SHiP Comprehensive Design Study: Status report

SHiP Collaboration

Abstract
Status of the SHiP experiment and the Comprehensive Design Study (CDS) with focus on the re-optimization, the simulation studies, and the detector and physics performance.

Keywords
SHiP, Comprehensive Design Study, CDS status report, CERN report.

Contents

1 Beam line

- beam extraction
- proton sharing
- operation in bunched mode (if there are hints for LDM signal from emulsion spectrometer)
- spill structure
- beam line with TauFV
- target complex
- target, extended to 12 lambda, prototype in beam
- magnetization of hadron stopper
- facility/experiment interface
- free standing muon shield, optimization using machine learning, field map, technology studies and tests
- Vacuum vessel layout engineering (decay volume + spectrometer section)
- experimental area updated layout + infrastructure
- updated detector layout
- experiment services and integration
- detector installation scheme

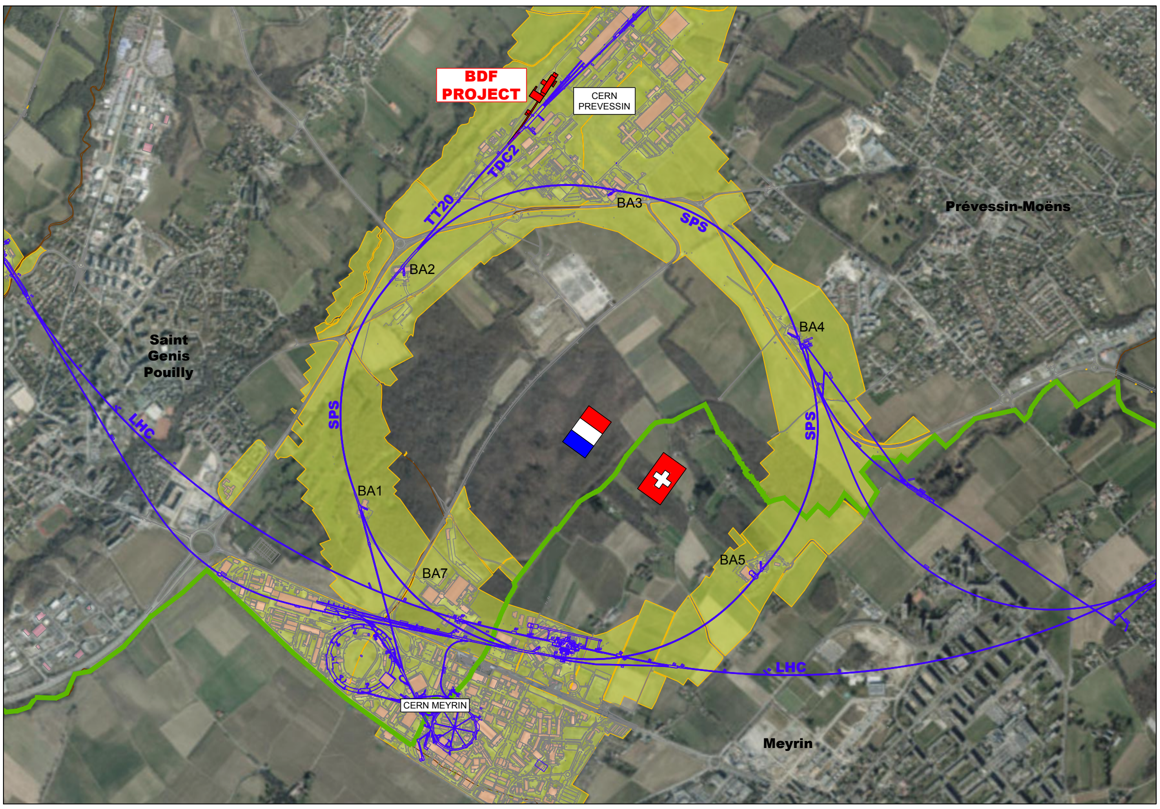

Figure 1:

The Comprehensive Design Study for the experimental facility has been carried out by the Beam Dump Facility working group and in its dedicated subgroups in the context of the Physics Beyond Collider Study Group in close collaboration with the SHiP experiment.

