BETA BEAMS*

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This paper gives an overview of the work done so far to produce sufficient neutrino fluxes for neutrino oscillation physics, using beta beams. The design study on a beta beam scenario, the EURISOL (European Isotope Separation On-Line Radioactive Ion Beam Facility) Design Study, a project funded by the European Commission (EC), is now published. The study is based on the acceleration of ^{6}He and ^{18}Ne ions to produce the (anti-)neutrino beam using the existing CERN infrastructure for acceleration of the ions. We will here describe the work with emphasis on how potential show stoppers, in particular radiation safety and equipment damage, have been dealt with. New results for the production of ^{6}He show very encouraging results. However, the ion production needed for the physics experiments could not, up to now, be reasonably satisfied for ^{18}Ne. Therefore, studies of alternative beta emitters, ^{8}Li and ^{8}B, with properties interesting for physics reach have been proposed. The production of these ions are studied within the EC funded EUROnu project, A High Intensity Neutrino Oscillation Facility for Europe. This project will end in 2012. A small storage ring, in which the beam traverses a target, creating the ^{8}Li and ^{8}B isotopes, that will be collected and accelerated, is studied in this proposal. During 2009 research on production of ^{18}Ne has given very satisfying results. Experiments are proposed to confirm the ideas. We present the status of the work achieved and an overview of ongoing activities to make the beta beam project a solid proposal for neutrino production within the EUROnu project.

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1. Introduction

The aim of beta beams is to produce (anti-)neutrino beams from the decay of beta active ions circulating in a storage ring [1]. The neutrino spectrum is well known from the electron spectrum and the reaction energy

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value, Q, is typically of a few MeV. The ions are accelerated up to a certain energy corresponding to a relativistic γ. The boosted neutrino spectrum is

$$E_\nu < 2\gamma Q \tag{1}$$

and the forward focusing of the neutrinos can be expressed as

$$\theta < 1/\gamma\,. \tag{2}$$

We get a pure electron anti-neutrino and neutrino beam from two different radioactive ions respectively.

The physics applications of beta beams are primarily neutrino oscillation physics including CP violation in the leptonic sector. Other fields of application, such as cross-section measurements of neutrino–nucleus interactions, should not be forgotten.

The radioactive isotopes must be produced in sufficient quantities to give satisfactory physics reach. The lifetime should be such that we get enough decays at high relativistic γ but not too many at low γ where decays are not useful. The optimum lifetime is given by the acceleration scenario and is usually in the order of a second in the ion rest frame. No dangerous waste products should be produced and it should be possible to extract the ions and transport them into an ion source. Noble gases are chemically stable and for this reason they are good candidates. The charge-to-mass ratio of the ions is also important for efficient acceleration and to minimize space charge effects in the accelerators.

It is useful to have some simple scaling laws in mind for different baselines, reaction energies (Q values), relativistic boost in the decay ring and decay ring length. We also have to take into account that an accelerator can accelerate fully stripped ions up to Z/A times the proton energy, where A is the total number of nucleons and Z is the atomic number of the ion.

The decay ring has to be longer at higher $\gamma_{\max}$ to ensure enough decays. The required length scales linearly with the relativistic boost factor. The baseline is proportional to the neutrino energy which scales like γQ, the flux scales inversely with the square of distance (the baseline) and the cross-section for the reactions in the detector scales with the neutrino energy. This leads to the concept of a factor of merit for an experiment $M = \gamma/Q$. For example, if the ions have the same γ in the decay ring and we use ions with a five times higher Q value, we need 5 times more decays in order to have the same merit factor.

It is also of importance to take into account the length of the decay ring and the inclination angle with respect to ground. Figure 1 illustrates the necessary depth of the decay ring for different baselines. We can compare this to the depth of a neutrino factory which is around 400 m.

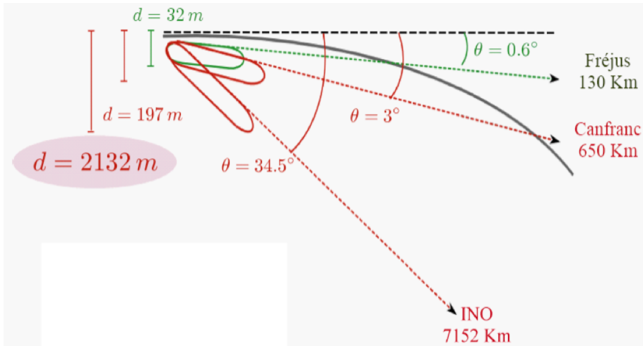


Fig. 1. Different baseline geometries for ^{6}He and ^{18}Ne ions. Courtesy P. Coloma.

