Beta Beams

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Beta Beams could address the needs of long term neutrino oscillation experiments. They can produce extremely pure neutrino beams through the decays of relativistic radioactive ions. The baseline scenario is described, together with its physics performances. Using a megaton water Čerenkov detector installed under the Fréjus, Beta Beams could improve by a factor 200 the present limits on $\sin^2 2\theta_{13}$ and discover leptonic CP violating effects if the CP phase δ would be greater than 30° and θ_{13} greater than 1°. These performances can be further improved if a neutrino SuperBeam generated by the SPL 4MW, 2.2 GeV, proton Linac would be fired to the same detector. Innovative ideas on higher and lower energy Beta Beams are also described.

1. Introduction

Long Baseline neutrino beams are the future facilities for neutrino oscillations. Only in a well controlled, fully optimized environment it will be possible to perform precision measurements of θ_{23} and δm^2_{23} and to search for the still unknown parameters θ_{13}, δ, sign(δm^2). These latter parameters can be explored by detecting sub leading $\nu_\mu \to \nu_e$ transitions, characterized by their smallness given the present experimental bound, from the Chooz experiment [1].

The present generation of LBL neutrino experiments: K2K , Minos, Opera and Icarus has been designed to confirm the SuperKamiokande result on atmospheric neutrinos through ν_μ disappearance or $\nu_\mu \to \nu_\tau$ transitions, with limited sensitivity to θ_{13}.

Second generation long baseline experiments, like the already approved T2K [2], and NOνA [3], will extend the sensitivity on $\sin^2 2\theta_{13}$ by more than one order of magnitude with respect to the present Chooz limit. However they will have very limited sensitivity to the CP phase δ even if complemented by high sensitivity reactor experiments [4].

A third generation of LBL neutrino experiments will be required to start a sensitive search of leptonic CP violation (LCPV). These future experiments will push conventional neutrino beams to their ultimate performances (neutrino SuperBeams), or will require new concepts in the production of neutrino beams.

Conventional neutrino beams are generated by secondary particle decays, mainly pions and kaons, producing a multiflavour neutrino beam (ν_e, $\overline{\nu}_\mu$, $\overline{\nu}_e$, besides the main neutrino component, ν_μ). Beam composition and fluxes are difficult to precisely predict because of the lack of knowledge of secondary particle production cross sections (hadroproduction).

These limitations are overcome if the neutrino parents can be selected, collimated and accelerated to a given energy. The neutrino beams from their decays would then be pure and perfectly predictable. This can be tempted within the muon or a beta decaying ion lifetimes. The first approach brings to the Neutrino Factories [5], the second to the Beta Beams.

Beta Beams have been introduced by P. Zucchelli in 2001 [6]. The idea is to generate pure, well collimated and intense ν_e ($\overline{\nu}_e$) beams by producing, collecting, accelerating radioactive ions and storing them in a decay ring. The ideal candidates are chosen with a lifetime around 1 s among the ions that can be artificially copiously produced. The best candidates so far are ^{18}Ne and ^{6}He for ν_e and $\overline{\nu}_e$ respectively. A baseline study for such a BetaBeam complex has been produced at CERN [7].

In this scenario Beta Beam neutrino energies are below 1 GeV and the ideal detector is a water

Čerenkov detector with a mass of the order of 1 megaton, necessary to reach the needed sensitivity. Such a detector would have excellent physics capabilities in its own, as fully described in reference [8], like ultimate sensitivities for proton decay, supernovae neutrinos, atmospheric neutrinos etc. A candidate site for this detector exists, located under the Frejus, at an appropriate baseline from CERN: 130 km.

Liquid Argon could be an excellent alternative to water, provided that the Icarus technology could be scaled to the 100 Kton scale [9].

2. The BetaBeam complex

The beta-beam complex is described in [7] and shown schematically in figure 1. Protons are delivered by a high power Linac. Beta Beam targets need 100 μA proton beam, at energies between 1 and 2 GeV.