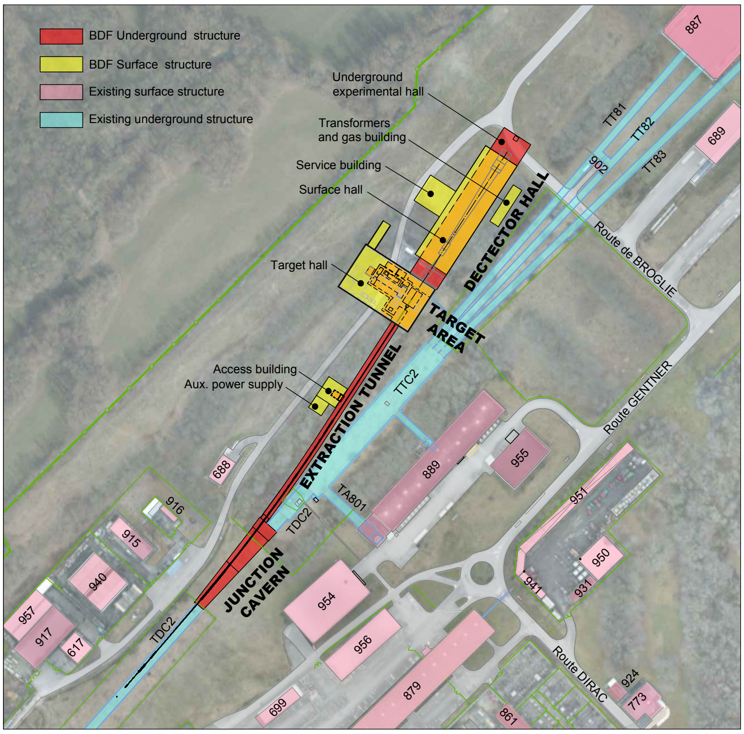

Figure 2:

Based on the request put forward in the addendum to the SHiP Technical Proposal [**?**], this study phase has consisted in a detailed elaboration of the SHIP operational scenario, and in a preliminary design of the main components of the proton delivery, the target and the target complex, and the experimental area, together with a detailed evaluation of the radiological aspects and mitigation. Several critical items have been prototyped to demonstrate the concepts, the new type of three-way combined beam splitter/kicker magnet and the target and a conceptual version of its enclosure.

In addition, it has been considered of high importance to perform a preliminary study of the integration of the whole complex, civil engineering design and execution process in order to produce a more precise cost estimate and time line for the project.

A full writeup of the Comprehensive Design Study for the Beam Dump Facility is available ([**?**] and references therein).

Assumptions and baseline parameters confirmed.

The sections below summarizes the changes, updated requirements, status and key conclusions related to the experimental facility and beam line.

Reference to feasibility studies in TP addendum and BDF working group, focus on re-optimization and updates, synthesis of conclusions BDF work

2 Proton yield and beam delivery

The SHiP operational scenario is based on a similar fraction of beam time as the past CERN Neutrinos to Gran Sasso (CNGS) program. The most favourable experimental conditions for SHiP are obtained with a proton beam energy of around 400 GeV. A nominal beam intensity of 4×10^{13} protons on target

