EMuS TARGET STATION STUDIES

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Abstract

The experimental muon source (EMuS) is a high-intensity muon source at China Spallation Neutron Source (CSNS), aiming to combine μSR applications, R&D efforts for a future muon-decay based neutrino beam, and neutrino cross-section measurements. The proton beam has 4 kW of power and is provided by the rapid cycling synchrotron (RCS) of CSNS to a capture system that consists of an adiabatic superconductive solenoid with a maximum field of 5 T and a graphite target located inside the 1st-coil, in order to maximize muons/pions capture and reduce their transverse momentum. In this article we present the challenging target system and the optimization studies that led to the current 4-coils/3-steps design. The challenge arises from the necessary extraction of the spent proton beam along the downstream area of the capture solenoid through a hole, in order to separate it from the muons and pions. In addition, shielding studies are presented in order to examine the effectiveness of the shields on the coils and the low radiation damage expected in the system.

INTRODUCTION

In this paper, a novel idea of a target station with a stepped superconductive solenoid is presented for the EMuS project at CSNS [1]. The optimization of the design is done in order to facilitate the high energy spent proton beam extraction and also to maximize the capture of both muons and pions. The physics objectives is to explore muon physics (like μSR applications) as well as a neutrino beam if possible. In addition, it could act as a R&D platform for MOMENT [2], a muon-decay medium-baseline neutrino beam facility, which shares similar charge separation and pion transport channel techniques with EMuS.

Table 1: CSNS [1,3] Parameters

Parameters	CSNS-I	CSNS-II
Beam power (kW)	100	500
RCS Energy (GeV)	1.6	1.6
Beam current (μA)	62.5	315
Repetition rate (Hz)	25	25
Proton per pulse [10^{13}]	1.56	7.8
Linac Energy [MeV]	80	250
EMuS power (kW)	4	20
Bunches per pulse	2	2
Bunch length (ns)	70	70

EMuS LAYOUT

The major aims of CSNS is to be among the leading neutron spallation sources internationally and also to operate as large platform for a broad range of high energy physics experiments within its facilities. The CSNS accelerator complex consists of an H^- Linac of 250 MeV in the final phase, a proton rapid cycling synchrotron (RCS) of 1.6 GeV and beam transport lines, with the ultimate beam power of 500 kW [3]. For EMuS, there is space reserved at the high energy proton experimental area (HEPEA) while a R&D fund has been approved by the National Natural Scientific Foundation of China (NFSC). The protons will be provided to the EMuS target station by RCS. The CSNS parameters are given in Table 1.

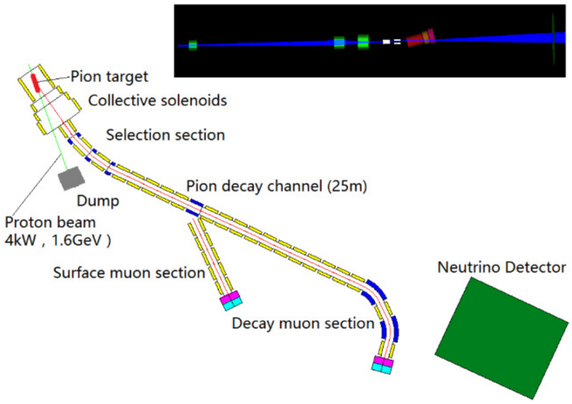

Figure 1: EMuS schematic layout.

Those protons are initially deflected by two dipoles before their entrance into the capture solenoid in order to facilitate downstream the spent protons extraction towards a beam dump. The target station consists of a superconductive solenoid with an adiabatic magnetic field of 5 T maximum. A graphite target is placed inside the solenoid in order to maximize the capture of decay muons and pions along with surface muons[1]. Downstream, the capture solenoid is connected through a matching solenoid to a bending section responsible for the charge selection, which in turn is connected to the pion decay channel where the surface muons are separated and the neutrino beam is produced. A μSR spectrometer is foreseen while the neutrino detector is envisaged 3 meters away from the end of the pion decay channel. A decay muon section is also envisaged from the EMuS layout shown in Figure 1. There are three independent operational beam modes for EMuS, the surface muons ($p_\mu = 29$ MeV/c ± 5%), decay muons ($p_\mu = 100\text{-}200$ MeV/c ± 10%) and the neutrino ($p_\pi = 300\text{-}500$ MeV/c) ones.

