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Abstract. We give the present status of the beta-beam study, which aims at producing intense ν_e and $\overline{\nu}_e$ beams from the decay of relativistic radioactive ions. The emphasis is put on recent technical progress and new ideas. The expected performances in terms of neutrino mixing parameters (θ_{13} and CP violating phase δ) using a megaton water Cerenkov detector installed in the Fréjus underground laboratory are shown to be excellent, and the synergy with a a companion SuperBeam is underlined.

Beta-Beams: present design and expected performances[1]

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I MOTIVATIONS

Super-Kamiokande has given strong evidence for a maximal oscillation between $\nu_\mu$and ν_τ [1], and several projects with accelerators have been designed to check this result. The first results of the K2K experiment [2] confirm the oscillation, and future projects (MINOS in the USA, OPERA and ICARUS at Gran Sasso) should refine the oscillation parameters by 2010.

More recently, after the results from SNO [3] and Kamland [4], a solid proof for solar neutrino flavour oscillations governed by the so-called LMA solution has been established. We can no longer escape the fact that neutrinos have indeed a mass, although the absolute scale is not yet known. Furthermore, the large mixing angles of the two above-mentioned oscillations and their relative frequencies open the possibility to test CP violation in the neutrino sector if the third mixing angle, θ_{13}, is not vanishingly small (we presently have only an upper limit set at 10 degrees on θ_{13}, provided by the CHOOZ experiment [5]). Such a violation could have far reaching consequences, since it is a crucial

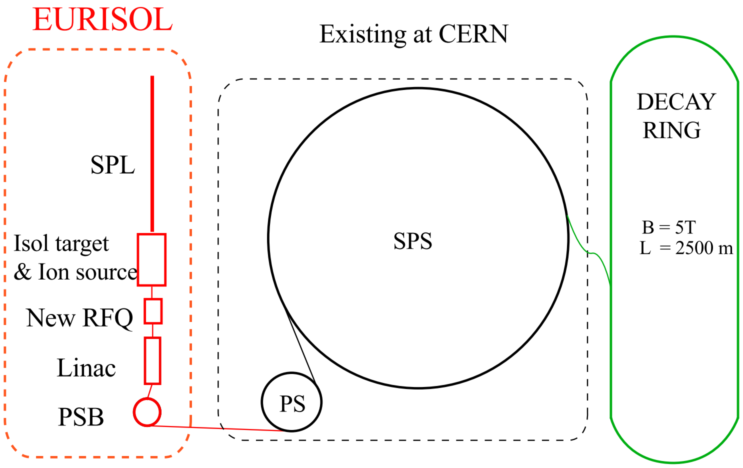

FIGURE 1. Schematic layout of the beta-beam complex. At left, the low energy part is largely similar to the EURISOL project. The central part (PS and SPS) uses existing facilities. At right, the decay ring has to be built.

ingredient of leptogenesis, one of the presently preferred explanations for the matter dominance in our Universe.

The ideal tool for these studies is thought to be the so-called neutrino factory, which would produce through muon decay intense neutrino beams aimed at magnetic detectors placed several thousand kilometers away from the neutrino source.

However, such projects would not be launched unless one is sure that the mixing angle θ_{13}, governing the oscillation between $\nu_\mu$and $\nu_e$at the higher frequency, is such that this oscillation is indeed observable. This is why physicists have considered the possibility of producing new conventional neutrino beams of unprecedented intensity, made possible by recent progress on the conception of proton drivers with a factor 10 increase in power (4 MW compared to the present 0.4 MW of the FNAL beam) The present limit on θ_{13} is 10 degrees, these new neutrino “superbeams” would explore θ_{13} down to 1 degree (i.e a factor 100 improvement on the ν_μ- $\nu_e$oscillation amplitude).

European working groups have studied a neutrino factory at CERN for some years, based on a new proton driver of 4 MW, the SPL. Along the lines described above, a subgroup on neutrino oscillations has studied the potentialities of a neutrino SuperBeam produced by the SPL. The energy of produced neutrinos is around 270 MeV, so that the ideal distance to study $\nu_\mu$to $\nu_e$oscillations happens to be 130 km, that is exactly the distance between CERN and the existing Fréjus laboratory. The present laboratory cannot house a detector of the size needed to study neutrino oscillations, which is around 1 million cubic meters. But the recent decision to dig a second gallery, parallel to the present tunnel, offers a unique opportunity to complete the needed extension in 2012 for a reasonable price.

