Optimizing the green-field beta beam: Small versus large $\theta_{13}$

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We discuss the optimization of a green-field beta beam in terms of baseline, boost factor, luminosity, and isotope pair used. We identify two qualitatively different cases: $\theta_{13}$ not discovered at the time a decision has to be made ($\theta_{13}$ small), and $\theta_{13}$ discovered at that time ($\theta_{13}$ large). For small $\theta_{13}$, it turns out that the obtainable sensitivity is essentially a matter of the effort one is willing to spend. For large $\theta_{13}$, however, one can find clear optimization criteria, and one can use the information on $\theta_{13}$ obtained until then.

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Beta beams [1–5] produce a neutrino beam by the decay of radioactive isotopes in straight sections of a storage ring. They have been studied in specific scenarios from low to very high γ’s [6–17]. In this talk, we discuss the green-field optimization of a beta beam, as it has been performed in Refs. [18–20]. Hereby, “green-field scenario” means that no specific accelerator, baseline $L$, boost factor $\gamma$, or isotope pair ($^{18}\text{Ne}, ^{6}\text{He}$) or ($^{8}\text{B}, ^{8}\text{Li}$) is assumed. We will typically assume $1.1 \times 10^{18}$ useful ion decays/year for neutrinos and $2.9 \times 10^{18}$ useful ion decays/year for anti-neutrinos, where the experiment is operated five years in the neutrino mode and five years in the antineutrino mode. In addition, we use a 500kt (fiducial mass) water Cherenkov detector or a 50kt (fiducial mass) magnetized iron calorimeter. These standard numbers will be referred to as a luminosity scaling factor $\mathcal{L} = 1$, which depends on the detector technology used. Note that $\mathcal{L}$ scales the number of useful ion decays/year $\times$ running time $\times$ detector mass $\times$ detector efficiency.

The goal will be to optimize the free parameters (such as isotope pair, luminosity, $L$, and $\gamma$) for the best physics potential. Note that we only discuss two specific detector technologies for the sake of simplicity here.

For a qualitative discussion of the beta beam spectrum, note that the peak energy is approximately given by $\gamma \cdot E_0$ and the maximum energy is approximately given by $2 \cdot \gamma \cdot E_0$, where $E_0$ is the endpoint energy of the decay. The total flux, on the other hand, is approximately proportional to $N_\beta \cdot \gamma^2$, where $N_\beta$ is the number of useful ion decays. Comparing different isotope pairs with different endpoint energies, one can relate these to each other by postulating a similar spectrum, leading to the same cross sections, baseline, physics (such as the MSW effect), etc.. Obviously, one can either use isotopes with lower endpoint energy and a higher $\gamma$, or vice versa. If one in addition requires a similar total flux, one obtains from the above relations that

$$\frac{N_\beta^{(1)}}{N_\beta^{(2)}} \simeq \left( \frac{E_0^{(1)}}{E_0^{(2)}} \right)^2, \quad \frac{\gamma^{(1)}}{\gamma^{(2)}} \simeq \frac{E_0^{(2)}}{E_0^{(1)}},$$

where 1 and 2 refer to the different isotope pairs. Since $E_0$ for ($^{8}\text{B}, ^{8}\text{Li}$) is about a factor of 3.5 higher (in average) than that of ($^{18}\text{Ne}, ^{6}\text{He}$), we have

$$N_\beta^{(8\text{B}, 8\text{Li})} \simeq 12 \cdot N_\beta^{(18\text{Ne}, 6\text{He})}, \quad \gamma^{(18\text{Ne}, 6\text{He})} \simeq 3.5 \cdot \gamma^{(8\text{B}, 8\text{Li})}$$

in order to have a similar physics output. Note that $N_\beta$ is (primarily) a source degree of freedom, whereas $\gamma$ represent the acceleration effort, it is not clear which of these two conditions dominate, and which isotope pair will be preferred in a green-field setup.

Let us first of all discuss beta beams for small $\theta_{13}$, where we refer to “small $\theta_{13}$” as values of $\theta_{13}$ not yet discovered by the reactor experiments and first generation superbeams. In this case, we optimize in the $\theta_{13}$ direction, which means that we require sensitivity to $\theta_{13}$, the mass hierarchy (MH), and CP violation (CPV) for as small as possible $\theta_{13}$. There are, however, two unknowns in this optimization. First of all, it is unclear for which values of (true) $\delta_{\text{CP}}$ such an optimization should be performed. And second, how small $\theta_{13}$ is actually good enough? It turns out that, to a first approximation, the higher the $\gamma$, the better [18], unless the detector technology runs into its limitations. In addition, the higher the luminosity, the better, as it is illustrated in Fig. [19] for the $\sin^22\theta_{13}$ sensitivity for two different isotope pairs/$\gamma$’s, and two different baseline choices [19].
Figure 1: The $\sin^2 2\theta_{13}$ sensitivity (3$\sigma$) as a function of a luminosity scaling factor (see main text) for a 50kt iron calorimeter. The panels represent the different isotopes and different $\gamma$ as indicated in the captions. The green dashed-dotted curves correspond to the magic baseline “MB” with $L = 7500$km fixed, the red solid curves to a short baseline with an $L/\gamma$ depending on the isotope. A true normal hierarchy is assumed. Figure from Ref. [19].

Therefore, the minimal reachable $\theta_{13}$ is more or less a matter of cost, and it is not possible to clearly identify a minimal setup measuring the unknown quantities.