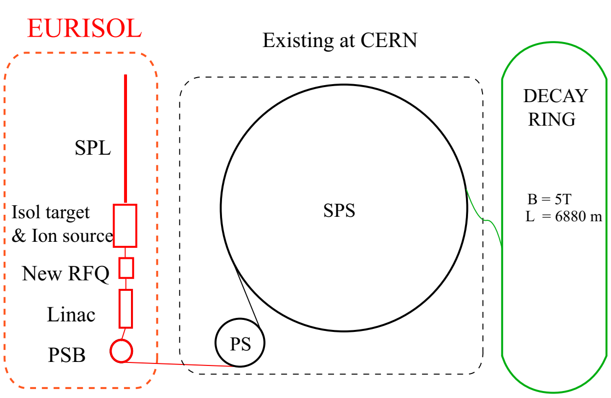


Figure 1. Schematic layout of the beta-beam complex. At left, the low energy part is largely similar to the EURISOL project. The central part (PS and SPS) uses existing facilities. At right, the decay ring has to be built.

In case the Super Proton Linac (SPL) [10] would be used, Beta Beams could be fired to the same detector together with a neutrino Super-Beam [11]. SPL is designed to deliver 2mA of 2.2 GeV (kinetic energy) protons, in such a configuration Beta Beams would use 10% of the total proton intensity, leaving room to a very intense conventional neutrino beam.

The targets are similar to the ones envisioned by EURISOL [12]: the ^{6}He target consists either of a water cooled tungsten core or of a liquid lead core which works as a proton to neutron converter surrounded by beryllium oxide [13], aiming for 10^{15} fissions per second. ^{18}Ne can be produced by spallation reactions, in this case protons will directly hit a magnesium oxide target. The collection and ionization of the ions is performed using the ECR technique [14].

Ions are firstly accelerated to MeV/u by a Linac and to 300 MeV/u, in a single batch of 150 ns, by a rapid cycling synchrotron . 16 bunches (consisting of 2.5 10^{12} ions each in the case of ^{6}He) are then accumulated into the PS, and reduced to 8 bunches during their acceleration to intermediate energies. The SPS will finally accelerate the 8 bunches to the desired energy using a new 40 MHz RF system and the existing 200 MHz RF system, before ejecting them in batches of four 10 ns bunches into the decay ring. The SPS could accelerate ^{6}He ions at a maximum γ value of $\gamma_{^6\mathrm{He}} = 150$.

The decay ring has a total length of 6880 m and straight sections of 2500 m each (36% useful length for ion decays). These dimensions are fixed by the need to bend ^{6}He ions up to $\gamma = 150$ using 5 T superconducting magnets. Due to the relativistic time dilatation, the ion lifetimes reach several minutes, so that stacking the ions in the decay ring is mandatory to get enough decays and hence high neutrino fluxes. The challenge is then to inject ions in the decay ring and merge them with existing high density bunches. As conventional techniques with fast elements are excluded, a new scheme (asymmetric merging) was specifically conceived [15].

2.1. Neutrino fluxes

^{18}Ne and ^{6}He ions can be stored together in the decay ring (of course, in different bunches). Due to their different magnetic rigidities, these ions would have relativistic γ factors in the 5 to 3 ratio, which is quite acceptable for the physics program. This will impose constraints on the lattice design for the decay ring, but no impossibility has been identified.

An ECR source coupled to an EURISOL target would produce $2 \cdot 10^{13}$ ^{6}He ions per second. Taking into account all decay losses along the accelerator complex, and estimating an overall transfer efficiency of 50%, one estimates that $4 \cdot 10^{13}$ ions would permanently reside in the final decay ring. That would give an antineutrino flux aimed at the Fréjus underground laboratory of $2.1 \cdot 10^{18}$ per standard year (10^7 s).

For ^{18}Ne, the yield is expected to be $1.6 \cdot 10^{12}$ ions in a 2 s exposing time. Due to this smaller yield, which could be certainly improved with some R&D, it was then proposed to use 3 EURISOL targets in sequence connected to the same ECR source. Again taking into account decay losses plus a 50% efficiency, this means that $4 \cdot 10^{13}$ such ions would reside in the decay ring, giving rise to a neutrino flux of $0.7 \cdot 10^{18}$ per standard year.

In the following it was supposed that the neutrino flux from ^{18}Ne could be increased by 50% over the present conservative estimate, having room for improvements both in the cycle duration of PS and SPS and in the ^{18}Ne production at the targets. A 40 % improvement was put on the ^{6}He generated antineutrino fluxes.

