The SHiP Facility

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On behalf of the SHiP Task Force
OUTLINE

• The requirements for SHiP
• The challenges
• Introduction to the facility
• Extraction and beam transport
• The target and target station
• The active muon shield
• The detector hall and detector implementation
• Civil engineering
• Radiation protection issues
• The impact on the SPS fixed target program
• R&D studies and Machine Developments
• Planning
• Outlook
THE SHiP REQUIREMENTS

• High-intensity proton beam: $4 \times 10^{13}$ ppp, $4 \times 10^{19}$ pot/yr
• Slow extraction to minimise pile-up (~1 sec flat top)
• $O(400 \text{ GeV})$ is optimal beam momentum
• Minimal impact on running North Area program
• Dense target to stop $\pi$ and K before they decay into $\mu+\nu$
• Effective muon shield
• Long evacuated decay volume to minimise interactions
• Effective veto system to reduce background

SHiP includes a new permanent facility for the North Area with unprecedented beam intensities for the NA
THE CHALLENGES

• High radiation doses
  Injectors, extraction, target, …
• Radiation damage
  Extraction septa, target and target station,
• Good compatibility with North Area operation
• Target design for survival
• Reliability and efficiency to be maintained
• Mitigation of muon and neutrino backgrounds
• Planning
  Partial dismantling of TDC2, radioactive concrete
• Cost containment
INTRODUCTION TO THE FACILITY

- Slow extraction into TT20 channel using existing septa
- Replace splitter 1 by laminated splitter/switch magnets
- Beam for SHiP is deflected towards Jura side by new splitter/switch magnets and 17 MBB magnets
- The beam exits from TDC2 via a junction cavern into the extraction tunnel
- The extraction tunnel: long to allow beam size to grow as well as getting away from the existing facilities (TCC2)
- Target cavern houses Mo+W target, water-cooled, followed by 5 m of iron (hadron stop)
- Active muon shield
- The detector cavern houses decay volume and detectors
Section 6:
EXTRACTION AND BEAM TRANSPORT

- Use slow extraction scheme as for NA, but 1 sec flat top
- SHiP cycle length is 7.2 s (note: CNGS cycle was 6 s)
- Momentum 5-10 GeV/c different from 400 GeV/c (safety interlock)
- $4 \times 10^{13}$ ppp is historical maximum for slow extraction: Unavoidable losses on septum concentrated in 1 second!
  Expect $4 \times 10^{11}$ protons per spill to hit wires: $T \rightarrow 800^\circ C$
  (operational limit is 1000$^\circ$C)

Conditioning may take up to a week.

SHiP operation doubles max. beam power so far: sparking!

Repairs may take long cool down times.

This requires some Machine Developments

Overall within reach, but requires more interlocking, diagnostics, surveillance, trending, long-term control.

Anyway good in general (ALARA)
ZS ELECTRISTIC SEPTUM:

- insulated anode support
- reference rods
- wires
- clearing electrodes
- cathode
Higher extraction losses → higher dose levels

Comparisons have been made with e.g. WANF and LSS2 extraction so far. Slow is better than fast-slow!
• Three new laminated splitters (small beam here for SHiP)
• 17 MBB magnets running at 1.73 T (8 mrad each)
OPTICS IN TT20

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Splitter magnets

Polarity to be switched between T6 and SHiP operation

Larger horizontal gap

R&D should start at least 2.5 years before installation date
Archimedean spiral

To protect the target: 5 spiral turns in 1 sec, i.e. sweep speed of 0.65 m/s
TARGET AND TARGET STATION

• The target must be as dense as possible
• This ensures that $\pi$ and $K$ are stopped before they decay and produce $\nu_e$, $\nu_\mu$ and muons
• Charm particles decay before being stopped and produce HNL (and others) as well as $\nu_\tau$
• However the high density leads to extremely high energy deposit per unit of volume, hence strong heating
• Hence the need of a cooling system (Tritium!)
• There are also issues with material damage due to atom displacement
• Beam power is 355 kW, over 1 sec spill up to 2.56 MW
## The target itself

### Hybrid solution:
- Molybdenum alloy TZM
- Pure tungsten

### Total length 116 cm
- Transverse size 30x30 cm²
- $4\lambda$ of TZM + $6\lambda$ of W

### Table: Target Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DONUT ¹)</th>
<th>CHARM ²)</th>
<th>SHiP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target material</td>
<td>W-alloy</td>
<td>Cu (variable (\rho))</td>
<td>TZM + pure W</td>
</tr>
<tr>
<td>Momentum (GeV/c)</td>
<td>800</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Intensity</td>
<td>$0.8\times10^{13}$</td>
<td>$1.3\times10^{13}$</td>
<td>$4\times10^{13}$</td>
</tr>
<tr>
<td>Pulse length (s)</td>
<td>20</td>
<td>$23\times10^{-5}$</td>
<td>1</td>
</tr>
<tr>
<td>Rep. rate (s)</td>
<td>60</td>
<td>~10</td>
<td>7.2</td>
</tr>
<tr>
<td>Beam energy (kJ)</td>
<td>1020</td>
<td>830</td>
<td>2560</td>
</tr>
<tr>
<td>Avg. beam power (spill) (kW)</td>
<td>51</td>
<td>$3.4\times10^7$ (fast)</td>
<td>2560</td>
</tr>
<tr>
<td>Avg. beam power (SC) (kW)</td>
<td>17</td>
<td>69</td>
<td>355</td>
</tr>
<tr>
<td>POT</td>
<td>Few $10^{17}$</td>
<td>Few $10^{16}$</td>
<td>$2\times10^{20}$</td>
</tr>
</tbody>
</table>
Energy deposition

