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Report

A new Experiment to Search for Hidden Particles (SHIP) at the SPS North Area

Preliminary Project and Cost Estimate

The scope of the recently proposed experiment Search for Heavy Neutral Leptons, EOI-010, includes a general Search for HIdden Particles (SHIP) as well as some aspects of neutrino physics. This report describes the implications of such an experiment for CERN.

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0.6	2014-05-28	87	Add executive summary and expand introduction. Complete estimate for costs and resources and updated timeline. Added input to cost and resource estimates as an appendix.
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Executive Summary

The proposed SHIP experiment is a new general-purpose fixed target facility at the SPS to search for hidden particles as predicted by a very large number of recently elaborated models of Hidden Sectors which are capable of accommodating dark matter, neutrino oscillations, and the origin of the full baryon asymmetry in the Universe. Moreover, the facility is ideally suited to study the interactions of tau neutrinos. The SHIP detector consists of two 40 m long evacuated decay volumes, each of which is followed by a 10m magnetic spectrometer, a calorimeter and muon detectors. An emulsion target surrounded by a magnetic field is located upstream of the decay volumes.

The SPS configuration and performance have been investigated under the assumption that SHIP shares the protons with the current North Area fixed target program in a way similar to CNGS. The performance of the ZS septa and the induced radioactivity in the SPS extraction region are likely to be key factors in the overall SHIP performance and require further studies. Realistic super-cycle compositions have been elaborated using past experience for the operation of the North Area, CNGS and LHC, and MDs.

The dedicated SHIP beam line branches of at the top of the existing TT20, in the TDC2 cavern. With a two-polarity splitter magnet replacing the current splitter, an extra beam line is possible. The production target is very challenging due to the very high energy and power density. Preliminary investigations show that required performance may be achieved with a 50 cm water cooled and segmented tungsten target embedded in a massive iron shielding that also acts as a hadron stopper. The target and the 5 m hadron stopper are followed by a 70 m long muon filter. The beam line is followed by a 120 m long and 20 m wide underground detector hall, which houses the SHIP detector and the emulsion target.

Although uncertainties persist at this preliminary design stage, the overall material cost of the beam and infrastructure is estimated to be about 114 MCHF and the manpower required is estimated to be 91 FTEs. The detectors themselves have an estimated cost of about 45 MCHF. The junction cavern with TDC2 has to be constructed and equipped during Long Shutdown 2. The aim is to start beam commissioning and operation during Run 3, i.e. around 2023.

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1. Introduction

At its meeting on Tuesday February 4th, the Enlarged Directorate took the decision to convene a joint study group between the Accelerator Sector, members of the team which made the proposal for an experiment to Search for Hidden Particles (SHIP), and the HSE unit to prepare a report including the layout, the timeline and the resources which are required to set-up the experiment. The task force met on 4 occasions and prepared this preliminary report for the DG in order to enable him to assess the implications of such an experiment at the SPS.

The proposed SHIP experiment is a new general-purpose fixed target facility at the SPS to search for hidden particles. These are predicted by a very large number of recently elaborated models of Hidden Sectors which are capable of accommodating dark matter, neutrino oscillations, and the origin of the full baryon asymmetry in the Universe. The high intensity of the SPS and in particular the large production of charm mesons with the 400 GeV beam allow accessing a wide variety of light long-lived exotic particles of such models and of SUSY. Moreover, the facility is ideally suited to study the interactions of tau neutrinos.

The SHIP detector consists of two 40 m long evacuated decay volumes, each of which is followed by a 10 m magnetic spectrometer, a calorimeter and muon detectors in order to allow full reconstruction and particle identification, together with an upstream emulsion target. As an example, with an integrated total of $2x10^{20}$ protons on target, the experiment achieves sensitivity for heavy neutral leptons that is four orders of magnitude better than previous searches, accessing a significant fraction of the unexplored parameter space consistent with cosmological constraints.

The SPS configuration and performance have been investigated under the assumption that SHIP shares the protons with the current North Area fixed target program in a way similar to CNGS. At the start-up of SHIP aimed at 2023, the fixed target operation will need to return to a longer flat top and slightly reduced duty cycle as during CNGS operation to accommodate the SHIP cycles. The baseline extraction will be a slow resonant extraction to TT20 with a 1 to 2.2 seconds long flat top at ~400 GeV/c. In these conditions, the findings allow considering a beam intensity of $4x10^{13}$ p/cycle as the baseline for the design of the critical components like the target, cooling, detectors and the general layout of the civil engineering works. The performance of the ZS septa and the induced radioactivity in the SPS extraction region are likely to be key factors in the overall SHIP performance and require further studies.

Realistic super-cycle compositions have been elaborated using the experience and schedule from 2011 and 2012 for the operation of the North Area, CNGS and LHC, and MDs. As an example of an operational scenario the delivery of 4 $x10^{19}$ protons per year on the SHIP target is feasible with a 40% reduction of the beam availability for the North Area fixed-target program from 2023 as compared to entirely dedicated operation. Thus the projected integrated flux of $2x10^{20}$ protons on target can be provided over 5 years of fully efficient operation in conditions which may be considered nominal. Ultimately, the super-cycle optimization will be based on a physics trade-off between SHIP and the North Area programs at the time of start-up, but also technical arguments such as the limits of the SPS extraction septa and the optimal target design. An ultimate scenario with an SPS intensity of $7\text{x}10^{13}$ per cycle has been explored. It would require major upgrades to the SPS.

The new dedicated SHIP beam line branches off at the top of the existing TT20, in the TDC2 cavern. With a new two-polarity splitter magnet replacing the current splitter, an extra beam line is possible, symmetric to the T6 beam line but to the left of the T2 line instead of to the right. A set of 10 additional dipole magnets will deflect the beam out of TDC2 into a new 150m extraction tunnel onto the SHIP target. The beam line up to the target is mainly composed of drift space apart from the critically important beam dilution, implemented with a pair of orthogonal conventional magnets with a fast Lissajous powering function.

The production target is one of the most challenging aspects of the proposed facility due to the very high energy and power density. The preliminary investigations show that required performance may be achieved with a 50 cm water cooled and segmented tungsten target embedded in a massive iron shielding that also acts as a hadron stopper. The results show that the projected operational conditions are not far from the limits of pure tungsten. A vigorous R&D program on materials and target configuration is therefore advocated.

A multi-compartment complex at 12 m depth respecting the radiological aspects has been outlined. The target bunker and the storage zone are embedded inside a helium-filled vessel atmosphere with online circulation and purification. Cooling and ventilation of the installation, the target handling and access have been considered.

The target and the 5m hadron stopper are followed by a 70 m long muon filter located in a tunnel at the same depth. The baseline design is a passive shielding with a 40 m long 100 t tungsten core completed with 2500 t of lead. This allows reducing the muon flux by the required six orders of magnitude. A potentially cheaper alternative based on a combination of magnetic sweeping and passive shielding is under study.

Conceptual designs of all the elements above are presented in this document. Overall, and despite some interesting challenges, the beam transfer, target and muon filter requirements seem feasible. RP aspects are important and have been addressed through preliminary simulations

The beam line is followed by a 120 m long and 20 m wide underground detector hall, which houses the SHIP detector and the emulsion target.

The layout and implementation in the North Area is described in detail, including the civil engineering aspects. The civil engineering studies were based on the assumption that the SHIP facility will be sited on the CERN Prevessin laboratory in France. All civil engineering works for the project are fully located within existing CERN land on the Prevessin campus. This location is extremely well suited to housing the SHIP project, with the very stable and well understood ground conditions, and very limited interference with the current building, galleries and road structure.

The infrastructure systems cost has been elaborated, even though at this stage no detailed design is available everywhere. This includes in particular the electrical and cooling and ventilation infrastructure systems, the access and safety systems and the costs of cranes, lifts and handling costs. The estimates are based on the description given in this report. In some cases the sizing and costs are rather based on similar installations elsewhere.

Although uncertainties persist at this preliminary design stage, the overall material cost of the beam and infrastructure is estimated to be about 114 MCHF and the manpower required is estimated to be 91 FTEs. The detectors themselves have an estimated cost of about 45 MCHF. The junction cavern with TDC2 has to be constructed and equipped during Long Shutdown 2. The aim is to start beam commissioning and operation during Run 3, i.e. around 2023.

2. Experimental motivation and requirements

2.1 Physics scope

The recent discovery of the Higgs boson with mass ~125.5 GeV implies that the Standard Model (SM) may well be a self-consistent, weakly-coupled, effective field theory all the way up to the Planck scale [1,2]. Nevertheless, it is clear that the SM is incomplete since it does not provide an explanation for the observations of neutrino oscillations, the excess of matter over antimatter in the Universe, and the presence of non-baryonic dark matter. These shortcomings may have their origin in new physics involving very weakly interacting particles such as predicted by models of portals to a hidden sector with heavy Majorana leptons, dark photons etc, or in SUSY [3-8]. Given the small coupling constants and typically long lifetimes, these new different particles have not been significantly constrained by previous experiments, and the reach at current collider experiments is limited by both luminosity and acceptance.

In this context, the current document pertains to a proposal of a general-purpose fixed target facility at the SPS to search for hidden particles [9,10]. In particular, the large production of charm mesons with the 400 GeV beam and the high intensity of the SPS allow accessing a wide variety of light long-lived exotic particles. As a starting point for the study of the sensitivity, the neutrino Minimal Standard Model (νMSM) has been used [11-16]. The νMSM can account simultaneously for neutrino masses and oscillations, baryogenesis, and dark matter. Figure 1 shows the expected sensitivity for the heavy neutral leptons of the νMSM model estimated with only the $N \rightarrow \pi\mu$ decay mode. As shown, a significant fraction of the unexplored parameter space which is consistent with cosmological constraints is accessible at the proposed facility.

As a second example here, the sensitivity to dark photons is shown in Figure 2. Dark photons, or secluded photons γ', appear in a large class of dark matter models [17] and a large region of mass and coupling may be explored through γ' production in π^0 decays and in γ' bremsstrahlung from the incoming proton beam.

The proposed detector is designed to fully reconstruct the exclusive decays of long-lived particles. In order to minimize the model dependence in the search, the detector incorporates dedicated particle identification in a wide range of momentum for discrimination of as many different decay modes as possible. Such a facility would be an essential complement to the LHC and the other fixed target programs in the search for new physics at CERN.

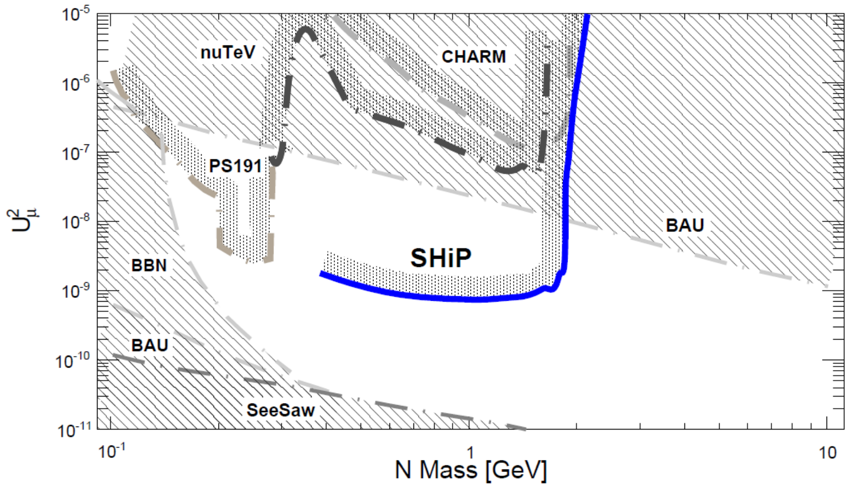


Figure 1: Expected sensitivity in the proposed experiment to the mixing of the Heavy Neutral Leptons with the muon neutrino compared with cosmological constraints and current experimental upper bounds.

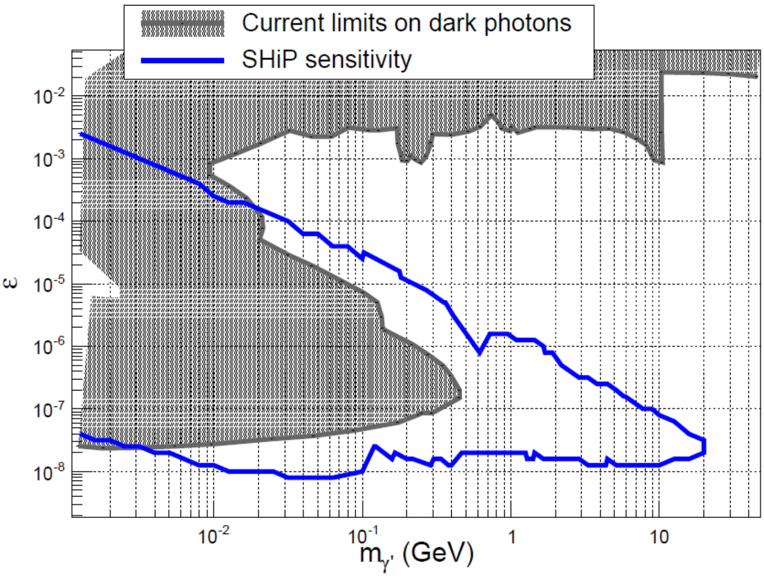


Figure 2: Expected sensitivity in the proposed experiment to dark photons compared to present experimental bounds. The preliminary sensitivity is based on the production mechanism through proton Bremsstrahlung and photonic meson decays.

The facility is also ideally suited for studying the energy threshold of ν_τ interactions and neutrino-induced charged-current charm production, as well as a first observation of the $\bar{\nu}_\tau$. It is expected that the sensitivity for ν_τ interactions is at least 400 times better that at previous experiments assuming that a 5m long compact tau neutrino detector based on emulsion similar to OPERA is added to the setup.

2.2 Operational Requirements

The experiment requires a 400 GeV proton beam from the SPS with the aim of producing a maximum number of charm mesons. The choice of the energy is driven by an optimization between maximizing the charm cross-section and signal acceptance with respect to the boost of the charm system, and minimizing the level of machine induced background and minimizing the length of the filter required to reduce the muon flux. In accordance with these requirements, the SPS provides the most favourable experimental conditions.

The estimation of the experimental sensitivities to the various physics modes is based on 2×10^{20} protons on target, which is assumed to be achievable in five years of full operation. This is based on the starting point of a minimal modification to the existing accelerator complex, a fully compatible shared operation with the current North Area experimental program and the LHC, and dedicating a similar fraction of beam time as was provided to the CNGS facility. Increased experimental reach could come as a by-product of a future SPS upgrade. The design of the proposed experiment will allow taking advantage of such a potential upgrade.

The large flux of muons and the requirement of accurate full reconstruction of both background events and signal events favour the choice of a relatively long extraction to reduce the detector occupancy per unit time. At the same time, the extraction type should not affect significantly the SPS cycle time as compared to CNGS. A spill length of 1.2 s would significantly ease the requirements on the detector and the reconstruction, as well as on the target design, and would reduce the requirements on the muon filter. Naively this would mean a 7.2 s SPS spill cycle, and consequently an acceptable reduction of the number of protons on target by 10% with respect to the CNGS operation. While the preference is a long extraction time with a profile which is as squared as possible, the continuous high-rate readout means that the experiment is not sensitive to time or momentum ripples in the extracted beam.

Since the particles of interest from the charm mesons decays have a significant polar angle with respect to the beam direction, there is no requirement to have a small beam spot as long as the bulk of the muon flux is contained within the aperture of the muon filter. Hence, the beam line design can be driven purely by the technical requirements and constraints.

For the same reason, the experiment does not impose stringent constraints on the optical parameters of the extracted beam. The required level of dilution of the beam energy deposition to satisfy the target requirements may therefore be obtained by allowing the transverse size of the beam to increase and by using a combination of orthogonally deflecting kicker magnets to produce a sweep on the target.

2.3 Experimental setup and detector configuration

The production of the charm mesons is accompanied by copious direct production of short-lived light resonances, pions and kaons, resulting in a large flux of muons as well as neutrinos. Interactions of neutrinos and muons in the material near the detection volume can produce long-lived V^0 decays, such as neutral kaons, which can decay in the detector fiducial volume and mimic signal events. To suppress neutrino-induced V^0 background events from the downstream end of the muon filter, the neutrino flux from long-lived meson decays must be minimised at the source. This is achieved by the use of a target material with the shortest possible interaction length. A tungsten target with a length of the order of half a metre would suffice. The target should be followed by a hadron absorber of a few metres length to absorb the residual non-interacting protons and the hadronic and electromagnetic radiation generated in the target in order to prevent exposition of the components of the muon filter and other instruments to direct radiation. As part of the absorber, a concrete shielding wall will close-off the very limited target bunker volume from the downstream muon filter tunnel.

The task of the muon filter is to reduce the flux of muons, mainly originating from the decays of prompt resonances in the target. Due to the relatively large production angles of the particles of interest, the experimental set-up must balance the opposing requirements of locating the detector as close as possible to the target while accommodating a sufficiently long muon filter to reduce the muon flux and the muon-induced background to an acceptable level. Two configurations are being pursued: a purely passive filter or a combination of magnetic deflectors and passive shielding. With a slow beam extraction and a plausible detector granularity and LHC speed readout, the detector occupancy from the muon flux is not a critical design parameter. The most stringent limit is given by the maximum rate of muons tolerated for each exposure of the emulsion detector of $10^4/\text{mm}^2$. Assuming ten exposures for 2×10^{20} protons on target, this corresponds to a limit of $<10^5$ muons per spill (5×10^{13} protons on target) over the whole SHIP spectrometer surface. The remaining muon-induced background is tagged by the use of the interaction tagger detector upstream of each of the two decay volumes, and topological cuts such as the impact parameter and the invariant mass.

In addition, the design of the muon filter must respect the radiological requirements. The optimization of the muon filter therefore requires a full simulation of this filter, the surrounding infra-structure and the detector, in consultation with the Radiation protection Group.

The proposed detector, shown in Figure 3, aims at fully reconstructing the exclusive decays of long-lived particles and at measuring their invariant mass. Identification of decay modes with electrons, neutral and charged π-mesons, and muons in the final state is required. Hence, the basic detector configuration consists of a 40 m long decay volume followed by a 10 m long magnetic spectrometer and detectors for particle identification. To reduce to a negligible level the background caused by interactions of muons and neutrinos with the air inside the decay volume, a pressure of less than 10^{-2} mbar will be required. In case of need this may be further decreased by two orders of magnitude. A detector element therefore consists of a 50 m long cylindrical vacuum vessel of 5 m diameter. A tracking station at the beginning of each decay vessel will be used to veto charged particles entering the fiducial volume. The first veto station together with a calorimetry-based interaction tagger detector at the end of the muon shield will also identify and reject upstream neutrino interactions. The spectrometer includes a 4 m long dipole magnet, two tracking stations upstream of the magnet, and two tracking stations downstream of the magnet. An electromagnetic calorimeter with good energy resolution and sufficiently high granularity, and a muon detector are located behind each vacuum vessel for π^0 reconstruction and lepton identification. The combined calorimeter and muon detector have a length of about 2 m. All the detector components could be based on existing technologies.

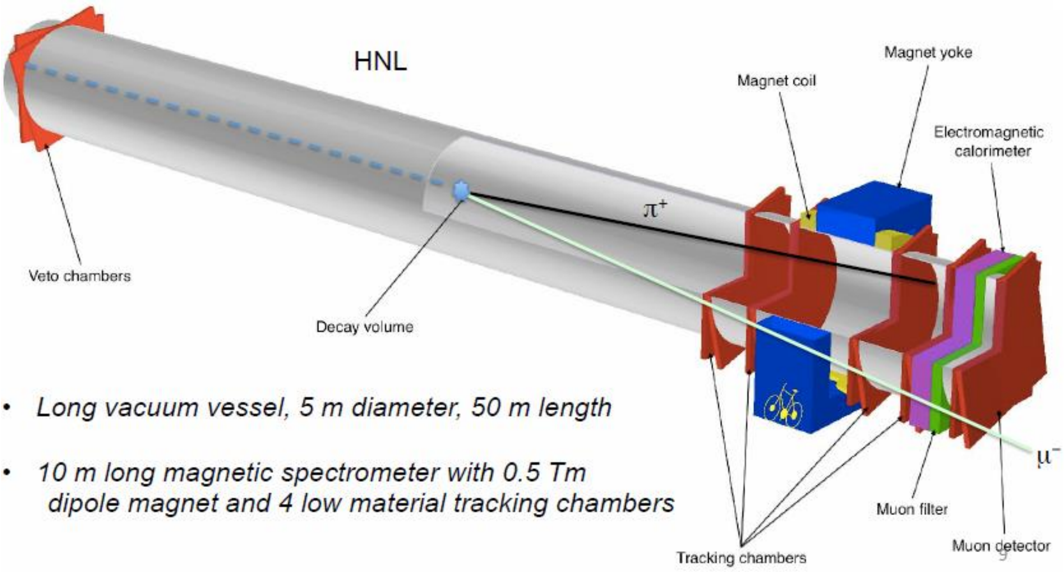


Figure 3: Layout of a SHIP detector

The use of two detector elements increases the geometric acceptance by 70% compared to a single element. Therefore, the proposed detector will have two almost identical detector elements resulting in a total length of about 110 m.

The study of ν_τ physics is based on a compact neutrino detector in the form of a 5m long emulsion and muon spectrometer which is located centred on the beam axis directly downstream of the muon filter and upstream of the SHIP decay volumes. In order to keep the excellent pattern recognition and precision of the emulsion technique, one can tolerate about 300 interactions per brick. To satisfy this constraint the emulsion needs to be exchanged each 2 x 10^{19} protons on target (i.e. a total of ten successive exposures).

3. The Experimental Area Considerations

The SHIP experiment requires a new beam line and a new experimental facility in the North Area of the SPS. The requirements and layout are described below. The projected nominal integrated flux of $2x10^{20}$ protons on target can be provided over a minimum of 5 years of fully efficient operation in conditions which may be considered as nominal (from Section 4). In practice, including commissioning, upgrades and possible extensions of the program, this means that the facility must be designed for at least 10 years of operation.

3.1 The basic layout

The SHIP experiment requires an extraction from point 2 to the North Area via the TT20 tunnel, from which the primary proton beam branches off at the level of the first splitter. Normally this splitter, consisting of 3 MSSB magnets, deflects part of the beam to the Salève side towards the T6 production target for the COMPASS beam line and the straight beam continues towards a second splitter distributing the beam over the EHN1 beams and NA62. This splitter must get an additional function to also switch the beam towards the new facility on the Jura side. About 100 m downstream of the splitter, strong dipole magnets will deflect the beam out of TDC2.

From here the beam drifts via an 85 m long junction cavern and a 170 m long tunnel towards the heavy and dense production target for the SHIP secondary beam line. As this tunnel will contain active elements, this tunnel must be ventilated and have an access point located in the middle of the transfer tunnel. A beam loss monitor will detect accidental losses of the beam near this access shaft. An associated surface building houses the infrastructure systems for the transfer beam line.

A ~10 m long hadron absorber, made of iron, surrounds the target, made of tungsten. In order to minimize activation by backscattering from the target, an upstream shielding is required with only a narrow passage for the beam. The target itself is located inside the hadron absorber, about 5 m upstream of the end of the absorber. The target and hadron absorber are housed in a single ~12 m deep underground compact cavern containing a helium volume to avoid oxidation and in particular activation of air. Both the target and the hadron absorber are actively cooled, probably via a water circuit that is cooled itself via a heat exchanger. In case of leaks of the cooling system, the water is collected and pumped away from a sump.

Immediately downstream of the target and hadron absorber, a 70 m long tunnel houses the muon filter. The first 20 m section has dimensions 8x10 m^2 and includes an access shaft in a surface building which is adjacent to the target station surface building, and a common crane. This first 20 m tunnel section houses mainly passive material and, optionally, a set of upstream sweeping magnets. For this reason a crane is also needed in this first section. The subsequent 50 m of the muon filter tunnel up to the experimental hall has dimension 5x5 m^2 and contains only passive absorber material. The muon filter tunnel is followed by the experimental hall which is 120 m long and with a section 20x14.5 $m^{2,}$ and which is equipped with a 40 ton crane.

By maintaining the entire beam line horizontal and at the same level as the switching in TDC2, the experimental hall ends up conveniently at a depth which avoids most of the radiation problems, even with magnetic sweeping, while still allowing easy direct access from top without a shaft. As was recommended by the SPSC, this also leaves open the option to reuse the tunnel and the hall for other types of experiments in the future, e.g. for neutrinos or experiment similar to DIRAC, NA62 or COMPASS.

3.2 The secondary 'beam line'

The target must be made of dense material, to stop the pions and kaons produced before they decay into muons and neutrinos. The beam spot can and must be large to minimize the risks of damage to the target. In order to fulfill the experimental requirement of less than 10^5 muons / 5×10^{13} pot, the muon filter needs to provide rejection power up to 350 GeV/c of incoming muon momentum, see Figure 4. For the low momentum muons, rejection powers exceeding 10^6 are required.

