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PROJECT FINAL REPORT

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4.1 Final publishable summary report

Executive Summary

One of the most important discoveries in Particle Physics in recent years is the observation that the neutrino changes type (or flavour) as it travels through space, a phenomenon referred to as neutrino oscillations. This means that neutrinos have a tiny, but non-zero mass and is the first indication that the so-called Standard Model of particle physics is incomplete. The implications are far reaching, e.g neutrino interactions may be responsible for the removal of all the anti-matter created in the Big Bang from the early Universe and the neutrino may have played a crucial role in the birth of the Universe itself.

Knowledge of the contribution of neutrinos in these areas needs precise measurements of the parameters governing neutrino oscillations. This will require a new high intensity beam-based neutrino oscillation facility in which neutrino beams are generated using new and highly challenging concepts. This Design Study has reviewed all three currently accepted methods of realizing this facility:

1) A neutrino Super-Beam, in which the neutrinos are made by firing a high power proton beam into a target to make pions, focusing the pions in the direction of a far detector and measuring the neutrinos from the pion decay. EUROnu has studied a CERN to Fréjus Laboratory Super-Beam, with a baseline of 130 km. The protons would be accelerated by the Superconducting Proton Linac (SPL) at CERN and the neutrinos observed in the 500 kt MEMPHYS water Cherenkov detector at Fréjus.
2) A Neutrino Factory, in which pions are created as for the Super-Beam, but then captured and allowed to decay to muons. The muons are accelerated and injected into a storage ring and the neutrino beams are produced from the muon decay. Both signs of muons are used to produce pure beams of neutrinos. The far detector in this case would be a 100 kt Magnetised Iron Neutrino Detector (MIND) at a baseline of about 2000 km.
3) A Beta Beam, which is similar to a Neutrino Factory, except that the stored beams are beta-emitting irons. These produce pure beams of electron neutrinos and anti-neutrinos. The far detector would again be MEMPHYS in the Fréjus Laboratory.

EUROnu has undertaken detailed studies of the three facilities, resulting in conceptual designs for each. The performance of the facilities, in terms of the properties of the beam produced, has then been determined. In addition, the performance of the near and far neutrino beam detectors been assessed. This information has then been combined to determine the overall physics reach in terms of the expected measurement errors for the unknown neutrino oscillation parameters, in particular the CP-phase. This has clearly demonstrated that the Neutrino Factory has the best physics reach and is still better when compared with the combination of the Super-Beam and Beta Beam.

EUROnu has also done a cost estimate for each facility, with a particular focus on the accuracy of the relative costs. This has shown that although the Neutrino Factory would be more expensive than building both the Super-Beam and the Beta Beam, the improvement in physics reach more than compensates for this. As a result, EUROnu strongly recommends the construction of the Neutrino Factory and has proposed a roadmap for doing this, using a number of steps. This recommendation has been passed on to the appropriate body for Particle Physics in Europe, the CERN Council, via an input to the CERN Strategy Update.

Further, EUROnu hopes to continue, in order to bring this recommendation about, via an appropriate programme in Horizon 2020.

Project context and objectives

EUROnu FP7 Design Study

The theories and discoveries of thousands of physicists over the past century have resulted in a remarkable insight into the fundamental structure of matter: everything in the Universe is found to be made from twelve basic building blocks called fundamental particles, governed by four fundamental forces. The particles are the electron, the muon and the tau, each with a partner neutrino, and six types of quark. The four forces are the electromagnetic force, gravity and the strong and weak nuclear forces. Our best understanding of how these twelve particles and three of the forces are related to each other is encapsulated in the Standard Model of particles and forces. Developed in the early 1970s, it has successfully explained a host of experimental results and precisely predicted a wide variety of phenomena. Over time and through many experiments by many physicists, the Standard Model has become established as a well-tested physics theory.

There are, however, theoretical concerns that suggest that the Standard Model cannot be the whole story. As a result, a lot this experimental work has also looked for physics which is not explained by it. So far, only one observation has been made that has required a modification to it. This is the discovery that a neutrino changes type (or flavour) as it travels through space, a phenomenon referred to as neutrino oscillations. For example, the fusion processes taking place at the centre of the sun, which produce its energy, lead only to the creation of electron neutrinos. However, when these neutrinos are measured at the earth, only about one third are still electron neutrinos, the others having changed to one of the other two types. As well as being fascinating in its own right, this observation has a number of very important consequences. The first is it means that neutrinos must have a mass, which the measurements suggest is tiny, much smaller than any of the other fundamental particles. This in turn implies that the Standard Model is incomplete, as this assumes that the neutrinos are massless. In addition, it does not naturally explain the small observed masses. Understanding how the Standard Model should be modified to include these masses could bring important information on the hierarchical nature of all particles masses.

In addition, neutrino oscillations could also provide a solution to a long standing puzzle in astronomy. In the Big Bang, matter and antimatter would have been created in equal quantities. However, what we see now is a matter dominated Universe, raising the questions: where has all the antimatter gone and why is there such a difference in the amount of matter and antimatter that we see today? Without this difference, the universe would be a very different place and we would not exist. It can only have arisen if the interactions of matter and antimatter are different in some way, requiring so-called CP-violating processes. These differences have been seen with quarks, but are so small that they cannot account for what we see today. Thus, some other mechanism for removing antimatter is required and this could come from CP-violating effects with neutrinos. As well as this, neutrinos may have played a crucial role in the birth of the Universe itself.

The theoretical description of neutrino oscillations is based on the assumption that there are three neutrinos, each of which has a tiny mass (the mass eigenstates). No two neutrinos have the same mass. Under this assumption, quantum mechanics implies that the three neutrino flavours may be considered to be mixtures of the three mass eigenstates, the relative weight of the mass eigenstates differing from one neutrino flavour to another. It is this quantum-mechanical mixing that leads to the phenomenon of neutrino oscillations. This phenomenological description, the Standard Neutrino

Model (SνM), requires that four mixing parameters and two mass-difference parameters be extracted from the data. Three of the mixing parameters take the form of mixing angles, the fourth is a phase parameter which, if it is non-zero, causes the interactions of neutrinos to be different to those of anti-neutrinos, violating the matter-antimatter symmetry that is present in the Standard Model i.e. CP-violation. It has been observed that the neutrino mixing angles are much larger than those of the quarks and the neutrino masses are tiny compared to the masses of all other fundamental particles (including the quarks). It seems, therefore, that a detailed understanding of the properties of the neutrino is required for an understanding of flavour, i.e. what is the physics that causes the observed differences between the properties of the quarks and those of the leptons and the properties of the particles in one generation from those in another.

The three mixing angles are labeled θ_{12}, θ_{23}, and θ_{13}, the CP phase δ_{CP} and the two mass differences, $\Delta m_{12}^2 = m_2^2 - m_1^2$ and $\Delta m_{23}^2 = m_3^2 - m_2^2$. At the start of EUROnu, only the first two mixing angles and the two mass differences had been measured. It was already clear that to measure the remaining parameters, the last mixing parameter, the CP phase and the sign of Δm_{23}^2 (the so-called mass hierarchy), would require new neutrino oscillation facilities. During EUROnu, a number of new facilities, in particular three in which neutrinos are produced in nuclear reactors (Daya Bay, Double Chooz and Reno) and one which makes them using a proton accelerator (T2K), have made the first measurement of the angle θ_{13}. Although the errors on the measurement are still quite large, they have demonstrated that the remaining two parameters, the CP-phase and the mass hierarchy, could be measured but would require a new high intensity beam-based neutrino oscillation facility in which neutrino beams are generated using new and highly challenging concepts, as studied by EUROnu. Such a facility would also be required to make the required, precise measurements of the other oscillation parameters.

This Design Study has studied all three currently accepted methods of realizing the new high intensity facility. These are the so-called neutrino Super-Beams, Beta Beams and Neutrino Factories. Its primary objectives were (1) to do a detailed study of the key technical challenges of the accelerator facilities and of the detector options necessary to measure the neutrino oscillation parameters, (2) to produce conceptual designs of the facilities, (3) to determine the physics reach of each, taking in to account a new relevant measurements, such as that of θ_{13} measurement, (4) to estimate the cost of construction of the facilities, and (5) based on this information, recommend to the appropriate authorities which facility we believe should be constructed in Europe. As described in the following sections, these objectives have all been achieved, significantly helped by the θ_{13} measurement.

The three facilities included in the Design Study are as follows. The first is a neutrino Super-Beam. This uses the same technique as existing facilities for the creation of the neutrino beam: a proton beam is fired into a target to make pions and the pions are focussed in the direction of a far neutrino detector. The neutrino beam is produced by the decay of the pions. The two main differences to the existing facilities are a much more powerful proton beam is used and the neutrino detector is much larger. These features will give a much better sensitivity to the neutrino oscillation parameters. The particular project being studied in EUROnu is a CERN to Fréjus Super-Beam, where the neutrino beam is created at the CERN laboratory close to Geneva and measured using a detector 130km away in the Fréjus tunnel under the Alps (see Figure 1).

The second facility, the Neutrino Factory (see Figure 2), goes a stage further than the Super-Beam. It produces pions and lets them decay, but this time the muons from the decay are captured. The muons are formed into bunches and their energy spread is reduced, before they are accelerated to around 10GeV. Once at this energy, they are injected into one or more storage rings and the neutrino beams are produced from the muon decays in the straight sections of these rings. These will be pointed at neutrino detectors up to 2500km away.

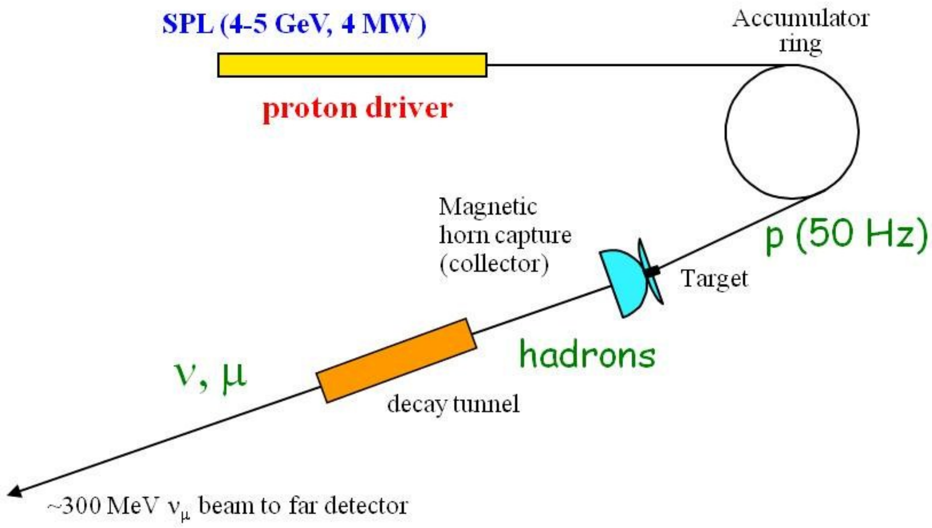

Figure 1: Layout of the CERN to Fréjus Super-Beam

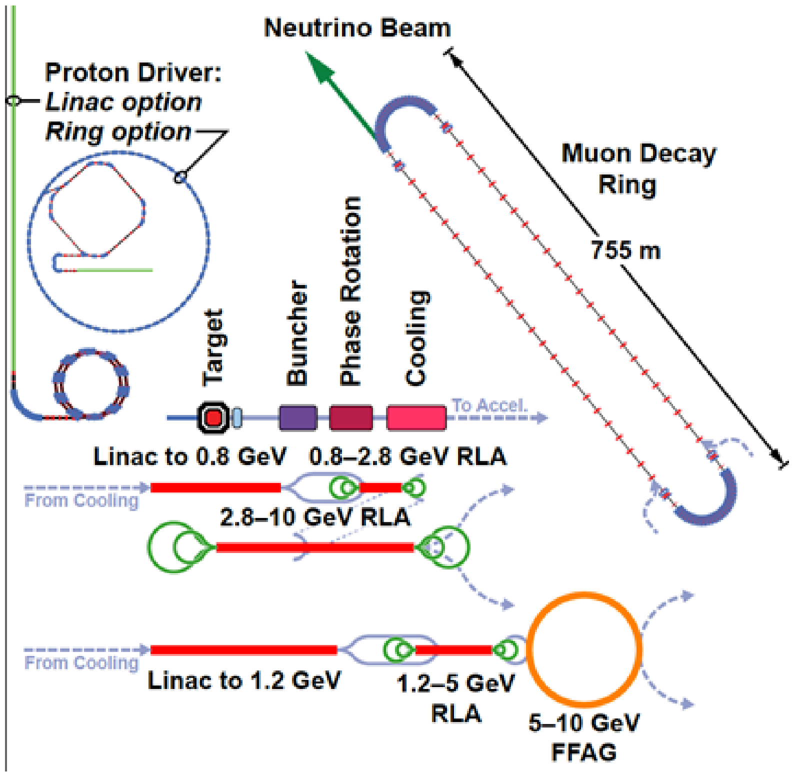

Figure 2: Layout of a Neutrino Factory.

The Beta Beam, the last facility, will use a different technique (see Figure 3). In this, beta-emitting radioactive ions are created, accelerated and stored in a storage ring. As in a Neutrino Factory, the neutrino beams are produced by the decay of the ions in the straight sections of the ring. The main issue with this facility is producing a sufficient flux of radioactive ions and EUROnu has focussed on novel methods of doing this. In this case, the accelerator would be located at CERN and the detector 130km away in the Fréjus laboratory.

