

Future R&D experiments for Super-Beams, Neutrino Factories and Beta-Beams

R Edgecock

University of Huddersfield, Queensgate, Huddersfield, HD1 3DH, UK; and
STFC Rutherford Appleton Laboratory, Didcot, OX11 0QX, UK.

E-mail: rob.edgecock@stfc.ac.uk

Abstract. There are three principle options for future beam based neutrino oscillation facilities that could discover and measure CP-violation in the lepton sector. These are conventional Super-Beams, Neutrino Factories and Beta Beams. Several projects have been taking place world-wide to study examples of these facilities. In Europe, one of the most important of these is the Framework Programme 7 supported project, EUROnu. These projects are in the process of identifying experimental R&D work that must be done before a technical design of the facility can be finalised and construction started. This paper will summarise this work for each type of facility, based largely on what has been done in EUROnu.

1. Introduction

The EUROnu project [1] started on 1st September 2008 and is due to run for four years. It is studying the following three facilities:

- The CERN to Fréjus Super-Beam [2].
- A Neutrino Factory, in close collaboration with the International Design Study for a Neutrino Factory (IDS-NF) [3].
- Two versions of the Beta Beam [4].

Each of these is discussed in more detail below, along with the experimental R&D already identified. In addition to the accelerator facilities, EUROnu is also studying the performance of the baseline detectors for each and determining the physics performance.

2. Super-Beam

In a conventional Super-Beam, the neutrino beam is created by impinging a proton beam onto a target to make pions, focusing the pions into a decay channel using a pulsed magnetic horn and producing the neutrino beam from the pion decay (see figure 1). Future, high intensity, facilities plan to use proton beam powers up to around 4 MW to produce a higher flux of neutrinos.

In the case of EUROnu, the facility being studied is the CERN to Fréjus Super-Beam, employing the high power Superconducting Proton Linac (HP-SPL) to produce a 4 MW proton beam of 5 GeV, pulsed at 50 Hz. The linac is followed by an accumulator ring for reducing the number of proton bunches, before delivering them to the target. To minimize neutron production and hence the heat load and radiation damage to the target surroundings, it is planned to use a low atomic number material for the target and to base both the target and the horn design as closely as possible on existing technology to reduce the amount of R&D that needs to be done.

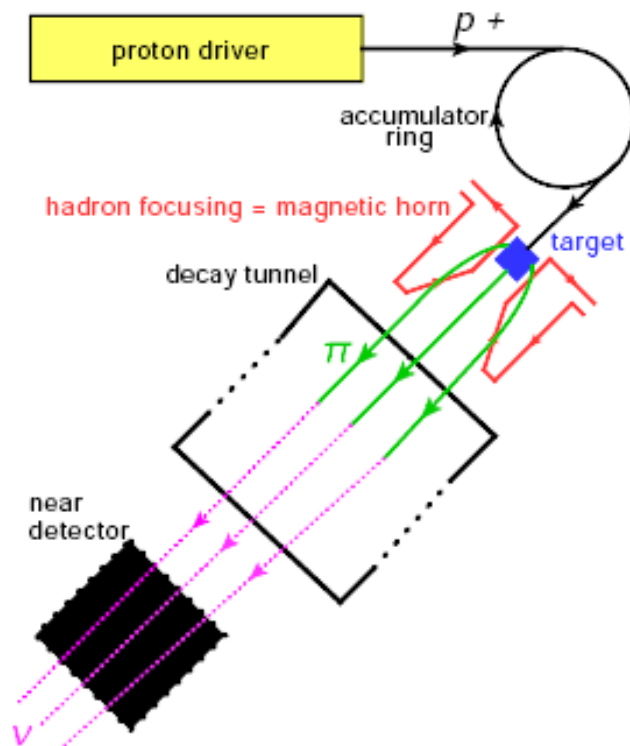


Figure 1. The layout of the CERN to Fréjus Super-Beam

If constructed, the HP-SPL will consist of a number of sections. The first of these, Linac 4 [5] is currently under construction at CERN, though an upgrade will be required to deliver sufficient current for 4 MW operation. This will accelerate the beam to 160 MeV and use entirely normally conducting technology. This will be followed by a number of superconducting sections, accelerating the beam first to 2.5 GeV, at which point it can be extracted for other uses, and then to 5 GeV.

