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Beta Beam

Summary:
- Optimization.
- Sensitivity to $\theta_{13}$ and $\delta$
- Comparison with the Neutrino Factory.


Nufact 03, New York, July 5-11, 2003
M. Lindroos and collaborators, see http://beta-beam.web.ch/beta-beam

Decay

Ring

B \rho = 1500 \text{Tm}
B = 5 \text{T}
L = 2500 \text{ m}

EURISOL

Decay ring

Isol target & Ion source

LINAC 3

LINA

C

3

PSB

Existing at CERN

SPS

PS

• 1 ISOL target to produce He\(^6\), 100 \(\mu\text{A}\), \(\Rightarrow 2.9 \cdot 10^{18}\) ion decays/straight session/year. \(\Rightarrow \bar{\nu}_e\).

• 3 ISOL targets to produce Ne\(^{18}\), 100 \(\mu\text{A}\), \(\Rightarrow 1.2 \cdot 10^{18}\) ion decays/straight session/year. \(\Rightarrow \nu_e\).

• The 4 targets could run in parallel, but the decay ring optics requires:

\[\gamma(\text{Ne}^{18}) = 1.67 \cdot \gamma(\text{He}^6).\]
Fiducial volume: 440 kton: 20 times SuperK.
60000 PMTs (20") in the inner detector, 15000 PMTs in the outer veto detector.
Energy resolution is poor for multitrack events but quite adequate for sub-GeV neutrino interactions.
It would be hosted at the Frejus laboratory, 130 km from CERN, in a $10^6 \, m^3$ cavern to be excavated.

The
killer detector for proton decay, atmospheric neutrinos, supernovae neutrinos.
### Fluxes

- **SPL $\nu_\mu$**
- **SPL $\bar{\nu}_\mu$**
- **Beta $\bar{\nu}_e$ (He$^6$)**
- **Beta $\nu_e$ (Ne$^{18}$)**

### CC Rates

- **SPL $\nu_\mu$**
- **SPL $\bar{\nu}_\mu$**
- **Beta $\bar{\nu}_e$ (He$^6$)**
- **Beta $\nu_e$ (Ne$^{18}$)**

### Table: Fluxes @ 130 km

<table>
<thead>
<tr>
<th></th>
<th>$\nu/m^2/yr$</th>
<th>$&lt;E_\nu&gt;$ (GeV)</th>
<th>CC rate (no osc) events/kton/yr</th>
<th>$&lt;E_\nu&gt;$ (GeV)</th>
<th>Years</th>
<th>Integrated events (440 kton $\times$ 10 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SPL Super Beam</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>4.78 $\cdot$ 10$^{11}$</td>
<td>0.27</td>
<td>41.7</td>
<td>0.32</td>
<td>2</td>
<td>36698</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>3.33 $\cdot$ 10$^{11}$</td>
<td>0.25</td>
<td>6.6</td>
<td>0.30</td>
<td>8</td>
<td>23320</td>
</tr>
<tr>
<td><strong>Beta Beam</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{\nu}_e$ ($\gamma = 60$)</td>
<td>1.97 $\cdot$ 10$^{11}$</td>
<td>0.24</td>
<td>5.2</td>
<td>0.28</td>
<td>10</td>
<td>28880</td>
</tr>
<tr>
<td>$\nu_e$ ($\gamma = 100$)</td>
<td>1.88 $\cdot$ 10$^{11}$</td>
<td>0.36</td>
<td>39.2</td>
<td>0.43</td>
<td>10</td>
<td>172683</td>
</tr>
</tbody>
</table>

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Beta Beam Backgrounds

Compared with a full simulation and reconstruction program. (Nuance + Dave Casper).

\[ \pi \text{ from NC interactions} \]

The main source of background comes from pions generated by resonant processes ($\Delta^{++}$ production) in NC interactions.

Pions cannot be separated from muons.

However, the threshold for this process is $\approx 400 \text{ MeV}$.

Angular cuts have not been considered.

\[ e/\mu \text{ mis-identification} \]

The full simulation shows that they can be kept well below $10^{-3}$ applying the following criteria:

- One ring event.
- Standard SuperK particle identification with likelihood functions.
- A delayed decay electron.

\[ \text{Atmospheric neutrinos} \]

Atmospheric neutrino background can be kept low only by a very short duty cycle of the Beta Beam. A reduction factor bigger than $10^3$ is needed.

