We discuss a scenario to extract up to 150 MeV neutrinos at a standard beta-beam facility using one and two detectors off-axis. In particular we show that the high-energy component of the neutrino fluxes can be subtracted through a specific combination of the response of two off-axis detectors. A systematic analysis of the neutrino fluxes using different detector geometries is presented, as well as a comparison with the expected fluxes at a low-energy beta-beam facility. The presented option could offer an alternative way to perform low-energy neutrino experiments.

PACS numbers: 13.15.+g,14.60.Lm,23.40.Bw,29.90.+r

Keywords: Low-energy neutrino interactions, beta-beams, off-axis neutrino fluxes

I. INTRODUCTION

Low-energy neutrino sources play an important role in neutrino physics. Depending on the applications, one typically can choose between single-spectrum but intense, sources such as reactors, or multi-spectra sources with lower intensity such as the proposed low-energy beta-beam facilities. In such facilities one can study neutrino-nucleus interactions, fundamental neutrino properties, and perform various electroweak tests.

Low-energy neutrino-nucleus interactions are important in several contexts. The response of the chemical detectors to low-energy neutrino sources such as the Sun and supernovae is dependent on their neutrino capture cross sections. Neutrino-nucleus cross sections are an important ingredient in understanding various astrophysical phenomena, for example, the dynamics of the core-collapse supernovae [1], calculating the yields of the supernova r-process nucleosynthesis [2], and assessing the formation possibility of a black hole from the fossil abundances of the r-process elements [3]. These interactions are also an important input into models of gamma-ray bursts [4, 5] and their understanding is fundamental to the observation of neutrino signals from astrophysical sources [6, 7]. In particle physics, low-energy neutrinos can be used as probes to test the electroweak component of the Standard Model [8].

Low-energy beta-beam facilities first proposed in Ref. [9] yield pure beams of electron neutrinos or antineutrinos produced through the decay of radioactive ions circulating in a storage ring [10, 11]. Several applications utilizing low-energy beta-beams have been discussed in the literature concerning neutrino-nucleus scattering [12, 13, 14], electroweak tests of the Standard Model [15, 16, 17, 18, 19], as well as core-collapse supernova physics [3, 20].

An extensive analysis of the physics potential of a beta-beam facility is currently ongoing, in parallel with the feasibility design study. One of the primary goals of a standard beta-beam facility is to test CP-violation in the lepton sector. Currently, experiments are in the planning stage to measure the third mixing angle, \( \theta_{13} \), at reactors [21, 22]. Beta-beam facilities will be able to measure this angle as well as the associated CP-violating Dirac phase. Various scenarios for beta-beam facilities have been considered as far as the measurement of \( \theta_{13} \) and CP violation in the lepton sector is concerned [12, 13, 14, 16, 17, 18, 19, 20]. Lepton number violating interactions are discussed in Ref. [38] (for a review, see Ref. [11]).

In this paper we discuss an alternative to using low-energy beta-beams, namely the possibility of extracting low-energy neutrino fluxes emitted from a standard beta-beam facility, using a specific off-axis configuration. The basic idea here is that if a detector is placed away from the principal axis of the storage ring, it will detect the least energetic neutrinos emitted from the parent nucleus. We also explore possible geometries for such off-axis detectors. From the practical point of view, the proposed idea presents several attractive features. First it would not require a devoted storage ring as discussed in previous works [3, 12, 13, 16, 17, 18, 19, 20]. Second, specific beamtime would not be needed since one would exploit the neutrino beams planned for CP violation studies. Third, one would benefit from their good duty cycle that would help reducing the atmospheric background.

---

*Electronic address: lazauska@lpsc.in2p3.fr
†Electronic address: baha@physics.wisc.edu
‡Electronic address: jjesus@physics.wisc.edu
§Electronic address: volpe@ipno.in2p3.fr
The main body of this paper is Section II. In this section we derive the formulas and discuss the neutrino flux profiles for three different scenarios: the original low-energy beta-beam scenario, used as reference (Section II A); one off-axis detector in a standard beta-beam facility (Section II B); and two off-axis detectors in a standard beta-beam facility (Section II C). A discussion of our results is then given in Section III.

