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Horn vs. Solenoid Options for Neutrino Factories

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Pion capture scheme is a key issue to realize neutrino factories based on high intensity muon source. Two options have been discussed in studies for neutrino factory. One is solenoid capturing scheme in which pions are trapped with strong solenoidal field. The other is magnetic horn focusing system which focus pions forward with pulsed toroidal field around the production target. In this paper, concepts of these options are reviewed, and pros and cons are compared for further discussion to evaluate the options.

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1. Introduction

In neutrino factories, neutrinos are generated from decay of accelerated muons. To inject muons in accelerators, muon beam should be focused in small radius and small divergence. Relatively low-energy pions, less than 1 GeV, is preferred to be collected to produce muons with momentum of 0.2 GeV/c for better ionization cooling. For super-beam experiments, magnetic horns are employed to collect and focus pions from production target. Horns are capable to focus forward-emitted pions from point to parallel. In a muon-to-electron conversion experiment, negative-charged muons have to stop in a thin foil. Muons with the momentum of less than 0.1 GeV/c is necessary at the stopping foil, while high energy muons should be suppressed to avoid background electrons against the rare decay search.

2 Solenoid options

2.1 Solenoid in neutrino factories

The solenoid system for neutrino factories has been considered in the US studies [1,2] and the study in Japan [3]. The US study shows a conceptual design of the capture solenoid system with the following specifications. The magnetic field at the production target reaches 20 Tesla by combining superconducting coil and normal conducting coil surrounding the target. The inner bore at the target is 15 cm. Then, pions with the transverse momentum of up to 0.45 GeV/c can be captured. Magnetic field is decreased gradually down to 1.75 Tesla in the decay solenoid with the inner bore of 60 cm. The field is tapered in 6 m.

2.2 Solenoid in mu-e conversion experiments

The solenoid capture system will be used in mu-e conversion experiments proposed in Japan [7] and US [8]. The experiments need low-energy pions and suppressed high-energy portion. Therefore the capture system collect backward emitted pions, which momentum have a peak around at 0.1 GeV/c. The maximum magnetic field is designed to be 5 Tesla in the capture solenoid. Proton beam escaping forward will be absorbed at the beam dump far from the solenoid. Solenoid system for neutrino factories could be used with low-energy proton beam at the early stage.

3 Horn options

3.1 Horns in neutrino factories

Horn capture system for neutrino factories has been discussed in the European neutrino factory studies [4]. The horn system is designed to be operated with pulsed current of 300 kA on the internal horn and 600 kA on the external horn. The internal horn has inner bore of 8 cm and the production target is embedded.

3.2 Horns in K2K

Horns have been used in the neutrino experiments to produce neutrinos from pion decays by focusing pions emitted forward and injecting them into decay volume. Double horn system was used in the K2K experiment. Pulsed current of 250 kA was loaded in 2.5 msec with 2.2 sec cycle. The horn body is made of aluminum alloy conductor. The production target with diameter of 3 cm made of aluminum is embedded in the first horn. The system has been successfully operated over one year, i.e. 10^7 pulses.

4 Comparison between horns and solenoid options

4.1 Muon yields

Muon yields in various studies using horn and solenoid capture systems are summarized in Ref.[6]. The US study-2a[1] shows a capability to obtain yields of 0.8 muons or pions for one 25-GeV proton on target. The CERN study[5] discuss about the horn system and estimate the yields of 0.022 muons or pions for a 2.2-GeV proton on target, while the solenoid is estimated to collect 0.037 muons or pions by the simulation with the same condition as in the horn case. The CERN study indicates that better yields can be achieved by making the inner conductor be thinner or by increasing operation current to 400 kA, although discussion on the strength of the conductor could become more severe.

The solenoid can capture both positive- and negative-charged pions, and can transport all of them to consequent accelerator, while the horn magnet focuses single-sign pions only. Reversed current should be loaded when we obtain muons with opposite sign.

4.2 Radiation dose and Life time

Horn focuses pions forward in parallel and inject them into consequent solenoids. The proton beam dump could be located outside the solenoid system, if proton beam can be extracted from the horn magnet. In the case, the gap between horn magnet and decay solenoid should be enough large. On the other hand, in solenoid capturing, it is difficult to extract proton beam off the solenoid. Therefore, all the beam energy should be absorbed inside the solenoid bore. Mercury pool inside solenoid magnet bore is designed as the beam dump. Mercury is injected in target region to act as pion production target, and then is stored in the solenoid.

For high power proton beam, radiation dose on the solenoid system is an issue. Portion of beam power deposited in the target cell is estimated to be 70%. For 1 MW proton beam, 0.6 MW will be loaded on the inner shielding, and 40 kW is deposited in the coaxial shield around the target. The peak dose rate is 10 W/g, i.e. 10^{11} Gy for one year operation. Life of the inner shielding is estimated to be 5 years due to high radiation dose by 1 MW proton beam power. Radiation dose on the superconducting coil is 6 MGy corresponding to its life of 16 years. In the horn capturing scheme, radiation shield can not be inserted in the horn around the production target to avoid absorption of produced pions, in principle. Life time of horn magnets is limited by yield strength after severe vibration by pulsed current.

4.3 Staging capability

Some of staging construction scenario to realize a neutrino factory is considered. The first scenario is upgrade from superbeam experiment. The superbeam experiments utilize the horn focusing and long decay volume to obtain neutrinos from pion decays. By combining the horn with the decay solenoid, we could realize a muon beam. This could be a first step towards a neutrino factory. Then, by replacing the horn capture system by the solenoid system, high intensity muon source could be achieved. The second scenario starts from a mu-e conversion experiment in which solenoid system is considered to backward-emitted low-energy pions are transported to decay solenoid. If beam dump scheme inside solenoid is confirmed, forward pions are also candidates of the muon source for mu-e conversion experiments at the early stage of neutrino factories. It should be noted that solenoid scheme can collect both-sign muons, therefore it is mandatory for a muon collider project.

5 Summary

Solenoid option is straight forward way to collect soft pions and then obtain muons in a decay solenoid. R&D on radiation damage of insulator up to 10 MGy is necessary. Horn can capture and focus pions forward in parallel. The output needs to match to decay solenoid in a Neutrino Factory scheme. R&D on pulsed operation is necessary to overcome 10^9 pulses in a year at 50 Hz cycle. Beam dump and radiation dose in target station is an issue. Also maintenance scenario should be established to realize high intensity neutrino factories.

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