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Upgrades of the ESSnuSB design to comprise a nuSTORM facility and Muon Collider Proton Complex Test Facility

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The high beam power 5 MW of the ESS 2 GeV linac can be used to produce uniquely intense low energy neutrino and muon beams. The results of a design-study of an ESS based neutrino Super Beam, ESSnuSB, is reported elsewhere in these proceedings. Here we propose design-studies of how to complement the ESS linac, which is currently under construction, and the ESSnuSB accumulator ring, for which a design has already been made, to achieve a Low Energy nuSTORM facility for the measurement of neutrino cross-sections below 0.5 GeV and search for sterile neutrinos and a Proton Complex test facility for the demonstration of the feasibility of compression of each of the 2.86 ms ESS linac proton pulses of ca 10^{15} protons to about 2 ns as required for a Muon Collider.

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1. Introduction

A design study, ESSnuSB, of an ESS based high intensity neutrino Super Beam is about to be concluded after four years of design work with the publication of a Conceptual Design Report [1]. In this design each 2.86 ms long linac pulse, produced 14 times a second and containing about 10^{15} H^- ions, is chopped into four subpulses separated by 0.1 μs. Each of these four subpulses is in turn stripped and injected in an Accumulator ring by multiturn injection and ejected in a single turn, resulting in a 1.3 μs long proton pulse split into 4 subpulses, each with 2.5×10^{14} protons. When each of these subpulses hits one of four laterally separated targets in the target station, there will be a copious production of not only neutrinos but also muons. These muons can be used with a low-energy version of nuSTORM to measure low-energy neutrino cross-sections and for search for sterile neutrinos. Furthermore, adding a compressor/buncher ring to the ESSnuSB Accumulator ring and modifying the operation of the linac and the Accumulator, it will be possible to compress the 1.3 μs proton pulse to about 2 ns as that is required for the generation of the initial beam of muons for a Muon Collider to subsequently be cooled and accelerated before being brought into collision. An International Muon Collider Design Study has been launched for which the design of a Proton Complex Test Facility based at ESS for the demonstration of the proton pulse compression and of a Muon-Cooling Test Facility based at CERN for the demonstration of muon cooling are being proposed.

2. A Low Energy nuSTORM at ESS

The basic idea of nuSTORM is to store muons from pion decays in a racetrack storage ring and use the muon and electron neutrinos that are created in the muon decays in one of the two straight sections to form a beam that can be used to measure neutrino cross-sections as well as search for sterile neutrinos. Contrary to a neutrino beam generated from pion decays, which contain nearly only muon neutrinos, like the ESSnuSB Super Beam, the nuSTORM neutrino beam will contain equal amounts of muon and electron neutrinos, thus making high statistics measurements of neutrino cross-sections possible. In particular precise electron-neutrino nuclear cross-sections are needed for the interpretation of the electron-neutrino spectrum detected by the ESSnuSB Far Detector.

So far, nuSTORM design studies have been made for the Fermilab and CERN accelerators with proton energies of order 100 GeV [2, 3]. Pions produced from protons of such energies have an average energy of ca 5 GeV and will decay to muons with an average ca 4 GeV energy, which will in turn decay to neutrinos of average ca 3 GeV energy. The length of the racetrack straight sections was chosen to be about 180 m. Even if the neutrino momentum distribution so produced is broad, it will hardly cover the neutrino momentum distribution of ESSnuSB which has an average energy of ca 0.4 GeV, nor the neutrino momentum distribution of Hyper-K for which the average energy is ca 0.6 GeV.