This is achieved by building 10 ns long ion bunches.
Optimizing the Lorentz Boost $\gamma$ (L=130 km): preferred values: $\gamma = 55 \div 75$

Higher $\gamma$ produce more CC interactions
More collimated neutrino production and higher cross sections.

![Graph showing CC Rate vs. $\gamma$]

Background rate rises much faster than CC interactions
From resonant pion production in $\nu_e$ NC interactions

$\nu$ flux must match the CP-odd oscillating term

Detection efficiency as function of $\nu$ energy

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Other sources of errors

Systematic errors: Beta Beam is the ideal place where to measure neutrino cross sections

- Neutrino flux and spectrum are completely defined by the parent ion characteristics and by the Lorentz boost $\gamma$.
- Only one neutrino flavour in the beam. in the storage ring.
- You can scan different $\gamma$ values starting from below the $\Delta$ production threshold.
- A close detector can then measure neutrino cross sections with unprecedent precision

A 2% uncertainty level on the systematics will be assumed in the following.

Errors on the other parameters

$p(\nu_\mu \rightarrow \nu_e)$ depends from all the mixing matrix parameters: errors on parameters influence the sensitivity of a CP search.

At the time of BetaBeam

- JHF will have measured $\delta m_{23}^2$ with a $\sim$ 10% resolution and $\sin^2 2\theta_{23}$ with $1 \div 2$ % resolution.
- Solar LMA parameters measured at $\sim$ 10% precision level by Kamland (after 3 years, see hep-ph/0107277).

Only diagonal contributions from $\delta m_{23}^2$, $\delta m_{12}^2$ and $\sin^2 \theta_{12}$ will be taken into account. Their contribution is anyway marginal.

Statistical method

If the number of events is greater than 12 use the classical gaussian chi2 with all the systematics included. If lower use the Poisson chi2, no systematic included. Given the above errors this approximation is largely acceptable.
The SuperBeam - BetaBeam synergy: CP, T and CPT

No other realistic scenario can offer CP, T and CPT searches at the same time in the same detector!!!!

**CP Searches**

- SuperBeam running with $\nu_\mu$ and $\bar{\nu}_\mu$.
- Beta Beam running with $^6\text{He}$ ($\bar{\nu}_e$) and $^{18}\text{Ne}$ ($\nu_e$).

**T searches**

- Compare Super Beam $p(\nu_\mu \rightarrow \nu_e)$ with Beta Beam $^{18}\text{Ne}$ $p(\nu_e \rightarrow \nu_\mu)$.
- Compare Super Beam $p(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ with Beta Beam $^6\text{He}$ $p(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$.

**CPT searches**

- Compare Super Beam $p(\nu_\mu \rightarrow \nu_e)$ with Beta Beam $^6\text{He}$ $p(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$.
- Compare Super Beam $p(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ with Beta Beam $^{18}\text{Ne}$ $p(\nu_e \rightarrow \nu_\mu)$.
The SuperBeam - BetaBeam synergy: a benchmark on $\theta_{13}$ sensitivity

Computed for $\delta_{CP} = 0$ and 5 years running.

- Super Beam $\rightarrow 96 \times$ CHOOZ.

- Super Beam + Beta Beam $\rightarrow 160 \times$ CHOOZ.

- Beta Beam can measure $\theta_{13}$ both in appearance and in disappearance mode. All the ambiguities can be removed for $\theta_{13} \geq 3.4^\circ$
Beta Beam - Super Beam synergy: CP sensitivity

\[ \delta m_{12}^2 = 7 \cdot 10^{-5} \, eV^2, \quad \theta_{13} = 1^\circ, \quad \delta_{CP} = \pi/2 \]