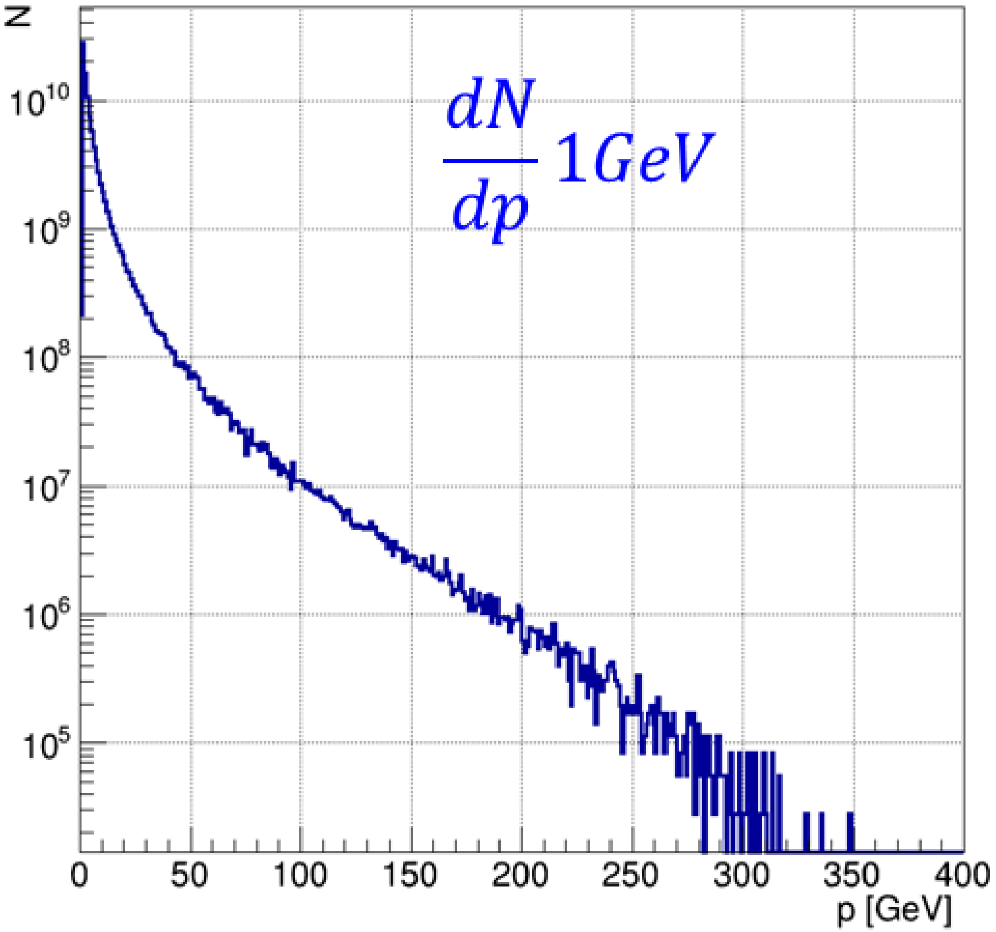


Figure 4: Muon flux after target and hadron absorber per 5×10^{13} pot obtained from Pythia8+Geant4 simulation.

The muon filter is located in a dedicated tunnel, separated from the target cavern. The current baseline design consists of a combination of tungsten and lead, where the amount of tungsten is minimized to shield mainly the high momentum muons, which are emitted from the target in a narrow cone. As shown in Figure 5, at a total length of 70m, about 100 ton of tungsten and 2500 ton of lead will be needed.

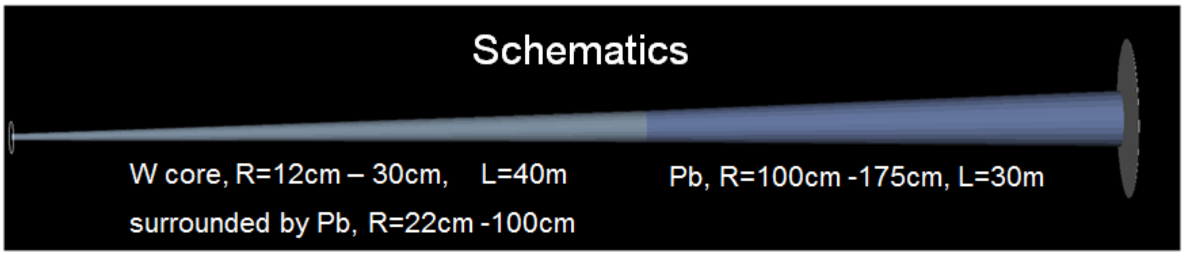


Figure 5: Passive muon filter setup.

An alternative solution being considered is based on the use of a mixture of active and passive shielding. The active shielding consists of conventional cheap dipole magnets filled with iron providing a field of 1.8 T. Three of such magnets of 6 m length would be needed to provide enough bending power up to the highest muon momenta, ~350 GeV/c. Low momentum muons bent back by the return field need to be stopped by blocks of iron placed behind the magnets.

Preliminary studies for the active shielding have been performed, partly by the detector team using GEANT and partly by the experimental areas team using the HALO program. The latter studies show a potential reduction of the remaining muon backgrounds by more than an order of magnitude in case H-shaped magnets with iron filled gap replace the upstream 16 m of passive shielding. Such magnets can be operated with very low current and power and may not even require water-cooling. In that case all tungsten can be replaced by e.g. iron (or lead).

The HALO program is very useful for optimization and comparative studies, but the final design must be fine-tuned and validated with a full simulation (GEANT and/or FLUKA). However, the muon energy spectrum in the studies with the HALO program differs significantly from the Pythia8/Geant4 simulation, while the magnetic field description in the Geant4 simulation is very approximate. The Geant4 studies performed by the detector team do not confirm a large improvement in the reduction of the muon background, more iron would be required than used in the HALO simulation to arrive at similar rates as with a full passive shielding. Further studies are needed to understand the differences.

In case of magnetic shielding, provision must be made for eventual water-cooling and comfort ventilation to allow possible interventions on the magnet. There is no significant activation or radiation protection issue in this tunnel, apart from prompt muon dose.

The 120 m long detector hall immediately follows this relatively narrow tunnel. This hall must be ventilated for temperature control and fresh air, but at this stage there is no requirement from the RP point of view. It must be equipped with a 40-ton crane. The hall houses the two decay volumes plus spectrometers and thus also two large spectrometer magnets.

In principle the background requirements from the SHIP experiment are such that the zone of the detectors will be compatible with the status of non-designated area. However, on the side of the detectors, the prompt muon dose is allowed to be higher and in future experiments the dose could be higher everywhere. Therefore it is necessary to foresee access control also in this hall, like for all other tunnels and halls, from the start. RP monitoring is and in future cases ventilation may become a RP requirement.

3.3 Infrastructure requirements

The experimental hall shall be located not too far from the EHN1 hall, so that basic infrastructure is available at not too large distances. The infrastructure shall include:

- Electrical infrastructure
- Cooling water
- Access control
- IT networks
- All the alarms (fire detection, gas detection, …)

Some surface buildings will be required. The target cavern needs associated space for CV equipment and for the controls, for the access to the target volume, a shielded buffer zone and a loading area. Also there must be a cask loading and storage area a few meters underground where used targets can be stored. An access shaft will be required for the upstream section of the muon shield tunnel. Above the detector hall there must be a surface building with top access to the underground hall, and including a control room and associated facilities.

3.4 Compatibility with the rest of the SPS fixed target program

The presently anticipated fixed target program at the SPS comprises COMPASS in EHN2, NA62 in ECN3, and NA61 plus test beams in EHN1. The so-called AWAKE facility is under construction in the CNGS cavern. It is assumed that these experimental facilities will also have running experiments beyond LS2. Therefore it is wise to design a beam extraction and primary beam transport that remains compatible with the long-term operation of these facilities. It is for the moment foreseen to replace the first splitter by laminated magnets which can serve as a splitter during fixed target operation in the North Area and can be used as a switch to send the protons towards the Jura side for SHIP operation on a cycle-by-cycle basis. A beam tunnel has to be constructed and connected to TCC2. At the junction, a cavern will be necessary, because of the length of the passage of the beam through the TCC2 side wall.

The extraction will preferably be a slow extraction with a flat top that must be a compromise between low occupancy and survival of the target and the other components (hence as long as possible) and on the other hand keeping the heat loss on the SPS and transfer line acceptable and the repetition rate as high as possible. Normally the SPS is operated with a 4.8s flat top with roughly a 15s repetition rate, resulting in a ~30% duty cycle. In order to maintain a vigorous fixed target program in the existing North Area in parallel to the operation of the SHIP facility, it seems appropriate to go back to a long flat top (9.6 s) for the North Area and a 22% duty cycle, like it was done during CNGS operation. It should be pointed out that in this case more protons per spill are required for the North Area. This would lead to increased losses and probably to a shortage of protons in case e.g. NA62 and COMPASS would run simultaneously.

4. Beam Parameters for the SHIP Experiment

The maximum beam intensities accelerated so far and extracted from the SPS (peak values) in the last 20 years are listed below:

- 4.8×10^{13} p/cycle (1997 – Slow+Fast Slow extraction – 9.6 s – 450 GeV/c)
- 4.5×10^{13} p/cycle (2008 – CNGS – Fast extraction – 6 s – 400 GeV/c)
- 4×10^{13} p/cycle (2009 – slow extraction – 15.6 s – 400 GeV/c)

The maximum intensity accelerated during machine studies (but not extracted) has been 5.3×10^{13} p/cycle (2004).

From the above we consider that a beam intensity of 4.5×10^{13} p/cycle can be reasonably assumed as baseline for the design of major/critical components like the dilution, target, its cooling system, detectors and the general layout of the civil engineering works. An “Ultimate” intensity of 7×10^{13} p/cycle can be considered as the very maximum for the same design. However, at present there is no approved construction project to increase the SPS Fixed Target (FT) beam intensity to this level, and any benefits which might arise as side effects from the LHC Injectors Upgrade program for the LHC beams will surely need to be supplemented by other measures to control beam losses both in the SPS and the PS and the transfer lines. The ultimate scenario is based on the target to accelerate up to 7×10^{13} p/cycle being studied in the frame of the LAGUNA/LBNO and it is for the moment hypothetical.

Among the possible extraction methods considered (fast extraction, fast-slow extraction on half-integer, slow extraction on third integer, multi-turn extraction) the slow extraction on the third integer to TT20 in the time scale of 1 second is retained as preliminary baseline for the beam parameters taken into account the following considerations:

- Maximum acceptable instantaneous particle flux at the detector
- Preliminary estimates of the power and power density deposition on the target

SHIP assumes a proton beam of 400 GeV/c. This beam momentum corresponds to the momentum of the proton beam extracted to the North target T2, T4 and T6 during proton fixed target operation. Machine Protection considerations require defining different extraction momenta for the beams circulating in the SPS according to their destination to allow proper interlocking. For that reason the momentum of the proton beam extracted from the SPS for SHIP should differ from 400 GeV/c by at least 5 GeV/c: 395 GeV/c or 405 GeV/c are proposed as possible energies.

The minimum cycle length that is compatible with the above parameters is 7.2 s provided that it can be proven that an extraction of 4.5×10^{13} p/cycle over ~1 s can be performed without damaging the electrostatic septa or significantly increasing the spark rate. An increase of the flat-top length to 2.4 seconds or even longer might be required if the instantaneous rate of extracted protons is not compatible with a safe operation of the electrostatic septa. In particular we consider a flat-top length of 2.4 s for ultimate beam parameters.

The maximum acceptable average resistive power dissipated in the main magnets for the SPS is 39 MW. This constraint limits the possible super-cycle combinations. Realistic super-cycle compositions are considered in the following both to estimate the expected integrated number of protons on target for the SHIP experiment and for the experiments served by the TCC2 targets in a typical year and to determine a realistic value of the average rate of protons on target and the average power deposited on the target.

The average power dissipated in the main magnets for the main cycles composing the SPS super-cycles during operation of the SPS for SHIP and for the fixed target experiments in the North Area as well as for LHC filling are listed below in Table 1. The cycles considered are based on the CNGS cycle used in 2011-2012 and the flat-top (limited to 300 ms for CNGS) has been increased in steps of 1.2 s (present basic period of the PS-SPS complex) to estimate the power consumption. Two cycles have been considered for the SHIP experiment:

- a cycle with flat-top length of 1.2 s (in the following called SHIP nominal) and allowing an effective spill length of 1 s;
- a cycle with flat-top length of 2.2 s (in the following called SHIP ultimate) and allowing an effective spill length of 2 s.

The flat-top duration of the cycles dedicated to fixed target physics with the TCC2 targets must be of the order of 9 s to profit of the maximum number of protons that can be accelerated per cycle in the SPS to 400 GeV/c compatible with the maximum event rate acceptable at present by the North Area experiments and with the thermo-mechanical stress of the splitter magnets. In this way the number of protons on the TCC2 targets has been maximized during CNGS operation [18][19]. The cycle considered for this operation is indicated with FT.

The cycles used for LHC set-up and filling are also listed and indicated with LHC pilot and LHC nominal, respectively. Two low energy cycles have been included:

- MD cycle used for machine studies (typically at 26 GeV/c) in parallel to fixed target operation during normal working hours

- ZERO cycle: a low energy cycle (here assumed 14 GeV/c) that could be used to reduce the average power consumption and keep it below the maximum value of 39 MW.

Cycle	Cycle duration [s]	Power [MW]
SHIP-nominal (1.2 s flat-top) – 400 GeV/c	7.2	32.5
SHIP-ultimate (2.2 s flat-top) – 400 GeV/c	8.4	38.5
FT (9.7 s flat-top) – 400 GeV/c	15.6	63.6
LHC nominal – 450 GeV/c	21.6	16.7
LHC pilot – 450 GeV/c	7.2	41.3
MD – 26 GeV/c	4.8	0.3
ZERO – 14 GeV/c	1.2	0.1
FT 2014 (4.9 s flat-top)	10.8	52.2

Table 1: Cycle duration and power consumption for the possible SPS cycles during the operation for SHIP.

For comparison the cycle for fixed target physics on the TCC2 targets to be used in 2014 is also listed (FT 2014). It is expected to extract up to 3.3×10^{13} p/cycle for this mode of operation.

In the above a momentum of 400 GeV/c has been considered both for the SHIP and FT cycles. Indeed the momentum of the proton beam delivered to the SHIP target should differ from 400 GeV/c by at least 5 GeV/c for machine protection considerations. This will not change significantly the conclusions.

Operation of SHIP will occur in parallel to:

- LHC operation;
- Fixed Target physics operation for the other TCC2 targets;
- Parallel Machine Development programme (during working days and working hours, typically from 8 to 18).

The super-cycles considered for parallel operation of SHIP and the TCC2 targets compatible with the limit of 39 MW are listed in Table 2.

Super-cycle	# LHC pilot	# LHC nominal	# SHIP nominal	# FT	# MD	# ZERO	Super-cycle duration [s]	Power [MW]
LHC set-up day	1	-	3	-	1	-	33.6	29.8
LHC set-up night	1	-	3	-	-	-	28.8	34.7
LHC filling day	-	1	1	-	1	-	33.6	17.7
LHC filling night	-	1	1	-	-	-	28.8	20.7
Fixed target SHIP/TCC2 day	-	-	5	1	1	-	56.4	38.4
Fixed target SHIP/TCC2 night	-	-	9	1	-	-	80.4	38.5

Table 2. Super-cycles considered for parallel operation of SHIP and TCC2 target.

In the above the super-cycle length for LHC set-up and LHC filling has been minimized to keep the LHC filling time to a minimum. The minimum filling time compatible with injection quality checks has been considered to be 27.6 s [20].

An estimate of the number of protons on target for the SHIP and TCC2 targets has been made with some assumption on the average intensities per cycle, the physics and the transmission efficiencies, and on the number of hours of fixed target operation, LHC set-up and filling and parallel MD. These assumptions are listed in Table 3.

Scheduled days of physics (Dedicated MD and Technical Stops excluded) [d]	217
Slots of parallel MD (10 h each)	137
Scheduled physics time (Dedicated MD and Technical Stops excluded) [h]	5112
Scheduled physics with parallel MD [h]	1380
Scheduled physics without parallel MD [h]	3732
Percentage of physics time spent for LHC set-up [%]	10
Percentage of physics time spent for LHC filling [%]	10
Efficiency for TCC2 Fixed Target physics [%]	80
Efficiency for SHIP Fixed Target physics [%]	80
Transmission Efficiency SPS to TCC2 targets [%]	90
Transmission Efficiency SPS to SHIP target [%]	95
Protons per TCC2 fixed target cycle - average (SPS flat-top) [10^{13}]	4.0
Protons per SHIP fixed target cycle – average (SPS flat-top) [10^{13}]	4.2

Table 3. Parameters used for the estimation of the number of protons on target for TCC2 and SHIP.

The 2011 LHC Injector schedule [21] and in particular the scheduled physics time for CNGS (217 days) have been considered for the estimate.

The efficiency for TCC2-FT and CNGS physics have been assumed to be similar to those obtained for TCC2-FT and CNGS physics in 2011-2012 [22]

The total amount of time spent for the injection of pilot, intermediate and nominal bunch trains in the LHC was 15% of the total LHC scheduled physics time in 2012 [23], nevertheless the beam quality is verified in the SPS before injecting in the LHC and the LHC cycles are running in the SPS for a longer period in particular the LHC nominal cycles to verify the intermediate and nominal beams consisting of bunches with nominal population. In Table 3 it has been assumed that 10% of the SPS scheduled physics time is devoted to run LHC pilot cycles and another 10% to run LHC nominal cycles.

It is also assumed that the total intensity of 4×10^{13} p/cycle can be extracted in a plateau of 9.7 s with a cycle length of 15.6 s as in 2012.

Based on the considerations above the total number of protons on target that could be delivered to SHIP and the other TCC2 targets would be:

- 5.68×10^{19} pot/year for SHIP
- 0.67×10^{19} pot/year for the TCC2 targets

This would provide the maximum flux to SHIP but it would penalize the physics experiments behind the TCC2 targets. Intermediate scenarios have been considered where SHIP is operating a fraction of the time and dedicated operation of the SPS for fixed target physics for the TCC2 targets (in parallel to LHC operation) is occurring.

When SHIP is not operating the super-cycles listed in Table 4 have been considered. Given the long flat-top and large power consumption of the FT cycles, cycles with low power consumption have to be inserted in the super-cycle to keep the average power consumption within the limit of 39 MW.

Super-cycle	**# LHC pilot**	**# LHC nominal**	**# SHIP nominal**	**# FT**	**# MD**	**# ZERO**	**Super-cycle duration [s]**	**Power [MW]**
LHC set-up day	1	-	-	1	1	5	33.6	38.4
LHC set-up night	1	-	-	1	-	9	33.6	38.4
LHC filling day	-	1	-	1	1	-	42	32.2
LHC filling night	-	1	-	1	-	-	37.2	36.4
Fixed target TCC2 day	-	-	-	1	1	5	26.4	37.7
Fixed target TCC2 night	-	-	-	1	-	9	26.4	37.6

Table 4. Super-cycles considered for fixed target operation for the TCC2 targets only.

The number of protons on TCC2 targets as a function of the number of protons on target for SHIP for this mode of operation is shown in Figure 6.

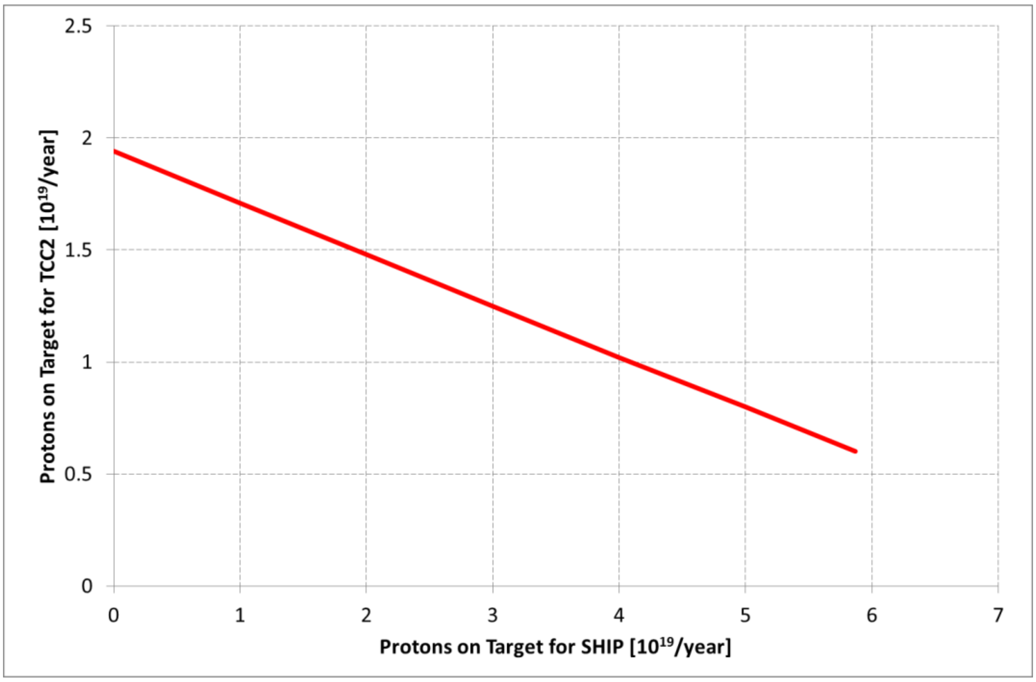


Figure 6: Number of protons on TCC2 targets vs. number of protons on target for SHIP for a flat-top duration of the FT cycle of 9.7 s.

The values of the power deposited on the target for the super-cycles considered in Table 2 are listed in Table 5 for different averaging periods (an energy of 400 GeV and a spill duration of 1 s have been assumed). For this mode of operation the maximum power deposited on the target averaged on one super-cycle (see column 4 of Table 3) is 22% lower compared to the average power deposited on the target for exclusive operation for SHIP when averaged over the super-cycle (this value correspond the power averaged over a single SHIP cycle – see column 2 of Table 3).

Super-cycle	**Average power on the target over the spill [MW]**	**Average power on the target over the cycle [MW]**	**Average power on the target over the super-cycle [MW]**
LHC set-up day	2.56	0.36	0.23
LHC set-up night			0.27
LHC filling day			0.08
LHC filling night			0.09
Fixed target SHIP/TCC2 day			0.23
Fixed target SHIP/TCC2 night			0.29

Table 5. Power deposited on the target for different averaging periods and super-cycles.

Figure 7 compares the performance for TCC2 versus SHIP for different values of the duration of the flat-top of the TCC2 fixed target cycle The super-cycle compositions have been selected to comply with the power limit of 39 MW while the length of the LHC super-cycles has been minimized as above. Assuming that the effective duration of the spill for the TCC2 fixed target cycle is shorter by 0.3 s as compared to the flat-top duration the average extracted proton current for the cycles considered ranges from 0.43 to 0.69×10^{13} p/s and should be compared with the corresponding maximum values for the fixed target cycles in 2012 (0.43×10^{13} p/s) and those expected in 2014 (0.72×10^{13} p/s).

The operation with TCC2 fixed target cycles with shorter flat-top length has the effect of:

- Increasing the average proton flux for the TCC2 targets at constant number of protons on target for the SHIP experiment. This implies a larger number of protons lost and therefore higher radiation at the TDC2 splitters/collimators which is specific of the operation for the TCC2 targets.
- Increasing the total number of protons delivered to the SHIP and TCC2 experiments. This will increase the radiation at the North extraction in the SPS.

The super-cycle compositions for the SHIP/TCC2 parallel operation and for the operation for TCC2 only (including operation for LHC) for the shortest FT flat-top duration (6.1 s) are listed in Tables 6 and 7, respectively.

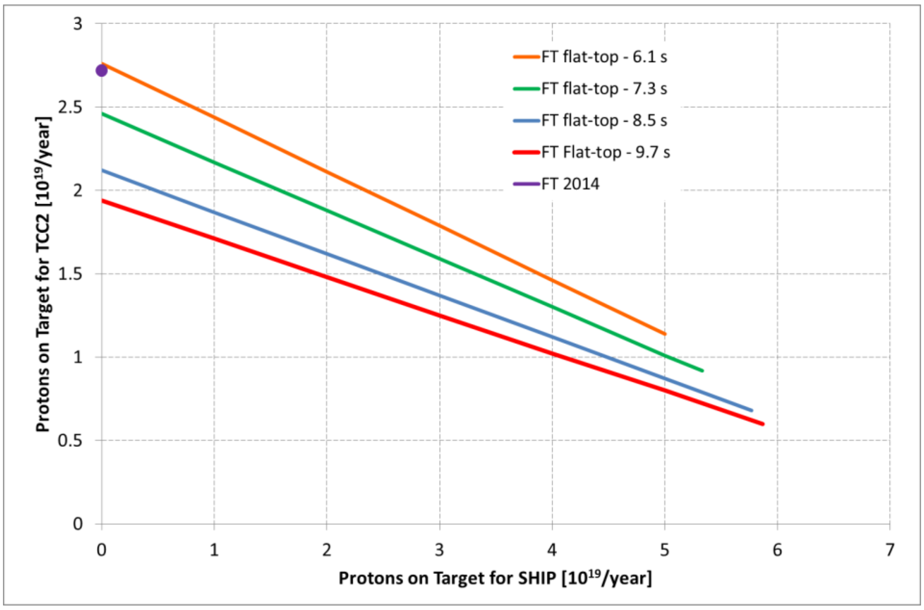


Figure 7: Performance for different flat-top durations of the FT cycle. The expected integrated proton number for exclusive operation of the TCC2 target with a super-cycle comparable to that planned for operation in 2014 is indicated.

Super-cycle	# LHC pilot	# LHC nominal	# SHIP nominal	# FT	# MD	# ZERO	Super-cycle duration [s]	Power [MW]
LHC set-up day	1	-	3	-	1	-	33.6	29.8
LHC set-up night	1	-	3	-	-	-	28.8	34.7
LHC filling day	-	1	1	-	1	-	33.6	17.7
LHC filling night	-	1	1	-	-	-	28.8	20.7
Fixed target SHIP/TCC2 day	-	-	1	1	1	-	24	38.4
Fixed target SHIP/TCC2 night	-	-	5	1	-	-	48	38.7

Table 6. Super-cycles considered for parallel operation of SHIP and TCC2 target for a FT flat-top duration of 6.1 s.