II. NEUTRINO FLUX PROFILES

Zucchelli first proposed the idea to use boosted radioactive ions as a new method to produce pure, collimated and well known electron (anti)neutrino fluxes [10]. The ions are stored in a storage ring where they decay. To get the fluxes one needs to integrate over the storage ring straight sections and the volume of the detector. The average neutrino flux at the detector is therefore given by (the precise formalism can be found in [12] and also in [39])

$$\tilde{\Psi}_{\text{tot}}(E_\nu) = f \tau \int_0^Z \frac{dl}{L} \int_V \frac{\Psi_{\text{lab}}(E_\nu, \vec{r})}{4\pi r^2} dV,$$

(1)

where $L$ is the total and $Z$ is the straight section lengths of the storage ring. In the stationary regime, the mean number of ions in the storage ring is $\gamma \tau f$, where $\tau = t_{1/2}/\ln 2$ is the lifetime of the parent nucleus and $f$ is the number of injected ions per unit time. In Eq. (1), the integration is performed over the detector volume $V$ and the nearest storage ring straight section, with $\vec{r}$ being the vector connecting two points in the storage ring and the detector.

Using Eq. (1), the total number of events per unit time with energies up to $E_{\text{max}}$, in the detector, is

$$dN/dt = n \int_0^{E_{\text{max}}} \tilde{\Psi}_{\text{tot}}(E_\nu) \sigma(E_\nu) dE_\nu,$$

(2)

with $n$ being the number of target particles per unit volume and $\sigma(E_\nu)$ the cross section.

The calculations we present are performed assuming parameters from the currently ongoing feasibility study [40, 41]. For the original beta-beam scenario, we assume a storage ring of total length $L = 6580$ m with straight sections of length $Z = 2501$ m. The $^{6}\text{He}$ expected intensity to produce antineutrino fluxes is $f = 2.53 \times 10^{13}$ ions/s. For the low-energy beta-beam, we consider $L = 1885$ m and $Z = 678$ m with $f = 2.65 \times 10^{12}$ ions/s [42]. It is important to emphasize that these ion intensities come from the first feasibility study and are very preliminary. In particular, a new production method has been proposed recently which might give increased intensities [43].

A. Reference scenario: the low-energy beta-beam facility

The idea of a low-energy beta-beam facility producing neutrinos in the 100 MeV energy range has been first proposed in [6]. The disposal of a devoted storage ring would probably be the ideal tool for low-energy neutrino physics [12]. The potential of such a facility has been stressed in several papers [3, 13, 14, 16, 17, 18, 19, 20]. In Table I we summarize the characteristics of the corresponding fluxes for the case of antineutrinos resulting from the decay of $\gamma = 7$ and $\gamma = 14$ $^{6}\text{He}$ ions. The maximal energy of the neutrinos in these cases are 55 MeV and 100 MeV, respectively.

We consider a cylindrical detector with $r = 4.5$ m (radius) and $h = 15$ m (depth), placed 10 m from the end of the straight section, as done in Refs. [13, 17].

| $\gamma$ | $\langle E \rangle$ | $\Gamma(E)$ | $E_{\text{max}}$ | $\Psi_{\text{max}}$ | $N_{\text{ev}}$ |
|---------|-----------------|-------------|-----------------|-----------------|-------------|
| 7       | 22.8            | 17.1        | 20.7            | 24.5            | 5782        |
| 14      | 42.6            | 19.9        | 37.0            | 28.4            | 42393       |

TABLE I: Average energy, energy dispersion $\Gamma(E) = (\langle E^2 \rangle - \langle E \rangle^2)^{1/2}$, peak-energy evaluated at $\Psi_{\text{max}}$ and peak-flux ($/10^9$) at a cylindrical detector placed 10 m away from a low-energy beta-beam running $^{6}\text{He}$ ions at $\gamma = 7$ and $\gamma = 14$. $N_{\text{ev}}$ gives the number of events for one year ($3 \times 10^7$ s) for the anti-neutrino scattering on protons from Eq. (2) considering water as a target material. Energies are in units of MeV, the flux in units of m MeV$^{-1}$s$^{-1}$.

