THE EURONU STUDY FOR FUTURE HIGH POWER NEUTRINO OSCILLATION FACILITIES*

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Abstract

The EUROnu project was a 4 year FP7 design study to investigate and compare three possible options for future, high power neutrino oscillation facilities in Europe. These three facilities are a Neutrino Factory, a neutrino superbeam from CERN to the Frejus Laboratory and a so-called Beta Beam. The study was completed at the end of 2012 and has produced conceptual designs for the facilities and preliminary cost estimates. The designs were used to determine the physics performance. These have been used to compare the facilities. This paper will describe the designs and physics performance and summarise the recommendations of the study.

INTRODUCTION

The measurements of the neutrino oscillation parameter θ_{13} over recent years 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.

EUROnu [5] was an EU-funded FP7 Design Study which finished in 2012. It undertook the conceptual design of three possible high intensity facilities that could address these physics goals: a conventional very high power Super Beam and two novel neutrino beams, a Neutrino Factory and a Beta Beam. It compared their performance and cost and, based on these, made a recommendation on the next steps.

Each facility is briefly described below and the physics comparison given.

CERN TO FREJUS SUPERBEAM

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 neutrino beam comes from the pion decay. EUROnu has studied the CERN to Fréjus Super Beam, using the High Power Superconducting Proton Linac (HP-SPL) [6] 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 [7] in the Fréjus tunnel. The main activities have been in designing and testing candidate targets and magnetic horns, integrating the targets and horns together, studying the required target station, designing the proton beam handling system beyond the SPL and determining the characteristics of the resulting neutrino beam for physics simulations.

Given the difficulty in producing a single target and horn able to work in a 4 MW beam, the option taken in EUROnu is to use four of each instead. The beam 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. The baseline design for the target is a pebble bed, consisting of 3 mm diameter spheres of titanium in a canister. These are cooled by flowing helium gas through vents in the canister. Modelling suggests that a sufficient flow rate can be achieved to cool the targets, even with a higher power beam. The horn design is based on that of the MiniBooNE experiment [8], but has been modified to optimise the pion production. An initial design of the target station has also been made, based on radiation and activation studies. This incorporates the necessary shielding and remote handling for 4 MW and also has storage for the old targets and horns.

The final area studied is the beam delivery from the SPL to the target. This requires an Accumulator ring to reduce the large number of bunches from the linac to a small number for delivery to the target. An initial design of this ring has been made. In addition, a design for the system to split the beam on to the 4 targets has been made and the engineering aspects of this have been studied.

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 20T super-conducting solenoid. 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, a re-circulating linear accelerator (RLA) and a non-scaling Fixed Field Alternating Gradient accelerator (ns-FFAG) to 1.2, 5 and

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10 GeV, respectively (see Figure 1). The muons are then injected into two storage rings, to produce beams of neutrinos and anti-neutrinos to a 100 kT mass Magnetised Iron Neutrino Detector (MIND) far detector at a baseline of about 2000 km.

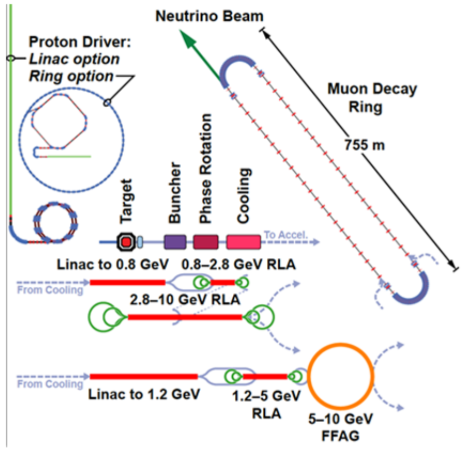

Figure 1: The Neutrino Factory.

The work in EUROnu was done in close collaboration with the International Design Study for a Neutrino Factory [9]. However, EUROnu focussed on the section from the pion production target to the muon acceleration system. The baseline target is a liquid mercury jet. However, modelling done in EUROnu has shown that the heat load from the secondaries produced in the super-conducting solenoids used to focus the pions is much too big, around 50 kW. The main problem is secondary neutrons. This has been fixed by adding more shielding and reducing the solenoid field somewhat.

A related issue is the transmission of secondaries into the muon front-end. As well as the required large flux of muons, there are also still many protons, pions and electrons. The front-end has been re-designed in EUROnu to include a chicane, to remove the higher momentum unwanted particles, and 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.

For the cooling channel, an engineering demonstration of the cooling technique, ionisation cooling, 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 2015. In addition, the RF cavities of the baseline cooling cell will be in a large magnetic field, resulting from the coils used to focus the beam to increase the cooling efficiency. Measurements done in the MuCool project [11] suggest this could limit the accelerating gradient before the cavities breakdown. Alternative cooling lattices have been studied in EUROnu that reduce the magnetic field at the cavities, while maintaining the same performance.

Two options exist for accelerating the beam to 10 GeV. The first uses a linac and two RLAs, while the second replaces the higher energy RLA with a ns-FFAG. As ns-FFAGs are an entirely novel type of accelerator, a proof-of-principle machine called EMMA [12] has been constructed at the STFC Daresbury Laboratory. This has recently demonstrated that many of the novel features of the muon accelerator, in particular serpentine acceleration and multiple resonance crossings, work.