Due to the schedule of the new gallery, a European project would be competitive only if the detector at Fréjus reaches a sensitivity on θ_{13} around 1 degree, since other projects in Japan (JHF phase 1) and USA (NuMI off-axis) will have reached 2.5 degrees by 2013. The working group has then decided to study directly a water Čerenkov detector with a mass around 1 megaton, necessary to reach the needed sensitivity. It has benefited from a similar study by our American colleagues, the so-called UNO detector [6] with a total mass of 660 kilotons. Simulations have shown that the sensitivity on θ_{13} at a level of 1 degree could indeed be fulfilled. However, the study of CP violation requires the SPL to be run sequentially with neutrinos and antineutrinos, and due to the fact that less antineutrinos are produced (less π^- than π^+ are produced) and that the $\overline{\nu}$ cross section is 5 times lower at the considered energies, 10 years of running should be shared roughly in 2 years with ν and 8 years with $\overline{\nu}$. This would be a strong limitation on CP sensitivity.

This is where the beta beam concept, initially proposed by Piero Zucchelli [7], comes into play. The idea is to produce well collimated and intense $\nu_e(\overline{\nu}_e)$ beams by producing, collecting, accelerating to energies with γ factor around 100 and storing in a final decay ring radioactive ions chosen for their ability to be copiously produced and with a lifetime around 1 second. The best candidates happen to be ^{18}Ne for $\nu_e$and ^{6}He for $\overline{\nu}_e$. A baseline study for such a BetaBeam complex has been produced at CERN [8], where there is a strong expertise on ion beams, both for nuclear physics through ISOLDE and for high energy experiments.

The initial goal was to produce a $\nu_e$beam which could be run simultaneously with the ν_μSPL SuperBeam, so that 10 years of data could be accumulated for the each of the 2 time reversed oscillations, $\nu_e \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$. This project was already presented at NuFact02 [9,10].

A workshop took place in march 2003 at Les Arcs [11], where nuclear physicists (mainly those concerned with the EURISOL project), neutrino physicists and machine scientists have met to discuss BetaBeam issues. The aim of this workshop was to get updated on recent progress on the BetaBeam project, explore the synergies between beta beams and EURISOL [12], and identify common studies which could benefit to both communities.

Apart from new ideas which simplify the overall BetaBeam design, the major innovation was the proposal to run simultaneously with both types of ions (β^+ and β^- emitters) stored in the ring. This opens up the exciting possibility of performing efficiently CP violation studies with beta beams alone, and get very useful redundancies by comparing SuperBeam and BetaBeam data.

The section 2 describes the machine aspects of beta beams, the section 3 gives the expected performances on the measurement of the mixing angle θ_{13} and the CP violating δ phase.

II THE BETABEAM COMPLEX

The beta-beam complex is shown schematically on figure 1. Technical details and recent progress on this project can be found at http://beta-beam.web.cern.ch/beta-beam/

The protons are delivered by the Super Proton Linac (SPL) [13], which is being studied at CERN in the framework of the neutrino factory [14]. Such an intense proton driver would deliver 2mA of 2.2 GeV (kinetic energy) protons hopefully by 2012. An ISOL target would need only 100 μA, that is 5 % only of the total proton intensity.

A The target and the ion source

The targets are similar to the ones envisioned by EURISOL [12]: for ^{6}He, it 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 [15] ,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. The pulsed "ECR-duoplasmatron" under development at Grenoble, using very dense plasmas ($10^{14}/\mathrm{cm}^3$) and high magnetic fields (2 to 3 Teslas) submitted to high frequencies (60 to 90 GHz) is aimed to produce 10^{12} to 10^{13} ions in very short bunches (20 to 100 μs) at 100 keV with repetition rates reaching 16 Hz [16]. The advantage over the standard ECR technique is that the downstream complex can be simplified, due to the achieved bunching and hopefully to ions which are totally ionized.

B First acceleration and storing

Then the first acceleration process can be achieved using a LINAC rather than a cyclotron or a FFAG as initially considered. Ions would be accelerated to 20-100 MeV/u in 16 batches per second. Then comes the first storage ring, a rapid cycling synchrotron using multiturn injection (40 turns), delivering a single 150 ns bunch at 300 MeV/u.