EUROnu has undertaken design studies of each of the three candidate facilities, with the aim of determining realistic parameters for the performance of each. In addition, it has also investigated the performance of the specific neutrino detectors to be used. For both the Super-Beam and the Beta Beam, this detector is the MEMPHYS detector in Fréjus, a 500 kt water Cherenkov detector. For the Neutrino Factory, it is a 100 kt Magnetised Iron Neutrino Detector (MIND) at a distance of around 2000 km. This has allowed a determination of the physics reach of each facility. To enable a complete comparison between them, EUROnu has also estimated the cost of construction. Using this information, it has made a recommendation on how to deliver the best facility for the future of accelerator-based neutrino oscillation studies.

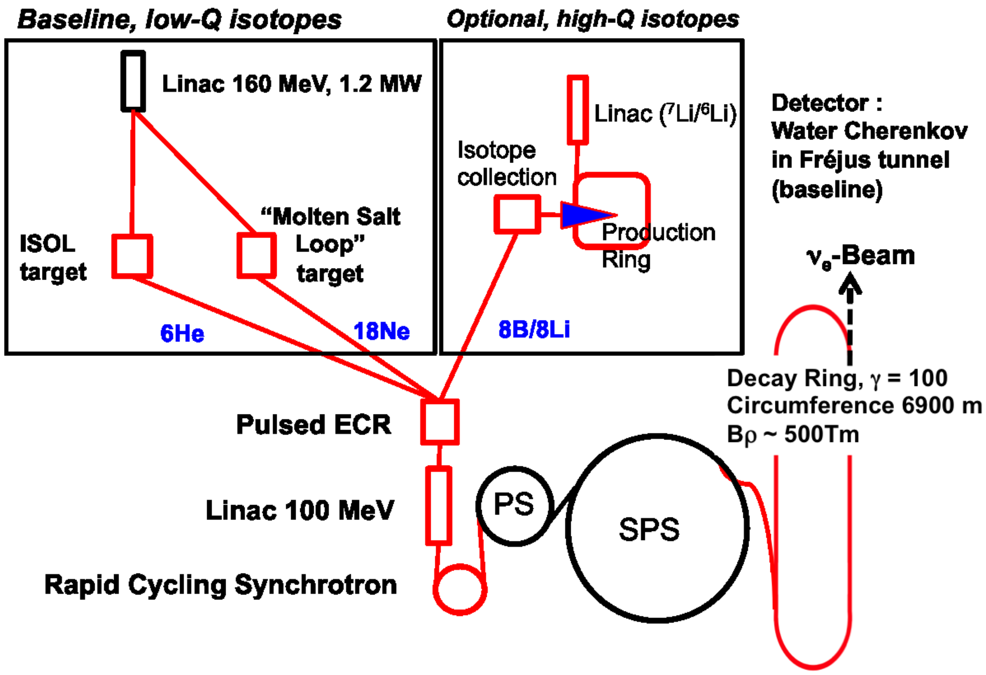

Figure 3: Layout of a Beta-Beam facility.

Main Science and Technology Results

The primary aims of EUROnu were to produce conceptual designs for the three candidates for a high intensity, accelerator-driven, neutrino oscillation facility in Europe, to determine their performance and cost and, based on this information, make a recommendation for which we believe should be built. The three facilities are:

- The CERN to Fréjus Super-beam, using the 4 MW version of the Superconducting Proton Linac (SPL) at CERN [1]. The baseline far detector is a 500 kT fiducial mass water Cherenkov detector, MEMPHYS [2].
- The Neutrino Factory, in which the neutrino beams are produced from the decay of muons in a storage ring. This work is being done in close collaboration with the International Design Study for a Neutrino Factory (IDS-NF) [3].
- The Beta Beam, in which the neutrino beams are produced from the decay of beta emitting ions, again stored in a storage ring.

These aims have all been achieved. In this section, we describe the results of the study, in particular the resulting conceptual designs and the performance and cost. In the subsequent Impact section, we describe our recommendations for the future and how these have been made.

The Super Beam

A Super Beam creates neutrinos by impinging a high power proton beam onto a target and focussing the pions produced towards a far detector using a magnetic horn. The neutrinos come from the decay of pions in a decay tunnel following the target, thus producing a beam in the direction of the tunnel (see Figure 1). EUROnu is studying the CERN to Fréjus Super Beam, using the High Power Superconducting Proton Linac (HP-SPL) [1] as the proton driver, producing a 4 MW beam. The baseline is 130 km and the planned far detector is the 500 kT fiducial mass MEMPHYS water Cherenkov detector [2]. This would be built in two new caverns in the Fréjus tunnel. It should be noted, however, that physics studies in EUROnu (see below) suggest that there would be benefits in placing the MEMPHYS detector further away, for example in the Canfranc Laboratory [4], at a distance of 630 km from CERN. This is possible for the SPL Super Beam, with the necessary changes in direction and downward angle of the beam.

The work on the High Power Superconducting Proton Linac was done outside of EUROnu. Based on our work, however, it will produce a 4 MW beam at 5 GeV and operate at a frequency of 50 Hz. It will consist of a number of sections. The first is these, up to 160 MeV, will be about 90 m long and will be normally conducting. The low power version of this, Linac 4 [5], is currently under construction at CERN. The remaining three sections will be superconducting and will accelerate the beam to 0.7, 2.5 and 5 GeV, respectively. The SPL will accelerate 42 bunches, which is too many for Super Beam operation. Hence an Accumulator ring has been designed by EUROnu to reduce the number of bunches to 6, each 120 ns in length. A significant amount of design work has already been done on the SPL and R&D has started on many components [6].

Given the difficulty in producing a single target and horn able to work in a 4 MW beam, EUROnu has identified an alternative option, using four of each instead. The beam from the Accumulator will then be steered on to each target in turn, so that they all run at 12.5 rather than 50 Hz and receive 1 MW. For the targets and the horns, this results in a smaller extrapolation from technology already in use. To achieve this, a system of two kicker and four bending magnets has been designed to steer the beam on to each target in turn.

An outline design for the 4 target and horn system is shown in Figure 4. To minimize the production of thermal neutrons and hence reduce the heat load and radiation damage to the surrounding horn, the baseline design for the target is a pebble bed, consisting of 3 mm diameter spheres of titanium in a canister, 200 mm long (see Figure 5). These are cooled by flowing helium gas through vents in the canister, at around 10 bar pressure. Thermal modeling shows that this should be sufficient to cool the targets up to a few MW. To verify this, offline tests of the cooling system will be undertaken in the future. These will use an inductive coil to heat the target at the required level and demonstrate that this heat can be successfully removed. A test target will also be subjected to a beam of the correct energy density using the HiRadMat [7] facility at CERN, to further verify the cooling and demonstrate that the titanium spheres and the target structure can withstand the thermal shock from the beam.

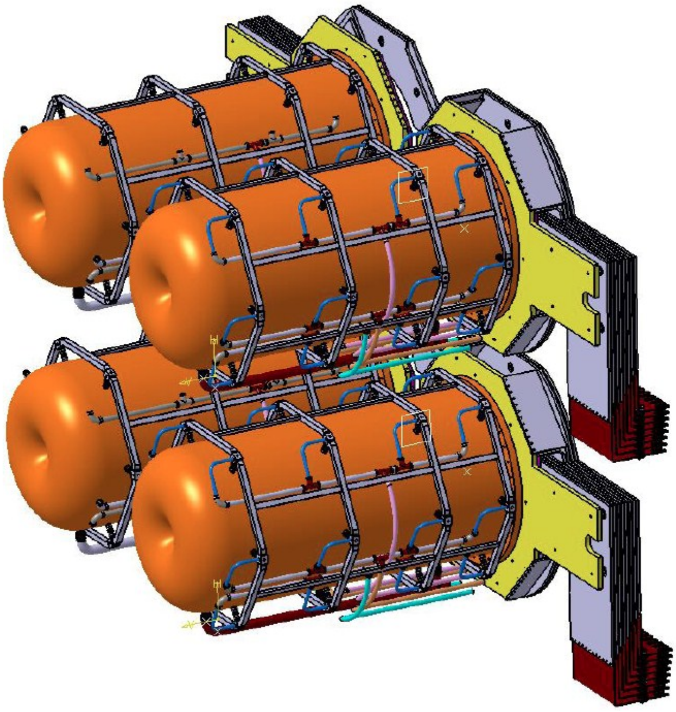

Figure 4: Conceptual engineering design of the 4 target and horn system for the Super Beam.

The EUROnu focusing horn design is based on that of the MiniBooNE experiment [8]. It will employ a single horn around the target, and will not have a reflector, and the design has been modified to optimise the pion production. As for the targets, four horns will be used and will need to be pulsed at least 300 kA, resulting in significant heating. Further heating will come from beam loss, resulting in a maximum of 12 kW on the surface around the target. Studies with thermal codes show that this can be removed with water cooling of the outer surface of the horn. The thermal stresses in the horn material resulting from the heating are a maximum of 18 MPa and prototype tests will be required to determine what the lifetime of a horn will be due to the resulting fatigue and from radiation damage. A support system for the 4 horn system under this load has been designed. The final aspect of the horn system is a pulsing circuit to deliver the required current at up 17 Hz (in case of the failure of one target+horn combination). A circuit to do this has been designed and it is planned to build a prototype of it (see Figure 6).

The targets and horns will need to be mounted in a target station which allows the change, storage and maintenance of targets and horns, in case of failure. To enable this, the target station will have a number of separate sections and activation studies have been done to determine the shielding requirements for each. A design of this has been made, based on these studies and experience gained with the T2K target station. It incorporates remote handling facilities, a hot cell for maintenance and a storage area for old targets and horns, called the morgue. It will allow access to the critical components of the system, for example the power supplies for the horns, and will allow the safe removal of activated components for disposal. The section of the target station that contains the targets and horns is shown in Figure 7.

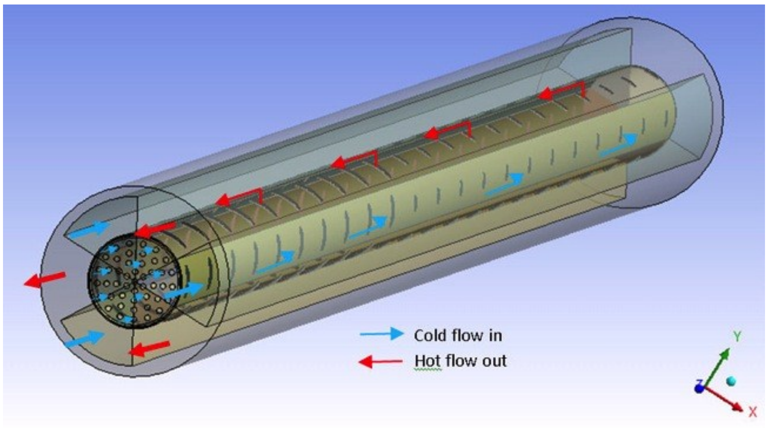

Figure 5: Proposed pebble bed target for the Super Beam.

To allow the determination of the physics performance, the pion and neutrino production by the Super Beam have been simulated. The resulting flavour composition of the beam is shown in Figure 8 for both neutrino and anti-neutrino beams. Note that the ν_e contamination in the beam is significantly less than 1% in both cases.

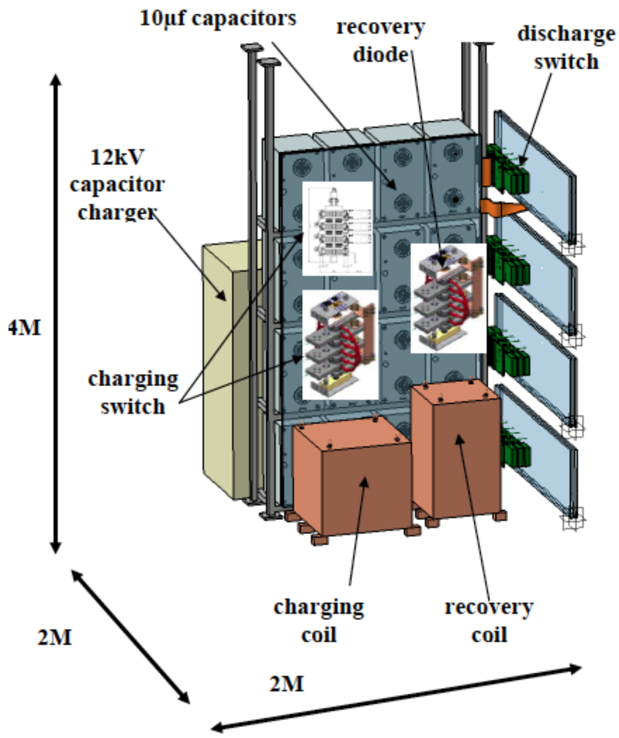

Figure 6: Design of the pulsing system for the Super Beam horns.

