

Neutrino Factory Based on Linear Collider

I. F. Ginzburg

*Sobolev Institute of Mathematics
and Novosibirsk State University,
Novosibirsk, 630090, Russia*

Abstract

The beams of Linear Collider after main collision can be utilized to build neutrino factory with exceptional parameters. We also discuss briefly possible applications of some elements of proposed scheme for standard fixed target experiments, new experiments with $\nu_\mu N$ interactions and in material sciences.

1 Introduction

The project of Linear Collider (LC) contains one essential element that is not present in other colliders. Here each electron (or positron or photon) bunch will be used only once, and physical collision leave two very dense and strongly collimated beams of high energy electrons or/and photons with precisely known time structure. We consider, for definiteness, electron beam parameters of the TESLA project [1]

$$\begin{aligned} & \textit{particle energy } E_e = 250 \textit{ GeV}, \\ & \textit{number of electrons per second } N_e = 2.7 \cdot 10^{14}/s, \\ & \textit{mean beam power } P_b \approx 11 \textit{ MWt}, \\ & \textit{transverse size and angular spread negligible.} \end{aligned} \tag{1}$$

The problem, how to deal with this powerful beam dump, is under intensive discussion.

Main discussed variant is to destruct these used beams with minimal radioactive pollution (see e. g. [1]). It looks natural also to use these once-used beams for fixed target experiments with unprecedented precision.

Recently we suggested to utilize these used beams to initiate work of sub-critical fission reactor and to construct neutrino factory [?]. Here we present estimates for one of these options. Real choice and optimization of parameters should be the subject of detail subsequent studies.

- The study of neutrino oscillations is one of the most important problems in modern particle physics. In this problem the neutrino factories promise most detailed and important results. The existing projects of neutrino factories (see e.g. [3, 4]) are very expensive and their physical potential is limited by expected neutrino energy and productivity of neutrino source.

The neutrino factory based on LC is much less expensive than those discussed nowadays [3, 4]. The combination of a high number of particles in the beam and high particle energy (1) provides very favorable properties of neutrino factory. The initial beam will be prepared in LC irrelevantly to the neutrino factory construction. The construction demands no special electronics except for that for detectors. The initial beam is very well collimated so that the additional efforts for beam cooling are not necessary. The use of the Ice-cub in Antarctic as a far distance detector (FDD) allows to see possible oscillations $\nu_\mu \rightarrow \textit{sterile } \nu$ via measurement of deficit of $\nu_\mu N \rightarrow \mu X$ events.

The neutrino beam will have very well known discrete time structure that repeats the same structure in the LC. This fact allows to separate cosmic and similar backgrounds with high precision during operations. Very simple structure of neutrino generator allows to calculate the energy spectrum and content of the main neutrino beam with high accuracy. It must be verified with high precision in nearby detector (NBD).

In this project neutrino beam will contain mainly muon neutrino's and antineutrino's with small admixture ν_e and $\bar{\nu}_e$ and tiny dope of ν_τ and $\bar{\nu}_\tau$ (the latter can be calculated with low precision). The neutrino energies are spread up to about 80 GeV with mean energy about 30 GeV, providing reliable observation of τ , produced by ν_τ from $\nu_\mu - \nu_\tau$ oscillations. In the physical program of discussed ν factory we consider only problem of oscillations $\nu_\mu - \nu_\tau$ and/or $\nu_\mu - \textit{sterile } \nu$. The potential of this ν factory in other problems of ν physics should be studied after detailed consideration of the project.

2 Elements of neutrino factory

2.1 Scheme

The proposed scheme deals with the electron beam used in LC and contains the following parts (see Fig. 1).