Super-cycle	# LHC pilot	# LHC nominal	# SHIP nominal	# FT	# MD	# ZERO	Super-cycle duration [s]	Power [MW]
LHC set-up day	1	-	-	1	1	2	26.4	37.3
LHC set-up night	1	-	-	1	-	6	26.4	37.2
LHC filling day	-	1	-	1	1	-	38.4	27.3
LHC filling night	-	1	-	1	-	-	33.6	31.1
Fixed target TCC2 day	-	-	-	1	1	1	18	38.2
Fixed target TCC2 night	-	-	-	1	-	5	18	38.1

Table 7. Super-cycles considered for fixed target operation for the TCC2 targets only assuming a FT flat-top duration of 6.1 s.

The values of the power deposited on the target for the super-cycles considered in Table 5 are listed in Table 8 for different averaging periods (an energy of 400 GeV and a spill duration of 1 s have been assumed).

Super-cycle	Average power on the target over the spill [MW]	Average power on the target over the cycle [MW]	Average power on the target over the super-cycle [MW]
LHC set-up day	2.56	0.36	0.23
LHC set-up night			0.27
LHC filling day			0.08
LHC filling night			0.09
Fixed target SHIP/TCC2 day			0.11
Fixed target SHIP/TCC2 night			0.27

Table 8. Power deposited on the target for different averaging periods and super-cycles for the super-cycle listed in Table 5.

In the ultimate scenario, based on the hypothetical possibility of accelerating up to 7x10^{13} p/cycle being considered in the frame of the LAGUNA/LBNO Study, the spill length should be doubled, and a flat top length of 2.2 s would be required with a cycle length of 8.4 s for the SHIP cycle (see Table 1).

The super-cycle composition during SHIP/TCC2 target operation is listed in Table 9. The duration of the super-cycles is significantly increased unless ZERO cycles are introduced. Zero cycles have been added to comply both with the constraints of keeping the power consumption below 39 MW and the super-cycle duration below 120 s.

Super-cycle	# LHC pilot	# LHC nominal	# SHIP nominal	# FT	# MD	# ZERO	Super-cycle duration [s]	Power [MW]
LHC set-up day	1	-	2	-	1	-	28.8	32.8
LHC set-up night	1	-	5	-	-	-	49.2	38.9
LHC filling day	-	1	1	-	1	-	34.8	19.7
LHC filling night	-	1	1	-	-	-	30	22.8
Fixed target SHIP/TCC2 day	-	-	11	1	1	4	117.6	38.7
Fixed target SHIP/TCC2 night	-	-	11	1	-	8	117.6	38.7

Table 9. Super-cycle composition in case of operation with a SHIP cycle with flat-top duration of 2.2 s and a cycle duration of 8.4 s.

The power on the target for different time constants is estimated in Table 10.

Super-cycle	**Average power on the target over the spill [MW]**	**Average power on the target over the cycle [MW]**	**Average power on the target over the super-cycle [MW]**
LHC set-up day	2.13	0.51	0.30
LHC set-up night			0.43
LHC filling day			0.12
LHC filling night			0.14
Fixed target SHIP/TCC2 day			0.40
Fixed target SHIP/TCC2 night			0.40

Table 10. Power deposited on the target for different averaging periods and super-cycles for a SHIP cycle with a flat-top duration of 2.2 s and assuming that 7x10^{13} p/cycle can be accelerated to 400 GeV/c in the SPS. A spill duration of 2 s has been assumed.

The performance for the ultimate scenario compared to the nominal scenario is presented in Figure 8. A clear gain in performance is visible but at the expense of larger average power on the target over the super-cycle. In this case the power is very close to that achieved with a dedicated operation for SHIP.

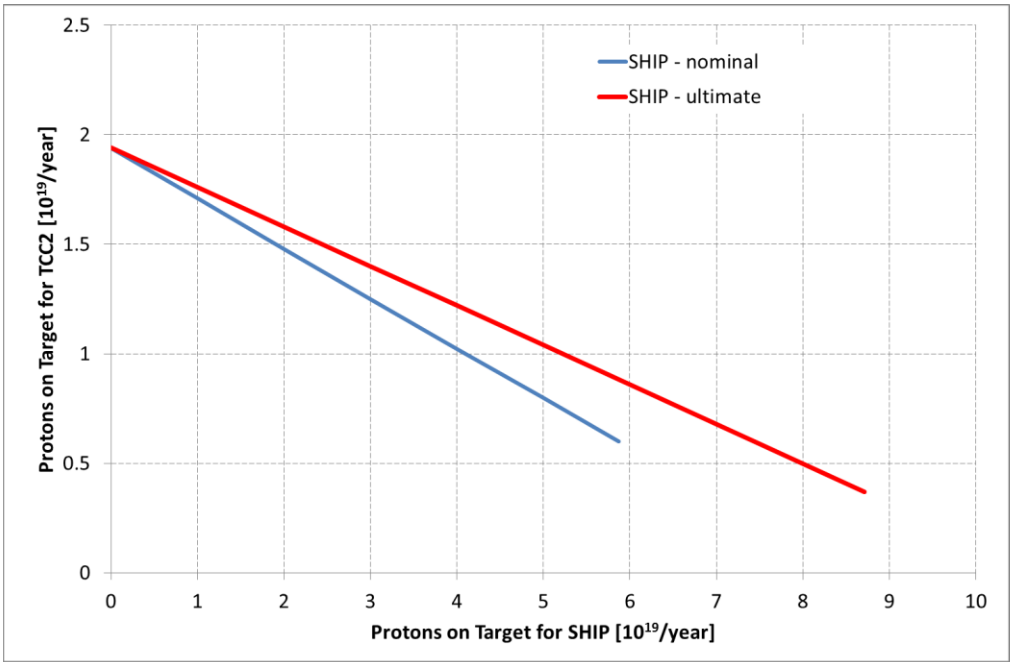


Figure 8: Performance for the nominal and ultimate scenarios for a FT flat-top duration of 9.7 s.

5. Beam extraction, transfer and dilution

5.1 Overview

The SHIP experiment prefers a ~1 s duration slow extraction from the SPS LSS2 using existing extraction equipment and transfer of the beam along the existing TT20 up to a switch into a short new section of transfer line. This line defines the beam geometry up to the target, and has to be equipped with a system to provide adequate spatial dilution of the beam on the target together with instrumentation and steering elements. In this section the requirements and constraints for these beam transfer systems are described together with the proposed design. Technical requirements for the different systems are detailed allowing preliminary cost and resource estimates. Preliminary requirements for technical infrastructure systems are detailed and areas of technical risk are highlighted.

The studies are based on the assumption that the SHIP target and experimental facility will be located upstream of EHN1 and some 10 m underground at the end of a ~350 m long new beam line which branches off from the top of the existing TT20, in the TDC2 cavern.

5.2 Extraction from SPS

Slow extraction from SPS is accomplished with a set of suitably located extraction sextupoles used to create a stable area in horizontal phase space. This initial phase space area is larger than the area occupied by the beam. A dedicated servo-quadrupole consisting of 4 short QMS quadrupoles moves the tune towards Q_H = 26.666 shrinking the stable phase space area. Protons with coordinates outside the stable area move away from the beam core along the outward going separatrices, and eventually cross the wires of the ZS septum, into its high field region. The ZS deflects the particles into the magnetic elements of the extraction channel consisting of thin MST and thick MSE septum magnets, which move the beam into TT20 proper.

Slow extraction from the SPS in LSS2 is routinely used in the SPS operation for supplying beam to the North Area. Reducing the spill length to 1 s with 4.5×10^{13} protons extracted risks being limited by the performance of the ZS electrostatic septa, which are liable to experience increased sparking, vacuum pressure rise, damage of the wires through beam heating and also secondary effects like high voltage feed-through damage. Simulations will be made to try to better understand these effects, for example the scaling of the wire heating with the proposed extraction. Machine Development tests can be planned at the end of the 2015 proton run to probe experimentally these limits, with increasing intensity extracted over 1 s to the North Area on the SHIP cycle. The performance of the ZS with these very high extracted beam intensities in a short spill is likely to be a key factor in the overall SHIP performance.

As shown in Figure 9, the extracted spill is likely to be somewhat non-trapezoidal, especially at the start, where an initial spike in the proton rate could be expected for this short extraction time. This can have some impact on the energy deposition in the target and could conceivably be mitigated by modifying the start of the sweep.

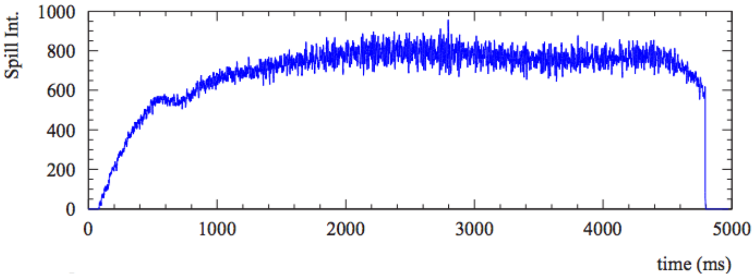


Figure 9: Well-regulated quasi-trapezoidal spill for SPS extraction (4.8 s spill).

To avoid activation of the internal SPS dump TIDVG, it would be preferable to extract all protons to the SHIP target, unlike the present beams to the North Area where a few percent are routinely dumped to preserve the spill quality. This 100% extraction can be accomplished but at the expense of the spill quality, and might be accompanied by a spike in the proton rate or different spill lengths depending on the total beam intensity – this is a topic which can be tested in a Machine Development.

The activation of the extraction region and of the aperture limits in the ZS will increase in proportion to the total number of protons extracted per year - with the SHIP extraction in addition to a North Area requirement assumed to be similar to recent past years, an increase of a factor of maybe 3 to 6 or even more in the radiation dose (a factor 2.6 compared to record year 2007) and equipment activation and degradation (e.g. of cables) can be expected. More detailed estimates can be made on the basis of the expected extraction duty cycle and yearly load, together with the data from past years' operation. Ways to reduce the beam losses should be investigated, for instance improved instrumentation in the extraction regions.

5.3 Transport along TT20

The SHIP target location allows the re-use of about 600 m of the present TT20 transfer line, which has sufficient aperture for the slow-extracted beam at 400 GeV/c. The powering scheme for the line remains basically unchanged up to the switch element, but re-matching of the final section of the line will be needed to allow the beam to pass with very low losses through the switch aperture – one potential issue to check is whether the line optics can be changed on a cycle-to-cycle basis within a super-cycle, at least for the quadrupole elements concerned. Interlocking of these magnet currents would also need to be provided on a cycle-to-cycle basis – this is not a conceptual problem.

The existing instrumentation is designed for slow extracted beams, and functionally should be adequate. The question of whether the systems need consolidating or extending due to the higher beam power remains to be investigated.

5.4 Switching from TT20

One of the main challenges of the North Area location of the SHIP experiment is the 400 GeV/c switch out of TT20 to the new beam line, due to the high beam rigidity and absence of space in the present beam line. An elegant suggestion is to replace the three existing MSSB2117 splitter magnets with newly built splitters, which allow negative polarity powering. This would provide an elegant way of doing this without sacrificing the full slow spill to one of the existing North Area beam lines. With a two-polarity splitter magnet, an extra beam line is possible, symmetric to the T6 beam line but to the left of the T2 line instead of to the right, see Figure 10.

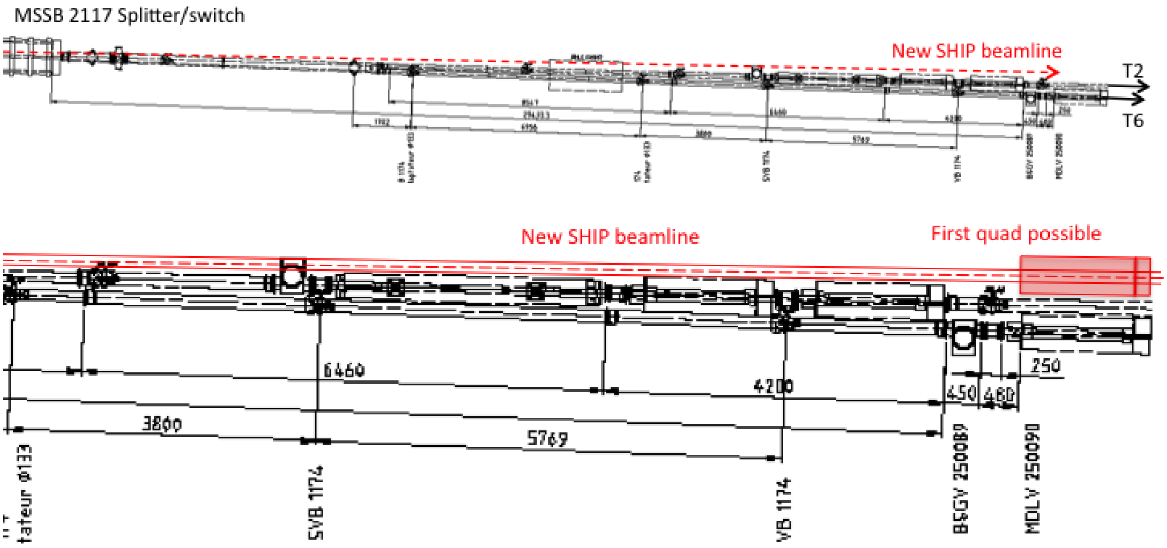


Figure 10: Schematic of start of new SHIP beamline, symmetric to T6 but to the left of the T2/T4 line, with polarity-reversed MSSB2117 splitter acting as a switch magnet.

The three existing MSSB magnets 211713, 211723 and 211732 need to be replaced by similar magnets which allow enough aperture for the beam deflected in the opposite direction. The main requirements for the new magnets are:

- Replicate existing splitter functionality for present NA beams;
- Polarity reversal possible within about 2 seconds;
- Adequate good-field region around both sides of field-free septum hole;
- Same $\int B.dl$ and physical length as present MSSB.

The present MSSB design [24] is an in-vacuum Lambertson septum, with a clever vacuum separation to keep the coils and water connections in air, built with radiation robust materials and low-maintenance assembly. The magnets operate with 0.8 T in the gap, and have a limit B_{max} of 1.6 T in the steel at the point of the septum element. Interestingly, for the NA splitter design, the wedge angle θ of the septum is 36°, and since $B_{max}.\sin\theta \approx B_{gap}$, it is therefore possible by running at higher current to increase the gap field to about 0.95 T without a major effect on the field quality – the alternative of using a higher saturation steel like FeCo would gain something, but would be much more expensive, mechanically tricky and lead to activation issues.

The gap is 75 mm high, which requires about 48 kA.turns at 0.8 T. The present coil scheme of 48 turns and 1 kA can be retained. The coil technology is special, using compacted MgO powder around a central copper current carrying water-cooled tube, mechanically supported by an external grounded copper sheath. The MgO is evacuated to avoid moisture degradation – the maximum voltage to earth is 1 kV.

The present MSSB are built with solid yokes, assembled from several precision machined pieces. Because of the need to switch the polarity between SHIP and normal FT cycles a laminated yoke is essential. A possible technology would be 1.5 mm punched laminations, blue-steamed for insulation and assembled with a stacking factor of ~98%. This technology is routinely used in the SPS for the extraction septa MSE/T that are also exposed to high radiation doses. The drive current (or the magnetic length, in case the power convertors are really limited to 1000 A) might need to be increased by 2% compared to the existing magnet to compensate for slight reduction in ∫B.dl.

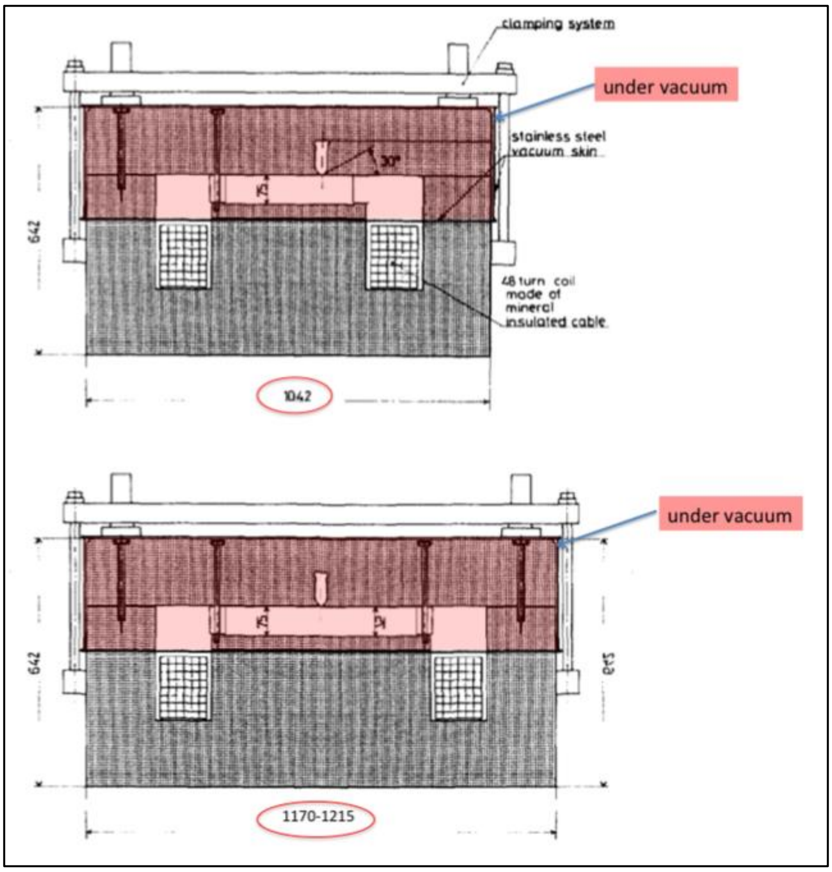


Figure 11: Cross section of existing MSSB magnets (top). A possible cross-section of the new magnets is shown below.

The new magnet cross-section can be a simple variation of the present MSSB, Figure 11, with the good field region extended to the other side of the septum hole. Here some advantage can be taken of the operation at 400 GeV/c – the maximum offset for the switched beam at the exit of the 3rd MSSB is around 90 mm. Allowing another 40 mm for the beam size and orbit, alignment tolerances, the good field region (and pole width) needs to be extended by 130 mm only, although an extra 150 mm would make the septum hole symmetric to the pole. The overall yoke width is likely to increase from 1042 mm to approximately 1170 mm, and the weight will increase from the present 24 tonnes to about 27 tonnes. Main parameters are compared to the existing MSSB in Table 11. The inductance and resistance are scaled from the existing magnet, with the preliminary pole width and coil size.

The main parameters of the new MSSB-S magnet are also given below in Table 11.

Parameter	**MSSB**	**New MSSB-S**
Magnetic length [m]	4.7	4.7
Gap field [T]	0.8	0.8
Stacking factor [%]	100	98
Coil turns	48	48
Current [A]	994	1014
Vertical gap [mm]	75	75
Pole width [mm]	400	530
Magnet inductance [H]	0.11	0.14
Coil resistance [mΩ]	65	66
Number of magnets in series	3	3
Minimum rise-time [s]	10 (tbc)	2
Maximum voltage to ground (3 magnets in series) [V]	~250	400

Table 11: Parameters of the existing and new (preliminary) MSSB magnet.

5.5 New beam line to target

A maximum deflection angle to exit the TDC2 tunnel is beneficial to reduce the longitudinal extent of the civil engineering works in the crucial junction region. Large bends of type MBB or MBN will be needed, which can run at almost 2 T and are 6.2 m or 5.0 m long, respectively. It must be noted that the MBN magnets are highly inductive, so pulsing rapidly a large series of magnets would require a converter with an unrealistically large voltage rating.

Overall, an angle of at least 80-100 mrad is needed with respect to TT20. In the first optics checks this was obtained with the 8 mrad from the three MSSB switch magnets, plus 9x MBB magnets running at a conservative field of 1.73 T giving 8 mrad each. A total of about 11 MBN magnets would be needed to reach the same deflection.

In the initial configuration studied, the MBBs are grouped into a single dipole as early as possible, and two ‘standard’ half-cells of 4 dipoles each. It is to be noted that no new dipoles are located near the second splitter, for reasons of installation, maintenance and radiation dose during operation.

The first version of the configuration is shown in Figure 12, below. New dipoles (MBB) and new quadrupoles (approximate locations) are indicated.

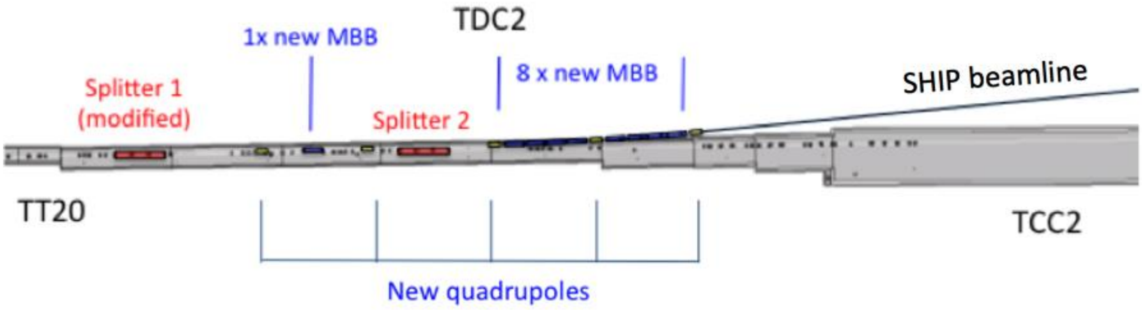


Figure 12: A first switch and branch-off layout for the new SHIP beam line based on modified MSSB and new MBB magnets. Dilution magnets are not shown.

The transverse optics has not been studied in detail but is not expected to pose problems – the main issue is just the acceptance for the beam, since anyway a large blow-up of the transverse beam size is needed at the target. It is assumed that about 5 new quadrupoles, of type QNL will be needed, with one new QSL slim quadrupole as the first magnetic element after the splitter/switch in the new beam line. A maximum of 6 corrector dipoles can also be assumed, which can be 50 A MDX-type.

The numbers and types of magnets needed for the beam line are given in Table 12, in addition to the number of converters and the required current/voltage.

Function	Magnet type	Max I [A]	Max V (V)	# magnets	# convertors
Switch	MSSB-S	1000	500	3	1
Main bends	MBN (MBB)	1500 (6000)	?	12 (10)	1
Main quads	QNL	400	?	5	5
Main quad (slim)	QSL	400	?	1	1
Corrector dipoles	MDX	50	?	6	6
Sweep dipole	MPLH?	400	?	2	2

Table 12. Number and types of magnets for new beam line, with power converter numbers and ratings.

5.6 Beam dilution on the target

The maximum beam energy density on the target is an issue for the target design. With a 1 s long extraction spill, a pair of orthogonal conventional magnets with a fast Lissajous powering function could be foreseen to maximise the length of the sweep on the target block. With a drift of at least 150 m available before the target and a sweep radius tentatively fixed at 30 mm, a maximum deflection of only 0.2 mrad per plane is needed. Possible magnet types could be MPLH (SPS extraction bumpers) that can ramp with a dI/dt of around 1’300 A/s. With a current of ~65 A corresponding to 0.2 mrad, a maximum sweep frequency of about 3 Hz would be possible using the present type of magnet and power converter.

A full optimisation of the sweep is required taking into account the possible magnet and powering characteristics, as well as the limitations of the target in terms of protons per mm^2. Some idealised sweep forms have been proposed for evaluation, for example an idealised Archimedean spiral (Figure 13) with a transverse spacing between turns of about 6 mm (1 sigma), 5 turns total in 1000 ms, a starting radius of 5 mm, a finishing radius of 35 mm and a constant sweep speed in mm/ms. This would imply a varying frequency of the sine/cosine waveforms, as also shown in Figure 13. For this example the product of the frequency and kick is constant and corresponds to 0.2 mrad at 3 Hz, which is within reach of the existing MPLH magnet. Starting with larger amplitude and spiraling inwards would probably be easier for the dilution magnet powering.

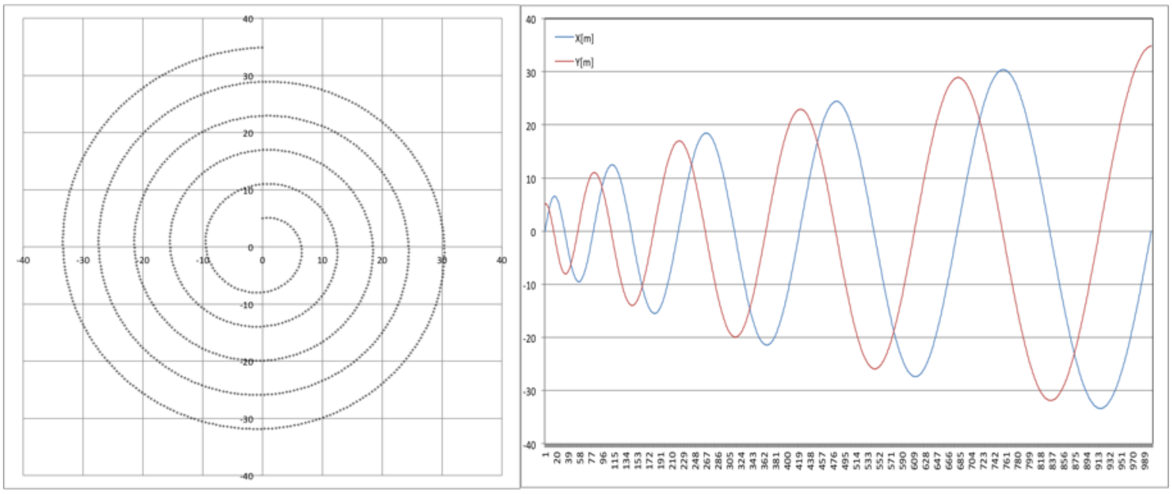


Figure 13: An idealised sweep shape (left) optimised for uniform proton density on the target. The corresponding powering functions in kick are also shown (right).

5.7 Magnet powering

The existing TT20 main bend MBE and MBB magnets are powered in series and no changes are foreseen. For the powering of the new MSSB magnets, a variant of the Linac4 transfer line converters (APOLLO family) can be used. These can be assembled in 4 modules to deliver the requested current/voltage, in order to allow all three magnets to be powered in series. If needed, the maximum voltage of around 400 V could be reduced by a factor of two with balancing the voltage in +/-, however this does not seem necessary to foresee at this stage as 400 V is well within the voltage limit of the MgO coil conductor.

