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CONCEPTUAL DESIGN OF THE MAGNETISED IRON BLOCK SYSTEM FOR THE SHADOWS EXPERIMENT

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Abstract

SHADOWS [1, 2] is an intended future beam dump experiment in the CERN North Area, aiming to search for feebly interacting particles (FIPs) [3] created in 400 GeV/c proton interactions. Due to its proposed off-axis location alongside the K12 beamline [4], the SHADOWS detector can be placed potentially very close to the beam dump, enabling it to search for FIPs in unexplored parts of the parameter space. In order to guarantee good quality of a potential signal, it is crucial to reduce any backgrounds of Standard Model particles as much as possible. The dominant background downstream the beam dump is caused by muons [1]. This introduces the need of a dedicated muon sweeping system consisting of magnetised iron blocks (MIBs) to actively mitigate this background component. We present the conceptional design studies in the framework of the Conventional Beams Working Group of the Physics Beyond Colliders Initiative at CERN [5, 6].

THE SHADOWS EXPERIMENT

FIPs with masses below the electro-weak scale are candidates for light dark matter, which could be helpful to explain matter-antimatter asymmetry in the universe, the strong CP problem, the hierarchy of scales, the origin of neutrino masses and other dark matter phenomena [3]. The search for FIPs in beam dumps is complementary to the LHC-driven high energy frontier and is addressed by the Physics Beyond Colliders Initiative, which has come to the foreground in recent years.

SHADOWS (Search for Hidden And Dark Objects With the SPS) is an intended beam dump experiment in the CERN North Area that would be able to search for these dark sector particles by using the K12 beamline in beam dump mode. In this mode, 400 GeV/c protons from the Super Proton Synchrotron (SPS) are dumped early in the beamline thereby potentially creating dark matter that can be detected further downstream. A high intensity upgrade of the ECN3 experimental hall is proposed [7, 8], which would enable SHADOWS to search for these particles more efficiently. In the studied scenario, SHADOWS would share the experimental hall with another experiment called HIKE (High Intensity Kaon Experiment) [9], which would simultaneously look for dark matter in the very forward region when operating in beam dump mode. While HIKE is thus on-axis with a detector that is about 200 m downstream of the beam dump, SHADOWS would be located alongside K12. Since off-axis the backgrounds are typically much lower, this would allow for its location to be closer to the beam dump.

THE MAGNETISED IRON BLOCKS

In previous studies [1, 10] it was found that the main background at the location of the SHADOWS detector would consist of muons. The experiment expects a muon flux rate of about 10^8/s in the full detector acceptance according to the SHADOWS Letter of Intent [1]. The muons are generated inside the beam dump (see Figure 1). Most of them are then deflected up- and downward by the two dipole magnets directly downstream the beam dump, which are part of the K12 beamline. However, some of the muons will also be swept sideways by the return yokes of the magnets and by doing so they would enter the acceptance of the SHADOWS detector. The purpose of the MIB system is to push these off-axis muons away from the detector to further reduce the muon flux rate through the experiment.

The MIBs would act on the muons in two ways. On the one hand, the stopping power of the iron leads to a decrease of the kinetic energy of the muons. Especially muons with low momentum can lose so much of their kinetic energy that they get absorbed or drop below the sensitivity of the detector, which means they remain unseen and cannot lead

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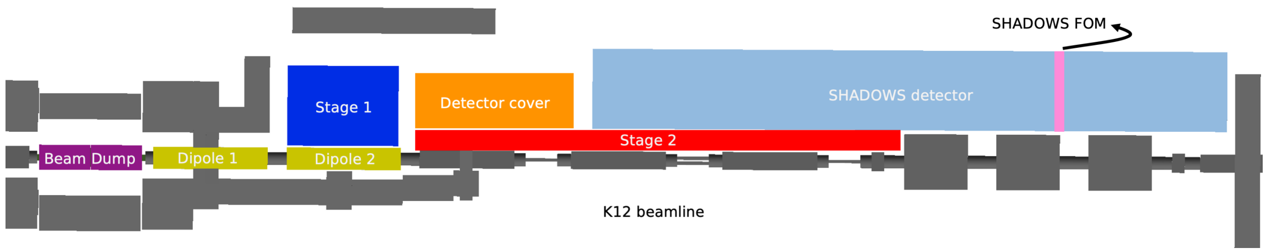

Figure 1: Setup of the MIB system alongside the K12 beamline consisting of Stage 1 and Stage 2 MIBs and detector cover.

