Future Neutrino Oscillation Facilities

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The European Commission FP7 Design Study called EUROnu is undertaking R&D on the most critical components of three possible candidates for a future, high intensity neutrino oscillation facility that could be built in Europe. These are a low energy neutrino Superbeam from CERN to the Fréjus tunnel in France, a Neutrino Factory and a Beta Beam based on ^{8}Li and ^{8}B ions. The study is following the recommendations of the CERN Council Strategy for Particle Physics and aims to deliver a performance and cost comparison between the facilities in 2012. The work is being done in close collaboration with international partners, in particular the International Design Study for a Neutrino Factory.

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1. Introduction

In July 2006, the CERN Council issued a Strategy Statement [1] outlining the European Strategy for particle physics. This contained the following statement concerning future neutrino oscillation facilities: *"Studies of the scientific case for future neutrino facilities and the R&D into associated technologies are required to be in a position to define the optimal neutrino programme based on the information available in around 2012; Council will play an active role in promoting a coordinated European participation in a global neutrino programme."* To meet the aims of the Council, a project called EUROnu [2] was created. This is a European Commission Framework Programme 7 Design Study entitled "A High Intensity Neutrino Oscillation Facility in Europe".

EUROnu is studying three possible options for this facility, namely a CERN to Fréjus Superbeam, a Neutrino Factory and a Beta beam. The primary objective of the study is a physics performance and relative cost comparison that will be delivered to the CERN Council via the CERN Strategy Group. Included in the work is the performance of the baseline detector technologies for each facility and a determination of the physics reach, with a detailed study of systematic errors. On an international scale, the International Design Study for a Neutrino Factory (IDS-NF) [3] is working in close collaboration with EUROnu, with the aim of delivering a Reference Design Report for a Neutrino Factory on the timescale of 2012.

Each of these facilities will be introduced in the following sections and some of the most important R&D projects underway will be discussed.

2.CERN to Frejus Superbeam

Superbeam here means a conventional neutrino beam created by the decay of pions, but using a proton driver with a beam power of around 4MW and a Mton water Cherenkov detector or equivalent. The layout of the CERN to Fréjus Superbeam is shown in figure 1. It will use a high power version of the proposed Superconducting Proton Linac (HP-SPL) at CERN to accelerate a 4MW proton beam to 2-5GeV. The proton bunches from the linac will be combined into around 100 bunches of 3μs duration in an accumulator ring and then impinged on to a target. The pions produced will be focussed using a magnetic horn to produce a low energy neutrino beam. This will be directed at the Modane Laboratory in the Fréjus tunnel under the Alps. The baseline detector will be a Mton scale water Cherenkov.

As there are already design reports for the proton driver [4], the work for this facility will focus mainly on the pion production target, the horn focussing system and the integration of these devices together and within the target station. However, the optimum parameters for the proton beam for neutrino oscillation measurements will also be determined from simulation studies.

2.1Target

The layout of the target for a Superbeam, based on a study for a Neutrino Factory, is shown in figure 2. The main issues for the target are the energy deposition from the beam, around 0.8MW for a high Z material and 0.2MW for a low Z, radiation damage affecting the material properties and the need to use the target within the horn. The baseline target for a Neutrino Factory is a liquid mercury jet, see section 3.1. However, there are a number of problems employing this technology within a horn, in particular delivering the mercury, the splash created by the beam and the effect of mercury on the aluminium of the horn. Due to these, the use of this technology looks difficult for this project.