The new main bend magnets (MBB, MBN) powering will likely need a new 6’000 A convertors similar to that used for main SPS magnets. One cost reducing option to investigate would be the feasibility of powering the new magnets in series with the existing string of MBB/MBE dipoles for TT20 using the same main convertor, with a suitable small trim convertor as done for the separate TT20 dipole families. This would, however, probably impose using MBBs or new MBB-compatible magnets for the bends.

For the new quadrupoles, likely to be 5-6 in number of type QNL, the 400 A and the 200 V converters will be similar in specification to those for the existing TT20 individual quadrupole converters. The first slim quadrupole will be of type QSL, for integration reasons, which uses the same converter.

The power converter location needs to be defined – BA80 contains all of the existing convertors for the TDC2/TCC2 region and the beam lines to the NA targets, but is completely full. Suitable space in any new auxiliary building needs to be reserved, of the order of 200 m2 in addition to provision for any new transformers.

5.8 Summary

The main technical challenges are the design and construction of a new splitter/switch magnet, which is likely to require a longer lead-time than a 'normal' design of warm magnet, and the achievable performance of the ZS septum with the high extracted beam intensity, linked to the activation of the extraction region. The design of the dilution system will require some care in the magnet and powering choice, but the difficulty is reduced by the small kick strengths needed.

Overall, and despite these interesting challenges, the beam transfer aspects appear feasible.

6. SHIP Target and Target Station Design

6.1 Introduction

The SHIP proposal requires the realization of a production target that has the twofold objective of producing the charmed mesons required by the physics program as well as to dump the SPS primary beam. Given the involved beam power, the experimental requirements are challenging, as a high-Z material with a short interaction length is needed in order to increase as much as possible the reabsorption of pions and kaons produced in the spallation process that would otherwise generate a background for the experiment. Hence the energy deposition is extremely dense, leading to high temperature and high levels of stress/strain in the material itself. A preliminary investigation on the feasibility of such a device has been conducted on a tungsten target, with a total length of at least 50 cm, corresponding to about 5.5λ at 400 GeV. A hadron absorber encloses the production target, with the double objective of absorbing the remaining hadrons emerging from the target and the non-colliding protons and to significantly reduce the radiation exposure of the muon filter which separates the target bunker from the experimental hall.

The production target is part of a target station which includes all services associated to its cooling, operation & control, manipulation, handling and storage. The shielding configuration as well as the air activation are taken into account already at this stage of the design since they will have a strong impact on feasibility and cost of the facility.

6.2 Target design

The production target is one of the most challenging aspects of the proposed installation, due to the very high energy and power density that will be reached during operation. In terms of beam power delivered on target, the installation will be in a similar operational regime as of the Spallation Neutron Source at ORNL (US) or to the Material Life Sciences spallation sources at JPARC (Japan).

For the analysis described in this section, the beam parameters presented in Table 13 have been taken into account:

Beam	**Baseline** protons	**Ultimate** protons
Momentum [GeV/c]	400	400
Beam Intensity [10^{13} p/cycle]	4.5	7.0
Cycle length [s]	7.2	8.4
Spill duration [s]	1.0	2.2
Expected r.m.s. spot size (H/V) [mm]	6/6	6/6
Average beam power on target [kW]	400	530
Average beam power on target during spill [kW]	2900	2030

Table 13: SPS beam parameters considered for the preliminary assessment of the target design.

It is important to note that given the SPS beam characteristics for the SHIP experiment (i.e. shorter spill duration in the "Baseline" case with respect to the "Ultimate") the average beam power on the target during the spill is roughly 40% higher for the Baseline configuration rather than for the Ultimate.

FLUKA Monte Carlo simulations have been performed to assess the total energy deposition and energy density produced by the interaction of the primary proton beam. For this preliminary assessment, a bare W rod – with a density of 19.3 g/cm^3 – of 50 cm length and 20 cm diameter has been taken into account. The beam footprint has been conservatively assumed as constituted by a uniform circular sweep of 3 cm radius with a sigma of 6 mm.

Simulations show that – for the current target geometry – roughly 81% of the energy is deposited inside the target, corresponding to a super-cycle-average power of 324 kW for the baseline scenario and 430 kW for the ultimate one. The maximum energy densities that are reached are in the order of 3.5 kJ/cm^3/pulse for the baseline beam and 5.5 kJ/cm^3/pulse for the ultimate one. See Figure 14 for the energy distribution.

The target must be actively cooled: light (or heavy) water and helium gas cooling are used in other laboratories and shall be studied in the framework of a technical design report. For this preliminary assessment active (light) water cooling has been considered.

In order to assess the feasibility of the proposed target, thermo-mechanical and computational fluid dynamical analyses have been performed, using the FLUKA-generated energy deposition map as heat source in conjunction with the parameters associated to the two scenarios of Table 13.

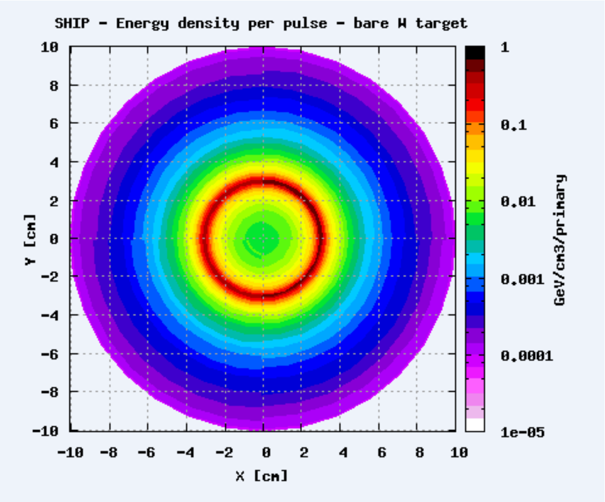


Figure 14: The figure shows a transversal cut of energy density induced by the 400 GeV/c primary beam on a bare W target with a 3 cm radius circular sweep. The average is made ±2 cm around the position of the peak energy density.

Three targets configurations have been studied:

1. Full solid W target, 50 cm long and 20 cm diameter.
2. Sliced W target, 20 cm diameter each, 10 cm length (5 discs).
3. Sliced W target, plates of 20x20 cm^2 each, with a longitudinal configuration of 4 plates of 5 cm each, 2 plates of 10 cm each and one last of 20 cm.

For configuration #1, only tangential water cooling has been considered, while for configuration #2 and #3, an additional cooling interface between the various faces has been considered to increase the surface of heat transfer. For all configurations, two water cooling regimes have been taken into account, i.e. 5 m/s and 10 m/s, assuming water at 25 °C and at atmospheric pressure. A CFD calculation has been employed to evaluate the correct heat transfer coefficient from the material surface to the water (assuming 1 cm gap between the target discs).

The present results show that the full tungsten cylinder (configuration #1) will not be able to withstand the compressive stresses and the temperatures associated with beam operation. Segmentation of the target is mandatory to allow decreasing the temperature and thus the stresses in the material core and to guarantee the experiment operation. Various types of W heavy alloys have been considered, including Inermet® and Densimet® because of their higher compressive strength with respect to pure W as well as for the improved corrosion resistance. It is important to stress that – even with a segmented target and the use of advanced alloys – the compressive stresses that will be produced during the pulse could reach up to 1.2 GPa, extremely challenging for the material properties and temperatures up to 780 °C (see Figure 15).

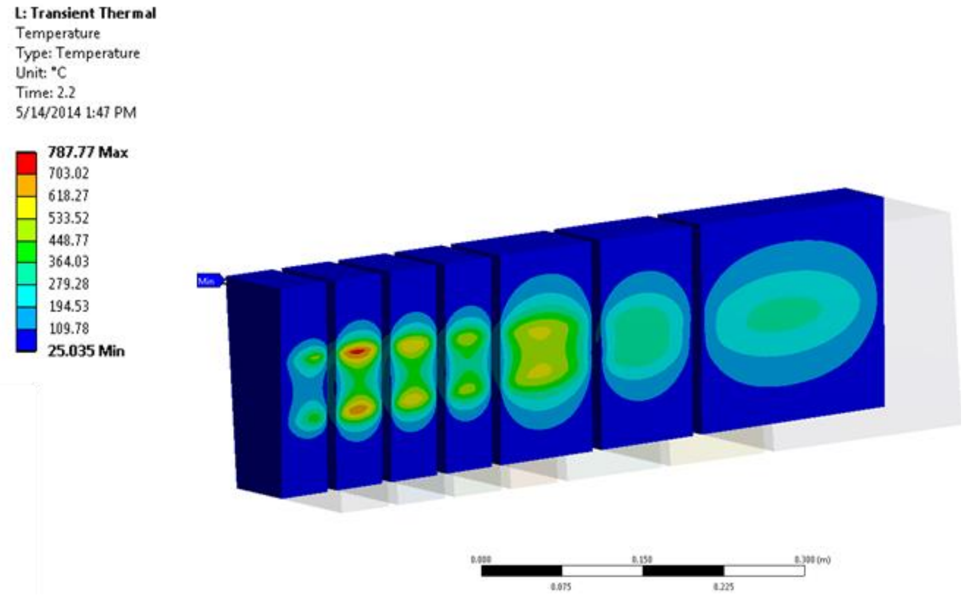


Figure 15: The figure shows the temperature distribution in the SHIP target configuration #3 (assumed constituted by Densimet®) after an "Ultimate" pulse and with an average beam power on target of 530 kW.

Furthermore, due to possible tungsten surface temperatures above 100 °C, the cooling loop must be pressurized to guarantee boiling points well above the maximum W surface temperature as well as to increase the heat transfer coefficient for the same water flow rate.

Clearly the geometry of the target as well as the sweep geometry will necessarily require further iterations with the SHIP experiment (i.e. to optimize the longitudinal gaps between the discs and the design of the pressurized vessel) as well as with the primary beam line design (total length, dilution shape and duration of the sweep). The proposed spiralling sweep (see Chapter 5) is being evaluated to assess its effect on the transient part of the FEM analysis. However, its use is not expected to significantly modify the conclusions obtained with the simpler circular sweep.

An issue that will have to be taken into account for the design of such a target with high flow velocities is cavitation. This phenomenon will occur if local vapour pressure is greater than local pressure, generating cavities or bubbles; as the cavities will leave the low pressure region they will collapse, potentially damaging the target vessel wall. One solution to reduce this effect is to avoid drastic bends (to reduce sudden pressure drops) as well as to increase circuit pressure, in order to guarantee that the pressure in all regions will be above the local vapour pressure. Increasing the water pressure will have the additional benefit of increasing the boiling point of water (as an example, water at 5 bar has a boiling point at 150 °C).

The present study did not take into consideration erosion/corrosion processes due to water flow nor the degradation of mechanical properties from radiation damage. The results show already that the projected operational conditions are not far from the limits of pure tungsten therefore a vigorous R&D program on materials (use of tungsten heavy or doped alloys, eventual claddings, etc.) and target configuration is certainly necessary to confirm the feasibility of the project. Some iteration with the SHIP experiments and on the extraction scheme from the SPS, as well as on the layout of the transfer line to eventually modify the size of the beam and of the dilution path might also have to be considered to find a good balance between physics output and cost.

6.3 Target station design

The SHIP target station design could profit from the work performed in the framework of the CERN Neutrino Facility (CENF) target facility. The design is adapted for shallow target installations, and is based on a multi-compartment solution in which volumes are well subdivided (from a ventilation point of view) and are constituted by underground areas accessible from a surface target hall (see Figure 16 for more information).

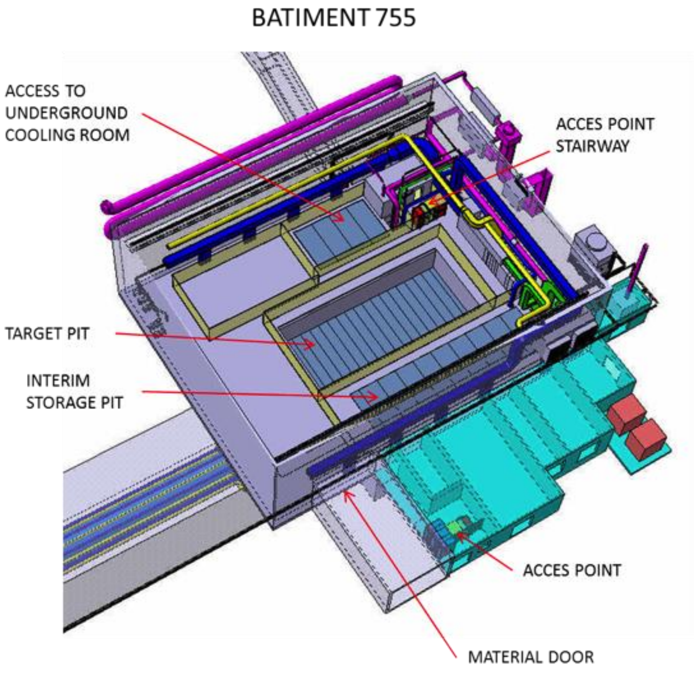


Figure 16: Isometric view of the proposed CENF target station hall.

Taking into account the on-going discussions with GS/SE, the SHIP target hall will be designed as a surface or semi-underground building roughly 38 meters long, 20 meters wide and 14.5 meters high. The target building includes also the first part of the muon filter tunnel, which will be accessible from the target hall itself.

The spallation target is located on the bottom of a shielded bunker, assumed to be roughly 10 meters long and 8.5 meters wide, for a total depth of about 12 meters with respect to the surface of the target hall (See Figure 17). A massive (~3.5 kton) iron shielding (i.e. hadron absorber) surrounds the spallation target in order to reduce the prompt dose rate during operation and the residual dose rate of the target during shutdown: according to preliminary RP evaluations, roughly 400 cm is needed above the target, 500 cm downstream (before the muon plug) and 320 cm below and laterally (on each side). In order to minimize the radiation issues in the primary beam line, the beam opening must be kept as small as possible, but still of the same order of magnitude as the target diameter (20 cm). A TAN-like system could be conceived to reduce the activation of the primary tunnel equipment due to neutral (essentially neutrons) particles travelling backwards from the target on the primary beam pipe.

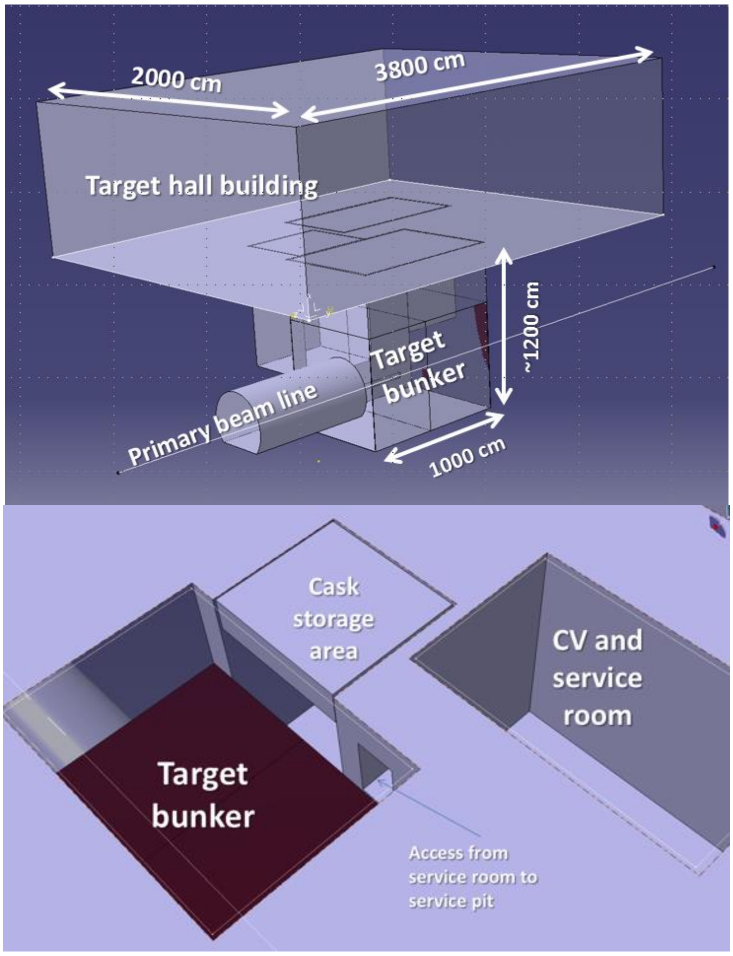


Figure 17: Preliminary view of the SHIP target station, with the proposed configuration of the target hall and of the target bunker.

Due to the very high residual dose rate of the target (and of the annex iron shielding), remote manipulation and handling is mandatory. In case of target failure (which must be foreseen as an operational possibly), an annex area of the target bunker ("cask storage") is foreseen to temporarily store the target for cooling down. The target hall must be equipped with a 40 ton – fully redundant – crane to allow the handling of the iron shielding blocks. Redundancy will be important in case of failure of any mechanical system (i.e. the gearbox) during target handling.

Similarly to what has been envisaged for the CENF target area, the target bunker and the target storage zone are embedded inside a helium-filled vessel atmosphere (see Figure 18), with online circulation and purification. This solution has two major advantages over an air filled solution:

1. Reduction of the air activation. This simplifies interventions in case of target failures that require opening of the internal shielding and reduces the environmental impact of the installation.
2. Reduction of the risks of radiation-accelerated corrosion of the target pressurized vessel (and associated equipment) and of the iron shielding.

A ~100 cm thick concrete wall separates the edge of the helium vessel from the primary beam line upstream, see Figure 18.

A buffer area – also called service pit – is foreseen on the top of the helium vessel, in order to permit human interventions on the various feed-throughs (water, helium, control signals) between the service areas and the internal part of the helium vessel/target bunker. An extra 160 cm concrete layer will additionally shield the service pit from the target hall. The latter will be removable to allow crane access to the target bunker.

The SHIP target station ventilation system will be designed respecting the ISO17874:2004 norms, with a pressure cascade between the various compartments, from -60 Pa of the target hall to -220 Pa of the most exposed zones. A recirculation system for the most radioactive areas (helium vessel and service pit) should be foreseen to allow the decay of short-lived isotopes before release into the environment. The air-tightness of the various areas will be a central part of the target station design and will be interlocked with beam operation.

The cooling and ventilation equipment required for the functioning of the installation (target cooling, hadron absorber/shielding cooling and helium circulation) will be located in an underground area (tentatively 1500 cm long and 750 cm wide, for a total depth of 8-10 meters) – constituted by two/three underground levels – connected to the target bunker via the service pit (see Figure 18). Access from the target hall will be possible by means of a dedicated stairwell.

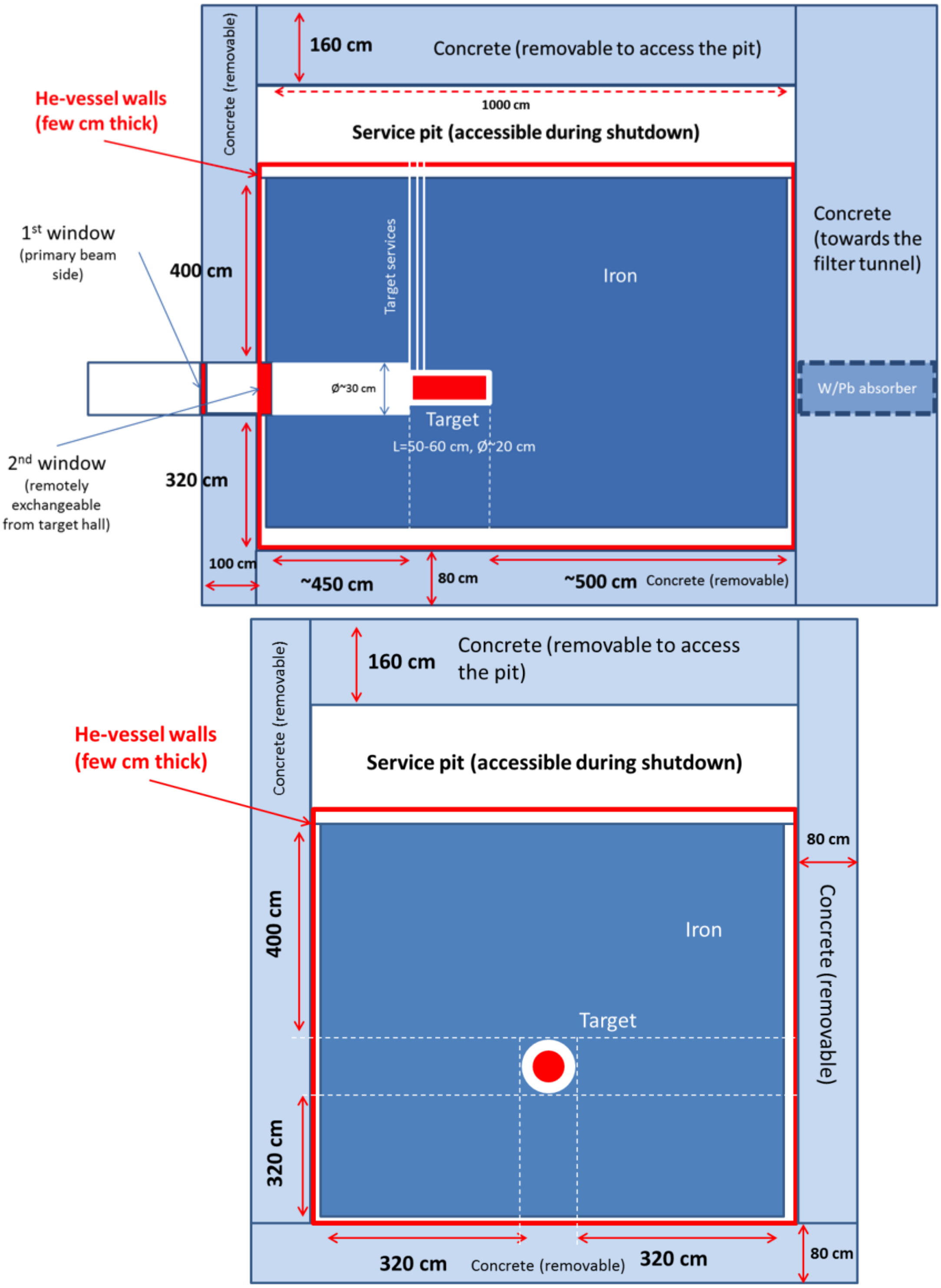


Figure 18: The schema shows a longitudinal (upper figure) and transversal (bottom figure) cut of the possible configuration of the underground target bunker, with the target and target shielding. The surrounding concrete layers must be considered as removable (for RP reasons) and therefore not part of the concrete structure of the installation.

The beam window between the target bunker and the primary beam line must be remotely exchangeable from the target hall, due to its proximity with the spallation target. An extra beam window is foreseen as well in the primary beam line to create a buffer area where eventual leakages from both neighbouring areas (vacuum in the primary line and He of the target bunker) can be measured.

A contiguous service building, 25 meters long and 15 meters wide is included as well. It houses the PAD/MAD to the target hall, RP monitoring control systems, intermediate heat exchangers for the target and shielding cooling circuit, target hall ventilation system as well as ancillary systems such as UPSs, control racks for access and safety systems, etc. The target hall or the service building will also house all the electrical cabinets, control PLCs as well as all electronics sensitive to radiation that cannot be stored in the underground areas. Finally, it also acts as a buffer transport loading/unloading area for target area equipment and new/spent targets. See Figure 19 for a schematic view of the target hall configuration.

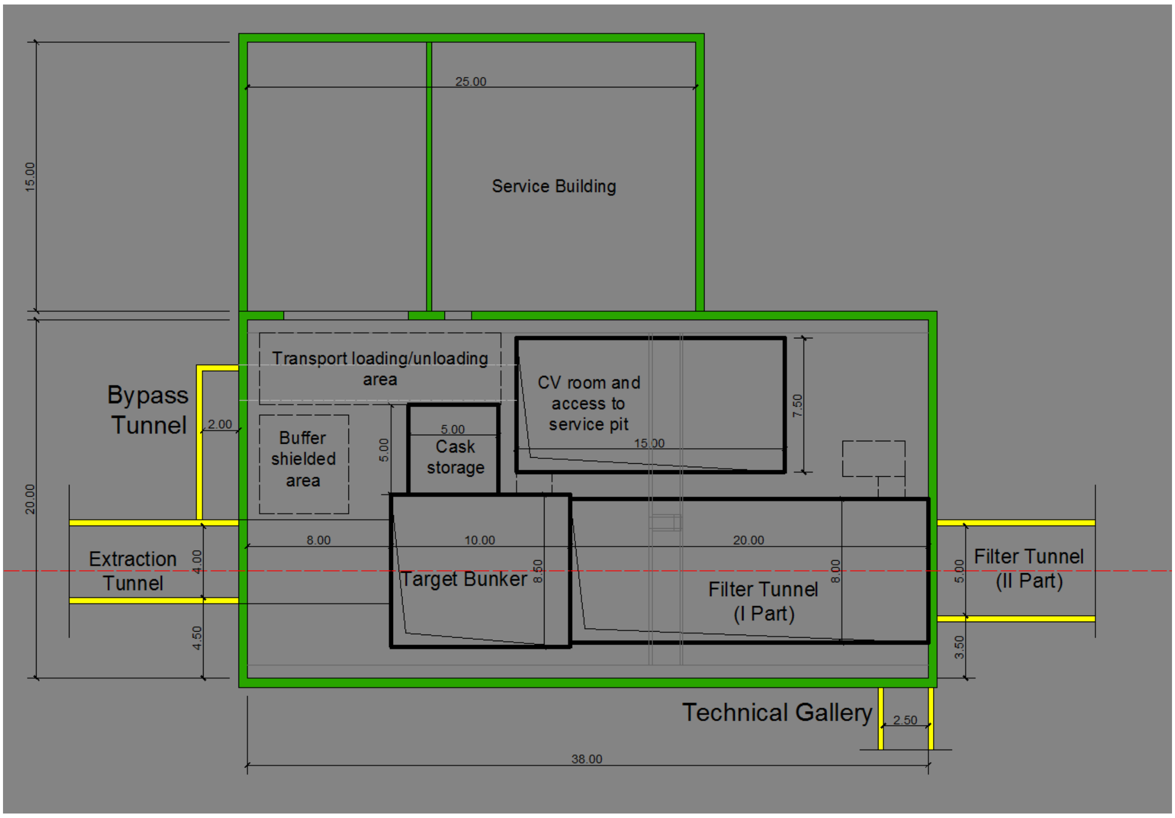


Figure 19: The schema shows a plan (to scale) view of the target hall with tentative sizes of the various areas in particular the target bunker, the cask storage area as well as the CV and service room.

