The Active Muon Shield

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Abstract

In the SHiP beam-dump of the order of \(10^{11}\) muons will be produced per second. An active muon-shield is used to magnetically deflect these muons out of the acceptance of the spectrometer. This note describes how this shield is modelled and optimized. The SHiP spectrometer is being re-optimized using a conical decay-vessel, and utilizing the possibility to magnetize part of the beam-dump shielding iron. A shield adapted to these new conditions is presented which is significantly shorter and lighter than the shield used in the Technical Proposal (TP), while showing a similar performance.
1 Introduction

SHiP (Search for Hidden Particles) is a new proposed fixed-target experiment at the CERN SPS accelerator which aim is to use decays of charm mesons to search for Heavy Neutral Leptons (HNLs) and other hidden, very weakly interacting particles. In order to be able to detect these particles, the experiment requires to reach \(2 \cdot 10^{20}\) protons on the target in 5 years of running. Along with this, the muon flux of \(10^{11}/\text{spill}\) is expected (Figure 1). These muons could incur background, and hence their flux has to be reduced by several orders of magnitude over the shortest possible distance to achieve the largest possible acceptance for HNLs. SHiP adopted the use of a series of magnets to deflect the muons out of the acceptance of the spectrometer. The TP design used a cylindrical decay vessel, hence the shield was optimized to avoid muons within a perimeter of \((x,y)=(5,10)\) m at the start of the decay vessel. SHIP now moved to a conical vessel design, which relaxes the requirement of the shield, having to clear only 5x10 m at the position of the last tracking station. Section 2 describes how this conical shield is optimized. The feasibility to magnetize the target bunker to use it as part of the shield was investigated. The muon shield module in the FairShip software was totally rewritten to

![Momentum and transverse momentum distributions of muons at their origin](image)

**Figure 1**: Top: Muon flux momentum distribution at the origin. Bottom: Transverse momentum versus momentum flux distribution at the origin.
be able to check different configurations in the full 3D simulation. The automatic tool for
magnet designing, which also takes into account more realistic magnet designs, is described in
Section 3. Section 4 compares the background conditions of a new magnet layout which takes
into account a conical decay vessel and the possibility to magnetize part of the target region,
with the design described in the TP [1]. Section 5 gives the conclusions.

2 2D Modeling and Optimization

The principle of the magnetic shielding is shown in Figure 2. The first part of the shield should
be long enough, i.e. providing sufficient $\int Bdl$, to separate even the largest momenta $\mu^\pm$ to
either side of the z-axis. For a 350 GeV muon, taking into account the $p_T$ distribution at its
production point, this requires a $\sim 18$ m long magnet with a field in the iron of 1.8 T. Lower
momenta muons will be swept out much further, and might traverse the return field of this
magnet, bending them back in the direction of the spectrometer as is shown in Figure 2 for a
50 GeV muon. To shield the spectrometer from these muons, an additional magnet is added
with its return field close to the z-axis, and hence the lower momentum muons will be swept
out again. At the start of this second magnet the two field polarities should be as close as
possible. A magnet design study [2] shows that one can get a gap as small as 2 cm between
the two field polarities without distorting the 1.8 T field in the Fe.

![Figure 2: Cross-section at y=0 showing the principle of magnetic shielding. The magnetic field is along the y-axis, and its polarity is indicated by the blue/green colour of the Fe poles of the magnets. The trajectory of a 350 (50) GeV muon is shown with a full (dashed) line.](image)

To test the concept described above for the momentum distribution of muons produced in
a 400 GeV proton beam-dump, a Geant like but much simplified program was written. Each
magnet is described by 7 parameters:

- the length of a magnet,
• the widths of the magnetic field at either end of the magnet,
• the gaps between field and return field at either end of the magnet,
• and the heights at either end of the magnet.

Muons are traced through a set-up with a step size of 5 cm, and only the following physics processes are taken into account:

• bending in the magnetic field,
• $dE/dx$ loss, using the PDG table for Fe [3] and
• Gaussian smeared multiple Coulomb scattering: $\frac{0.0136}{p(\text{GeV})} \sqrt{\frac{x}{X_0}} (1 + 0.038 \ln(\frac{x}{X_0}))$, where $p$ is the momentum of the muon, and $\frac{x}{X_0}$ is the Fe thickness in radiation lengths.