1 The calculations presented in this paper are for antineutrinos only. However, they are also valid for neutrinos emitted at beta-beam facilities. In what follows, we refer to neutrinos as a generic term.
B. Off-axis neutrino fluxes at a standard beta-beam facility

Let us now consider the possibility of extracting low-energy neutrinos from the standard beta-beam facility \[10\], where ions are boosted at \( \gamma = 60 - 100 \) and the neutrinos produced with energies up to \( 600 \) MeV. The accelerated ions emit the highest energy neutrinos along the boost direction. Therefore, by placing the detector off the storage ring straight section axis (Figure 1), one gets rid of the highest energy component of the neutrino flux. The idea of off-axis neutrino beams was first proposed in \[44\]. The highest energy neutrinos reaching the point \( D \) in Fig. 1 will be emitted from the most distant point in the storage ring straight section (point \( A \)). If one wishes that only neutrinos with energy less or equal to \( E_{\text{cut}} \) arrive at point \( D \), the angle \( \theta = \angle ADO \) has to satisfy the condition

\[
\theta = \arccos \left( \frac{\gamma - (Q - m_e)/E_{\text{cut}}}{\sqrt{\gamma^2 - 1}} \right),
\]

where \( Q \) is the \( Q \)-value of the reaction. The actual location of the detector depends on the desired antineutrino cut-off energy.

In Figure 2, we compare the off-axis antineutrino fluxes evaluated at point \( D \) of Fig. 1 for two different ion boosts and neutrino energy cuts. The neutrino flux from a low-energy beta-beam (le) at \( \gamma = 14 \) is shown for comparison.

In Figure 2 we compare the off-axis antineutrino fluxes evaluated at point \( D \), which lies on the perpendicular to the storage ring straight section derived from the turning point \( O \) (\( x = 0 \); see Fig. 1). The distance \( y = AD = AO \cdot \tan \theta \)

\[\text{Note that the corresponding storage ring can not be used to store ions with low } \gamma, \text{ considered in Sec. II A.}\]
is determined using Eq. (3) and by constraining the maximum energy of the neutrinos ($E_{\text{cut}}$) reaching that point. The presented results correspond to the cases where the $^6\text{He}$ ions are boosted at $\gamma = 60$ and $\gamma = 100$, and when $E_{\text{cut}}$ is set to 100 and 150 MeV. In particular, if $\gamma = 60$ and $E_{\text{cut}} = 100$ MeV, the distance $y$ is 74.7 meters (Fig. 1). If the ions are stored at $\gamma = 100$, $y$ reduces to 61.4 meters, since the neutrino beam is more collimated. The main characteristics of such fluxes are summarized in Tables II and III. In order to compare these results with the low-energy beta-beam fluxes of Table I, the values of $\bar{\Psi}_{\text{max}}$ and $N_{\nu}$ are normalized by the same detector volume.

| $E_{\text{cut}}$ (MeV) | $\langle E \rangle$ | $\Gamma(E)$ | $E_{\text{max}}$ | $\bar{\Psi}_{\text{max}}$ | $N_{\nu}$ | $y$ (m) |
|------------------------|------------------|-------------|------------------|----------------|---------|---------|
| 100                    | 32.7             | 19.6        | 21.0             | 0.64           | 626     | 61.4    |
| 150                    | 49.6             | 29.5        | 32.5             | 1.03           | 2998    | 48.0    |

TABLE II: Same as Table I but for an off-axis flux at a point in space with coordinates $x = 0$ and $y$ such that the maximum energy of the neutrinos is $E_{\text{cut}}$ (value in the first column). The ions are boosted at $\gamma = 100$. Energies are in units of MeV, the flux in units of $\text{m MeV}^{-1}\text{s}^{-1}$.

| $E_{\text{cut}}$ (MeV) | $\langle E \rangle$ | $\Gamma(E)$ | $E_{\text{max}}$ | $\bar{\Psi}_{\text{max}}$ | $N_{\nu}$ | $y$ (m) |
|------------------------|------------------|-------------|------------------|----------------|---------|---------|
| 100                    | 32.9             | 19.7        | 21.4             | 0.70           | 693     | 74.7    |
| 150                    | 50.2             | 29.6        | 33.5             | 1.20           | 3512    | 56.0    |

TABLE III: Same as Table II but for $\gamma = 60$.

From Tables II and III, one can see that the off-axis antineutrino flux profiles are determined by the choice of $E_{\text{cut}}$ (which determines the angle $\theta$) and come out to be not very sensitive to the boost of the ions. Note, however, that $N_{\nu}$ is reduced by $10\%$ to $20\%$ when $\gamma$ changes from 100 to 60. The flux shapes are strongly asymmetric, centered at low energies, and have a long high-energy tail.

| $E_{\text{cut}}$ (MeV) | $\langle E \rangle$ | $\Gamma(E)$ | $E_{\text{max}}$ | $\bar{\Psi}_{\text{max}}$ | $N_{\nu}$ | $y$ (m) |
|------------------------|------------------|-------------|------------------|----------------|---------|---------|
| 100                    | 29.3             | 17.7        | 18.5             | 0.57           | 405     | 61.4    |
| 150                    | 43.6             | 26.3        | 28.0             | 0.87           | 1799    | 48.0    |

TABLE IV: Same as Table III but for a cylindrical detector with $r = 4.5$ m and $h = 15$ m.