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[1] Surface muons are produced on the target surface and produce a beam of maximum spin polarization from positive pions decays at rest, while decay muons are defined as the ones produced from pions decays in the capture solenoid

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TARGET AND SOLENOID OPTIMIZATION

A graphite target is foreseen with density, length and radius of 1.82 gr/cm^3, 30 cm and 2.28 cm respectively, and is placed at the center of the solenoid with an optimal polar angle of 15 degrees in respect to the solenoid central axis. In order to maximize the protons-target interactions, protons enter the solenoid with the same polar angle but a slightly deferent azimuthal one due to their helical trajectories, and the target direction cosines are the same with the proton beam ones when the latter are crossing the center of the target. Such an arrangement is necessary in order to increase the surface muons production and to facilitate the extraction and separation of the spent protons[2] from the solenoid and the muons/pions beams respectively, and is a novel idea [4]. The choice of graphite is based on studies performed with FLUKA[3] monte carlo [5,6] that show superior particles yields, lower neutron production and energy deposition than other materials with higher atomic number as titanium, copper and tungsten at the nominal proton kinetic energy of 1.6 GeV [4]. Alternatively, beryllium could be used.

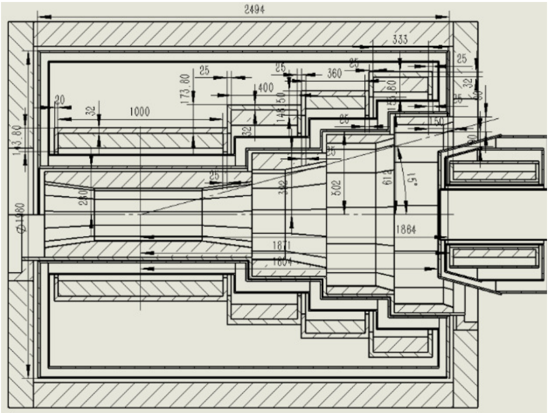

Figure 2: An EMuS conceptual 4-coils/3-steps, 2.5 m long solenoid design with a hole downstream for high energy spent proton extraction.

The solenoid is foreseen to be a 4-coils/3-steps design in order to reduce the cost of the NbTi superconducting wires at the expense of limited magnetic volume and lower shielding thickness especially for the 1st-coil. The adiabatic magnetic field has a maximum of 5 T about the middle of 1st-coil that is reduced to a minimum of 2.3 T at the entrance of the matching transport solenoid. The adiabatic field is used to reduce the transverse momentum of the captured charged particles thus reducing their beam divergence. The high magnetic field of 5 T is a requirement only for pions and subsequently for the neutrino beam and not for surface muons [4]. An inverse cubic taper polynomial function was chosen as field representation that led to the coil design because of the slower adiabatic decrease of the field compared to other polynomial functions [7], which allows thicker shielding for the coils due to the slower adiabatic expansion of the muons/pions beams. Furthermore, there are two options for the NbTi superconductor wire under consideration, one with aluminum stabilizer (Rutherford cable) and another with monolith copper matrix or wire-in-channel configuration [8].

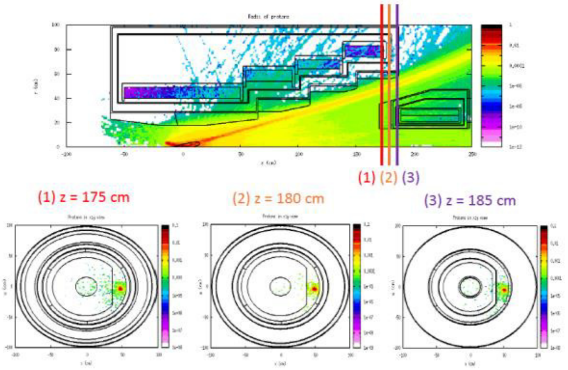

Figure 3: Proton beam raytracing within the capture solenoid. The minimal interaction with the shield and extraction of the high energy spent protons is shown.

A careful optimization has been performed between the proton beam parameters, adiabatic magnetic field, target orientation and apertures of the shields in order to minimize any secondary interaction of spent protons with the shields. Their extraction is done downstream between the shields of the 4th-coil and the transport matching solenoid. That way, they are not contaminating the muons/pions beams. That study led to the solenoid design in Figure 2. The protons raytracing can be seen in Figure 3.

Our physics requirement for EMuS is to capture and transport at least 10^8 to 10^9 (with 80-82% polarization) and 10^{11} surface and decay muons per second respectively depending on their beam divergence, which are achieved [4] and comparable or better than other facilities [9].

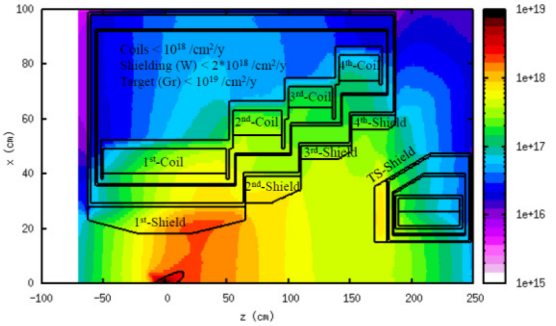

Figure 4: Neutron flux / cm^2 / year. The flux is reduced by 20-50% for neutrons with E_k > 100 keV.