The shielding of the target hall shall be designed to keep the radiation levels low enough to allow its classification as a supervised area, in order to permit access to the building even during the operation of the experiment. The access to the underground areas – on the contrary – will be forbidden during beam.

7. Civil Engineering for the SHIP experiment

7.1 Overview

Civil Engineering costs for projects such as SHIP typically represent approximately one third of the overall budget. For this reason, particular emphasis has been placed on Civil Engineering (CE) studies, to ensure a cost efficient conceptual design. This chapter provides an overview of the designs adopted for the civil engineering.

The CE studies were based on the assumption that the SHIP facility will be sited on the CERN Prevessin laboratory in France. A new machine extraction tunnel will be required in the North Area, leading to a new Target and Experimental facility. All civil engineering works for the project are fully located within existing CERN land on the Prevessin campus.

Figure 20 is a schematic layout of the civil engineering complex for the SHIP project.

Figure 20: Schematic layout of the civil engineering complex.

The key features of this layout are:

- 85m long Junction Cavern in the TDC2 line
- 170m long machine Extraction Tunnel (4m wide by 4m high similar to TDC2)
- 15m long by 15m wide Access building including a shaft to reach the Extraction Tunnel line

- 38m long by 20m wide Target Area
- 25m long by 15m wide Service building directly connected on one side to the Target Area
- 140m long Technical Gallery (2.5m wide by 2.5m high similar to GT801)
- 70m long Filter tunnel downstream Target Bunker
- 120m long by 20m wide Detector Hall
- 40m long by 20m wide Access building on top of the Detector Hall

All underground works are to be excavated using the “cut-and-cover” method.

The civil engineering studies presented in this chapter have been performed by the GS-SE Group with various technical experts within the SHIP team. External consultancy firms have also contributed in some areas of these designs.

7.2 Civil Engineering

This section describes the civil engineering envisaged both on surface and underground for the SHIP Project.

7.2.1 Location

The proposed siting for the SHIP Project is fully located within existing CERN land on the Prevessin campus. The on-surface alignment of the complex consists of green areas and woodland.

This location is extremely well suited to housing the SHIP project, with the very stable and well understood ground conditions. Detailed geological records exist and have been utilised for this study to minimise the costs and risk to the project. The underground works will be constructed in the stable Moraine glacial deposits at a depth of approximately 10 m in an area with little seismic activity.

The governments of France and Switzerland have long standing agreements concerning the support of particle accelerators in the CERN region, which make it very likely that the necessary planning permissions could be granted in a relatively short timeframe.

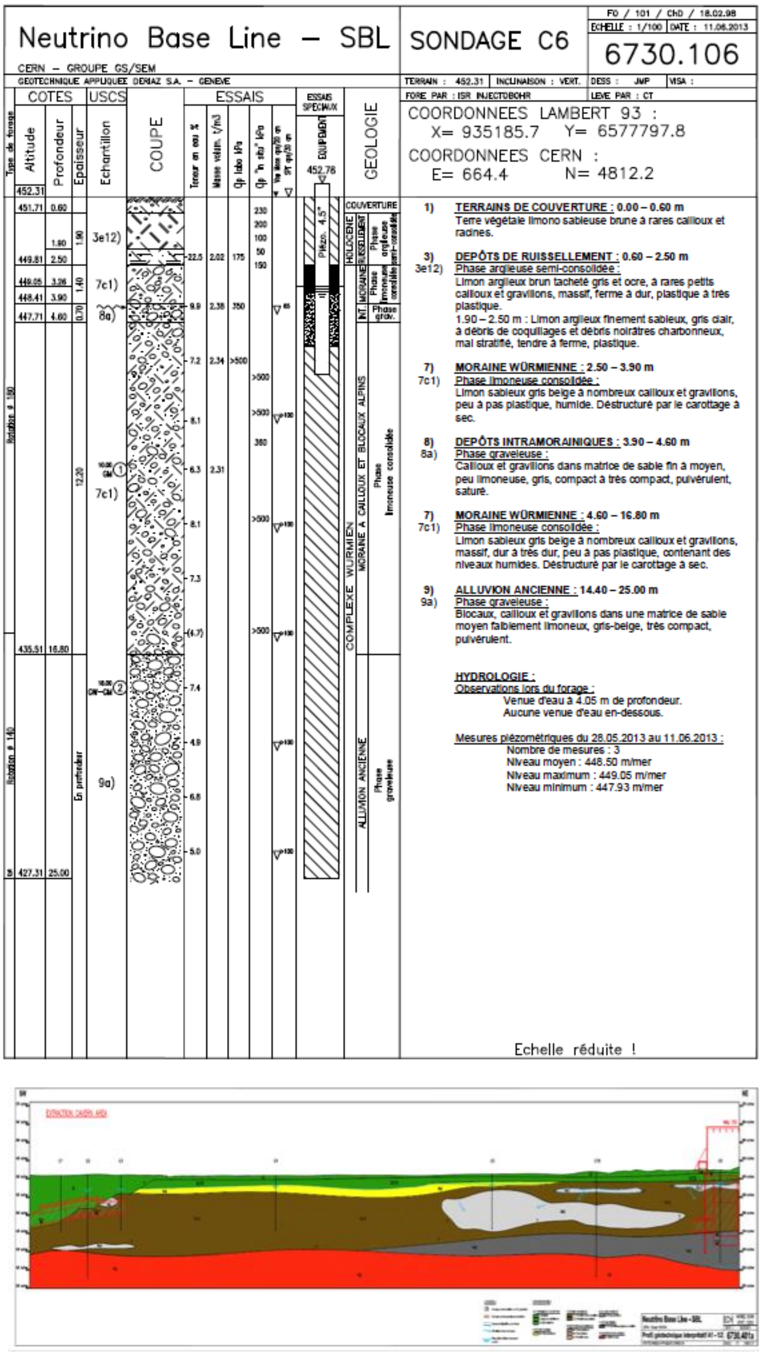
7.2.2 Land Features

The proposed location for the project is situated within the Swiss midlands embedded between the high mountain chains of the Alps and the lower mountain chain of the Jura. CERN is situated at the feet of the Jura mountain chain in a plain slightly inclined towards the lake of Geneva. The surface terrain was shaped by the Rhone glacier which once extended from the Alps to the valley of the Rhone. The water of the area flows to the Mediterranean Sea. The absolute altitude of the surface ranges from 430 to 500 m with respect to sea level.

7.2.3 Geology

The proposed path of SHIP is situated within the Geneva Basin, a sub-basin of the large North Alpine Foreland (or Molasse) Basin. This is a large basin which extends along the entire Alpine Front from South-Eastern France to Bavaria, and is infilled by clastic “Molasse” deposits of Oligocene and Miocene age. The basin is underlain by crystalline basement rocks and formations of Triassic, Jurassic and Cretaceous age. The Molasse, comprising an alternating sequence of marls and sandstones (and formations of intermediate compositions) is overlain by Quatemary glacial moraines related to the Wurmien and Rissien glaciations.

Figure 21 shows a typical geological borehole log for the Moraines in the SHIP area.



COORDONNEES LAMBERT 93 :
X= 935185.7 Y= 6577797.8

COORDONNEES CERN :
E= 664.4 N= 4812.2

1) **TERRAINS DE COUVERTURE : 0.00 – 0.60 m**
Terre végétale limono sableuse brune à rares cailloux et racines.

3) **DEPÔTS DE RUISSELLEMENT : 0.60 – 2.50 m**
3e12) Phase argileuse semi-consolidée :
Limon argileux brun tacheté gris et ocre, à rares petits cailloux et gravillons, massif, ferme à dur, plastique à très plastique.
1.90 – 2.50 m : Limon argileux finement sableux, gris clair, à débris de coquillages et débris noirâtres charbonneux, mal stratifié, tendre à ferme, plastique.

7) **MORAINE WÜRMIENNE : 2.50 – 3.90 m**
7c1) Phase limoneuse consolidée :
Limon sableux gris beige à nombreux cailloux et gravillons, peu à pas plastique, humide. Déstructuré par le carottage à sec.

8) **DEPÔTS INTRAMORAINIQUES : 3.90 – 4.60 m**
8a) Phase graveleuse :
Cailloux et gravillons dans matrice de sable fin à moyen, peu limoneuse, gris, compact à très compact, pulvérulent, saturé.

7) **MORAINE WÜRMIENNE : 4.60 – 16.80 m**
7c1) Phase limoneuse consolidée :
Limon sableux gris beige à nombreux cailloux et gravillons, massif, dur à très dur, peu à pas plastique, contenant des niveaux humides. Déstructuré par le carottage à sec.

9) **ALLUVION ANCIENNE : 14.40 – 25.00 m**
9a) Phase graveleuse :
Blocaux, cailloux et gravillons dans une matrice de sable moyen faiblement limoneux, gris-beige, très compact, pulvérulent.

HYDROLOGIE :
Observations lors du forage :
Venue d'eau à 4.05 m de profondeur.
Aucune venue d'eau en-dessous.

Mesures piézométriques du 28.05.2013 au 11.06.2013 :
Nombre de mesures : 3
Niveau moyen : 448.50 m/mer
Niveau maximum : 449.05 m/mer
Niveau minimum : 447.93 m/mer

Figure 21: Typical geological borehole log and long profile for the area.

7.2.4 Site Development

As the SHIP Project is located on the CERN site at Prevessin, it is assumed that the existing facilities such as office space, restaurant, main access, road network etc are sufficient and have not been costed. However, some additional site development will need to be included in the cost estimate:

- New access road and car park
- Drainage networks
- Landscaping and planting
- Spoil dumps

All temporary facilities needed for the construction works will also have to be included in the cost estimate.

7.2.5 Construction Methods

It is envisaged that all underground works will be executed using "open-cut' rather than tunnelling methods. The TDC2 tunnel itself was excavated in 1972 using the "cut and cover" technique.

Figure 22 shows the start of the tunnelling for the TT20 line going down towards the SPS.

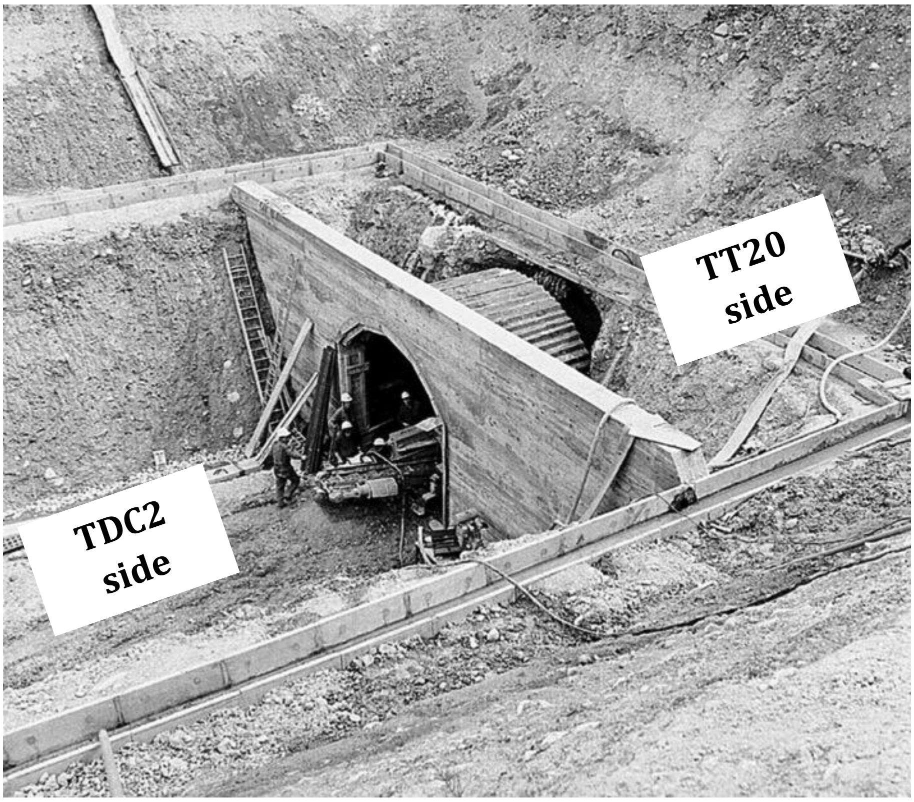
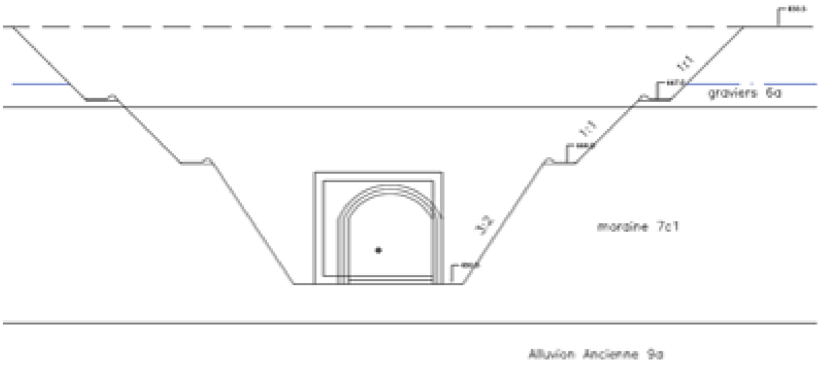
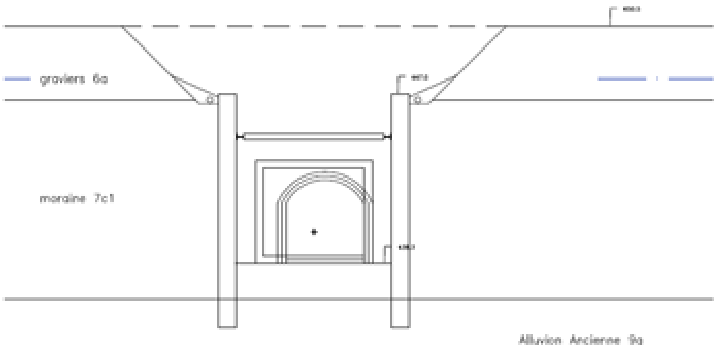


Figure 22: Photo from May1972 showing the start of tunnelling for TT20 line going down to SPS.

The new civil engineering works will be downstream of the TT20/TDC2 area, so it is envisaged that all the excavation works will either be entirely open cut, or with the aid of retaining walls, as shown in Figure 23.



'Open-Cut' Excavation



Excavation with Retaining Walls

Figure 23: Proposed excavation methods for SHIP

7.2.6 TDC2 Junction Cavern

The junction cavern consists of an 85 m long new facility in the existing TDC2 complex, providing the starting point for the new extraction tunnel as shown in Figure 24. This will mean that an approximately 100 m length of existing machine and services will have to be removed to allow demolition works to be executed. The potential risk of the existing concrete and surrounding earth being radioactively contaminated still needs to be assessed. This could potentially have a significant impact on the cost of the SHIP project.

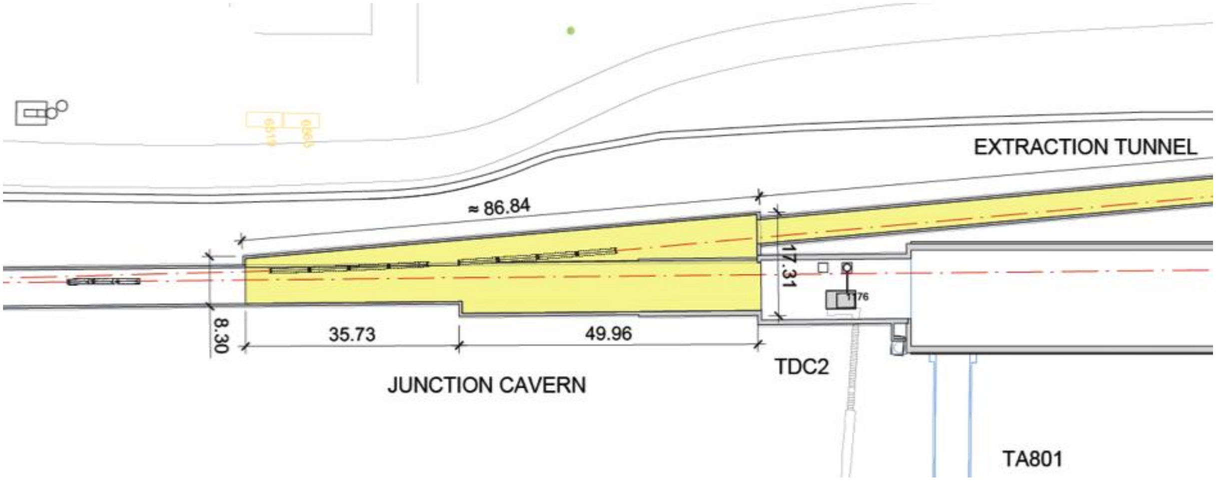


Figure 24: New Extraction Cavern in the TD2 complex.

Extra care will have to be taken to ensure that any movement of the existing tunnels is minimised to an acceptable level and no new water ingress problems are created due to the civil engineering works in adjacent structures.

The excavated depth to the invert of the tunnel is approximately 10 m, which means there will be 5.5 m of land fill over the top of the completed structure.

7.2.7 Machine Extraction Tunnel

It has been assumed for costing purposes that the internal dimensions of the 170 m long machine extraction tunnel will be 4 m wide by 4 m high (similar to the TTDC2 tunnel). This size has been determined by inserting all known machine components / services into a 2D drawing while maintaining free space for transport vehicles and safe passage of personnel.

A machine lattice file was used to determine the alignment of the new tunnel. A surface building, including an "Auxiliary Power Supply" area with plan dimension of 10m by 10m, for the ventilation systems and access to the underground structures, equipped with a 40 ton crane, is located approximately halfway along the extraction tunnel.

The floor level of the extraction tunnel is set at a constant 441masl (above sea level), which is same as TCC2 complex.

An emergency egress through a bypass tunnel at the end of the Extraction Tunnel will be foreseen, in order to avoid dead ends, to reach the Target Area located downstream.

A typical Cross Section for the machine extraction tunnel is shown in Figure 25.

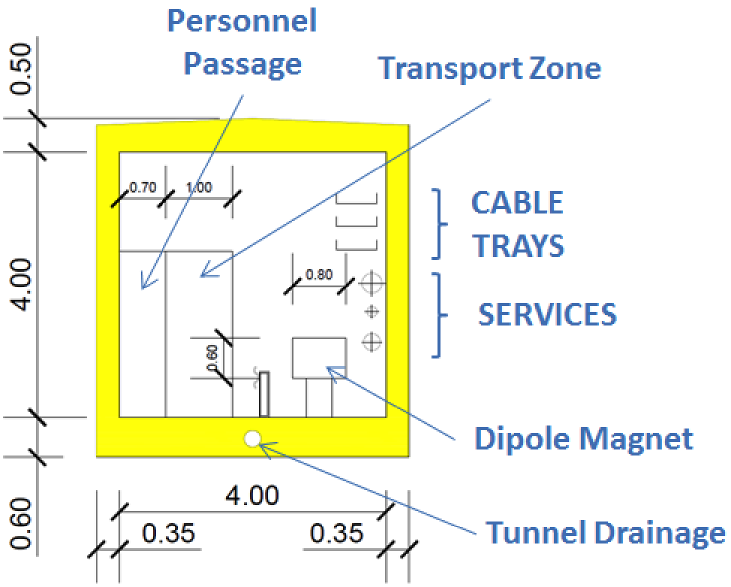


Figure 25: Typical machine extraction tunnel cross section.

7.2.8 Target Area

The Target Area complex will be characterized by a main hall on surface, equipped with a 40 ton crane, which will have approximate plan dimensions of 38 m by 20 m and a service building, on the Jura side, with plan dimensions of 25 m by 15 m, as shown in Figure 26. Due to potential radiation contamination, special measures will have to be taken in the target area to minimise the amount of ground water that is able to penetrate the surrounding soils and come in contact with the underground facility.

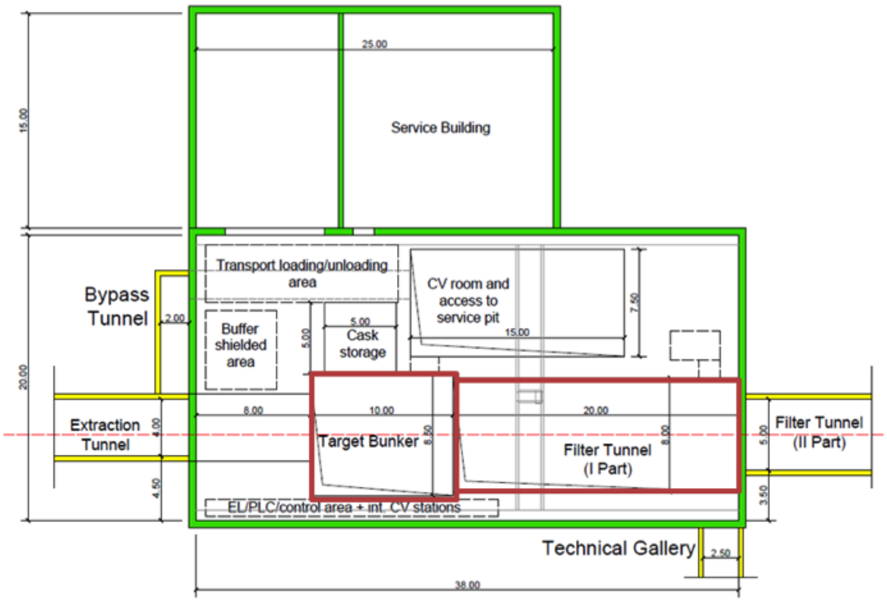


Figure 26: Target Area plan view.

The spallation target would be located on the bottom of a shielded bunker, assumed to be 10 m long and 8m wide, for a total depth of about 10m with respect to the surface of the target hall. An annex area of the target bunker (“target storage”) with approximate plan dimensions of 5m by 5m has to be foreseen in order to temporarily store the target for cooling down.

The cooling and ventilation equipment required for the functioning of the installation (target cooling, hadron absorber/shielding cooling and helium circulation) could be located in an underground area (15m long and 7.5m wide, for a total depth of 8-10m) connected to the target bunker via the service pit.

The final layout of the Target Hall is completed by a buffer area, a dedicated zone for all the electrical cabinets, control PLCs as well as all electronics sensitive to radiation that cannot be stored in the underground areas and finally a transport loading/unloading area next to the trucks access.

The Target Area cross section is shown in Figure 27.

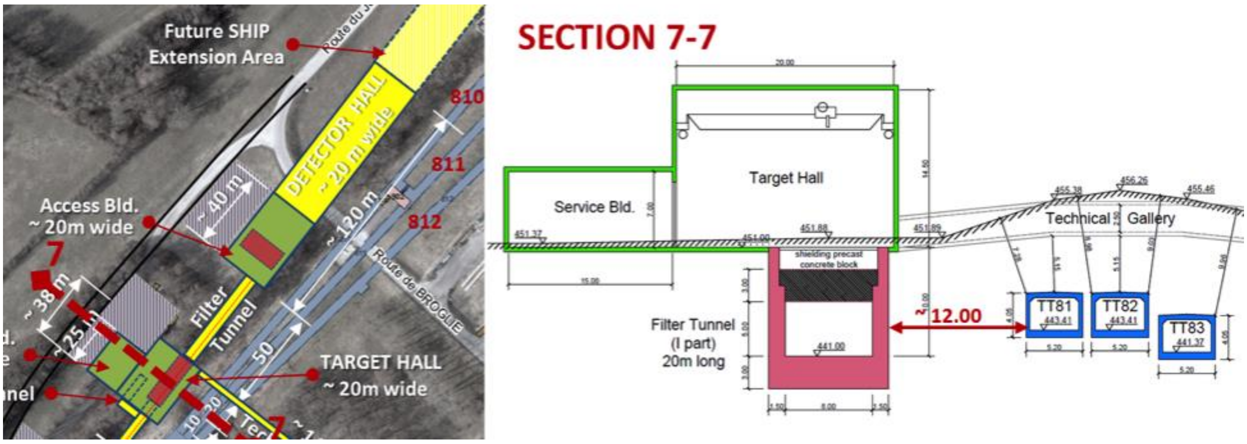


Figure 27: Target Area cross section.

7.2.9 Filter Tunnel

The Filter tunnel will be 70 m long with the invert level at 441 masl. The first part (20 m long) will be embedded beneath the target hall where a separate personnel access will be provided. The equipment located in this area will be installed using the target hall crane. The tunnel cross section will be 8 m wide by 5 m high.

The second part (50 m long) downstream the target area up to the detector building will be 5 m wide by 5 m high, as indicated in Figure 28.

