# SPL and Beta Beams to the Frejus

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Physics potential of a conventional neutrino beam generated by the 2.2 GeV, 4MW, Superconducting Proton Linac and of a Beta Beam fired to a gigantic water Čerenkov detector hosted below Frejus, 130 km away from CERN, are briefly summarized. $\theta_{13}$ sensitivity could be improved by up to 3 orders of magnitude with respect to the present experimental limit and a first sensitive search for leptonic CP violation could be performed.

## 1. Introduction

The CERN-Frejus project proposes the construction of a gigantic water Čerenkov detector, 440 kton fiducial (20 times SuperKamiokande), 130 km from CERN. Two different neutrino beams could be fired to the detector: a conventional neutrino beam generated by a 4MW, 2.2 GeV proton Linac, the SPL, and a Beta Beam. This project would have excellent sensitivity to $\theta_{13}$ and to the CP phase $\delta_{\rm CP}$ besides the water Čerenkov detector physics capabilities in its own, like ultimate sensitivities for proton decay, supernovae neutrinos, atmospheric neutrinos etc. [1].

It would be the natural follow up of T2K phase I [2], the first experiment optimized for $\theta_{13}$ searches through $\nu_e$ appearance, with a sensitivity 20 times better than the present experimental Chooz limit [3] but no sensitivity on $\delta_{\rm CP}$ .

In this paper will be summarized the physics potential of the SPL SuperBeam (SPL-SB), of the Beta Beam and of their combination.

## 2. SPL SuperBeam at CERN

The Super Proton Linac (SPL) is a proton driver designed to deliver 2mA of 2.2 GeV (kinetic energy) protons [4]. It could be the driver either of a Beta Beam or of a Neutrino Factory. Protons would be delivered to an accumulator, that could be hosted in the ISR tunnel, in order to have beam batches 23 ns long. Pions are produced by the interactions of the 2.2 GeV proton beam with a liquid mercury target [5] and focused with magnetic horns [6]. The resulting neutrino flux [6] has a neutrino energy $\langle E_\nu \rangle = 260$ MeV and the optimal baseline would be of about 100 km.

There are several advantages by running at such small $\nu$ energies. Given the relatively short baseline, matter effects are negligible and don't compete with leptonic CP violating effects. Protons are below the kaon production threshold, reducing $\nu_e$ backgrounds and the incertitudes related to their estimation. $\pi^\circ$ rejection is favored thanks to the wide $\gamma$s opening angle [1]. Charged current (CC) events are for the largest part quasi elastics, the event category best reconstructed in a water Čerenkov detector.

On the other hands cross sections are small at these energies and change very rapidly with energy. Antineutrino interaction rates are suppressed either because antineutrino/neutrino cross sections ratio is at a minimum: ($\simeq 1/4$) and because $\pi^-$ hadroproduction is disfavored at 2.2 GeV, [2]. Fermi motion prevents an accurate event energy reconstruction. Atmospheric neutrino backgrounds are severe because of the high flux below 0.5 GeV and the limited rejection factor provided by the poor angular resolution; this is the reason why an accumulator is needed downstream the proton driver to keep the duty cycle low. Given the baseline, sign($\delta m^2$) cannot be measured. It should be noted that CC rates

[1]Indeed better rejections than T2K (running at $\langle E_\nu \rangle \simeq$ 0.8 GeV) can be obtained for signal efficiencies greater by about a factor 2.

[2]To compensate that, 2 years of $\nu_\mu$ and 8 years of $\overline{\nu}_\mu$running must be planned for the leptonic CP violation searches.

generated by the SPL SuperBeam at the optimal baseline, 41 CC events/kton/year, are smaller than T2K phase I rates, $\sim 100$ events/kton/year, the driver of T2K (50 GeV) having 6 times less power.

SPL SuperBeam performances have been computed in [7] for a counting experiment (it has been shown in a recent paper [8] that energy reconstruction may be used at the SPL-SB energies having beneficial effects). $\theta_{13}$ sensitivity is shown in figure 2, while $\delta_{\rm CP}$ discovery potential ($3\sigma$) is shown in figure 3. These plots don't take into account the sign($\delta m^2$) and $\pi/2 - \theta_{23}$ ambiguities, for a computation of SPL-SB sensitivities having them included see reference [9].