RADIATION STUDIES

Radiation studies have been performed for the capture solenoid at 4 kW power, 1.6 GeV kinetic energy and 1 Hz repetition rate of the protons. The studies include energy deposition, neutron fluxes and radiation damage in terms of dpa (displacement per atom [10]) on the shields and coils. Of primary concern is the shielding of the 1st-coil where the maximum of the radiation is released. Several shield thicknesses from 5 to 15 cm are being studied us-

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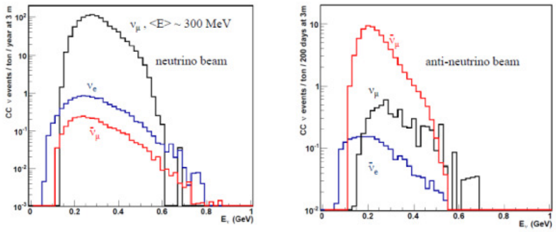
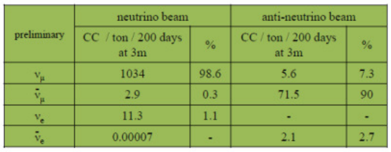
[2] According to the exponential low of the nuclear interaction length, 48% of the proton beam is interacting with a target length of 30 cm.

[3] FLUKA is also used for the next studies presented in this paper.

ing either tungsten or a combination of copper and tungsten, the latter in order to moderate better the neutrons. Maximum values are found to be in the order of 1 mW / cm^3, 10^{18} n / cm^2 / year[4] and 0.001 dpa / year for energy deposition, neutron flux (with $E_k > 100$ keV) and radiation damage respectively. The neutron flux in the capture solenoid for tungsten shielding is shown in Figure 4. Those results indicate the feasibility of the project and also validate the geometrical design. The radiation studies are on-going with shielding optimization, cooling design and the choice of the NbTi wire type since the copper cable is cheaper but more prone to radiation damage than the aluminum one.





preliminary	neutrino beam		anti-neutrino beam	
	CC / ton / 200 days at 3m	%	CC / ton / 200 days at 3m	%
ν_μ	1034	98.6	5.6	7.3
$\bar{\nu}_\mu$	2.9	0.3	71.5	90
ν_e	11.3	1.1	-	-
$\bar{\nu}_e$	0.00007	-	2.1	2.7

Figure 5: A preliminary calculation of the EMuS neutrino and anti-neutrino beams assuming 100% charge separation and transmission efficiencies for π^+ and π^- after the capture solenoid.

THE EMuS NEUTRINO BEAM

The possibility of a neutrino beam at the EMuS in order to measure neutrino cross sections below 1 GeV is being studied [11]. In order to study the physics potentiality of the beam, a pion decay channel with length of 25 m, aperture of 30 cm with a constant solenoidal field of 3 T has been simulated preliminary. The detector was considered 3 meters after the end of the decay channel. Both neutrino and anti-neutrino beams are studied. The ν_μ flux and charged currents (CC) are calculated to be 2.6×10^{16} ν_μ / m^2 / year and about 1000 CC / ton / year with an average energy of 200 and 300 MeV respectively. That number of CC events indicates the feasibility of a CC cross section measurement at 300 MeV. Studies have shown possible upgrades of EMuS as proton power up to 20 kW at CSNS-II and larger apertures of the capture coils and pion decay channel, could increase the neutrino rate by a factor of 25, thus opening possibly the window to explore also sterile neutrino searches [11]. The CC events for different neutrino flavors for the neutrino and antineutrino beams at CSNS-I are shown in Figure 5.

CONCLUSIONS

The high intensity muon source project at CSNS is optimized for both muon and neutrino experiments. A high intensity muon beam could be achieved and used for μSR or other muon experiments while the neutrino beam could provide a large number of CC events for a cross section measurement.

All those physics potentialities are achieved with a novel and cost effective design of a superconductive solenoid that has four coils in a stepped arrangement and a tilted cylindrical target, which allows the extraction of the high energy spent protons through a hole at the corner of the 4th-coil and their separation from the muons/pions beams. This particular capture system configuration is used in order to extend the experimental potentialities of EMuS with the aforementioned decay muons and neutrino beams by capturing higher momentum pions. Confidently, the radiation studies support the feasibility of the project due to low proton beam power.

ACKNOWLEDGEMENTS

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[4] A year equals to 200 days of accelerator operation or 2.7×10^{20} protons on target at EMuS.