C Final acceleration

16 bunches (consisting of 2.5 10^{12} ions each in the case of He) are then accumulated into the PS, and reduced to 8 bunches during their acceleration to intermediate energies. Due to the fact that the PS is a slow machine, this

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1) Talk presennted at NuFact 03, 5th International Workshop on Neutrino Factories & Superbeams, 5–11 June 2003, Columbia University, New York.

is the place where radiation levels due to ion decays is the most severe (the replacement of the PS by a more rapid machine would ease this problem and many others in the CERN complex of accelerators). Furthermore, the space charge bottleneck at SPS injection will require a transverse emittance blow-up. The SPS will finally accelerate the 8 bunches to the desired energy ($\gamma \simeq 100$) 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.

D The decay ring

This ring has the shape of an hippodrome, with a total length of 6880 m (matching the SPS) and straight sections of 2500 m each (36%). 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 for this task [17]. It schematically consists in injecting an off-momentum ion bunch on a matched dispersion trajectory, then rotate this fresh bunch in longitudinal phase space by a 1/4 turn into a starting configuration for bunch merging. This technique had been proven to work on computer simulations [17], but it received very recently a first experimental confirmation [18].

E Neutrino fluxes

One of the ideas presented at the Moriond meeting was that it should be possible to run together Neon and Helium ions in the decay ring (of course, in different bunches). Due to their different 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 for $\gamma = 60$. 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 only $8 \cdot 10^{11}$ ions per second. 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 $2 \cdot 10^{13}$ such ions would reside in the decay ring for $\gamma = 100$, giving rise to a neutrino flux of $0.35 \cdot 10^{18}$ per standard year.

All these numbers are preliminary and need to be refined. They are however based on the present state of the art for the technology, and suppose using the present PS, while the SPS cycle is set at 16 s; a shorter cycle for the SPS would improve the accumulation factor substantially, while a faster PS would increase the intensity of ions making it to the decay ring.

In the following study, it was supposed that the neutrino flux from ^{18}Ne could be increased by a factor 3 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 with a dedicated R&D, while only a 40 % improvement was put on antineutrino fluxes.

F 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 [19], 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.

III PHYSICS REACH

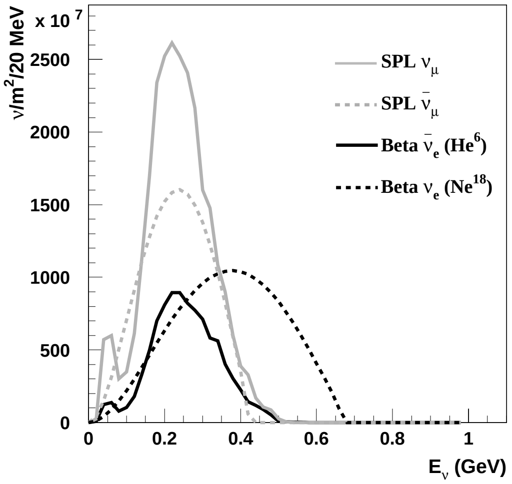
The following study is based on the hypothesis that a UNO-like water Cerenkov detector (440 kt fiducial mass) will be installed in the underground Fréjus laboratory and receive neutrino beams produced at CERN, 130 km away.

A Signal and backgrounds

The neutrino beam energy depends on the γ of the parent ions in the decay ring. As discussed in ref. [10], the optimization of this energy, 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 (see the following) and the better match with the probability functions. Given the decay ring constraint (see sect. II D): $\gamma(^6He)/\gamma(^{18}Ne) = 3/5$ the optimal γ values result to be $\gamma(^6\mathrm{He}) = 60$ and $\gamma(^{18}\mathrm{Ne}) = 100$. A flux of $2.9 \cdot 10^{18}$ ^{6}He decays/year and $1.1 \cdot 10^{18}$ ^{18}Ne decays/year, as discussed in sect. II E, will be assumed. Fig. 2 shows the

BetaBeam neutrino fluxes computed at the 130 Km baseline, together with the SPL Super Beam (SPL-SB).

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 and in the following all the sensitivities are computed for a counting experiment with no energy cuts.



	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
ν_μ	$4.78 \cdot 10^{11}$	0.27
$\overline{\nu}_\mu$	$3.33 \cdot 10^{11}$	0.25

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.