Running with this simplified model one can trace of the order of $1 \text{ M}$ muons through the shield in a few min running 16 processes in parallel on lxplus. The shield layout as used for the TP [1] was obtained by varying the sizes of the magnets by hand and judging the results of the iterations by inspecting the trajectories of muons which ended up in the acceptance of the decay-vessel starting 10 m downstream of the shield.

To adapt the shield to a conical decay-vessel, and explore different options for magnetizing part of the beam-dump shielding iron, the optimization was done using Minuit [4] to reduce the number of muons in the acceptance by varying the size of the magnets. The function which Minuit is required to minimize is chosen to depend on:

• The muons are traced to 64 m downstream of the shield, which corresponds to the position of the last tracking station T4. For muons with $|y| < 5. \text{ m}$, their x-position is converted into $\chi^2_{\mu} = \sqrt{(5.6 - (x + 3.))/5.6}$ for $-3 < x < 2.6 \text{ m}$, else $\chi^2_{\mu} = 0$.
• $A_{HNL} = (1. - L/100.):$ Acceptance of HNLs, where $L$ is the length of the shield in m.
• $W$: Weight of the shield in tons of Fe.

This is combined in the penalty function to minimize as follows: $\frac{0.01 \times W \times (1+\Sigma\chi^2_{\mu})}{A_{HNL}}$, and its several components are shown in Figure 3.

Only muons with $p(\mu) > 1 \text{ GeV}$ at T4 are considered as background muons, and thus included in the penalty function. Widths of fields and gaps are only allowed to vary by quanta of 1 cm steps. Lengths are only allowed to vary by quanta of 10 cm steps. The tracing of each muon is always started with the same (seeded by its momentum) random number to avoid a different multiple scattering contribution for muons which traverse the same Fe.

In magnetizing the target and the shielding Fe behind the target we consider 3 regions [5] in the simulation:

• Target: fixed length of 1.2 m.
• Stop-1: fixed length of 1.4 m, representing the water cooled mobile Fe shield just behind the target.
Figure 3: Top left: $\chi^2_\mu$ of muons in T4. Top right shows $\Sigma \chi^2_\mu$ for several muons. Bottom left shows the acceptance function $A_{HNL}$ and the last plot shows the total penalty function for some combination of shield weights, lengths and the number of muons in the acceptance.

- Stop-2: fixed length of 3.4 m, representing the fixed Fe shielding of the target bunker.

In comparing the different options, the heights of all magnets were fixed, $p_y^\mu = 0$ and five magnets were given to Minuit behind the target bunker. The result of these optimizations is given in Table 1. An optimization typically needed a few hundred cycles using the “SIMPLEX” option for Minuit, and all ended without any muons in the acceptance of T4. The required length of the shield used in the TP was 48 m, which was mainly due to imposing an elliptical

<table>
<thead>
<tr>
<th>What Z-interval (m)</th>
<th>Target</th>
<th>Stop-1</th>
<th>Stop-2</th>
<th>Active-shield length (m)</th>
<th>Relative Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field (Tesla)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>34.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Field (Tesla)</td>
<td>0</td>
<td>0</td>
<td>1.8</td>
<td>32.9</td>
<td>0.51</td>
</tr>
<tr>
<td>Field (Tesla)</td>
<td>0</td>
<td>1.8</td>
<td>1.8</td>
<td>29.5</td>
<td>0.35</td>
</tr>
<tr>
<td>Field (Tesla)</td>
<td>1.0</td>
<td>1.8</td>
<td>1.8</td>
<td>26.0</td>
<td>0.28</td>
</tr>
<tr>
<td>Field (Tesla)</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
<td>25.2</td>
<td>0.25</td>
</tr>
</tbody>
</table>
decay-vessel and requiring that the largest momentum muons did not intersect with the vessel walls. Table 1 shows that even when the target area is not magnetized (Target, Stop-1 and 2 have no field), with a conical vessel the shield length can already be reduced considerably. Adding a field in the target bunker allows the shield to be further reduced in length, and mainly saves on Fe. Since it is considered difficult to obtain a magnetic field in the Mo+W target itself while the gain is marginal, the option with no field over the target and 1.8 T fields in the Stop-1 and 2 areas is pursued further with also leaving the heights of the magnets as free parameters. This yields the layout as shown in Figures 4.

