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nuSTORM ACCELERATOR CHALLENGES AND OPPORTUNITIES

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Abstract

The nuSTORM facility uses a stored muon beam to generate a neutrino source. Muons are captured and stored in a storage ring using stochastic injection. The facility will aim to measure neutrino-nucleus scattering cross-sections with uniquely well-characterized neutrino beams; to facilitate the search for sterile neutrino and other Beyond Standard Model processes with exquisite sensitivity, and to provide a muon source that makes an excellent technology test-bed required for the development of muon beams capable of serving as a multi-TeV collider. In this paper, we describe the latest status of the development of nuSTORM, the R&D needs, and the potential for nuSTORM as a Muon Collider test facility.

INTRODUCTION

Accelerator-driven neutrino sources, so-called 'superbeams', are typically created by bringing protons onto a target. Resultant pions decay to produce a beam composed mostly of muon neutrinos. Uncertainties arise in the flux and flavour composition of the resultant neutrino beam due to uncertainties in the flux and energy of the pions, as well as uncertainty in the flux of impurities such as muons and kaons. Neutrino oscillation experiments seek to measure the disappearance of muon neutrinos and the appearance of electron neutrinos, due to flavour oscillation of the neutrinos, at a detector far from the neutrino source. The measurement is compromised by poor understanding of the initial neutrino beam. A detector near to the source is typically used to measure this composition, but the resolving power of the detectors is fundamentally limited by poor understanding of the interaction of neutrinos with the atomic nucleus.

There is significant uncertainty apparent in the behaviour of neutrino oscillations over short baselines, which is inconsistent with the predictions from observation of neutrino oscillations over longer baselines. This has been attributed to the presence of so-called sterile neutrinos.

There is growing interest in a muon collider as an avenue to reach very high energy collisions on a footprint comparable to existing facilities. The muon collider will face significant challenges in the production of high brightness muon beams to reach satisfactory luminosity.

nuSTORM is proposed to address these issues [1,2]. nuSTORM will create a neutrino beam by means of multi-GeV muons decaying in long straights of a racetrack-shaped storage ring. The kinematics of muon decay is well understood. By making detailed measurements of the muon beam, the resultant neutrino beam may be characterised in considerably more detail than a superbeam. With such a well-understood source, neutrino-nucleus scattering may be studied in great detail, enhancing the resolving power of long baseline neutrino cross-section measurements. A variable muon energy enables the study of scattering over a variety of neutrino energies.

The well-characterised neutrino source enables study of beyond standard model processes with exquisite sensitivity. Changes in polarity of the capture system enable the production of electron and muon neutrino and antineutrino beams in a manner that is robust to systematic effects.

nuSTORM faces many similar challenges to the muon collider in terms of high power targetry, management of uncontrolled pion losses (especially in the vicinity of superconducting magnets), muon decay and resultant beam contamination. Additionally, it may be possible to use the nuSTORM target as a source of muons for a test of muon cooling.

NUSTORM FACILITY

A schematic of the nuSTORM facility is shown in Fig. 1. Under the proposal, protons from SPS are brought to an approximately 200 kW target employing horn focussing to bring outgoing pions into a decay channel, similar to the CNGS target.

The pion momentum is selected in a double bend achromatic chicane before passing into the storage ring decay straight by means of a fixed-field dipole. Muons that decay backwards in the pion rest frame have a significantly lower momentum than the pions and muons from forwards-decay. The optics of the injection dipole and storage ring capture these lower momentum muons while the higher momentum pions are diverted onto a beam dump.

The muons are stored in the storage ring until they decay. By employing large aperture combined-function fixed field accelerator magnets in the arcs, a large acceptance may be maintained. Simulations indicate a momentum acceptance of ± 16 % and transverse acceptance of 1 mm rad unnormalised at 3.8 GeV/c. A schematic of the FFA storage ring is shown in Fig. 2. A FoDo-based storage ring has also been considered.

In order to realise neutrino beams having momentum range with the same characteristics as the current and next generation neutrino oscillation experiments, the potential for a broader range of pion momenta is under study. Storage rings having enhanced acceptance and reduced dispersion in the straight, which can reduce the number of useful neutrinos, are also under study.

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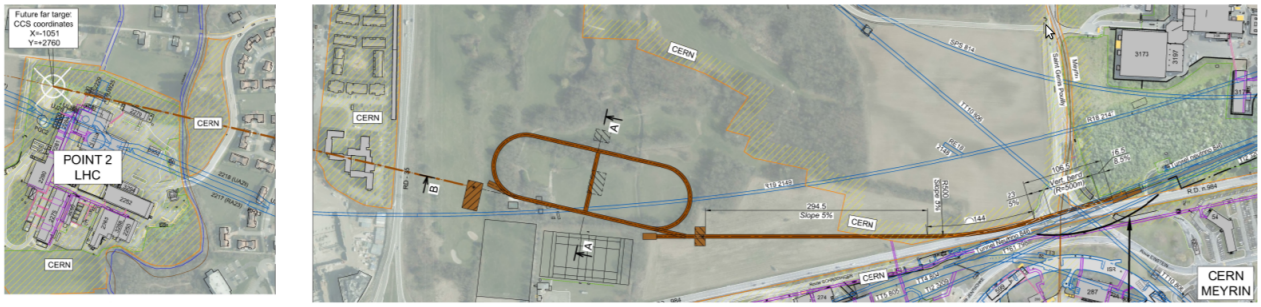

Figure 1: A schematic of the nuSTORM facility as proposed for the CERN site [1].