2. The EURISOL scenario

The EURISOL scenario is based on CERN infrastructure and machines, and on existing technologies. The ion choices are ^{6}He and ^{18}Ne with decay times at rest of 0.8 s and 1.67 s, respectively. The Q value of ^{6}He is 3.5 MeV and for ^{18}Ne 3.3 MeV. They are produced using ISOL technique. The ions are accelerated in an ion linac after being collected in a charge breeding ECR source [2]. They then pass through a Rapid Cycling Synchrotron (RCS) [3], the CERN PS synchrotron and the last acceleration stage before the decay ring is the CERN SPS. The decay ring [4] would have a circumference of 6900 m and a straight section length of 2500 m. The main bending magnet field is 6 T; consequently superconducting technology is necessary. The EURISOL scenario is shown in Fig. 2.

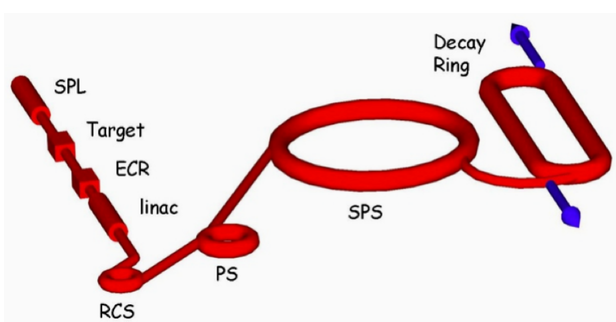


Fig. 2. The EURISOL layout.

The SPS allows maximum γ-value of 150 (^{6}He) or 250 (^{18}Ne). The choice of energy, corresponding to $\gamma = 100$, was made to optimize the physics reach at the chosen baseline: the MEMPHIS detector in the Fréjus tunnel, 130 km from CERN, which will be a Mton water Čerenkov detector.

The required annual rates are 2.9×10^{18} anti-neutrinos from ^{6}He and 1.1×10^{18} neutrinos from ^{18}Ne. The EURISOL design study is a top down approach, which assumes that the needed ions can be produced [5].

3. Ion loss

The ions start to decay from the moment of production and during acceleration. The evolution of the intensity can be seen in Fig. 3. Only 50% of ^{6}He and 80% of ^{18}Ne eventually reach the decay ring.

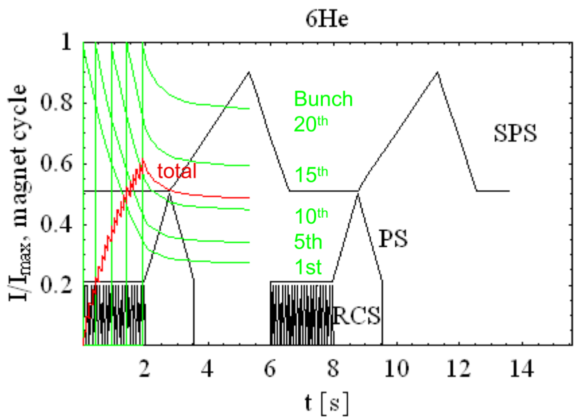


Fig. 3. Intensity evolution of ^{6}He during acceleration. The RCS, PS and SPS cycles are shown. The intensity of every 5th bunch from the RCS is also presented. Only one third of the first bunch from the RCS survives. The total intensity is shown as the initially serrated line.

The results of studies of the radiation doses for maintenance and of doses to the population from the airborne activity released in the environment, are shown in Tables I and II. The results are compatible with the CERN rules for radiation safety, and do not represent a show stopper, see [6]. The SPS has not yet been studied. The Decay Ring study does not include the collimation losses.

TABLE I

Residual Ambient Dose Equivalent Rate at 1 m distance from the beam line (mSv h^{-1}).

	RCS (quad, ^{18}Ne)	PS (dipole, ^{6}He)	SPS	DR (arc, ^{6}He)
1 hour	15	10	—	5.4
1 day	3	6	—	3.6
1 week	2	2	—	1.4

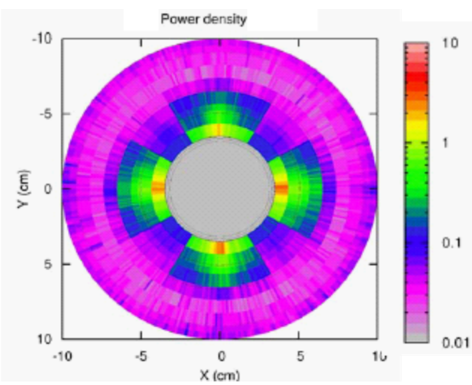
TABLE II

Annual effective dose to the population (μSv).