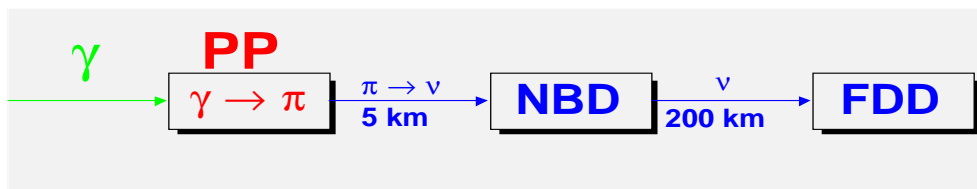


Figure 1: Main parts of neutrino factory.

- Pion producer (PP),
- Neutrino transformer (NT),
- Nearby detector (NBD),
- Far distance detector (FDD),
- Beam turning magnet (BM) before PP.

2.2 Beam turning magnet

The system should start with the magnetic system which turns the used beam at an angle necessary to reach FDD with sacrifice of monochromaticity but without growth of angular spread. The vertical component of turning angle α_V is determined by Earth curvature. Let us denote the distance from LC to FDD by L_F . To reach FDD the initial beam (and therefore NT) should be turned before PP at the angle $\alpha_V = \arcsin[L_F/(2R_E)]$ below horizon (here R_E is Earth radius).

The horizontal component of turning angle can be minimized by suitable choice of the proper LC orientation (orientation of incident beam near the LC collision point).

2.3 Pion producer (PP)

The next stage is pion production in the PP in the form of a 20 cm long water cylinder (*20 cm is one radiation length*). The water in cylinder should rotate for cooling. In this PP almost each electron will produce bremsstrahlung photon with energy $E_\gamma = 100\text{--}200$ GeV. The angular spread of these photons can be estimated as angular spread of initial beam (about 0.1 mrad). The

bremsstrahlung photons have additional angular spread of about $1/\gamma \approx 2 \cdot 10^{-6}$. These two spreads are negligible for our problem.

Then these photons collide with nuclei and produce pions,

$$\gamma N \rightarrow N' + \pi' s, \quad \sigma \approx 110 \mu b. \quad (2)$$

This process gives about $10^{-3} \gamma N$ collisions per 1 electron, which is about $3 \cdot 10^{11} \gamma N$ collisions per second. On average, each of this collisions produces one pion with high energy $E_\pi > E_\gamma/2$ (for estimates $\langle E_\pi^h \rangle = 70$ GeV) and at least 2-3 pions with lower energy (for estimates, $\langle E_\pi^\ell \rangle \approx 20$ GeV).

Mean transverse momentum of these pions is 350-500 MeV. The angular spread of high energy pions with energy $\langle E_\pi^h \rangle$ is within 7 mrad. The increase of angular spread of pions with decrease of energy is compensated by growth of the number of produced pions. Therefore, for estimates we accept that the pion flux within angular interval 7 mrad contains $3 \cdot 10^{11}$ pions with $E_\pi = \langle E_\pi^h \rangle$ and the same number of pions with $E_\pi = \langle E_\pi^\ell \rangle$ per second. Let us denote the energy distribution of pions near forward direction by $f(E)$.

Certainly, more refined calculations should also consider production and decay of K mesons, etc. Reaction mentioned in ref. [6]

$$\gamma N \rightarrow D_s^\pm X \rightarrow \nu_\tau \bar{\tau} X. \quad (3a)$$

plays the most essential role for our estimates. Its cross section rapidly increases with energy growth and

$$\sigma \approx 2 \cdot 10^{-33} \text{ cm}^2 \text{ at } E_\gamma \approx 50 \text{ GeV}. \quad (3b)$$

2.4 Neutrino transformer (NT). Neutrino beams

For the neutrino transformer (NT) we suggest a low vacuum pipe of length $L_{NT} \approx 1$ km and radius $r_{NT} \approx 2$ m. Here muon neutrino ν_μ and $\bar{\nu}_\mu$ are created from $\pi \rightarrow \mu\nu$ decay. This length L_{NT} allows more than one quarter of pions with $E_\pi \leq \langle E_\pi^h \rangle$ to decay. The pipe with radius r_{NT} gives an angular coverage of 2 mrad, which cuts out 1/12 part of total flux of low and medium energy neutrinos. With the growth of pion energy two factors act in opposite ways. First, with this growth initial angular spread of pions decreases, therefore the fraction of flux cut out by the pipe increases. Second, with this growth the number of pion decays within relatively short pipe decreases. These two tendencies compensate each other in the resulting flux.