Let us briefly discuss how the off-axis antineutrino flux changes close to the point D of Fig. 1. First, the flux is clearly symmetric with respect to a rotation around the straight section $AO$; it does not vary significantly along the line $AD$ for distances of order $y << AO$. Nevertheless, the flux is very sensitive to variations of the angle $\theta$ and reduces significantly once one moves away from the storage ring straight section. Therefore, in order to have the highest count rate at the detector, one should place it by aligning its longitudinal part with $AD$. In Tables V and VI we present the results for a cylindrical detector with $r = 4.5$ m and $h = 15$ m. One can see that taking into account the physical size of the detector reduces the flux at the peak only by about $10\%$; however, it strongly affects its high-energy tail and therefore the events count rate.

From these results, it is clear that both the off-axis flux at the peak intensity and the related number of events $N_{\nu}$ are considerably smaller – by factors of 20-100 – than those of the low-energy beta-beam option. Such drastic reduction clearly makes this option hardly realizable for low-energy neutrino physics applications, unless higher ion intensities are achieved.

### C. Alternative scenario: two off-axis detectors at a standard beta-beam facility

In order to remove the high-energy neutrinos from the flux, the off-axis detector should be placed relatively far away from the straight section ($y > 50$ m). This renders the intensities very low. It is worth noting that the neutrino

---

$^3$ This is the same detector geometry as considered in the low-energy beta-beam scenario of Section II A.
TABLE V: Same as Table III but for a cylindrical detector with $r = 4.5$ m and $h = 15$ m.

| $E_{\text{cut}}$ | $\langle E \rangle$ | $\Gamma(E)$ | $E_{\text{max}}$ | $\bar{\Psi}_{\text{max}}$ | $N_{\nu}$ | $y$ |
|-----------------|-----------------|-------------|-----------------|-----------------|---------|---|
| 100             | 30.3            | 18.2        | 19.5            | 0.63            | 497     | 74.7 |
| 150             | 45.6            | 27.1        | 30.2            | 1.05            | 2405    | 56.0 |

flux has almost the same energy dependence at any point along the $AD$ (Figure 1). Furthermore, the flux intensities along this line are inversely proportional to the distance from point $A$. However, if one gets closer to point $A$, the signal starts being contaminated by the high-energy neutrinos emitted from the bending part of the storage ring.

To overcome this difficulty, we introduce a novel technique which consists in comparing the response of two off-axis detectors, placed in a specific configuration close to the storage ring axis. By using the subtraction procedure described below, one is able to extract the low-energy antineutrino flux and gain one order of magnitude in the intensity.

Let us consider the neutrino fluxes in two points $D_1$ and $D_2$, as shown in Figure 3. We split the neutrino flux $\tilde{\Psi}_{D_1}(E_{\nu})$ in point $D_1$ in two parts: one component produced in the segment $AB$ of the storage ring, i.e. $\tilde{\Psi}_{D_1}^{(AB)}(E_{\nu})$, and the other produced in the segment $BO$, $\tilde{\Psi}_{D_1}^{(BO)}(E_{\nu})$. Since the triangles $ABD_1$ and $AOD_2$ are similar, the flux fraction $\tilde{\Psi}_{D_1}^{(AB)}(E_{\nu})$ in point $D_1$ is proportional to the neutrino flux $\tilde{\Psi}_{D_2}(E_{\nu})$ in point $D_2$:

$$\tilde{\Psi}_{D_1}^{(AB)}(E_{\nu}) = \tilde{\Psi}_{D_2}(E_{\nu}) \frac{AO}{AB}$$

(4)

The flux $\tilde{\Psi}_{D_1}^{(BO)}(E_{\nu})$ can be obtained combining the responses of the two detectors located in $D_1$ and $D_2$, by using the following subtraction procedure:

$$\tilde{\Psi}_{D_1}^{(BO)}(E_{\nu}) = \tilde{\Psi}_{D_1}(E_{\nu}) - \tilde{\Psi}_{D_2}(E_{\nu}) \frac{AO}{AB}$$

(5)

