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SHiP progress report 2024

This document outlines developments within the Search for Hidden Particles (SHiP) collaboration since our last meeting with SPSC referees in Sept 2024. At that meeting, the collaboration agreed that it would be appropriate to present our annual report in Sept 2025, with the goal of reviewing the collaboration's funding plans, progress toward TDRs and the intended start of data-taking in advance of Long Shutdown 4 (LS4). The latter is motivated by having scope to commission the Beam Dump Facility and the experiment before LS4, and thus having the shutdown to complete the detector and take any remedial action that is required. Since our last report to the SPSC, CERN have confirmed the shift of LS4 by a year, with the shutdown now scheduled to start in 2034. It remains the SHiP collaboration's aim to have the target complex, muon shield, decay volume and main spectrometer installed such that commissioning with the first data can take place and the background suppression be verified. This implies construction will need to start around 2029, with a several-year long design and procurement phase before then.

Beyond progressing with the technical and design challenges, several of which are discussed further below, a key obstacle for the collaboration remains getting firm commitments from funding agencies on this compressed timescale. In discussions to expand the collaboration, the uncertainty with respect to CERN's plans for a Forward Physics Facility continues to result in institutes and countries taking a 'wait and see' approach. This is clearly incompatible with CERN's request that the experiment be ready to fully exploit the facility's physics potential in a timely manner, but it is difficult for the collaboration to communicate this to the funding agencies with any authority.

Since our last report to SPSC the collaboration have made progress in many areas, and major developments were reported at the collaboration's recent SHiP-week, held in Freiburg in early October. In particular, progress has been made in:

- plans to replace the SHiP vacuum vessel with a helium-filled gas bag;
- plans to integrate the neutrino detector within the muon shield;
- development of the muon shield;
- optimisation of the spectrometer;
- and the continued expansion of the SHiP collaboration.

Each of these items is discussed in more detail below.

1 Replacing the vacuum vessel with a helium-filled balloon

Background rejection requirements for SHiP's hidden-sector searches demand the 1.5×10^{12} neutrinos and antineutrinos generated every SPS spill give rise to only a very limited number of interactions within or around the decay vessel. Deep-inelastic scattering of neutrinos can produce decay products that can be combined with other combinatorial particles to generate backgrounds for hidden-sector searches.

The material of the steel decay vessel that was proposed to sustain a vacuum gives rise to a significant number of neutrino interactions, necessitating the decay volume be surrounded by a $\sim 700\,\mathrm{m}^2$ scintillator veto system, which requires the introduction of further material.

Simulation has been used to show that the background can be controlled if the 1 mbar vacuum is replaced with helium at 1 atm pressure. While with helium the number of background events for fully-reconstructed and partially-reconstructed final states are higher by an order of magnitude, even a basic selection can bring the background back down to a level less than 1 event. The neutrino spectrum has now been simulated with the Genie3 generator, which has a somewhat harder spectrum than previous studies with Genie2. With helium, the steel vacuum vessel can be replaced by a lightweight gas bag, held in place by a structure of aluminium frames (see Fig. 1). As well as substantially reducing the material and hence cost, this will be much easier to construct and give greater flexibility in the shape. It will also dramatically simplify the design of the main tracker, which need not be in vacuum. A large-volume circulation and purification system will be needed in order to maintain the quality of the helium.

2 Integrating the neutrino detector within the muon shield

The positioning of the SHiP scattering and neutrino detector, SND, behind the muon shield, is motivated by the reduced occupancy in this region. The detector requires a magnetic field for muon momentum determination and charge-id and the system occupies around 8 m of space along the beam line. This reduces the space available

Figure 1: (Left) The steel decay vessel considered for the SHiP comprehensive design study; (centre) a photo of the kind of large helium bag envisaged; (right) the aluminium frames envisaged to hold the bag in place.

for the muon shield and/or results in a decay vessel further from the target, increasing the transverse size needed to cover a given solid angle.

