Beta Beams for Neutrino Production

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Abstract
The aim of this paper is to give 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 ready to be published. The study is based on the acceleration of ^{6}He and ^{18}Ne ions to produce the electron (anti-) neutrino beam using the existing CERN infrastructure for acceleration of the ions. We will here briefly 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. We are now confident that this ion is a good choice to produce antineutrinos. 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. The status of the work achieved and an overview of ongoing and planned activities to make the beta beam project a solid proposal for neutrino production within the EUROnu project.

1   Introduction

The aim of beta beams is to produce electron (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 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

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

and the forward focusing of the neutrinos can be expressed as

$$\Theta \leq 1/\gamma \tag{2}$$

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 field of application, such as cross section measurements of neutrino-nucleus interactions, are also important for physics reach.

The radioactive isotopes needed for beta beams are not commonly produced. Specific research is needed to produce them in sufficient quantities. The life time should be short enogh to get sufficient rate of decays at the final energy to which these ions are accelerated, but long enough to minimize decay losses during acceleration. The optimum isotope 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 γ 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 maximum proton momentum, 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 γ to ensure enough decays. The required length scales linearly with the relativistic boost factor. The baseline, i.e. the distance between the decay ring and the detector, is proportional to the neutrino energy which scales like γQ, the flux scales inversely with the square of 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=γQ. 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.
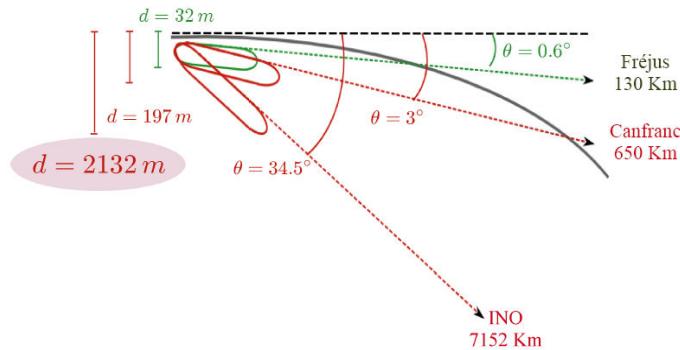
Fig. 1: Different baseline geometries for ^{6}He and ^{18}Ne ions. Courtesy: P. Coloma.

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 an 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 EUROSOL scenario is shown in Figure 2.
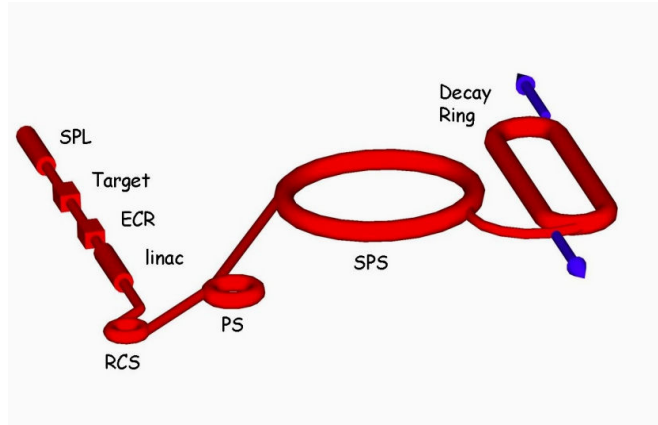
Fig. 2: The EURISOL Layout

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 Cherenkov detector.

The required annual rates are $2.9 \cdot 10^{18}$ antineutrinos from ^{6}He and $1.1 \cdot 10^{18}$ neutrinos from ^{18}Ne. The EURISOL layout is a top down study, which assumes that the needed ions can be produced. The EURISOL Beta Beam Design Report is foreseen to be published by the end of 2009 (extensive information on the study can be found in Ref. [5]).