R&D is required on all sections of the linac, in addition to that already envisaged for the low power SPL, though a number of projects are already underway. Work on an H^- ion source with a large enough duty cycle, delivering sufficient current with a high reliability needs to continue and significant R&D is required on the superconducting RF system. The latter includes the upgrade of an existing test stand at CERN, prototyping and testing of the superconducting cavities, the design and test of the high power RF couplers, higher order mode dampers and tuners required, the prototyping of the high power klystron modulators and the cryomodules. Further, injection into the accumulator ring will employ charge exchange and this will require the beam to be stripped at full power. This system will also require careful design and R&D.

To minimize the extrapolation required for the target and horn compared to existing facilities such as T2K [6] and MINOS [7], it is planned to employ four of each and scan the beam across them (see figure 2). As a result, each will need to run at 12.5 Hz, rather than 50, and each will see about 1 MW, rather than 4. To do this, a system will need to be devised which will deliver the beam to each target in turn, while keeping beam losses within allowed levels, ensuring the remnant proton beam is correctly dumped and maximizing the flux of captured pions. The baseline target design is a so-called pebble bed target consisting of 3mm diameter spheres of either beryllium or titanium tightly packed within a canister. This has slots in it which allows helium gas at a pressure of around 10 bar to flow through, taking away the heat deposited in the bar. Modelling suggests that this will keep the temperature of the

spheres at such a level that their strength will be more than sufficient compared to the thermal shock from the beam. Nevertheless, a prototype of such a target will need to be constructed and the cooling tested by using a coil to heat the spheres. Furthermore, the target should be subjected to a beam of the correct energy density, while at the operating temperature, using, for example, the HiRadMat facility at CERN, to verify the effects of thermal shock and to further test the cooling. The lifetime of the target due to radiation damage and fatigue will also need to be determined. Finally, although each target will only see 1 MW, a 4 MW target station will need to be designed, located at CERN and a license to operate it obtained. Due to the location and nature of the laboratory, this will not be entirely straight-forward.

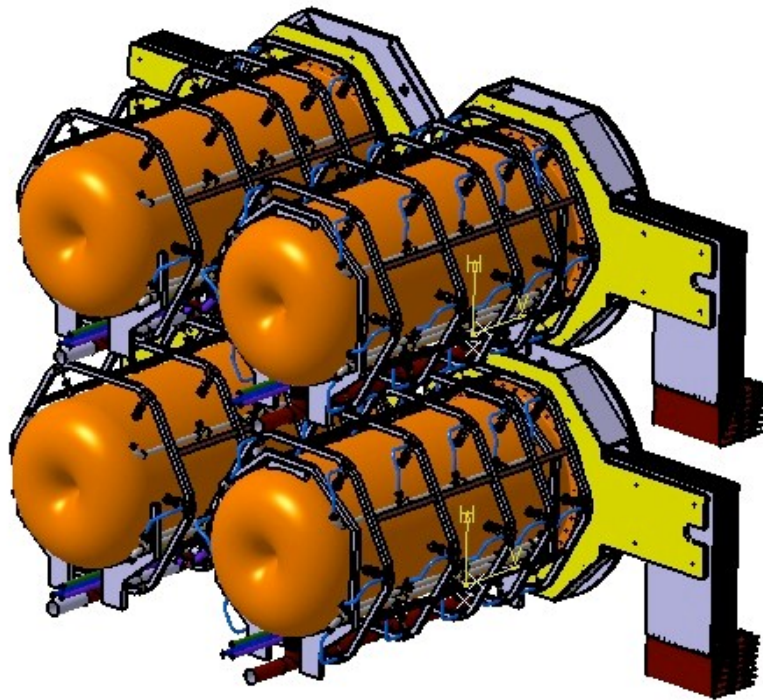


Figure 2. The arrangement of four targets and horns planned for the Super-Beam project. The targets are located within each horn.

