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Advanced neutrino beams

Rob Edgecock

Rutherford Appleton Laboratory, Chilton, Didcot, UK

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Abstract. The observation of neutrino oscillations forms one of the most exciting results in physics in the last decade. It has generated a lot of interest world-wide and many new experiments have been conceived to verify this observation and measure the oscillation parameters. However, a complete understanding of neutrino oscillation phenomenology requires new, high intensity terrestrial facilities. This paper will discuss a number of these new facilities, focussing particularly on the Neutrino Factory. The challenges posed by the design of the machine and R&D required to prove that it can be built will be described.

PACS. 29.20.-c Cyclic accelerators and storage rings – 14.60.Pq Neutrino mass and mixing

1 Introduction

The discovery of neutrino oscillations by the Homestake [1], Super-Kamiokande [2], SNO [3], KamLAND [4], etc, experiments forms one of the most important results in particle physics in the last decade [5]. It has lead to the creation of a number of new projects to investigate oscillations in more detail. For example, to measure more precisely the parameters describing atmospheric oscillations, a number of so-called long baseline neutrino oscillation facilities, in which the neutrinos are produced by an accelerator and detected several hundred kilometers away, are under construction, e.g. MINOS [6] and CNGS [7]. However, these projects are unlikely to have any impact on the so far unmeasured parameters of neutrino oscillations, θ_{13}, the CP-violation angle δ and the sign of Δm^2_{23}. For these, new, more advanced neutrino beams will be required and these are the subject of this paper.

There are three candidate types for these advanced beams: conventional superbeams (see Fig. 1), a Neutrino Factory (see Fig. 2) and a Beta-beam (see Fig. 3). In a conventional superbeam facility, e.g. J-PARC to Super-Kamiokande [8], the neutrinos are produced in the "standard" manner, by bombarding a target with a proton beam and focussing the pions created. However, the superbeam projects are different in two respects from the long baseline facilities currently under construction: (1) the proton beam power is much higher, and (2) most plan to use the off-axis technique in which the pion beam is pointed a few degrees away from the direction of the detector. This has the effect of kinematically suppressing the high energy neutrino tails and producing more neutrinos of a useful energy. In a Neutrino Factory, the neutrinos come from the decay of muons in a storage ring at an energy between 20 and 50 GeV. This has many advantages over a conventional neutrino beam, in particular the composition, intensity and energy spectra of the neutrino beams are precisely known and high intensities are possible. A beta-beam has a number benefits in common with a Neutrino Factory. However, the stored particles in this case are beta-emitters, in particular ^{6}He and ^{18}Ne which produce $\bar{\nu}_e$ and ν_e, respectively. As for the Neutrino Factory, the result is neutrino beams of precisely known composition, intensity and energy spectra.

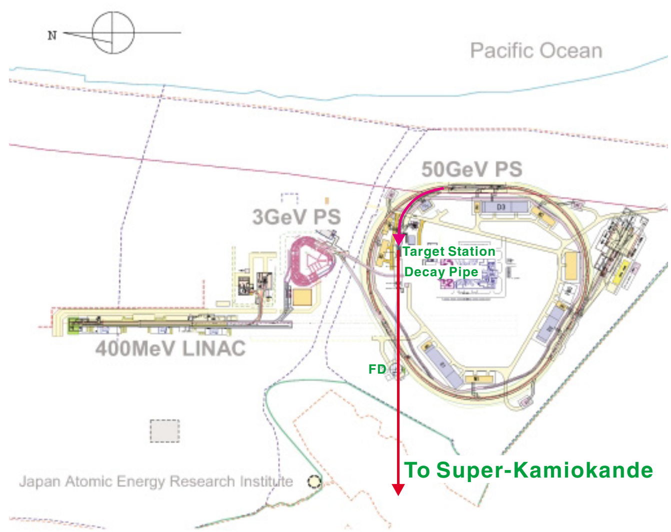

Fig. 1. The J-PARC to Super-Kamiokande neutrino superbeam project. The neutrinos are produced by extracting protons from the J-PARC 50 GeV Proton Synchrotron and firing them into a target to make pions. The pion beam will be at an angle of around 2^o to the direction to Super-K. Two phases of the project are envisaged: the first uses Super-K and an approximately 0.7 MW proton beam power. The second would use an upgraded beam power of 4 MW and 1 MT fiducial mass water Cherenkov detector. Neither are yet approved