Energy deposition, $Y = [-1:1]$ cm, $I = 4e13$ proton/pulse

Max. energy deposition, $I = 4e13$ proton/pulse

TZM  W
The target core is contained in a double walled stainless steel container. The first containment is filled with He gas.
Displacement Per Atom (DPA)

May lead to significant bulk damage, e.g. change of yield strength

R & D
Dose around the Ship target

Yearly dose at 10 cm around target is 400 MGy

For $2 \times 10^{20}$ pot
Max. temperatures in blocks 9 (TZM) and 14 (W) Reached after 5 SPS cycles Compressive stresses seem not too severe If sweep fails, T rises up to 1400 °C (risk of fracture, solved by interlocking, no melting)
The Target Complex

- Design profits from studies done for CENF
- Target is located underground, with surface hall 15 m above
- Target building includes first 15 m of muon shield
- Cast-iron hadron absorber encloses production target
  - The first layer is water cooled (embedded stainless steel pipes), the outer layers are passive blocks.
  - The total volume is 18+440 m$^3$
- Target and hadron absorber are inside helium vessel
Section 8:

Target Hall, 40m long

Service Bld., 25m long

Technical Gallery

TT81

TT82

TT83

DW

CERN

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Required R&D for target

- Analysis of assembly, configuration and fabricability of cladded blocks
- Material R&D on TZM and W
- Study feasibility of water-cooled cast iron blocks with embedded steel pipes
- Develop full-metal plug-in systems
- Develop design of helium gas cooled target as possible alternative to water cooling
THE MUON SHIELD

• Original idea (in EOI): passive shield
  110 tons of W, 2500 tons of Pb
  Total length 70 m

• Reduces muon flux per spill from $10^{10}$ to ≈$10^5$
• Now replaced by ‘active’ shield (i.e. magnetised)
Active muon shield

- Muons are swept out of detector acceptance
- Challenge: avoid that low-momentum muons are swept back into the detectors by the return fields
- Muons are no longer stopped, but deflected: RP impact
- Muons may scatter back from cavern walls: CE impact
- Need an intelligent and optimised design (by SHiP): position return fields where there are (almost) no muons
- $\text{BL} = 86.4 \text{ Tm, bending } \mu \text{ up to } 350 \text{ GeV/c out of acceptance}$
- Total length 48 m, B-field 1.8 T
- Reduces muon flux per spill from $10^{10}$ to $\approx 7 \times 10^3$
Magnetic layout of shield

350 GeV
- 10 mrad
- 0 mrad
- 10 mrad

30 GeV
- 38 mrad
+ 28 mrad
Some design considerations

- Grain oriented steel is more expensive, but reduces current

- Hence air cooling, lower power and conductor costs
DETECTOR HALL AND DETECTORS
**Height:** defined by detector and magnet height

- Height: \( \approx 12 \text{ m} \)
- Length: \( \approx 80 \text{ m} \)
Width: defined by muon impact on cavern walls
Section 9:

DH's Service building, 40m long

Detector Hall, 120m long
CIVIL ENGINEERING

- SHiP fits entirely on the Prévessin site
- Demolition of existing TDC2 to allow new junction cavern.
- Implies removal of almost 100 m of beam lines and infrastructure (need cool down before → ion run?)
- 166 m long extraction tunnel with access building + shaft
- 40x30 m² target hall with underground areas + service bldg
- 120x20 m² detector hall with 40x30 m² access building
- 140 m long technical gallery
- All underground works excavated with diaphragm walls (RP safe distance, water table levels)
- A detailed integration study is needed before CE tendering
Junction cavern and ET

- The junction cavern and most of the extraction tunnel must be constructed during a long stop.
- TDC2 to be demolished over 100 m, this implies radioactive material and dust.
- Backfilling of demolished concrete and activated earth as first layer of new junction cavern and downstream facilities is being discussed.
- Extraction tunnel has 40 ton crane.
- The detector hall could later be extended by up to ~100 m.
WP1 is very critical for and **drives the planning**, as it requires the North Area to be stopped (not SPS for LHC)
RADIATION PROTECTION ISSUES