BETA BEAM

Production of (anti-)neutrinos from beta decay of radioactive isotopes circulating in a race track shaped storage ring was proposed in 2002 [13]. Beta Beams produce pure electron neutrino or electron antineutrino beams, depending on whether the accelerated isotope is a β+ or β- emitter. The facility studied here is based on CERN's infrastructure to reduce cost (see Figure 2).

One of the main issues studied by EUROnu is 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 [14], is 6He and 18Ne, accelerated to $\gamma = 100$ in the SPS and stored in the Decay Ring. At the end of EURISOL, the flux of 18Ne that looked possible was a factor of 20 too small. This has been addressed in two ways in EUROnu. The first was to consider a production ring (12 m circumference) with an internal gas jet target to make an alternative ion pair, 8Li and 8B. In this, a 25 MeV beam of 7Li and 6B is injected over a gas jet target of d and 3He, respectively. Significant studies of this have been undertaken, including the measurement of the double differential cross-sections for the reactions, studies of achievable gas flow rates in the ring and the construction of a prototype device for collection of the produced isotopes. These have shown that the required target gas-flow would be very challenging and that it would be very difficult to achieve the required rates.

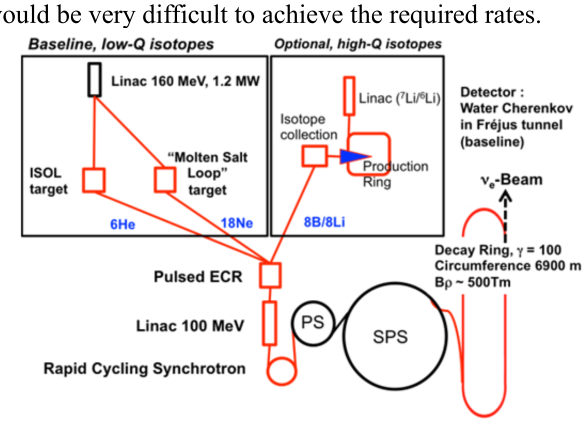

Figure 2: The Beta Beam facility.

As a result, research on a novel 18Ne-production method, using a molten salt loop (NaF) by the reaction 19F(p,2n)18Ne, has been undertaken. Modelling suggests that this could achieve the required production rate with an upgrade of Linac 4 at CERN from 4 to 6 mA. An experiment to demonstrate the method took place at ISOLDE at CERN in June 2012. As a result, the 6He and 18Ne ion pair is the baseline for the Beta Beam.

Research and development of a 60 GHz pulsed ECR source to bunch the ions produced are continuing. A prototype device has been constructed and successful magnetic tests have been done. These will be followed by tests with the gyrotron and with beam.

The baseline isotopes could use the MEMPHYS detector [7]. For the 8Li and 8B option, a detector some 700 km away would be needed.

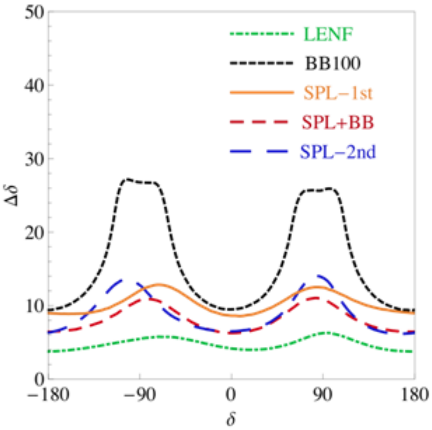

Figure 3: The 1σ measurement errors for the CP angle δ as a function of δ. The facilities studied are as follows. LENF: the Low Energy Neutrino Factory, with a 10 GeV muon energy, $1.4x10^{21}$ decays per year and a single 100 kt mass Magnetised Iron Neutrino Detector (MIND) at a baseline of 2000 km; 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.

PHYSICS COMPARISON

A comparison of the physics reach of the three facilities for CP-violation and determining the neutrino mass hierarchy after 10 years of operation are shown in figures 3 and 4. 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. The figures also demonstrate the physics potential of an SPL-based Super Beam, if the detector could be placed at the second oscillation maximum.

CONCLUSIONS

Based on the work done and the physics studies, the conclusion of EUROnu is the best facility for future neutrino oscillation studies is a Neutrino Factory. We further conclude that this should be constructed in a number of steps: (1) nuSTORM [15], a project using a 300 kW proton beam to create pions within a muon storage ring and the neutrinos from the muons produced to search for sterile neutrinos, measure the ν_eN scattering cross-sections and do neutrino detector development. (2) 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 [16]. (3) A 4 MW Neutrino Factory using 10 GeV muons and a 100 kt MIND detector at a baseline of around 2000 km.

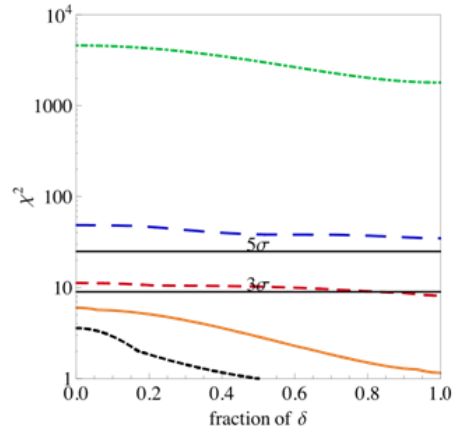

Figure 4: The range of δ for which a 3 and 5σ measurement of mass hierarchy can be made by for the same facilities as in Figure 3.

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