Neutrino Factory

In a Neutrino Factory, the neutrinos are produced from the decay of muons in a storage ring. The muons are produced by impinging a 4 MW proton beam onto a heavy metal target and focussing the pions produced into a decay channel using a 20 T super-conducting solenoid. In the original baseline, the muons from the pion decay are captured, bunched, phase rotated and finally cooled in the muon front-end, before being accelerated using a linac, two re-circulating linear accelerators (RLAs) and a non-scaling Fixed Field Alternating Gradient accelerator (ns-FFAG) to 0.9 GeV, 3.6 GeV, 12.6 GeV and 25 GeV, respectively (see Figure 9). The muons are then injected into two storage rings, to produce beams of neutrinos and anti-neutrinos to two far detectors. Stored μ^+ beams will produce pure electron neutrino and muon anti-neutrino beams, while μ^- will produce pure electron anti-neutrino and muon neutrino beams. To be able to distinguish signal from background, it is essential that the far detector can separate μ^+ from μ^- with high efficiency. As a result, the baseline detector is a Magnetised Iron Neutrino Detector (MIND).

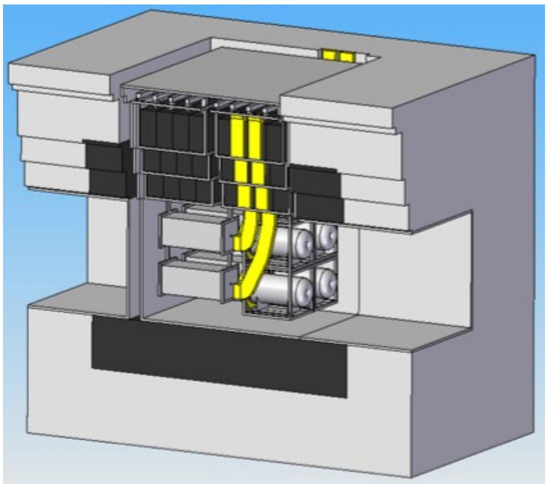

Figure 7: Conceptual design of the section of the target station for the 4 targets and horn systems. The beam enters from the left. The horn pulsing circuits will be mounted on top of the shielding, so the strip lines exit vertically.

However, following the recent measurement of θ_{13} [9], the required muon energy has been reduced to 10 GeV and only one decay ring will be used. The envisaged neutrino baseline is now around 2000 km. The work described below has been done by EUROnu in collaboration with the International Design Study for a Neutrino Factory. Particular emphasis is given to the EUROnu contributions.

Two options have been considered for the Neutrino Factory proton driver. The first is a super-conducting linear accelerator. Indeed, if the facility was to be built at CERN, this would be the HP-SPL [1]. This would be followed by an Accumulator ring, as for the Super Beam, and a Compressor ring to reduce the proton bunch length to 3 ns. The other option employs a rapidly cycling synchrotron, working at 50 Hz, to accelerate the beam to 10 GeV. This would use a normally conducting linear injector to accelerate the beam to 180 MeV.

The baseline pion production target is a continuous liquid mercury jet. This would be fired across the proton beam at a small angle so that the beam and target overlap for two interaction lengths. The pions produced would be focused by a combined normal and super-conducting magnet of 20 T around the target (see Figure 10). Both the beam and target would also be at a small angle to the axis of the solenoidal field, so that the mercury collects in a pool. As well as allowing the mercury to be re-circulated, this could also form a part of the proton beam dump. The magnetic field would be ramped down adiabatically to 1.5 T at the entrance of the pion decay channel, using a succession of superconducting coils. However, simulations done in EUROnu of secondary particle production in the target and subsequent absorption in the super-conducting coils have shown that the heat load in the coils around and close to the target is much too large, up to 50 kW. The main problem comes from secondary neutrons.

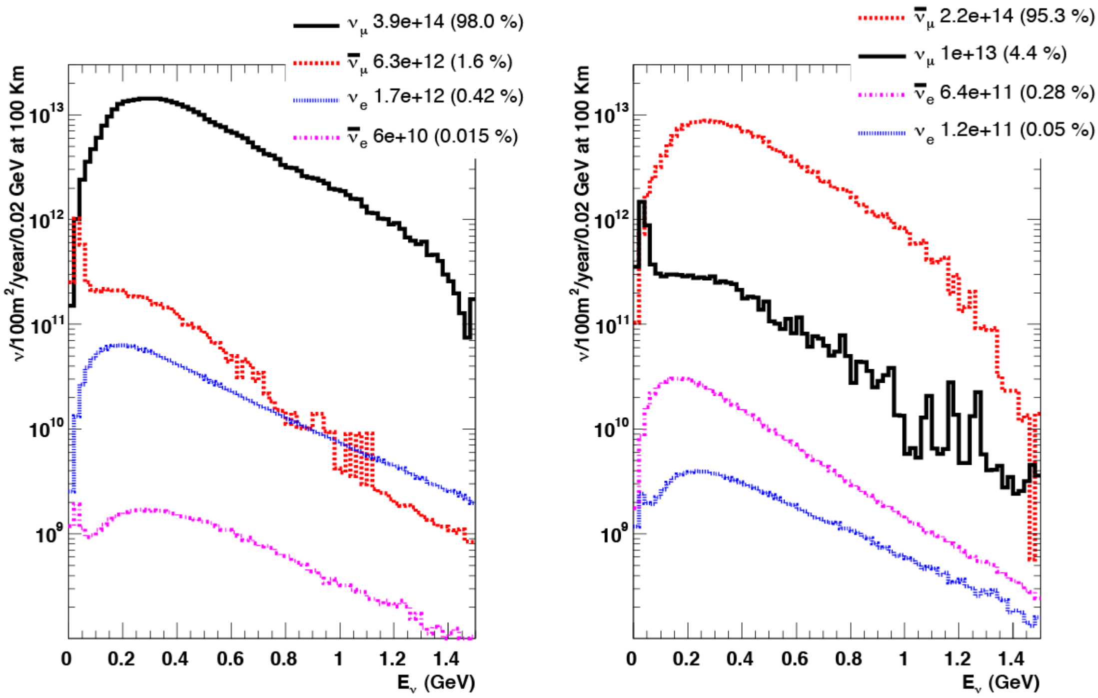

Figure 8: The composition of the neutrino beam produced by the Super Beam facility.

Various options are being considered to reduce this heating. The most obvious is simply to add more shielding. It has been demonstrated that this will work, but it would mean that the radius of the super-conducting coils would double, making these significantly more difficult to build and operate. A study of pion production has shown that similar production rates to those in mercury can be achieved with lower atomic number elements (see Figure 11), but these produce significantly fewer neutrons. As a result, targets with lower atomic number are under study. An interesting candidate is gallium, which has a low enough melting point that it could be used as a liquid, in a similar way to a mercury jet. In addition, the fact that it is a solid at room temperature makes storage and disposal after activation significantly easier.

The target is followed by the pion decay channel and the muon front-end. The former is a solenoidal channel of 100 m length, employing 1.5 T magnets to maximize the captured muon flux. The aim of the muon front-end is to prepare the muon beam for acceleration. It consists of a chicane, a buncher, a phase rotator and a cooling channel. The chicane has been designed in EUROnu because, as well as the required large flux of muons in the front-end, there are also still many protons, pions and electrons. If nothing is done about these, they will be lost throughout the front-end, resulting in levels of activation about 100 times above the canonical level for hands-on maintenance. As a result, the chicane is used to remove the higher momentum unwanted particles. It is followed by an absorber, to remove those at lower momentum. The efficiency for transmission of useful muons is about 90%, while the unwanted particles are reduced to a manageable level. The chicane is followed by a section, 33 m long, which uses RF cavities to bunch the beam. This in turn is followed by a phase rotation section 42 m long, which utilises the correlation between position in the bunch train and energy that has built up by this stage. It uses RF cavities to slow down the faster going muons at the front and speed up the slower going particles at the back and thereby reduces the energy spread of the beam.

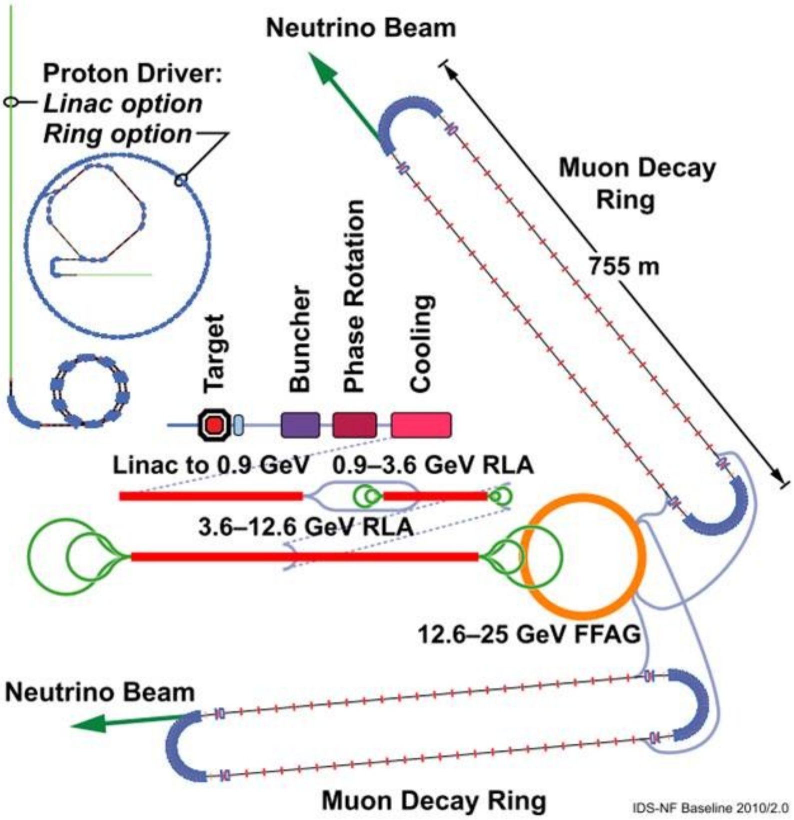

Figure 9: Original baseline layout of the Neutrino Factory.

The phase rotation section is followed by the cooling channel, which will employ the technique of ionization cooling. In this, an absorber is used to reduce both the longitudinal and transverse components of the muon momentum. The lost longitudinal momentum is then restored using RF cavities, giving a net reduction in transverse momentum and hence transverse cooling. However, as well as cooling through energy loss, the absorber also heats through multiple scattering and the best balance between the two is achieved by using a low atomic number material, such as liquid hydrogen or lithium hydride. In addition, the cooling efficiency is significantly increased if the absorber is in region in which the beam is highly convergent or divergent, thus requiring a superconducting field around the absorber region. Superconducting magnets are also required around the RF cavities to aid transport. The result is that the cooling cell is a complex object (see Figure 12).

Due to the complexity, an engineering demonstration of the cooling technique is being constructed at the STFC Rutherford Appleton Laboratory. This project, called MICE [10], is due to give a first demonstration of ionisation cooling during 2013. In addition, as the RF cavities of the baseline cooling cell will be in a large magnetic field, measurements of the effect this will have on the accelerating gradient are being made by the MuCool project [11]. To minimize potential problems, alternative cooling lattices have been studied in EUROnu that reduce the magnetic field at the cavities, while maintaining the same performance [12].

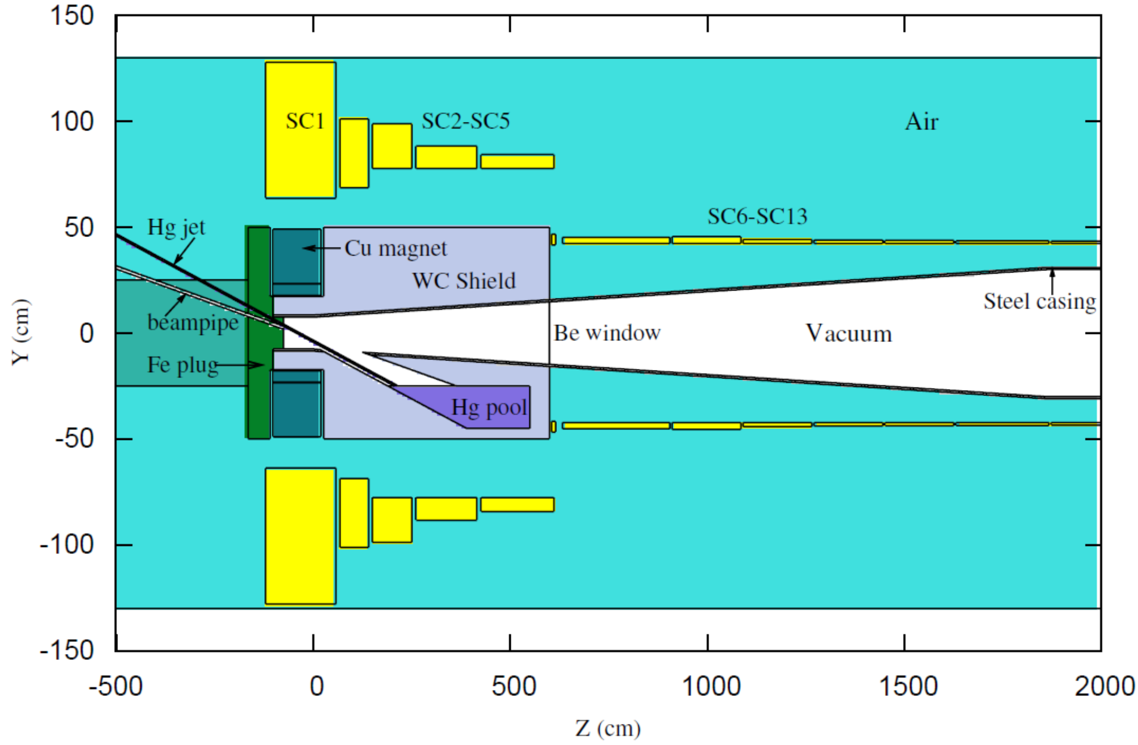

Figure 10: Conceptual layout of the Neutrino Factory pion production target and capture system.

