NEUTRINO FACTORY / COOLING EXPERIMENT

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Abstract

A Neutrino Factory based on a muon storage ring is perhaps the ultimate tool for studies of neutrino oscillations and possibly of leptonic CP violation. It may also open the way to muon colliders. Linear accelerators and their technologies are likely to play a dominant role in a Neutrino Factory complex. An overview of the different scenarios studied in the US, Japan and Europe will be presented. The basic layout of a Neutrino Factory consists of a high power proton driver, a high power target where pions are produced, which decay rapidly into muons. These muons are accelerated and fed into a storage ring producing a well-collimated neutrino beam by their decay. Emittance reduction ("cooling") of the muon beam is an important issue. A cooling experiment is therefore planned and some details will be discussed. Other ways for producing neutrino beams ("Super beams" and "Beta beams") will be briefly indicated.

1 INTRODUCTION

Is there any point in presenting the Neutrino Factory to a Linac community? On first sight the answer one is tempted to give, may be "No", because circular machines seem to play the most important role (Figs. 1,2,3). However, crucial parts of such a facility still rely on linac technology. The motivation to study and eventually to build a Neutrino Factory comes from the fascinating physics which is linked to neutrinos and for which the interest has strongly grown in recent years.

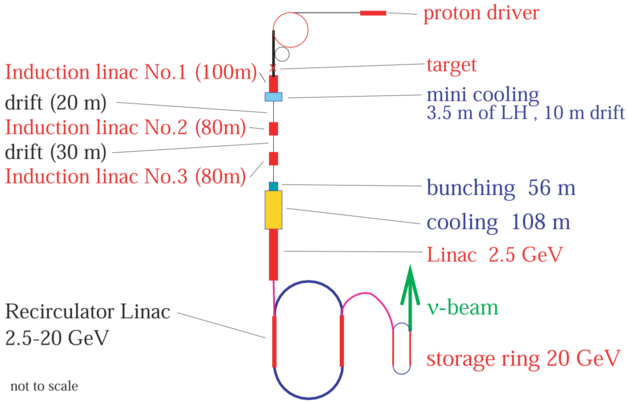

Figure 1: American (Study II) Scheme

A Neutrino Factory based on a muon storage ring is widely considered to be the ultimate tool for studies of neutrino oscillations, including possibly leptonic CP violation. The concept of neutrino oscillations implies that neutrinos have mass in contradiction to the Standard Model in Particle Physics. Although their mass does not seem large enough to explain dark matter in our cosmos, it is nevertheless an indication of new physics.

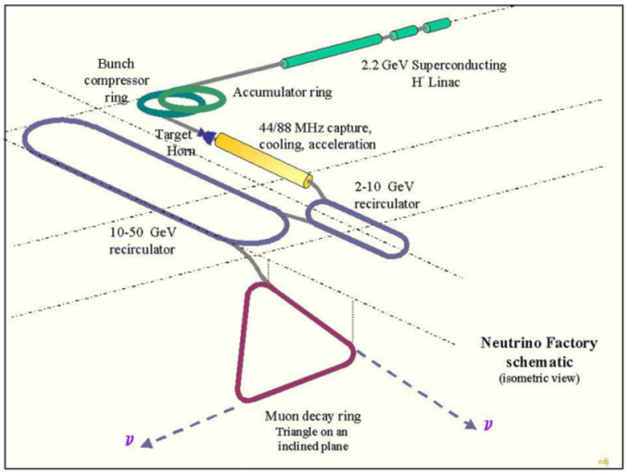

Figure 2: European Scenario

The possibility of discovering CP violation with leptons may shed light on the baryogenesis and might possibly explain the apparent asymmetry of matter and antimatter in our universe.

In spite of the high interest in neutrino physics, the origin of muon accelerator research was the concept of Muon Colliders first proposed in the 60s. It needed the idea of ionisation cooling to become a realistic scenario. Eventually this led to the formation of the Neutrino Factory and Muon Collider Collaboration (MC) [1] in 1995. The increased interest in neutrino physics resulted in a proposal for a Neutrino Factory based on a muon storage ring [2]. This has triggered a considerable international activity on Neutrino Factories, with international workshops held at Lyon in 1999, Monterey in 2000, Tsukuba in 2001, and most recently at the Imperial College in London in 2002 [3, 4, 5, 6]

2 BASIC PRINCIPLE OF A NEUTRINO FACTORY

A Neutrino Factory is an accelerator complex aiming at the production of a neutrino beam by the decay of muons. The muons are produced by the decay of pions, which are created by dumping a proton beam onto a target. The quality of the "beam" generated in this way is very poor. Its emittance in six dimensional phase space is huge (10^6 to 10^8 times larger than LEP). In order to achieve reasonable neutrino intensities, it is necessary to reduce the phase space occupied (beam cooling) and (or at least) to reduce the energy spread. This allows acceleration of maximum beam intensity in the subsequent machines without the need for expensive huge acceptances.