The collaboration have decided to position SND *within* the muon shield, where there is already a magnetic field. The detector concept is shown in Fig. 2. Plates of iron absorber material serve as the target for the neutrinos and are interspersed with detection planes. The shorter distance from the target will increase the neutrino flux and the space freed behind the muon shield will allow for a longer shield and/or closer decay vessel. The detection technology employed must be able to cope with the increased occupancy that will result from the new position and should facilitate installation independent of the shield, as well as having a modular design suitable for future expansion. The analysis strategy for the reconstruction of neutrino interactions is still being discussed but will be based on the missing-energy carried away by neutrinos from tau decays and the impact parameter of the leptons produced.

3 Development of the muon shield

Every SPS spill of 4×10^{13} protons will produce 10^{10} muons that must be swept out of the SHiP decay volume in order to avoid generating an unacceptably large detector occupancy. In order not to contribute significant background to hidden-sector searches, the muon flux needs to be reduced by around six orders of magnitude. For SHiP's comprehensive design study, a series of conventional warm magnets were proposed that could achieve this.

The proposed shield design has now been adapted to a hybrid solution, where the first section will consist of a $\sim$7 m long, 5 T high-temperature superconducting magnet, followed by $\sim$15 m of warm magnets. Throughout

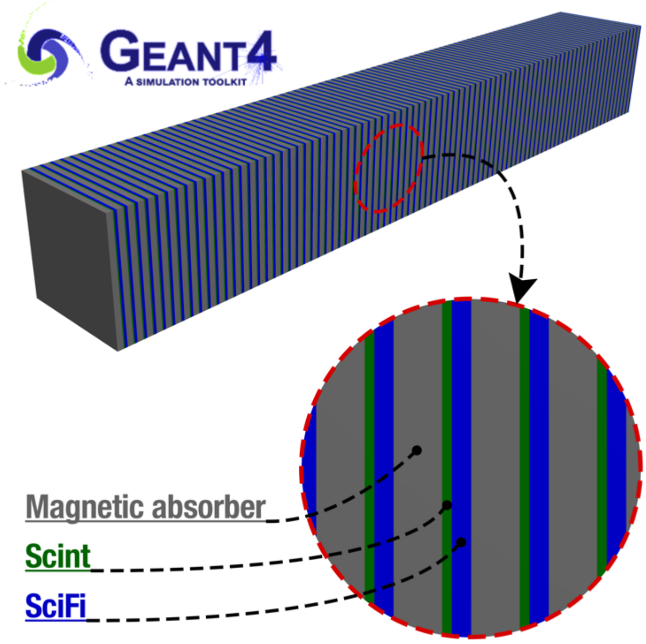

Figure 2: Concept for the neutrino detector that will be integrated within SHiP's muon shield.

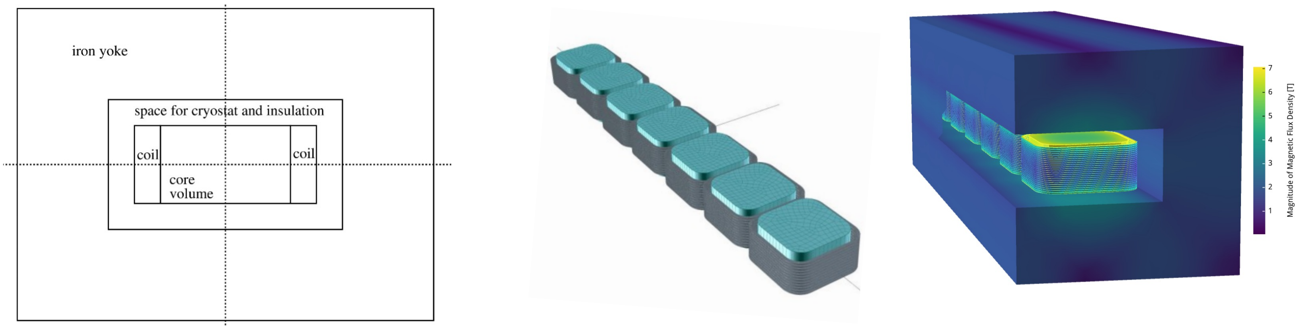

Figure 3: (Left) transverse cross-section of the proposed high temperature superconducting magnet that will form the first element of the SHiP muon shield; (Centre, right) the proposed arrangement of coils within the superconducting magnet.

the system the field is not required to be particularly homogenous, provided the desired sweeping effect is achieved.