The ESS-based Low Energy nuSTORM (LEnuSTORM) would use protons of 2.5 GeV from which a muon average energy of 0.46 GeV will be obtained (see upper left frame in Fig. 1). It would be difficult to generate a sufficiently powerful beam from the CERN PS 1.4 GeV Booster or the CERN 26 GeV PS to cover the low neutrino energies of ESSnuSB and Hyper-K with sufficient statistics. In view of this it is proposed to carry out a design study of a LEnuSTORM

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using the 2.5 GeV ESSnuSB-upgraded ESS linac. The target to produce the muons could be either the already designed targets used for producing the neutrino Super Beam with the 1.3 μs proton pulses or a new dedicated target. The length of the racetrack straight sections will be much shorter than in the Fermilab and CERN designs and the required strength of the large aperture magnets in the racetrack arcs is much lower. The lattice design could be of the FFAG or FODO type or a mixture of both.

In the right part of Fig. 1 the lay-out of ESSnuSB on the ESS site is shown with of the positions of the LEnuSTORM racetrack ring and, in this case, of a dedicated target station. The LEnuSTORM straight section is directed such that the neutrino beam produced will first hit a LEnuSTORM Near Detector indicated in this lay-out and then the ESSnuSB Near Detector, which is not visible in this figure but located to the right and just above the figure, that would be used as the far detector for the LEnuSTORM beam.

3. A Proton Complex Test Facility for the Muon Collider at ESS

As already mentioned it is proposed to make, as part of the International Muon Collider design study project [4], a design study of a Muon Collider Proton Complex Test Facility which will be based on the use of the ESS linac, on the already designed ESSnuSB accumulator ring and on a new compressor/buncher ring. If CERN should decide around 2030 to go forward with the construction of a high energy Muon Collider with a collision energy of 3, 10 or 14 TeV, the construction of such a Proton Complex Test Facility at ESS could be started around same time for the purpose of demonstrating that 2 ns proton pulses of 10^{14}-10^{15} protons at a rate of 14 Hz can actually be produced in practice. Such a test facility at ESS would require substantial funding but even more funding would be required to start the construction at CERN of such a test facility, as the build-up of a 5 MW proton accelerator would have to be initiated and this well before 2030 to be in time. Moreover, with such a Proton Complex in operation at ESS and with muon cooling being demonstrated at low intensity in a Muon Cooling Test Facility at CERN, this would open the way - in a longer perspective - for the construction at CERN of a High Energy 3, 10 or 14 TeV Muon Collider at CERN for Energy Frontier experiments and at ESS of a 125 GeV Higgs Factory Muon Collider with a unique potential for measurements of the Higgs self-coupling, extremely rare decays and the width of the Higgs boson [5].

The design study of a Muon Collider Proton Complex at ESS would be based on, inter alia, a faster chopping scheme for the linac, a new operation scheme for the accumulator ring, a new design of a compressor/bunch rotation ring and, in a second phase, a separate target station with a target and capture system (horn or solenoid) that could withstand the 2 ns short bunches of 10^{15} protons. The basic principle for the generation of the 2 ns long pulses from the 2.86 ms 10^{15} proton linac pulses is illustrated in the lower left corner of Fig. 1. The linac pulse is chopped into many short pulses that are injected into the accumulator ring and then extracted into the compressor/buncher ring where they are phase-rotated to ca 2 ns length (1.5 ns in the figure). This calls for the development of a high frequency chopper acting at the level of the linac H- source and an adaptation of the accumulator ring acceptance, rf system, timing and optics. As to the design of the accumulator and the compressor/buncher rings, there has been a design based on the use of the 5 GeV 4 MW SPL proton linac, that was planned for construction at CERN [6] as well as a design based on the use of the 8 GeV high power Project-X proton linac, that was

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planned at Fermilab [7]. These designs will be used as starting points for the design and simulation of a compressor/buncher ring based on use of the ESS linac. In Fig. 1 is indicated the direction of the ejected 2 ns pulsed muon beam towards an area at ESS, where there is free space for a second phase project to use the so-produced beam to build and test a target station and cooling front-end set-up there. In Fig. 1 the compressor ring is tentatively assumed to be located in the same tunnel as the accumulator.

