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APPLICATION OF QUADRUPOLE SYSTEMS FOR SHAPING THE HIGH INTENSITY NEUTRINO BEAMS

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Abstract

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The article considers the opportunity of using of quadrupole systems for shaping the high intensity neutrino beams with different spectra in wide energy region. The shaped beams are characterized by low level of ν_e contamination. As an example there are presented the calculated spectra at the proton energy of 50 and 450 GeV.

Аннотация

Чирков П.Н., Карташев В.П., Котов В.И. Применение систем из квадрупольных линз для формирования высокоинтенсивных нейтринных пучков: Препринт ИФВЭ 2002–7. – Протвино, 2002. – 9 с., 10 рис., 6 табл., библиогр.: 5.

Рассматривается возможность использования оптических систем из квадрупольных линз для формирования интенсивных нейтринных пучков с различными спектрами в широкой области энергий. Формируемые пучки характеризуются низким уровнем ν_e примеси. В качестве примера представлены рассчитанные спектры при энергии протонов 50 и 450 ГэВ.

1. The channel structure

The increased requirements to the quality of high intensity neutrino beams in proton accelerator complex stimulate the searching of new optical schemes. With that end in view we have considered the opportunity of using optical channels containing quadrupoles.

The structure of such a channel is presented schematically in Fig. 1.

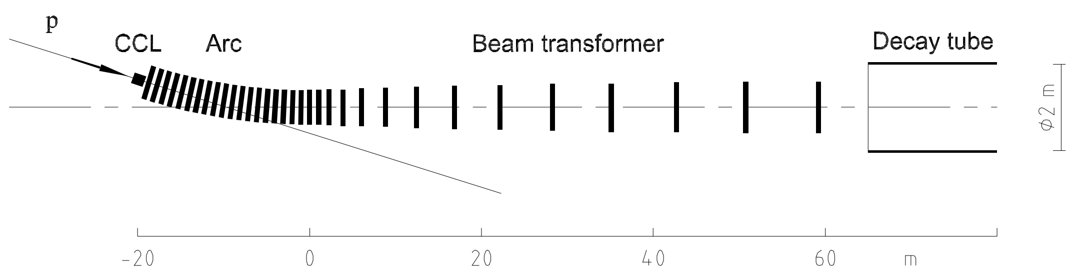

Fig. 1. The quadrupole channel for shaping the high intensity neutrino beams.

The proton beam extracted from the accelerator is guided to the target built into the current coaxial lens (CCL) which provides the effective capture of π^+, K^+mesons in the regular tightly packed quadrupole FD-system (the FD-arc). Inside this arc the secondary particle beam is bent to be removed away from non-interacted protons and background secondary particles. The dipole magnetic field needed for this purpose is introduced by small lens misalignments in the plane of arc curvature with opposite signs for F- and D-quadrupoles.

In the beam transformer following the arc the angular sizes of the beam are reduced in several times and its linear sizes are increased in as much times. The transformer is FD-structure along which apertures of quadrupoles and distances between them increase.

If we cut out the arc from the scheme presented in Fig. 1 we'll receive the straight scheme for shaping the high intensity neutrino beams with wide energy spectrum.

1.1. The current coaxial lens with a target

An angular acceptance of quadrupole systems is not large enough for the effective takeoff of the high intensity beam of secondary particles from the target. An axially focusing element is necessary to intensify the gathering of the secondary particles.

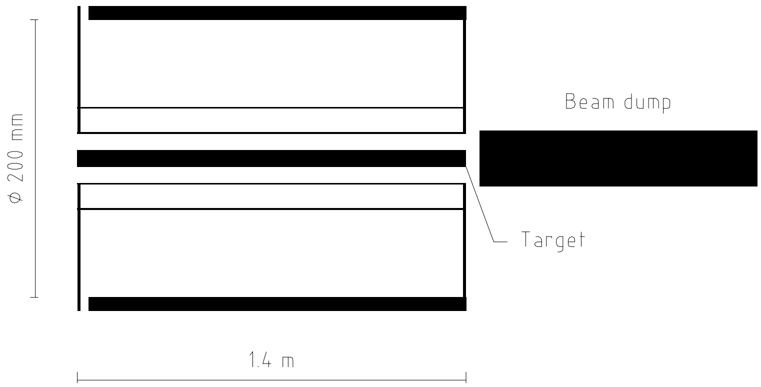

Fig. 2. The current coaxial lens with a target.