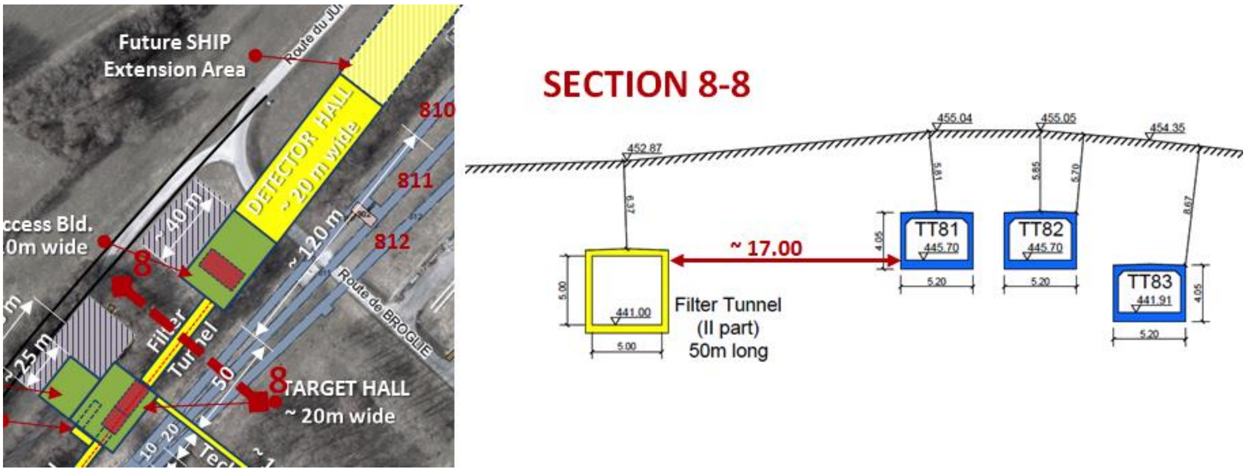


Figure 28: Filter Tunnel Cross Section.

7.2.10 Detector Building

The Detector Building will be 120 m long by 20 m wide and equipped with a 40 ton crane.

The floor level of the experiment is set at 437.93 masl. This level was calculated taking into account the beam line level, which remain the same (442.18 masl) along the entire SHIP complex, and the equipment volume (vacuum vessel + magnet) around the beam line.

The detector hall will be almost fully underground. A surface building (30 m long) for assembly and installation purposes will be positioned over the detector hall. This building will be equipped with a 40 ton crane and have an opening, which can be covered with precast concrete beams, providing a vertical access to the underground area.

A cross section with the access building and the detector hall below is shown in Figure 29.

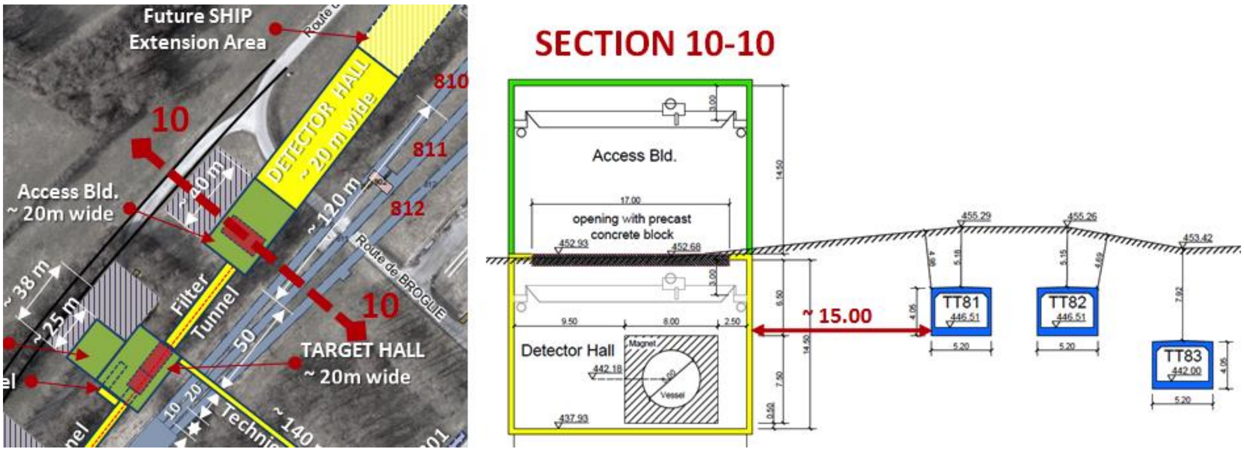


Figure 29: Detector Building.

7.2.11 Civil Engineering Cost Estimate for WP

The cost estimate for the SHIP Project is based on the layouts presented in this chapter. The estimate includes all aspects of construction, final engineering designs and construction management. Many of the rates used to formulate this estimate will be based on real construction costs from LHC experience (1998-2005).

The total cost for each Work Package obtained taking into account the main works activities related is shown in Chapter 9. The estimated accuracy is ±30%. Not included in this estimate are:

- GS-SE resources
- Earthworks assume stockpiling on CERN site and no special treatment required for radiation
- Instrumentation for ground stability monitoring not included
- Special foundation support for facilities (e.g. Detector, etc) not included
- Shielding precast concrete blocks not included
- Infrastructure systems not included (ventilation, electricity, etc)

7.2.12 Civil Engineering Scheduling and Resource Considerations.

A preliminary schedule has been studied for the construction of the SHIP Project using the knowledge acquired from the construction of previous similar schemes at CERN. This timeline is shown, along with the other activities in the SHIP project in Chapter 9.

Two years are needed for pre-construction activities (design studies, building permits, tendering) after formal approval of the project. The CE works are split in three packages. The first one includes the Extraction Tunnel and the Target Area works for a period of 15 months scheduled before the LS2. Then during the LS2 period has been scheduled to carry out the Junction Cavern (15 months), adding the demolition of the existing TDC2 portion. The last package (18 months) is finally expected at the end of LS2 for the Filter Tunnel and Detector works.

In order to cause minimal interference to the operation of the current fixed target program in the North Area, maximum advantage must be taken from the LS2 shutdown (2018-2019) to construct the junction cavern and install the splitter and proton line magnets.

8. Preliminary radiation protection considerations for SHIP

The high number of protons impinging on the SHIP target of 2×10^{20} within 5 nominal years combined with the proposed location of the SHIP experiment close to ground level poses several challenges for radiation protection. Radiation protection guidelines for the design of such a high powered facility are given in Appendix 1. The five most important aspects to be studied initially for the SHIP facility from a radiological viewpoint are:

- Prompt radiation: sufficient shielding is needed to reduce the levels of radiation in areas accessible during beam operation to levels that allow the classification as

Supervised Radiation Area or Non-Designated Area [26]. In particular the production of high-energy muons (very difficult to shield) close to surface level including pertinent shielding requirements has to be studied carefully.

- Residual radiation after beam stop: only remote handling is possible in and around the target area. The design of the cooling circuits in the target requires detailed studies as the liquids will become radioactive and any handling needs to be optimised. In addition, disposal pathways for radioactive liquids need to be identified.
- Air activation: the air volume in the target area has to be minimised in order to reduce the production and releases of air-born radioactivity. The target bunker plus shielding, including the storage zone should be housed inside a helium-filled vessel.
- Environmental impact due to possible activation of soil and ground water: the hazard might be mitigated by using a CENF like design (shielding and geo-membrane around the target station).
- Radiological accident and incident scenarios need to be studied, in particular the dose to workers and members of the public.

It is worth mentioning that the design of the SHIP facility will strongly benefit from studies performed for the CENF project where similar concerns exist.

Radiation losses at the extraction from the PS have been a limiting factor for CNGS and they will also be high for SHIP, but some improvements have been made during LS1. An additional and important radiation protection aspect of the SHIP facility is the beam losses in the SPS accelerator and extraction area towards SHIP. Estimated beam losses during future SPS operation with up to 7×10^{13} protons per extraction are about a factor of 7 higher than for CNGS beams[1]. Such high beam loss levels would result in unacceptable residual dose rate and air activation levels in the SPS, having a strong impact on the accessibility of the SPS and on the dose given to the public via airborne radioactivity releases. In case these losses occur in unshielded locations the lifetime of cables installed nearby will be reduced significantly. Similar issues might exist at the PS as well. In order to prevent such high losses, future beam intensities shall be limited to CNGS-like beam intensities or other means have to be found to reduce beam losses at higher intensities.

Already at nominal beam intensity the dose levels will be a factor 3-6 higher than in previous years. Without mitigation, this could lead to dose levels of 12 mSv/hr after a month of cool-down. This needs careful study.

8.1 Radiation levels in TDC2

The beam extraction point for SHIP is presently foreseen at one of the most radioactive areas in TDC2, namely, at the first splitter magnets. Therefore, personnel will be exposed to high dose rate levels at work places during removal/installation/modification of beam line elements. A careful planning of these

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[1] Quotation from collimator LIU review minutes

activities combined with an optimized work and dose planning will be essential. A detailed RP survey has been performed in October 2013 (after 10 months of cooling time) in TDC2 and TCC2 to allow a thorough work and dose planning for cable exchange activities in those areas in 2013/2014. The results of these surveys can be found in EDMS [27]. For illustration, the ambient dose equivalent rates at the first splitter magnet location are shown in Figure 30 below.

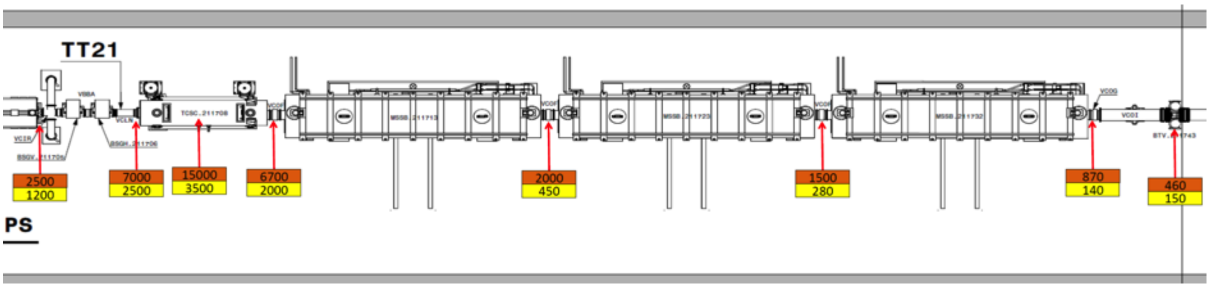

Figure 30: Ambient dose equivalent rates measured (in μSv/h) at the first splitter magnets in October 2013. Values in orange are measured at contact to the objects, in yellow at a distance of 40 cm.

Extraction of the SHIP beam line from TDC2 requires partial demolishing of the existing tunnel structure of TDC2. The concrete wall of TDC2 and the soil close to TDC2 tunnels are activated. In order to quantify the amount of activation as well as the lateral distribution (volume) of activated soil it is advised to take soil samples close to the TDC2 area.

Removal of existing beam line components has to be foreseen before civil engineering work in TDC2 can start. Furthermore, the CE contractor needs to be authorised by his national authority to send workers in radiation areas of a third party (for more information see “Working on CERN site” [28]). The CE workers need to be classified as Radiation Worker, have to receive all required safety trainings and need to be individually monitored.

Although it is not directly related to SHIP, RP strongly advises studying the possibility to add shielding around existing high beam loss points in TDC2. This will significantly reduce the activation of the concrete wall and surrounding soil as well as the dose rate on the surface above the high beam loss points during future operation.

8.2 Prompt dose rate around the SHIP target

Preliminary FLUKA Monte Carlo simulations have been performed to estimate the required shielding around the SHIP target. Therefore, simplified geometries have been setup in FLUKA which consisted of the SHIP target surrounded by iron and concrete shielding, see Figure 31. The (cylindrical) target was assumed to be made of tungsten with a density of 19.3 g/cm^3, a diameter of 20cm and a length of 50cm (5.5λ). The target is surrounded by massive iron shielding of a lateral thickness of 4 m. The prompt dose equivalent rate at ultimate beam intensity (see Table 13) around the target is shown in Figure 32.

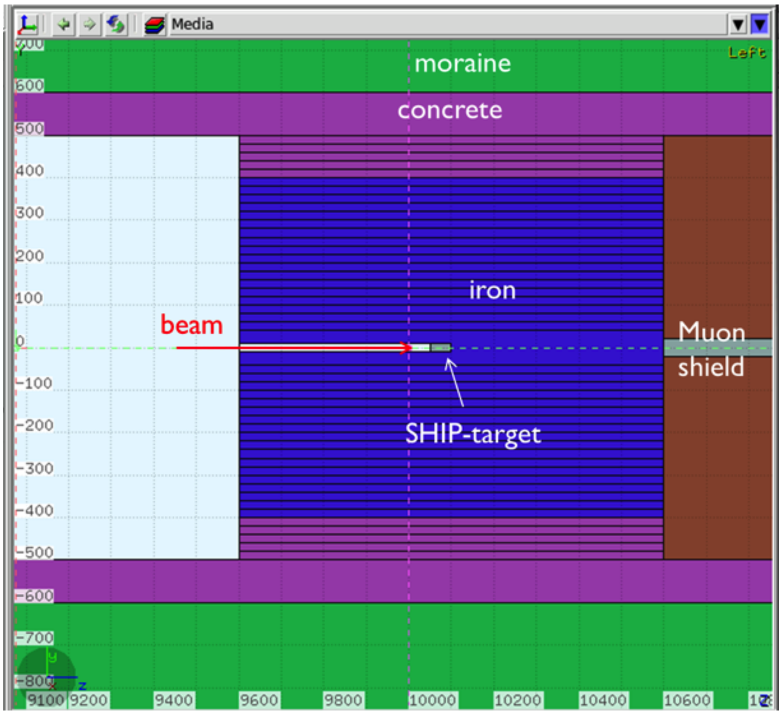

Figure31: Simplified (cylindrical) FLUKA geometry of the SHIP target shielding configuration; units are given in cm.

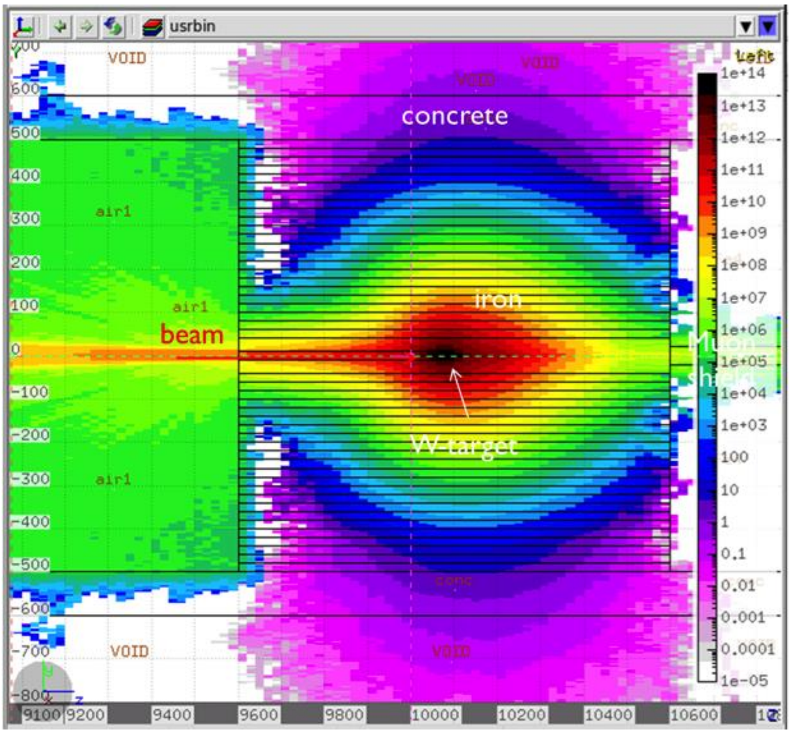

Figure 32: Prompt dose equivalent rate (at ultimate beam intensity) around the SHIP target. Units of the colour legend are in μSv/h.

8.3 Preliminary shielding requirement around the SHIP target

The shielding around the SHIP target has to be sufficient to reduce the dose rates in the surface building to levels allowing the classification as a Supervised Radiation Area. The dose rates outside the buildings should be compatible with that of a Non-Designated Area. Since the target area will be close to the surface the thickest shielding is required on top of the target. First studies show that about 4m of iron and 1.6 m of concrete above the target reduce the prompt equivalent dose rate H*10 above the shielding to Supervised Radiation Area levels (here to ~1 μSv/h) whereas 3.2 m of iron and 0.8 m of concrete on the side and below of the target will reduce the dose rate to 500 μSv/h outside the concrete shielding blocks (and to ~100 μSv/h at the beginning of the soil considering 80 cm thick concrete tunnel walls), see Figure 33. The corresponding baseline shielding design around the SHIP tungsten target is shown in Figure 34.

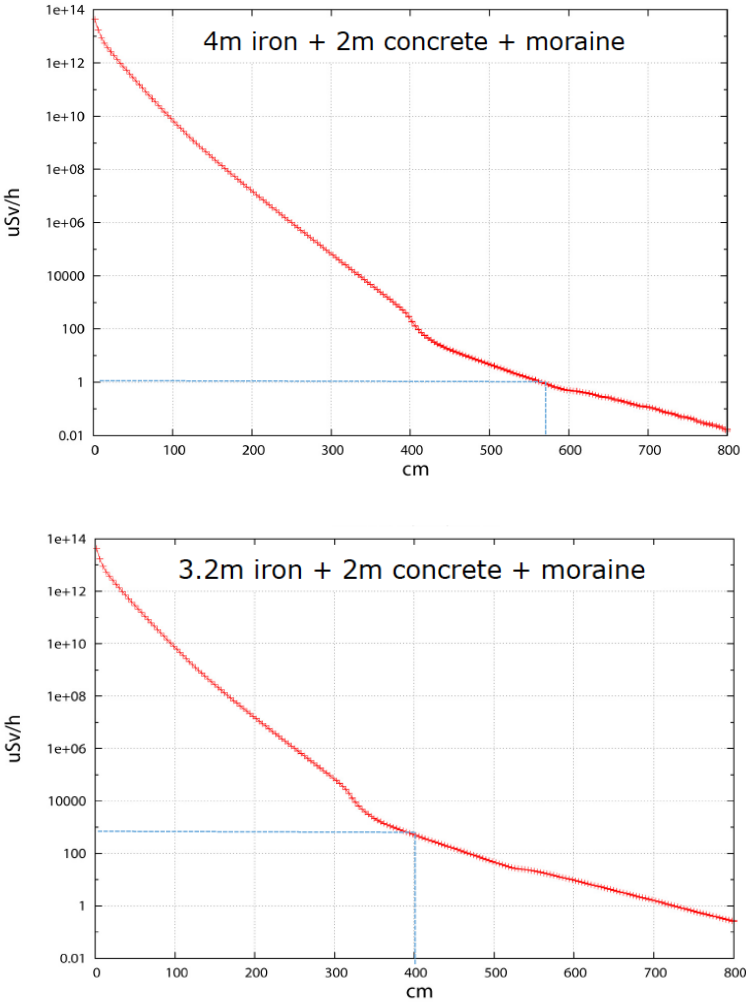

Figure 33: Ambient dose equivalent rate in the shielding laterally to the SHIP target for 2 different shielding configurations at ultimate beam intensity.

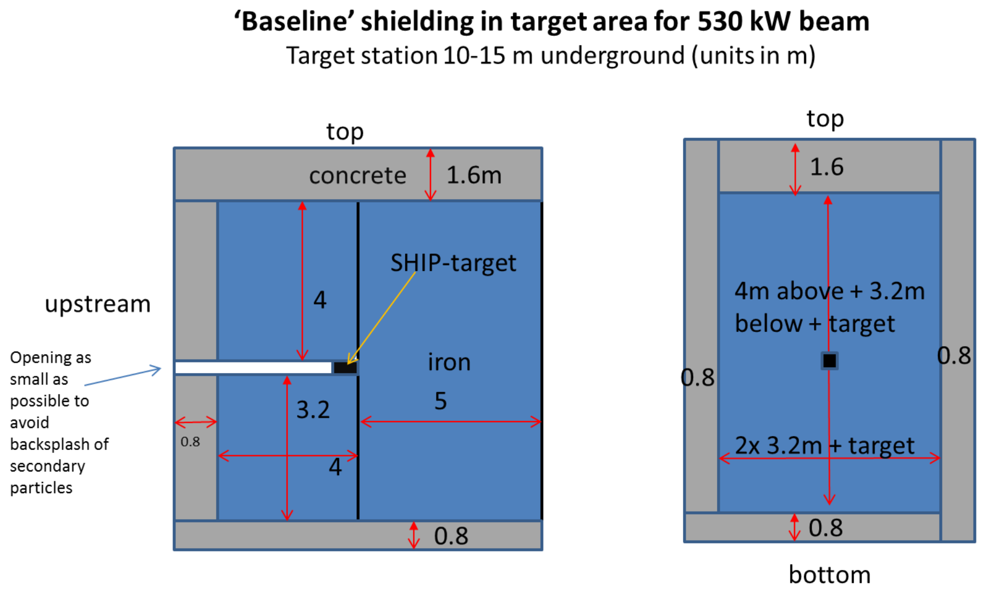

Figure 34: Minimum shielding requirements around the SHIP target for ultimate beam intensity. Note that the concrete shielding is needed in addition to the concrete tunnel walls.

It should be noted that the present study does not consider gaps or openings in the shielding. Necessary feed-throughs in the shielding for infrastructure systems like cooling and cabling will decrease the efficiency of the target shielding. Furthermore, the opening in the shielding upstream of the target has to be kept as small as possible to avoid streaming of radiation into the primary beam tunnel area. This particle 'back splash' will activate upstream beam line components and also the air in the proton beam tunnel. A hadron absorber downstream of the last primary beam tunnel element might be needed to shield the beam line elements and to reduce their activation.

Detailed FLUKA simulations and further environmental studies are required to finalise the shielding requirements.

8.4 Handling of the SHIP target

Handling of the SHIP target (in case of failure) and the shielding blocks have to be done remotely due to the very high residual dose rate of the items after beam stop. The residual dose rate levels on contact of the SHIP target (after one year of ultimate beam intensity and a cooling time of one month) will be ~10 Sv/h (see Figure 35) and will still be in the order of a Sv/h after one year of cooling time (see Figure 36). Thus, an exchange of a broken target will become an intervention with high radiological risks and further studies and optimisation of such an intervention are absolutely necessary.

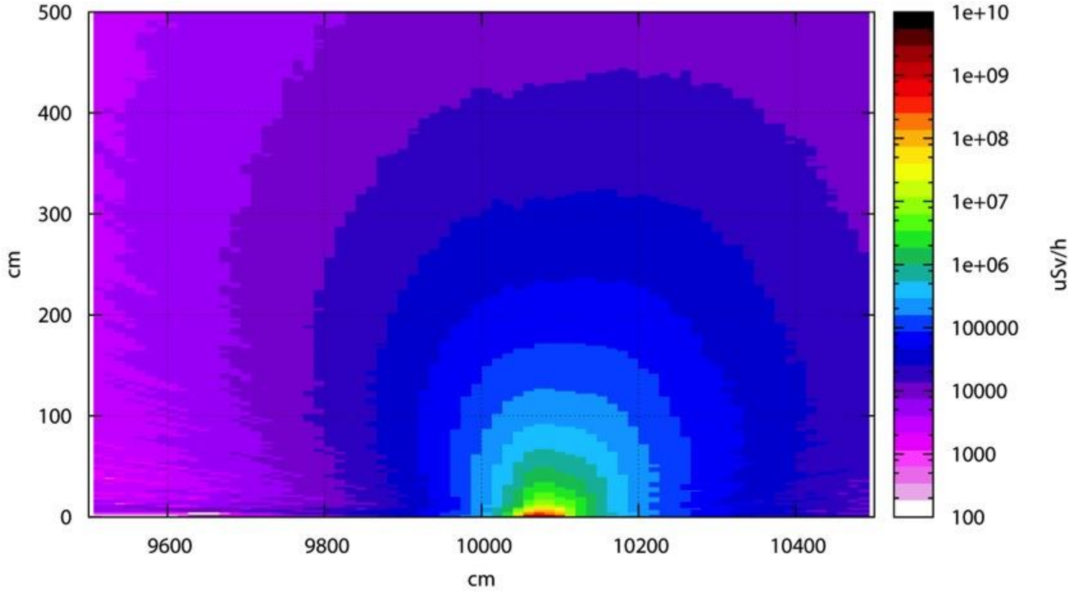

Figure 35: Residual dose rate (in μSv/h) around the dismantled SHIP target after one operational year at ultimate intensity and 1 month cool down time. The beam is impinging the target from the left; only the upper half is shown in the figure.

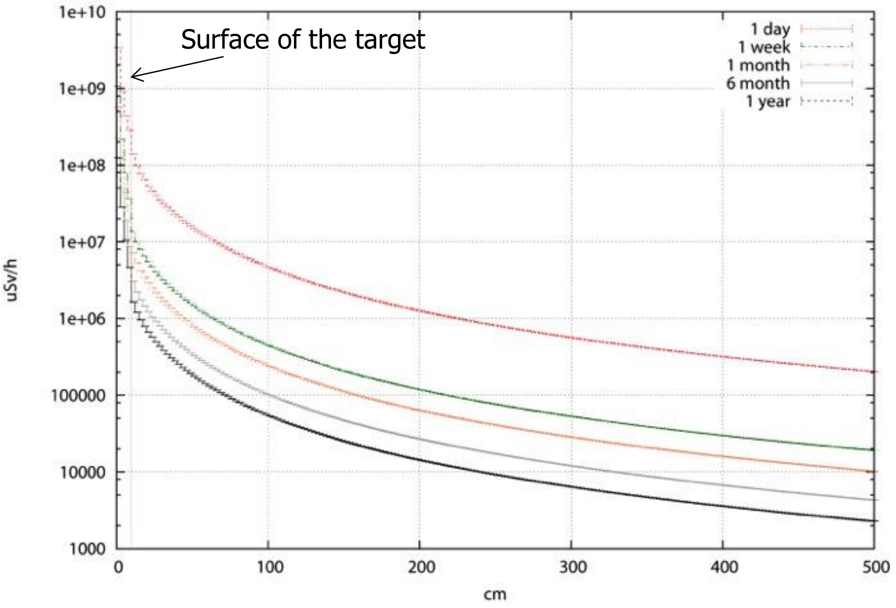

Figure 36: Residual dose rate (in μSv/h) of the unshielded SHIP target after one operational year and different cooling times as a function of radial distance from the target centre.