Note that this flux contains only neutrinos with energies less than $E_{\text{cut}}$, set by Eq. (3). The subtracted flux of Eq. (5) has a similar energy dependence as the flux at the point

$$x = AD_1 \cos \theta - AO,$$

$$y = AD_1 \sin \theta,$$

(6)

(7)

but its intensity is higher by a factor of $y/y_{D_1}$. In practice one will be subtracting the number of events measured by the two detectors. Therefore the subtracted number of events associated with the flux $\tilde{\Psi}_{D_1}^{(BO)}(E_{\nu})$ is obtained as follows:

$$N_{D_1}^{(BO)} = n \int dt \int \sigma(E_{\nu}) \tilde{\Psi}_{D_1}^{(BO)}(E_{\nu}) dE_{\nu} = N_{D_1} - N_{D_2} \frac{AO}{AB}$$

(8)

In Section II B  we found that a $y$-distance of 48 m to 75 m is required in order to get low-energy neutrinos from the off-axis flux (Figure 2 and Tables II and III). Here, the detector $D_1$ can be placed very close to the storage ring. This
implies a neutrino flux intensity enhancement by $\sim 10$. The position of the detector at $D_2$ with respect to the position of the detector at $D_1$ is fixed by the choice of the desired maximal neutrino energy ($E_{\text{cut}}$) of the subtracted flux. The same arguments are valid for the realistic, large size detectors: one should place two detectors having the same shape, but the detector in $D_2$ should have its linear dimensions larger by a factor of $OD_2/BD_1$ than the detector in $D_1$.

Once one considers a finite size detector, it is clear that the remote regions of the detector will see much fewer neutrinos than the regions close to the subtraction axis ($BD_1$ for the detector located at $D_1$, or $AD_2$ for the detector located at $D_2$). For large size detectors their shape and its orientation should play an important role. Probably the best detector geometry would be the long and thin, hollow inside, cone. For such a geometry, one will have the subtracted fluxes very similar to the ones shown in Figure 3 but with an intensity higher by $\sim y/y_{D_1}$. The cone-like detector geometry has been considered in a recent theoretical study [39]. Nevertheless, the technical realization of such detectors is expected to be difficult.

In order to show the sensitivity of the presented technique to the detector geometry, we now consider the neutrino fluxes at four large detectors, having standard shapes (spherical or cylindrical), whose dimensions are given in Table VI. All four detectors are taken to have the same volume; detector type $d_4$ also has the same shape as the reference detector of Section II A. In Figure 4 we compare the subtracted neutrino fluxes as well as differential number of events for the four detectors. The latter are obtained by using the subtracted fluxes multiplied by the anti-neutrino on proton cross sections from Eq. (8) and considering that the detectors are filled with water. The subtracted flux characteristics are given in Tables VII and VIII for two different ion boosts, i.e. $\gamma = 60, 100$ and neutrino maximum energy cuts (100 and 150 MeV). The cylindrical detectors are considered to be placed longitudinally along the subtraction axis ($BD_1$ for the detector located at $D_1$ or $AD_2$ for the detector located at $D_2$) as shown in Figure 3. In the case of spherical detectors, the center of the first one is placed at $x = R_{\text{det}}$ and $y = R_{\text{det}} + 5$ m. For the disc detector, the upper surface touches the subtraction axis and is inclined along it. One can see that the longest detector ($d_1$) picks the most neutrino flux: two times more than the spherical detector ($d_4$). The flux profile is even more asymmetric than for the single off-axis detector case (Figure 2). Note that the average energy is pushed towards much lower energies (around 10-20 MeV) compared to the low-energy beta-beam flux. The expected intensities are significantly higher than in the case of the single off-axis detector, but still a few times weaker than for the low-energy beta-beam discussed in Section II A.

We have also studied the sensitivity to the ion boosts and $E_{\text{cut}}$ choices as well as the $y$ distance from the storage ring. In Figure 5 we compare the subtracted fluxes and differential number of events for type-$d_1$ detectors, when one is placed at $y = 5$ m from the storage ring straight section and its twin detector is placed in such a way that the subtracted neutrino flux is either $E_{\text{cut}} = 100$ MeV or 150 MeV. The ions in the storage ring are considered to be boosted to $\gamma = 100$ and 60 (Tables VII and VIII). One can see that for large size detectors, a lower ion boost is advantageous. For example, one gains more than 30% in intensity by reducing the boost from 100 to 60. Figure 6 shows how the subtracted flux intensities and the differential numbers of neutrino events vary by placing the detector at different distances from the storage ring (the closest points are $y = 5$, 7.5 and 10 m away from the storage ring, respectively). If the detector has a small size compared to $y$, the subtracted intensity should scale as $1/y$. On the