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 Super-Kamiokande identification algorithms (tightening the cut on the pid likelihood value), and the detection of the muon decay into an electron. Background rates and signal efficiency have been studied in a full simulation, using the NUANCE code [20], reconstructing events in a Super-Kamiokande-like detector.

The Beta Beam is intrinsically free from contamination by any different flavor of neutrino. However, background 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

TABLE 1. Event rates for a 4400 kt-y exposure. The signals are computed for $\theta_{13} = 3°$, $\delta = 90° \; sign(\Delta m^2) = +1$. "$\delta$-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 $\sin^2 2\theta_{13} = 0.12$, $\delta = 0$.

	Beta Beam		SPL-SB	
	$^6He(\gamma = 60)$	$^{18}Ne(\gamma = 100)$	ν_μ(2 yrs)	$\overline{\nu}_\mu$(8 yrs)
CC events (no osc, no cut)	19710	144784	36698	23320
Oscillated at the Chooz limit	612	5130	1279	774
Total oscillated ($\delta = 90°$, $\theta_{13} = 3°$)	44	529	93	82
δ oscillated	-9	57	-20	12
Beam background	0	0	140	101
Detector backgrounds	1	397	37	50

seems feasible [8], this background becomes negligible [10]. Moreover, out-of-spill neutrino interactions can be used to normalize this background to the 1% accuracy level.

Signal and background rates for a 4400 kt-yr exposure to ^{6}He and ^{18}Ne beams, together with the SPL SuperBeam (SPL-SB) fluxes [9], are reported in table 1

B Systematic errors

A facility where the neutrino fluxes are known with great precision is the ideal place where to measure neutrino cross sections. In the Beta Beam the neutrino fluxes are completely defined by the parent ions beta decay properties and by the number of ions in the decay ring. A close detector of ~ 1 kton placed at a distance of about 1 km from the decay ring could then measure the relevant neutrino cross sections. Furthermore the γ factor of the accelerated ions can be varied. In particular a 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 $\sin^2 2\theta$, already reached after the recent SNO-salt results [3] and a 5% and 1% error on δm^2_{23} and $\sin^2 2\theta_{23}$ respectively, as expected from the J-Parc neutrino experiment [21]. Only the diagonal contributions of these errors are considered. In the following the default values for the oscillation parameters will be $\sin^2 2\theta_{23} = 1$, $\delta m^2_{23} = 2.5 \cdot 10^{-3} eV^2$, $\sin^2 2\theta_{12} = 0.8$, $\delta m^2_{12} = 7.1 \cdot 10^{-5} eV^2$, $sign(\Delta m^2)$=+1.

C Parameter correlations and degeneracies

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 Fig. 3.

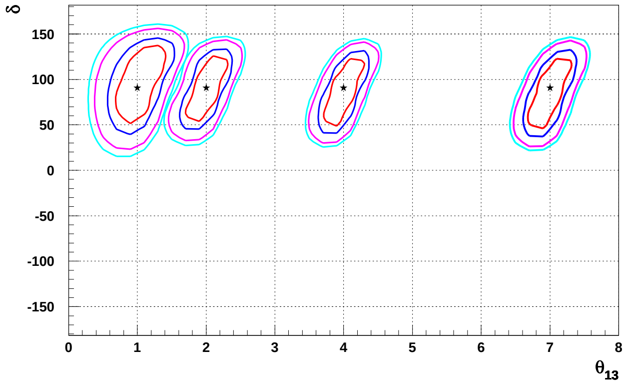


FIGURE 3. Fits to θ_{13} and δ after a 10 yrs BetaBeam run. Plots are shown for $\delta = 1°, 2°, 4°, 7°$. For the other neutrino oscillation parameters see the text. Lines show 1σ, 90%, 99% and 3σ confidence levels.

The net effect of the $sign(\Delta m^2)$ambiguity is to make undetectable sign($\delta \cdot sign(\Delta m^2)$). This derives by the negligible matter effects at the 130 km, so that a change of $sign(\Delta m^2)$is equivalent to a change of the sign of δ. The performances of the BetaBeam to the two opposite values of sign($\delta \cdot sign(\Delta m^2)$) are different because the neutrino and antineutrino runs have different statistics and backgrounds. This effect will be illustrated in fig. 5 and fig. 6.