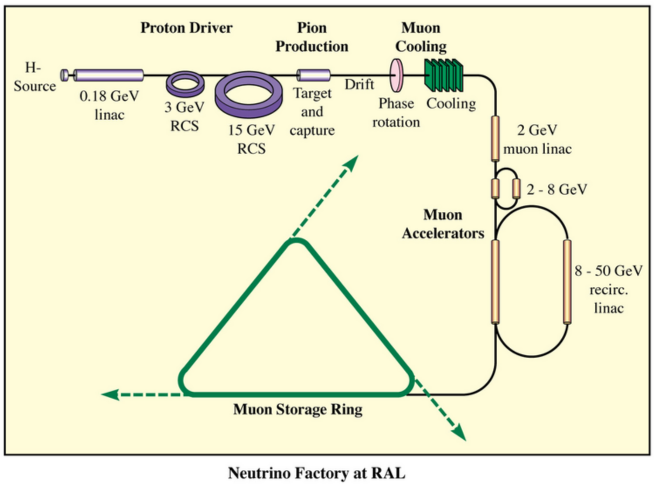

Fig. 2. A possible layout for a Neutrino Factory

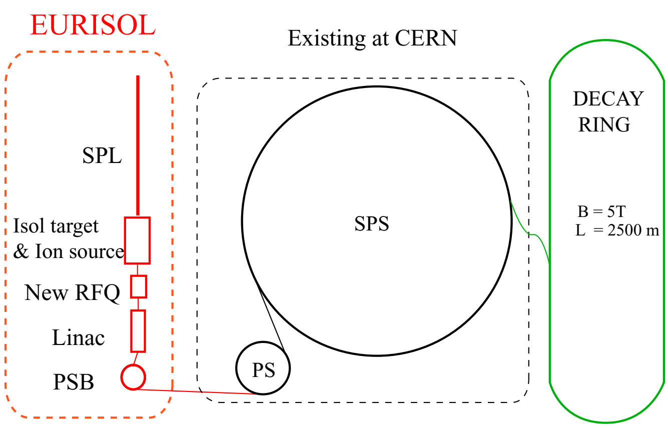

Fig. 3. Schematic layout of a beta-beam complex. The low energy part at the left is largely similar to the EURISOL project [9]. The middle section uses accelerators that already exist at CERN, while the storage ring on the right is entirely new

As current simulations indicate that the Neutrino Factory has the best sensitivity to the three unmeasured parameters of neutrino oscillations [10], the rest of this paper will concentrate on this machine. Section 2 will give an overview of the facility, while Sect. 3 will introduce the main technical challenges and describe some of the theoretical and experimental work being undertaken to solve these. Section 4 will draw conclusions.

2 Overview of a neutrino factory

A possible layout for a Neutrino Factory is shown in Fig. 2. As outlined in Sect. 1, the primary aim is the production of intense neutrino beams for precise long baseline neutrino oscillation measurements from the decay of muons in a storage ring. The muons are made by firing an intense proton beam into a target to make pions. As many of these pions as possible are focussed magnetically into a decay channel in which they decay to give muons. The

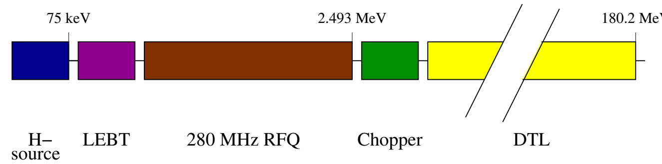

Fig. 4. The layout of the linear injector for the RAL Neutrino Factory layout in Fig. 2

muons produced have a large spread in energy and this must be reduced otherwise only a very small fraction of them will be captured in the subsequent accelerators. This compression takes place in two stages: phase rotation and cooling. The muons are then accelerated in a number of steps before injection into the storage ring.

Theoretical studies suggest that the muons must have an energy of at least 20 GeV and that two different baselines are desirable, preferably one around 3000 km and another of the order of 7000 km [11]. Typically these studies assume a total of 10^{21} muon decays per year in the storage ring, with up to 40% being in a straight-section and hence useful for physics. These parameters determine the performance of rest of the elements of the accelerator complex and lead to many challenges in their design and construction. These, and the R&D being undertaken to solve the problems, are described in the next section.

3 Main challenges and R&D

3.1 Proton driver

To achieve a sufficient number of muons, the proton driver should have a beam power of 4 MW, bigger than any equivalent machine that exists. At this power level it is essential to minimise beam losses at higher energies where they would cause significant activation, resulting in problems with access. This imposes stringent requirements on the preparation and handling of the beam. In addition, to aid in the compression of the energy spread of the muons via phase rotation, the proton bunch should be about 1 ns long. Thus, the large proton current required to achieve 4 MW must be compressed into a very short bunch.

