0×10^{13}
Cycle length	7.2 s
Spill duration	1 s
Avg. beam power on target	355 kW
Avg. beam power on target during spill	2560 kW
Protons on target (PoT)/year	4×10^{19}
Total PoT in 5 years data taking	2×10^{20}

An operational model that incorporates the SHiP cycle into regular SPS operations has been developed, based on the beam performance routinely achieved for the recently completed CERN Neutrinos to Gran Sasso (CNGS) programme [18]. A reduction of a factor of four in the beam loss per proton at extraction is assumed, and present levels of beam loss per proton at the splitters.

Compatibility with the existing NA program has been considered, and Fig. 4 shows the number of protons on the current NA targets as a function of the number of protons on the SHiP target for a typical year of operation including LHC and other users, and realistic transmission and availability figures [19]. The assumed sharing delivers an annual yield of 4×10^{19} protons on target to BDF/SHiP and a total of 1×10^{19} to the other physics programs at the NA, in a year with no fixed-target ion operation.

5 Readiness and expected challenges

The main features of the SPS BDF were described in the SHiP Technical Proposal of 2015. In 2016 the BDF team were charged by the CERN management to complete key technical feasibility studies in time for the ESPP update. This was in conjunction with the recommendation by the CERN Research Board to the SHiP experiment to prepare a Comprehensive Design Study as input to the ESPP update. Material and personnel resources were made available and work packages formed to perform in-depth studies and prototyping as appropriate. Topics covered: extraction and beam transfer; target and target complex; Radiation protection; Safety engineering; Integration and CE.

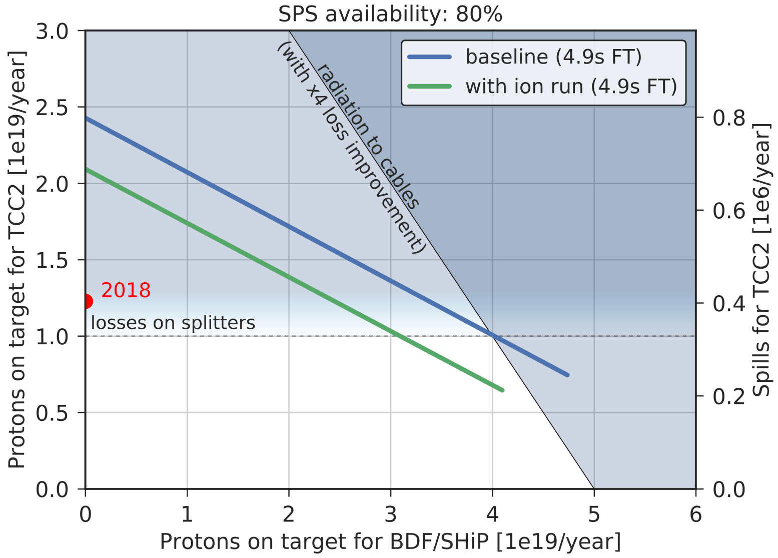

Fig. 4: Projection of number of protons and number of spills on the North Area targets (TCC2) as a function of the number of protons on target for BDF/SHiP. The blue line shows the situation with only proton operation. The green line shows a scenario including ion operation. Both scenarios include operation of HiRadMat and AWAKE as in 2018. The integrated number of protons on the targets with the super-cycle used in 2018 is indicated in red.

There has been sustained effort on all fronts with excellent progress. A reduction of extraction losses per proton by a factor three has been demonstrated with beam, the transfer line, junction cavern and CE designs have all been advanced, the target design has been validated with beam tests, the target complex design has been improved and an overall integration study has been performed. A realistic construction and installation plan has been developed around the SPS and LHC's third long shutdown (LS3), and a detailed analysis of the beam sharing shows that the target PoT can be reached.

Three specific aspects remain to be fully demonstrated or completed. These are the deployment of extraction loss reduction techniques onto operational beams (planned for the SPS run starting in 2021), the construction and testing of the prototype laminated switch/splitter magnet, and site investigations of the ground for the detailed progression of the CE design.

A schedule has been drawn up and is detailed in the addendum to this document. A significant challenge for BDF will be to optimise the scheduling of the CE works to minimise the impact on SPS NA operation, since the CE work package related to the junction cavern and first section of extraction tunnel cannot be accommodated in the currently foreseen 12 month shutdown of the SPS in LS3 (2025).

6 Summary

Since the inception of the PBC hosted BDF feasibility study in 2016, the study has addressed all pertinent technological challenges. In-depth studies and prototyping have been performed or are already well underway for all critical components. Through a mixture of novel hardware development, beam physics and technology, the study and prototype validations have shown that SPS can deliver the beam with the required characteristics and with acceptable losses, to a robust target housed in a suitable target complex.

The feasibility is proven, the technologies and techniques, although challenging, appear to be within CERN's established competencies, and the project, given the resources, is ready to move towards the detailed design and execution phase.

The BDF team gratefully acknowledge the support and trust shown by the CERN management.

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