• 355 kW primary proton beam power → RP determines design of the facility
• Prompt dose rates, residual dose rates → shielding and remote interventions in target area
• SPS extraction becomes crucial factor
• The target area and muon shield are particularly critical
• Environmental impact, dismantling, etc yet to be studied
• The SHiP facility has been implemented in a FLUKA simulation
RP for target complex

- Target hall can be accessed during operation, but not target bunker, dose reduced to few μSv/hr in target hall

- Ground activation remains acceptable (prompt dose < 1 mSv/hr)
RP after muon shield

Few $\mu$Sv/h in access building above detector hall (supervised area)

< 1 mSv/h in soil just behind muon shield, ok for soil activation
Impact on other facilities

SHiP operation has no impact on surrounding experimental areas.
Dose at CERN fence is smaller than 5 $\mu$Sv/yr: acceptable.
Residual doses around target

- Target region is most critical: 100 Sv/hr after 1 week, but only few μSv/hr above He vessel.
- The dose of the Mo (TZM) part of the target drops to few 10s of Sv/hr after 1 week, the W part to 10 Sv/hr.
- Remote handling is crucial
RP for SPS extraction

- From data from LSS2 and LSS6 one expects 12 mSv/hr in the aisle next to the ZS, comparable to LSS6 data from the ring survey.
- It is therefore of prime importance to reduce the losses at the ZS (more interlocking, better instrumentation, …)
- Prompt dose rates from North Area operation indicate that **8 m soil thickness** is required around TDC2 and TCC2 during NA operation. This impacts SHiP CE works → WP1.
- Continuous 5% loss of regular North Area fixed target beam on splitters give 650 mSv/h. Therefore 50 m or concrete or 20 m of iron shield are needed to allow work in the extraction tunnel during operation.
IMPACT ON NA PROGRAMME

• Just adding SHiP cycles in the SPS-super-cycle would reduce the duty cycle for a ‘classical’ NA fixed target physics programme in a way similar to CNGS operation.
• Like for CNGS this can be partly compensated by going to a longer flat top for the North Area beam lines.
• There are constraints on the flat top and super-cycle from RMS power (39 MW for SPS) and magnet heating. They are slightly more severe for SHiP because of the 1 sec flat top.
• Several scenarios have been studied based on a set of cycles composing the super-cycle.
• Typically 18% duty-cycle for the NA can be achieved (cf ~20% during CNGS operation).
R&D AND MACHINE DEVELOPMENTS

- SHiP requires some R&D activities and machine development studies already in the near future.
- Many of them are necessary for SHiP but are also extremely useful for the ‘classical’ North Area fixed target program (COMPASS, NA62, …)
- Main R&D concerns the extraction and beam transport and the target and target station
- On the short term necessary preparations for civil engineering WP1 include integration studies for the beam lines with their infrastructure
R&D for extraction and beam lines

- Deployment of the new SHiP cycle
- Extraction loss characterisation and optimisation
  - Reduce p density on septum wires
  - Probe SPS aperture limits during slow extraction
- ZS performance versus intensity
- Development of new TT20 optics
  - Change beam at splitter on cycle-to cycle basis
- Characterisation of spill structure
- R&D and development of laminated splitter and dilution (sweep) magnets
The SHiP target is feasible but, even if the SHiP target complex takes advantage of the CENF studies, R&D is necessary:

- Analysis of assembly, configuration and fabricability of the cladded refractory metal blocks
- Material irradiation R&D on TZM, Mo, W and W-TiC
- Feasibility of water-cooled cast iron blocks with embedded stainless steel pipes
- Develop high-pressure, high-flow rate compatible full-metal plug-in systems for fast and remote connection
- Design of He gas cooled SHiP production target
Planning rationale

• Motivated by timeliness and wide interest in physics case
• Respect the operation schedule of CERN complex and technical and financial constraints
• Take maximum advantage of existing shutdowns
• Short facility validation run with partial detector
• Start full physics as soon as possible

• Fully exploit the long shutdowns, for critical civil engineering and the beam and infrastructure modifications in and around TDC2
• **Start some preparations (+ resources) early on!**
A planning
## Cost of the facility

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost MCHF</th>
<th>Staff FTE</th>
<th>Fellows MCHF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Civil engineering</td>
<td>57.4</td>
<td>10</td>
<td>0.7</td>
</tr>
<tr>
<td>Infrastructure and services</td>
<td>22.0</td>
<td>17.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Extraction and beam line</td>
<td>21.0</td>
<td>31.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Target and target complexes</td>
<td>24.0</td>
<td>35</td>
<td>2.6</td>
</tr>
<tr>
<td>Muon shield</td>
<td>11.4</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td></td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>135.8</strong></td>
<td><strong>102.7</strong></td>
<td><strong>6.3</strong></td>
</tr>
</tbody>
</table>

Fellows are already included in the cost
OUTLOOK

- SHiP would add a new facility to the North Area with much higher intensities than before
- The proposal has been presented at the SPSC in June
- If approved, the construction would take about 8 years and would take maximum advantage of long shutdowns
The SHiP Task Force


and many others who contributed