---

**FIG. 4**: Comparison of the different low-energy neutrino fluxes (left panel) and the corresponding number of antineutrino-hydrogen events for the water detectors (right panel). The presented results are obtained for a standard beta-beam exploiting two detectors off-axis (Figure 3) and the subtraction method described in the text (these fluxes are multiplied by 6). The different curves correspond to four different detector geometries, namely the cylinder-sausage ($d_1$), the cylinder-normal ($d_2$), the cylinder-disc ($d_3$), and the spherical (Table VII). As a comparison, the fluxes from a low-energy beta-beam (le), and for a single off-axis detector $d_2$ as described in Section II B (HE), are given. The last flux is multiplied by 20.
other hand, for the large detector we consider one gains much less in intensity by placing it closer to the straight section (e.g. \(y = 10\) and \(y = 5\) m fluxes differ only by 50%).

\[
\begin{array}{cccc}
\gamma = 100 & \langle E \rangle & \Gamma(E) & E_{\text{max}} \\
\gamma = 60 & \langle E \rangle & \Gamma(E) & E_{\text{max}} \\
\end{array}
\]

\[
\begin{array}{ccccccccc}
d_1 & 21.3 & 18.5 & 13.50 & 4.42 & 1.9(6) & 2487 & 1949 & 28.7 & 19.1 & 15.0 & 6.09 & 8.9 (5) & 4013 & 1334 \\
d_2 & 20.4 & 14.7 & 9.32 & 3.36 & 5.4(5) & 879 & 1039 & 21.4 & 15.1 & 10.3 & 4.60 & 2.7(5) & 1363 & 735 \\
d_3 & 39.0 & 26.3 & 20.6 & 5.44 & 1.9(6) & 8162 & 1949 & 41.27 & 26.8 & 23.3 & 7.63 & 8.9(5) & 13240 & 1334 \\
d_4 & 31.1 & 21.9 & 15.0 & 4.22 & 5.4(5) & 3481 & 1039 & 33.07 & 22.5 & 17.2 & 5.93 & 2.7(5) & 5789 & 735 \\
\end{array}
\]

TABLE VII: Same as Table I for the detector \(d_1\) geometry of Table VI. The upper (lower) line corresponds to a cut-off energy of 100 MeV (150 MeV). The fluxes were obtained with the subtraction method described in the text for a standard beta-beam facility running \(^6\text{He}\) ions at \(\gamma = 100\) and \(\gamma = 60\). The quantity \(\hat{\Psi}_{\text{max}}\) is multiplied by \(10^9\). For \(N_{\text{ev}}^{\text{tot}}\), the number given in parenthesis corresponds to the exponent. The statistical error \(\sigma_{N_{\text{ev}}}\) associated to \(N_{\text{ev}}\) is also given.

For the \(d_1\) and \(d_4\) detector geometries, Table VIII presents the total and subtracted number of events associated to anti-neutrino proton scattering as well. Since the cross sections grow approximately as the square of the neutrino energy, the total number of events in the detector is considerably larger than the subtracted events at low energy. Therefore the statistical error associated to the subtracted number of events is always significant since it is determined by the error on the total number of events: \(\sigma_{N_{\text{ev}}} \approx \sqrt{2N_{\text{ev}}^{\text{tot}}}\). If from the point of view of the characteristics of the subtracted fluxes the low and high gamma value options are almost equivalent, the low gamma option (and small radial size of the detector) becomes crucial once the statistical error on the subtracted number of events is considered. Indeed, for considered ion intensities at the storage ring only the \(d_1\) and \(d_3\) (with \(E_{\text{cut}} = 150\) MeV) detector scenarios get statistical errors which are significantly small. However, if further feasibility studies with improved production methods show that a higher ion intensity can be achieved the statistical errors for the \(d_2, d_4\) geometries can become small. Besides, one should keep in mind that in the presented Tables we have shown results on protons considering large volume detectors filled with water. Such a choice is made only based on the fact that neutrino scattering on protons is the only case for which reliable cross sections in a wide energy range are available. The use of heavy target nuclei should be more favorable for the subtraction technique, since then the detector volume can be significantly reduced and render all the discussed geometries particularly interesting.
FIG. 5: Neutrino fluxes obtained by placing two detectors \( d_1 \) (Table VI) off-axis and using the subtraction method described in the text. The different curves correspond to two ion boosts and maximum neutrino energy cutoff. The first detector is located at \( y = 5 \) m.

