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NEUTRINO FACTORIES

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Over the last decade there has been significant progress in developing the concepts and technologies needed to produce, capture and accelerate $O(10^{21})$ muons/year. This development prepares the way for a new type of neutrino source : a Neutrino Factory. This article reviews the motivation, design and R&D for a Neutrino Factory.

1. Introduction

Over the last decade there has been significant progress in developing the concepts and technologies needed to produce, capture and accelerate $O(10^{21})$ muons/year. This prepares the way for a Neutrino Factory (NF) in which high energy muons decay within the straight sections of a storage ring to produce a beam of neutrinos and anti-neutrinos. The NF concept was proposed[1] in 1997 at a time when the discovery that the three known types of neutrino (ν_e,ν_μ,ν_τ) can change their flavor as they propagate through space (neutrino oscillations[2]) was providing a first glimpse of physics beyond the Standard Model.

2. Concept, Beam Properties, and Physics Reach

Conventional neutrino beams are produced from charged pions ($\pi^\pm$) decaying in a long channel. The resulting beam consists of ν_μ ($\bar{\nu}_\mu$) from π^+ (π^-) decays. To fully explore neutrino oscillations it is desirable to also have ν_e ($\bar{\nu}_e$) beams by, for example, exploiting the decays $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ ($\mu^- \rightarrow e^-\nu_\mu\bar{\nu}_e$). Since $\mu^\pm$ live 100 times longer than $\pi^\pm$, a linear muon decay channel would need to be tens of kilometers long. To overcome this difficulty, in a NF the muons are injected into a storage ring with long straight sections. The fraction *f* of muons

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that decay in the straight section is given by the ratio of the straight section length to ring circumference. In NF designs typically $f \sim 0.3$.

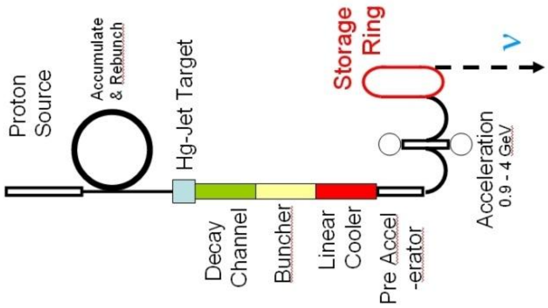

Figure 1: Neutrino Factory schematic.

A NF is shown schematically in Fig. 1. It consists of:

i) A high-power multi-GeV proton source.

ii) A target within a high-field solenoid followed by a lower field larger radius solenoid $\pi^{\pm}$ decay channel.

iii) A system of rf cavities to capture the daughter muons into a bunch train, and then apply a time-dependent acceleration to increase the energy of the slower (low energy) bunches and decrease the energy of the faster (high energy) bunches (phase rotation).

iv) A cooling channel that reduces the beams transverse phase space so that it fits within the acceptance of the first acceleration stages.

v) An acceleration scheme that accelerates the muons.

vi) A storage ring with at least one long straight section that points through the earth to a distant detector.

End-to-end NF simulations show that if the primary proton beam power is ~4MW there will be up to $O(10^{21})$ muons per year decaying in the beam-forming straight section. In a near detector the resulting event rates would be very large. For example, a few tens of meters from the end of a 50 GeV NF, 10^{21} muon decays would result in $O(10^{7})$ neutrino events/g/cm^2. Perhaps even more