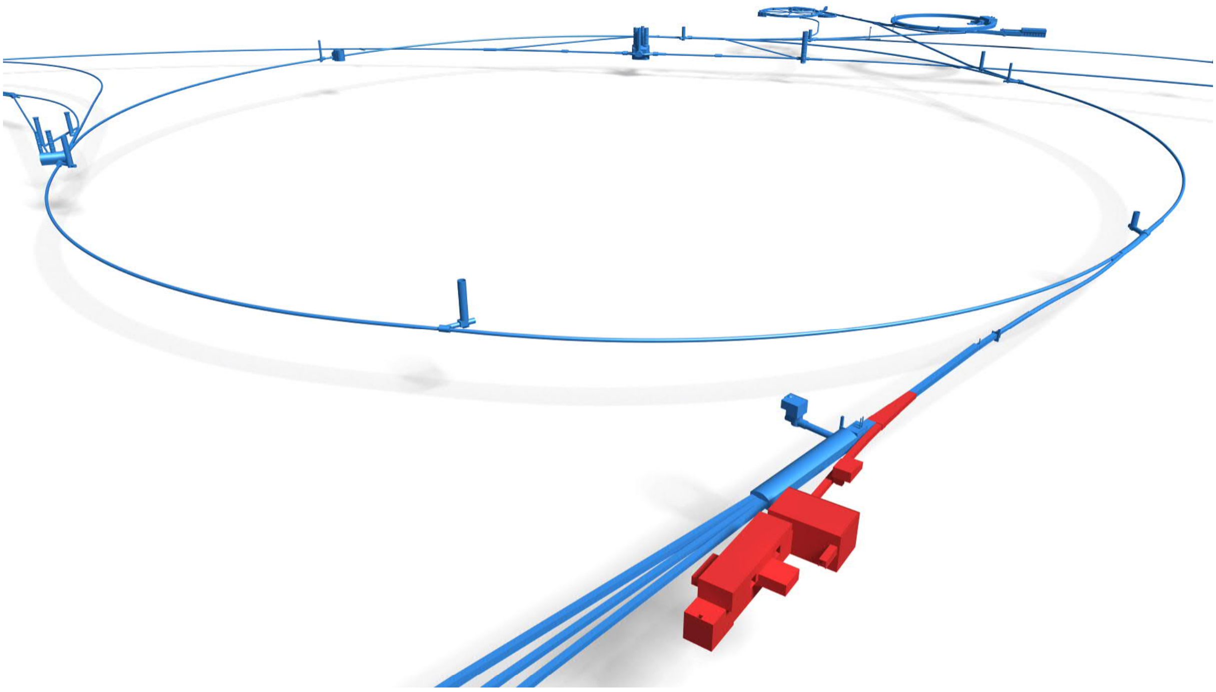

Figure 3:

per spill is assumed for the design of the experimental facility and the detector. In the baseline scenario, the beam sharing delivers an annual yield of 4×10^{19} protons to the SHiP experimental facility and a total of 10^{19} to the other physics programs at the CERN North Area, while respecting the beam delivery required by the LHC and HL-LHC . The physics sensitivities are based on acquiring a total of 2×10^{20} protons on target, which may thus be achieved in five years of nominal operation.

Significant progress has been made in the studies of techniques to reduce the beam losses and activation during the slow extraction process which is necessary to achieve the baseline intensity of 4×10^{19} protons on target per year. The current status confirms the intensity reach to within a factor of two, and further techniques presently under deployment are aiming to provide the additional reduction to allow the full intensity.

2.1 Operation with slow-extraction in bunched mode

SHiP profits from the unique feature in the SPS of slow extraction of a de-bunched beam over a timescale of around a second. It allows tight control of combinatorial background, and allows diluting the large beam power deposited on the proton target both spatially and temporally. Should an observation require consolidation, a second mode of operation with slow extraction of bunched beam is also foreseen in order to further increase the discrimination between the signature of a Light Dark Matter object, by measuring their different times of flight, and background induced by neutrino interactions.

3 Target system

Target extended from 10 to 12 interaction lengths, radius changed from square block 30x30 to cylindrical with radius of 12.5cm.

4 Updated experiment layout

The main experimental challenge concerns the requirement of highly efficient reduction of beam-induced backgrounds to below 0.1 events in the projected sample of 2×10^{20} protons on target. To this end, the experimental configuration includes a unique design of a muon shield based on magnetic deflection to reduce the flux of muons emerging from the target by six orders of magnitude in the detector acceptance.

The SHiP experiment incorporates two complementary apparatuses. The first detector immediately downstream of the muon shield consists of an emulsion based spectrometer optimised for recoil signatures of hidden sector particles and τ neutrino physics.

4.1 Magnetization of the target hadron stopper

Contract and activity with RAL

4.2 Free-standing Muon shield

The design of the muon shield and the residual rate of muons depends on the momentum distribution of the muons produced in the initial proton collision. The latest shield optimisation and rate estimates were performed using `PYTHIA` simulations. In order to validate these simulations a test beam campaign is starting in July to measure the muon flux using a replica of SHiP's target. Further details can be found in Ref. [SHiP-EOI-016]. Depending on the outcome of this test beam campaign, a further optimisation of the shield configuration will be performed.

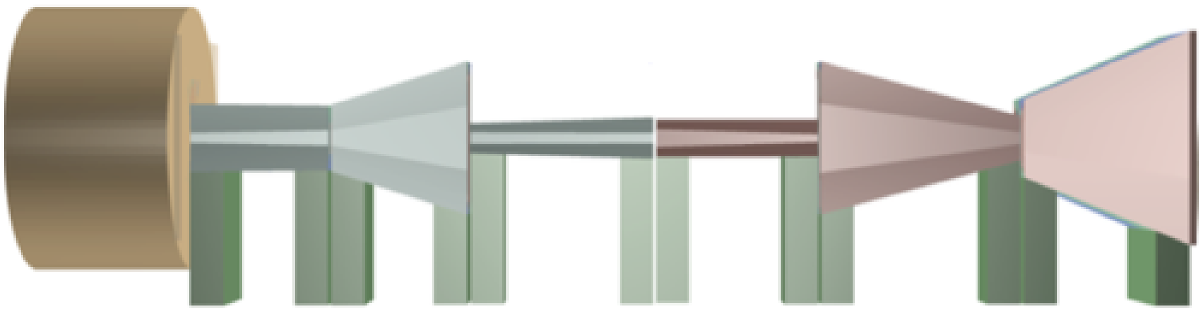

Figure 4: Side view of the optimized muon shield magnets.