RCS	PS	SPS	DR (only from decay)
0.67	0.64	—	5.6

Irradiation damage of accelerator equipment may require development of extra shielding and handling methods. What has been studied so far is the impact of the radiation on the PS magnet coils: 60 years of operation with a EURISOL-type beta beam seems possible [7].

The decay products have a different magnetic rigidity than the parent particles and are essentially deposited in the magnet mid-planes. Decayed ions are deposited in the horizontal plane for the dipoles. For quadrupoles the particles impinge on both the horizontal and vertical mid-planes depending on the accelerator optics. The decay ring magnets are superconducting and may quench due to the energy deposited in the superconducting coils. Therefore, feasibility studies on open midplane dipole and quadrupole magnets have been carried out based on energy deposition calculations, see [8–10]. The idea is to avoid placing superconducting coil windings where the particles impinge, see example in Fig. 4.



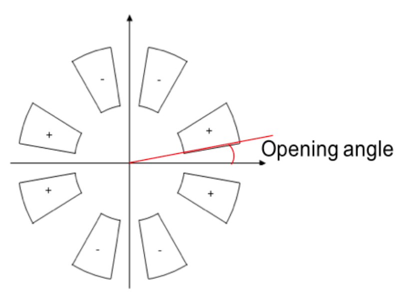


Fig. 4. A typical energy deposition pattern in a quadropole from decay products (left) (transverse cut of a quadrupole cold mass). A proposed coil-block distribution to avoid heat deposition on the coils (right).

The quadrupole study is made parametrically, which means that once the necessary opening angle is specified (between 0 to 6 degrees), the relation aperture/gradient can be obtained according to needs for the decay ring.

Injection of the beam into the decay ring in short bunches of 5×10^{12} ions, 5 ns long [11] necessitates momentum collimation of almost 50% of the ions, see Fig. 5. The work on collimation is ongoing. Some 5×10^{12} ^{6}He ions have to be collimated per cycle (6 s). The decay into ^{6}Li corresponds to 5×10^{12} ions per meter that has to be either dumped after the straight sections or taken care of inside the accelerator equipment like dipoles and quadrupoles in the arcs. The dipoles in the collimation sections would receive between 1 kW and 10 kW of power and shielding should be considered. The dump at the end of the Decay Ring straight sections would receive 30 kW of beam-power.

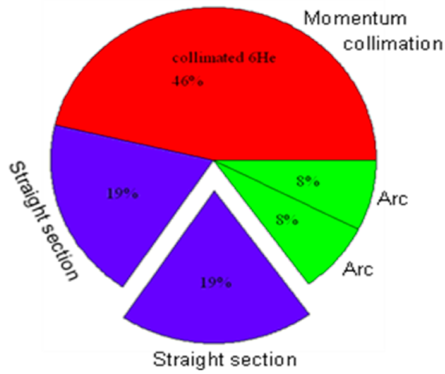


Fig. 5. The distribution of losses in the decay ring.

The RF system in the decay ring would experience unprecedented heavy transient beam loading from the short and intense bunches. Since there is no net energy transfer to the beam, the problem might be resolved using a linear phase modulation in the absence of the beam, to reduce gap transients. A high-Q superconducting cavity would be a preferred choice. The feasibility of this proposal still needs to be confirmed.

4. Ion production

The ions required for beta beams are not those that have great interest for nuclear physics. Therefore, the research on production of these ions has not been of high priority so far. The EURISOL study was top down, and now we have to make sure the feasibility of the beta beam can be confirmed. Very encouraging results for ^{6}He have already been achieved [12]. Direct production methods for ^{18}Ne have been proposed at Université Catholique de Louvain, Belgium. Results indicate that the production rates obtained may scale to production rates compatible with the beta beam to Fréjus.

Recent research on new ideas for ion production is shown in the Tables III and IV. Interesting is the proposal to use the Linac4 presently being built at CERN. The option named LinacX1 is a non conventional Linac (170 mA of ^{3}He) and needs R&D efforts.

TABLE III

Summary of proposed production methods. This table shows the different machines and beams used for production. Courtesy T. Stora (^{18}Ne and ^{6}He) and C. Rubbia (^{8}B and ^{8}Li).