The R&D activity on the proton driver is currently focussed on the low energy components of the linac injector (see Fig. 4). This is because these are crucial for the preparation of the beam to avoid losses at higher energy and it is essential to check their performance at the high beam currents required. In addition, although there are a number of designs for the higher energy stages of the proton drivers, the components of the injectors are the same for all Neutrino Factory designs and a number of other projects. An example is the HIPPI (High Intensity Pulsed Proton Injector) project [12] recently approved for funding from the EC Framework 6 programme [13]. In this, it is planned to construct a test stand consisting of a H-source, Low Energy Beam Transport, RFQ and chopper and to check their operation.

3.2 Target and pion collection

The target is a particular problem for the Neutrino Factory. As described in Secte. 3.1, the large proton power has to be compressed into a short bunch. In addition, to maximise the production of pions, the target cannot be too large transversely to prevent large losses from re-interactions. Thus, the energy density in the target is very large. This causes sudden heating, leading to severe stress in a solid target, and huge activation. Although targets of similar energy density already exist, they are run at a much lower frequency (∼1 Hz compared to up to 50 Hz) and there are indications that they are damaged by the beam [14]. In addition, it is very likely that the activation of the target and surroundings will be sufficient that the target area will require the same safety precautions as for a nuclear reactor.

As a result, R&D on targetry are essential. Two types of target have been proposed and are currently under study: a liquid metal (mercury) jet and a solid, rotating band. For the former, a liquid mercury jet has been tested both, but separately, by impinging a high intensity beam on to it and passing it through a strong magnetic field to simulate that used to capture the pions [15]. However, all of the jet velocities, beam energy density and magnetic field strength were less than required for a Neutrino Factory. In the future it is planned to perform the beam and magnet tests simultaneously and try to use parameters closer to those of the real situation. Special treatment of the mercury will be needed from the point of view of activation and this will also need to be investigated in detail.

For solid targets, the most important problems are the lifetime due to stress induced by the proton shock and the heating. Both of these are eased by using a rotating target of some form, so that different parts of the target are exposed to different proton bunches. Nevertheless, it is important to determine what the lifetime of such a target would be. Theoretical simulations suggest this would only be one proton pulse, though the existence of higher energy density targets suggests this is not the whole story. A series of lifetime tests on thin tantalum strips employing an electron beam used for electron beam welding have already been done [16]. The results from these are encouraging and further tests, under cleaner conditions, are planned. If successful, it is planned to extend these tests by employing a high energy density proton beam at ISOLDE at CERN [17] or at RAL.

3.3 Muon frontend

The "muon frontend", that is the section of the machine from the start of the pion decay channel to the first muon accelerator, is another section of the machine requiring particular R&D. As already discussed, the muons from the pion decay occupy a large volume in phase space and this must be reduced before the muons are accelerated otherwise the efficiency will be too small. This compression is performed in two stages: phase rotation and cooling. The currently preferred method for doing the first of these, phase rotation, is to use RF accelerating cavities to speed up the slower muons and to slow down the faster muons. This produces a compression in the muon energy, but does not cool the beam as it requires several 10s of meters to do this and the muon bunch spreads longitudinally due to the distribution of muon velocities. Looking in the plane of position in the bunch versus particle energy, we start with a distribution which has a small spread in postion and a large spread in energy and rotate it into one with a small (hopefully) spread in energy and a large spread in position. Hence the name phase rotation. Cooling the muon beam is particularly difficult as none of the existing accelerator cooling techniques will work quickly enough for muons. As a result, a new technique, ionisation cooling, has been proposed for a Neutrino Factory. In this, the muons are passed through some material, call an absorber, in which they will lose both longitudinal and transverse momentum via standard ionisation energy loss. If the lost longitudinal momentum is restored with RF-cavities after the absorber, this will result in a net reduction in transverse momentum and a net transverse cooling. Of course, things are never that simple and as well as cooling coming from the energy loss there is also heating coming from multiple scattering. The net cooling is a delicate balance between the cooling and heating terms:

$$\frac{d\epsilon_{\perp,N}}{dz} = -\frac{\epsilon_{\perp,N}}{\beta^2 E}\frac{dE}{dz} + \frac{\beta_{\perp}(13.6MeV/c)^2}{2\beta^3 E m_{\mu} L_R}$$