The reference fluxes are then $2.9 \cdot 10^{18}$ ^{6}He useful decays/year and $1.1 \cdot 10^{18}$ ^{18}Ne decays/year.

2.2. Radiation issues

The main losses are due to decays of He ions, and reach 1.2 W/m in the PS and 9 W/m in the decay ring. This seems manageable, although the use of superconducting bending magnets in the decay ring requires further studies. Activation issues have been recently addressed [16], and show that the dose rate on magnets in the arcs is limited to 2.5 mSv/h at contact after 30 days operation and 1 day cooling. Furthermore, the induced radioactivity on ground water will have no impact on public safety.

3. Physics reach

Beta Beam sensitivity have been computed assuming a water Čerenkov detector of 440 kt fiducial mass installed in the underground Fréjus laboratory, with a 130 km baseline. Most of the results of this section are taken from reference [17].

3.1. Signal and backgrounds

The neutrino beam energy is defined by the γ of the parent ions in the decay ring. The energy optimization is a compromise between the advantages of the higher γ, as a better focusing, higher cross sections and higher signal efficiency and the advantages of the lower γ values as the reduced background rates and the better match with the probability functions [18].

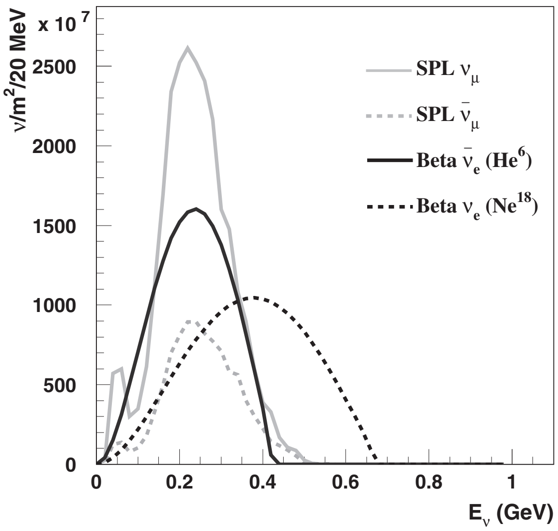
Given the decay ring constraint (see section 2.1): $\gamma(^6\mathrm{He})/\gamma(^{18}\mathrm{Ne}) = 3/5$ the optimal γ values result to be $\gamma(^6\mathrm{He}) = 60$ and $\gamma(^{18}\mathrm{Ne}) = 100$. Fig. 2 shows the BetaBeam neutrino fluxes computed at a 130 Km baseline, together with the SPL Super Beam (SPL-SB) fluxes.

The mean neutrino energies of the $\overline{\nu}_e$, ν_e beams are 0.24 GeV and 0.36 GeV respectively. They are well matched with the CERN-Frejus 130 km baseline. On the other hand energy resolution is very poor at these energies, given the influence of Fermi motion and other nuclear effects. Sensitivities are computed for a counting experiment with no energy cuts.

A different optimization holds if each ion can be run separately at its optimal γ value. In this case the single fluxes can be doubled just filling all the SPS batches with the same ion, and in 10 years the same integrated number of useful decays/year is obtained. Under this hypothesis the optimal choice seems to be $\gamma_{^6\mathrm{He}} = \gamma_{^{18}\mathrm{Ne}} = 75$.

It has been recently pointed out [19] that using the algorithm tools discussed in section 4, Beta Beam performances could be further improved by accelerating the ions to $\gamma_{^6\mathrm{He}} = 150$ with a baseline of 300 km.

The signal in a Beta Beam looking for $\nu_e \rightarrow \nu_\mu$ oscillations would be the appearance of ν_μ charged-current events, mainly via quasi-elastic interactions. These events are selected by requiring a single-ring event, the track identified as a muon using the standard SuperKamiokande identification algorithms (tightening the cut on the pid likelihood value), and the detection of the muon decay into an electron. Background



	Fluxes $\nu/m^2/yr$	$\langle E_\nu \rangle$ (GeV)
$\overline{\nu}_e(\gamma = 60)$	$1.97 \cdot 10^{11}$	0.24
$\nu_e(\gamma = 100)$	$1.88 \cdot 10^{11}$	0.36

Figure 2. Beta Beam fluxes at the Frejus location (130 km baseline). Also the SPL Super Beam ν_μ and $\overline{\nu}_\mu$ fluxes are shown in the plot.

rates and signal efficiency have been studied in a full simulation, using the NUANCE code [20] and reconstructing events in a SuperKamiokande-like detector [21]. The efficiency curve for ν_μ and $\overline{\nu}_\mu$ events is displayed in figure 3.