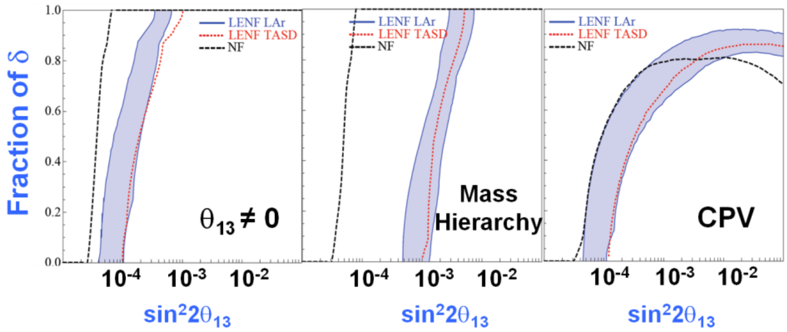

Figure 2: Fraction of all possible values of CP phase δ for which a discovery would be made at >3σ, shown as a function of $\sin^2 2\theta_{13}$ for a low energy 4 GeV NF (labeled LENF) and high energy 25 GeV NF (labeled NF). A discovery would be made in the regions to the right of the curves. Figure based on Ref. 3.

exciting, in a very distant detector the event rates are sufficient to probe neutrino flavor transition probabilities down to $O(10^{-4} - 10^{-5})$.

Since muon decays are well understood, a NF offers low systematic uncertainties on beam fluxes and spectra. This provides an advantage compared to conventional neutrino beams, but the real NF advantage comes from the ν_e ($\bar{\nu}_e$) in the beams since the transitions $\nu_e \leftrightarrow \nu_\mu$ ($\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$) are expected to play a special role in future measurements. In a conventional beam the initial flavor is ν_μ and experiments must search for $\nu_\mu \rightarrow \nu_e$ transitions. The experimental sensitivity is eventually limited by a small ν_e component in the initial beam and by backgrounds in which π^0s from ν_μ interactions are misidentified as electrons, faking ν_e interactions. This makes it difficult to probe oscillation probabilities below $O(10^{-2})$. However, a NF experiment can search for ν_μ appearance from $\nu_e \rightarrow \nu_\mu$ transitions by looking for a "wrong-sign muon[1]", i.e. a muon of opposite sign to the muons stored in the NF. It is straightforward to suppress backgrounds to $\leq O(10^{-4})$ of the total event rate.

A series of studies[4,5] have explored the ability of NF experiments to establish a non-zero value for the mixing angle θ_{13}, determine the neutrino mass hierarchy, and observe CP violation (CPV). The sensitivity depends upon $\sin^2 2\theta_{13}$ and the CP phase δ. In Fig. 2 the simulated sensitivity for a 25 GeV NF is compared with corresponding sensitivity for a lower energy 4 GeV NF. The NF would extend the "physics reach" in $\sin^2 2\theta_{13}$ –space down to O(10^{-3} – 10^{-4}).

3. Design and R&D

Over the last decade NF R&D has been advanced by a series of design and simulation studies complemented by component development and experimental tests. Studies[6] in the U.S. established viability, defined an initial R&D program, and produced a first NF cost estimate. The later studies improved the design to increase performance and reduce cost. During this period NF R&D also became "internationalized". In 2006 the International Scoping Study (ISS), hosted by RAL in the U.K., produced physics[5], accelerator[7], and detector[8] reports.

3.1. *Proton Beam and Target*

At the NF front-end the proton source must deliver short high-intensity multi-GeV bunches onto a target. The ISS baseline parameters are:

(i) Proton energy $5 < E_p < 10$ GeV, chosen to maximize $\pi^{\pm}$ production at fixed beam power.

(ii) Bunch length $\sigma_t \leq 3$ns, needed because the downstream phase rotation channel requires initially short muon bunches.

(iii) Beam power = 4MW.

(iv) A liquid Hg-jet target injected into a 20T solenoid. A high-Z target is chosen to maximize $\pi^{\pm}$ production. The 20T solenoid radially confines essentially all $\pi^{\pm}$ coming from the target. The Hg-jet choice avoids the shock and radiation damage related target-lifetime issues that arise in a solid target. A system of solenoids downstream of the target matches the 20T solenoid into a larger bore 2T decay channel.