where $\frac{d\epsilon_{\perp,N}}{dz}$ is the rate of change in the normalised transverse emittance as a function of distance z, E, m_{μ} and β are the muon energy, mass and velocity, respectively, $\beta_{\perp}$ is the transverse betatron function of the muon beam and L_R is the radiation length of the absorber. It is clear from this that for a given muon energy, the heating term is smaller if L_R is larger and/or $\beta_{\perp}$ is smaller. The best compromise between energy loss and radiation length is for liquid hydrogen and $\beta_{\perp}$ is smaller when the beam convergence or divergence is large. This can be achieved using strong - superconducting - magnetic focussing. Thus, a "cooling cell" in ionisation cooling will be a complex device consisting of liquid hydrogen absorbers, high gain RF-cavities and superconducting magnets (see Fig. 5). As a result, a programme of R&D is required to check the physics of cooling, show that a cooling channel can be built and will cool and learn more about the cooling process.

This programme has three parts:

1. MuScat [19]: this is an experiment measuring the heating term in the cooling formula above, i.e. the muon multiple scattering, as this has not so far been measured. MuScat has had two runs at the TRIUMF laboratory in Canada and is currently analysing the data taken.
2. MuCool [20]: this is building the components of a cooling cell for a cooling channel with the aim of showing that they can be built and will work together. In addition, it is planned to check they still work when exposed to a high intensity (proton) beam from the proton linac at FNAL.

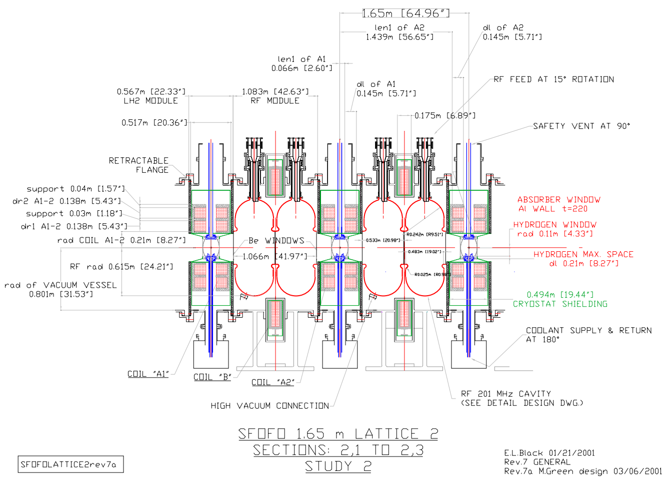

Fig. 5. The 1.65m SFOFO cooling cell from US Feasibility Study II [18]

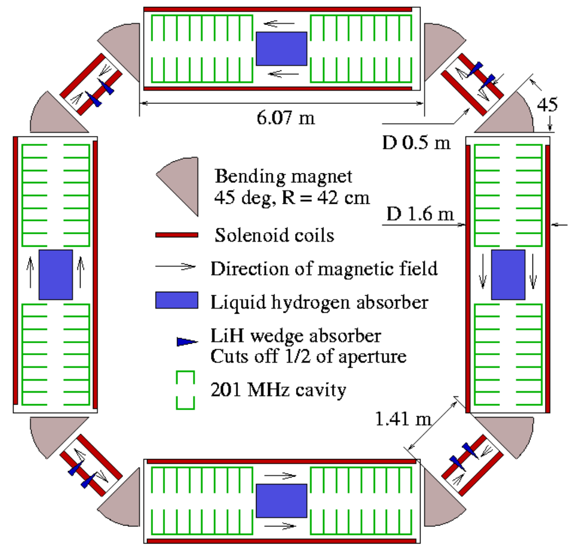

Fig. 6. The so-called Balbekov cooling ring, the first such ring proposed for a Neutrino Factory and Muon Collider

3. MICE [21]: this is the Muon Ionisation Cooling Experiment and will use two cooling cells developed in collaboration with MuCool. It will show that they will actually cool a muon beam and investigate the cooling process in great detail.

The main focus of cooling channel development recently has been on rings, rather than linear channels (see Fig. 6). There are two main advantages in doing this:

1. Although a linear cooling channel cools in both transverse planes, it tends to heat longitudinally due to fluctuations, or straggling, in the energy loss. A circular channel, on the other hand, has dispersion in the bending magnets, so that particles of different momentum travel along different paths. This means that higher momentum particles can be made to pass through more material than lower momentum particles by employing wedge-shaped absorbers. Thus a ring cooling channel can be made to cool longitudinally as well as transversely and give a much larger overall 6-D cooling.
2. A ring is clearly much more efficient as all the components are re-used many (about 10) times and hence, hopefully, much cheaper than a linear channel.