Progress has been made in developing the high-temperature superconducting (HTS) magnet. The proposed design considers an HTS configuration with a 1 m×0.5 m iron-filled inner core encapsulated in a cryostat and in the associated 0.2 m depth of insulation. The surround iron yoke is envisaged to be a further ∼1 m depth, bringing the total transverse dimension to ±2 m (see Fig. 3). To respect current limitations on the production of HTS tape, the magnetisation will be provided by an array of square coils with inner and outer iron yoke (see Fig. 3). The baseline design assumes ∼125 km of single-wound ReBCO tape operating at 30 K with a current of ∼650 A. The tape will be wound with the no-insulation technique and will be epoxy impregnated. A closed-cycle neon refrigeration system is envisaged with the relevant cooling tubes running throughout the system. The collaboration are actively exploring several options for the procurement of the initial quantity of HTS tape. A programme to determine the feasibility of each of the major elements of the design has been developed and will initially focus on the winding process and coil characterisation.

Pending more evidence for the feasibility and understanding of the performance of the HTS magnet, the work on the warm section of the muon shield focuses on developing a generic model of the magnets and the integration of the SND detector into the central return yoke. The collaboration are also putting considerable effort into improving the machine-learning optimisation of the field configuration.

The length and magnetisation of the hadron absorber situated before the muon shield are also aspects that are being considered for further optimisation. For the CDS study, a single, gas cooled, resistive coil positioned above the absorber was considered to provide 1.5 T along the 5 m length (see Fig. 4). Challenges for the implementation of this include provision of the services and the handling in a region receiving a radiation dose of 200 kGy/year. The interface with the target complex will require any solutions are developed in close collaboration with the CERN team responsible for the facility.

4 Optimisation of the spectrometer

The precision with which momenta require determination within SHiP demand a spectrometer magnet with a field integral of 0.6-0.8 Tm, which can be readily achieved with a peak field of about 0.15 T. The geometry of the

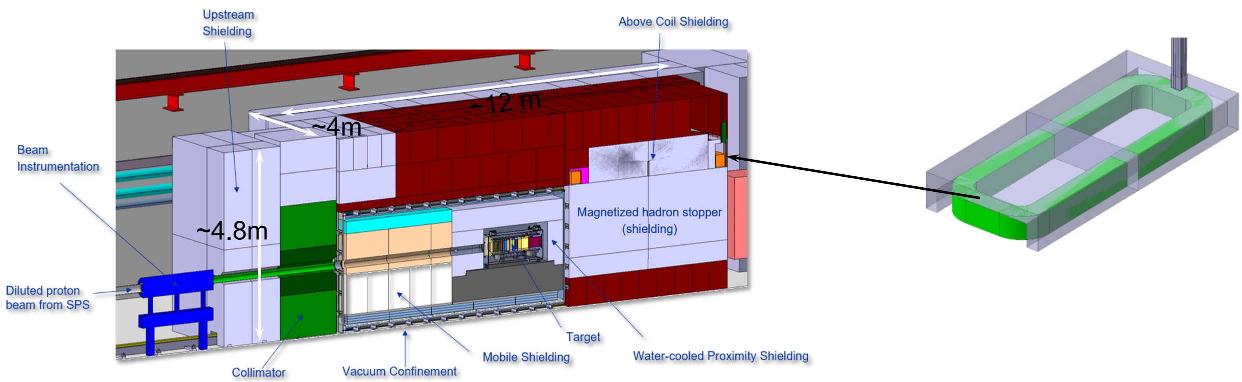

Figure 4: The target and hadron absorber region - the insert shows the coil designed to magnetise the hadron absorber.

tracker requires optimisation with the helium-filled decay volume to ensure the best overall angle determination, which depends on the B.dl integral and the positioning of the stations.

The aperture required is $4\times\ 6\,\mathrm{m}$, necessitating a nominal design with total transverse dimensions $6\times 8.5\,\mathrm{m}$ (see Fig. 5). Given the possibility to map the field in-situ at the 5-10% level, the integrated field is again more important than the field homogeneity.