3   Ion Loss

The ions start to decay from the moment they are produced and throughout acceleration. The evolution of the intensity can be seen in Figure 3. Only 50% of ^{6}He and 80% of ^{18}Ne eventually reach the decay ring.
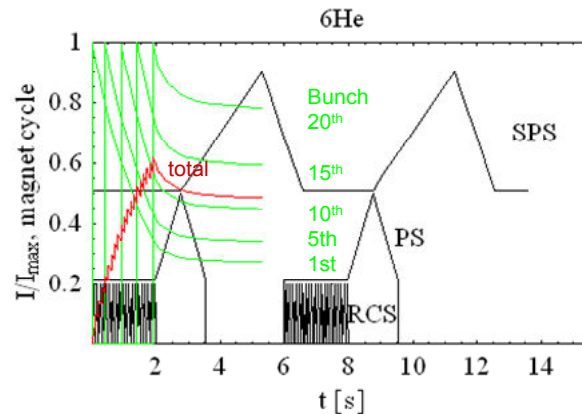
Fig. 3: Intensity evolution of ^{6}He during acceleration. The RCS, PS and SPS cycles are shown. The intensity of every 5th batch from the RCS is shown in green. Only one third of the first batch from the RCS survives. The total intensity is also shown (in red).

The result of studies of the radiation doses for maintenance and for doses to the population from the airborne activity released in the environment, are shown in Tables 1 and 2. The results are compatible with the CERN rules for radiation safety, see [6]. The SPS has not yet been studied. The radiation safety work on the Decay Ring does not include the collimation losses.

Table 1: 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	x	5,4
1 day	3	6	x	3.6
1 week	2	2	x	1.4

Table 2: Annual effective dose to the population (μSv)

RCS	PS	SPS	DR only from decay
0.67	0.64	x	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], [9] and [10]. The idea is to avoid placing superconducting coil windings where the particles impinge, see example in Figure 4. Complementary calculations have to be performed to confirm that this approach is good for the beta beam magnets, Liners inside the coil aperture can be used to enhance the coil protection, but the magnet aperture will then be smaller.
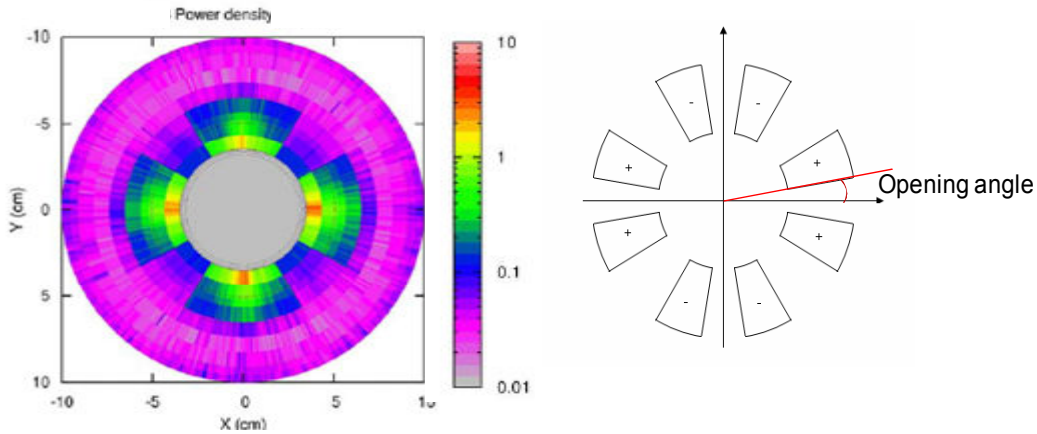
Fig. 4: A typical energy deposition pattern in a quadropole from decay products (left) (transverse cut of a quadrupole cold mass). A proposed coil-block distribution to avoid heat deposition on the coils (right).

The quadrupole study is made parametrically, which means that once the necessary opening angles 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 $5 \cdot 10^{11}$ ions each, ~ 5 ns long [11] necessitates momentum collimation of almost 50% of the ions, see Figure 5. The work on collimation is ongoing. Some $5 \cdot 10^{12}$ ^{6}He ions have to be collimated per cycle (6 s). The decay into ^{6}Li corresponds to