The design and performance of the muon shield poses certain technological challenges. These include how to best assemble sheets of Grain Oriented steel without disrupting the magnetic circuit, how to cut the GO sheets into desired configurations, and how to best connect the GO sheets to achieve the desired stacking factor. In order to address these questions a prototyping campaign is underway.

Obtained optimized parameters of magnets were used to build 3D CAD model of the muon shield, presented in Fig. 5.

This model was used to model realistic magnetic field with OPERA??? package. Fig. 6 illustrates calculated magnetic field in and around the shield body, presented in the quadrant cut out. Modelled field demonstrates a good expected homogenity and strength in the regions responsible for deflecting high momentum muons and minor degradation in unimportant outer corners regions.

Optimized magnet shapes are far from rectangular. The entire 30 meter construction is made from Grain Oriented (GO) steel sheets, which are only 0.3 mm thick. The tentative design of the magnet body is illustrated in Fig. 7, and consists of 50 mm thick packs of sheets connected together by riverts, spot welding or screws. Packs are bolted together into rectangular blocks of about 50 cm depth. One block is thus made of about 1000 metal sheets of the same size, that makes mass production of such sheets

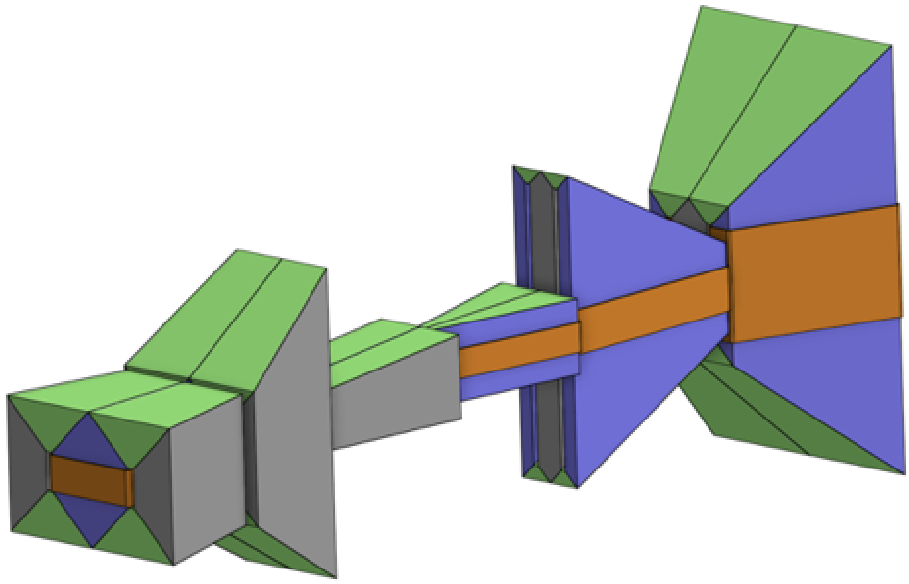

Figure 5: 3D view of the optimized muon magnetic shield. Description ????

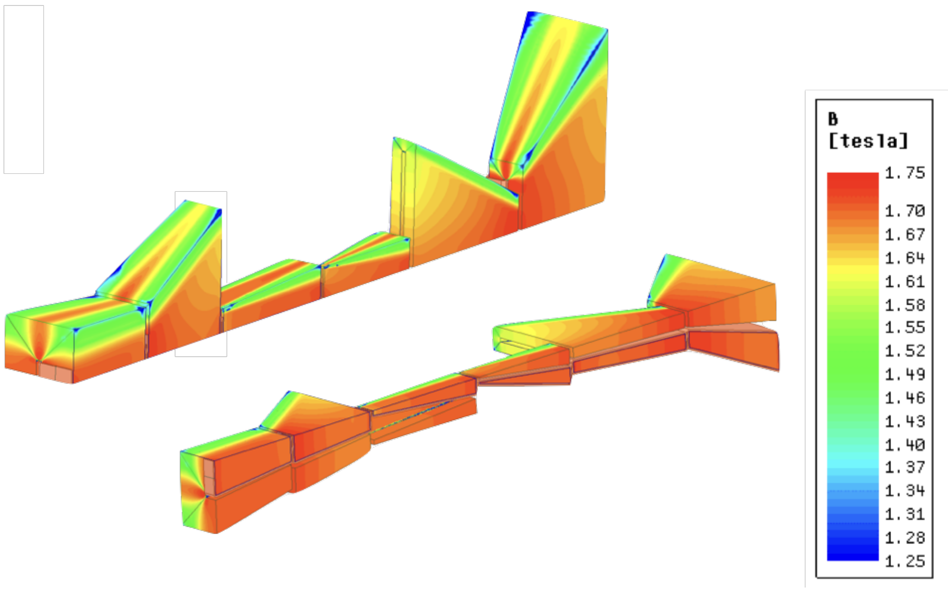

Figure 6: Modelled magnetic field distribution with nominal field intensity set to 1.7T. Quadrant cut out is shown.

reasonable cheap. Finally, blocks of different shapes are installed on the support beams. Fig. 8 illustrates a tentative design of the shield constructed as a set of rectangular blocks.