The Beta Beam is intrinsically free from contamination by any different neutrino flavor. However, backgrounds can be generated by inefficiencies in particle identification, such as mis-identification of pions produced in neutral current single-pion resonant interactions, electrons (positrons) mis-identified as muons, or by external sources such as atmospheric neutrino interactions.

The pion background has a threshold at neutrino energies of about 450 MeV, and is highly suppressed at the Beta Beam energies. The electron background is almost completely suppressed by the request of the detection of a delayed Michel electron following the muon track. The atmospheric neutrino background can be reduced mainly by timing the parent ion bunches. For a decay ring straight sections of 2.5 km and a bunch length of 10 ns, which seems feasible [7], this background becomes negligible [6]. Moreover, out-of-spill neutrino interactions can be used to normalize it to 1% accuracy level.

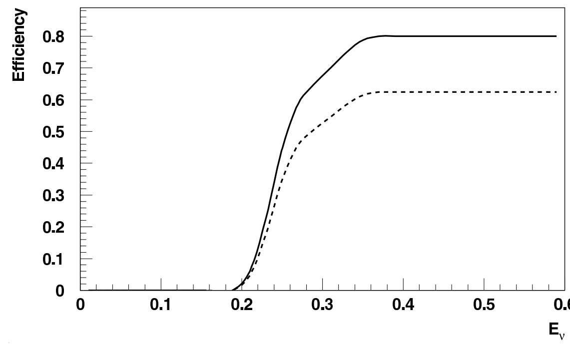


Figure 3. Detection efficiency for $\overline{\nu}_\mu$(solid) and ν_μ (dashed) events. ν_μ efficiency is smaller given the probability for a μ^- to be absorbed before decaying.

Signal and background rates for a 4400 kt-yr exposure to ^{6}He and ^{18}Ne beams are reported in Table 1. The default values for the oscillation parameters are $\sin^2 2\theta_{23} = 1$, $\delta m^2_{23} = 2.5 \cdot 10^{-3}\text{eV}^2$, $\sin^2 2\theta_{12} = 0.8$, $\delta m^2_{12} = 7.1 \cdot 10^{-5}\text{eV}^2$, sign($\delta m^2$)=+1.

3.2. Systematic errors

Systematic errors could spoil the sensitivity of any experiment looking for leptonic CP violations. To this purpose a beam without any contamination where the neutrino fluxes are known with great precision, like the Beta Beam, is the ideal facility.

A major concern is the knowledge of neutrino cross-sections in an energy range where experimental data are poor and the cross sections are roughly proportional to E^2_ν. On the other hand Beta Beams are the ideal place where to measure neutrino cross sections. Being the neutrino fluxes precisely known, a close detector of $\sim$ 1 kton (fiducial) placed at a distance of about 1 km from the decay ring could directly measure the rele-

Table 1
Event rates for a 4400 kt-y exposure. The signals are computed for $\theta_{13} = 1°$, $\delta = 90°$ sign$(\delta m^2) = +1$. "δ-oscillated" events indicates the difference between the oscillated events computed with $\delta = 90°$ and with $\delta = 0$. "Oscillated at the Chooz limit" events are computed for $\sin^2 2\theta_{13} = 0.12$, $\delta = 0$.

	^6He ($\gamma = 60$)	^{18}Ne ($\gamma = 100$)
CC events (no oscillation)	19710	144784
Oscillated (Chooz limit)	612	5130
Oscillated ($\delta = 90°$, $\theta_{13} = 3°$)	44	529
δ oscillated	-9	5712
Beam background	0	0
Detector backgrounds	1	397

vant neutrino cross sections. Furthermore the γ factor of the accelerated ions can be varied. In particular an energy scan can be initiated below the background production threshold, allowing a precise measurement of the cross sections for resonant processes.

It is estimated that a residual systematic error of 2% will be the final precision with which both the signal and the backgrounds can be evaluated.