In the considered channel the target is built directly into the current coaxial lens (CCL) [1] which consists of two–three thin aluminum current-carrying tubes inserted coaxially one into another (see Fig. 2). Such a system of the current-carrying tubes can produce magnetic field with quasi-constant gradient. It is possible to consider CCL as an discrete analogue of a lithium lens with the smaller average density of substance in a beam than that of lithium.

CCL captures the beam of secondary particles of a necessary charge sign in large angular and momentum intervals from the target and essentially reduces angular beam sizes at its exit. At the same time the secondary particles of the opposite charge sign are thrown out effectively from the shaped beam. Only small part of these particles transiting in the tube of the smallest diameter where magnetic field is absent remains in the beam. This part can essentially be reduced by carrying a small current through the target.

Unlike the channel with the arc in the straight channel the clearing of the shaped beam from particles of the opposite charge sign is carried out by the first axially focusing element only. This means that it is necessary to use the careful joint optimization of a target and an axial focusing element in point of the antineutrino impurity in the neutrino beam.

Thus CCL with the target may be considered as a high intensity source of the secondary particles of the single charge sign with sufficiently small angular and linear sizes. In the following simulation we adopt the target made of a light matter with nuclear interaction length of $\simeq 40$ cm. However in the real design technical issues of target material choice and its configuration should be considered in more detail.

1.2. The FD-arc

The tightly packed FD-structure has the largest acceptance among another quadrupole systems. The FD-structure transports particles of both charge signs in a wide momentum range determined by a requirement of stable motion [2]

$$-2 < Sp(M) = m_{11} + m_{22} < 2 \ ,$$

where m_{ij} — transformation matrix coefficients for the structure period. (The trace $Sp(M)$ is independent of the starting period point).

The area of the maximum phase ellipse in a cross phase plane (the acceptance) may be estimated approximately by the expression

$$S \simeq \pi R^2 \sqrt{\frac{-m_{21}}{m_{12}}} \ ,$$

where R — aperture radius of quadrupoles; m_{ij} — transformation matrix coefficients for the structure period with the starting point at the center of a focusing quadrupole. In the thin-lens approximation there are

$$Sp(M) = 2(1 - \frac{\eta^2}{2}) ,$$

$$S = \frac{\pi R^2}{2d} \eta \sqrt{\frac{2-\eta}{2+\eta}} ,$$

where

$$\eta = \frac{3Gld}{p}$$

— dimensionless parameter; l — effective quadrupole length in m; d — length of the half-period in m; G — gradient of quadrupoles in kGs/cm and p — particle momentum in GeV/c. The acceptance is reduced to zero at $\eta = 0$ and $\eta = 2$ (boundaries of the stability region) which correspond to $p = \infty$ and

$$p_{cr} = \frac{3}{2} Gld .$$

Particles with momenta below critical value p_{cr} are outside the region of the stability and abandon the structure, and particles with momenta above p_{cr} are in the region of stable motion. The acceptance reaches maximum value at $\eta = \sqrt{5} - 1$.

The acceptances of FD-structure in cross phase planes are identical and 2D-acceptance can be estimated as

$$V = S * S = \frac{\pi^2 R^4}{4d^2} f(\eta) ,$$

where

$$f(\eta) = \eta^2 \frac{2-\eta}{2+\eta} .$$

The dependence $F(p) = f(\eta(p))$ at: $R = 110$ mm, $l = 0.7$ m, $d = 1.0$ m, $G = 0.66$ kGs/cm is presented in Fig. 3.