The horn design is based on that of MiniBooNE. Each horn will need to be pulsed at 12.5 Hz using a current between 300 and 450 kA, depending on the physics requirements. It will subject to significant heating due to the combined effects of secondary particles and the current, corresponding to a maximum of 12 kW in the section closest to the target. A number of cooling schemes have been studied and modelling suggests these can keep the maximum temperature at the 300 K level. Nevertheless, a prototype will need to be constructed and tested to verify this. Furthermore, the pulsing will result in a maximum stress on the horn of at least 18 MPa and the fatigue lifetime resulting from this will need to be assessed. The horn will also be subject to significant radiation damage and the implications of this on the lifetime will need to be determined. Finally, the pulsing circuit will need to deliver a repeatable current pulse with the correct characteristics to the horn. A prototype circuit will need to be built and tested.

3. Neutrino Factory

The design of the Neutrino Factory is being studied by the IDS-NF, of which EUROnu is an important part, forming the bulk of the European contribution to the study. The baseline layout for the accelerator is shown in figure 3. The neutrino beams are produced by the decay of stored μ^+ and μ^- beams in two storage rings. To meet the physics aims, the muons are created by firing a 4 MW proton beam into a heavy metal target and focusing as many of the pions produce as possible into a decay

channel using a 20 T solenoid built from combined normally and superconducting coils. The muons from the decay are captured, bunched, phase rotated and cooled, before being accelerated as quickly as possible using a combination of a linac, two re-circulating linear accelerators and a non-scaling Fixed Field Alternating Gradient (FFAG) accelerator. They are then injected into the storage ring, the neutrino beams being produced from the muon decays in the straight sections pointed towards the far detectors.

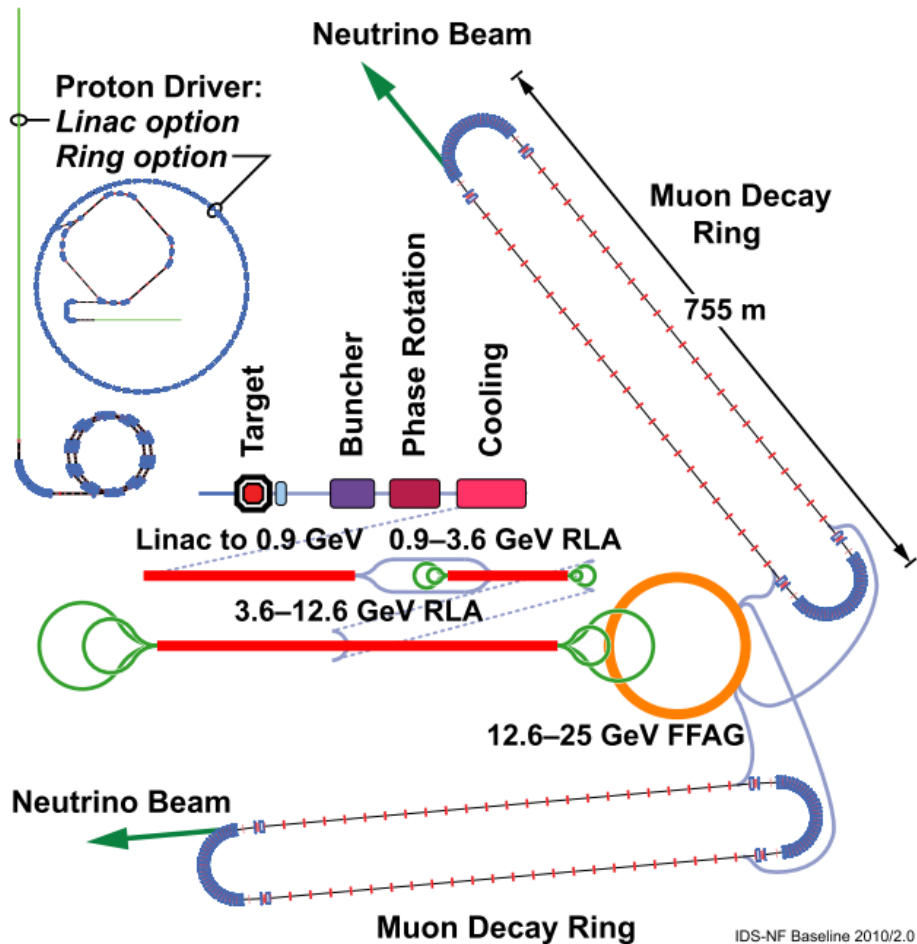


Figure 3. Current layout for the Neutrino Factory.