There are also a number of difficulties, of course, in particular heat deposition in the liquid hydrogen absorber and injection into the ring. In the case of the heat deposition, in a linear cooling channel this amounts to about 600W per absorber. In a ring, when the beam passes through each absorber 10 or more times, this now becomes 6kW! R&D are required to see how this amount of heat can be removed. The problem with injection is the enormous emittance of the muon beam which requires a very powerful kicker magnet to kick the beam cleanly into the ring. This magnet will need a much greater power than any existing equivalent kicker and R&D are again required to determine how to build it.

3.4 Muon acceleration

The acceleration of the muons needs to be fast, due to the muon lifetime, but the cost has to be kept under control. The requirement for rapid acceleration essentially eliminates conventional synchrotrons because of the time required to cycle the magnets (the current fastest cycling synchrotron is ISIS at RAL [22], which has a frequency of 50 Hz and hence cycle time of 20 ms). On the other hand, although acceleration via linear accelerators is fast, it is expensive for the muon energies required. As a result, two other techniques are under study: re-circulating linear accelerators [23] and Fixed Field Alternating Gradient synchrotrons (FFAGs) [24]. The former comprises a linac injector into a ring consisting of two linacs connected together with a number of separate magnetic arcs, each set for a different momentum. This re-uses each linac a number of times (4) and but avoids the need to ramp the magnets in the arcs. Nevertheless, the second US Feasibility Study [18] still showed this to be an expensive option. An FFAG, on the other hand, employs large aperture magnets with a strong gradient in the magnetic field as a function of radius (see Fig. 7) so that as they are accelerated, the muons move to a larger radius and see a stronger magnetic field. It again has the advantage that the magnets do not have to be ramped and that the RF-cavities are passed through many times (typically 10). In addition, a FFAG naturally has a large transverse acceptance and, if low enough frequency RF is used, it can also have a large longitudinal acceptance. As a result, it may be unnecessary to cool the muons if FFAGs are used for the acceleration. In fact, the Japanese Neutrino Factory layout utilises four FFAG rings, accelerating in steps from 300 MeV/c to 20 GeV/c without cooling [25]. Nevertheless, there are a number of challenging aspects of FFAGs that require R&D. Even though the idea of such a machine has existed since the 1950's, very few have actually been built,

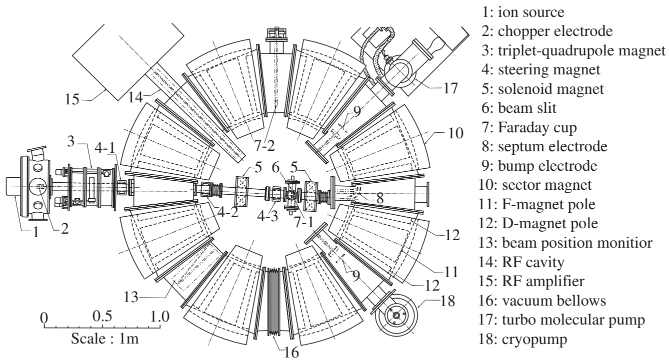

Fig. 7. The Proof-of-Principle 500 KeV proton FFAG built at KEK in Japan to test the principles of this form of acceleration. This is the world's first proton FFAG

principally because it has been very difficult to build the magnets. In addition, to have a sufficient longitudinal acceptance to avoid the need for cooling, the RF cavities in the first of the four FFAGs must have a sufficiently low frequency. However, they must still have sufficient gain to accelerate the muons in ten turns and this combination of relatively high gain at low frequency will not be easy to achieve.

4 Conclusions

Neutrino oscillations form one of the most exciting discoveries in physics in recent years and are the first indication of physics beyond the Standard Model. They have created huge interest and a large number of new experiments have been conceived to measure the oscillation parameters more precisely and to learn more about the phenomenology. Despite all these experiments, however, much will still not be known, in particular θ_{13}, δ and the sign of Δm^2_{23} are likely to be unmeasured. For this, new high intensity accelerator driven neutrino beams are required. There are three candidate types for these: conventional superbeams, betabeams and a Neutrino Factory. Each of these are technically very challenging and beyond the state of the art and will require considerable R&D. The ultimate long baseline neutrino oscillation machine is the Neutrino Factory, as this has the best sensitivity to all the "missing" parameters. Some of the most challenging R&D required for this has been summarised in this paper.

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