Nevertheless, in order to achieve 10^{21} neutrinos per year as requested by a large fraction of the neutrino physics community, very large beam powers (typically up to 4MW) are needed for the proton beam. There are currently several projects to produce such beams being worked upon in different continents:

The *European* study [7] envisages using a superconducting linac accelerating a H$^-$ beam to 2.2 GeV, which fills an accumulator and compressor ring by charge exchange injection (Fig 2). As a target for this beam, a mercury jet is being studied, which together with a magnetic horn produces a maximum of pions for injection into a solenoidal channel where the pions decay into muons. To reduce the energy spread ("phase rotation") and the phase space ("cooling"), RF cavities are used together with liquid hydrogen absorbers. In order to have a clean bunch to bucket transfer, the RF frequency is identical to (or a harmonic of) the proton accumulator and compressor ring frequency. Fast acceleration of the muons is carried out in a high gradient linac, followed by recirculating linear accelerators (RLAs) and injection into a decay ring with long straight sections, where the decay of the muons produces the directed high intensity neutrino beam.

In the *American* study (Fig. 1)] fast cycling synchrotrons at considerably higher energies (16-24 GeV) are proposed. Capture of the pions is made with a high field superconducting solenoid and the reduction in energy spread is achieved with induction linacs. Rebunching the beam with RF cavities and RF acceleration combined with hydrogen absorbers performs the necessary cooling.

The *Japanese* study [8] foresees a proton driver of 50 GeV. FFAG (fixed field alternating gradient) accelerators are used for muon acceleration (Fig. 3). These machines have intrinsically a large phase space acceptance, so that cooling is not a priori necessary. Nevertheless some cooling would help several aspects of the scheme, like for example injection and ejection. Cooling in the FFAGs is also being studied.

It must be stressed that the main activity so far has been in the US, executed by the American Neutrino Factory and Muon Collaboration. This work has resulted in two studies, the first one at FNAL [9] and the second one at BNL [10] helped by a large collaboration of other laboratories. It has been demonstrated that the construction of a Neutrino Factory is technologically feasible. Nevertheless further R&D is recommended, in particular to try to reduce the cost of such a facility.

3 SPECIAL SYSTEMS IN THE NEUTRINO FACTORY AND TECHNOLOGICAL CHALLENGES

3.1 Proton Driver

The pion yield of the target is mainly dependant upon the power of the proton driver, needing up to 4 MW to generate the desired high muon intensity (10^{21}/yr). To a first approximation the pion production is independent of the proton energy (if it is above 2 GeV). However, there are some differences in the energy and direction of the produced pions.

At CERN the HARP experiment is studying the pion production mechanism in detail. However, it is already known, that at 2 GeV only high Z targets yield a satisfactory π^- production. Therefore, in the 2.2 GeV CERN scheme it is necessary to use a high Z target material, which unfortunately makes the use of carbon targets impossible. Carbon targets seem fairly robust, even at higher beam powers (beyond 1 MW) and might be interesting for schemes with higher proton energies.

CERN studies the use of a superconducting H$^-$ linac, followed by an accumulator and compressor ring to produce very short (1 ns rms) bunches at 44 MHz in a 3.3 μs long train. The repetition frequency of this scheme is 50 Hz yielding an average beam power of 4 MW.