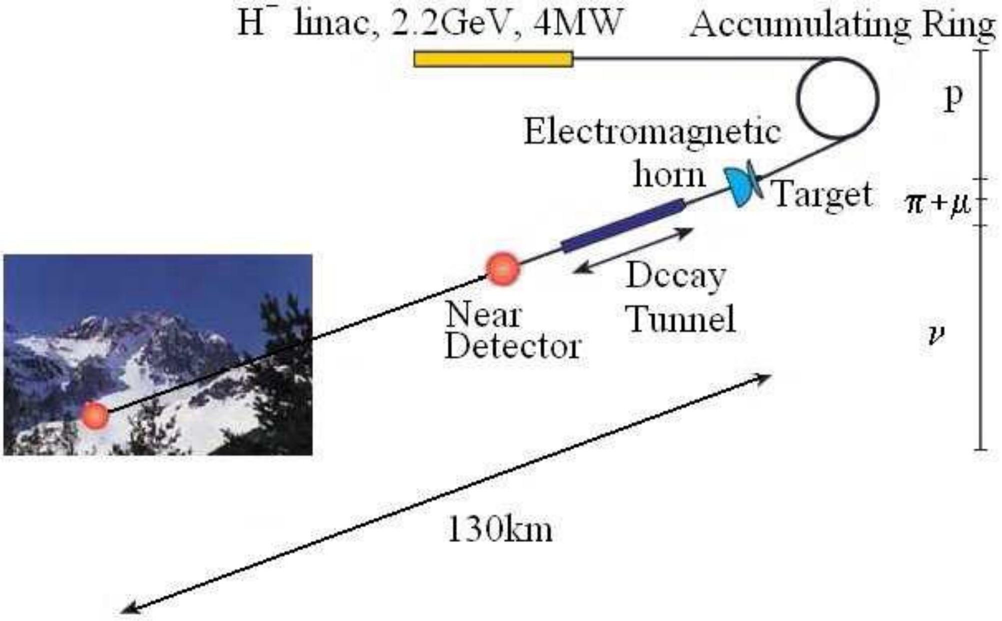


Figure 1: The baseline layout for the CERN to Fréjus Superbeam.

The alternatives are to use a modification of the current standard for neutrino beamlines, a graphite target, or to go to something more radical. For the former, because of the energy deposition, it is not possible to use a single graphite target. However, the use of, for example, 4 targets reduces the heating to a level comparable to existing facilities, such as for T2K [5]. The current plan is, therefore, to investigate the possibility of utilising four separate graphite targets, each mounted within its own horn. The main difficulty with this arrangement is delivering the proton beam to each target in turn and capturing the pions produced into a single decay channel. If this proves to be unfeasible, a possible back up is to employ a particle jet target [6], though this technology requires a significant amount of R&D before it could ever be used.

2.2Horn

As currently proposed, the Superbeam horn will consist of an inner conductor with a current of 300kA and an outer conductor, or reflector, with a 600kA current. Both of these will need to be pulsed at the proton beam repetition rate of 50Hz. The very large currents and high pulsing rate are well beyond the state of the art and will create significant heating and stress within the horn. Furthermore, there will be additional heating from the incident primary proton beam and secondary particle production from the target. It is estimated that the combined effect of these will reduce the lifetime of the horn to less than 6 weeks. A further technical challenge is the design of the power suppy required to pulse the horn. Each of these challenges are currently being assessed within EUROnu and possible solutions being evaluated. The four target option discussed in section 2.1 would obviously help significantly as it would reduce the heating and radiation effects on an individual horn.

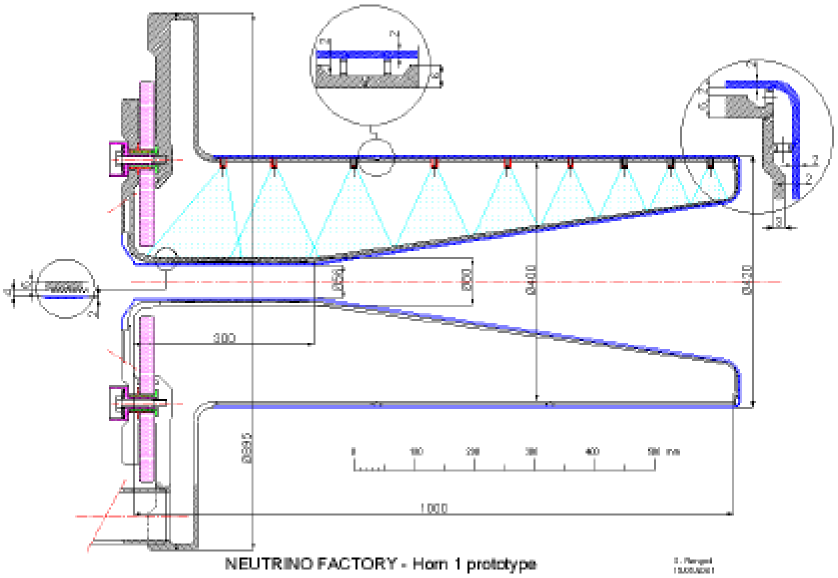


Figure 2: Cross-section of the magnetic horn for the Superbeam. The proton beam enters from the left and the target will be in the narrowest section of the horn at the left hand end.