Finally the $\theta_{23}/(\pi/2 - \theta_{23})$ ambiguity is formally taken into account, but no effect is found because the BetaBeam performances are computed for the central value of SuperKamiokande: $\theta_{23} = 45°$. A study of the performances of the BetaBeam for different values of θ_{23} is beyond the purpose of this article.

We stress the fact that an experiment working at very short baselines has the smallest possible parameter degeneracies and ambiguities and it is the cleanest possible environment where to look for genuine leptonic CP violation effects.

D θ_{13} /δ sensitivities

The θ_{13} angle can be independently explored both with $\nu_e$and $\overline{\nu}_e$disappearance measurements. We note that the comparison of the $\nu_e$and $\overline{\nu}_e$disappearance experiments could set limits to CPT violation effects. Sensitivities to θ_{13} , computed for a 5 yr run and for systematic errors equal to 2%, 1% and 0.5% are shown Fig. 4left). For comparison sake, shown in the same plot are the sensitivities reachable with the appearance channels, computed for $\delta = 0$.

Indeed 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 ($\delta m^2_{23} = 2.5 \cdot 10^{-3}$ eV^2), as shown in Fig. 4right). In the same plot the sensitivity of the SPL-SB computed for a 5 yrs $\nu_\mu$run is displayed . It can be noted the very large variation of the SPL-SB sensitivity for the different values of δ, characteristic of the single flavour run. The BetaBeam, having both CP neutrino states in the same run, exhibits a much more favourable dependence to the CP phase δ.

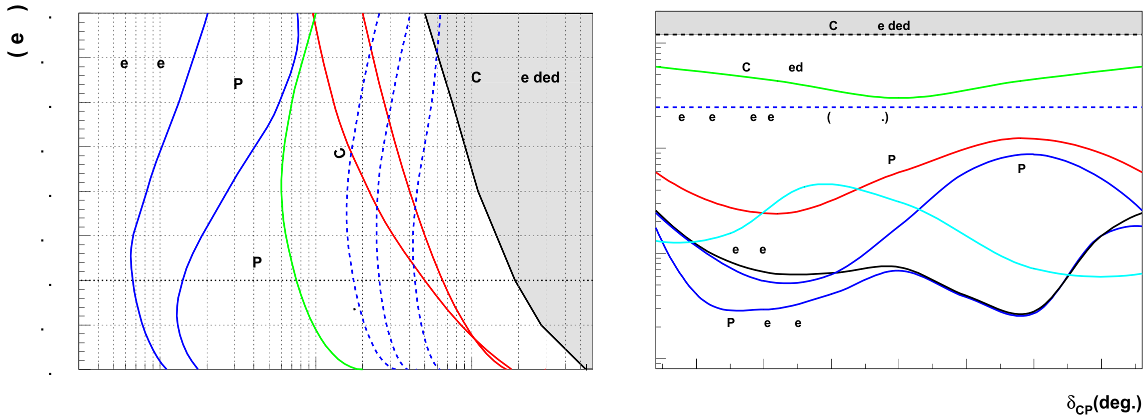


FIGURE 4. LEFT: 90%CL sensitivity of the disappearance channel to θ_{13} in a 5 yrs run drawn as dotted lines. The labels 0.5%, 1% and 2% indicate the systematic errors with which are computed. Also shown are the appearance sensitivities of Beta and SPL beams, computed for $\delta = 0$, $sign(\Delta m^2)$=+1. The combined CNGS limit is taken from ref. [22], J-Parc from [21], Minos from ref. [24]. RIGHT: 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 ref. [22], BNL from ref. [23]. All the appearance sensitivities are computed for $sign(\Delta m^2) = +1$.

A search for leptonic CP violation can be performed running the Beta Beam with ^{18}Ne and ^{6}He, and fitting the number of muon-like events to the $p(\nu_e \rightarrow \nu_\mu)$ and to the p($\overline{\nu}_e \rightarrow \overline{\nu}_\mu$) probabilities. The fit can provide the simultaneous determination of θ_{13} and δ, see fig. 3.

Event rates are summarized in Table 1. The region of 99% CL sensitivity to maximal CP violation ($\delta = 90°$) in the δm^2_{12} and θ_{13} parameter space, following the convention of [25], is plotted in Fig. 5.