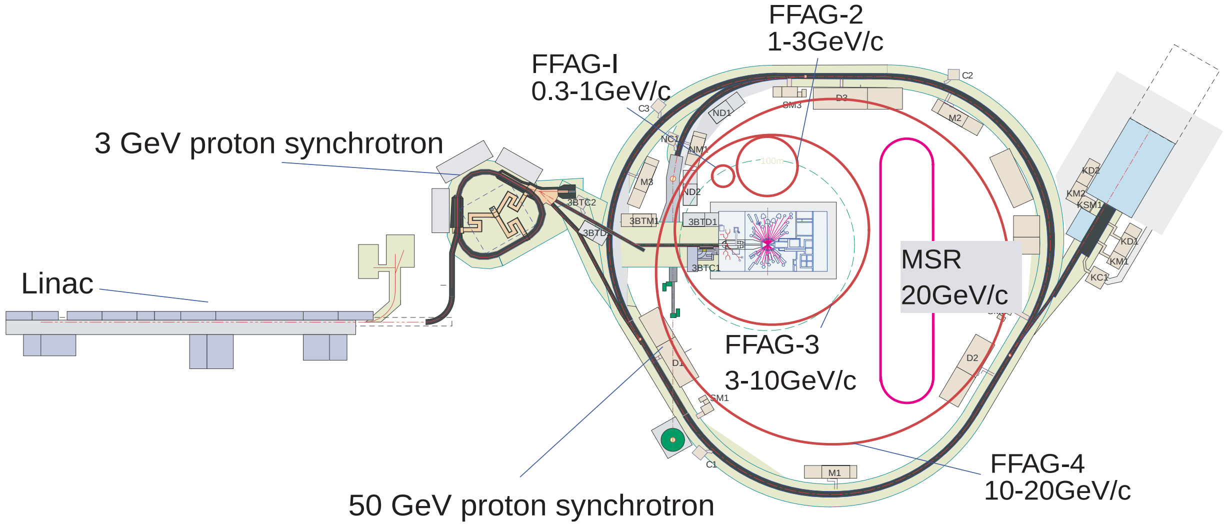

Figure3: Japanese Proposal (3 and 50 GeV rings are part of JAERI-KEK Joint Project)

Fast cycling synchrotrons were also studied and seem to be economical with some advantages due to the lower repetition rate. In particular a rapid cycling 8 Hz/30 GeV synchrotron has been studied, which could not only serve the neutrino factory but could also replace the 40 year old PS machine. The final decision for the proton driver energy will be influenced by cost issues and by possible dual uses of the machine.

The proton driver proposed in the American Study-II is an upgrade of the BNL Alternating Gradient Synchrotron (AGS) and uses most of the existing components and facilities. The existing booster is replaced by a 1.2-GeV superconducting proton linac. The AGS repetition rate would be increased from 0.5 Hz to 2.5 Hz. The total proton charge (10^{14} ppp in six bunches) is only 40 % higher than the current performance. The six bunches are extracted separately, spaced by 20 ms, so that the target, induction linacs, and rf systems that follow need only deal with single bunches at an instantaneous repetition rate of 50 Hz (average rate of 15 Hz). The average proton beam power is 1 MW. A possible future upgrade to 2×10^{14} ppp and 5 Hz could increase this value to 4 MW.

If the facility were to be built at Fermilab, the proton driver would be a new 16 GeV rapid cycling booster synchrotron. The initial beam power would be 1.2 MW, and a future upgrade to 4 MW would be possible. A less ambitious and more cost-effective 8 GeV proton driver option has also been considered for Fermilab.

Technological challenges: High power is a challenge in terms of beam losses, which can cause undesired activation of the machine components making hands-on maintenance impossible. The stability of the very short bunches is also not a trivial issue. In the CERN scheme of an H^- linac with charge exchange injection into an accumulator ring the stripping foil needs very careful attention. A common problem of all proton drivers is the production of very short bunches, in order to reduce finally the energy spread of the muons with a scheme involving debunching and phase rotation.

Target

Targets using liquid mercury are being studied extensively and are at present the choice for the CERN scheme. The high Z of mercury makes it suitable for the low proton energy and in addition it is believed that a liquid metal jet is best suited for high instantaneous beam powers. A big advantage of a mercury target might be the possibility of removing a large part of the induced radioactive products by distillation. Extensive studies of Hg targets are being made by BNL and CERN. BNL is also investigating the use of different alloys and of special carbon targets.

Technological challenges: The target must cope with a very high instantaneous beam power, which may destroy it within a few pulses. To replace the target for every beam pulse is an attractive solution. A mercury jet for example could offer fresh mercury to the next beam pulse, provided the sputtered mercury can be removed quickly enough. The use of rotating toroidal targets was also proposed. Stationary targets are most likely limited to well below 4 MW. The repetition frequency plays a very important role. On one hand, the target with a higher repetition rate can more easily survive one pulse as the power per pulse is lower. On the other hand, providing a new target for every beam pulse is easier with a lower pulse repetition rate. In all cases, huge amounts of radioactive material will be produced which must be taken care of. This implies a delicate choice of the target material and its surroundings. In any case remote-handling facilities must be foreseen.

Pion Capture and decay channel

In the CERN scheme a magnetic horn is used to focus the pions into a solenoidal channel. The American studies prefer a 20 T solenoid with its field gradually decreasing to the field used in the decay channel. The length of this channel is typically 30 m, allowing most of the pions to decay into muons.