$5 \cdot 10^{12}$ ions per cycle. These ions have to be either dumped after the straight sections or are they taken care of by special arrangements 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.
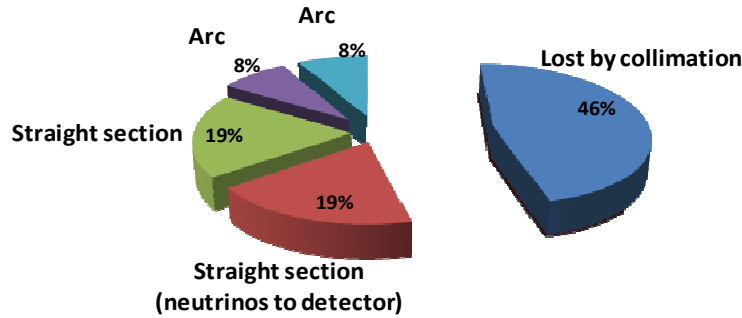
Fig. 5: The distribution of losses in the decay ring.

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 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 [12].

4   Ion Production

The ions required for beta beams are not those that have great interest for nuclear physics today. Therefore, the research on production has not been of high priority so far. The EURISOL study was top down, and to make sure the feasibility of the beta beam can be confirmed the realistic production of the needed isotopes has to be addressed. The presently known production rates of beta beam isotopes is shown in Table 3 in which also other possible ions for beta beams, that will be discussed below, are shown for completeness. The required production rate for both isotopes is $2 \cdot 10^{13}$ ions per second. There is an evident shortfall of ^{18}Ne. By making proposals for experiments and for beam time availability at the ISOLDE facility at CERN, results can be used to verify whether sufficient production rates can be obtained. Very encouraging results for ^{6}He have already been achieved at ISOLDE, see [13][14]. With more available beam power the production rates can be pushed one order of magnitude. There are new proposals for ^{8}Li and ^{18}Ne at ISOLDE. Direct production methods (the impinging beam is directly reacting with the target material to give the wanted isotope) for ^{18}Ne have been proposed at Université Catholique de Louvain, Belgium. Results indicate that the production rates obtained scale to production rates compatible with the beta beam to Frejus.

**Table 3:** Production rates, estimated, ions/ second

	^{6}He	^{18}Ne	^{8}Li	^{8}B
ISOL	$> 2 \ 10^{13}$	$< 1 \ 10^{11}$	$> 2 \ 10^{13}$	?
Direct	?	$< 1 \ 10^{13}$	?	?
Ring	?	?	$> 1 \ 10^{14}$	$> 1 \ 10^{13}$

It is now of great importance to do the necessary complementary research for ^{18}Ne to confirm the feasibility of a beta beam from CERN to Frejus. In table 3, "Ring" means that the isotopes are produced in a small accelerator ring. This will be described in next chapter.

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 [15]. This proposal suggests using ^{8}Li and ^{8}B as antineutrino 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 in the decay ring, is larger. However due to the scaling, we would need ~ 5 times more ions in the decay ring. This is, according to the simple scaling considerations, a general problem for high-Q isotopes. Another aspect is the use of other detectors (Liquid Argon) which would be advantageous at these neutrino energies. Detector development may need long time scales. The beta beam has to supply the additional necessary neutrino intensities needed. Evaluation of this additional intensity 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" [17].
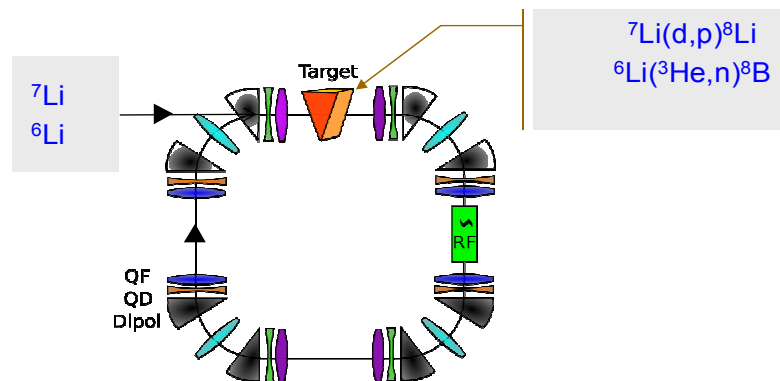

Fig. 6: A way to produce radioactive ions for beta beams using multiple traversals of a gas jet target, serving also as stripper and for ionization cooling of the beam.
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A circulating beam of ^{6}Li or ^{7}Li produces the beta beam isotopes by repetitive traversals of a supersonic gas jet target, (see Figure 6). The target serves as a stripper and will also be used for beam cooling. In the case of the ^{7}Li beam, the energy is 25 MeV and the energy loss over the target is 300 keV.