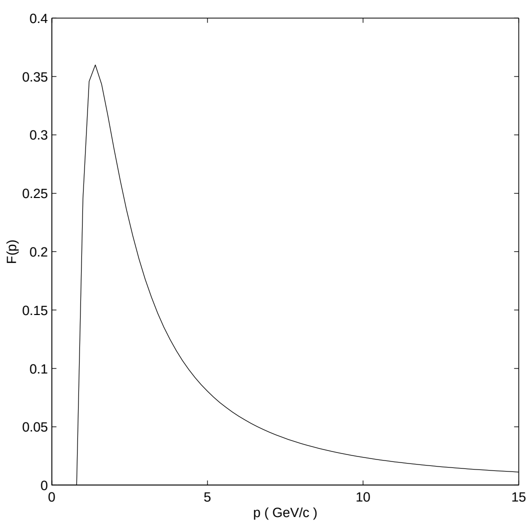

Fig. 3. Function $F(p)$ for FD-structure.

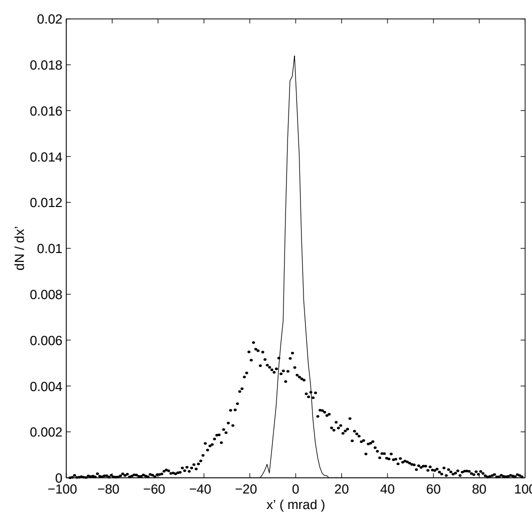

Fig. 4. The angular distribution of the shaped beam at the exits from the arc (points) and the beam transformer (solid line).

In order to remove the non-interacted protons and the particles with high momenta from the shaped beam of the secondary particles it is necessary to install bending magnets in FD-structure. But it gives rise to intolerable large losses in the shaped beam intensity. As it was already noted it is possible to introduce the dipole component of magnetic field in FD-structure by displacing quadrupoles in the arc curvature plane. Small displacements of quadrupoles (not greater than $0.1R$) do not cause the considerable intensity losses.

The total bending angle of the secondary particle beam in the arc is defined by

$$\varphi[mrad] = \frac{3Gl < h > n_a}{p_0} ,$$

where $< h >$ — the average displacement value of the reference trajectory in lenses in mm; p_0 — momentum corresponding to this trajectory in GeV/c; n_a — number of quadrupoles in the arc that should be enough for an extraction of the non-interacted protons from the arc.

1.3. The beam transformer

Before to release the beam of the secondary particles from the arc to the decay space it is necessary to reduce the angular beam sizes in two–three times. If the transition from the tightly packed FD-structure to the rarefied FD-structure is carried out slowly with the conservation of the acceptance then the transported beam of the secondary particles remains in the channel and emerges from the transformer with the minimum angular sizes. The angular distribution of the shaped beam is shown in Fig. 4 at the exits from the arc and the transformer when in the arc: $R = 110$ mm, $l = 0.7$ m, $d = 1.0$ m, $G = 0.66$ kGs/cm.

In the thin-lens approximation the conservation of the acceptance means the conservation of the dimensionless parameter η for each momentum and the expression R^2/d, i.e.

$$Gld = const ,$$

$$\frac{R^2}{d} = const .$$

It follows that at the constant length of quadrupoles their aperture radius and gradient vary with d as $R \sim \sqrt{d}$ and $G \sim 1/d$. At the same time the linear and angular sizes of the shaped beam are proportional to $\sqrt{d}$ and $1/\sqrt{d}$ accordingly. For the slow variation of the parameter d along the beam transformer the following dependence is used

$$d_i = 0.5 d_0 \Big(1 - \cos(\pi \frac{i}{n_t + 1})\Big) ,$$

where i — the quadrupole number; n_t — the total number of quadrupoles in the transformer.

Such a manipulation with the secondary particle beam requires quadrupoles with large apertures and very small gradients in comparison with the usually used ones.