8.5 Muon shielding

The SHIP experiment requires a very low level of background in the detector acceptance. FLUKA simulations have been performed of the passive shield close to the configuration described in Section 3.2. The baseline muon filter (as shown in Figure 5) consists of a truncated tungsten cone of 40 m length surrounded by a heavy material (here lead) followed downstream by another 30m of heavy shielding material (here also lead), see Figure 37. With this shielding the muon flux downstream of the muon filter will be sufficiently low for the experiment (<1.0×10^4 muons/mm^2). However, the ambient dose equivalent rate outside the 'extended cone' will be ~10 μSv/h, see figure 38. This requires a radiological classification of the detector hall during beam operation as a Supervised or Simple Controlled Radiation Area.

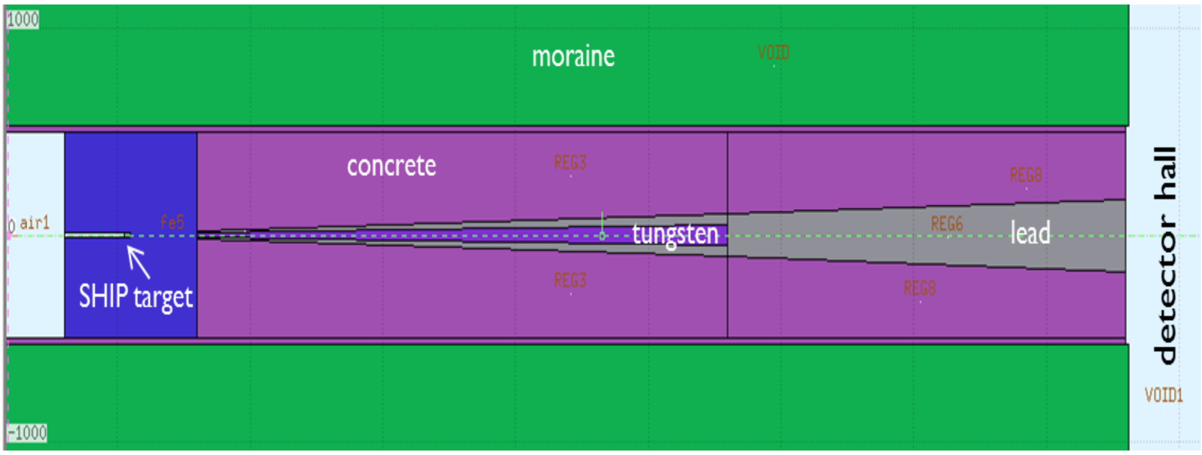

Figure 37: baseline design of the muon filter.

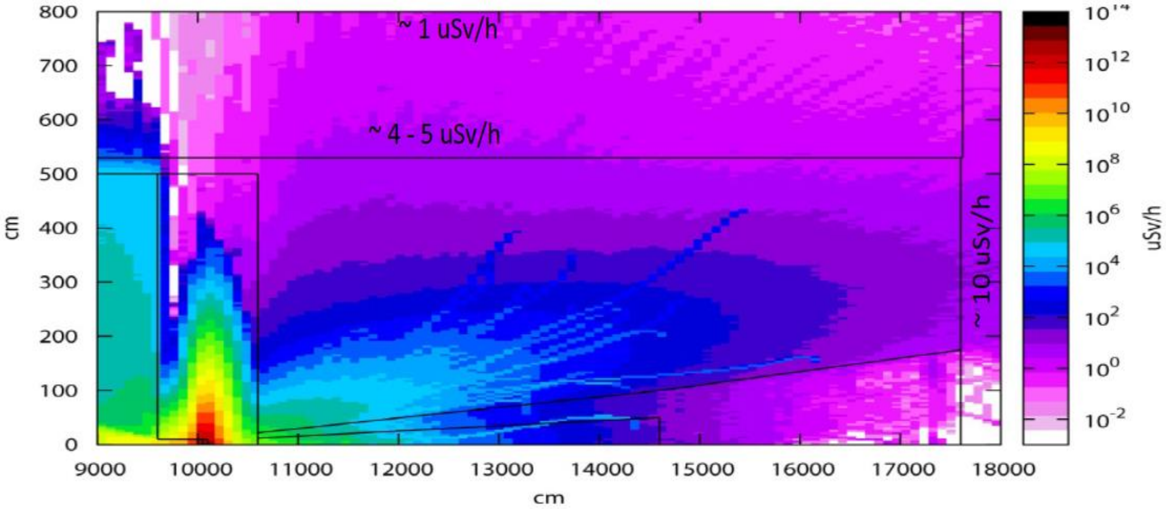

Figure 38: ambient dose equivalent in the muon absorber and in the detector hall. Only the upper half of the facility is shown.

The preliminary FLUKA calculations indicate that the upstream part of the muon absorber will be slightly activated. In addition to dose rate estimates, the use of such heavy Z material (like Pb, W, etc.) as shielding in areas with the risk of activation will also require an assessment in terms of specific activities (especially of nuclides emitting α-particles), contamination risks, waste disposal and also toxicological risks.

Consequently, it is strongly recommended to replace at least the lead shielding by iron keeping the same area density (g/cm^2) as used in the case of lead.

Accessible areas outside of the facility should be classified as Non-Designated Areas. The annual dose to people should not exceed 100 μSv on the CERN site. Members of the reference group of the public should not receive more than 10 μSv per year. These limits seem to be achievable with the present shielding and layout.

Additional RP studies (like production of radioactive waste, waste disposal, dismantling of the facility, etc.) and environmental issues (releases of radioactivity via air or water pathways, activation of soil, etc.) are not studied yet. This will however be needed at a later stage of the project.

9. Timeline and Resources

The time line is defined not only by technical and financial constraints, but also by the operating schedule of the CERN accelerator complex. The construction of the junction cavern with TDC2 and the transfer tunnel up to the SHIP target area, and the modification of the splitter region and installation of the proton beam line are critically linked to Long Shutdown 2. Construction work elsewhere may be performed during LHC Run 2 and Run 3 with the aim to start beam commissioning and operation of SHIP during Run 3, with the aim nominal operation in 2023. A preliminary timeline is shown in Figure 39.

A first and preliminary cost estimate is based on the conceptual design described in this document and is shown in Table 14. With the exception of civil engineering, this includes no contingencies. The infrastructure systems have been included as well, even though no detailed design is available everywhere. In some cases the sizing and cost is estimated based on similar installations built or studied at CERN.

The rough and very preliminary estimate of the CERN staff manpower is shown in Table 15. Also the cost of CERN fellows is shown for clarity, but in fact this cost is already included in the materials budget shown in Table 14. The assumptions used and the preliminary estimates are appended (unpolished, i.e. as received from the groups involved) at the end of this document.

The cost for the detectors is separate and is estimated to be of the order of 45 MCHF, including the tau neutrino detector.

Item	**Cost [MCHF]**
Extraction and proton beam line	19.9
Extraction upgrades, beam interlock	0.4
New MSSB splitter/switch magnets	4.2
Other magnets	1.6
Powering, including cables	6.0
Beam vacuum	3.0
Beam instrumentation	1.9
Beam interlocks	0.4
Other beam line costs	2.4
Target Station	17.1
Target (+spare) plus exchange system	4.6
Hadron absorber	8.1
Helium enclosure of target station	2.0
Removable shielding	0.5
Controls	0.9
Prototypes and testing	1.0
Muon filter	11.0
Muon shield, passive option, reusing 800 t of lead from OPERA	11.0
Civil Engineering	45.1
Junction cavern	5.0
Extraction tunnel	8.4
Target cavern	8.9
Muon filter tunnel	1.9
Experimental cavern	15.1
New access road	0.9
Site investigation	0.2
Studies	0.7
Contingency	4.0
Infrastructure	20.8
Cooling plants	4.9
Ventilation plants	5.1
Electrical infrastructure beam line zone	0.8
Electrical infrastructure target area and muon filter	1.4
Electrical infrastructure detector cavern	1.8
Access system beam lines, target and detector cavern	1.8
Safety systems	1.0
Radiation protection	1.5
Transport: cranes target station, detector cavern, shafts	1.9
Transport and handling	0.6
Total	**113.9**

Table 14: Material costs for the SHIP facility (excl. detectors), including the cost of fellows.

Item	**Staff FTE**	**Fellows MCHF**
Extraction and proton beam line	31.5	1.5
Extraction upgrades	1	0.1
New MSSB splitter/switch magnets	3	0.2
Other magnets	2	
Powering, including cables	12	
Beam vacuum	2	0.2
Beam instrumentation	4	0.4
Interlocks	1	
Other beam line costs	6.5	0.6
Target Station	35	1.6
Target (+spare) & exchange syst	35	0.6
Hadron absorber		0.6
Helium enclosure of target station		
Removable shielding		
Controls		0.4
Prototypes and testing		
Muon filter		
Muon shield, passive opt.,OPERA PB		
Civil Engineering	10	0.7
Junction cavern	10	0.7
Extraction tunnel		
Target cavern		
Muon filter tunnel		
Experimental cavern		
New access road		
Site investigation		
Infrastructure	14.4	1.2
Cooling plants	3.0	
Ventilation plants	2.0	
Electrical infrastructure	1.3	0.8
Access &safety beam lines+detector	1.5	
Safety systems	1.3	
Radiation protection	4.0	0.4
Transport : cranes, lifts, tooling	1.3	
Total	**90.9**	**5.0**

Table 15: Very preliminary manpower estimates for the SHIP project. Fellows are listed for information, but their cost is included in Table 14.

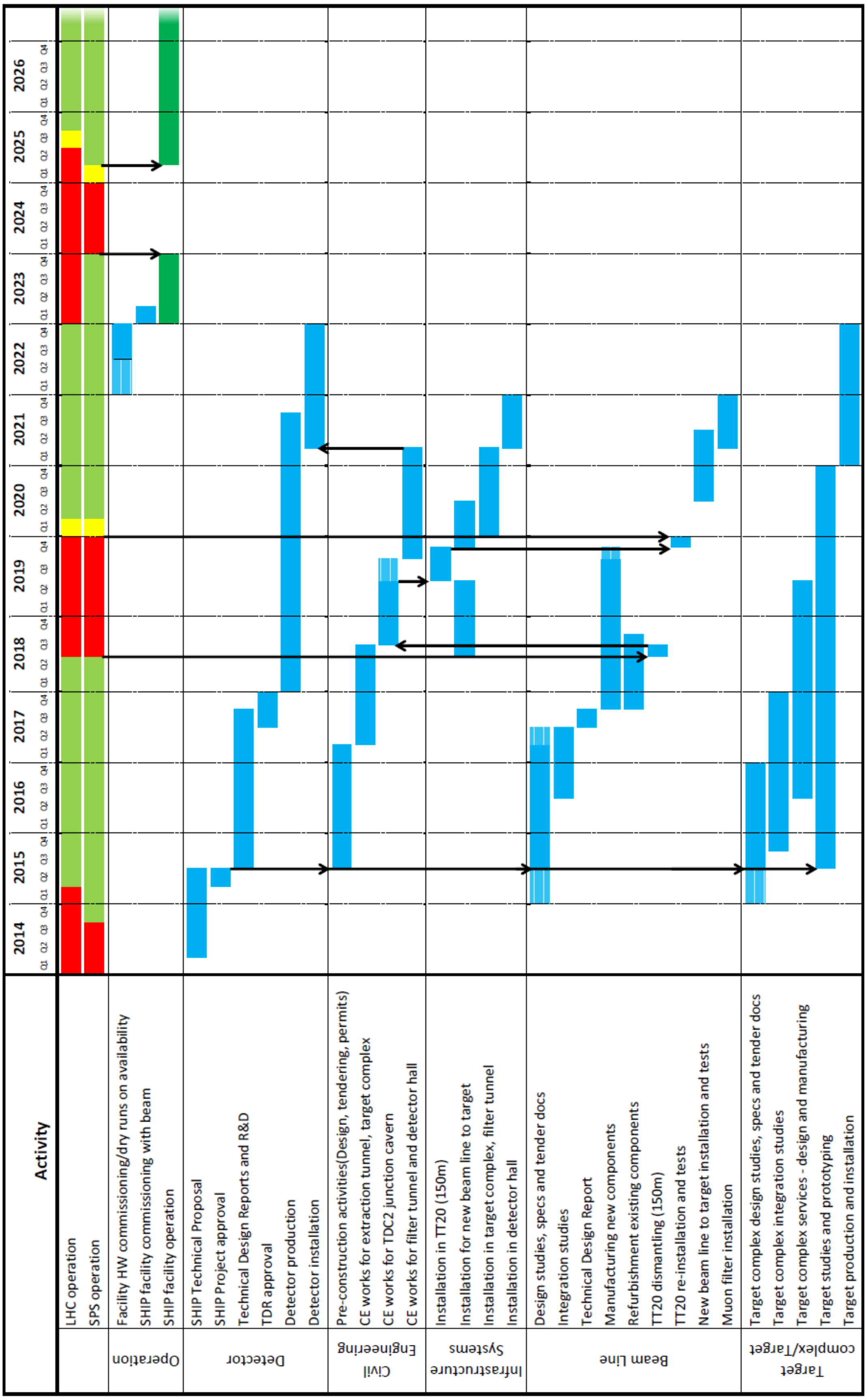

Figure 39: The timeline for the SHIP installation

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APPENDIX I

General RP guidelines

A few general guidelines (non-exhaustive) have to be followed in order to design and build a facility being compatible with CERN's radiation protection regulation: ALARA (optimization) starts already at the design phase

- The design of the entire facility must not only respect legal dose limits but must also satisfy the optimization principle (ALARA) with respect to individual and collective doses for workers and the public. The design goals for individual and collective doses are valid for commissioning, normal beam operation, maintenance and accidents.
- Use 'correct/good' materials with respect to activation - the ActiWiz material catalogue should be consulted [25].
- Install only absolutely necessary equipment in areas of high radiation levels. Equipment has to be able to withstand these high radiation levels.
- Minimize air volumes in areas of high levels of prompt radiation or even better use a Helium environment or vacuum environment.
- Complete separation of different air volumes, i.e. separate the air in the target area, from adjacent areas and outside; static (e.g., sealing of air volumes) and dynamic (e.g., leak extraction) air confinement are key elements.
- Pressure cascade (Onion Principle) is required, i.e. air pressure has to be lowest in the area with the highest radiological risk, higher in adjacent areas and highest outside of the facility.
- Treatment of air in the target area: a 'closed' ventilation circuit has to be used and HEPA filters have to be installed in the air handling units of this circuit. The air exhaust of the target area needs to be equipped with HEPA filters too and the air borne radioactivity released into the environment needs to be monitored.
- Separate closed cooling circuits for highly radioactive elements (like target and dump cooling) have to be foreseen.
- Water sumps in areas with high concentration of tritium have to be avoided. Don't install A/C ventilation units in areas with increased tritium concentration in air.
- Avoid installation of the facility in a 'wet' area. A hydrological study is a pre-requisite.
- Avoid activation and/or contamination of ground water and earth.
- Soil samples should be taken and analysed for their chemical and radiological composition (especially close to TDC2 and TCC2).
- Foresee remote maintenance/repair if residual dose rates are too high for manual interventions. Optimize any component such that maintenance time and repair needs are minimized.
- The design must consider aspects of radioactive waste disposal.

APPENDIX II

In Chapter 9 of this document a summary of resource estimates and a time line are given for the design and construction of the SHIP facility on the Prévessin site of CERN. The technical description of the facility is provided in the main document.

All cost and manpower estimates given are preliminary and there are some uncertainties. Cost estimates are in 2014 prices. They do not include contingencies, with the exception of the Civil Engineering cost.

The estimates are based on contributions from the different groups. However, in Table 14 infrastructure systems costs (electrical, cooling and ventilation, access and safety, handling and transport systems) are removed from the individual contributions for the beam line and target station teams and they show up under infrastructure systems costs and the estimates from the infrastructure system providers supersede the corresponding estimates by the accelerator teams. Industrial labour is included in the material cost. So are fellows, although they are marked for information and expressed in money (at 120 kCHF/year) in the manpower table. CERN manpower is expressed in FTE (= man-years).

The costs of the experiment have not evolved since the presentation of the detector costs to the SPSC referees in January, with the exception of the additional emulsion detector for tau neutrino physics. Therefore the detector cost has gone up from ~30 to 45 MCHF.

The individual contributions to the cost and resource estimates are given 'as received', i.e. without polishing and without modifications for consistency.

APP.II-1: EXTRACTION AND BEAM LINE (Source: B.Goddard)

Group	Item	Material, contracts , FSU [kCHF]	FELL, PJAS, ASS, TS, TTE, PHD, … [kCHF]	CERN staff manpower [MY]	BA space [m2]	New BA racks	Incl. cables?	Comment	kCHF/MY
TE/ABT	Upgrade ZS protection interlocking (sparks, vacuum)	250	120	1.0			Y	Development needed	250
TE/MPE	Beam Interlock System	300		0.5	5	1	Y	New BIC for new beamline, connection to LSS1	600
TE/MPE	FMCM	75		0.5	5	1	Y	4 units needed	150
TE/ABT	Beam dynamics, commissioning, coordination		300	3.0				Incl. 1 Fellow for 3 years	0
BE/BI	Instrumentation	1,500	400	4.0	9	3	Y	New position, profile, loss and current monitors.	375
EN/MEF	Integration, drawings and DBs	250		0.5				Design support	500
BE/OP	Operational software systems		100	1.0				new BQM system, SIS changes, CCC application SW modifications and additions	0
TE/MPE	Warm Magnet Interlocking	250		0.5	5	1	Y	For new beamline	500
TE/MSC	New MSSB++ switch splitters	4,000	200	3.0				Special technology and development needed	1333
TE/MSC	New dilution magnets (H+V+spares)	600		1.0			N	Large aperture, low inductance design similar to SPS.MPLH	600
TE/MSC	Other magnet refursbishment	600		0.5			N	10-12 MBBs or MBNs, 5-6 QNLs, 1 QSL, 6 MSDs	1200
EN/MME	Magnet supports and alignment targets	400		0.5				about 20 main magnets, 20 other elements	800
TE/MPC	Power converters and controls	4,000		10.0	120		N	Depending on detailed technical design	400
TE/VSC	Vacuum	2,000		2.0	15	6	Y	159 mm diameter, including temporary chambers in TT20	1000
GS/ASE	Access and safety systems	1,000		1.5	15	6	Y	Includes tunnel, surface building, fire, ODH etc. NOT target/secondary beam	667
EN/HE	Transport and handling	250		1.0				Incl. installation and new tooling, plus power rail	250
BE/ABP	Alignment in tunnel	250		0.5				TT20 and new beamline. Manpower available if activity is not in LS2	500
EN/EL	Magnet powering cables	2,000		2.0				Approx 50% of converter cost, agreeing with other projects	1000
EN/EL	Other cabling	500		0.5				Scaled from HiRadMat/CNGS (timing, ethernet, GSM, …)	1000
EN/CV	Water cooling	2,000		2.0				First estimate	1000
BE/CO	Controls and high level SW	100	200	1.0	5	1	Y	Includes logging, alarms, FESA classes, …	100
Total		**20,725**	**1,320**	**37.0**	**184**	**20**			**560**

Total **22,045**

Year	Material (kCHF)	Manpower (CERN FTE)
2015	0	3.5
2016	1543	7.0
2017	4850	7.0
2018	8157	7.0
2019	6393	7.0
2020	1102	3.5
2021	0	2.0

For the **power consumption** of the SHIP beamline TE/ABT provided the following information:

- water cooling 1.7 MW
- air cooling 75 kW

These estimates are based on 14 main dipoles, 7 main quadrupoles, 7 correctors and 2 dilution magnets.

It is assumed that only the main dipoles have water cooled cables - all the others have normal cables, which generates the heat the air cooling needs to evacuate.

They didn't take any margin nor include any other equipment, so maybe 2 MW water and 100 kW air would be minimum numbers, plus what you normally add as margin.

They also assumed all magnets are DC - in reality they may be cycled, which makes things better.

Electrical power	**1764 kW**
Water cooling	**1690 kW**
Air cooling	**74 kW**

Details in the table below for interest:

Circuit Name	Description	Nb of magnets in Series	R per Magnet (20° C) [mOhm]	L per magnet [mH]	Imax Magnet [A]	Imatching [A]	I max requested [A]	Mode DC or Cycling	Cable total length [m]	Irms I_Max x 0.58	Cable section Cu/Al [mm2]	Cable R Cu Al [mOhm]	Load R 45°C [mOhm]	Load L [mH]	Umax DC [V]	Number circuits	Circuit Power [kW]	Total Power [kW]	Water cooling power [kW]
MBN.2801xx	Main bends	14	61	170	1340	1200	1250	DC	400	1250	150	47	992	2380	1240	1	1549	1549	1549
MQ.28xxxx	Main quads	1	223	390	416	400	250	DC	300	250	100	53	304	390	76	7	19	133	98
MBD.28xxxx	Dilution bends	1	100	40	200	200	250	DC	200	250	100	36	149	40	37	2	9	19	13
MDX.26xxx	Correctors	1	300	221	240	100	120	DC	300	120	20	267	624	221	75	7	9	63	30

App.II-2: Target station and Hadron absorber (source M.Calviani)

Target, hadron absorber and target station	**MCHF**
Target head + spare	3.5
Target exchange system	0.5
Target cooling system *(400 kW)*	2.0
Hadron absorber + radiation shielding, iron blocks, (500 m^3, density 7.2),15 kCHF/m^3	7.5
Hadron absorber cooling system *(100 kW)*	1.0
Helium atmosphere system and tank	2.0
Concrete removable shielding - 1 kCHF/m^3 (400 m^3 + cont.)	0.5
Ventilation system	2.0
Access and safety system	0.5
Radiation protection system	1.0
General safety systems (fire detection, ODH, emergency stops, signs, etc)	0.5
Overhead crane and backup crane + special lifting tools	1.2
Electrical infrastructure	0.4
Controls	0.5
Prototype and testing	1.0
Total	**24.1**

Considering the budget of the order of 20 MCHF for the whole target station area (excluding the civil engineering part), EN/STI thinks that about 35 FTE will be required for the design and construction of the production target as well as of the target station area with services (CE excluded).

At this stage they are in a position to be more precise on both aspects (e.g. sharing between staff/ fellows/PJ and technical infrastructures).