3.Neutrino Factory

The baseline layout for the Neutrino Factory, produced by the International Scoping Study [7], the predecessor to the IDS-NF, is shown in figure 3. In this, a 4MW proton driver in the energy range 5-10GeV impinges a beam onto a high Z target to produce pions. As large a fraction of the pions as possible are focussed by a combined normally and super-conducting solenoid into a decay channel. The muons produced by the decay are transported into the muon front end, where they are bunched, phase rotated to reduce the energy spread and then cooled transversely. They are then accelerated to 22.5GeV by a combination of linear, recirculating linear and FFAG accelerators, before injection into one or more storage rings. The neutrino beams are produced by the muon decays in the straight sections of the storage ring and directed at one or more far neutrino detectors.

All aspects of the Neutrino Factory accelerator complex are well beyond the state of the art. Two of these, the target and the muon acceleration system, and their associated R&D, are described in the following sections. The muon cooling system and MICE experiment are discussed in another contribution to this conference.

3.1Neutrino Factory Target

Although there are many similarities between the targets for a Neutrino Factory and a Superbeam, there are also a number of differences. In the Neutrino Factory case, it is necessary to capture both signs of pions simultaneously, to produce muon beams of both charges. As this is not possible with a horn, the proposed pion capture mechanism is a 20T solenoid, built from a normally conducting inner core and a superconducting outer (see figure 4). This removes a number of constraints. However, the proton bunch length needs to be small, around 1ns long, and the target not too long to enable the manipulation of the muon phase space in the muon front end. Further, the production of pions in the appropriate, lower, momentum range required for a Neutrino Factory is bigger with higher Z, denser materials. Both of these mean that the preferred target materials are tungsten or mercury. However, the energy deposition from beam in these is about 0.8MW per pulse, leading to a 100°C temperature rise with each pulse. This necessitates changing the target between pulses.