The θ_{13} and δ sensitivities are computed taking into account a 10% error on the solar δm^2 and $\sin^2 2\theta$, and a 5% and 1% error on δm^2_{23} and $\sin^2 2\theta_{23}$ respectively, as expected from the T2K neutrino experiment [2]. Only the diagonal contributions of these errors are considered.

3.3. θ_{13} / δ sensitivities

θ_{13} can be measured either with ν_e and $\overline{\nu}_e$ disappearance and with ν_μ , $\overline{\nu}_\mu$ appearence. The disappearance channels offer a cleaner extraction of θ_{13} from the experimental result, but are limited by systematic errors. The comparison of the ν_e and $\overline{\nu}_e$ disappearance measurements could also set limits to CPT violation effects.

θ_{13} and δ are so tightly coupled in the appearance channels that the sensitivity expressed for $\delta = 0$ is purely indicative. A better understanding of the sensitivity of the BetaBeam is expressed in the (θ_{13} , δ) plane, having fixed all the other parameters, as shown in Fig. 4).

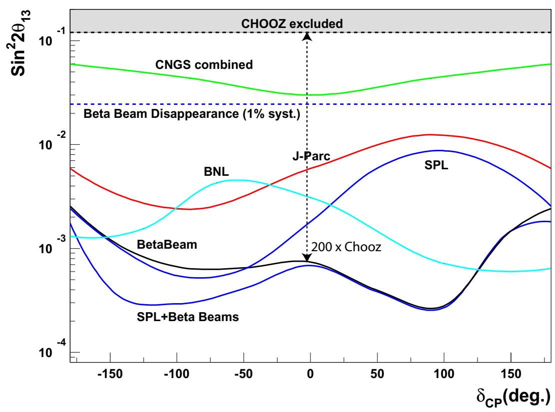


Figure 4. 90%CL sensitivity expressed as function of δ for $\delta m^2_{23} = 2.5 \cdot 10^{-3} eV^2$. CNGS and J-Parc curves are taken from [23], BNL from [24]. All the appearance sensitivities are computed for sign$(\delta m^2)) = +1$ and 5 years of data taking.

A search for leptonic CP violation can be performed fitting the number of muon-like events to the $p(\nu_e \to \nu_\mu)$ and to the p$(\overline{\nu}_e \to \overline{\nu}_\mu)$ probabilities. The fit can provide the simultaneous determination of θ_{13} and δ, see figure 5. Event rates are summarized in Table 1. The (θ_{13} ,δ) parameter space where the experiment could measure a 3σ LCPV effect is shown in figure 6. Discovery potential curves are drawn for 2%, 5% and 10% systematic errors. The 5% systematic error curve is roughly equivalent to the 2% curve computed with a detector having half the mass, showing the absolute need to keep systematic errors low in this kind of measurements.

3.4. Parameter correlations, degeneracies and clones

Correlations between θ_{13} and δ are fully accounted for, and indeed they are negligible as can be seen in the fits to θ_{13} and δ shown in figure 5. These correlations are tiny because at the baseline of 130 km matter effects are negligible and do not compete with genuine LCPV effects. A full computation of degeneracies, correlations and clones for the Beta Beam sensitivities can be found in [22], assuming that at the time Beta Beam will start no informations about the values

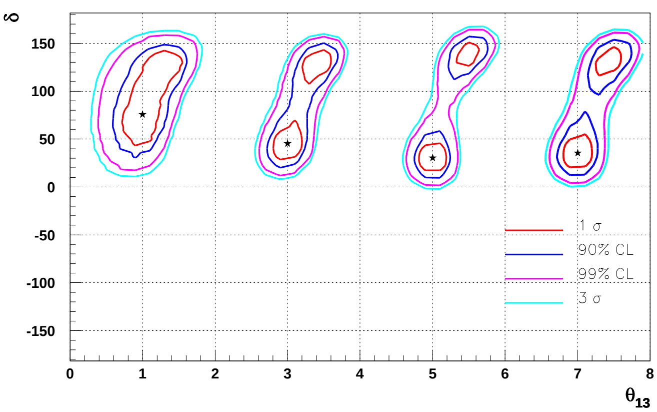


Figure 5. Fits to θ_{13} and δ after a 10 years run. Plots are shown for the (θ_{13} ,δ) values indicated by the stars. For the other neutrino oscillation parameters see the text. Lines show 1σ, 90%, 99% and 3σ confidence levels.

of sign(δm^2) and θ_{23} will be available.