All parts of the Neutrino Factory are well beyond the state of the art and hence a significant amount of R&D is required. For the proton driver, two options are considered: a linac option or a ring option. As far as EUROnu is concerned, the linac option is also the HP-SPL, so much of the R&D is the same as described in section 2. However, an additional ring is required to compress the proton bunch lengths to the required 3 ns. For this, and for the ring option, R&D is required to ensure this can be achieved, to study injection and extraction and to ensure beam losses are kept under control.

Much R&D is also still required for the target and the target station. Of particular concern is the heat load in the target station from the secondaries produced and the remnant proton beam. With the original baseline, the heat load in the first two superconducting solenoid coils far exceeds a manageable level and various methods are being considered to reduce this. Adding more shielding will allow the heat load to be brought to tolerable levels, but increases the radius of the coils by a factor of two. The design of these was already difficult due to the magnetic forces and the stored energy. In addition, more than a MW is deposited in the shielding and this must be removed. Recent experience in existing high power target stations has shown that water cooling can be problematic due to tritium

production. Another alternative being considered is the use of lower atomic number elements for the target as these should produce a smaller thermal neutron flux and hence reduce the heat load. This work is at an early stage.

Two major R&D projects are already underway for the next section of the machine, the muon front-end. MuCool [8] is prototyping the main components of the muon cooling channel and, in particular, testing what accelerating gradient can be achieved in the RF cavities, which will be in the strong magnetic field of the focusing solenoids of the channel [9]. The MICE experiment (see figure 4) plans to do a detailed study of the cooling process, ionization cooling. In addition to these, a number of other R&D studies are underway. Modelling suggests that as well as the desired large flux of both signs of muons, a number of other particle species, including protons, pions and electrons make it a significant way down the front-end. Although these are lost throughout the front-end, there are certain regions in which the losses are particularly high. The result is that the beam power lost would far exceed the conical 1 W/m required for hands-on maintenance. As a result, a chicane is being studied at the start of the front-end to ensure these particles are lost in a controlled way.