The energy distribution of neutrino's obtained from π decay with energy E is uniform in the interval $(aE, 0)$ with $a = 1 - (m_\mu/m_\pi)^2$. Therefore, the energy distribution in neutrino energy ε is obtained from energy distribution of pions near forward direction $f(E)$ as (note that $f(E) = 0$ at $E > E_e$)

$$F(\varepsilon) = \int_{\varepsilon/a}^{\infty} f(E)dE/(aE), \quad a = 1 - \frac{m_\mu^2}{m_\pi^2} \approx 0.43. \quad (4)$$

The increase of angular spread in the decay is negligible in the rough approximation. Finally, at the end of NT we expect to have the neutrino flux within the angle 2 mrad

$$\begin{aligned} &0.6 \cdot 10^{10} \nu/s \text{ with } E_\nu = \langle E_\nu^h \rangle \approx 30 \text{ GeV}, \\ \text{and } &0.6 \cdot 10^{10} \nu/s \text{ with } E_\nu = \langle E_\nu^\ell \rangle \approx 9 \text{ GeV}. \end{aligned} \quad (5)$$

We denote below neutrino's with $\langle E_\nu \rangle = 30$ GeV and 9 GeV as *high energy neutrino's* and *low energy neutrino's* respectively.

- **The background ν_τ beam.**
- **The background $\bar{\nu}_\tau$ beam.**

The τ neutrino are produced in PP. Two mechanisms were discussed in this respect, the Bethe-Heitler process $\gamma N \rightarrow \tau \bar{\tau} + X$ [5] and process (3) which is dominant [6]. The cross section (3) is 5 orders less than $\sigma(\gamma N \rightarrow X)$. Mean transverse momentum of ν_τ is given by m_τ , which is more than 3 times higher than that for ν_μ . Along with e.g. $\bar{\nu}_\tau$ produced in this process, in NT each τ decays to ν_τ plus other particles. Therefore, each such reaction is a source of a $\nu_\tau + \bar{\nu}_\tau$ pair. Finally, for flux density we have

$$N_{\nu_\tau} \sim 10^4 \nu_\tau / (s \cdot \text{mrad}^2) \lesssim 8 \cdot 10^{-6} N_{\nu_\mu}. \quad (6)$$

The ν_τ (or $\bar{\nu}_\tau$) energy is typically higher than that of ν_μ by factor $2 \div 2.5$.

Besides, ν_τ will be produced by non-decayed pions within the protecting wall behind NP in the process like $\pi N \rightarrow D_s X \rightarrow \tau \nu_\tau X$. The cross section of this process increases rapidly with energy growth and equals $0.13 \mu\text{b}$ at $E_\pi = 200$ GeV [7]. Rough estimate shows that the number of additional ν_τ propagating in the same angular interval is close to the estimates given in (6). In the numerical estimates below we consider for definiteness first contribution only. The measurement of ν_τ flux in the NBD is a necessary component for the study of neutrino oscillations in FDD.

- Other sources of ν_μ and ν_e change these numbers only weakly.

2.5 Nearby detector (NBD)

• **Main goal** of nearby detector (NBD) is to measure the energy and angular distribution of neutrino's within the beam as well as N_{ν_e}/N_{ν_μ} and N_{ν_τ}/N_{ν_μ} .

• We suggest to position the NBD behind NT and a concrete wall (to eliminate pions and other particles from initial beam). For estimates, we consider the NBD in a form of water cylinder of radius about 2-3 m (roughly the same as NT) and length $\ell_{NBD} \approx 100$ m.