1.4. Special quadrupole lenses

Standard quadrupoles are not suitable to configure the arc which is situated in the region of the higher-level radiation: first of all it is necessary to take the quadrupole winding away from the median plane where the peak fluxes of protons and secondary particles are concentrated. Moreover there will be the need for using such windings resistant to radiation.

The basic types of the required quadrupoles $Q1$ for the arc and $Q2 - Q3$ for the beam transformer are shown in Fig. 5.

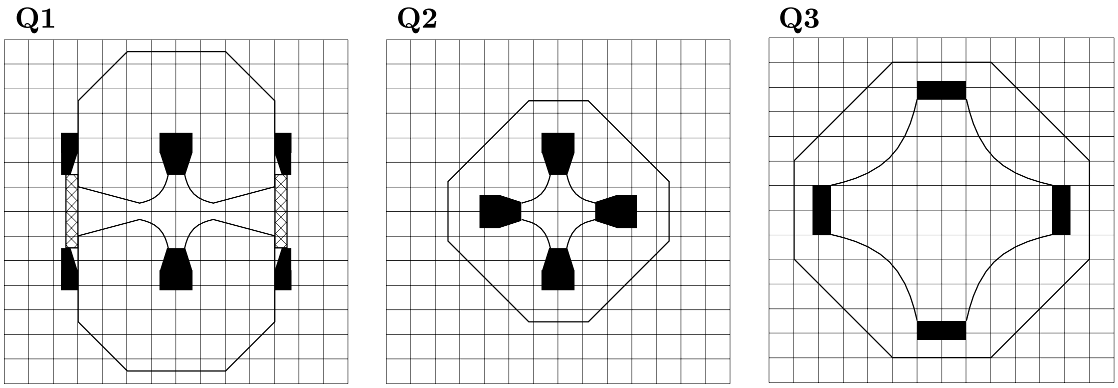

Fig.5. The basic quadrupole types. (One grid division corresponds to 100 mm).

Calculations carried out with the program POISSON have shown the possibility of producing such types of lenses with the required parameters (see Table 1).

Table 1. Parameters of the quadrupoles.

	Q1	Q2	Q3
Radius of the aperture, mm	100	100	300
Overall dimensions, mm×mm	900×1300	900×900	1200 ×1200
Weight, t/m	6.4	3.9	4.9
Gradient, kGs/cm	0.8	0.8	0.08
Total current, kA	33	32	29

2. Examples of the channels and ν-spectra

As an example the quadrupole channels for shaping the high intensity neutrino beams at the proton energy of 50 GeV (see [3]) and 450 GeV (see [4]) are considered. The calculations have been carried out with the program simulating the secondary particle production from the target according with Malensk's formula [5] and taking into account the actual geometry of the target and the optical elements. The program GEANT was not used. But the more detailed simulation with this program may increase up to 2 times values of electron neutrino contaminations given in Tables 3–6 for the straight channels.

3. The channel at the proton energy of 50 GeV

In this case calculation of the ν-beams were performed at the parameters of the target and CCL summarized in Table 2, where l — the length; r — the radius and δr — the thickness of tube walls.

Table 2. Parameters of the target and CCL.

	l m	r mm	δr mm	I kA
Target	1.4	5		10
Tube1	1.4	17	1.0	100
Tube2	1.4	34	1.0	200
Shell	1.4	100		

The FD-arc of the channel contains 20 quadrupoles with the following values of main parameters: $R = 110$ mm, $l = 0.7$ m, $d = 1$ m, $G_{max} = 0.8$ kGs/cm. The maximum displacements of the reference trajectory in focusing and defocusing quadrupoles are equal to -5.4 and 4.5 mm accordingly. At the same time the length and the total bending angle of the arc are equal to 20 m and 56 mrad.

The beam transformer consists of 12 quadrupoles. The distance between the entrances of the adjacent quadrupoles varies from $d = 1$ m at the start to $d = 9$ m at the finish of the beam transformer. The total transformer length is equal to 60 m. The beam transformer can be considered as a part of the channel decay space.

The radius and the length of the decay tube are determined in calculations to be equal to 1000 mm and 60 m. Thus in this case the total length L of the decay space is equal to 120 m. The distance to the neutrino detector is equal to 295 km.