<table>
<thead>
<tr>
<th></th>
<th>SuperBeam</th>
<th>Beta Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ \nu_\mu ]</td>
<td>[ \bar{\nu}_\mu ]</td>
<td>[ \bar{\nu}_e (He^{6}) ]</td>
</tr>
<tr>
<td>(2 yrs)</td>
<td>(8 yrs)</td>
<td>[ \gamma = 60 ]</td>
</tr>
<tr>
<td>CC events (no osc, no cut)</td>
<td>36698</td>
<td>23320</td>
</tr>
<tr>
<td>Total oscillated</td>
<td>1.7</td>
<td>33.3</td>
</tr>
<tr>
<td>CP-Odd oscillated</td>
<td>-25.5</td>
<td>16.9</td>
</tr>
<tr>
<td>Beam backgrounds</td>
<td>141</td>
<td>113</td>
</tr>
<tr>
<td>Detector backgrounds</td>
<td>37</td>
<td>50</td>
</tr>
<tr>
<td>Statistical Error</td>
<td>13.4</td>
<td>13.6</td>
</tr>
<tr>
<td>Error on [ \theta_{23} ]</td>
<td>2.1</td>
<td>1.7</td>
</tr>
<tr>
<td>Error on [ \delta m_{12}^2 ]</td>
<td>2.8</td>
<td>1.9</td>
</tr>
<tr>
<td>Total Error</td>
<td>13.9</td>
<td>14.6</td>
</tr>
</tbody>
</table>

M. Mezzetto, “Beta Beam”, NUFAC03, Columbia University, NY, 5-11 July 2003
• The asymmetric statistics and background rates in the $\nu_e$ and $\bar{\nu}_e$ beams produce an asymmetric response to the positive and negative values of $\delta$.

• Even if the matter effects are negligible, the $p(\nu_\mu \rightarrow \nu_e)$ formula contains odd $\text{sign}(\delta m^2_{13})$ terms.

• The change of $\text{sign}(\delta m^2_{13})$ produces non negligible changes in the oscillation formula. No attempt made so far to fit $\text{sign}(\delta m^2_{13})$, $\theta_{13}$ and $\delta$ at the same time.

• Results are shown in the following for positive values of $\delta$ and $\text{sign}(\delta m^2_{13})$.
  - $\sin^2 2\theta_{23} = 1.0$
  - $\delta m^2_{23} = 2.5 \cdot 10^{-3} \text{ eV}^2$
  - $\sin^2 2\theta_{12} = 0.8$
A comparison of CP sensitivities: Beta Beam vs. Nufact

CP sensitivity, defined as the capacity to separate at 99%CL max CP ($\delta = \pi/2$) from no CP ($\delta = 0$).

Nufact sensitivity as computed in J. Burguet-Castell et al., Nucl. Phys. B 608 (2001) 301:

- 50 GeV/c $\mu$.
- $2 \cdot 10^{20}$ useful $\mu$ decays/year.
- 5+5 years.
- 2 iron magnetized detectors, 40 kton, at 3000 and 7000 km.
- Full detector simulation, including backgrounds and systematics.

\[ \Delta m_{12}^2 (x10^{-4}) \text{ eV}^2 \]

\[ \sin^2 \theta_{13} \]

- Nufact
- SPL SuperBeam
- Beta Beam
- SB+BB, 440 kton
- SB+BB, 1 Mton

Best LMA, hep-ph/0212127
Some comments about the comparison

The sensitivity computation depends from many implicit assumptions, input parameters, degeneracy treatment, statistical methods, tricks, bugs etc.

A fair comparison should be made by the same group using the same methods for the different facilities (a call for collaboration ...)

The plot doesn’t tell anything about the fits in a arbitrary $(\theta_{13}, \delta)$ point.

The small $\theta_{13}$ region is particularly delicate: going the absolute probabilities down to zero, it’s very sensitive to:

- Background levels.
- Statistical treatment of data
- Input parameters and their errors.

In the large $\theta_{13}$ region the CP asymmetry is small. This favours the Super-Beta Beams, because they don’t have to compete with matter effects.

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Conclusions

Beta Beam is a (CERN based) realistic facility that could profit of very deep synergies with:
- Nuclear physicists aiming at a very intense source of radioactive ions.
- A gigantic water Cerenkov detector with great physics potential in its own.

The Super-Beta Beams combination can address $\delta_{CP}$ discovery with a sensitivity similar to the Neutrino Factory having the distinctive possibility of:
- Combine CP, T and CPT searches
- Use $\nu_e$ disappearance to solve all the ambiguities for reasonable large values of $\theta_{13}$.

The Super-Beta Beams combination cannot compete with the Neutrino Factory in measuring $\text{sign}(\delta m_{13}^2)$ or matter effects (however, if you are focused in Leptonic CP, this is an advantage.)

If a gigantic water Cerenkov detector will be built in the world, CERN-Frejus could offer it an excellent combination of beams and a very deep site.