FIG. 6: Same as Figure 5 but for different \( y \) locations.

As we were completing this paper, the authors of Ref. [39] presented an analysis of how neutrino spectral shapes change at low-energy beta-beams depending on the detector geometry and different locations within the same detector. The analysis presented in the current paper and in Ref. [39] are complementary in exploring the potentials of standard and low-energy beta-beam facilities, respectively.

III. CONCLUSIONS

In this article we explored the feasibility of extracting low-energy neutrinos from the standard beta-beam facility by placing detectors at off-axis. We found that with a single off-axis detector the low-energy neutrino fluxes extracted are rather small. We proposed a two off-axis detector option, which allows, after suitable subtractions, a significant increase in the number of low-energy events. The drawback of this method is an increase in the statistical error. The present work is based on various preliminary assumptions such as the ion intensities. Smaller statistical errors can then be achieved for the two off-axis detector option if the ions circulate with higher intensities in the storage ring. If that would be the case, the option of a single detector would also have to be revisited since the low-energy flux would be larger. In the case of the two detectors option, the energy spectra of the neutrinos are pushed to lower energies than for the low-energy beta-beam. The covered energy range is of interest for fundamental tests and for core-collapse supernovae physics. We also studied the dependence of the flux intensity and energy spectrum on the location and geometry of the detectors.

We conclude that the option of two off-axis detectors at a standard beta-beam facility might be an alternative to the reference scenario of a low-energy beta-beam facility for the realization of low-energy neutrino experiments.
Acknowledgments

The authors acknowledge the CNRS-Etats Units 2005 and 2006 grants which have been used during the completion of this work. This work was also supported in part by the U.S. National Science Foundation Grant No. PHY-055231 at the University of Wisconsin, and in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation. C.V. and R.L. acknowledge the financial support of the EC under the FP6 "Research Infrastructure Action-Structuring the European Research Area" EURISOL DS Project; Contract No. 515768 RIDS.