Technological challenges: Magnetic horns have been built for many different applications for several decades. However, a horn that is operating at high currents (typically 300 kA or higher), at a high frequency (50 Hz in the CERN scheme), in an extremely high radiation environment and possibly with corrosive mercury is quite a novelty and success is not a priori guaranteed. The American proposal of a 20T solenoid using a combination of a super conducting coil on the outside and a copper coil inside, operating in a high radiation environment is also not trivial. Nevertheless, calculations have shown that the lifetime is quite reasonable.

Phase rotation

Phase rotation in the CERN scheme is achieved with 88 MHz rf cavities. The American scheme uses induction linacs. In both cases one lets the muon beam generated via the very short (1 ns rms) proton beam spread longitudinally and then use the corresponding time-position correlation to correct the energy of the muons with a time-varying electric field. In the Japanese scenario this is done with low frequency RF cavities inside the first FFAG.

Technological challenges: The cavities in the phase rotation and cooling channel require high accelerating gradients. This is to achieve a fast acceleration of the muons in order to limit decay losses. Relatively low frequencies (40 to 200 MHz) are required to cope with the bunch length while providing a reasonable aperture for the beam. These cavities consume a large amount of rf power and therefore Be windows are planned in the cooling channels of the American study. These windows have to survive rf breakdown and must be cooled and should not detune the cavity when heated. In addition the production of dark-current either from one cavity or in "collaboration" between several cavities must be prevented in order not to excessively load the liquid hydrogen absorbers.

Cooling / Cooling Rings

To perform cooling, the beam is sent through liquid hydrogen absorbers, reducing the transverse and longitudinal momenta. Subsequent reconstitution of the longitudinal momentum occurs with RF cavities operating at 88 (CERN) and 200 MHz (US) respectively. Basically the cooling channel is a linear accelerator with liquid hydrogen absorbers.

The cooling channel will be fairly long and expensive, hence the interest in "ring coolers", where cooling is done over many revolutions. Also the Japanese scenario might use some cooling inside the FFAGs.

Technological challenges: RF cavities have similar problems like the ones in the phase rotation part. In addition the liquid hydrogen absorbers require several hundred Watts of cooling power at cryogenic temperatures. There is am eminent safety problem connected to the large amounts of hydrogen and the fragile windows, which must not contribute to the heating of the beam by scattering. Great progress has been made for the ring coolers, the problem of injection is solved (although expensive), but more technically realistic scenarios need to be introduced into the simulations.

Acceleration with RLAs

After the cooling the muons have to be accelerated to energies between 20 and 50 GeV. Normal synchrotrons are too slow and the decay losses of muons would not be tolerable (the muon's life time is only 2.2 μs). So-called recirculating linacs (RLA) are a good compromise between cost and speed. The scheme currently under investigation foresees a racetrack shaped RLA with separate arcs for each energy/pass. The beam spreader uses passive elements. This is only possible for muon energies above 2-3 GeV, making a first acceleration up to this energy necessary. One interesting alternative is the possible use of a rapidly pulsed synchrotron (risetime of tens of microseconds) feasible by making use of the fairly low repetition rate, at least in the US scheme [6].

Acceleration with FFAGs

For the time being only the Japanese proposal is using FFAGs. FFAGs have so far only been demonstrated with electrons, but a POP (proof of principle) machine at 1 MeV has been built at KEK for protons. Another FFAG with higher energy (150 MeV) is under construction. The very large transverse and longitudinal acceptance seems to be very attractive as phase rotation can be achieved inside the FFAG (using several turns instead of a long and expensive linear beam line) and transverse cooling might not be needed. It is clear, however, that this is not the way to go for muon colliders, where a small transverse phase space will be required to achieve the necessary luminosity.

Technological challenges: Injection and ejection is not easy, but a new "yoke-free" design of the bending magnets could ease that problem. Decay losses are higher, because of the relatively slow acceleration. The RF cavities have to operate at low frequency and high gradients.

Decay ring

This ring can have different shapes, but must have long straight sections in the direction where the experiment is located. In the most simple case it could be a race track, inclined to aim at an experiment that is hundreds or thousands of kilometres away. The second straight section will hence point up to the sky, where – most likely – there will not be any experiment. Triangles or bow-tie shapes are needed in case of two detectors.

Technological challenges: Although this is in principle an uncritical item, the radiation emitted by the decaying muons is quite high. Therefore, special precautions are required to protect the (superconducting?) magnets.