Anizotropic magnetic properties of the GO steel are important for the shield construction, as this allows to make magnetic field of strength about 1.8 T in solid body, that cooresponds to about 1.7 T effective magnetic field considering unavoidable sheet packing factor. That strong field is necessary to deflect highest momentum muons that may be produced in the target. Different sections across the magnet must have different grain orientation, thus corresponding pieces must be connected to form magnetically connected sections with different anizotropy orientation. Welding by electron beam technology is tentatively chosen for connecting sections together. It is well known however that strong mechanical or thermal impact can degrade or destroy the anizotropy structure of the GO steel. Dedicated tests were

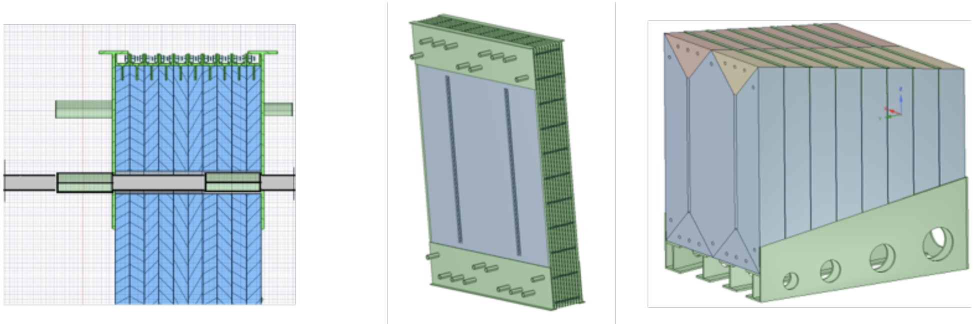

Figure 7: Tentative mechanical design of magnets. GO steel sheets are packed into sections about 50 mm thick (left). Packs are bolted together into rectangular block about 50 cm thick (left, central). blocks of different dimensions are installed on the support beams (right).

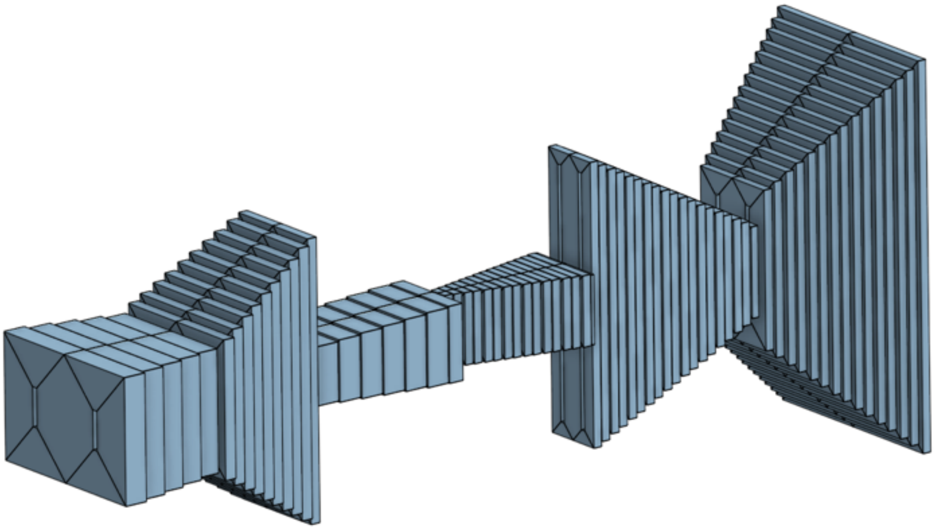

Figure 8: Tentative construction of the muon shield made of rectangular blocksfullMechanics.png.

made to measure magnetic properties of actual GO steel samples, as well as possible degradation of these properties by the welding procedure. Green lines in Fig. 10 demonstrates measured properties of the initial GO steel sample along and across the anisitropy orientation direction. Blue line corresponds to the sample that has been welded by the electron beam. Magnetic quality of the sample degrades significantly. The degradation is driven by the thermal and mechanical stress in the area of the weldet joint. Microscopic image in Fig. 9 indeed demonstrates a carbon structure which appeared in the joint after the welding. The annealing procedure can reduces tension thus improving material properties. The annealings at 500°C and 700°C were separately applied to the welded test samples, that indeed helped to recover the most of original magnetic properties of the material, as illustrated in Fig. 10.