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, the new synchrotron PS2, in the simulations. The PS2 has a smaller aperture than the PS. Preliminary studies have shown that the Ne beam would have a very small contingency. A high priority is to calculate the beam performance of PS2 for the beta beams.

A preliminary lattice design (see Figure 7) for the production ring is available [18], and target models have been developed with Geant4 to be part of simulations to verify the cooling conditions in the production storage ring [19]. Transverse coupling will also be needed for this purpose [20].

Fig. 7: Lattice for Production Ring
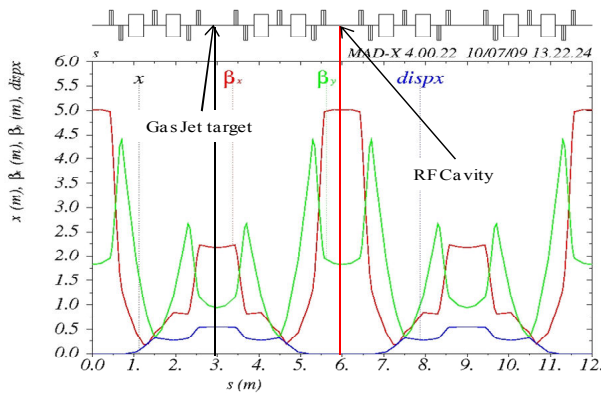
12m circumference
Mirror symmetric structure
1.5T dipoles
5 quadrupole-families
Dx = 0 in cavity-section
Best choice of Dx in target-section
(depends on wedge angle of the target)

The supersonic gas jet target [15] with a jet velocity of 2200 m/s (volume 4.3 m^3/s) has not yet been studied. Plans for tests at GSI are under discussion.

The collection of the ions after production in the target (see Figure 8) 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.
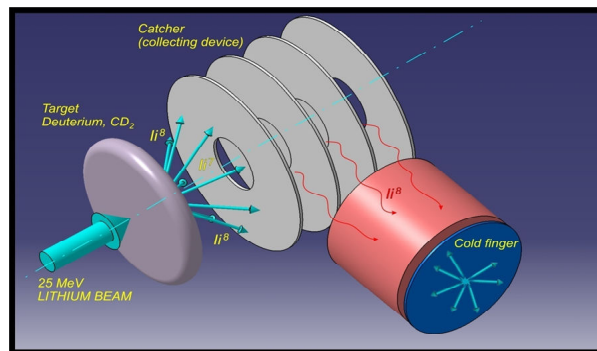
Fig. 8: A catcher for Li ions.

Cross section measurements of the reactions are measured at 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 [2], France, within a collaboration involving several laboratories and institutes. Source assembly and tests of a 28 MHz gyrotron for 2010 are foreseen, see Figure 9.
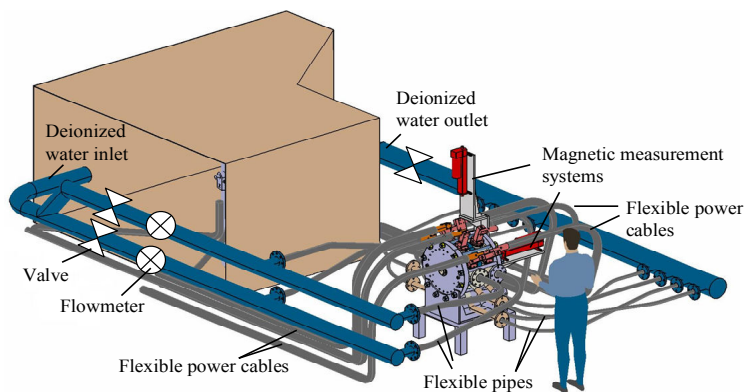

Fig. 9: Setup for the ECR source for beta beams (magnetic field test).

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$_4$C. Intensities, largely superior to those required for the beta beam, would be available. Direct production of ^{18}Ne is also under investigation.