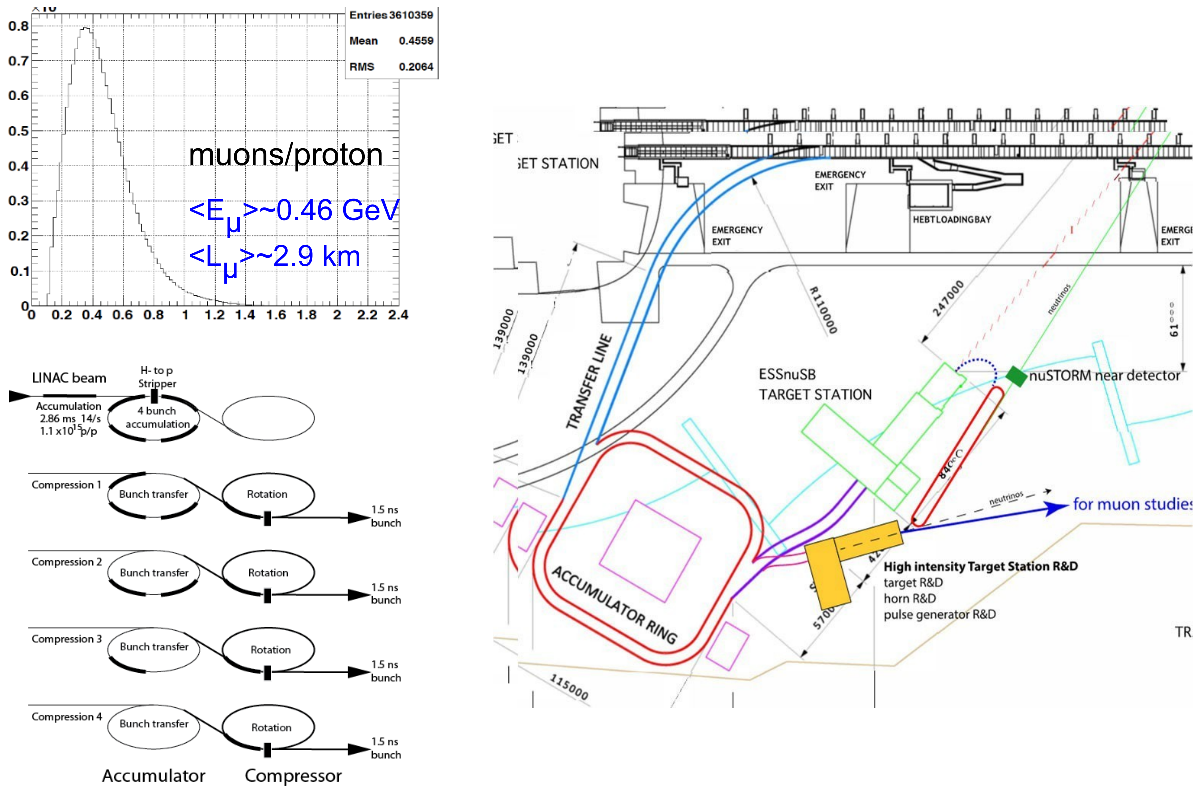

Fig. 1 The ESSnuSB neutrino momentum distribution (upper left side), a conceptual scheme for the operation of the Accumulator and Compressor rings to achieve 2 ns long proton pulses (lower left side) and the ESS site lay-out with the LEnuSTORM ring and the direction of the 2 ns pulse beam indicated (right side).

4. Conclusions

The interpretation of the measurements of neutrino oscillations with the ESSnuSB beam will require muon and electron neutrino cross-sections to be well known for energies below 0.5 GeV. This can be provided by a LEnuSTORM facility based on the use of the ESSnuSB 2.5 GeV proton beam and a design study of such a facility is proposed. The Muon Collider will require the production of nanosecond short proton pulses of the order 10^{15} protons per pulse. It is proposed to make a design study of a test facility at ESS to produce such intense and short proton pulses based on an upgrade of the ESS linac and of the ESSnuSB accumulator ring.

References

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