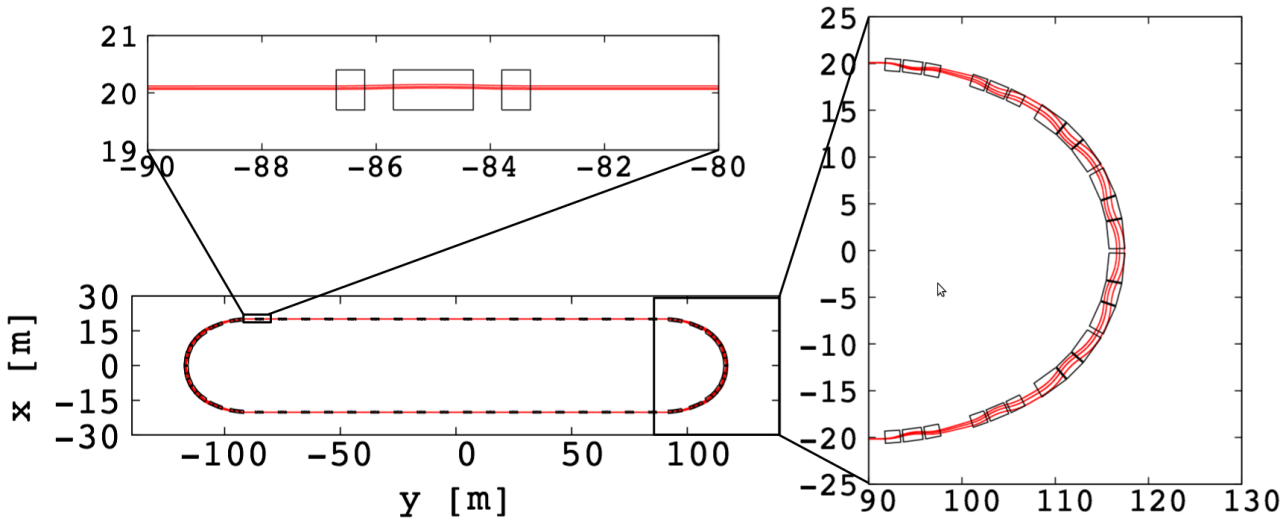

Figure 2: A schematic of the FFA-based decay ring [3].

MUON COLLIDER COOLING DEMONSTRATOR

The pion production target may also be used as a source for a cooling demonstrator. Ionisation cooling is the technique proposed to reduce muon beam emittance for a muon collider, in order to yield a beam having satisfactory luminosity. In muon ionisation cooling, muons lose energy in an absorber, resulting in a reduction of momentum in all directions, and a reduction in normalised emittance. Energy is restored in the longitudinal direction by RF cavities. Ionisation cooling was recently demonstrated by the Muon Ionization Cooling Experiment [4].

The muons used in nuSTORM are too high energy to be suitable for muon cooling; energy straggling is rather severe at these high energies, which causes longitudinal emittance growth, and significant energy loss and re-acceleration would be needed to achieve satisfactory transverse emittance reduction. However, the muon beam may be used as a muon source for a cooling experiment.

Low momentum pions which are not required by nuSTORM may be taken directly from the target region. Alternately the off-momentum beam at the downstream end of the decay straight may have its energy degraded and be diverted into a cooling apparatus.

Several cooling channel options are under consideration, including ring coolers, linear cooling channels having extremely high field solenoids, parametric ionisation cooling channels and. The so-called 'rectilinear' cooling channel is particularly appealing. In a full cooling channel of this sort, several orders of magnitude in 6D emittance reduction may be achieved. A shorter stretch would be appropriate for a cooling demonstrator, enabling demonstration of 6D cooling at very low longitudinal and transverse emittances. A schematic of one such rectilinear cooling channel is shown in Fig. 3.

Significant challenges remain in realising such a cooling channel. High field solenoid magnets, having opposite polarity and hence significant hoop stress, are placed in quite close proximity. High gradient RF cavities are placed between the magnet assemblies; offsetting the inter-coil forces while preserving a heat shield between the cavities and the superconducting magnets is also challenging. Recent results have shown promise in realising higher gradient RF cavities than was previously thought possible, even in high magnetic fields, so it may be possible to maintain or even enhance the real estate gradient despite these challenges. Optimisation is ongoing.

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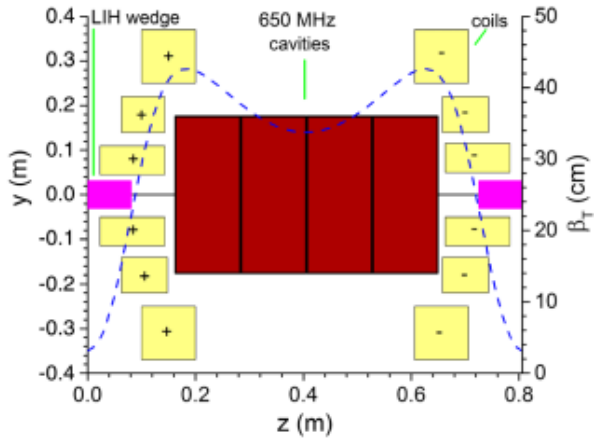

Figure 3: A schematic of the proposed rectilinear cooling channel. Beam is incident from the left. Absorbers are shown in magenta, RF cavities are shown in red and superconducting magnet coils are shown in yellow [5].

CONCLUSIONS

The nuSTORM facility has been proposed as a means to produce a remarkably well-characterised beam of neutrinos. This will enable studies of neutrino-nucleus scattering cross-sections, a topic of interest in its own right, but also one that may reduce systematic uncertainty in current and future long baseline neutrino oscillation experiments. It will also enable studies of beyond standard model physics such as the search for sterile neutrinos. While the nuSTORM facility has lower beam power, many of the obstacles that nuSTORM will face are similar to those for a future muon collider. In addition, the nuSTORM pion beam would make an excellent source for a future muon cooling experiment.

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