For $E_\nu = 30$ GeV the cross section for ν absorption is

$$\begin{aligned}\sigma(\bar{\nu}N \rightarrow \mu^+h) &= 0.1 \frac{m_p E_{\bar{\nu}}}{\pi v^4} \approx 10^{-37} \text{ cm}^2, \\ \sigma(\nu N \rightarrow \mu^-h) &= 0.22 \frac{m_p E_\nu}{\pi v^4} \approx 2 \cdot 10^{-37} \text{ cm}^2.\end{aligned}\tag{7}$$

At these numbers the free path length in water is $\lambda_{\bar{\nu}} = 10^{13}$ cm and $\lambda_\nu = 0.45 \cdot 10^{13}$ cm. That gives

$$\begin{aligned}(3 \div 6) \cdot 10^7 \text{ } \mu/\text{year} & \text{ (with } \langle E_\mu \rangle \sim 30 \text{ GeV);} \\ 400 \div 800 \text{ } \tau/\text{year} & \text{ (with } \langle E_\tau \rangle \sim 50 \text{ GeV)}\end{aligned}\tag{8}$$

(here 1 year = 10^7 s). These numbers look sufficient for detailed measurements of muon neutrino spectra and verification of calculations of ν_τ backgrounds.

2.6 Far Distance Detector (FDD)

• **Main goal of FDD — study of neutrino oscillations.** We consider $\nu_\mu - \nu_\tau$ oscillations and oscillations with sterile neutrino. We consider separately the potentials of two possible positions of FDD, assuming the length of oscillations to be [8]

$$L_{osc} \approx E_\nu / (50 \text{ GeV}) \cdot 10^5 \text{ km}.\tag{9}$$

• FDD I

The first opportunity is to place FDD at the distance $L_F = 200$ km. In this case the initial beam should be turned at 16 mrad angle. This angle can be reduced by 3 mrad (one half of angular spread of initial pion beam).

We consider this FDD in the form of water channel of length 1 km with radius $R_F \approx 40$ m. The transverse size is limited by water transparency.

The fraction of neutrino's reaching this FDD is given by ratio $k = (R_F/L_F)^2 / [(r_{NT}/L_{NT})^2]$. In our case $k = 0.01$. Main effect under interest here is $\nu_\mu \rightarrow \nu_\tau$ oscillation. They add $(L_F/L_{osc})^2 N_{\nu_\mu}$ to initial N_{ν_τ} .

In FDD of chosen sizes we expect the counting rate to be just 10 times lower than that in NBD (8) for $\nu N \rightarrow \mu X$ reactions with high energy neutrino. We also expect the rate of $\nu_\tau N \rightarrow \tau X$ events to be another 10^5 times lower (that is about 10 times higher than the background given by initial ν_τ flux,

$$\begin{aligned} N(\nu_\mu N \rightarrow \mu X) &\approx (3 \div 6) \cdot 10^6 / \text{year}, \\ N(\nu_\tau N \rightarrow \tau X) &\approx (30 \div 60) / \text{year} \end{aligned} \quad \text{in FDDI.} \quad (10)$$

For neutrino of lower energies effect increases. Indeed, $\sigma(\nu N \rightarrow \tau X) \propto E_\nu$ while $L_{osc} \propto E_\nu$. Therefore, observed number of τ from oscillations increases $\propto 1/E_\nu$ at $E_\nu \geq 10$ GeV. The additional counting rate for $\nu_\tau N \rightarrow \tau X$ reaction with low energy neutrino (with $\langle E_\nu \rangle = 9$ GeV) cannot be estimated so simply, but rough estimates give numbers similar to (10).

These numbers look sufficient for separation of $\nu_\mu - \nu_\tau$ oscillations and rough measurement of s_{23} .

Note that at given FDD size the counting rate of $\nu_\tau N \rightarrow \tau X$ reaction is independent on FDD distance from LC, L_F . The growth of L_F improves the signal to background ratio for oscillations. The value of signal naturally increases with growth of volume of FDD.