[1] A. B. Balantekin and G. M. Fuller, J. Phys. G 29, 2513 (2003) [arXiv:astro-ph/0309519].
[2] B. S. Meyer, G. C. McLaughlin and G. M. Fuller, Phys. Rev. C 58, 3696 (1998) [arXiv:astro-ph/9809242].
[3] T. Sasaqui, T. Kajino and A. B. Balantekin, Astrophys. J. 634, 534 (2005) [arXiv:astro-ph/0506100].
[4] M. Ruffert, H. T. Janka, K. Takahashi and G. Schafer, Astron. Astrophys. 319, 122 (1997) [arXiv:astro-ph/9606181].
[5] J. P. Kneller, G. C. McLaughlin and R. Surman, J. Phys. G: Nucl. Part. Phys. 32, 443 (2006) [arXiv:astro-ph/0410397].
[6] P. Vogel and J. F. Beacom, Phys. Rev. D 60, 053003 (1999) [arXiv:hep-ph/9903554].
[7] J. F. Beacom, W. M. Farr and P. Vogel, Phys. Rev. D 66, 033001 (2002) [arXiv:hep-ph/0205220].
[8] G. ’t Hooft, J. Phys. G 30 (2004) L1 [arXiv:hep-ph/0303222].
[9] C. Volpe, J. Phys. G 34, R1 (2007) [arXiv:hep-ph/0605033].
[10] J. Serreau and C. Volpe, Phys. Lett. B 634 (2006) 180 [arXiv:hep-ph/0512310].
[11] A. B. Balantekin, J. H. de Jesus and C. Volpe, Phys. Lett. B 634 (2006) 180 [arXiv:hep-ph/0512310].
[12] A. B. Balantekin, J. H. de Jesus, R. Lazauskas and C. Volpe, Phys. Rev. D 73, 073011 (2006) [arXiv:hep-ph/0603078].
[13] J. F. Beacom, W. M. Farr and P. Vogel, Phys. Rev. D 66, 033001 (2002) [arXiv:hep-ph/0205220].
[14] B. S. Meyer, G. C. McLaughlin and G. M. Fuller, Phys. Rev. C 58, 3696 (1998) [arXiv:astro-ph/9809242].
[15] T. Sasaqui, T. Kajino and A. B. Balantekin, Astrophys. J. 634, 534 (2005) [arXiv:astro-ph/0506100].
[16] M. Ruffert, H. T. Janka, K. Takahashi and G. Schafer, Astron. Astrophys. 319, 122 (1997) [arXiv:astro-ph/9606181].
[17] J. P. Kneller, G. C. McLaughlin and R. Surman, J. Phys. G: Nucl. Part. Phys. 32, 443 (2006) [arXiv:astro-ph/0410397].
[18] P. Vogel and J. F. Beacom, Phys. Rev. D 60, 053003 (1999) [arXiv:hep-ph/9903554].
[19] J. F. Beacom, W. M. Farr and P. Vogel, Phys. Rev. D 66, 033001 (2002) [arXiv:hep-ph/0205220].
[20] G. ’t Hooft, J. Phys. G 30 (2004) L1 [arXiv:hep-ph/0303222].
[21] C. Volpe, J. Phys. G 34, R1 (2007) [arXiv:hep-ph/0605033].
[22] J. Serreau and C. Volpe, Phys. Lett. B 634 (2006) 180 [arXiv:hep-ph/0512310].
[23] A. B. Balantekin, J. H. de Jesus and C. Volpe, Phys. Lett. B 634 (2006) 180 [arXiv:hep-ph/0512310].
[24] A. B. Balantekin, J. H. de Jesus, R. Lazauskas and C. Volpe, Phys. Rev. D 73, 073011 (2006) [arXiv:hep-ph/0603078].
[25] J. F. Beacom, W. M. Farr and P. Vogel, Phys. Rev. D 66, 033001 (2002) [arXiv:hep-ph/0205220].
[26] G. ’t Hooft, J. Phys. G 30 (2004) L1 [arXiv:hep-ph/0303222].
[27] C. Volpe, J. Phys. G 34, R1 (2007) [arXiv:hep-ph/0605033].
[28] J. Serreau and C. Volpe, Phys. Lett. B 634 (2006) 180 [arXiv:hep-ph/0512310].
[29] A. B. Balantekin, J. H. de Jesus, R. Lazauskas and C. Volpe, Phys. Rev. D 73, 073011 (2006) [arXiv:hep-ph/0603078].
[30] J. F. Beacom, W. M. Farr and P. Vogel, Phys. Rev. D 66, 033001 (2002) [arXiv:hep-ph/0205220].
[31] G. ’t Hooft, J. Phys. G 30 (2004) L1 [arXiv:hep-ph/0303222].
[32] C. Volpe, J. Phys. G 34, R1 (2007) [arXiv:hep-ph/0605033].
[33] J. Serreau and C. Volpe, Phys. Lett. B 634 (2006) 180 [arXiv:hep-ph/0512310].
[34] A. B. Balantekin, J. H. de Jesus and C. Volpe, Phys. Lett. B 634 (2006) 180 [arXiv:hep-ph/0512310].
[35] A. B. Balantekin, J. H. de Jesus, R. Lazauskas and C. Volpe, Phys. Rev. D 73, 073011 (2006) [arXiv:hep-ph/0603078].
[36] J. F. Beacom, W. M. Farr and P. Vogel, Phys. Rev. D 66, 033001 (2002) [arXiv:hep-ph/0205220].
[37] G. ’t Hooft, J. Phys. G 30 (2004) L1 [arXiv:hep-ph/0303222].
[38] C. Volpe, J. Phys. G 34, R1 (2007) [arXiv:hep-ph/0605033].
[39] J. Serreau and C. Volpe, Phys. Lett. B 634 (2006) 180 [arXiv:hep-ph/0512310].
[40] A. B. Balantekin, J. H. de Jesus and C. Volpe, Phys. Lett. B 634 (2006) 180 [arXiv:hep-ph/0512310].
[41] A. B. Balantekin, J. H. de Jesus, R. Lazauskas and C. Volpe, Phys. Rev. D 73, 073011 (2006) [arXiv:hep-ph/0603078].
[42] A. B. Balantekin, J. H. de Jesus, R. Lazauskas and C. Volpe, Phys. Rev. D 73, 073011 (2006) [arXiv:hep-ph/0603078].
[43] A. B. Balantekin, J. H. de Jesus, R. Lazauskas and C. Volpe, Phys. Rev. D 73, 073011 (2006) [arXiv:hep-ph/0603078].
[44] A. B. Balantekin, J. H. de Jesus, R. Lazauskas and C. Volpe, Phys. Rev. D 73, 073011 (2006) [arXiv:hep-ph/0603078].