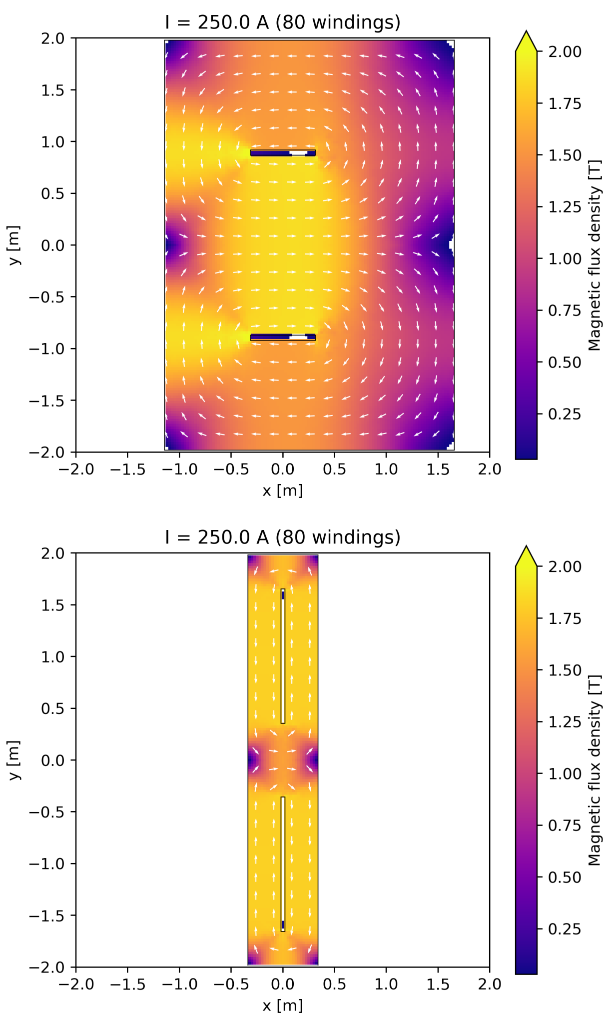

Figure 2: Conceptual design and simulated magnetic field of Stage 1 (top) and Stage 2 (bottom). When looking upstream K12 would be located on the left hand side.

to false signals. On the other hand, the magnetic field inside the MIBs is used to actively push the muons away from the detector region.

The conceptual design foresees a two-staged muon sweeping system, where Stage 1 aims for a separation of the two muon charges thereby preparing the distribution for Stage 2 that can then push the muons away from the detector more effectively. The proposed solution is a figure8-shaped iron yoke with coils that go from one hole into the other so that they induce a strong magnetic field in all of the iron yoke. Due to the fact that the location is off-axis no gap for a beam-pipe is needed.

The software FEMM [11] was used to model the MIB and calculate its magnetic field, which was then used to accurately describe the magnet within Monte Carlo frameworks. A python framework was created that enabled the authors to modify the MIB design parameters and perform FEMM simulations to extract the fieldmaps for 20,000 different sets of design parameters. In order to rank them, a measure for the efficiency in mitigating the muon background was defined which combines the energy-weighted muon distribution at the MIB location and the magnetic field that these muons would traverse with respect to the purpose of each Stage — charge separation for Stage 1 and sweeping for Stage 2. Instead of using the best MIB sample already, a deep neural network (DNN) was trained to predict the efficiency for any given set of MIB design parameters, which could then be used to further improve the design. The optimisation was done in two steps, so that the optimisation of Stage 2 already took into account the impact of Stage 1. The muon distributions were simulated with a model of the K12 beamline [10, 12] using the Geant4-based particle-tracking software BDSIM [13, 14].

The preliminary finite element layouts of the two MIBs are shown in Figure 2 and their fields were simulated using FEMM [11]. The optimisation implies that for Stage 1 a wide central part of the yoke with a large magnetic field is beneficial because it enables the MIB to open up a wide gap in the muon background. This gap is naturally limited by the location of the holes, which is where the return yoke starts to work against the muon separation by pulling the low momentum muons back. Stage 2 will work best if chosen to be a slim and high MIB with a strong field in all the outer yoke regions. This is due to the fact most muons directly after the beam dump, and even more so the high momentum ones, are usually found close to the beam axis, meaning that a high magnetic field is more effective there than further away from the beamline. In fact both — the number of muons and the muon momentum — decrease exponentially with the distance from the beam axis [1]. In order to make this setup work, it is necessary that the polarity of the two Stages is opposite.