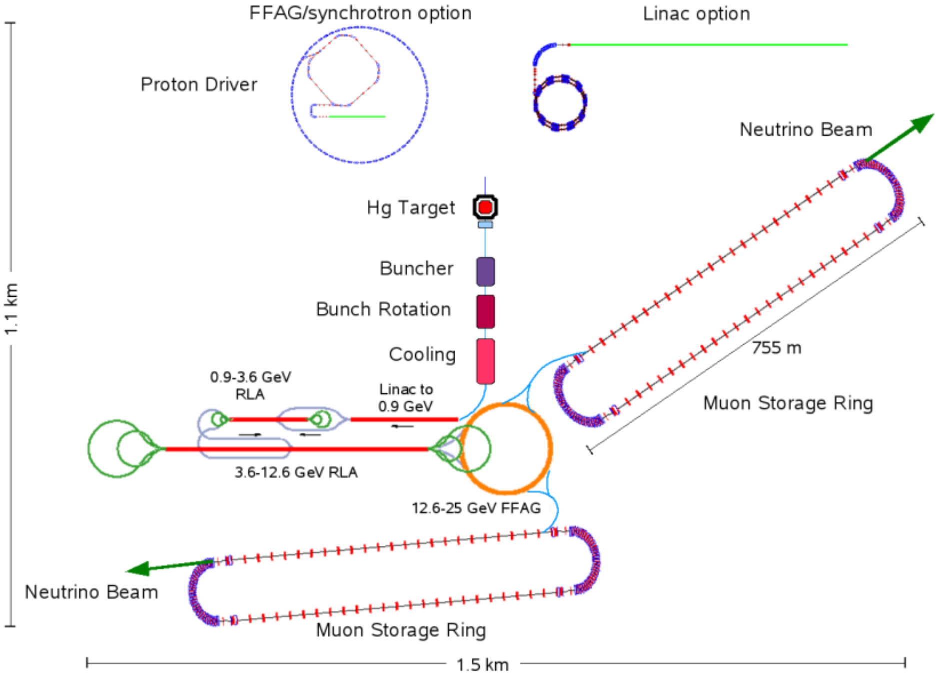
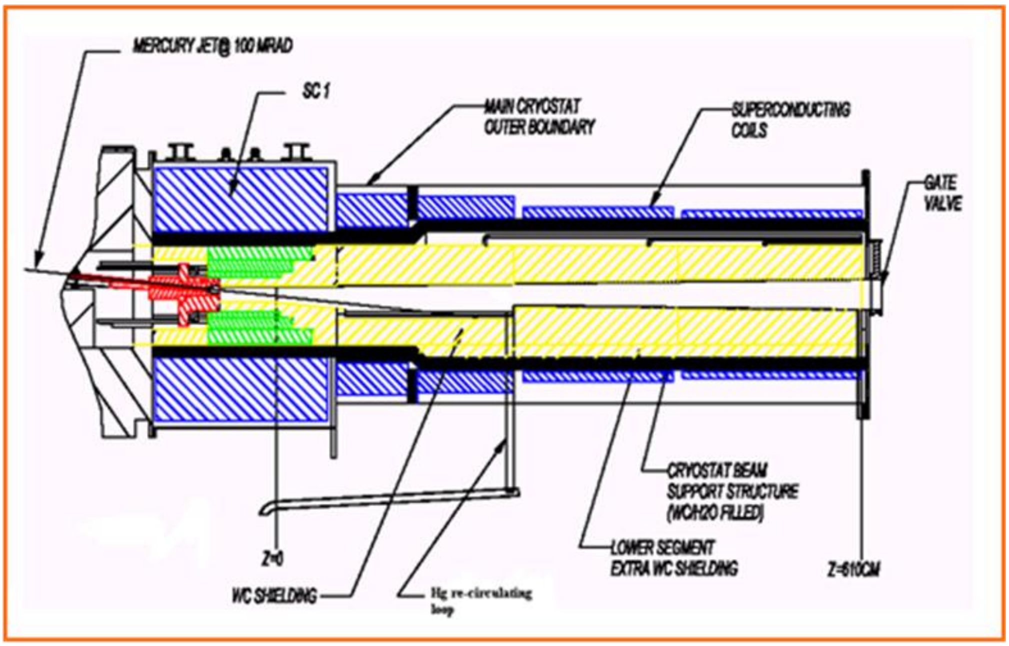


Figure 3: The layout of the baseline Neutrino Factory.

The current baseline technology is a 20m/s liquid mercury jet, 1cm in diameter, as shown in figure 4. This has the advantage that the heat deposited in the target is carried away by the jet. The issues of injecting the jet into a 20T field and the effect of the beam on the jet have been studied by the MERIT experiment [8]. This ran at CERN in 2007 and the analysis of the data is on-going, though advanced. This analysis has demonstrated a number of positive outcomes. For example, the quality of the jet from the noozle is rather poor, but is significantly improved by the effect of the magnetic field. Further, although the beam disrupts the jet, producing mercury droplets up to 100m/s in velocity and mercury filaments up to 60m/s in velocity, the disruption occurs after the proton pulse has passed and before the next proton pulse arrives 20ms later. This means the density of mercury seen by the protons is not noticably reduced.

Following on from the success of MERIT, there are a number of issues that still need to be addressed for a liquid jet target, primarily in the field of engineering. Examples include the effect of the mercury filaments and the jet itself on the surrounding target station, the design of the mercury loop and its potential erosion by the mercury and the radiation safety of a liquid target.



Study-2 capture solenoid

Figure 4: Layout of the baseline target station for a Neutrino Factory.