Fig. 6 shows the energy spectra of muon neutrino ν_μ from π^+, K^+ decay, muon antineutrino $\tilde{\nu}_\mu$ from π^-, K^- decay and electron neutrino ν_e from μ^+ decay for the channel with an arc (for two regimes: $G = 0.53$ kGs/cm, $p_0 = 2$ GeV/c and $G = 0.8$ kGs/cm, $p_0 = 3$ GeV/c) and for the straight channel with $G = 0.5$ kGs/cm in quadrupoles at $L = 120$ m and $L = 60$ m. The neutrino spectra are normalized on cm^2 and 10^{21} protons on a target (pot). In the channel with an arc the neutrino spectra decrease sharply by two orders of magnitude as viewed from high energies.

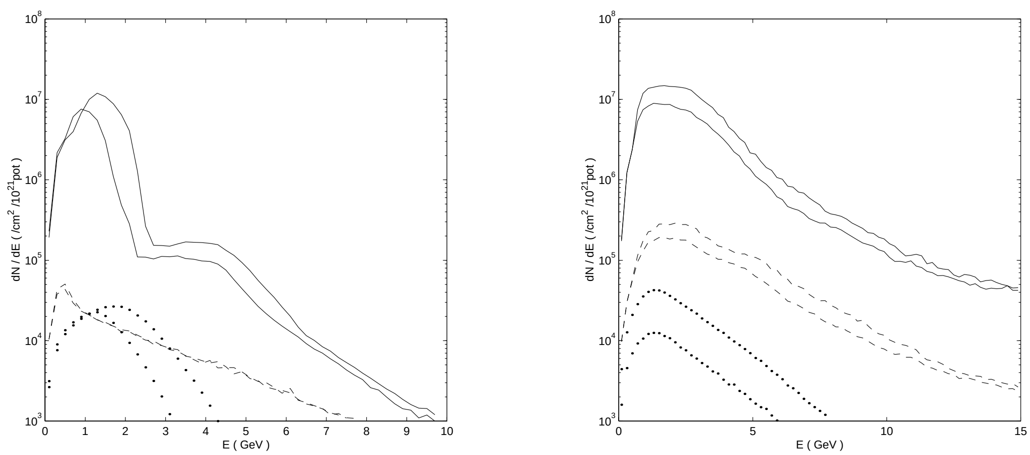

Fig. 6. The ν-spectra for the channel with an arc (left) and the straight channel (right): ν_μ — solid lines, $\tilde{\nu}_\mu$ — dashed lines, ν_e — points.

The flux ratios $\tilde{\nu}_\mu/\nu_\mu$ and ν_e/ν_μ are given in Table 3. For the channel with an arc the ratios are calculated in the ν_μ peak region. It follows the decrease of the decay space L in the straight channel reduces the neutrino flux in 1.7 times. At the same time the ν_e/ν_μ flux ratio is reduced in 2.0 times.

Table 3. The $\tilde{\nu}_\mu$ and ν_e contaminations in the ν_μ beams.

	$\tilde{\nu}_\mu/\nu_\mu$	ν_e/ν_μ
Channel with an arc: p_0=2 GeV/c	0.0059	0.0039
Channel with an arc: p_0=3 GeV/c	0.0038	0.0030
Straight channel: L=120 m	0.0240	0.0025
Straight channel: L=60 m	0.0273	0.0012

4. The channel at the proton energy of 450 GeV

In this case the calculation of the neutrino beams were performed at the parameters of the target and CCL summarized in Table 4.

Table 4. Parameters of the target and CCL.

	l m	r mm	δr mm	I kA
Target	2.8	5		10
Tube1	2.8	15	1.0	120
Tube2	2.8	30	1.0	240
Shell	2.8	100		

The FD-arc of the channel contains 20 quadrupoles with the following values of main parameters: $R = 90$ mm, $l = 2.6$ m, $d = 3$ m, $G_{max} = 0.9$ kGs/cm. The maximum displacements of the reference trajectory in focusing and defocusing quadrupoles are equal to -5.4 mm and 4.5 mm accordingly. At the same time the length and the total bending angle of the arc are equal to 60 m and 21 mrad.