The important question is to which extend degradation of magnetic properties in joints affects the nominal magnetic field in the most critical volume of the magnet - the sectors which deflect high momentum muons. Another important factor which needs careful consideration is a stacking factor. As the magnet body is made of batch of thin sheets rather than solid peaces, there is unavoidable clearance between sheets, thus the magnet body volume is filled by the magnrtic material not 100%. Fig. 12 demonstrates effective magnetic field in the crytical volume of the first magnet of the shield by comparing ideal joint case with the case of measured magnetic properties of the welded joint. Stacking factors of 95% and 90% are presented for GO steel scenario. Calculations show minor degradation of the overall

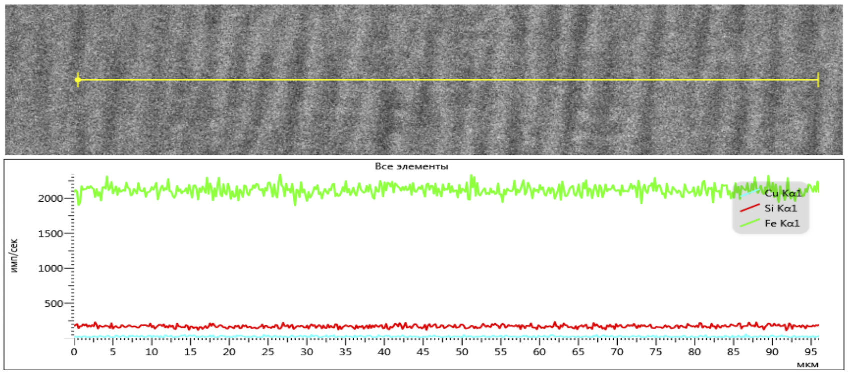

Figure 9: Carbon structure in the welded joint before the annealing.

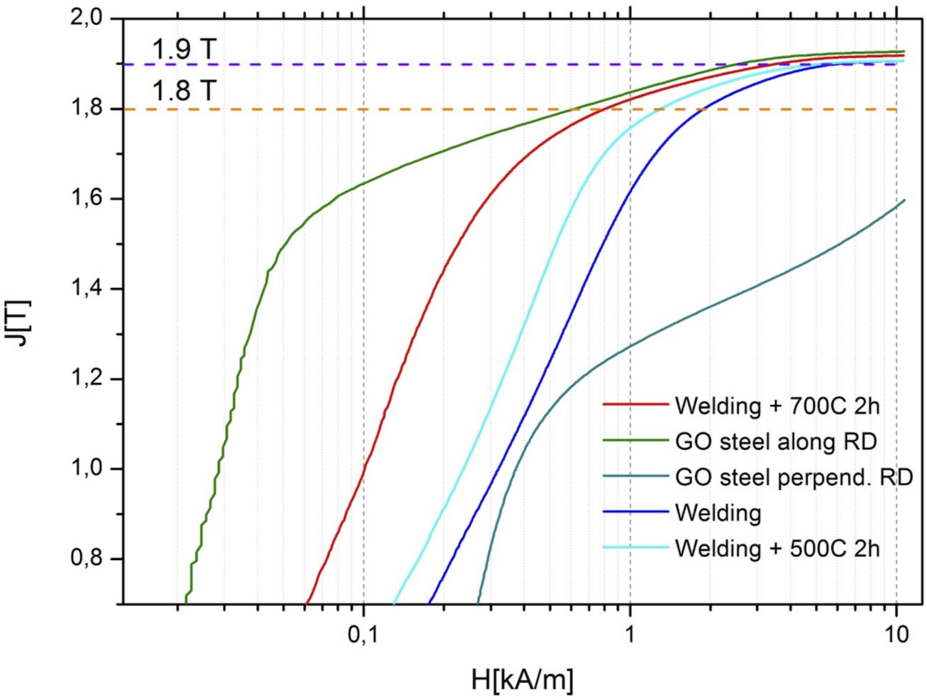

Figure 10: Measured magnetic properties of the Grain Oriented steel batch: unprocessed sample along (green) and perpendicular (dark green) to rolling direction, after the welding (blue), after the following annealing at 500°C (cyan) and 700°C (red).

magnet deflecting performance in spite of significant degradation of the field in joints. Fig. 12 illustrates the actual map of the magnetic field in different assumptions about joints and stacking factors. The current is chosen to provide effective field 1.7 T in the critical magnet area.