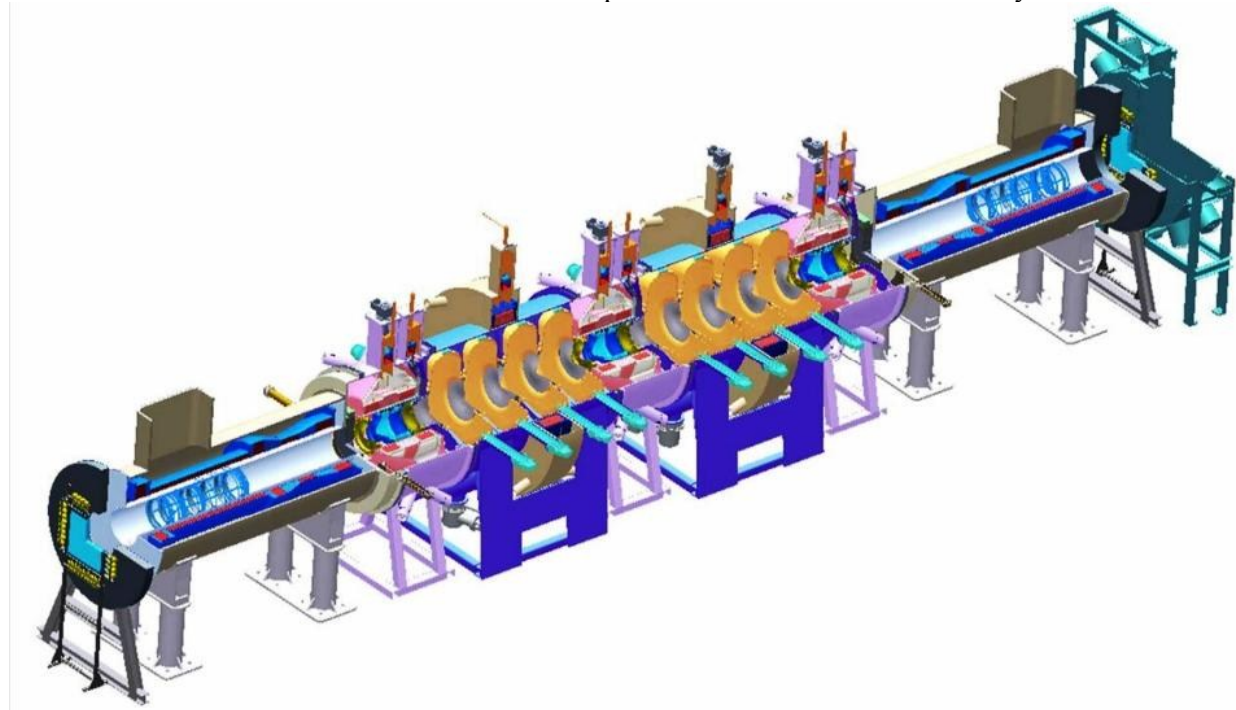


Figure 4: The MICE experiment. The two cooling cells in the centre are surrounded by instrumentation to identify muons and measure their parameters precisely.

In case the solenoid magnetic fields have too big of an impact on the RF gradient in the cavities, alternative cooling lattices which reduce this field are also under study. Promising results have already been achieved, but further work is required. Once the conceptual design of the front-end has been finalized, a full engineering design and layout will be required.

The muon acceleration systems consists of a linear accelerator to increase the beam energy to 0.9 GeV from 250 MeV, two re-circulating linear accelerators (RLA) going to 3.6 and 12.6 GeV, respectively, and a non-scaling FFAG accelerating to 25 GeV. For the linacs and RLAs, a full lattice design and physical layout still need to be made. Once this is done, R&D will be required on the main lattice components, in particular the “spreader” magnets used to steer the beam into the correct arcs of the RLAs, the arc magnets and the RF system. For the FFAG, a major R&D project has already taken its first main step. This is the EMMA non-scaling FFAG ring, see figure 5. As well as being a proof-of-principle project for this type of accelerator, EMMA is also testing out many of the features of the muon FFAG for a Neutrino Factory. For example, it has recently demonstrated that both serpentine

acceleration and multiple integer resonance crossings work [10]. Nevertheless, there are still a number of issues that need to be studied, including matching the FFAG to the other Neutrino Factory systems, 6D tracking, prototyping the main ring magnets and prototyping the injection and extraction systems from the ring.