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REDUCTION OF THE MUON BACKGROUND FOR SHADOWS

All of the components have been assembled in the BDSIM model alongside the K12 beamline to assess the effectiveness of the background mitigation with Geant4 simulations [14]. The full setup is shown in Figure 1. Stage 1 is placed alongside the second 3.5 m long dipole magnet downstream the beam dump to separate the muons that have already been pushed off-axis by the first dipole. Since the slim design of Stage 2 allows for placing the MIB alongside the SHADOWS detector without the need to move SHADOWS further off-axis, it was chosen to make it as long as possible. This not only helps to reduce the background by redirecting them with the magnetic field, but also has the advantage that the high momentum muons will experience a significant decrease in momentum due to interactions in the iron. Muons with momenta between 1 and 100 GeV/c, which represent the bulk of the background, will lose almost 2 GeV/c for every meter of iron they traverse [15]. Therefore, the 15.2 m long yoke will stop many muons before they pass through and make it to the detector. To shield the detector against muons that miss Stage 2 at its off-axis side, it was found that introducing an additional iron detector cover with a height/width/length of 3.5/1.5/5 m alongside the first few meters of Stage 2 would help to reduce the muon background even further.

The simulation of the muon background was done with the BDSIM model of the K12 beamline in beam dump mode, starting from the primary protons at the beginning of the beamline. Muon biasing methods [16] were used to increase the statistics. A kinetic energy cut-off for particles below 3 GeV/c had to be used to limit the simulation time for each event, adequate for a conceptual design. With these settings, a sample equivalent to 10^{12} protons on target was simulated, which can be used to extrapolate to the 5×10^{19} protons on target that SHADOWS expects to receive over its full run-time [1].

The end of the decay vessel of SHADOWS marks the beginning of the tracking system and therefore can serve as a Figure of Merit (FOM) for the evaluation of the MIB system. This location is expected to be about 55 m from the beginning of the beamline. Figure 3 shows a comparison of the simulated muon background without and with MIB system. The proposed detector location is indicated in red. As the comparison demonstrates, the flux of muons in the region of interest can be significantly reduced with the MIB system. The muon background in the marked region was decreased by a factor of 120 which would potentially bring the expected muon flux rate from 10^8/s down to 8×10^5/s, which is acceptable for the experiment [1].

FUTURE IMPROVEMENTS

In the future, reducing the MIB size whilst preserving the sweeping performance will be studied. This would avoid making excavations from the experimental hall and make space for radiation shielding. Another natural next step would be to check whether magnetising the iron of the detector cover could further reduce the muon background due to additional sweeping. If the experiment is approved, the studies for a technical design will commence.

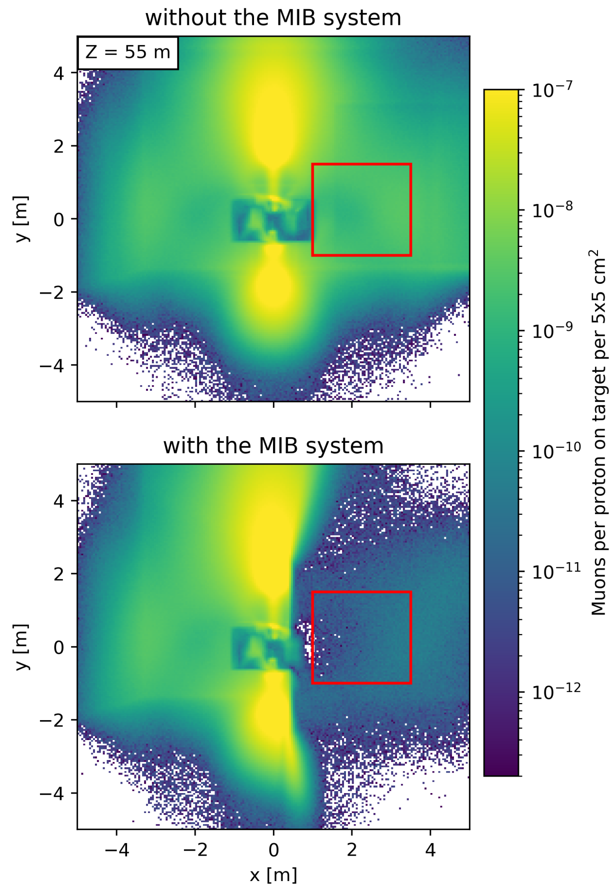

Figure 3: Comparison of the simulated muon background without (top) and with (bottom) the MIB system at the SHADOWS FOM at 55m (see Figure 1, marked in red, viewpoint upstream) showing a reduction by a factor of 120.

CONCLUSION

A conceptual design of a muon sweeping system for SHADOWS was introduced and its performance evaluated. A first idea of the shape and the size of its constituents was given and the impact of the assembled system was studied in detail with simulations using the Geant4-based software BDSIM. It was found that the magnetised iron block system can be expected to reduce the muon background above 3 GeV/c by a factor of 120 at the location of the SHADOWS detector, which would lower the muon flux rate that is expected by the experiment from 10^8/s down to 8×10^5/s.

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