4.3 Vacuum vessel

Baseline is a .... Consist of several sections

The preliminary studies of the vacuum system for the approximately 1750 m^3 SHiP vacuum vessel shows that the requirements can be satisfied with a system of combined root-screw pumps, piezo and membranes gauges for pressure monitoring and manual valves for operation and venting purposes [**?**](EDMS 2000025). A low outgassing epoxy paint is considered to be deposited on the steel surface under vacuum

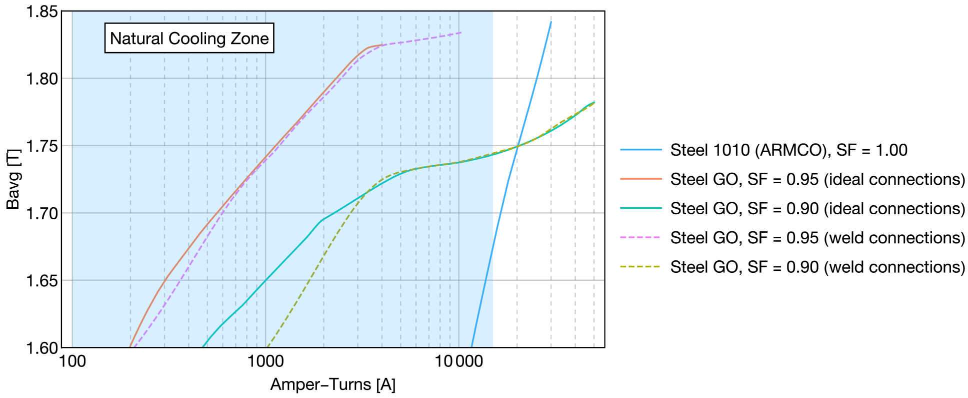

Figure 11: Magnetic field in the critical magnet region, as calculated for the magnet 1 of the shield, for different steel properties, joint properties and stacking factors as a function of the total current in magnet coils.

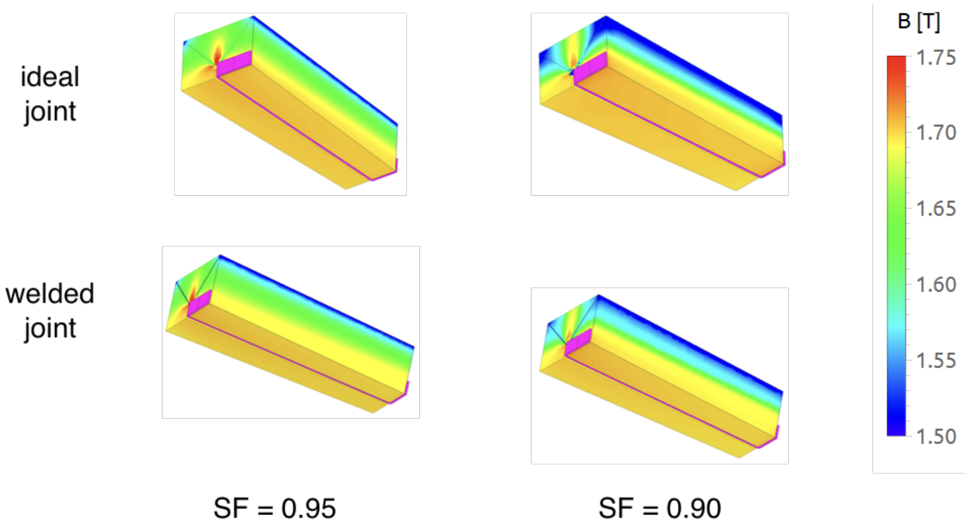

Figure 12: Modelled magnetic field map for ideal and welded joints, for stacking actors 95% and 90%. The current is set to provide effective magnetic field of 1.7 T in the critical magnet area.

Figure 13: Simulated hit rates caused by muons passing magnetic shield. Comparison of ideal magnetic field setup (red) and realistic magnetic field (blue).

Figure 14: Reconstructed track rates caused by muons passing magnetic shield. Comparison of ideal magnetic field setup (red) and realistic magnetic field (blue).

in order to reduce the surface outgassing. The longitudinal vacuum forces which are taken into account in the design of the vacuum chamber are around 300t.