3 3D Modeling in Geant4

SHiP simulations are performed in the software package FairShip [1]. FairShip is mostly a collection of libraries and scripts based on the FairRoot framework [6], which is fully based on the ROOT system. In the framework users can construct their detectors, simulate and analyse it without any code dependence on a specific Monte Carlo engine. FairRoot uses the ROOT geometry package TGeo [7] to build, browse, track and visualize a detector geometry. In the package, basic bricks of the geometry which are used to build pieces and position them with respect to others are called ”volumes” and ”nodes”. Volumes are fully defined geometrical objects having a given shape and medium. Nodes represent just positioned instances of volumes inside a container volume and they are not directly defined by the user. They are automatically created as a result of adding one volume inside another or dividing a volume [8]. To define the simplest geometry in TGeo one needs to:

1. Create a volume as an object of TGeoVolume class:
   - define the name of the object;
   - define its material (expected to be created before);
   - define its half length along the z-axis and other space coordinates which depend on a chosen basic shape;
2. define optional parameters, as color of volume, presence of magnetic field, etc.;
3. position the volume (in the top volume or in any other, if required);

Figure 5 shows the muon shield as it was implemented for the TP. The muon shield comprises three different magnet types (bottom picture in the Figure 5) which can be described by up to 12 volumes of TGeoArb8 [9] type with different magnetic field directions. The function CreateMagnet() can create all three magnets and is implemented in the class ShipMuonShield() in the way that users don’t need to take care about TGeoArb8 volumes and their interposition. The function also checks if sufficient space is allocated for coils, and automatically switches to geometry b) instead of a) (see Figure 5) if more coil space is required.

CreateMagnet() takes as input parameters:

1. The name of the magnet which will be added in the volume title to the name of the each particular part as char object.
Figure 4: Top: cross-section showing the layout from the Minuit optimization in the x-z plane. Trajectories of some typical muons are overlaid. Bottom: cross-section showing the half height of the vertical B-field from the Minuit optimization in the y-z plane.

2. Material of the volume as object of the class TGeoMedium.

3. The parent volume.
Figure 5: Geometry view of the muon shield in the technical proposal configuration. Top: \( z-y \) plane; Middle: \( z-x \) plane. The bottom shows the cross-section in the \( x-y \) planes at a, b and c position as indicated in the top panel.

4. The list of magnetic fields of the magnet as TGeoUniformMagField objects (As magnetic field lines should form closed loops).

5. Field direction, "up" or "down", defining the direction of the field flux in the magnet.

6. Half-width and half-height of the magnet with a field value which was chosen to sweep muons out of the detector aperture at the lowest and highest \( z \)-position. Half-length of the magnet.

7. The distance between two "field" magnet pieces, in case when one want to split it (= 0 for a) and b) and \( \neq 0 \) for c) in Figure 5.

8. The height at which the expansion for the coils starts, (b) in Figure 5.

9. Gaps between field and return field volumes at the beginning of magnet and at its end.
10. The z-position of a magnet, which is calculated by the ConstructGeometry() function described below.

All input parameters for CreateMagnet() are set in the Initialize() method as elements of arrays. All magnets are created in the function ConstructGeometry(). The following boundary conditions are imposed to assure a realistic implementation of the magnets:

- Minimum gap between field and return field is 2 cm (can be changed in CreateMagnet()).
- Minimum gap for coils in xy plane is 20 cm (can be changed in CreateMagnet()).
- Minimum gap between magnets along z is 10 cm (can be changed in Initialize()).
- Mitred joints between volumes with horizontal and vertical fields are imposed to lower their magnetic reluctance.

The configuration with magnetized Stop-1 and Stop-2 (see Table 1) was adopted as prototype for a re-optimized detector, and this was implemented in FairShip using the tools described above. The corresponding geometry is shown in Figure 6.

4 Prototype Shield Performance

To test the background with the prototype shielding only target, muon-shield, tracking stations and spectrometer magnet were considered. This not only speeds up the simulation, but also avoids having to adapt the other elements to the new conical shape. In this set-up the last tracking station (T4) is located 65 m downstream, of the last shielding magnet. A view of the test layout is shown in Figure 7. From simulations we expect to produce $5.7 \cdot 10^{11}$ muons per spill. Muons produced in the proton interactions can interact inelastically with the material surrounding the HS decay volume. These interactions can generate particles that enter the decay volume and mimic signal events. Additionally, the muon flux should be suppressed to protect the tau neutrino detector from additional hits to have no more than ten films changes during the five years of running. Hence, it needs to reduce the flux of muons in the decay vessel and detector region at least by six orders of magnitude. The rate of hits in the first and fourth tracking stations was used to quantify the background rates. Table 2 shows the number of hits per spill for the TP geometry and prototype in the first and last straws. In this case, the TP geometry includes upgrades which were presented in Section 3 as more realistic model in terms of being able to construct the magnets.