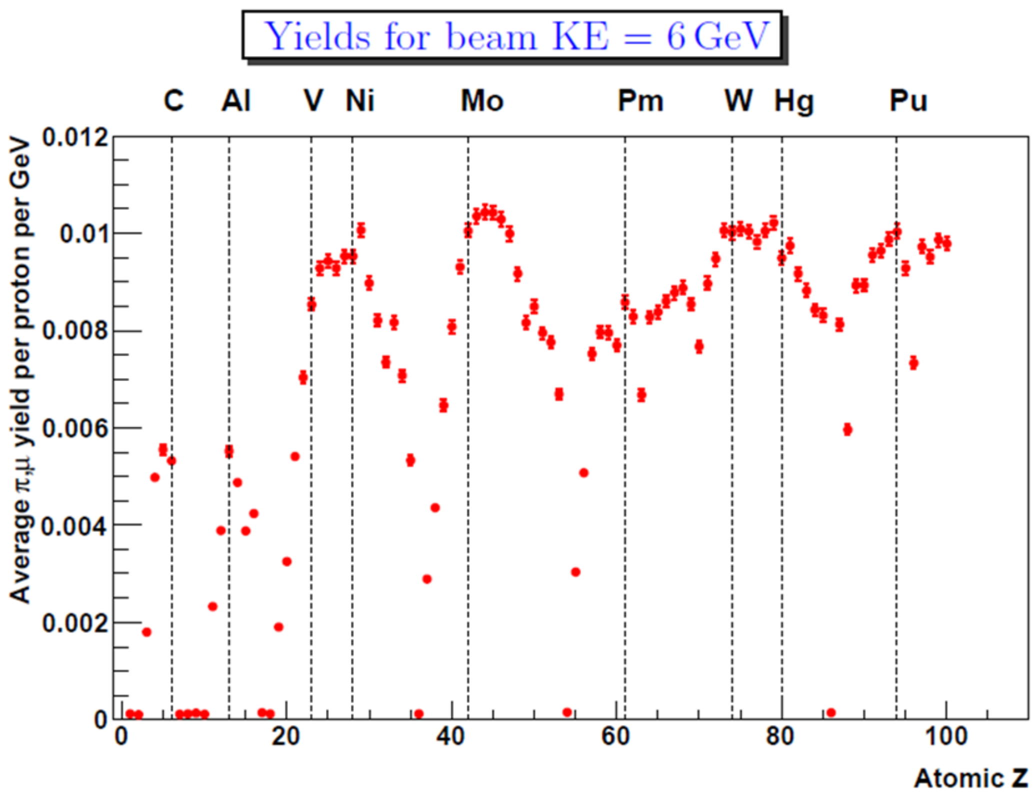

Figure 11: Pion production as a function of atomic number, assuming a cylindrical target 20cm long and 2cm in diameter.

Following the reduction of muon energy to 10 GeV, two options now exist for the muon acceleration system (see Figure 2). The first uses a linac to 0.8 GeV, followed by two Re-circulating Linear Accelerators (RLAs), one to 2.8 GeV and the second to 10 GeV. The second option uses a linac to 1.2 GeV, an RLA to 5 GeV and a non-scaling Fixed Field Alternating Gradient (ns-FFAG) accelerator to 10 GeV. Both options have been studied in EUROnu to determine which would be best based on performance and cost.

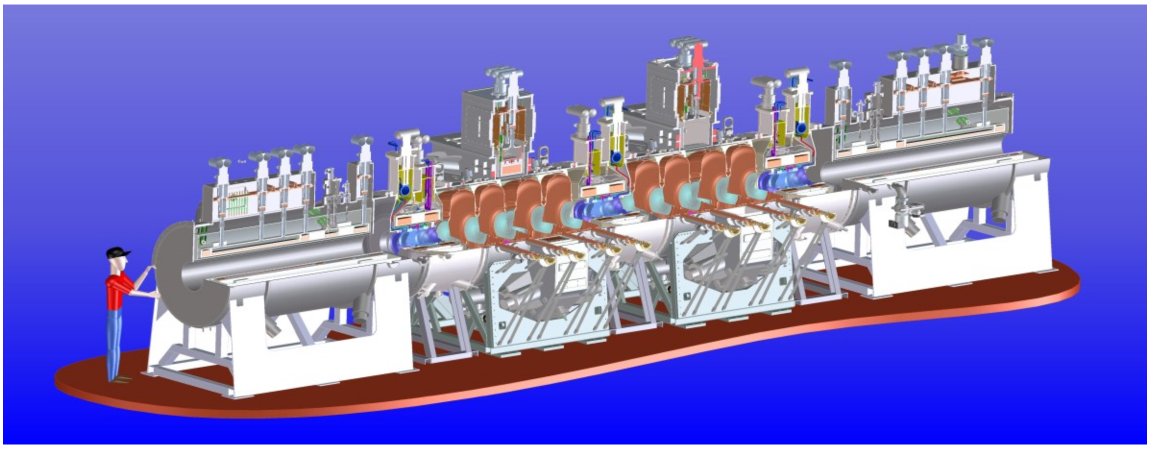

Figure 12: Engineering drawing of the MICE experiment. The central region shows two ionization cooling cells, with instrumentation regions on either side for measuring the parameters of muons entering and leaving these cells.

An ns-FFAG is proposed as its properties of fixed magnetic fields and pseudo-isochronous operation mean that muon acceleration will be very fast, plus it has the large acceptance required for the high emittance muon beam, even after cooling. However, it is an entirely novel type of accelerator, so a proof-of-principle machine called EMMA [13] has been constructed at the STFC Daresbury Laboratory (see Figure 13). This has recently demonstrated that many of the novel features of the muon accelerator, in particular serpentine acceleration and multiple resonance crossings [14], work. The full EMMA experimental programme has recently started and will study the remaining issues.

The final part of the Neutrino Factory is the decay ring, designed in EUROnu. It is planned to produce and accelerate bunches of μ^+ and μ^- at the same time. These will arrive in three bunches each, of 250 ns length, separated by 120 µs. The decay ring will have a total circumference of 1286 m, of which 470 m will form a production straight for neutrinos in the direction of the far detector for both muon charges. The ring will be tilted at an angle of about 10^o degrees for the 2000 km long baseline. An outline injection system design has been made that will inject all of the bunches into the ring. A minimum separation of at least 100 ns is required between bunches to make it possible to determine which bunch detected neutrinos come from. With the expected 2% energy spread of the muon beam, this will exist for 4 muon lifetimes, allowing the vast majority of muons to decay.

The Beta Beam

The production of (anti-)neutrinos from the beta decay of radioactive isotopes circulating in a race track shaped storage ring was proposed in 2002 [15]. Beta Beams produce pure beams of electron neutrinos or antineutrinos, depending on whether the accelerated isotope is a β^+ or a β^- emitter. The facility discussed here is based on CERN's infrastructure and will re-use some existing accelerators, though with modifications. This will significantly reduce the cost compared to a green field site, though it will constrain the performance (see Figure 3). It will consist of an ion production system, using a linac to accelerate particles and create the required ion species in a target. This will be followed an ion collection device and a 60 GHz ECR source for bunching. There will then be an ion acceleration system, using a linac to 100 MeV, a Rapid Cycling Synchrotron, the existing Proton Synchrotron and the Super Proton Synchrotron, before injection in to a decay ring.

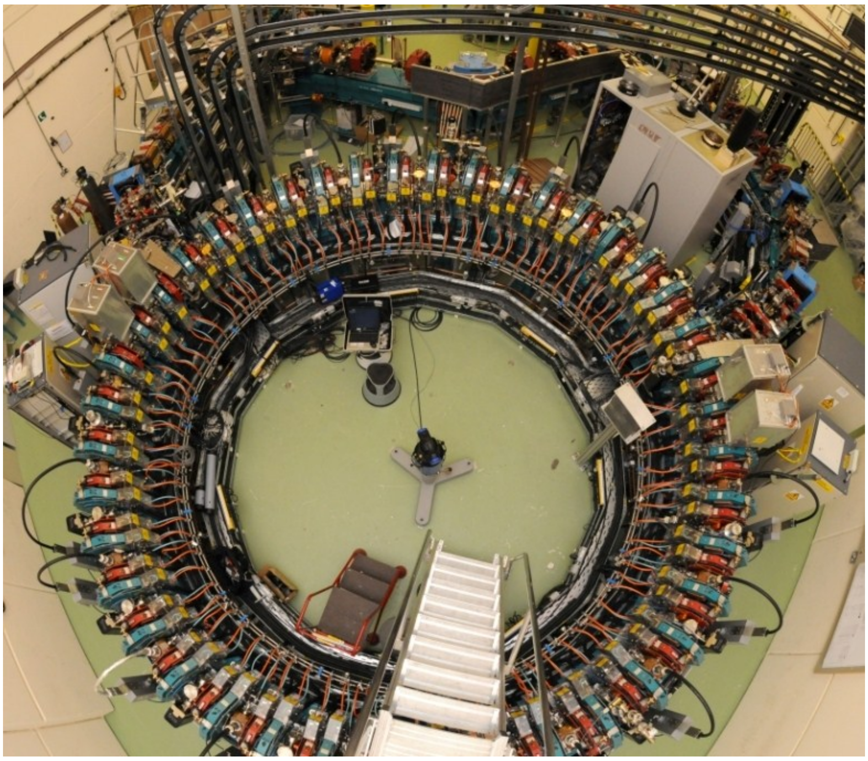

Figure 13: The EMMA proof-of-principle accelerator at the Daresbury Laboratory.

A particular emphasis in EUROnu has been on one of the most important issues for a Beta Beam: the production, acceleration and storage of a sufficient flux of ions to meet the physics goals. The isotope pair that was first studied for neutrino production, in the EURISOL FP6 Design Study [16], is ^{6}He and ^{18}Ne, accelerated to $\gamma = 100$ in the SPS and stored in a Decay Ring [17]. Physics studies have indicated that the required fluxes of these ions are 6×10^{13} and 1×10^{13} ions/second, respectively. At the end of EURISOL, it looked possible to produce the required flux of ^{6}He, but that of ^{18}Ne looked a factor of 20 too small. This has subsequently been addressed in two ways in EUROnu. The first was to consider a production ring (12 m circumference) with an internal gas jet target [18] to make an alternative ion pair, ^{8}Li and ^{8}B. As the neutrinos from the decay of these ions have about 5 times larger energy than those for ^{6}He and ^{18}Ne, the required baseline has to be 5 times larger and the flux of ions required for the same physics is 10^{14} ions/second. In the production ring, a 25 MeV beam of ^{7}Li and ^{6}Li is injected over a gas jet target of d or ^{3}He, respectively. To determine the production rate, the double differential cross-sections for both processes, ^{7}Li(d,p)^{8}Li and ^{6}Li(^{3}He,n)^{8}B, have been measured at the Laboratori Nazionali de Legnaro in Italy [19]. The first measurements were performed using the 8πLP experiment (see Figure 14) and are comparable with results obtained at lower energy. The ^{8}B production cross-section was measured using Time of Flight techniques. The results from this are consistent with theoretical calculations, but three times larger than measurements performed using a different technique. This is still being investigated.

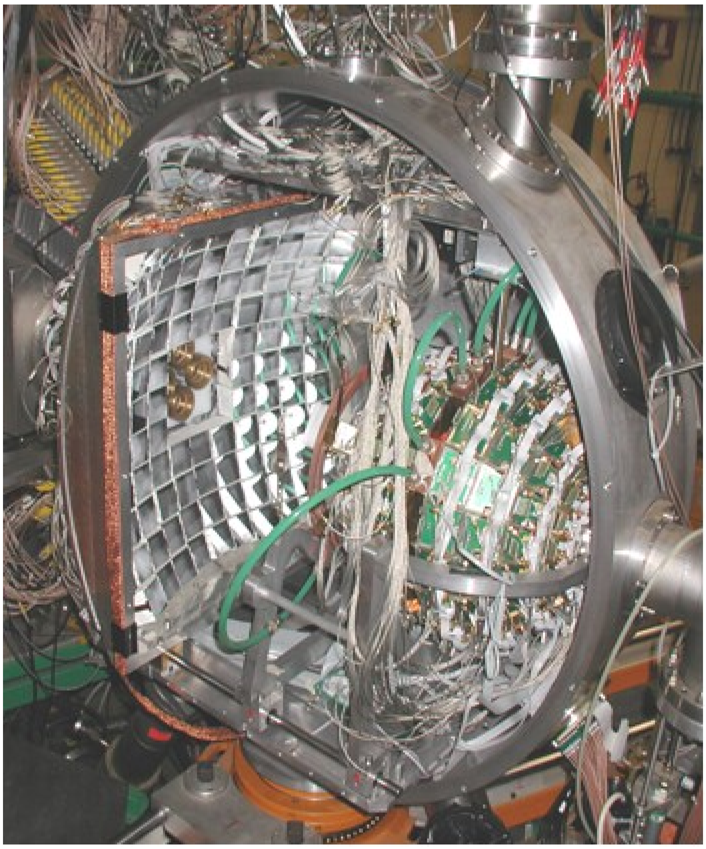

Figure 14: The 8πLP experiment used for measurement of the $^{7}Li(d,p)^{8}Li$ cross-section.