5 Experimental Area and Infrastructure

6 Potential siting of a search for Lepton Flavour Violation experiment

(Pictures from presentation at BDF WG)

Motivation (yield)

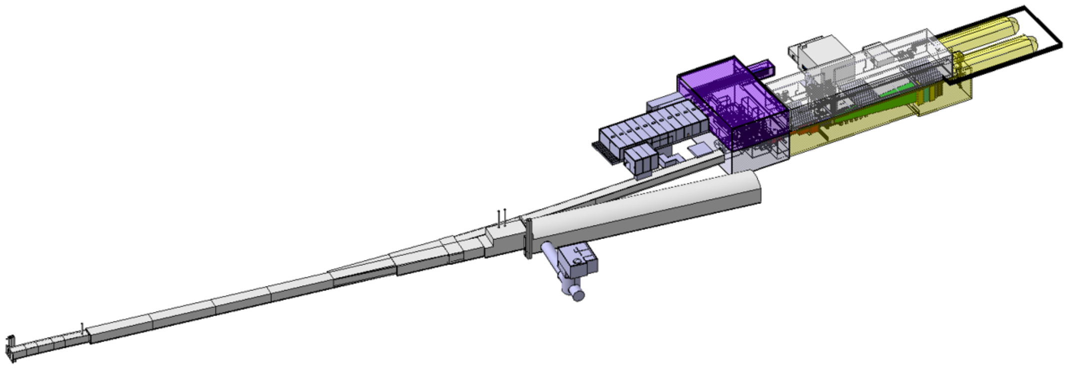

Figure 15:

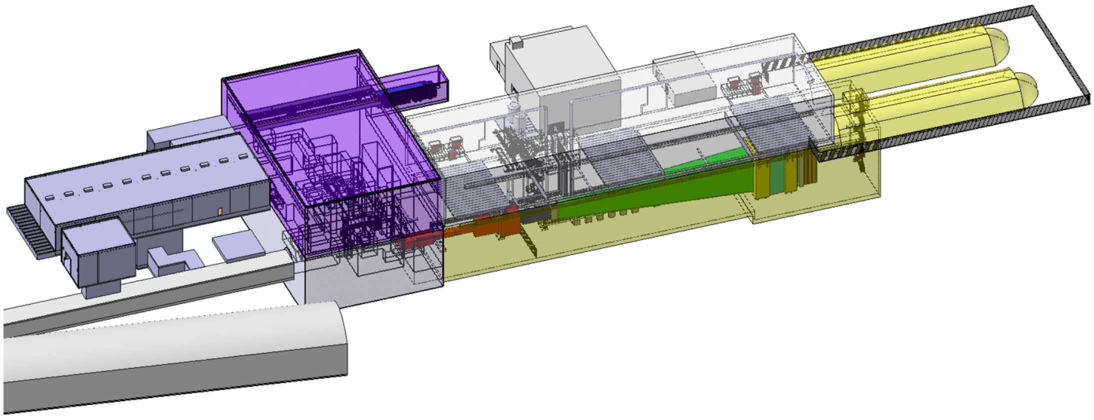

Figure 16:

From the beam optics point of view, several locations can provide the required beam conditions and the beam drift space to accommodate the detector along the new $200\ m$ transfer line between the TDC2 switch yard cavern and the BDF target station without affecting the location of the BDF experimental area and without significant changes to the configuration of the beam line. The choice is instead driven by considerations related to the civil engineering in the vicinity of the existing installations, radiological protection, and to access and transport requirements above ground and underground. Lateral space is required on both sides for shielding in order to limit the radiation exposure of the surrounding underground area to levels typical for the rest of the beam line.

The preferred location under study is situated $60\ m$ upstream of the BDF target bunker. An access and service complex for the transfer line is already foreseen at this location. It would be extended and reconfigured to include a bypass tunnel, the detector bunker, service cavern and the required surface complex.

By a modest reconfiguration of the existing beam elements, the location provides a beam spot of $\sigma_x = 4.4\ mm\ \times \sigma_y = 1.1\ mm$ and a drift space of $20\ m$ to implement the detector and the shielding. A compensator magnet is foreseen to allow the experimental dipole magnet and the need to swap polarity. The downstream dilution system which is required to sweep the beam in a circle on the BDF target to dilute the beam power will have to be twice as strong in this configuration.

A first check of the characteristics of the proposed target configuration and beam induced effects on the material has revealed no showstopper. The target and the silicon-pixel detector will share a common closed volume containing an inert gas in circulation to prevent radiation induced corrosion and to ensure external cooling of the target and the detector.

A preliminary FLUKA study of the radiological aspects has been performed. It confirms that the radiation environment will be very challenging for the detectors. Remote handling will be required to move the detectors out of their data taking position into an adjacent service cavern for interventions. A shielding wall will separate the service cavern from the detector bunker during operation. No access is allowed underground during operation. An important challenge concerns preventing irradiation of the downstream beam elements due to radiation leakage through the whole in the shielding for the beam line.

A preliminary check of the surrounding environment shows no problems with respect to environmental limits or fluxes in neighbouring underground areas at the North Area, but this requires further studies. The additional flux of muons and neutrinos which enter the SHiP experiment will be studied as soon as the TauFV experimental configuration reaches more maturity.