The 3σ sensitivity to δ, having fixed $\delta m^2_{12} = 7.1 \cdot 10^{-5}$ eV^2, is shown in Fig. 6.

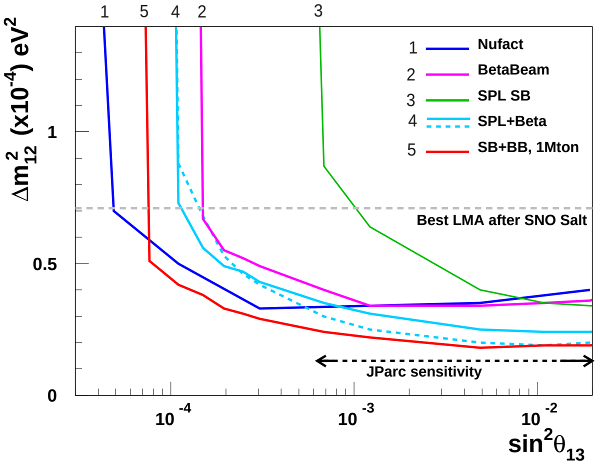


FIGURE 5. 99%CL δ sensitivity of the Beta Beam, of the SPL-SuperBeam, and of their combination, see text. Dotted line is the combined SPL+Beta sensitivity computed for $sign(\Delta m^2)$=-1. Sensitivities are compared with a 50 GeV Neutrino Factory producing $2 \cdot 10^{20} \mu$ decays/straight section/year, and two 40 kton detectors at 3000 and 7000 km [25].

E Synergies between the SPL-SuperBeam and the Beta Beam

The Beta Beam needs 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. fig. 2), with the Beta Beam being tunable, offers the fascinating possibility of exposing the same detector to 2×2 beams ($\nu_\mu$and $\overline{\nu}_\mu \times$ ν_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 result only in an increase in the statistics of the experiment, but it would also offer clear advantages in the reduction of the systematic errors, and it would offer the necessary redundancy to firmly establish any effect of violation of CP within the reach of the experiment.

The CP violation sensitivities of the combined BetaBeam and SPL-SB experiments are shown in Fig. 5 and Fig. 6.

IV CONCLUSIONS

Betabeams are a novel concept which can give very precise insight on the problem of neutrino mixing. Their design has many common features with the EURISOL project aiming at producing high intensity radioactive beams for nuclear physics studies with astrophysical applications. This synergy has been outlined at the Moriond workshop, and common technical studies are already going on. Recently, the potentialities of low energy betabeams (γ factors below 10) has also been emphasized [26].

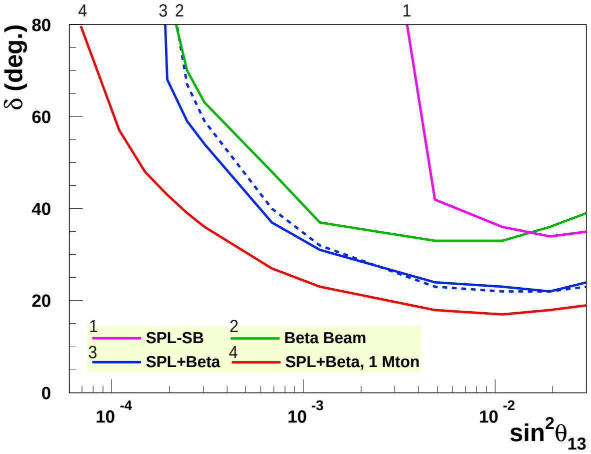


FIGURE 6. δ discovery potential (3σ) as function of θ_{13}. Dotted line are sensitivities computed for $sign(\Delta m^2)$=-1

On the other hand, there have been for some time projects of megaton detectors to study proton decay and detect supernova explosions, but they never got financial support. The fact that they would also be perfect targets for low energy neutrino superbeams or betabeams considerably increases the physical interest of these detectors. Fortunately enough, a possible site exists near CERN at the right distance and could house as soon as 2015 such a detector. CERN has a long lasting expertise on ion production and acceleration, and has announced officially to be site candidate for the Eurisol project.

This offers Europe and CERN a unique opportunity to contribute significantly to megaton physics, neutrino physics, and Eurisol physics by joining efforts of several communities on an ambitious and multidisciplinary project.

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