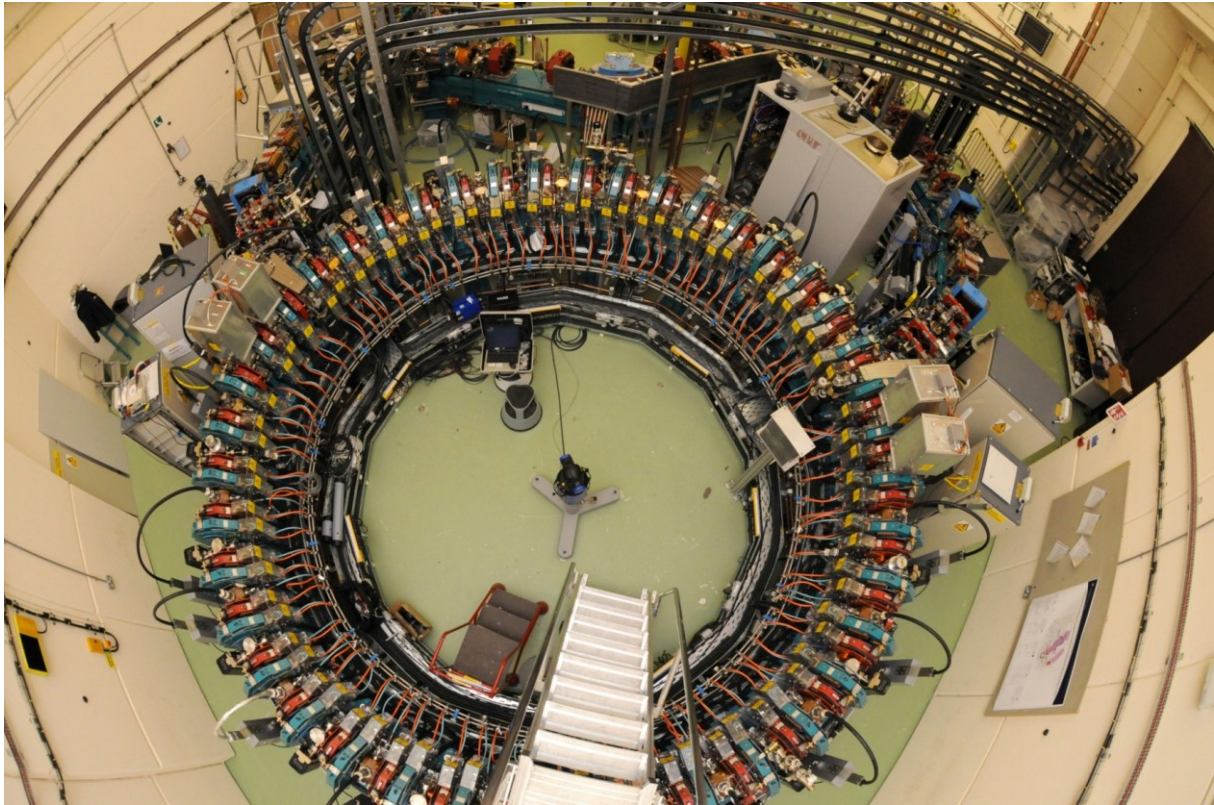


Figure 5. The EMMA FFAG, showing the ring, the injection line (to the right), a diagnostics beamline (to the left) and part of the ALICE accelerator [11], which is used as the injector (in the background).

4. Beta Beam

In a Beta Beam facility, the neutrino beams are produced by the decay of stored beta emitting ions. Two ion species are required, one decaying to electron neutrinos and the other to electron anti-neutrinos. The facility, shown in figure 6, is split into three sections: (1) ion production, capture, bunching and initial acceleration; (2) further acceleration in existing CERN machines; and (3) the ion decay ring (DR). The main challenge for the project is to create, accelerate and store a sufficient flux of both ion species to meet the physics goals and this has formed the focus of activities so far and will continue to do so for the near future.

Two pairs of ion species are being studied, ${}^6\text{He}/{}^{18}\text{Ne}$ and ${}^8\text{Li}/{}^8\text{B}$. The first of these was originally studied by the EURISOL project [12] and this determined that a sufficient flux of ${}^6\text{He}$ could be produced by existing techniques, but ${}^{18}\text{Ne}$ was more problematic. As a result, EUROnu has studied the production of ${}^8\text{Li}$ and ${}^8\text{B}$ via a production ring and more recently, ${}^{18}\text{Ne}$ via another technique compared to EURISOL. It should be noted that the Li and B produce higher energy neutrinos, requiring the neutrino far detector to be further away than for He and Ne. The net result is that five times the flux of these ions is required for the same physics sensitivity.