Detectors

A neutrino factory is of course not complete without detectors. Due to their exclusive coupling to the weak force most of the neutrinos pass through the detector without interaction. Therefore the number of events is proportional to the detector mass, making it compete with beam intensity in achieving the necessary statistics. Detectors may be as far away as 7000 km.

Muon Colliders

Some time ago regarded by some people as science fiction, it must be noted that the advances in cooling theory and technology are so impressive as to consider this type of machine as a real possibility in the future.

4 OTHER BEAMS

Super Beam

The generally accepted definition of a Super Neutrino Beam is a very intense neutrino beam from pion decay produced by a high power (>1 MW) proton accelerator. Although this is a conventional method of producing neutrinos, it is still technically challenging due to the high power and the high radiation environment. A Super Beam can be seen as a first step for a Neutrino Factory up to the target and including some focusing. Recent developments include the proposal of off-axis detectors to cut the high-energy part of the neutrino spectrum.

Beta Beam

The decay of muons is not the only possible source of neutrinos. Beta decay is another well-known mechanism. To produce a Beta Beam [11] radioactive isotopes are produced, in a synchrotron (e.g. SPS up to a few 100 GeV/u), fed into a storage ring and left there to decay. The isotopes ^{6}He and ^{18}Ne are envisaged with lifetimes of 0.8 and 1.67 s respectively. The problem of producing these isotopes in sufficient quantities and to accelerate them (10^{13} s^{-1}) does not seem too difficult. The main difficulties are the compression into the short bunches required to obtain a reasonable signal/background ratio in the detectors, and the activation of the machines.

5 COOLING EXPERIMENT

In both the American and European schemes, cooling plays an important role. Although nobody doubts scattering and dE/dx calculations, the detailed engineering of the cooling section is difficult. The object of the experiment is not to demonstrate the principle of cooling, which is expected if all components work, but more to learn how to build and operate a device that performs as desired, and additionally to verify the performance with a beam [12].

The concept of a cooling experiment has been extensively studied, and an international collaboration is being set up to realize it. It consists of a section of a cooling channel with emittance measurements before and after cooling. It appears feasible to reduce the emittance of a muon beam by 5-10%, and to measure this emittance reduction with an absolute precision of considerably less than 1%. To achieve this, a new concept for emittance measurement had to be developed: the single particle method. Unlike traditional measurements, the track of each particle is recorded in a solenoidal magnet. From this data, the six phase space coordinates x, y, p_x, p_y, E and t are calculated. This single particle data is then convoluted into emittances or phase space densities.

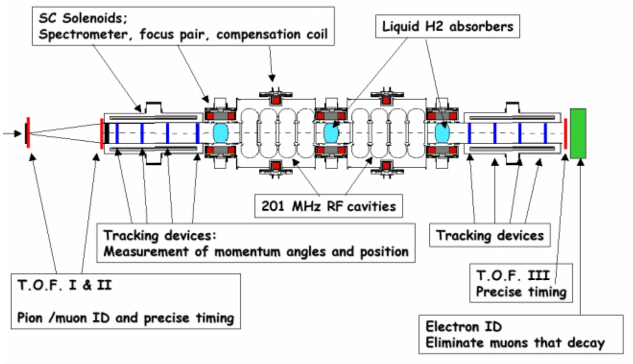

Figure 4: MICE Cooling Experiment

Layout of the experiment

Fig. 4 outlines the main elements of the cooling experiment for the baseline scenario. It uses two cells of the first part of the American 200 MHz cooling channel.

The incoming muon beam encounters first a beam preparation section where the appropriate input emittance is generated by a pair of lead scatterers. In addition, a precise time measurement is performed and the incident particles are identified. There follows a first measurement section, in which the particles' tracks are measured. Then comes the cooling section itself, with hydrogen absorbers and RF cavities, the focusing being provided by a series of superconducting solenoids. The tracks of the outgoing particles are measured in a measurement section identical to the first one. Finally, another time-of-flight (TOF) measurement is performed together with particle identification to eliminate those muons that have decayed in the apparatus.

6 CONCLUSIONS

There is no doubt that a Neutrino Factory could be built. The main question is how to reduce the cost of the investment and also the operating costs. There is still a lot of R&D work to do in order to find optimised solutions.

We would welcome more collaborators (even part time), in particular also with specialised know-how in cavities, high accelerating gradients, breakdown, dark-current, RF amplifiers, superconductivity (magnets and cavities), beam dynamics, radioactive activation of materials and many other fields. In case you are interested: Please contact us [1, 13, 14]!

7 ACKNOWLEDGMENTS

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