Multi-GeV multi-MW proton source designs are now being developed at a number of laboratories around the World, motivated by a broad range of interests which include, for example, high-intensity convention neutrino beams. Proton source R&D is being pursued within this broader context. We can anticipate that at least one viable design for a NF-class proton source will exist within a few years. Target R&D has also advanced in recent years, and has culminated in the Mercury Intense Target experiment (MERIT[9]) which has successfully demonstrated a Hg-jet injected into a 15T solenoid and hit by a suitably intense beam from the CERN PS. The jet was viewed by high speed cameras which enabled measurement of (i) the time before the jet was disrupted, (ii) the velocity of jet fragments after disruption, (iii) the length of the segment disrupted, and (iv) the time before the jet re-established itself. Preliminary results suggest this technology could support beam powers > 4MW.

3.2. *RF in Magnetic Channels*

The bunching, phase rotation, and cooling channel designs require high gradient normal conducting rf cavities operating in a magnetic channel. The initially preferred design exploited the penetrating nature of muons by using cavities in which the normally open rf cells are closed with thin conducting windows. At fixed peak power this doubles the effective accelerating gradient, and hence halves the required number of rf power sources. Thin beryllium windows for this purpose have been demonstrated in an 805 MHz test cavity. However, tests show that when this type of cavity is operated within a multi-Tesla co-axial solenoid the maximum rf gradient that can be achieved before breakdown is reduced. It is possible that, with further R&D, surface treatments can be found to mitigate this effect. Other solutions have also been proposed including:

(i) Using cavities filled with high pressure hydrogen gas[10]. An 805 MHz cell has been built and tested in a high field solenoid. No appreciable degradation of performance was observed with increasing magnetic field. In the coming months this technology will be tested in the presence of an intensely ionizing beam. It is possible that the ionization created in the cavity will limit its performance.

(ii) Using "magnetically insulated" cavities[11]. The magnetic field is designed so that it is parallel to surfaces where the rf gradients are maximum. This is expected to prevent energetic electrons from hitting these surfaces and causing problems.

(iii) Designing cooling channels in which the cavities are in regions of low magnetic field. This is not a preferred solution since it will mean longer less efficient channels.

Within the next couple of years the ongoing R&D is expected to determine which of these options are viable.

3.3. *Bunching, Phase Rotation and Cooling*

At the end of the decay channel the daughter muons have drifted some tens of meters, resulting in a time-energy correlation with the high-energy particles leading the low-energy particles. The decay channel is followed by a buncher section that uses rf cavities to form the beam into a bunch train, and a phase-energy rotating section that decelerates the early-rf-phase high energy bunches and accelerates the late-rf-phase low energy bunches, so that each bunch has the same mean energy. Present designs deliver a bunch train that is 50m long, captured within a 2T solenoid channel. The buncher parameters are determined by considering reference particles (1, 2) with velocities β_1 and β_2. The rf voltages are increased along the channel, with frequencies f_{rf} and phases set to place 1 and 2 at the center of bunches. This can be accomplished if the rf wavelength λ_{rf} increases along the buncher[12]:

$$N_B \lambda_{rf}(s) = N_B \frac{c}{f_{rf}(s)} = s\left(\frac{1}{\beta_2} - \frac{1}{\beta_1}\right) \tag{1}$$

where s is the distance from the target. N_B is an integer. In the present design, at the end of the channel all bunches have a mean momentum ~230 MeV/c, with μ^+ and μ^- bunches interleaved within the cycle. The reduction in overall energy spread effectively increases the number of useful muons by about a factor of 4.