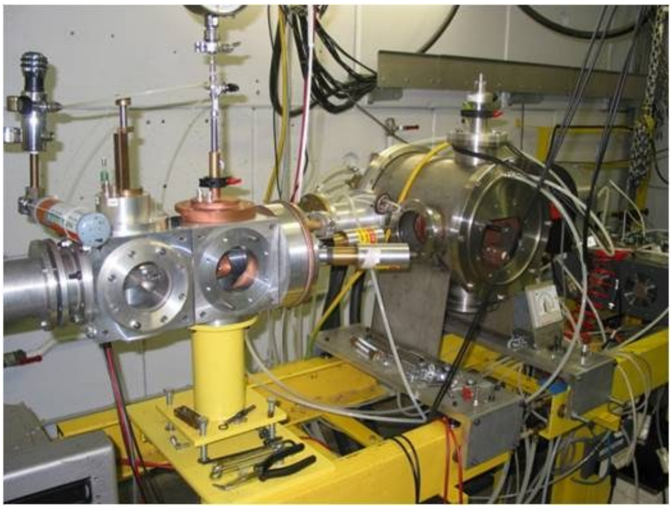

Figure 15: The prototype ion collection device constructed for Beta Beam studies.

Based on these measurements, significant design work has been done on the production ring and a prototype device for collection of the ions has been built and tested (see Figure 15). The studies have shown that the thickness of the gas jet target needed to produce the required flux of ions, 10^{19} atoms/cm^2, is four orders of magnitude bigger than any in current use and will create significant problems for the ring vacuum. Alternative production possibilities have been looked at, for example liquid lithium films, but it remains extremely difficult to meet the ion production goals.

As a result, research on a novel ^{18}Ne production method, using a molten salt loop (NaF) by the reaction ^{19}F(p,2n)^{18}Ne, is currently being undertaken (see Figure 16). Modelling suggests that this could achieve the required production rate with a 160 MeV proton linear accelerator at a current of 6 mA. This would be achievable at CERN with an upgrade of Linac 4 [5]. An experiment to validate the method took place at ISOLDE at CERN in June 2012 and demonstrated that the required flux could be achieved [20]. As a result of the work done so far, the ^{6}He and ^{18}Ne ion pair is the recommended baseline for the Beta Beam.

To accept the intense continuous flux of ^{6}He or ^{18}Ne produced, ionize the gas and bunch the ions with the high efficiency, it is planned to use a 60 GHz pulsed Electron Cyclotron Resource (ECR) ion source. A prototype device called SEISM (Sixty gigahertz ECR Ion Source using Megawatt magnets) has been designed and the magnetic confinement structure successful built and tested (see Figure 17) by EUROnu. It is planned to test plasma production at 28 GHz, to allow comparison with existing ion sources, before proceeding to a 60 GHz plasma.

As shown in Figure 3, after bunching, the ions will be accelerated to 100 MeV/u using a purpose built linear accelerator about 110 m long. This will be followed by a Rapid Cycling Synchrotron, 251 m in circumference that will accelerate the ions to a maximum magnetic rigidity of 14.47 Tm, corresponding to 3.5 GeV protons, 787 MeV/u for $^{6}He^{2+}$ and 1.65 GeV/u for $^{18}Ne^{10+}$. Final acceleration of the ion beams will take place in the existing PS and SPS. Simulations of these show that, although not optimal, they can deliver the required performance. Preliminary activation studies have also been done and these show that the effect of the Beta Beams compared to high intensity proton running varies with the component or material being activated, but the rate is never significantly higher and this should not prevent operation. Collective effects have also been studied and, while these are difficult, they should be possible with 20 bunch operation.

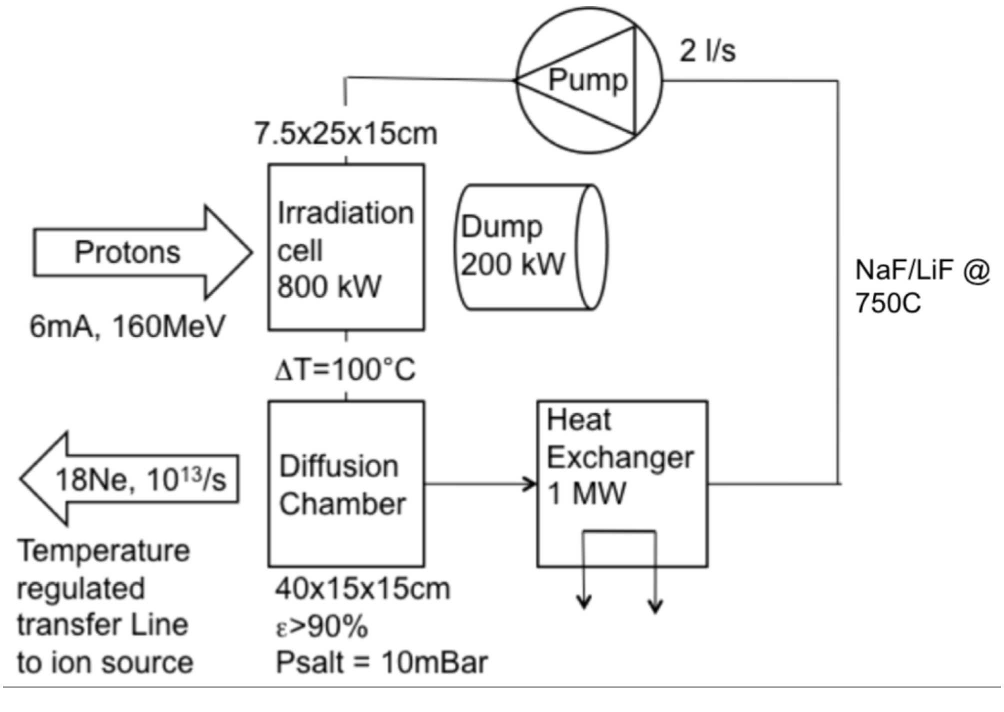

Figure 16: A NaF molten salt loop for the production of ^{18}Ne ions.

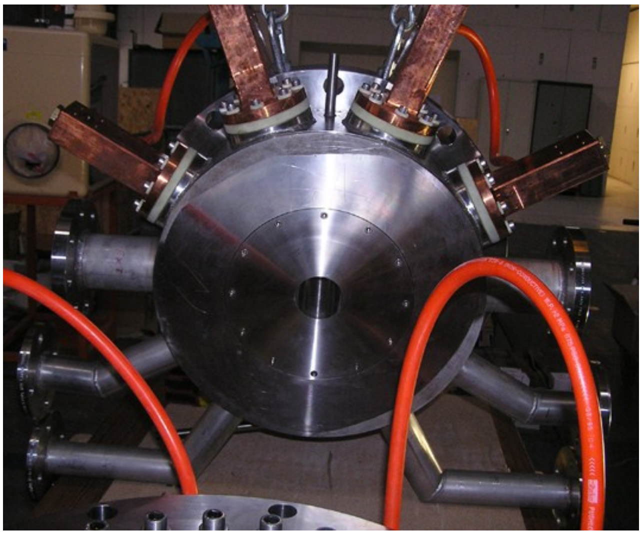

Figure 17: The SEISM 60 GHz ECR source prototype.

The final element of the Beta Beam is the decay ring. As for the Neutrino Factory this will have a race track shape, with a total circumference the same size as the SPS, 6.9 km, and a production straight which is 37% of this size to maximize the neutrino flux. To reduce space charge effects in the PS, the beam will be delivered to the decay ring in 20 bunches and further beam will need to be accumulated to replace decay losses. The preferred method of doing this is to use a dual frequency RF and inject new beam at a slightly different energy from that already in the ring. The voltage and phase of the two cavity families will then be varied to perform the merging. This technique has been simulated and in part successfully tested. As the ring will use super-conducting magnets, the decay losses are a significant problem. The solution is to use open mid-plane magnets, so that most of the radiation escapes without impacting them. Another major problem is collective effects and these ultimately will limit the intensity in the ring. In particular, the so-called head-tail effect, in which particles in the tail of the bunch are affected by the field created by the particles in the head, is a serious problem. Although the intensity limit is above the required intensity for ^{6}He, this is not true for ^{18}Ne, where it is only about 20% of that required. Studies are continuing to find a solution to this problem.

As a far detector, the baseline isotopes, ^{6}He and ^{18}Ne could use the MEMPHYS detector [2] in the Fréjus tunnel, at a distance of 130 km. Due to the higher energy of the neutrinos, the ^{8}Li and ^{8}B option would need a detector at some 700 km and may need a different detector technology, such as liquid Argon [21]. The first option is the baseline in EUROnu.

Detectors

The focus of EUROnu has been on the conceptual design of the accelerator facilities. Nevertheless, to make a genuine determination of the physics reach of each facility, it is also important to include the neutrino detectors in the study. Thus, the project has studied the baseline detectors for each facility, with the aim of determining their performance in detecting neutrinos and delivering physics measurements.

The baseline for the Neutrino Factory is a Magnetised Iron Neutrino Detector (MIND) [22]. This is an iron-scintillator calorimeter, with alternating planes of 3 cm thick iron and 2 cm thick solid scintillator. One detector is now planned, of 100 kT mass at a distance of around 2000 km. From CERN, this baseline is possible with a detector in the Pyhäsalmi mine in Finland. The design, shown in Figure 18, has been based on that of the MINOS detector [23]. It will have a transverse size of 14 by 14 m and be 140 m long, meeting the constraints coming from typical underground laboratories [24]. It will have a toroidal magnetic field of >1T to distinguish μ^+ and μ^- events. Detailed simulations of the detector performance have made in EUROnu using GENIE to generate the neutrino events and GEANT 4 for the detector modeling. Events are reconstructed using, for example, a Kalman filter for track reconstruction. Some results are shown in Figure 19.

Migration matrices, which relate the true neutrino energy to the reconstructed energy, have been produced for MIND, for use in the physics reach determinations. In addition, the systematic errors on the reconstruction of signal and background events have been conservatively estimated at 2% and 5%, respectively.

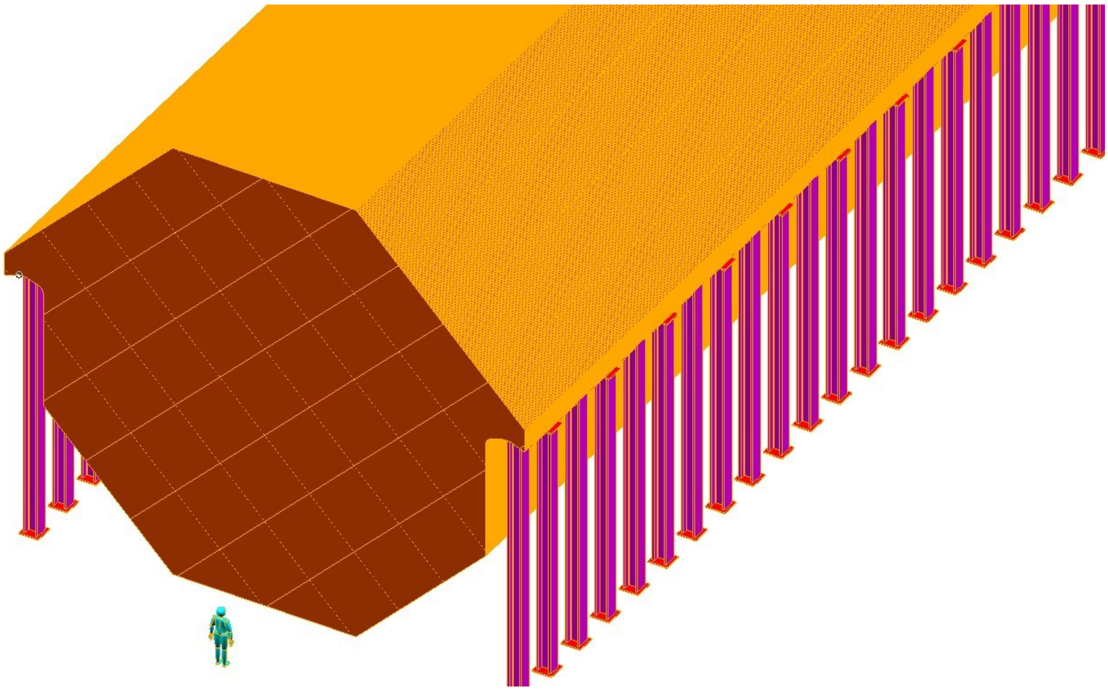

Figure 18: The Magnetised Iron Neutrino Detector for a Neutrino Factory.

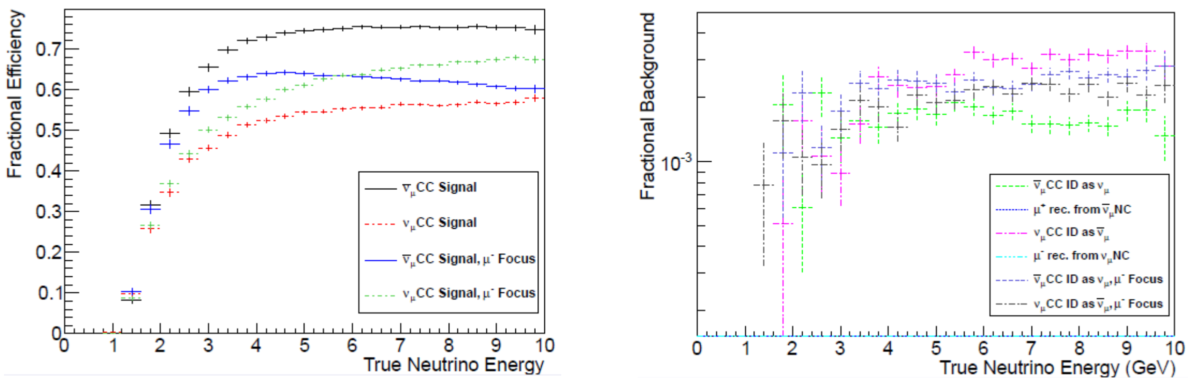

Figure 19: Performance of the MIND detector. (Left) The efficiency for detecting the muon signal events. (Right) The fractional backgrounds.