Type	Accelerator	Beam	I_{beam} [mA]	E_{beam} [MeV]	P_{beam} [kW]
ISOL & n-converter	SPL	p	0.1	2×10^{3}	200
ISOL & n-converter	Saraf/GANIL	d	25	40	1000
ISOL	Linac 4	p	4	160	640
ISOL	Cyclo/Linac	p	10	70	700
ISOL	LinacX1	^{3}He	>170	21	3600
P-Ring	LinacX2	^{7}Li	0.160	25	4
P-Ring	LinacX2	^{6}Li	0.160	25	4

TABLE IV

Summary of the results estimated from the proposed production methods. Courtesy T. Stora (^{18}Ne and ^{6}He) and C. Rubbia (^{8}B and ^{8}Li).

Type	Accelerator	Beam	Target	Isotope	Flux [s^{-1}]
ISOL & n-converter	SPL	p	W/BeO	^{6}He	5×10^{13}
ISOL & n-converter	Saraf/GANIL	d	C/BeO	^{6}He	5×10^{13}
ISOL	Linac 4	p	^{19}F Molten NaF	^{18}Ne	2×10^{13}
ISOL	Cyclo/Linac	p	^{19}F Molten NaF	^{18}Ne	2×10^{13}
ISOL	LinacX1	^{3}He	Mg0 80 cm disk	^{18}Ne	2×10^{13}
P-Ring	LinacX2	^{7}Li	d	^{8}Li	1×10^{14}
P-Ring	LinacX2	^{6}Li	^{3}He	^{8}B	1×10^{14}

It is now of great importance to allocate the resources needed for setting up experiments to produce ^{18}Ne to confirm the feasibility of a beta beam from CERN to Fréjus.

5. A new framework for beta beam research

To deal with the presently unsatisfactory yields of ^{18}Ne a new proposal for the production of ions for beta beams has been made [13]. This proposal suggests using ^{8}Li and ^{8}B as anti-neutrino and neutrino emitters respectively. Increased physics reach with respect to the ^{6}He and ^{18}Ne case would be achieved. In this case, the baseline would be around 700 km (CERN-Canfranc or CERN-LNGS). The reaction Q value for these ions is larger (16.0 and 17.0 for ^{8}Li and ^{8}B, respectively) and therefore the energy of the neutrinos, for the same relativistic γ-max of the ions, is larger. However due to the scaling, we would need 5 times more ions in the decay ring. Another aspect is the use of other detectors (Liquid Argon) needed at these energies. Detector development may need long time scales. We have to add the additional necessary intensities needed. This information has to be available for the high-Q option beta beam (it is not negligible).

This proposal is being studied within the European Framework Programme FP7, design studies, EUROnu [14].

A circulating beam of ^{6}Li or ^{7}Li produces the beta beam isotopes by repetitive traversals of a supersonic gas jet target, (see Fig. 6). The target serves as a stripper and will also be used for beam cooling. The ^{7}Li beam energy is 25 MeV and the energy loss over the target is 300 keV.

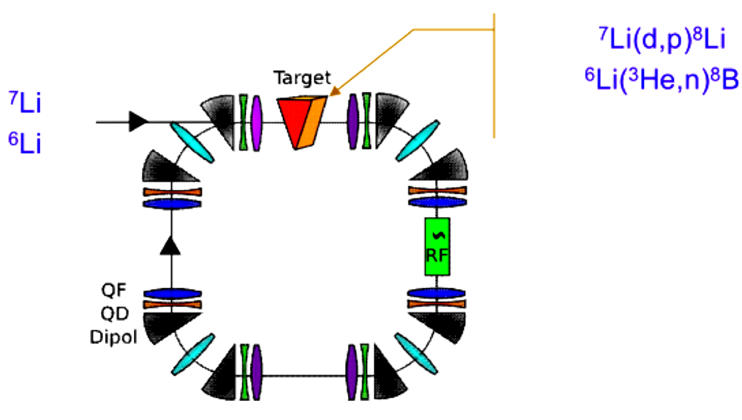


Fig. 6. A way to produce radioactive ions for beta beams using multiple traversals of a gas jet target, serving also as stripper and for ionization cooling of the beam.

The study will focus on the ion production but the end to end simulation of the ions through the accelerator chain will show available intensities in the decay ring which is the final aim of the study. We have to include the possible upgrade of the CERN PS or a new synchrotron replacing the PS, in the simulations.