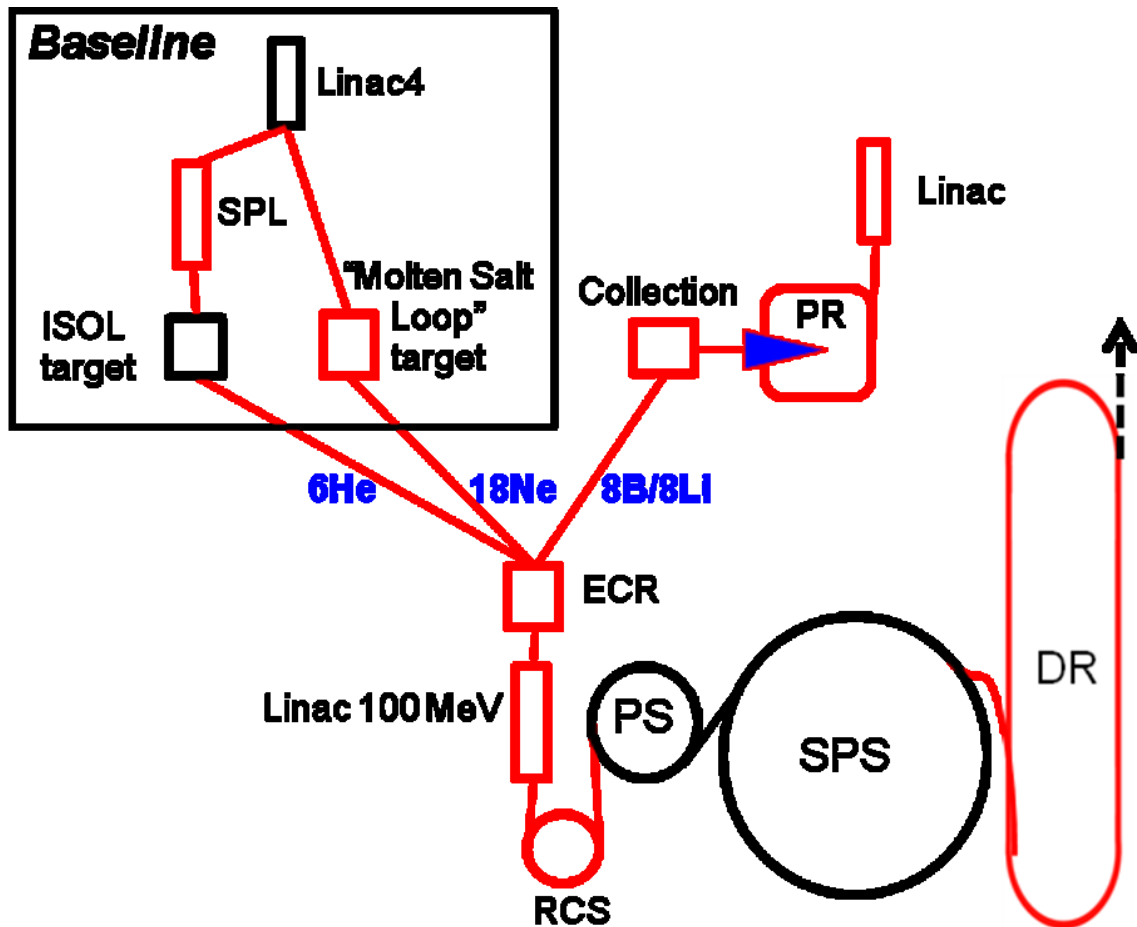


Figure 6. The layout of a Beta Beam facility. The proposed production mechanisms for both pairs of ions are shown. New installations are shown in red, while those that already exist at CERN are shown in black.

Initial studies of ^8Li and ^8B production via a gas jet target in a production ring suggest that it may be very difficult to achieve the required rate as the target density would need to be too high and it could lead to vacuum problems. As a result, an alternative direct production method using liquid film targets has been proposed. To determine what is possible, the cross-sections for both production processes are being measured in Legnaro (see figure 7). Meanwhile, studies of ^{18}Ne direct production using a Linac 4 upgraded to 6 mA and a molten salt loop target have proved encouraging. It is now planned to undertake an experiment at ISOLDE to verify that the predicted production rate can be achieved. For now, the $^6\text{He}/^{18}\text{Ne}$ pair is considered to be the Beta Beam baseline.

In addition to the ion production, R&D is also underway on the ion collection devices and a 60 GHz ECR ion source. A prototype collection device has been built and is now being tested using ^8Li . A prototype ECR has also been built and has been tested to ensure it achieves the required magnetic fields. It is now planned to modify it and test its performance with an ion beam.

Another major potential problem for the Beta Beam facility is collective effects in the accelerators and DR due to the very high ion intensity. Detailed studies of this are on-going and it is planned to make measurements wherever possible, in particular in the existing accelerators. Another significant problem is decay losses. These have been studied for the baselines ions up to the PS and no insurmountable problems have been identified. This work now needs to be extended to the SPS. The DR uses superconducting magnets and there is a problem with the heat load in these. The original plan

of using open mid-plane magnets helps, but does not solve this problem. Further, a study adding more shielding in front of the magnets has been inconclusive. More work is required on this problem.