Given the scale, a warm magnet would require 1 MW of power. The CERN TE-MSC group have therefore made exploratory studies of superconducting options making use of NbTi / Nb3Sn / MgB2 / ReBCO wire operating at 20 K. An energy-efficient dipole design with MgB_2 subcables is under investigation with a phase-1 demonstrator having been constructed, thermally cycled and subjected to quench testing with no observed effect of training. A further test with a warm yoke and coil at 20 K integrated into a dedicated cryostat with gaseous cooling is envisaged for 2025. The next step will involve a full-size prototype for which the collaboration are currently procuring ∼50 km of MgB_2 cable.

The coil design needed for an H-type iron yoke has been simulated and is implemented in the SHiP simulation (see Fig. 5). Three double pancakes are envisaged in each of two symmetric racetrack-type coils with 16 turns per layer and 3 kA per turn. The simulation will allow evaluation of the performance with a helium-filled decay volume and the spectrometer in air. The electromagnetic design, conceptual design of the cryostat and cooling architecture are all under study.

5 Expansion of the SHiP collaboration

Since our September meeting with the SPSC referees the SHiP collaboration has been joined by the Institute of Nuclear Physics, Kazakhstan. The collaboration board will consider the application from the University of Ghent, Belgium at their next meeting. The SHiP collaboration now comprises 40 institutes from 18 countries, in addition to CERN.

The membership committee are in discussion with seven groups from Austria, Italy, the Netherlands and the UK. Preliminary discussions have also been initiated with new groups in Finland, France and Sweden.

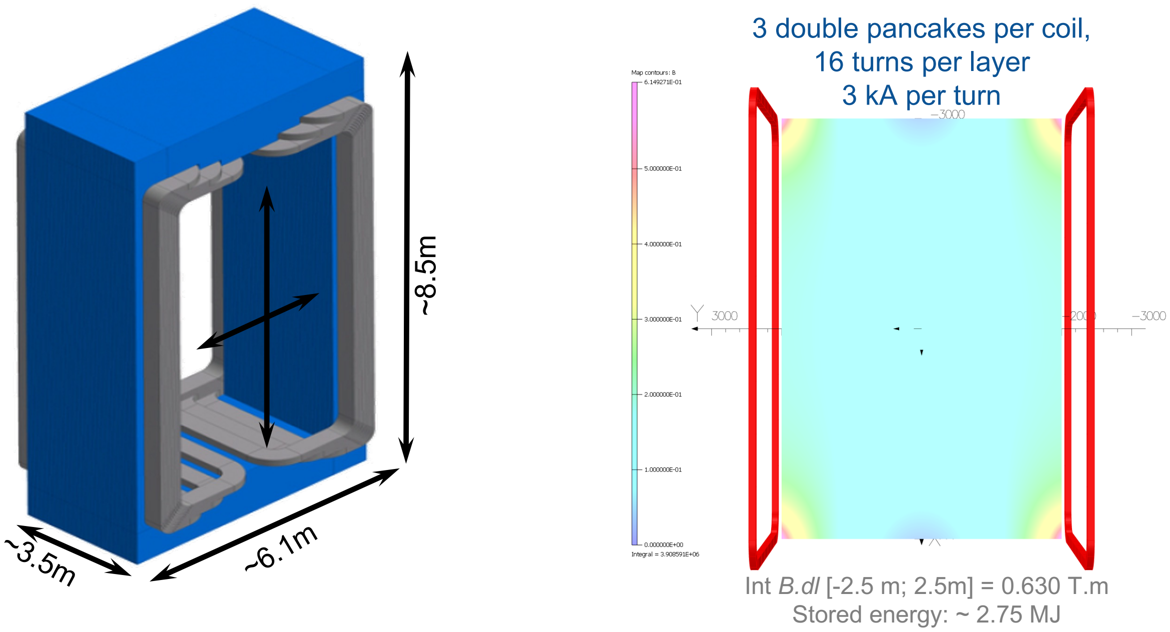

Figure 5: (Left) Proposed layout of the spectrometer yoke and coils; (Right) spectrometer magnet modelled in finite-element calculation software.