The baseline for both the Super Beam and Beta Beam facilities is the MEMPHYS detector [2], a 500 kT fiducial mass water Cherenkov detector. The original proposal was to locate this in the Laboratoire Souterrain de Modane in the Fréjus tunnel in France, at a distance of 130 km from CERN. However, recent physics studies following the measurement of θ_{13} (see below) have shown that a longer baseline would have a number of benefits. As a result, the Laboratorio Subterráneo de Canfranc in Spain, at a distance of 630 km, is now also of interest. The current plan is to build the detector from two modules, 65 m in diameter and 103 m in height (see Figure 20), in two separate caverns. Based on a large experience from the SuperKamiokande experiment [25], light will be detected using 12000 8" or 10" PMTs in each module. To reduce costs, it is planned to group readout electronics [26]. To test this and other aspects of the detector, a prototype called MEMPHYNO [27] has been built at Université ParisVII and is being tested (see Figure 21). As for MIND, a simulation has been developed to determine the detector performance, also using GENIE for event generation and GEANT 4 for modeling the detector response. As an example, Figure 22 shows the reconstructed energy from identified muon rings compared with the real energy. Migration matrices have been produced for MEMPHYS and are being made available for physics performance determinations. Note that using the same detector would make it possible to run the Super Beam and Beta Beam at the same time, thereby improving the physics performance compared to both facilities alone.

Figure 20: The proposed MEMPHYS detector for the Super Beam and the Beta Beam.

Near detectors are essential for all three facilities to:

- measure the neutrino flux to 1% precision to allow the extrapolation to the far detector;
- measure the ν_e and ν_μ cross-sections to control systematic errors;
- measure the charm production for the Neutrino Factory, as this is an important background.

In addition, the near detectors can also be used for physics, in particular the measurements of parton density functions, $\sin^2\theta_W$ and non-standard interactions from taus. A sketch of the near detector for a Neutrino Factory is shown in Figure 23. It consists of a high resolution section using a scintillating fibre tracker for flux measurements, a Mini-MIND detector for flux and muon measurements and a vertex detector for charm and tau measurements. The near detector for a Super Beam and Beta Beam would be similar, except without the vertex detector and including a water target.

Figure 21: The MEMPHYNO detector under test.

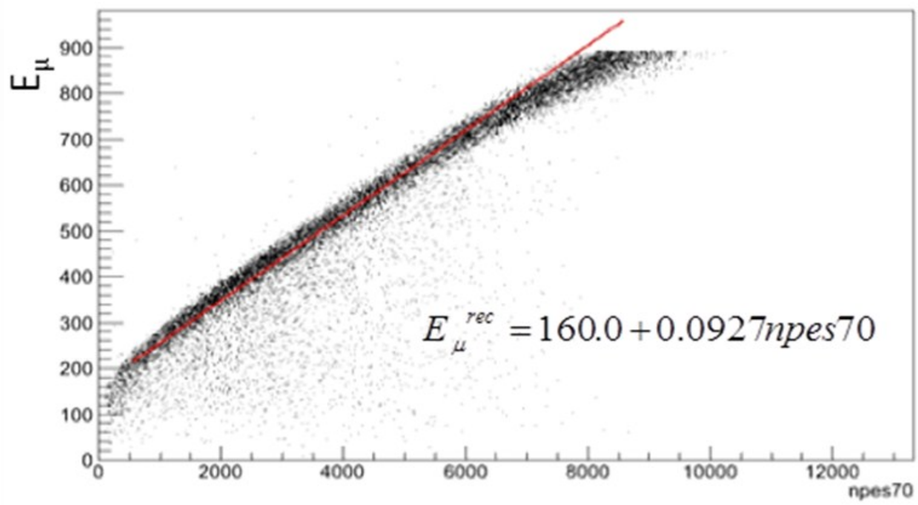

Figure 22: Performance of the MEMPHYS detector. The reconstructed energy of a muon from a neutrino interaction is compared with the real energy, as a function of the number of photoelectrons detected.

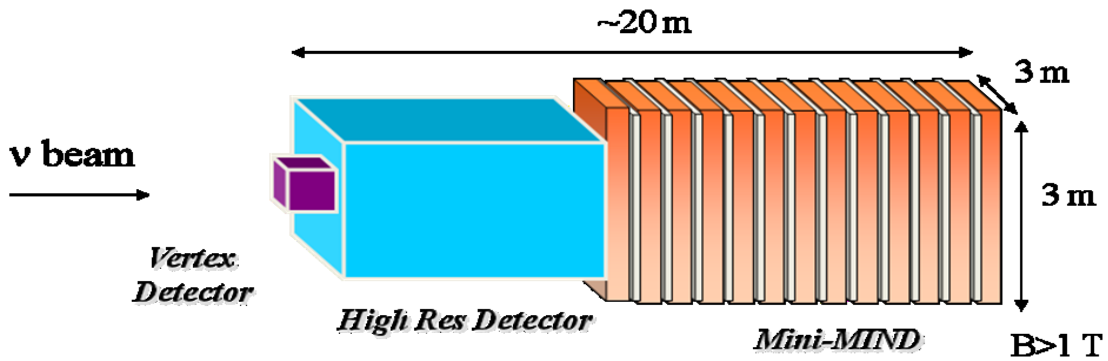

Figure 23: The near detector for a Neutrino Factory.

Physics Performance

The physics group in EUROnu is determining the physics reach of each facility and combination of facilities using the parameters provided for the accelerators and detectors. They also assess and include the corresponding systematic errors in a uniform way and optimize the performance based on information from other experiments. Following the recent indications of large θ_{13}, an initial physics reach comparison between the three EUROnu facilities and others has been made. The results are shown in Figures 24 to 26. For the Low Energy Neutrino Factory, the signal systematic error used is 2.4%, while it is 5% for the other facilities. The systematic error used for the background in all cases is 10% and 10 years running time is assumed.

The figures clearly demonstrate that the Neutrino Factory has the best physics reach of all the future proposed projects, covering more than 80% of δ after 10 years of running and determining the mass hierarchy at 5σ on a much shorter time scale. The SPL Super Beam with a detector at the second oscillation maximum also has a good physics reach, measuring CP over 65% of δ and determining the mass hierarchy for all values of δ after 10 years of operation.

Costing

As well as determining the physics performance of the three facilities, EUROnu has undertaken a comparative costing for the construction of each. This is clearly a very important input into the decision on what the consortium's recommendation for the future should be. As the resources available to do this costing have been limited, the focus has been more on the relative cost of each facility. A lot of care has been taken to ensure similar assumptions have been made and common costs used wherever possible. For the purpose of this comparison, it has assumed that all three facilities would be located at CERN, to put the costing on the same basis. To do this, layouts of each facility have been made on the CERN site (see Figures 27-29).

To ensure that all methodology used in the costing and all the assumptions made are well documented, a separate "Costing Paper" has been written [28]. It is essential that anybody using the costs given here read that document before doing so. The results of the costing are shown in Tables 1-3, taken directly from the Costing Paper. The cost is given as a lower bound and an upper bound. The lower bound is the estimated total cost, including staff costs. For each estimated cost that goes into this total, an error is also determined to reflect the uncertainties in that cost. The total error is taken to be the sum of all these errors, as this is the most conservative, though pessimistic, approach. The upper bound given is the lower bound, plus this total error. Table 1 gives the estimated total cost for each of the accelerator facilities, Table 2 the estimated costs for the corresponding detectors and Table 3 the total estimated costs of the accelerator facilities and detectors.

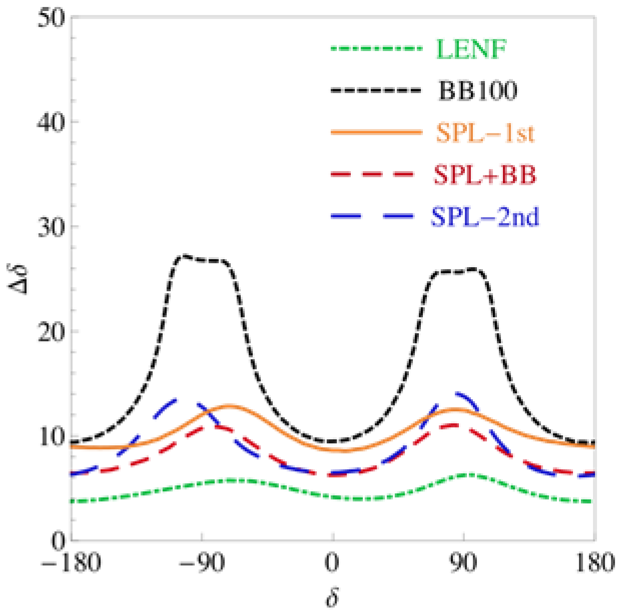

Figure 24: The 1σ measurement errors for the CP angle δ as a function of δ. The facilities studied are as follows. LENF: the Low Energy Neutrino Factory, with a 10 GeV muon energy, 1.4×10^{21} decays per year and a single 100 kt mass Magnetised Iron Neutrino Detector (MIND) at a baseline of 2000 km; BB100: a γ=100 Beta Beam, with $1.3/3.5\times10^{18}$ decays per year of Ne/He and a 500 kt Water Cherenkov detector (MEMPHYS) at Fréjus; SPL-1st: a 4 MW SPL Super Beam with 500 kt water Cherenkov detector at Fréjus, corresponding approximately to the first oscillation maximum; SPL-2nd: as above, but with the detector at Canfranc, corresponding to approximately the second oscillation maximum; SPL+BB: the combination of BB100 and SPL-1st.

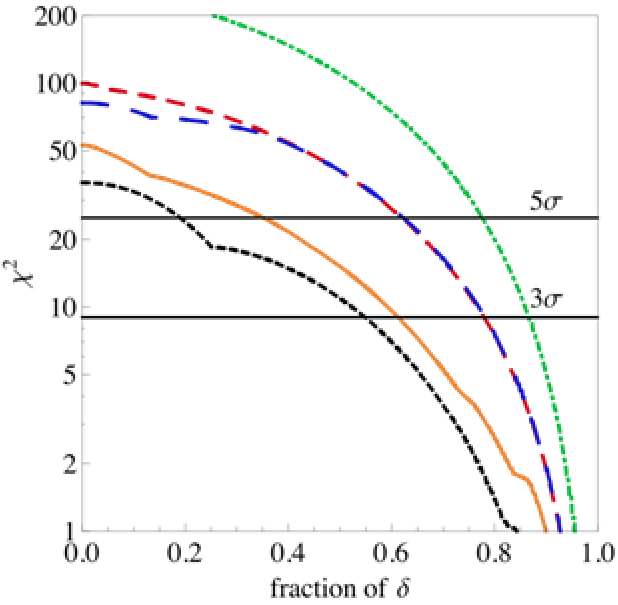

Figure 25: The range of δ for which a 3 and 5σ measurement of CP violation can be made by the same facilities as in Figure 24.

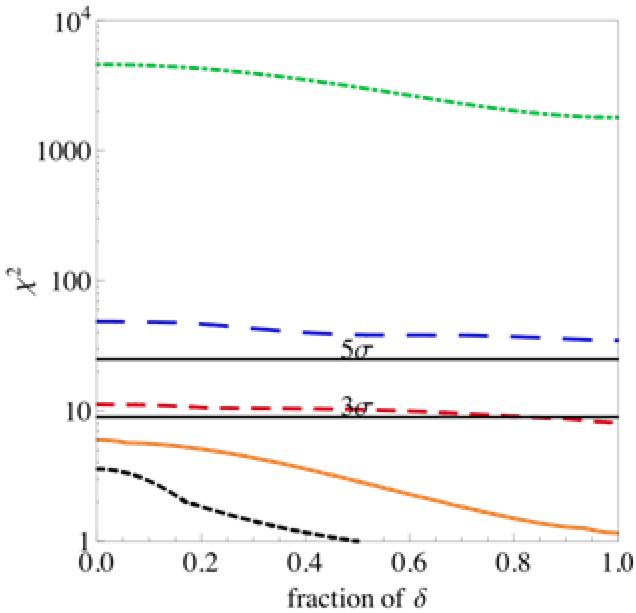

Figure 26: The range of δ for which a 3 and 5σ measurement of mass hierarchy can be made by for the same facilities as in Figure 24.

Table 1: Total cost of the three accelerator facilities

	Lower bound [MEUR]	Upper bound [MEUR]
Super Beam	1,193	1,566
Beta Beam	1,415	2,270
Neutrino Factory	4,663	6,504

Table 2: Total cost of the near and far detectors. The near and far detectors are the same for the Super-Beam and Beta Beam. If both facilities operated simultaneously, two near detectors would be required, but only one far detector. The near detector cost for a Neutrino Factory is for two detectors.