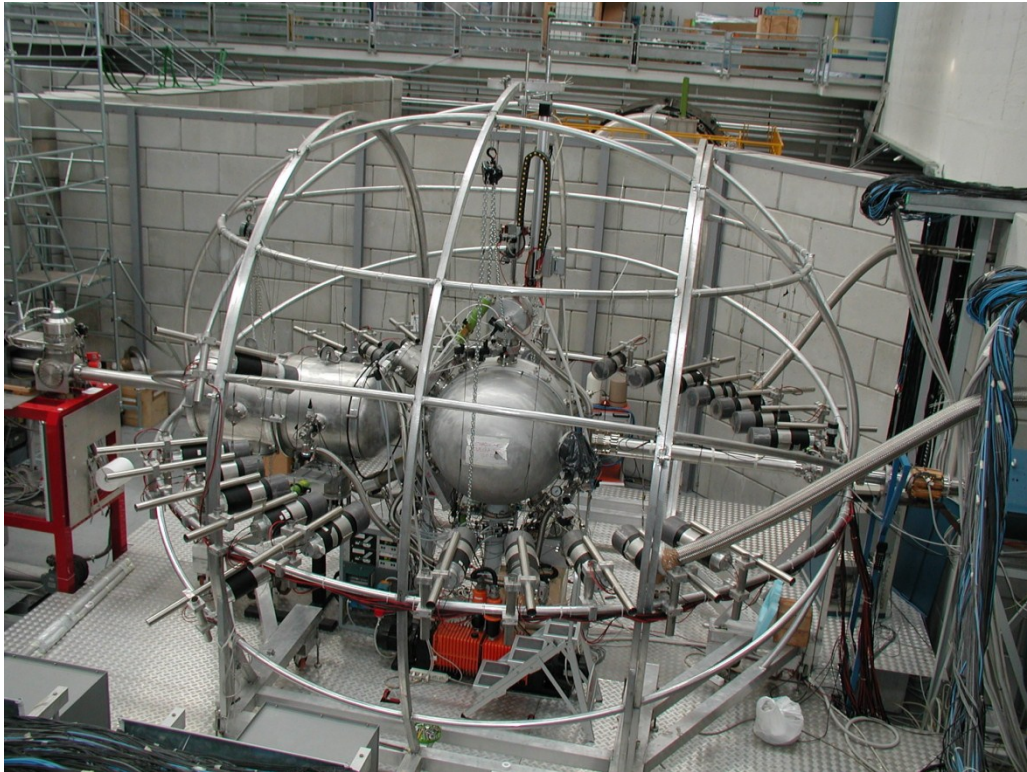


Figure 7. The RipeN detector used to measure the cross-section for 8B production.

References

- [1] See <http://www.euronu.org>
- [2] Longhin A 2011 A new design for the CERN-Fréjus neutrino Super Beam arXiv:1106.1096 [physics.acc-ph]
- [3] Choubey S *et al* 2011 International Design Study for the Neutrino Factory, Interim Design Report IDS-NF-20
- [4] Lindroos M and Mezzetto M 2010 Beta Beams *Ann. Rev. Nucl. Part. Sci.* **60** 299-325
- [5] Arnaudon L *et al* 2006 Linac4 technical design report CERN-AB-2006-084
- [6] Nakadaira T *et al* 2008 T2K Target *AIP Conf. Proc.* **981** 290-292
- [7] Abramov A G *et al* 2002 Beam Optics and Target Conceptual Designs for the NuMI Project *Nucl. Instrum. Methods Phys. Res. A* **485** 209-227
- [8] Li D *et al* 2008 MUCOOL/MICE RF Cavity R&D Programs *AIP Conf. Proc.* **981** 299-302
- [9] Palmer R *et al* 2008 RF Breakdown with and without External Magnetic Fields arXiv:0809.1633 [physics.acc-ph]
- [10] Machida S *et al* 2011 Acceleration in the linear non-scaling fixed field alternating gradient accelerator EMMA, Electron Model for Many Applications, Submitted to *Nature Physics*
- [11] Alexander J *et al* 2009 Progress on the Commissioning of ALICE, the Energy Recovery Linac-Based Light Source at Daresbury *Proc. Part. Acc. Conf. 2009 (Vancouver, Canada, 4-8 May 2009)* pp 1281-1283
- [12] Blumenfeld Y 2007 The EURISOL Project *AIP Conf. Proc.* **891** 147-154