The alternative to a liquid mercury jet is a number, around 200, solid tungsten bars, each 20cm long and 2cm diameter. This option was intially rejected because it was believed that the thermal shock created by the beam impact would be sufficient to damage a bar in a single pulse. However, extensive study of this shock, using a pulsed electric current, has demonstrated that this should not be the case and that each bar should have a lifetime in excess of 10 years. It is planned to verify this using a proton beam in the near future. In addition, with the 200 bar option, each target will receive a dose rate lower than the tungsten target currently employed in the ISIS facility [9]. As a result, it is believed that radiation damage will not be an issue and experience already exists in handling and disposing of the activated targets. The remaining issue is how to change targets between beam pulses. An option being considered for the European Spallation Source, which has very similar problems, is to mount the targets on a rotating wheel. For the Neutrino Factory, this would require splitting the magnets around the target region, creating an Helmholtz coil. In this situation, it is believed that it will be very difficult to support the forces created between the two superconducting sections of the coil. Mounting the wheel in front of the solenoids results in a captured pion rate which is about 60% of that from the liquid mercury target. Studies are underway to find an alternative that will increase this to closer to 100%.

3.2Muon acceleration

The two main requirements of the muon acceleration system are that it has a large beam acceptance – the muon emittance after cooling is 30πmmrad – and the acceleration must be fast due to the muon lifetime. The scheme designed to achieve this is shown in figure 5. It consists of a linear accelerator, two recirculating linear accelerators (RLA) and a non-scaling Fixed Field Alternating Gradient (NS-FFAG) accelerator.

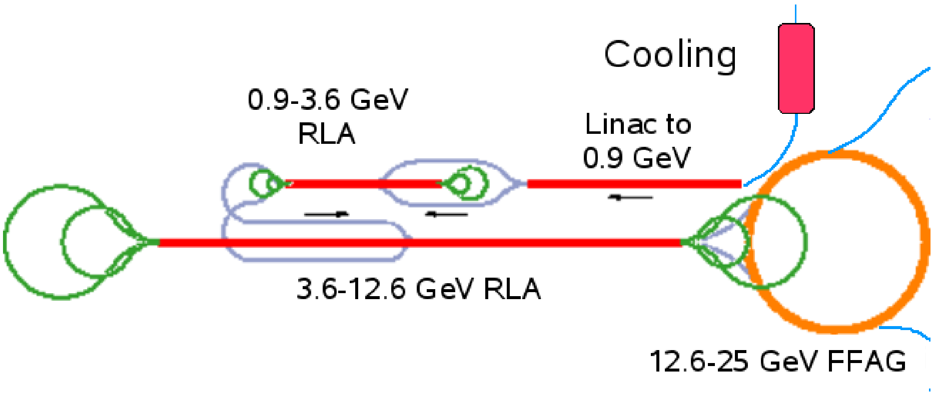


Figure 5: The Neutrino Factory muon acceleration scheme.

The RLAs consist of a linac with fixed field strength magnetic arcs at each end, each corresponding to a fixed momentum. The beam passes around the appropriate arc after acceleration through the linac and is returned correctly phased for acceleration in the opposite direction. Thus the beam makes multiple turns through the linac. The number of times this can be done is limited to about 4 by the complexity of the steering magnets delivering the beam efficiently to the correct arc.

At higher energies, it becomes possible to use an NS-FFAG for the acceleration. As the beam can make 10 or more turns in this type of device, it is believed that this will be the more cost effect option to complete the acceleration. An NS-FFAG has a number of benefits for muon acceleration. The magnetic field strengths are held constant during the acceleration cycle and, because the momentum compaction is very large, the orbit excursion is small compared to other fixed field accelerators. This allows the use of 200MHz RF cavities and hence higher field gradients. The fields in the magnets have only a linear variation with radius, with the result that the accelerator has a large dynamic aperture and hence the acceptance required. Further, this linear field dependence means that the time of flight of the beam around the machine varies parabolically with energy, which in turn makes it possible to use fixed frequency RF cavities and hence provides the very fast acceleration required.