3.5. Synergies between the SPL-SuperBeam and the Beta Beam

The Beta Beam can run with the SPL as injector, but consumes at most $\sim 10\%$ of the SPL protons. The fact that the average neutrino energies of both the SuperBeam and the Beta Beam are below 0.5 GeV (cfr. figure 2), with the Beta Beam tunable, offers the fascinating possibility of exposing the same detector to 2×2 beams (ν_μ and $\overline{\nu}_\mu \times \nu_e$ and $\overline{\nu}_e$) having access to CP, T and CPT searches in the same run.

It is evident that the combination of the two beams would not only result result an increase of the experimental statistics, but would also offer clear advantages in the reduction of the systematic errors and the necessary redundancy to firmly establish any LCP within the reach of the experiment.

The CP violation sensitivities of the combined BetaBeam and SPL-SB experiments are shown in figure 6.

4. High energy scenarios

It has been pointed out in [25] that allowing for higher values of γ, that is exploiting a higher

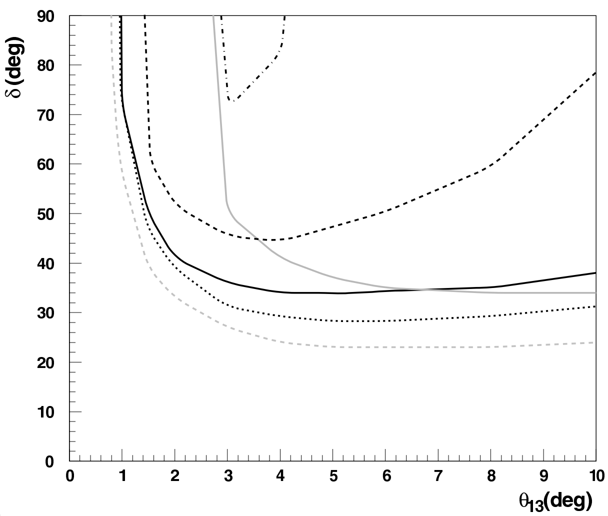


Figure 6. δ discovery potential at 3σ (see text) computed for 10 years running time. Black curves are computed with 2% systematic errors (solid), 5% (dashed) and 10% (dot-dashed). Dotted curve is the Beta Beam computed by running the two ions at $\gamma = 75$ (2% systematic error). Gray solid curve is SPL-SuperBeam sensitivity, gray dashed is the Beta Beam plus SPL Superbeam sensitivity curve, both curves are computed with a 2% systematic error.

energy proton synchrotron than the SPS, performances of the Beta Beam could be significantly enhanced. In the paper three different scenarios are compared: the baseline scenario described in section 2 (Setup I), $\gamma_{^6\mathrm{He}} = 350$ with a baseline $L \sim 730$ km (Setup II), and $\gamma_{^6\mathrm{He}} = 1500$ with $L \sim 3000$ km (Setup III). The same fluxes of the baseline scenario have been assumed (the ion currents entering the decay ring correspond to ~ 0.5 MW at $\gamma_{^6\mathrm{He}} = 350$ and to ~ 2MW at $\gamma_{^6\mathrm{He}} = 1500$) and it should be noted that the decay ring length, linearly proportional to $\gamma_{^6\mathrm{He}}$, would be of 16 (70) km for $\gamma_{^6\mathrm{He}} = 350(1500)$ if computed with the same parameters of the baseline scenario.

The main advantages of the most promising Setup-II scenario would be

- the mean neutrino energy would be $E_\nu \simeq$ 1.2 GeV and so water Čerenkov detectors are still suitable;

- a factor ~ 10 increase in ν_μ charged current event rate (1.5 increase at constant accelerator power) with respect to the baseline scenario;
- the possibility to exploit energy spectrum (more powerful fits to θ_{13} , δ);
- the possibility of measuring sign(Δm^2) (baseline $\simeq 700$ km).

On the other hand, as discussed in section 3.1, the background rate induced by charged pion production in NC events is very high at these energies. However the longer the pion track, the higher the probability it interacts in water missing the signature of the decay electron. A modest cut in the visible neutrino energy can reduce background fractions below $3 \cdot 10^{-3}$ for an integrated efficiency of $30 - 50\%$ [25].