The optimal baseline depends for any specific scenario (specific luminosity, isotope pair, and $\gamma$) on the performance indicator. For example, CP violation in general prefers shorter baselines, whereas the mass hierarchy requires strong matter effects and therefore long baselines [18]. For the higher $\gamma$ options and, for instance, a iron calorimeter, two sets of suboptimal baselines can be identified [19]: A “short” baseline with $L/\gamma \simeq 0.8$ for ($^{18}$Ne, $^6$He) or $L/\gamma = 2.6$ for ($^8$B,$^8$Li), and the “magic” baseline $L \simeq 7500$km [21] to resolve correlations and degeneracies. With this detector, in principle, the MH is best measured with a ($^8$B,$^8$Li) beam at the magic baseline, whereas CPV is best measured with a ($^{18}$Ne, $^6$He) beam at the short baseline. For the $\sin^2 2\theta_{13}$ sensitivity and ($^8$B,$^8$Li), it turns out that the magic baseline performs better for $\gamma \gtrsim 350$, whereas below that value the shorter baseline performs better (for $L \gamma = 1$). For the ($^{18}$Ne, $^6$He) beam, one would prefer the short baseline in most of the cases. Note, however, that the baseline choice depends on statistics as well, as illustrated in Fig. 1 for two different isotope pairs and $\gamma$’s. If the luminosity is different from the nominal luminosity $L \gamma = 1$, the optimal baseline for $\theta_{13}$ indeed changes. The kink in these scalings comes from the resolution of degeneracies with a certain threshold statistics, whereas for the magic baseline, there are no such degeneracies a priori. One can also read off from Fig. 1 that Eq. (2) is satisfied: In this figure, the $\gamma$ is increased by a factor of about 3.5 from the left to the right panel, where ($^{18}$Ne, $^6$He) instead of ($^8$B,$^8$Li) is used. Indeed, one can read off from the kink at the short baseline, that for ($^{18}$Ne, $^6$He) about a factor of ten lower luminosity is required than for ($^8$B,$^8$Li). Note that the $L/\gamma$ for the shorter baselines are just related by the endpoint energy ratio.

Compared to the small $\theta_{13}$ case, in which one optimizes for $\theta_{13}$ reaches as good as possible, the minimum wish list for small $\theta_{13}$ from the physics point of view could be rather straightforward: A $5\sigma$ independent confirmation of $\sin^2 2\theta_{13} > 0$, a $3\sigma$ determination of the MH for any (true) $\delta_{CP}$, and
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Figure 2: Possible baseline range for a $^{18}\text{Ne},^6\text{He}$, left, or $^8\text{B},^8\text{Li}$, right, beta beam as a function of the luminosity scaling factor $L$ for a 500kt water Cherenkov detector. In these figures, $\gamma$ is fixed to 150 (left) and 170 (right), respectively. The baseline ranges are given for a Double Chooz best-fit $\sin^2 2\theta_{13} = 0.08$. The “sensitivity” for large $\theta_{13}$ is defined in the main text.

A $3\sigma$ establishment of CPV for 80% of all (true) $\delta_{CP}$. Since we have assumed that $\sin^2 2\theta_{13}$ has been measured, one can use this knowledge to optimize the experiment. Therefore, we postulate these sensitivities in the *entire remaining allowed* $\theta_{13}$ *range*, which means the range remaining after a $\sin^2 2\theta_{13}$ discovery (in fact, we assume the range after three years of Double Chooz operation [22]). In this case, one can approach the optimization of the experiment from different points of view. For example, in Ref. [20], an optimization in the $L$-$\gamma$ plane was performed to identify the minimal $\gamma$ for which the above performance indicators can be measured. It has turned out that a $\gamma$ as high as 350 might not be necessary [7]. The MH sensitivity typically imposes a lower bound on the baseline $L \gtrsim 500\text{km}$. The CPV sensitivity typically (for not too large luminosities) imposes a lower bound on $\gamma$. Compared to Ref. [20], one can also perform the optimization for a fixed $\gamma$. For instance, we show in Fig. 2 the possible baseline range for a $^{18}\text{Ne},^6\text{He}$ beam (left panel) and a $^8\text{B},^8\text{Li}$ beam (right panel) to a 500kt water Cherenkov detector for a fixed $\gamma = 150$ (left panel) and a fixed $\gamma = 170$ (right panel), respectively, as a function of the luminosity scaling factor $L$. These fixed $\gamma$’s correspond to the maximum which might be possible at the CERN SPS. As one can read off from this figure, $L = 1$ may not be sufficient for the $^{18}\text{Ne},^6\text{He}$ beam, especially since sensitivity is only given in a very small baseline window. However, if a $^8\text{B},^8\text{Li}$ beam was used with a slightly more (about a factor of two) better luminosity, which may, for instance, be achieved by using a production ring for the ion production, the required sensitivities might be achievable in a relatively wide baseline range $850\text{km} \lesssim L \lesssim 1350\text{km}$.

In summary, we have discussed the optimization of a green-field beta beam in terms of baseline, $\gamma$, luminosity, and isotopes used. If $\theta_{13}$ is not discovered at the time a decision for an experiment has to be made, the optimization might be primarily driven by $\sin^2 2\theta_{13}$ reaches as good as possible. In this case, there are no obvious criteria, such as a specific value of $\sin^2 2\theta_{13}$ which may be interesting, which means that the sensitivity is essentially a matter of how much effort one is willing to spend. For large $\theta$, i.e., if $\theta_{13}$ has been discovered, however, relatively objective criteria
for the optimization can be found, and the knowledge on $\theta_{13}$ can be used. In this case, a beta beam with a $\gamma$ reachable by the CERN SPS could be sufficient if ($^8$B,$^8$Li) with a sufficiently high luminosity was used.

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