Although NS-FFAGs look very attractive, there are a number of potential problems. For example, no such accelerator has ever been built, the beam crosses multiple resonances during the acceleration cycle, the longitudinal beam dynamics are unique and the codes used to model these machines have not been benchmarked against anything similar. As a result, a 20MeV electron proof-of-principle NS-FFAG called EMMA [10] (see figure 6) is under construction to study this type of accelerator in detail and demonstrate its feasibility for a Neutrino Factory and other applications.

4.Beta Beam

In a Beta Beam, pure beams of electron neutrinos and anti-neutrinos are created by the decay of beta emitting radioactive ions stored in a ring (see figure 7). The baseline version of a Beta Beam has been studied by the FP6 EURISOL Design Study [11] and uses beams of ^{6}He and ^{18}Ne. The problem is, with the standard ion production method, the flux of He achievable is about a factor of 2 smaller than required to meet the physics specifications and the flux of Ne about a factor of 25 too small. While an alternative production method for these ions, direct production [12], is being considered, EUROnu is also investigating another pair of ions, ^{8}Li and ^{8}B, created using an ion production ring.

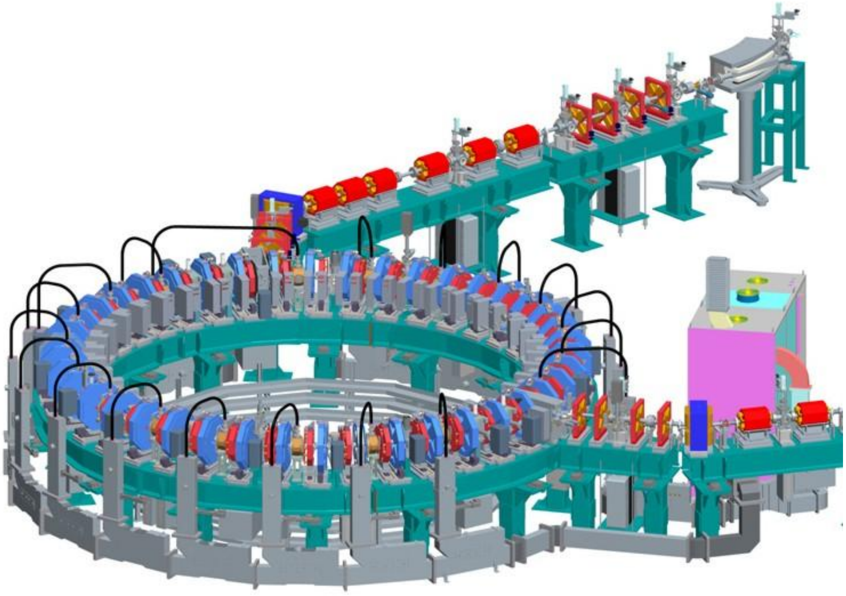


Figure 6: Layout of the EMMA proof-of-principle NS-FFAG.

The ion production ring [13], shown in figure 8, employs a gas jet target of either deuterium or ^{3}He and lithium beams to create the required ion species via the reactions

$$^{7}Li(d,p)^{8}Li$$

and

$$^{6}Li(^{3}He,n)^{8}B$$

The ions are passed around the ring and through the target many times to increase the produced ion flux. The energy lost in the target is restored using an RF cavity. With the beam energies used, 20-30MeV, and the gas jet target, it is believed that transverse blow up of the beam will be reduced via ionisation cooling and a sufficient flux of the beta emitters will be created. In addition, these ions have a higher Q-value than the baseline ions and hence will produce higher energy neutrinos.