SPL energy, 2.2 GeV, was originally fixed having in mind the re-usage of LEP RF cavities. More modern cavities could allow higher energies. In a recent paper [10], $\theta_{13}$ sensitivities as function of the proton beam energy, keeping fixed the power of the machine and the experimental baseline, have been computed. At an energy of 3.5 GeV, and focusing higher momentum pions, most of the weak points of the SPL-SB are cured: hadroproduction becomes more favorable and an higher energy neutrino beam can be produced ($\langle E_\mu \rangle \simeq 350$ MeV) allowing for a moderate energy binning (200 MeV/bin). CC interaction rate would be raised from 41 to 122 events/kton/year, [3]. Performances in this new configuration (SPL-SB 3.5GeV) are shown in figure 2 and 3. [4]

## 3. Beta Beams

Beta Beams ($\beta$B) have been introduced by P. Zucchelli in 2001 [11]. The idea is to generate pure, well collimated and intense $\nu_e$ ($\overline{\nu}_e$) beams by producing, collecting, accelerating radioactive ions and storing them in a decay ring in 10 ns long bunches, to suppress the atmospheric neutrino backgrounds. This approach overcomes the limitations of conventional neutrino beams: $\beta B$ would be virtually background free and fluxes could be easily computed by the properties of the beta decay of the parent ion and by its Lorentz boost factor $\gamma$.

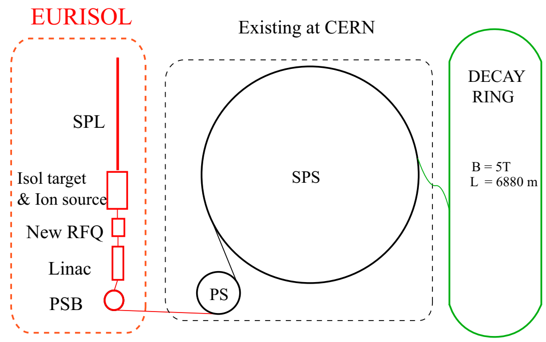


Figure 1. Schematic layout of the Beta Beam complex. At left, the low energy part is largely similar to the EURISOL project [13]. The central part (PS and SPS) uses existing facilities. At right, the decay ring has to be built.

The best ion candidates so far are $^{18}Ne$ and $^{6}He$ for $\nu_e$ and $\overline{\nu}_e$ respectively. A baseline study for a Beta Beam complex has been produced at CERN [12] and shown schematically in figure 1. In this scenario Beta Beam neutrino energies are below 0.5 GeV and the ideal detector technology would be again water Čerenkov.

The reference $\beta$B fluxes are $2.9 \cdot 10^{18}$ $^6$He useful decays/year and $1.1 \cdot 10^{18}$ $^{18}$Ne decays/year. The SPS could accelerate $^6$He ions at a maximum $\gamma$ value of $\gamma_{^6{\rm He}} = 150$ and $^{18}$Ne ions up to $\gamma_{^{18}{\rm Ne}} = 250$. In the baseline scenario the two ions circulate in the decay ring at the same time. This is feasible provided that their $\gamma$ are in the ratio $\gamma_{^6{\rm He}}/\gamma_{^{18}{\rm Ne}} = 3/5$. The same fluxes can be obtained by running the two ions separately [14]. This allows a better optimization of the physics potential of the machine [15].

The baseline scenario physics potential has been computed in [16] for $\gamma_{^6{\rm He}} = 60$, $\gamma_{^{18}{\rm Ne}} = 100$, see figure 2 and 3. In the same plots performances computed with both ions at $\gamma = 100$, exploiting energy shape information (200 MeV/bin), are also displayed ($\beta{\rm B}_{100,100}$), with a clear gain in sensitivity. The overall optimization and the assesment of the physics potential of the baseline Beta Beam will be the argument of forthcoming papers. Sensitivities taking into account all the parameter degeneracies and ambiguities have been computed in [9].