The beam transformer consists of 12 quadrupoles. The distance between the entrances of the adjacent quadrupoles varies from $d = 3$ m at the start to $d = 14.6$ m at the finish of the beam transformer. The total transformer length is equal to 121 m.

The radius and the length of the decay tube are determined in calculations to be equal to 1250 mm and 1000 m. The distance to the neutrino detector is equal to 732 km.

Fig. 7 shows the energy spectra of muon neutrino ν_μ from π^+, K^+ decay, muon antineutrino $\tilde{\nu}_\mu$ from π^-, K^- decay and electron neutrino ν_e from μ^+ decay for the channel with an arc ($G = 0.7$ kGs/cm, $p_0 = 26$ GeV/c) and for the straight channel ($G = 0.5$ kGs/cm). The neutrino spectra are normalized on m^2 and 1 pot.

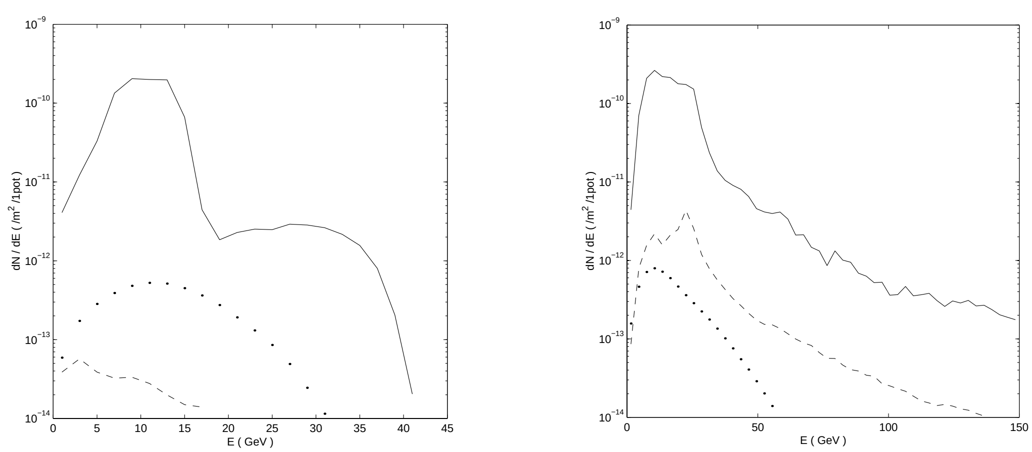

Fig. 7. The ν-spectra for the channel with an arc (left) and the straight channel (right): ν_μ — solid lines, $\tilde{\nu}_\mu$ — dashed lines, ν_e — points.

The flux ratios $\tilde{\nu}_\mu/\nu_\mu$ and ν_e/ν_μ are given in Table 5. For the channel with an arc the ratios are calculated in the ν_μ peak region.

Table 5. The $\tilde{\nu}_\mu$ and ν_e contaminations in the ν_μ beams.

	$\tilde{\nu}_\mu/\nu_\mu$	ν_e/ν_μ
Channel with an arc: p_0=26 Gev/c	0.0003	0.0037
Straight channel: wide spectrum	0.0139	0.0033

5. The regular FD-structure as a decay space

The entire decay space of the neutrino channel can be fabricated of quadrupoles. This already took place above (see 2.1) when the decay space coincides with the beam transformer.

Here we consider two decay spaces involving 12 quadrupoles ($R = 250$ mm, $l = 1$ m, $d = 5$ m, $G = 0.2$ kGs/cm): the regular straight FD-structure and the regular FD-arc. In the last case the total bending angle and the proton angle on the target equal to 60 mrad and -30 mrad accordingly so that the arc ends lay on the neutrino detector direction (Fig. 8). It is worth noting that in the straight FD-structure can been used a more sparse one. The neutrino spectra at the proton energy of 50 GeV are given in Fig. 9. They are normalized on cm^2 and 10^{21} pot. In the FD-arc can be obtained the softest energy spectrum with the lower tail at the high energy. The similar energy spectrum can be obtained in the FD-structure turned through 30 mrad relative to the neutrino detector direction.