A preliminary lattice design for the production ring (see Fig. 6) is available [15], and target models have been developed with Geant4 to be part of simulations to verify the cooling conditions in the production storage ring [16]. Transverse coupling devices will also be needed for this purpose [17].

The supersonic gas jet target [13] with a jet velocity of 2200 m/s (volume 4.3 m^3/s) has not yet been studied in detail. The preliminary studies have shown that the technical challenges are major and solutions are orders of magnitude less performing than needed for satisfactory production.

The collection of the ions after production in the target (see Fig. 7) is being studied at CRC, Louvain-la-Neuve, Begium. The development of the collection device for ^{7}Li is progressing, first beam tests are foreseen for December 2009 and full beam experiments for 2010. Boron is chemically reactive and active research on material choices and possible compounds of B that can be extracted from the catcher is ongoing and the results will be used in the cooling simulations of the production ring.

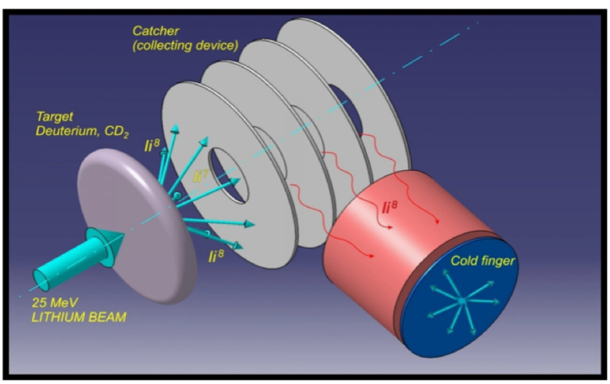


Fig. 7. A catcher for Li ions.

Cross-section measurements of the reactions are measured in INFN-LNL, Legnaro, Italy. Treatment of data from measurements of ^{8}Li from 2008 is ongoing.

The 60 GHz ion source is developed by Laboratoire de Physique et de Cosmologie in Grenoble France [2], within a large collaboration. Source assembly and tests of a 28 MHz gyrotron for 2010 are foreseen, see Fig. 8.

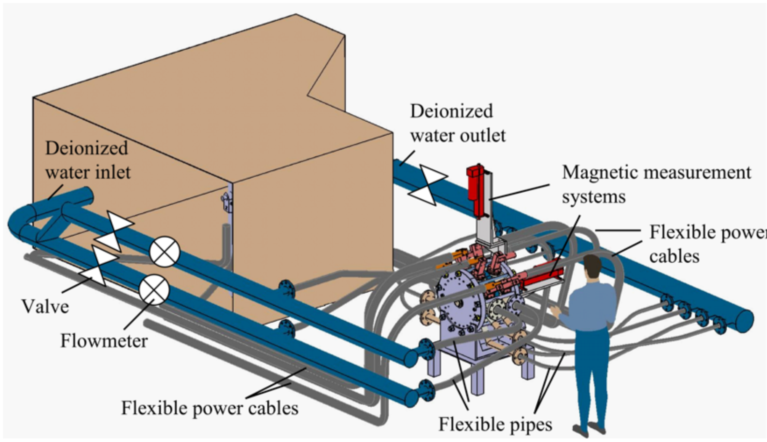


Fig. 8. Setup for the ECR source for beta beams (magnetic field test).

The Weizmann Institute of Science, Revohot, is studying production of ^{6}He and ^{8}Li by designing a high-temperature furnace for extraction of ^{6}He and ^{8}Li radioisotopes out of neutron irradiated targets of BeO and B_4C. Intensities, largely superior to those required for the beta beam, would be available.

The higher neutrino energy for the ^{8}B and ^{8}Li ions permits better atmospheric background suppression in the detector. The hard requirements to have very high bunch charge (5.9 μC for ^{18}Ne) and very short bunch duration (5 ns) which is necessary for background suppression in the case for ^{6}He and ^{18}Ne, would be relaxed. It would also be of great interest to avoid collimation (scraping) of particles in the decay ring and consequently we would be able to keep more of the ions in the decay ring for physics.

Barrier buckets could be used to inject the ion beam into the decay ring and for bunching the beam so that the duty factor needed can be achieved. However, extensive studies of the physics reach with relaxed duty factors [18] shows that the duty factors cannot be relaxed beyond 1%, see Fig. 9. Figure 9 shows the θ_{13} and the $\delta_{\rm cp}$ sensitivity for different duty factors for intensities in the decay ring corresponding to production rates taken from [13]. For duty factors of 1% and less, barrier-buckets are not efficient. We have to use the existing merging system used for the EURISOL beta beams [11]. We may relax somewhat the requirement for short bunches and/or inject more bunches to increase the flux.