Energy reconstruction is much more demanding at 1.2 GeV, in particular the non quasi elastic fraction of CC events becomes important, but the methods introduced in the paper allow for an efficient (though indirect) true neutrino energy estimation from the measured charged muon momentum.

The 99% CL discovery potential curves in the three different scenarios, computed including no systematic errors are shown if figure 7.

4.1. Another high energy scenario

In [26] it has been introduced the case of the highest energy that could be accessible at LHC: $\gamma_{^6\mathrm{He}} = 2488$. It was assumed that the same fluxes of the baseline scenario could be used and that the decay ring could be partially accommodated inside the LHC tunnel. The neutrino fluxes at the CERN-Gran Sasso baseline (732 km) would be so high that just counting the muons produced by neutrino interactions in the rock, with a 15×15 m^2 counter detector, the sensitivity on $\sin^2 2\theta_{13}$ could be increased by about one order of magnitude (for $\delta = 0$) with respect to the baseline scenario. Given the neutrino energy and the baseline, the experiment would be strongly off-peak, and no information about δ or sign(δm^2)would be available.

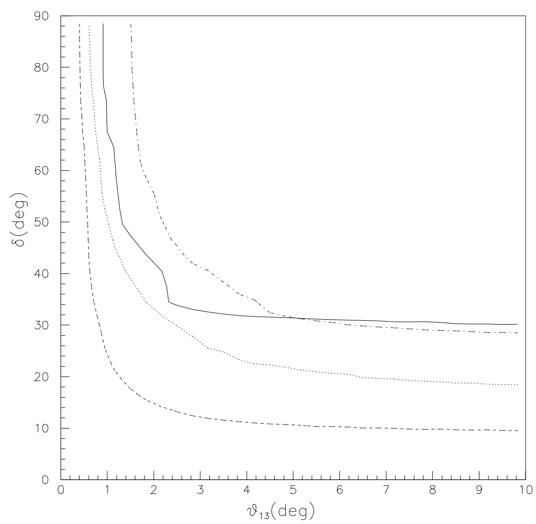


Figure 7. From reference [25]: region where δ can be distinguished from $\delta = 0$ or $\delta = 180°$ at 99% CL for Setup-I (solid), Setup-II with a water Čerenkov detector of 400 kton (dashed) at a baseline of 730 km and with the same detector with a factor 10 smaller mass (dashed-dotted) and Setup-III (dotted) with a 40 kton tracking calorimeter. In all cases 10 years of running time are considered.

5. Low energy scenarios

As discussed in section 3.2, Beta Beams are the ideal place where to measure neutrino cross sections. This could allow for precision measurements in the range of interest of astrophysics (supernovae explosions, nucleosynthesis etc.): $E_\nu = 10 - 100$ MeV, corresponding to $\gamma_{^6\mathrm{He}} = 7 - 14$. This experimental possibility is fully discussed in [27].

6. Conclusions

Beta Beams are a novel concept which can provide a very clean and powerful facility for the search of leptonic CP violation: a single flavour beam and no competition with the fake CP phenomena induced by matter effects.

The baseline scenario has been designed to be based on available technology with some conservative extrapolations. Its design has a very strong synergy with the EURISOL project aiming at producing high intensity radioactive beams for nuclear physics studies with astrophysical applications.

The gigantic far detector needed for these studies has excellent physics capabilities in its own, i.e. to study proton decay and detect supernova explosions. A possible site exists near CERN at the right distance.

Physics potential in neutrino oscillations would be a $\sin^2 2\theta_{13}$ sensitivity more than two orders magnitude better than the present experimental limit, having the distinctive feature to look for θ_{13} also in ν_e and $\overline{\nu}_e$ disappearance channels, and a 3 σ discovery potential on leptonic CP violation for CP phase δ values greater than 30° and for θ_{13} greater than 1°.

These performances can be further improved if a neutrino SuperBeam generated by the SPL 4MW, 2.2 GeV, proton Linac would be fired to the same detector. In this configuration the two beams could address leptonic CP and T violation, and could also explore CPT violation in neutrino oscillations.

Several new ideas about the baseline option optimization and extensions to higher and lower energies have been recently published, showing the great and partially still unexplored potential of the Beta Beams.

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