	Near detector(s) cost [MEUR]		Far detector cost [MEUR]		Total detector cost [MEUR]	
	Lower bound	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound
Super Beam or Beta Beam	35	46	739	887	774	933
Neutrino Factory	82	106	522	678	604	784

Table 3: Total cost for the accelerator facilities and the relevant detectors. Note that the lower bound without staff costs just uses a 40% scaling factor.

	Lower Bound [MEUR] (excluding staff costs)	Lower bound [MEUR]	Upper bound [MEUR]
Super Beam	1,405	1,967	2,499
Beta Beam	1,564	2,189	3,203
Neutrino Factory	3,762	5,267	7,288

Figure 27: Layout of the CERN to Fréjus Super-Beam on the CERN site.

Conclusions

The primary aims of EUROnu have been to produce conceptual designs of a CERN to Fréjus Super Beam, a Neutrino Factory and Beta Beam and to determine their physics reach and cost. This has been done and the information created has been used for a comparison between the facilities and to make a recommendation to the CERN Council on which to take forward. Based on the physics performance and a preliminary cost comparison, EUROnu is strongly recommending the construction and operation of a 10 GeV Neutrino Factory as soon as possible [29]. We believe this should be done using the following staged approach:

1) Completion of the necessary design and R&D work to allow a full proposal for a Neutrino Factory to be written in 2017.
2) The construction of νSTORM [30]. This project will use an existing proton driver of around 300 kW beam power to create pions in a target. Forward going pions with an energy of 5 GeV (±10%) will be focussed into a transport line, before injection into a straight of a storage ring. Muons of around 3.8 GeV from the decay will then be transported around the ring and the neutrinos from their decay used for the following studies:
   - the search for sterile neutrinos,
   - the measurement of $\nu_e N$ scattering cross-sections,
   - neutrino detector development.

   In addition, this facility will be a valuable prototype for the Neutrino Factory construction.
3) The construction of a low power version of the Neutrino Factory, using an existing proton driver, without muon cooling and using a lower mass MIND detector, around 20kt. This will already have a very competitive physics potential [31].
4) The construction of the 4 MW Neutrino Factory using 10 GeV muons and a 100 kt MIND detector at a baseline of around 2000 km.

This recommendation has been submitted to CERN Council via the Update of the CERN Strategy for Particle Physics 2011-2012 [32].

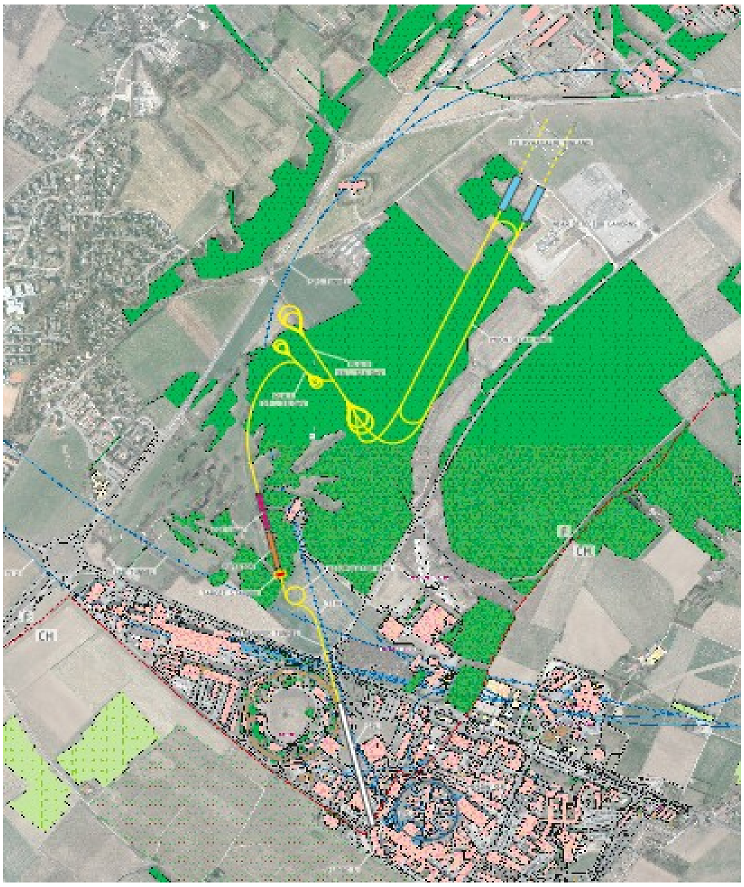

Figure 28: Layout of the Neutrino Factory on the CERN site

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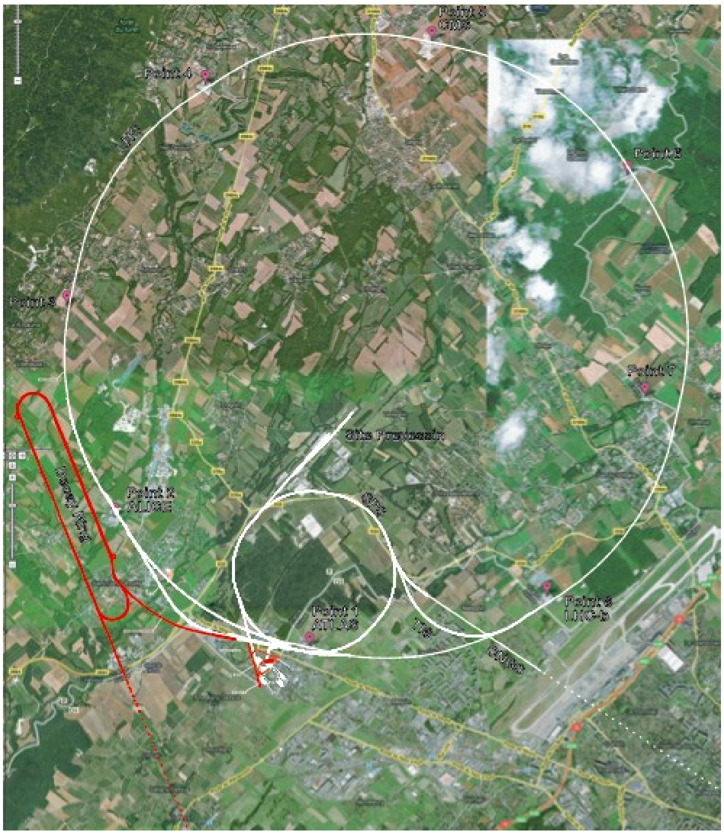

Figure 29: Layout of the Beta Beam on the CERN site.

Impact

As explained previously, the primary objective of EUROnu was to determine which of the three facilities it has studied is the best and recommend to the appropriate body in Europe the next steps in this area. This body is the CERN Council, which determines strategy for particle physics in Europe. The main mechanism by which it does this is a periodic review of strategy, involving scientists not just from Europe, but from around the World. The first strategy review took place in 2006. The first update of this started this year, with input requested by 31st July. EUROnu took this as an opportunity to meet our primary objective and submitted the input below to this review. In addition, it ensured that this input was well represented in presentations at an open meeting of the strategy update process in September and is being included in the summary documents resulting from this. The outcome of the strategy update will not be known until next year. Nevertheless, we will continue to ensure that our input is used. It should be noted that there is growing interest at CERN and in Europe and elsewhere in one of the first steps in our strategy: the construction of the νSTORM project (see below). A Letter of Intent about the project was recently submitted to FNAL in the US and was well received there. It is planned to submit another to the appropriate body in CERN, with aim of getting CERN involved in the project.

In addition, the fact that EUROnu has been able to reach a consensus and make a recommendation is extremely important. For example, the International Committee for Future Accelerators (ICFA), whose membership consists of the directors of all the major Particle Physics accelerator laboratories in the World is now creating an international Neutrino Panel with the mandate: "*To promote international cooperation in the development of the accelerator-based neutrino oscillation program and to promote international collaboration in the development of a Neutrino Factory as a future intense source of neutrinos for particle physics experiments.*" We plan to present our recommendations as widely as possible in the meantime.

EUROnu input to the CERN Strategy Update

The recent measurement of the neutrino oscillation parameter θ_{13} and the demonstration that this angle is large, around 9^o [1,2,3,4], has shown that a number of extremely important physics goals could now be within reach. These include:

- The discovery of CP violation in the lepton sector and a precise measurement of the CP phase, δ.
- The neutrino mass hierarchy.
- Precise measurement of other oscillation parameters, thereby testing, for example, the unitarity of the mixing matrix.

In addition to the indispensable knowledge of the properties of neutrinos, these measurements are likely to have very important consequences elsewhere, for example bringing insight to the nature of particle masses and the question of flavour, to a solution to the baryon asymmetry of the Universe and to the evolution of the early Universe and determining the neutrino contribution to dark matter. Clearly, the measurements should be a high priority for European Particle Physics.

It is felt in EUROnu that the first of these physics goals is by far the most important and that the neutrino strategy should focus on the discovery of CP violation. The FP7 Design Study EUROnu [5] has completed this year the conceptual design of three possible future high intensity facilities: a conventional very high power Super Beam, from CERN to Fréjus, and two novel neutrino beams, a Neutrino Factory and a Beta Beam. These and other studies show that of all the future proposed facilities, the Neutrino Factory, with 10 GeV muons and a 2000 km baseline, has the best chance of measuring the CP angle δ at 5σ and is almost certain to do so, if the expected performance is achieved. Figures 1 and 2 show a comparison of this measurement after 10 years of operation for each of the EUROnu facilities.

As well as CP violation, the Neutrino Factory is also expected to bring the best precision in the measurement of θ_{13} and the atmospheric oscillation parameters and can rapidly determine the mass hierarchy at more than 5σ, once running (see Figure 3). It should be noted that layouts of the Neutrino Factory and the other two facilities have been made by civil engineers at CERN (see Figure 4) [6] and that an optimal baseline is available in Europe [7][8].

These studies also show that the effect of the mass hierarchy is large, making a statistically significant measurement possible at more conventional facilities than those studied in EUROnu. These include a CNGS-like neutrino beam from CERN to a large detector at around 700 km or more [9] and atmospheric neutrinos [10].

In addition to the physics performance studies, EUROnu has also undertaken a relative cost comparison between the three facilities. This has demonstrated that although the Neutrino Factory is the most expensive to build, this is more than offset by the improved physics it will bring.

In consequence, EUROnu strongly recommends the construction and operation of a 10 GeV Neutrino Factory as soon as possible, implemented using the staged approach described below.

Figure 2 also demonstrates the physics potential of an SPL-based Super Beam, particularly if the detector could be placed at the second oscillation maximum. In particular, if the MEMPHYS detector is constructed, much of the accelerator infrastructure required to deliver a Super Beam to it is already part of a Neutrino Factory. It would, therefore, be possible to have both facilities with limited additional funding. This Neutrino Factory + Super Beam combination would bring a significant improvement in physics potential, both for oscillation measurements and in other important physics areas [11], though the issue of maximising the number of protons delivered to both facilities would need to be addressed.

Staged approach to a Neutrino Factory

We envisage a staged approach to delivering a 4 MW, 10 GeV Neutrino Factory, with important physics possibilities at most steps. The stages are:

1) Completion of the necessary design and R&D work to allow a full proposal for a Neutrino Factory to be written in 2017.
2) νSTORM [12]. This project will use an existing proton driver of around 300 kW beam power to create pions in a target. Forward going pions with an energy of 5 GeV (±10%) will be focussed into a transport line, before injection into a straight of a storage ring. Muons of around 3.8 GeV from the decay will then be transported around the ring and the neutrinos from their decay used for the following studies:
    - the search for sterile neutrinos,
    - the measurement of $\nu_e N$ scattering cross-sections,
    - neutrino detector development.

In addition, this facility will be a valuable prototype for the Neutrino Factory construction. A Letter of Intent for νSTORM was recently been submitted to the FNAL PAC [12]. This was well received and the collaboration was asked to prepare a full proposal. Another is planned to be submitted to CERN in the near future, to allow members of CERN staff to contribute to the project.

3) A low power version of the Neutrino Factory, using an existing proton driver, without muon cooling and using a lower mass MIND detector, around 20kt. This will already have a very competitive physics potential [13] – see Figure 5.
4) A 4 MW Neutrino Factory using 10 GeV muons and a 100 kt MIND detector at a baseline of around 2000 km.