The intensities needed for the longer baseline are presently under study. At least a factor two more ions in the decay ring, compared to the ^{6}He and ^{18}Ne scenario, would be required.

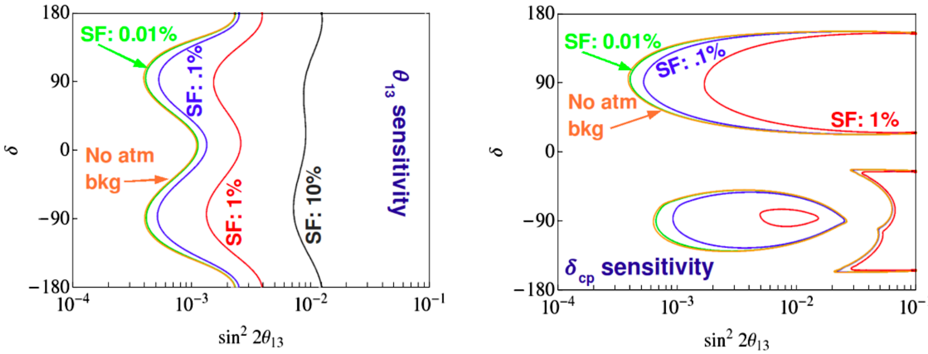


Fig. 9. The θ_{13} (left) and $\delta_{\rm cp}$ (right) sensitivity for different duty factors (SF). The 0.1% duty factor gives similar sensitivity to the 0.01% SF and with 1% SF the sensitivity has decreased slightly. These results are based on fluxes proposed in [13].

6. Other beta beam applications

Alternative strategies to determine the neutrino mass hierarchy by making use of the future possible neutrino facilities at Fermilab are described in [19]. The neutrino channel would come from the NuMi beam-line whereas the anti-neutrinos would be produced from ^{6}He and ^{8}Li at the same E/L. ^{6}He and ^{8}Li are the radioactive ions, proposed for beta beams, which can be produced relatively easily. The Tevatron (^{6}He, $\gamma = 350$) and the Main Injector (^{8}Li, $\gamma = 55$) would be used to send the ions to Noνa and a new detector situated at a distance of 300 km. This proposal is presently not worked on.

Very good physics reach for beta beams at CERN is proposed by using ^{6}He and ^{18}Ne, gamma 350 and a 500 kton Water Čerenkov detector at 650 km [20]. ^{8}Li and ^{8}B sent to the magic baseline at 7000 km, with ring dip angle 34°, would outperform a neutrino factory for $\sin^2 2\theta_{13} \geq 10^{-3}$.

Low energy beta beams extracted from the CERN PS and stored in a small storage ring with a close detector could be useful for n-nucleus cross-sections measurements (for detector respons, r-processes and double beta decay) and for studies of fundamental interactions.

Monochromatic beta beams can be produced by beams of nuclei decaying by Electron Capture (EC) [21]. Experimental intentions for measuring yields of ^{156}Yb, which is decaying by both EC and beta decay, are presently being framed. Interest from the physics community for these ions is supporting these experiments [22]. There may be interest to investigate the CERN accelerator implications of the combined EC and beta decay. The proposed baselines would be Fréjus, Canfranc or Boulby. A MW proton driver would be necessary for production of these proton rich isotopes.

7. Conclusion

The EURISOL beta beam design study has been published [5]. It is the first coherent beta beam study. The beta beam seems a feasible approach to neutrino production, but we are presently facing a significant shortfall of ^{18}Ne. However, within the FP7 Beta Beam Studies, recent proposals suggest that this problem can be remedied either by a production ring by direct methods or by new developments at ISOLDE for all the presently considered beta beam isotopes (^{6}He, ^{8}Li, ^{18}Ne and ^{8}B). Supporting these new ideas is important to make the beta beam a promising neutrino facility. Sufficient amounts of ^{6}He have been produced at ISOLDE.

The EUROnu high-Q beta beam is in its initial development phase. Important challenges related to the proposed methods for increased ion production, have to be faced. The acceleration of very high intensity beams through the CERN complex is an important challenge. Work to optimize the machines and the beams for good physics is presently ongoing. High-Q isotopes seems to be a difficult option to produce neutrinos. We soon need the information on what increase in intensities we need for the LAr (or other detector type) detectors needed for higher energy neutrinos.

Studies of methods to suppress atmospheric background in the detectors would be beneficial for beta beams.

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