The number of muons accepted by the downstream accelerators can be further increased by reducing the two-dimensional phase-space-area (emittance) in each transverse direction (ε_x and ε_y) by a factor of a few. This can be accomplished using "ionization cooling[13]" in which the muons lose energy by ionization as they pass through an absorber. This reduces their momenta in the longitudinal- and transverse-directions. An rf cavity then replaces the lost energy by reaccelerating in the longitudinal direction. After repeating the process many times, the transverse momenta (and transverse emittances) are reduced. The rate at which the normalized transverse emittance $\varepsilon_{xN} = \beta\gamma\, \varepsilon_x$ changes as muons with energy E_μ (GeV) lose energy by ionization loss dE_μ/ds within material with radiation length L_R is given by:

$$\frac{d\varepsilon_{Nx}}{ds} = -\frac{dE_\mu}{ds}\frac{\varepsilon_{Nx}}{E_\mu} + \frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu L_R} \tag{2}$$

where $\beta_\perp$ is the "betatron function" which characterizes the focusing strength at the absorber. The second term describes heating due to scattering in the absorber which ultimately limits the cooling process. To minimize the impact of scattering it is desirable to use a low Z (high L_R) absorber (e.g. liquid hydrogen or LiH) and to focus the muons strongly (small $\beta_\perp$) so that the focusing angles are much larger than typical scattering angles. The present baseline cooling channel design consists of a sequence of LiH absorbers and 201 MHz rf cavities within a lattice of solenoids that provide the required focusing. Simulations show that the cooling channel increases the number of useful muons by about a factor of 2. To provide a proof-of-principle demonstration, the international Muon Ionization Cooling Experiment (MICE[14]) at RAL is preparing to test an ionization cooling channel cell in a muon beam. MICE will measure the response of individual muons to the cell as a function of the incident muon parameters (momentum, position, direction) and the various channel parameters (absorber type, magnetic fields, rf parameters). The initial phase of the experiment, which establishes the muon beam and measurement systems, has begun. It is anticipated that MICE will be completed by 2011-2012.

3.4. *Acceleration and Storage*

Since muons are short-lived, acceleration must occur at high average gradient. The accelerator must also accommodate the phase-space occupied by the beam. Typically the normalized transverse emittances are $\varepsilon_{xN} \cong \varepsilon_{yN} \sim 4$ mm-rad, longitudinal emittance $\varepsilon_L \sim 36$ mm, momentum spread $\sigma_{\Delta p/p} \sim 0.1$, and bunch length $\sigma_Z \sim 0.16$m. The need for large transverse and longitudinal acceptances favors using low frequency rf. Acceleration systems have been designed assuming Superconducting rf (SCRF) gradients at 201 MHz ranging from 11 MV/m (already demonstrated[15]) to 17 MV/m.

Various acceleration schemes have been studied. Typically they begin with a linear "pre-accelerator" that accelerates the beam to about 1 GeV. The muons are then sufficiently relativistic to use a Recirculating Linear Accelerator (RLA) in which arc-sections return the muons to the same linac several times. Higher energies can be obtained using further RLAs and/or FFAG (Fixed Field Alternating Gradient) accelerators. The ISS scheme uses a new accelerator type (a "non-scaling FFAG[16]") to accelerate to 25 GeV. The EMMA[17] experiment at Daresbury will study non-scaling FFAG beam dynamics, which are interesting because the particles are accelerated out of the rf bucket. EMMA results will enable the attractiveness of this particular scheme to be better assessed.

After acceleration the interleaved μ^+ and μ^- bunches are injected into the NF ring, where they circulate until they decay. Both racetrack (two straight sections) and triangular (three straight sections) geometries have been proposed. In principle both μ^+ and μ^- bunches can be stored in a single ring, injected in opposite directions. However, in the ISS baseline design there are two separate racetrack rings, one for each muon sign, with the beam-forming straight sections pointing to two distant detectors at different baselines.

4. Outlook

The next NF step, which has begun, is the so called International Design Study (IDS) which hopes to deliver a "Reference Design Report" by 2012. By this time it is anticipated that all of the proof-of-principle tests will be completed and a NF could then become part of the particle physics "road map". If the community wishes to proceed, after a few years of additional R&D, it is plausible that construction could start as early as the late 2010's.

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