APP.II-3: CIVIL ENGINEERING (Source: J.Osborne)

Work Package	Ref	Detail	Partial Cost (CHF)	Total Cost (CHF)	Notes
1. CIVIL ENGINEERING **JUNCTION CAVERN**	1.1	Excavations between DW	382,500		**1.1:** An average value of 15m has been considered for the JC width; **1.3:** 1:1 slope for excavations outside DW; **1.5:** Excavation+RC structure; **1.6:** 50cm concrete walls thick, 60cm concrete slabs thick.
	1.2	Refilling between DW	223,125		
	1.3	Excavations outside DW	8,500		
	1.4	Refilling outside DW	8,500		
	1.5	Diaphragm Walls (DW) *-2 walls-*	1,785,000		
	1.6	Junction Cavern *(in m3 of concrete)*	1,593,113		
	1.7	Demolition existing tunnel	500,000		
	1.8	Engineering studies and PM	540,089		
				5,040,826	**(CHF)**
2. CIVIL ENGINEERING **EXTRACTION TUNNEL**	2.1	Excavations between DW	297,500		**2.3:** 1:1 slope for excavations outside DW; **2.6:** Cross section, 4m(H) by 4m(W), 35cm concrete walls thick, 50/60cm concrete slabs thick; **2.7:** Open-Cut to one side, while DW on the other; **2.9:** Cross section, 8m(L) by 5m(W), 50cm concrete walls thick, 50cm foundation slab; **2.13:** Cross section, 2m(H) by 2m(W), 35cm concrete walls thick, 50cm concrete slabs thick.
	2.2	Refilling between DW	191,250		
	2.3	Excavations outside DW	17,000		
	2.4	Refilling outside DW	17,000		
	2.5	Diaphragm Walls (DW) *- 2 walls-*	3,808,000		
	2.6	Extraction Tunnel *(in m3 of concrete)*	1,151,665		
	2.7	Excavations "O-C" around shaft	33,000		
	2.8	Refilling "O-C" around shaft	15,000		
	2.9	Shaft *(in m3 of concrete)*	141,950		
	2.10	Access Surface building *(in m2)*	675,000		
	2.11	Auxillary Power Supply building *(in m2)*	300,000		
	2.12	1 x Main door	150,000		
	2.13	Bypass tunnel *(in m3 of concrete)*	113,475		
	2.14	Crane main rails and support	100,000		
	2.15	Trenches for services, Landscaping, Car Park	450,000		
	2.16	Engineering studies and PM	895,301		
				8,356,141	**(CHF)**
3. CIVIL ENGINEERING **TARGET AREA**	3.1	Excavations between DW	121,875		**3.3:** 1:1 slope for excavations outside DW; **3.6:** TB_Cross section, 5m(H) by 8.5m(W), 200cm concrete walls thick, 300cm concrete slab thick // FT(I part)_Cross section, 5m(H) by 8m(W), 150cm concrete walls thick, 300cm concrete slab thick; **3.7:** CV_Cross section, 15m(L) by 7.5m(W), 50cm concrete walls thick, 50cm foundation slab // CS_Cross section, 5m(L) by 5m(W), 50cm concrete walls thick, 50cm foundation slab; **3.8:** 2 times the volume of CV&CS has been cosidered; **3.15:** TG_Cross section (same as GT801 along r. Gentner), 2.5m(H) by 2.5m(W), 30cm concrete walls thick, 30cm concrete slabs thick.
	3.2	Refilling between DW	0		
	3.3	Excavations outside DW	3,000		
	3.4	Refilling outside DW	3,000		
	3.5	Diaphragm Walls (DW) *- 2 walls-*	672,000		
	3.6	Target Bunker + Filter tunnel (I part) *(in m3 of concrete)*	1,729,750		
	3.7	CV room and Cask Storage *(in m3 of concrete)*	425,000		
	3.8	Excavations "O-C" around CV&CS	103,200		
	3.9	Refilling "O-C" around CV&CS	51,600		
	3.10	Target Surface building *(in m2)*	2,280,000		
	3.11	Service Surface building *(in m2)*	1,125,000		
	3.12	Crane main rails and support	200,000		
	3.13	Excavations "O-C" for new TG	112,000		
	3.14	Refilling "O-C" for new TG	80,500		
	3.15	Technical Gallery to Electrical Bld. *(in m3 of concrete)*	399,840		
	3.16	1 x Main door	150,000		
	3.17	Fast water drain system	200,000		
	3.18	Trenches for services, Landscaping, Car Park	300,000		
	3.19	Engineering studies and PM	954,812		
				8,911,577	**(CHF)**

4. CIVIL ENGINEERING **MUON FILTER TUNNEL**	4.1	Excavations between DW	90,000		**<u>4.3:</u>** 1:1 slope for excavations outside DW; **<u>4.6:</u>** Cross section, 5m(H) by 5m(W), 50cm concrete walls thick, 60cm concrete slabs thick.
	4.2	Refilling between DW	52,500		
	4.3	Excavations outside DW	5,000		
	4.4	Refilling outside DW	5,000		
	4.5	Diaphragm Walls (DW) *-2 walls-*	1,050,000		
	4.6	Muon Filter Tunnel *(in m3 of concrete)*	518,500		
	4.7	Engineering studies and PM	206,520		
				1,927,520	**(CHF)**
5. CIVIL ENGINEERING **DETECTOR FACILITY**	5.1	Excavations between DW	1,134,000		**<u>5.3:</u>** 1:1 slope for excavations outside DW; **<u>5.6:</u>** Cross section, 14.5m(H) by 20m(W), 50cm concrete walls thick, 50cm concrete slabs thick.
	5.2	Refilling between DW	189,000		
	5.3	Excavations outside DW	12,000		
	5.4	Refilling outside DW	12,000		
	5.5	Diaphragm Walls (DW) *-2 walls-*	3,528,000		
	5.6	Detector Hall *(in m3 of concrete)*	4,692,000		
	5.7	Crane main rails and support	600,000		
	5.8	Service Surface building *(in m2)*	2,400,000		
	5.9	Crane main rails and support	200,000		
	5.10	1 x Main door	150,000		
	5.11	Trenches for services, Landscaping, Car Park	525,000		
	5.12	Engineering studies and PM	1,613,040		
				15,055,040	**(CHF)**
6. NEW ACCESS ROAD	6.1	Route du Jura deviation + new access *-7m Wide-*	875,000		
7. SITE INVESTIGATION			250,000		
			SUB-TOTAL:	**40,416,104**	**(CHF)**
			+10% on contingency for unkown/missing items:	**4,041,610**	**(CHF)**
			GRAN TOTAL:	**44,457,714**	**(CHF)**

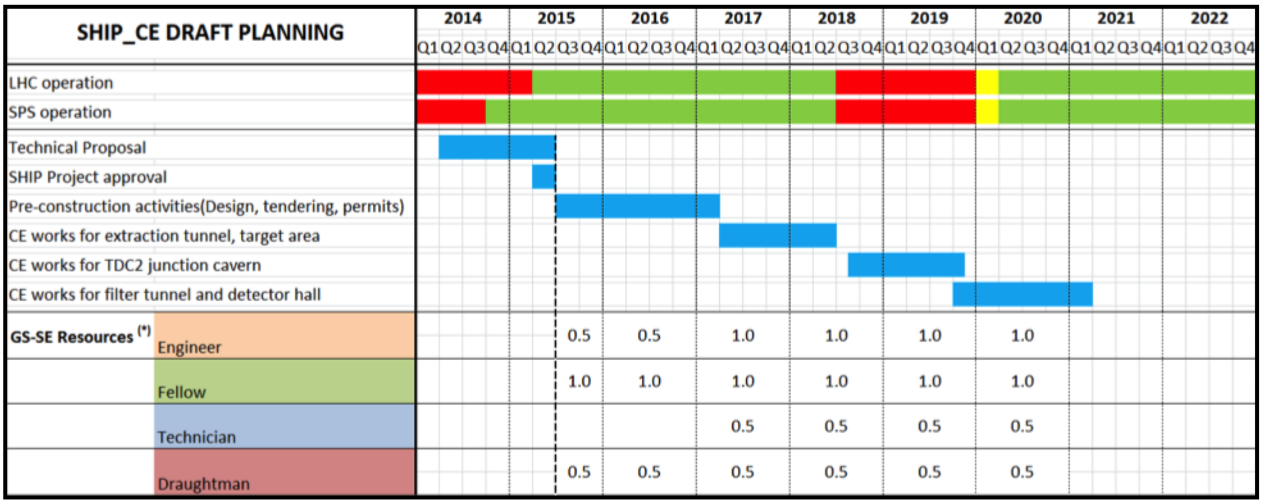
<u>Assumptions:</u>

- **Estimate Accuracy: ± 30%**
- **GS-SE Resources not included**
- Earthworks assume stockpiling on CERN site and no special treatment required for radiation
- Instrumentation for ground stability monitoring not included
- Special foundation support for facilities (e.g. Detector, etc) not included
- Shielding precast concrete blocks not included
- Services not included (ventilation, electricity, etc)

The cost estimate for the SHIP Project is based on the layouts presented in the WG report. The estimate includes all aspects of construction, final engineering designs and construction management. Many of the rates used to formulate this estimate will be based on real construction costs from LHC experience (1998-2005).

The total cost for each Work Package obtained taking into account the main works activities related is shown in Table 14 of the main document.

Estimated resources for the civil engineering studies/works for the SHIP Project are shown below:



SHIP_CE DRAFT PLANNING		2014	2015	2016	2017	2018	2019	2020	2021	2022
GS-SE Resources (*)	Engineer		0.5	0.5	1.0	1.0	1.0	1.0		
	Fellow		1.0	1.0	1.0	1.0	1.0	1.0		
	Technician				0.5	0.5	0.5	0.5		
	Draughtman		0.5	0.5	0.5	0.5	0.5	0.5		

(*) *The resources given in this table are over and above the existing resources currently in GS-SE Group*

App.II-4: Cooling and Ventilation infrastructure (Source: M.Nonis)

Please find hereunder a rough estimate of the cost for CV plants for SHIP, made on the basis of the information received and the short time available to make the work.

Cooling plants:

- Total cost: 4’900 kCHF
- Manpower: 2 FTE (CP E) + 1 FTE (CP C) (other supervision and drawing work is included in the material cost).
- Remarks:
    - Standard solution for cooling: deltaT 10 °C, 25 °C inlet, redundancy….
    - Inlet pressure and delta p not known.
    - Cooling tower: additional cell to bldg 893, cooling power around 8 MW, not in concrete as the other ones
    - Civil engineering costs (trenches for piping, slabs, passages through walls etc.) not included
    - routing of piping to be checked.
    - circuit target: delta T by 10 °C tbc; to control very low level of conductivity →100% flow through cartridges and more powerful pump ,therefore additional cost (100+20 kCHF?)
    - circuit target: if degasing for all flow +100 kCHF (very preliminary estimate, not possible to know until a layout will exist)
- Tolerance: ± 30%

Ventilation plants :

- Total cost : 5'100 kCHF
- Manpower : 2 FTE (CP E + 1 FTE (CP C) (other supervision and drawing work is included in the material cost).
- Remarks :
    - The ventilation of the target complex is based on the input received for the CENF study
    - It is supposed that the thermal load in the Junction cavern does not require a dedicated ventilation but the one existing at present is sufficient.
    - No control on humidity foreseen.
    - Ambient conditions: similar to industrial halls
    - Routing of ducts needs to be verified when further details on the premises will be available.
    - Civil engineering costs for CV plants not included.

General remark:

- It is not possible to define the needed surface for the CV plants or, whether the allocated areas are sufficient.
- Layout of the cooling and ventilation stations not defined, to be detailed further.

App.II-5: Electrical infrastructure costs (Source: F.Duval)

SHIP Experiment - Electrical power supply description:

The following electrical power supply configuration is proposed for the SHIP experiment and associated infrastructure.

- Creation of a new HV Electrical substation within the main service building to supply new stable and pulsed loads associated with the experiment.
- Installation of new 18kV/0.4kV cast resin transformers to supply power converter, experiment and general services loads
- Dual redundant UPS to be located within the Target Hall Service Building, serving the whole facility
- Installation of EL SCADA monitoring equipment to supervise the new infrastructure.
- Installation of AUG buttons within each of the buildings as a pre-requisite for safe operation of the facility.
- Electrical containment, normal lighting, emergency lighting and power distribution to new underground areas and technical galleries
- Dedicated 48V DC system to supply new electrical infrastructure.
- Future extension of the secure power network on the Prevessin site to provide power for critical process and life safety requirements within the new complex.

The electrical distribution as proposed will require the creation of a trench linking all three proposed buildings to allow the distribution of electrical power and control cables away from radioactive areas within the tunnel.

Access Building

Power converter loads will be supplied from the pulsed network via two 18kV/0.4kV transformers, connected to two dedicated Type 4 electrical switchboards. Low voltage general services will be supplied from a low voltage cable feed from the Target Hall Service Building, supplying a Type 2 electrical distribution board. A low voltage interconnect will be provided to the pulsed network to re-supply of general services in a reduced power mode during maintenance of the transformer in the service building or an extended network failure. Equipment supplied from the general services distribution within the Access Building will include:

- Gantry crane
- Cooling and ventilation supplies
- Auxiliary supplies for power converters
- General lighting and small power for the surface building
- General lighting and small power for the extraction tunnel

A low voltage feed from the secure power network will be provided to supply life safety loads, derived from a 3.3kV/0.4kV transformer located external to the main service building. A Type 3 electrical switchboard will be located external to the access building, consistent with the philosophy for life safety power distribution as employed throughout the SPS complex.

Target Hall and Service Building

The access building will contain a new high voltage substation for the distribution of pulsed and stable power to the SHIP experimental complex. Two 18kV switchboards will provide high voltage Pulsed and Stable distribution to the Access Building, the Target Hall and Service Building and the Experimental Zone. The new high voltage switchboards shall be located within a dedicated room and shall include 25% spare capacity for future expansion, with 2 spare circuit breakers provided for each network. The electrical substation will include a dedicated 48V DC distribution system to support the experiment and an EL SCADA data acquisition rack to allow the supervision of all electrical equipment installed within the complex.
Low voltage general services will be supplied by an 18kV/0.4kV transformer situated externally to the Service Building, with a Type 1 electrical distribution board located within the building for distribution. A low voltage interconnect will be provided to the Access Building to supply general services power for normal operation. Equipment within the Target hall and Service Building supplied from the general services distribution will include:

- Gantry crane
- Cooling and ventilation supplies
- General lighting and small power for the surface building
- General lighting and small power for the underground target areas
- Dual redundant 20kVA UPS installed to provide power to sensitive loads (Fire detection equipment, PLC’s, IT Star Points etc.)

A low voltage feed from the secure power network will be provided from a pre-fabricated electrical substation including a 3.3k/0.4kV transformer and a Type 2 electrical switchboard. This substation will supply secure power to Type 3 Switchboards located outside the Access Building, the Target hall and Service Building and the Experimental zone via low voltage cables, in a manner consistent with the philosophy for life safety power distribution as employed throughout the SPS complex.
Emergency lighting for all areas of the new infrastructure will be provided by dual redundant AES units supplied from the secure power network at low voltage, with fire resistant cable distribution throughout the surface and underground areas.

Experimental Zone

Power converter loads for experiment magnets will be supplied from the pulsed network via two 18kV/0.4kV transformers, connected to two dedicated Type 4 electrical switchboards. The experimental zone will be supplied from two 18kV/0.4kV transformers, one dedicated to general services provision and another reserved for experimental loads.
Low voltage general services will be supplied by an 18kV/0.4kV transformer situated externally to the Experimental Zone, with a Type 1 electrical distribution board located within the building for distribution. A low voltage interconnect will be provided to the experiment distribution to allow the re-supply of general services in a reduced power mode during transformer maintenance. Equipment supplied from the general services distribution within the access building will include:

- Gantry crane
- Cooling and ventilation supplies
- General lighting and small power for the surface building
- General lighting and small power for the extraction tunnel

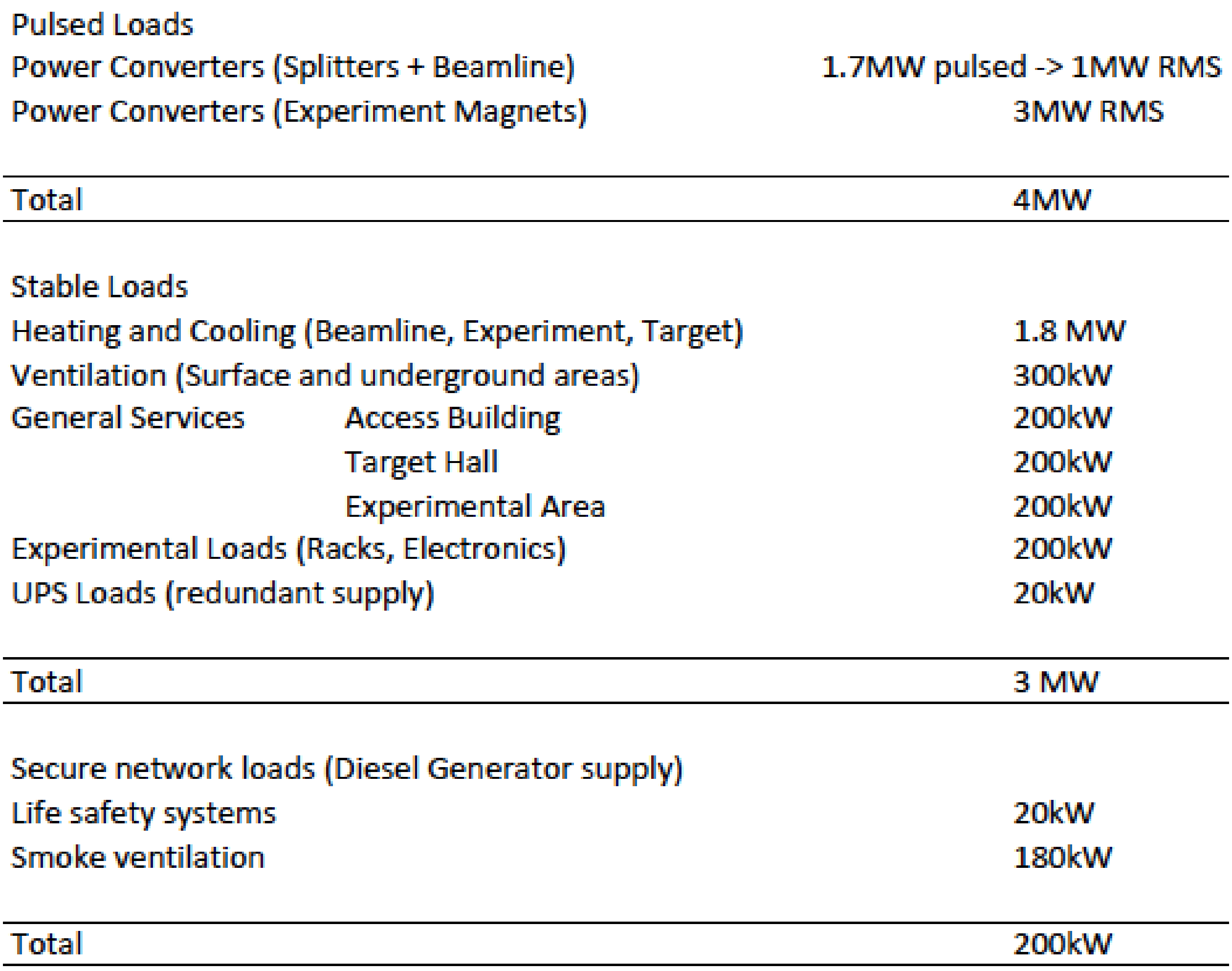
Experimental loads (Racks, detector electronics etc.) will be supplied from dedicated Type 1 and Type 2 distribution boards located within the experimental zone surface access building.

A low voltage feed from the secure power network will be provided from the Service Building to a Type 3 electrical switchboard will be located external to the Experimental Zone.

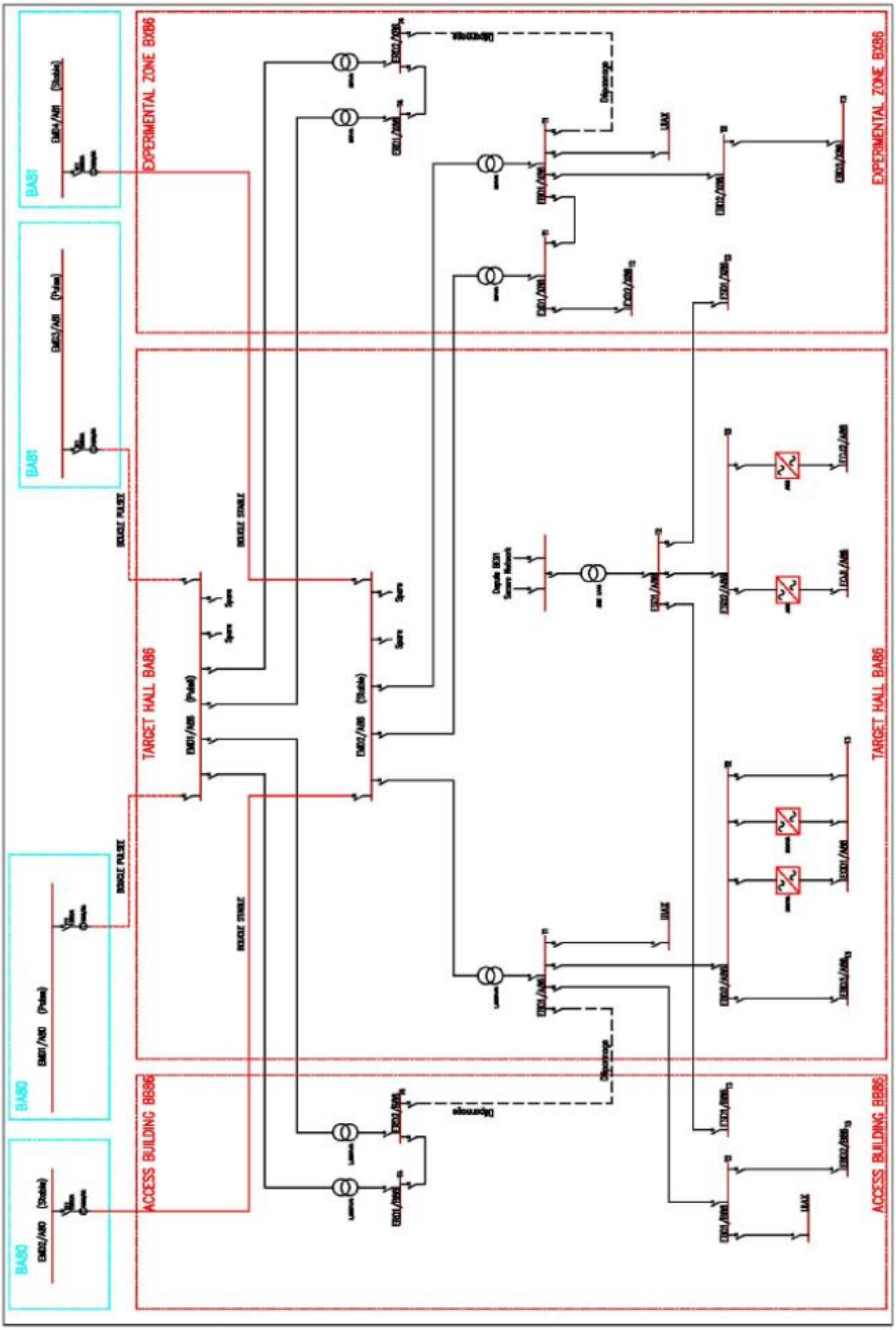
Basis for design

This outline description, single line diagram and electrical budget are based on the draft information for the project available at the time of writing. Changes to the scale and scope of the project will have implications for the provision of electrical infrastructure. Approximately 100m of additional trenches will be required to permit the installation of the electrical infrastructure as described, not currently included in the civil engineering proposals.

SHIP Experiment: Load schedule **5/23/14**



Pulsed Loads		
Power Converters (Splitters + Beamline)		1.7MW pulsed -> 1MW RMS
Power Converters (Experiment Magnets)		3MW RMS
Total		4MW
Stable Loads		
Heating and Cooling (Beamline, Experiment, Target)		1.8 MW
Ventilation (Surface and underground areas)		300kW
General Services	Access Building	200kW
	Target Hall	200kW
	Experimental Area	200kW
Experimental Loads (Racks, Electronics)		200kW
UPS Loads (redundant supply)		20kW
Total		3 MW
Secure network loads (Diesel Generator supply)		
Life safety systems		20kW
Smoke ventilation		180kW
Total		200kW


EXPERIMENTAL ZONE BX86
TARGET HALL BA86
ACCESS BUILDING BB86
BA81
BA80
BOUCLE PULSE
BOUCLE STABLE
Spare
UAX

APP.II-6: Access system costs (Source: P.Ninin)

Please find below a draft cost estimate for the SHIP Experiment.

SHIP (Search for HIdden Particles) is a new fixed-target experiment that should be connected to the SPS to search for Heavy Neutral Leptons and other hidden very weakly interacting particles.

Time-line: 2015-2017: R&D, civil engineering; LS2: connection of extraction line to the SPS; starting detector installation, >2020 fist beam; >2023 data taking.

The facility is made of:

- a primary area that should be connected after the TT20 at the TDC2 level . It will consist of a junction cavern (85m), an extraction tunnel (170m) served by an access building, delivering beam to a Target Hall (40m*20m) equipped also with an access point, the particle continue in a "Filter tunnel". No door between the Target Hall and Filter Tunnel.
- a secondary area : a 150m* 20m Detector facility is located at the end of the Filter tunnel. From the drawing we see only one single access point for the underground and Detector Hall.

Main risks: radiation, the levels that are necessary to determine the Safety Integrity Level of the facility will be given by a Fluka simulation done at a later stage.

Determining also the border between the primary and the secondary areas.

<u>Proposed Personnel Protection System:</u>

Redundant safety system (path A: PLC based, Path B hardwired logic), compliant with the Regulatory body requirements (INB, OFSP).

Patrol mechanism, safety token, interface with ventilation, evacuation system.

Public Address,

3 complete access points, 10 EIS access, search boxes,

Access Point made of a Personnel Access Device, Material Access Device, Mini-MAD, Biometry check, Single Passage Check, Emergency door.

Remote monitoring from CCC; local monitoring and key delivery from Detector control room.

A global estimate is given according to the cost of the Personnel Protection System of recent similar size facilities, it covers the 3 zones and includes power supplies, cabling and the optical fibres cabinets.

As one system covers the functionalities of the primary area and the Detector Hall, one single quote is given.

Man Power: 1.5 Man/year

Remarks:

Cost are given according to the 2014 price market.
The estimation may vary according to the results of the preliminary risk analysis
The system will be part of the new SPS access system

CTF Complex	**Cost (kCHF)**
Access and safety system	1’050
Civil Engineering/grids	100
Door	100
Power Supplies	120
Cabling	330
Optical fibers cabinets	40
Contingency	200
Total	
Grand Total	**1’940**

App.II-7: Safety systems other than access

Ci dessous les estimations en KCHF et Man/Month qui avait été faite pour le projet SBLNF (CENF) pour les autres systèmes de sûreté, pas aussi cher que l'accès mais malgré tout environ 1 MCHF et 16 Man/Month.

Item			**Cost (kCHF)**	**Man-Months**
SUSI + video			150	2
Evacuation			150	2
SIP panel			10	1
BIW			150	2
ODH	2.0	60	160	3
Fire detection			250	3
Red telephone			50	1
Upgrade CSAM / MMD			30	2
Total			**950**	**16**

App.II-8: Transport and Handling (Source: R.Rinaldesi, I.Ruehl)

Please find below a table with the cost estimation for handling needs in the SHIP project. The FTE item covers CERN staff engagement for technical specification, contract management and installation follow-up.

We agreed that an additional 5 ton overhead crane (crane n.4) could be useful for the installation activities inside the filter tunnel; as you can see it doesn't increase sensibly the total cost, so I guess it's wise to leave it in for the moment.

SHIP - HANDLING COST ESTIMATIONS			
Overhead crane 1			
	capacity	40 ton	
	span	20 m	
	lifting height	24 m	
	rails length	30 m	
			550,000 CHF
Overhead crane 2			
	capacity	40 ton	
	span	10 m	
	lifting height	20 m	
	rails length	120 m	
			260,000 CHF
Overhead crane 3			
	capacity	40 ton	
	span	20 m	
	lifting height	25 m	
	rails length	30 m	
			280,000 CHF
Overhead crane 4			
	capacity	5 ton	
	span	5 m	
	lifting height	5 m	
	rails length	50 m	
			75,000 CHF
Lift			
	capacity	2.1 ton	
	n. of people	26	
	height	14 m	
	cabin width	2 m	
	cabin length	2 m	
			300,000 CHF
Auxiliary lifting equipment (special spreaders, slings...)			
			250,000 CHF
Remote shielding blocks handling system			
			200,000 CHF
Design and integration studies			
			50,000 CHF
Transport and handling service			
			560,000 CHF

TOTAL	2,525,000 CHF
FTE CERN	15 man month