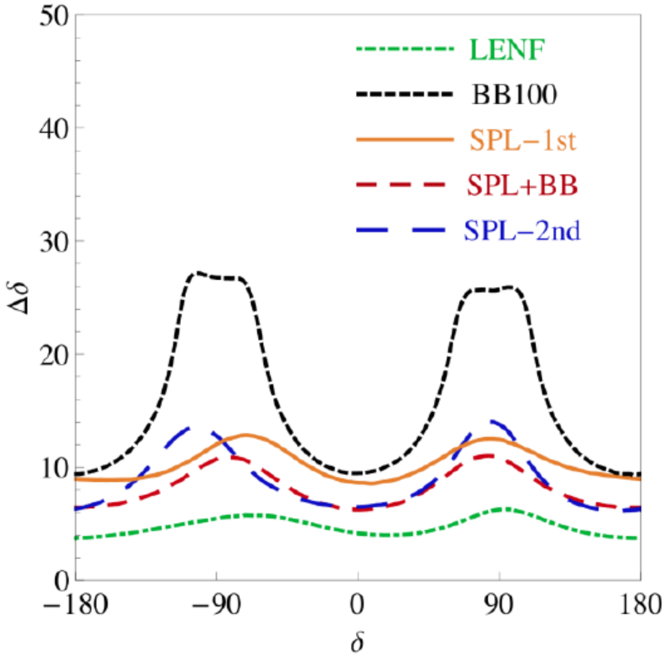

Figure 1: *The 1σ measurement errors for the CP angle δ as a function of δ. The facilities studied are as follows. LENF: the Low Energy Neutrino Factory, with a 10 GeV muon energy, 1.4x10^{21} decays per year and a single 100 kt mass Magnetised Iron Neutrino Detector (MIND) at a baseline of 2000 km; BB100: a γ=100 Beta Beam, with 1.3/3.5x10^{18} decays per year of Ne/He and a 500 kt Water Cherenkov detector (MEMPHYS) at Fréjus; SPL-1st: a 4 MW SPL Super Beam with 500 kt water Cherenkov detector at Fréjus, corresponding approximately to the first oscillation maximum; SPL-2nd: as above, but with the detector at Canfranc, corresponding to approximately the second oscillation maximum; SPL+BB: the combination of BB100 and SPL-1st.*

EUROnu input to the CERN Strategy Review

To deliver the physics potential of a Neutrino Factory in a timely manner, using the staged approach described above, we believe the European Strategy for Particle Physics should:

- Ensure that the R&D and design work necessary to deliver a full proposal for a Neutrino Factory in 5 years, before the next Strategy Review, is undertaken.
- Recommend an active participation in the νSTORM project, including the possibility of construction at CERN.
- Emphasise the importance of a high power proton upgrade at CERN, to the 4 MW level, preferably via the High Power SPL route, and support the required R&D in this direction.

Further documentation and supporting material will be found in a special directory under Documents on the EUROnu website at: http://euronu.org.

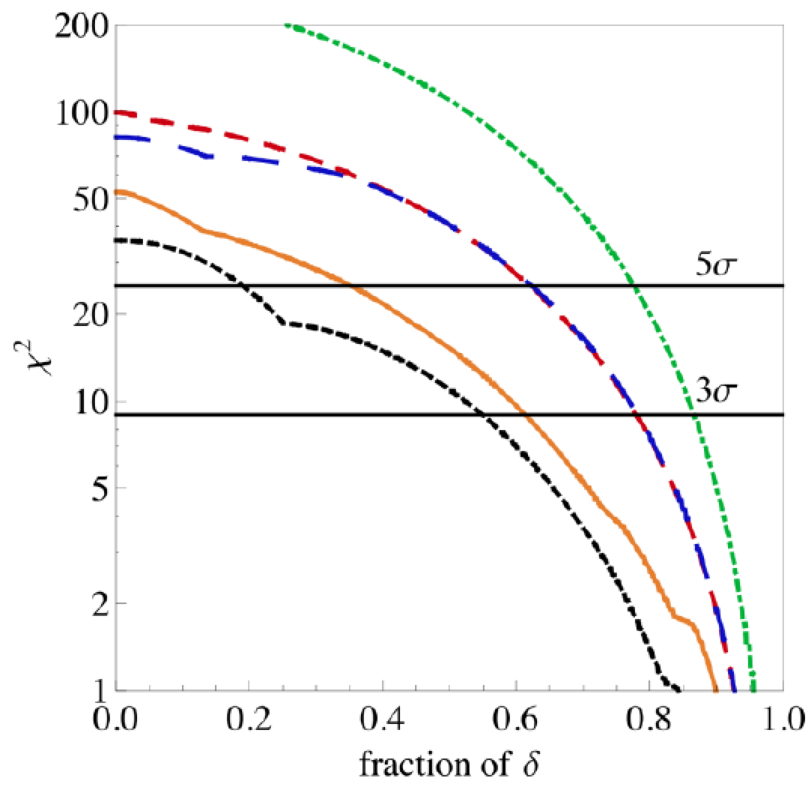

Figure 2*: The range of δ for which a 3 and 5σ measurement of CP violation can be made by the same facilities as in Figure 1.*

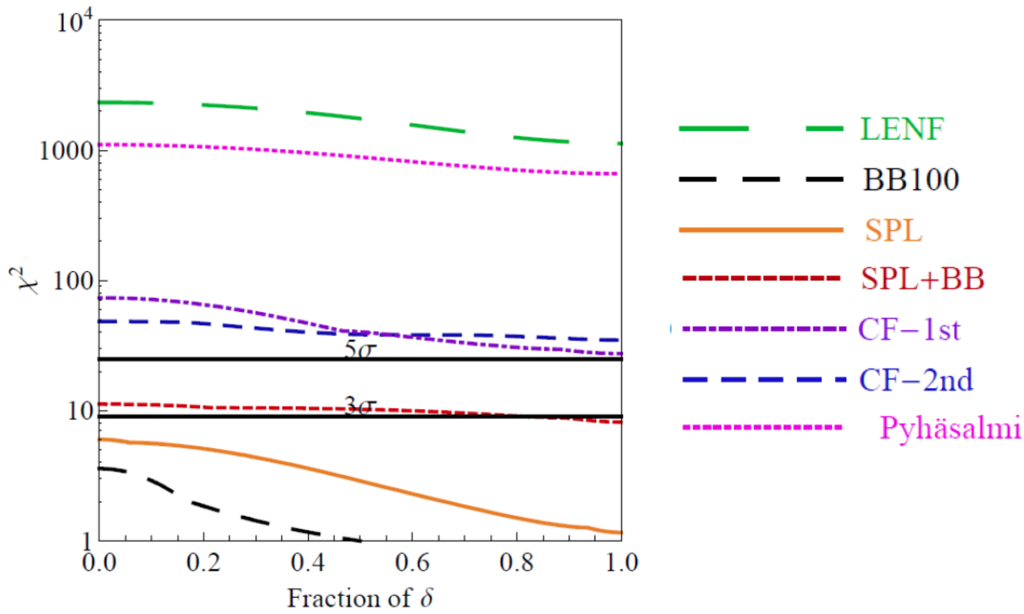

Figure 3: *The range of δ for which a 3 and 5σ measurement of mass hierarchy can be made by the EUROnu and other facilities.*

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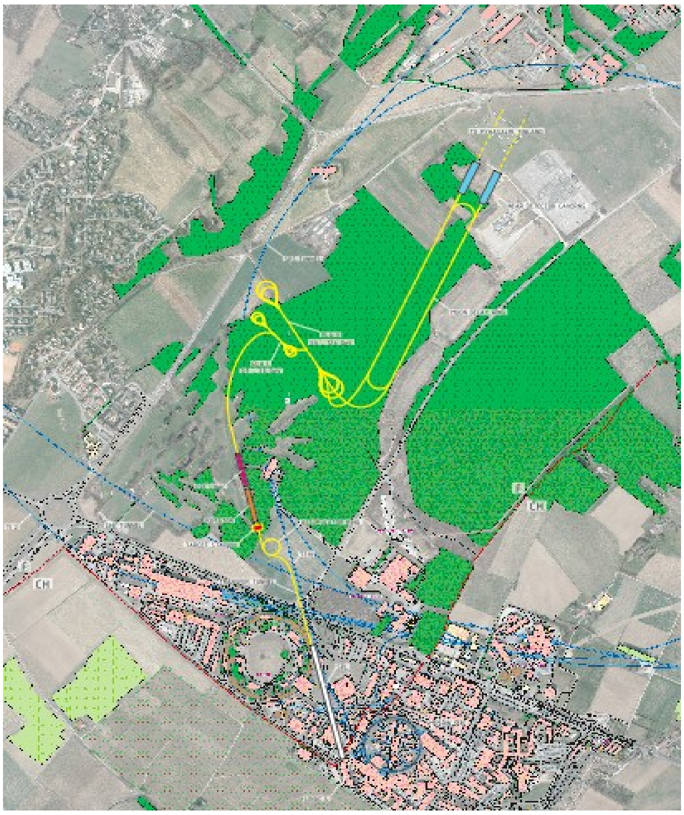

Figure 4: *Preliminary layout of a 10 GeV Neutrino Factory on the CERN site, with neutrino beams pointing at the Pyhasalmi mine in Finland, 2300 km away.*

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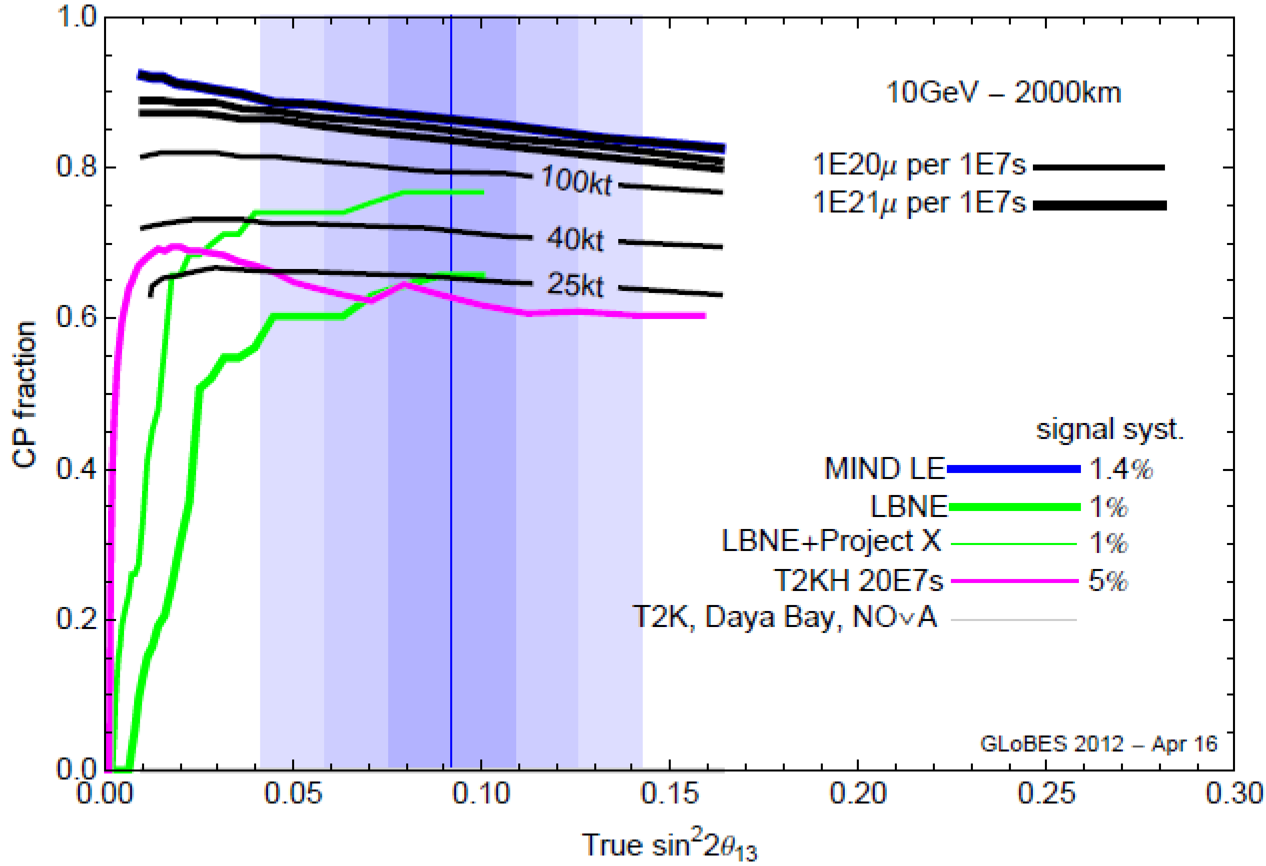

Figure 5: *A study of possible staging scenarios for a Neutrino Factory. The plot shows the fraction of the CP angle for which a measurement can be made for various MIND detector masses and the number of neutrinos produced per year. The current measured value of θ_{13} is shown as a vertical line. The potential of the Neutrino Factory is compared to other possible future facilities in the US (LBNE) and Japan (T2KH). The plot shows that a Neutrino Factory with a factor of 10 smaller neutrino flux than the full 4 MW version and a 25 kt MIND is already competitive.*

Additional impact

As well as providing important input to the CERN Strategy Review, the recommendations of EUROnu have already been presented at a number of important meetings, for example the 36th International Conference on High Energy Physics and meetings of the European Committee for Future Accelerators. It is planned to continue this at workshops and conferences, particularly those focussed on neutrino physics, this year and next.

Due to the importance of the EUROnu results, a special edition of the journal Physical Review Special Topics: Accelerators and Beams, one of the standard journals for the publication of results in the field of accelerator science, is being created for us. Most of the papers have already been submitted, though a few are still in preparation. They include an overview of EUROnu, an overview of the results of each work package in EUROnu and more detailed papers. They will be refereed in the usual way.

Finally, it should be noted that should a Neutrino Factory be constructed and operated, it will be a large project, even on the scale of CERN. As a result, it will only be possible to do it as an international project, with contributions from Japan and the US, as well as Europe. It will thus bring funding into Europe from outside. It is also likely to have a significant impact in the new media.

Future of EUROnu

It has already been agreed in EUROnu that the project should continue, to bring about the recommendations we have made. It is hoped to apply for funding to Horizon 2020 to do this. As the CERN Strategy Update will provide a very important input to this programme for Particle Physics, we will wait for the output of that before deciding how to proceed.