$\beta$B and SPL-SB are perfectly compatible both

[3] This improvement includes a longer (20m to 40m) and wider (1m diameter to 2m) decay tunnel.

[4] $\theta_{13}$ sensitivity of figure 2 is better than what quoted in [10] because it is computed taking into account the energy information.

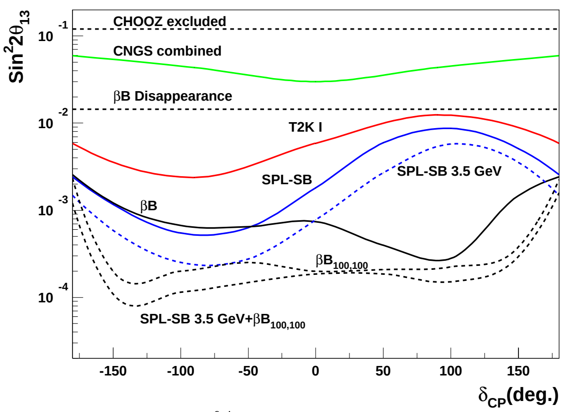


Figure 2. $\theta_{13}$ 90%CL sensitivity as function of $\delta_{\rm CP}$ for $\delta m^2_{23} = 2.5 \cdot 10^{-3} eV^2$, sign($\delta m^2$) $= 1$, 2% systematic errors. SPL-SB sensitivities have been computed for a 5 years $\nu_\mu$ run, $\beta$B for a 5 years $\nu_e$+ $\overline{\nu}_e$ run.

in terms of SPL proton economics and in terms of optimal baseline. The same detector could then be exposed to 2×2 beams ($\nu_\mu$ and $\overline{\nu}_\mu$ × $\nu_e$ and $\overline{\nu}_e$) having access to CP, T and CPT searches in the same run. Physics potential of this combination of beams is illustrated in figure 2 and 3.

## 4. Conclusions

The CERN Frejus project covers several important physics themes, ranging from the very deep synergies with EURISOL, aiming at producing high intensity radioactive beams for nuclear physics studies, to the excellent physics capabilities of the megaton detector in its own.

Two beams can be designed for this project allowing for a significant improvement of the T2K phase I $\theta_{13}$ sensitivity and for the first sensitive search of leptonic CP violation. In particular Beta Beams could offer a very clean and elegant environment with a $\theta_{13}$ sensitivity ∼ 30 times better than T2K phase I (for $\delta_{\rm CP} = 0$) and a 3 $\sigma$ $\delta_{\rm CP}$ discovery potential for $\delta_{\rm CP}$ bigger than $\sim 25°$ provided that $\sin^2\theta_{13} > 10^{-4}$ ($\theta_{13} > 0.6°$).

The combination of a Beta Beam with the SPL-SB could address leptonic CP and T violation and could also explore CPT violation in neutrino oscillations.

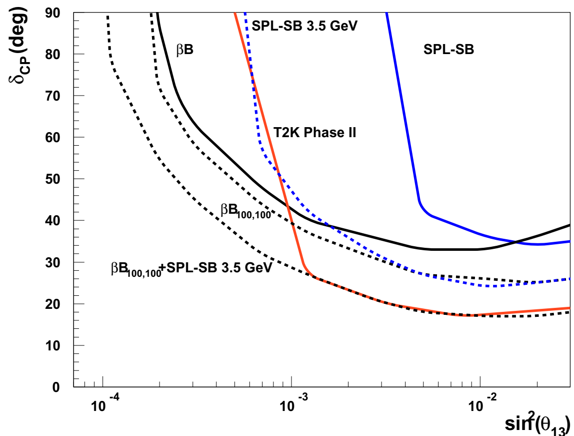


Figure 3. $\delta_{\rm CP}$ discovery potential at $3\sigma$ (see text) computed for a 10 years run, 2% systematic errors. T2K phase II curve is taken from [17].

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