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 (5.9μC 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 find a way 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 would be achieved. However, extensive studies of the physics reach with relaxed duty factors shows that the duty factors cannot be relaxed beyond 1%, see Figure 10. Figure 10 shows the θ$_{13}$ and the δ$_{cp}$ sensitivity for different duty factors for intensities in the decay ring corresponding to production rates taken from [15]. 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 [12]. We may relax somewhat the requirement for short bunches and/or inject more bunches to increase the flux. It has to be noted that the study was made with high production rates that might not be compatible with the intensity limits in our present accelerators (4.3·10^{13} ions in the SPS in 20 bunches, 1.8·10^{15} ions in the decay ring with 1% duty factor) taking into account that present upgrade studies of the SPS aim at achieving proton intensities of 7·10^{13} distributed over most of the circumference. Possible proton intensities up to 7·10^{13} at 400 GeV have been mentioned in [22].
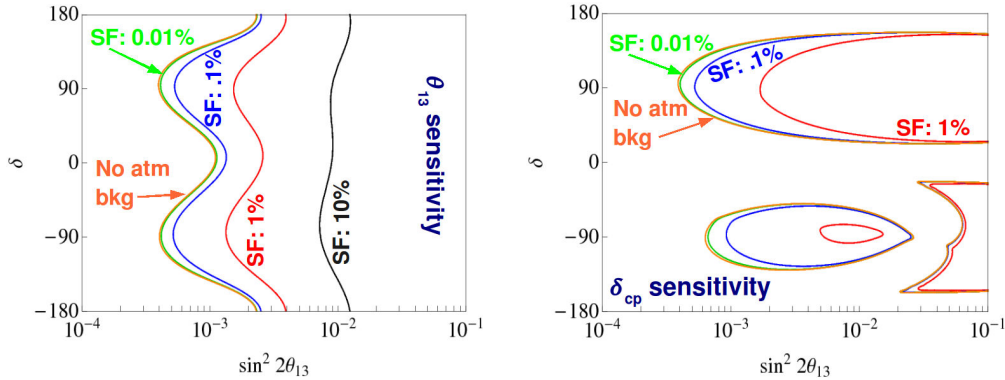
Fig. 10: The θ$_{13}$ (left) and δ$_{cp}$ (right) sensitivity for different duty factors. The 0.1% duty factor (blue) gives similar sensitivity and with 1% SF (red) the sensitivity has decreased slightly. These results are based on fluxes proposed in [15].

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.

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 [23]. 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 (energy/baseline). ^{6}He and ^{8}Li are the radioactive ions, proposed for beta beams, which can be produced relatively easily. The Tevatron (^{6}He, γ = 350) and the Main Injector (^{8}Li, γ = 55) would be used to send the ions to Nova and to 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 Cherenkov detector at 650 km [24]. ^{8}Li and ^{8}B sent to the magic baseline at 7000 km, with ring dip angle 34°, would outperform a neutrino factory for $\sin^2 2\theta_{13} \geq 10^{-3}$ (note however the depth and the length of the tunnel needed, see Fig. 1)

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 measurments (for detector response, r-processes and double beta decay) and for studies of fundamental interactions [25].

Monochromatic beta beams can be produced by beams of nuclei decaying by Electron Capture (EC)[26]. 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 [27]. There may be interest to investigate the CERN accelerator implications of the combined EC and beta decay. The proposed baselines would be Frejus, 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 is now coming to an end and the design report will be published in 2009. It is the first coherent beta beam study. The beta beam seems a feasible approach to neutrino production. However we are presently facing a significant shortfall of ^{18}Ne. Recent proposals suggest that this problem can be remedied either by a production ring or by new developments at ISOLDE for all the presently considered beta beam isotopes (6He, 8Li, 18Ne and 8B). 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 another important challenge. Work to optimize the machines and the beams for good physics is presently ongoing to evaluate if high-Q isotopes is a good option to produce neutrinos. Could the requirements for increased intensities needed for higher energy neutrinos sent to LAr detectors be relaxed by improved detector technology?Studies of methods to suppress atmospheric background in the detectors would be beneficial for beta beams.

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