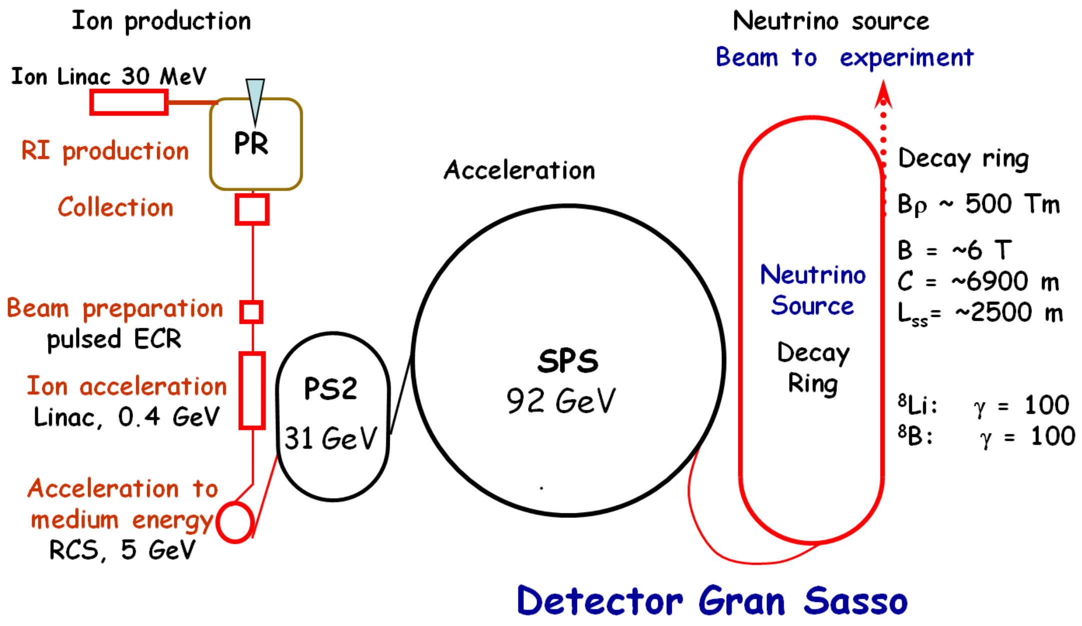


Figure 7: Version of a Beta Beam employing an ion production ring.

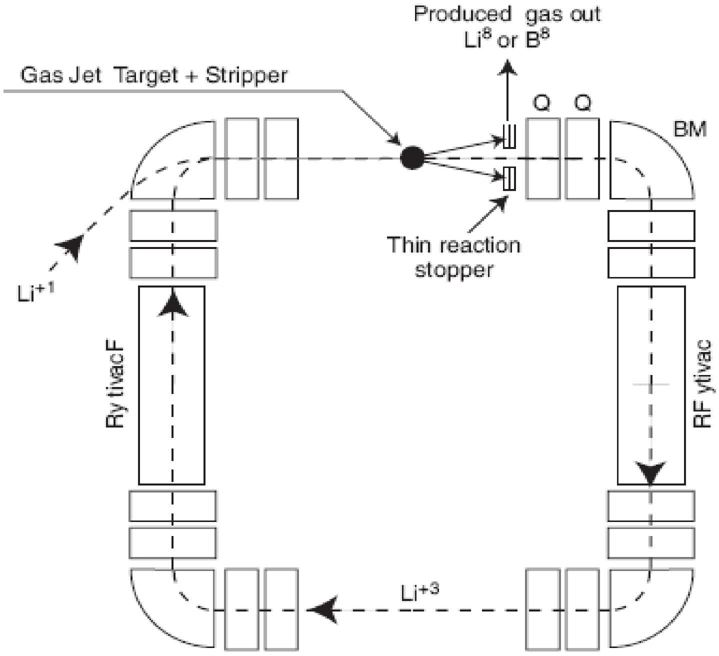


Figure 8: Beta Beam ion production ring.

EUROnu is studying, in particular, the direct production method for the baseline ions and these higher Q ions and the beam dynamics, design and performance of the ion ring for the latter. Note that a similar ring, used for creating intense thermal neutron beams from a circulating proton beam, has already been built and tested at the KEK laboratory in Japan [14]. EUROnu will also study the collection and bunching of the higher Q ions and any necessary modifications to the rest of the complex over the baseline design in EURISOL.

5.Conclusions

Following the recommendations of the CERN Strategy for Particle Physics, the European EUROnu project, in partnership with collaborators outside Europe, is studying possible candidates for the next generation accelerator driven neutrino oscillation facility. The three specific facilities being considered are a CERN to Fréjus superbeam, a Neutrino Factory and a Beta Beam. The particular focus is on the critical R&D for each of these facilities and the aim is deliver a performance and cost comparison on the timescale of 2012.

Acknowledgements

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