Table 2: Hits rate in straws for technical proposal design and for new short muon shield design.

<table>
<thead>
<tr>
<th>Hit’s origin</th>
<th>TP design</th>
<th>Short design</th>
<th>TP design</th>
<th>Short design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T1</td>
<td>T1</td>
<td>T4</td>
<td>T4</td>
</tr>
<tr>
<td>All hits</td>
<td>$1.6 \cdot 10^7$</td>
<td>$9. \cdot 10^8$</td>
<td>$6.6 \cdot 10^6$</td>
<td>$5.7 \cdot 10^8$</td>
</tr>
<tr>
<td>Hits produced by muons</td>
<td>$7.0 \cdot 10^5$</td>
<td>$3.7 \cdot 10^6$</td>
<td>$4.5 \cdot 10^5$</td>
<td>$2.3 \cdot 10^6$</td>
</tr>
<tr>
<td>Hits produced by muons $&gt; 3 \text{ GeV}$</td>
<td>$2.6 \cdot 10^5$</td>
<td>$1.5 \cdot 10^6$</td>
<td>$2.2 \cdot 10^5$</td>
<td>$4.5 \cdot 10^5$</td>
</tr>
</tbody>
</table>

The number of muons reconstructed in the spectrometer in the TP-design with momenta larger than 1 GeV and 3 GeV is 40 kHz and 23 kHz respectively. In the prototype-design this is
Figure 6: 3D muon shield geometry with magnetized target bunker area and with expected conical hidden sector (HS) volume.

202 kHz and 55 kHz respectively. The numerical difference of values for hits caused by all kind of particles can be explained by absence of any material between shield magnets and straws in the test setup which rules out the possibility for electrons, positrons and low momentum muons to be absorbed. The detailed examination of events which cause hits in the straws revealed that final muon hits rate can be lower, as a fraction of muons hits T1 at large x, but close to the maximum y of T1 (Figure 8), i.e. they are outside of the conical HS volume. In the final re-optimization the size of the T1 should be shrunk according to the cone shape of the decay volume which means that these muons will not be in the detector’s aperture anymore.

The transverse momentum versus momentum flux distribution of muons at their origin which hit T4 is shown in Figure 9. The distribution of muons in the xy plane just after the shield is shown in Figure 10.

Trajectories of muons are shown in Figure 11. For the xz projection the muons are required to have \(|y| < 500 \text{ cm}\) at the fourth tracking station. Similarly for the yz projection the requirement is \(|x| < 250 \text{ cm}\). Red lines indicate the end of muon shield. The length of the shield in the TP configuration was 48 m + 5 m of the target absorber and its weight was 2896 t.
Figure 7: Configuration of the experiment in the simulation for performance tests showing the target area and muon-shield on the left, the spectrometer and the surrounding concrete walls of the experimental hall.

Figure 8: Example of muon trajectories which hit straws.

The new short muon shield configuration length is 33.8 m and its weight is 1845 t.
Figure 9: The transverse momentum versus momentum flux distribution of muons at their origin which hit T4.

Figure 10: The distribution of muons in the xy plane just after the shield.
Figure 11: Trajectories of muons which show the muon free zone. For the left plot $|y| < 500cm$ at the fourth tracking station; For the right plot $|x| < 250cm$ at the fourth tracking station;
5 Conclusions

The optimization of the active muon shield for the SHiP experiment is presented. New procedures were developed for simulation and optimization of shield magnets taking into account total mass of magnets and background level from muons in the spectrometer. A special function was written in the FairRoot framework to configure the magnets taking into account the necessary space for their coils and shaping their armature to reduce their magnetic reluctance. Total mass of Fe material for muon shield was reduced to 1845 tons from 2896 tons by moving from the TP design to a design with a conical vessel, and magnetizing part of the target bunker. Background level from muons remains at an acceptable level.

6 Acknowledgements

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References