• FDD II

The second opportunity is to use for FDD well known *Ice-cub detector* in Antarctica with volume 1 km^3 . The distance to FDD in this case is $L_F \approx 10^4 \text{ km}$. This opportunity requires relatively expensive excavation work for NT and NBD at the angle about 60 deg under horizon.

At this L_F for ν with energy about 30 GeV we expect the conversion of $(L_F/L_{osc})^2 \approx 1/36$ for $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \text{sterile } \nu$.

In this FDD the number of expected events $\nu_\mu \rightarrow \mu X$ with high energy neutrino will be about 0.01 of that in NBD,

$$\begin{aligned} N(\nu_\mu N \rightarrow \mu X) &\approx (3 \div 6) \cdot 10^5 / \text{year}, \\ N(\nu_\tau N \rightarrow \tau X) &\approx 10^4 / \text{year} \end{aligned} \quad \text{in FDDII.} \quad (11)$$

The contribution of low energy neutrino increases both these counting rates.

Therefore, one can hope that a few years of experimentation with reasonable τ detection efficiency will allow to measure s_{23} with percent accuracy, and similar period of observation of μ production will allow to observe the loss of ν_μ due to transition this neutrino to sterile ν .

3 Discussion

- All technical details of proposed scheme including sizes of all elements, construction, and materials of detectors can be modified in the forthcoming simulations and optimization of parameters. The numbers obtained above represent first rough estimates only. In particular, we did not discuss here methods of μ and τ registration and their efficiency. Next, large fraction of residual electrons, photons and pions leaving the PP will reach the walls of the NT pipe. The heat sink and radiation protection of this pipe must be taken into account.

- More detailed physical program of this neutrino factory will be similar to the one discussed in other projects [3, 4].

4 Other possible applications of LC used beam

- **Pion producer of neutrino factory in the fixed target experiment.** The proposed PP can be used also as γN collider with luminosity $3 \cdot 10^{39} \text{ cm}^{-2}\text{s}^{-1}$. Therefore, the PP with additional standard detector behind PP can be used for precise experiments in the fixed target regime for the γN collider with huge luminosity. Here one can study rare processes in γN collisions, B physics, etc.

- **Additional opportunity for using NBD of neutrino factory.** High rate of $\nu_\mu N \rightarrow \mu X$ processes expected in NBD allows to study new problems of high energy physics. The simplest example is the opportunity to study charged and axial current induced diffraction ($\nu N \rightarrow \mu N' \rho^\pm N$, $\nu N \rightarrow \mu N' b_1^\pm N, \dots$) with high precision. Measurements of charged current induced structure functions present the second example.

- **Material sciences.** The interaction of beam having exceptional energy density (1) with different materials will be of great interest for material physics (for example, to understand what happens at collision of micro-meteorite with spacecraft).

I am thankful to D. Naumov, L. Okun, V. Saveliev, A. Sessler, A. Skrin-sky, V. Telnov, M. Vysotsky, M. Zolotarev for comments and new information. This work is supported by grants RFBR 05-02-16211, NSh-2339.2003.2.

References

- [1] R.D. Heuer et al. *TESLA Technical Design Report*, DESY 2001-011, TESLA Report 2001-23, TESLA FEL 2001-05 (2001); hep-ph/0106315
- [2] G. Rubbia et al., CERN/95-44(ET) (1995); Ya. Ya. Stavitsky, INR 0901/95 (Moscow)
- [3] M. Alsharo'a et al. *Phys. Rev. ST Accel. Beams* **6** (2003) 081001; hep-ex/0207031; D. Kaplan, *Nucl. Instr. Meth. A* **453** (2003) 37; physics/0507231
- [4] A. Ferrari, A. Guglielmi, P.R. Silva, hep-ph/0501283.
- [5] A. N. Skrinsky, *Sov. Phys. Uspechi* **25** (1982) # 9
- [6] V. I. Telnov, *Talk at SLAC seminar* (1992), unpublished.
- [7] S. Barlag et al., *Z. Phys. C* **49** (1991) 555.
- [8] M. Vysotsky, private communication.