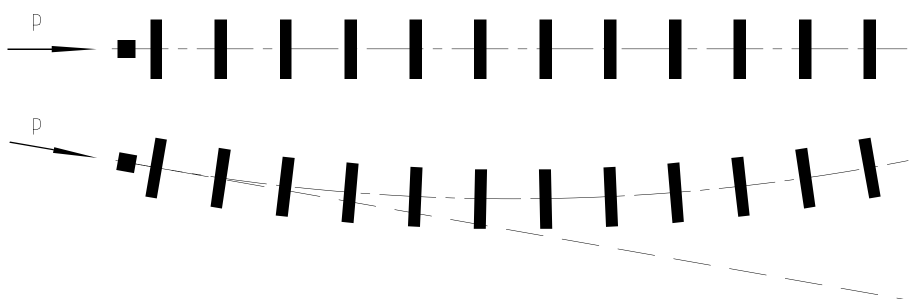

Fig. 8. The neutrino FD-channels.

Moreover if in the FD-structure the small defocusing current is passed through the target and the beam dump is set behind it (see Fig. 2) then it is possible to get the neutrino spectra with sharp edges and small antineutrino contamination.

The secondary particles of the necessary charge sign are defocused in the first tube and are focused outside it. At the same time the secondary particles of the opposite charge sign are subjected to the inverse action and the beam dump included in the scheme reduces sufficiently their contamination in the shaping beam. The transverse sizes of the defocusing target can be enlarged without noticeable losses of the secondary particles.

The neutrino spectra are given in Fig. 10. (compare with Fig. 6(left)).

The $\tilde{\nu}_\mu/\nu_\mu$ and ν_e/ν_μ flux ratios are presented in the Table 6.

Table 6. The $\tilde{\nu}_\mu$ and ν_e contaminations in the ν_μ beams.

	$\tilde{\nu}_\mu/\nu_\mu$	ν_e/ν_μ
FD-arc: p_0=1.75 Gev/c	0.0334	0.00108
FD-structure: wide spectrum	0.0184	0.00099
Defocusing target: I=-20 kA	0.0154	0.00115

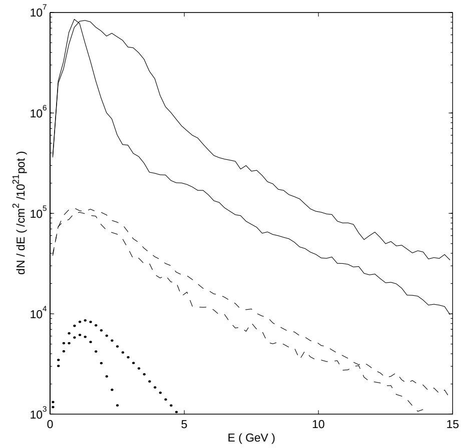

Fig. 9. The ν-spectra for the straight FD-structure and the FD-arc: ν_μ — solid lines, $\tilde{\nu}_\mu$ — dashed lines, ν_e — points.

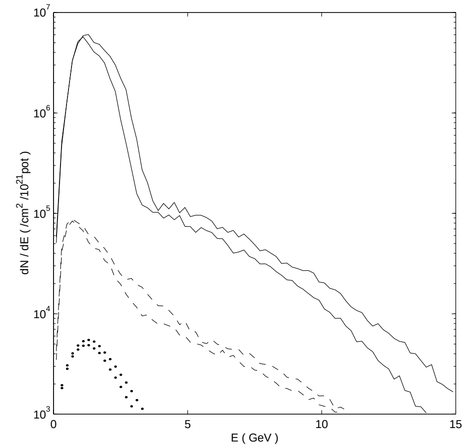

Fig. 10. The ν-spectra for the target current $I =$ -20 kA and -40 kA: ν_μ — solid lines, $\tilde{\nu}_\mu$ — dashed lines, ν_e — points.

The made analysis shows that the proposed optical schemes of the neutrino channels with quadrupoles offer ample scope for their optimization, can be used in the wide energy range and are quite competitive in comparison with the standard channels containing horns.

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