Subcritical Fission Reactor and Neutrino Factory Based on Linear Collider

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The beams of Linear Collider after main collision can be utilized in two ways. First, one can build an accelerator–driven sub–critical reactor. Second, one can build neutrino factory with exceptional parameters.

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]

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

In the Photon Collider mode the used beams contain photons, electrons and positrons. They are not monochromatic but have the same characteristic particle energy (with large low energy tail) and the same mean power.

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.

In this paper we suggest to utilize these used beams in two new ways.

- To initiate work of subcritical fission reactor.
- To construct neutrino factory.

Below we present first estimates for both these options. Real choice and optimization of parameters should be the subject of detail subsequent studies.

2. ACCELERATOR-DRIVEN SUB-CRITICAL REACTOR

The idea to work with sub–critical nuclear reactor, initiated by proton or electron beam, for foolproof production of energy and/or cleaning of nuclear pollution is well known (see e. g. [2]). Here proton or electron beam with particle energy of about 1 GeV is supposed to produce neutrons in the cascades within body of reactor. The problem here is in obtaining necessary beam power $P_b \geq 5$ MW.

According to (1), each used beam of LC is two times more powerful than necessary for this reactor but electron energies are two orders larger. In the suitable target this particle energy can be transmitted to low energy particles to initiate fission process in reactor.

2.1. Qualitative Description

• The first redistribution of beam energy to a large number of "working" electrons and photons can be realized in special *degrader* – e.g., 0.5 m water pipe with the radius of a few cm. (Water should rotate to prevent vapour explosion.) After passing the degrader, particles with mean energy in hundreds MeV penetrate into the main body of reactor filled with uranium or thorium. After the photons reach the energy of about 10 MeV in the electromagnetic cascades, they get absorbed by nuclei (in giant resonance), producing neutrons.

The scheme of proper reactor is a subject of separate study of reactor specialists.

• To realize this reactor, the crab crossing scheme for main collision may be preferable to place the reactor away from accelerator beam. We assume for definiteness the crab crossing angle of 15 mrad.

One or two sub–critical reactors can be situated at about 500 m from collision point, at about 7 m from accelerating channel providing good protection of collider beam pipe. (Considered used beam should move towards the reactor through low pressure gas after it passes some window protecting high vacuum of collider.)

• The obtained accelerator–driven foolproof sub–critical reactor can be used for energy generation and extra nuclear pollution cleaning. The economical problems are beyond this proposal.

3. NEUTRINO FACTORY

3.1. General

The study of neutrino oscillations is one of the most important problems in particle physics. In this problem the neutrino factories promise most detailed and important results. The existing projects of neutrino factories (see e.g. [3]) are very expensive, their physical potential is limited by expected neutrino energy. The latter point makes it difficult to directly measure the $\nu_\mu - \nu_\tau$ mixing and mixing of ν_μ with sterile neutrino.

The used beam of LC can be the base for the construction of neutrino factory. The combination of a high number of particles in the beam and high particle energy provides very favorable properties of this factory.

The neutrino factory based on LC is much less expensive than that discussed above [3]. 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 neutrino beam will have very well known discrete time structure that repeats the same structure in the LC. This fact allows to separate backgrounds with high precision during operations. Very simple structure of neutrino generator allows to calculate the energy spectrum and content of neutrino beam with high accuracy. It can be verified with high precision in nearby detector.

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 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 $\nu_\mu -$ *sterile* ν. The potential of this ν factory in other problems of ν physics should be studied after detailed consideration of the project.

Unlike refs [3], we present neutrino flux only within very narrow angular interval, covered completely by nearby detector.

3.2. Scheme

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

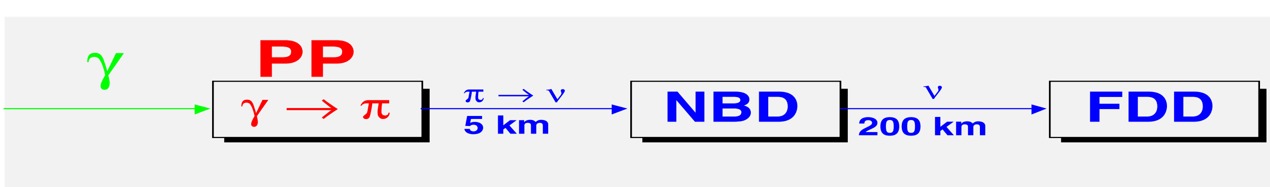

Figure 1: Main parts of neutrino factory.

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

3.3. Beam Turning Magnet

The system should start from the beam turning magnetic system providing the turning of used beam at necessary angle with sacrifice of monochromaticity but without growth of angular spread. The turning angle depends on anticipated position of far distance detector (see below).

3.4. 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 $E_\gamma = 100 - 200$ 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,

$$\gamma N \to N + \pi' s, \quad \sigma \approx 110\, \mu b. \tag{2}$$

This process gives about 10^{-3} γN collisions per 1 electron, which is about $3 \cdot 10^{11}$ γN 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 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 $f(E)$.

Roughly the same quantities describe flux of pions produced by photon beam.

3.5. 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 $\pi \to \mu\nu$ decay. This length L_{NT} allows more than one quarter of pions with $E_\pi \le \langle E_\pi^h \rangle$ 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 $E > E_e$)

$$F(\varepsilon) = \int\limits_{\varepsilon/a}^{\infty} f(E) dE/(aE)\,, \qquad a = 1 - \frac{m_\mu^2}{m_\pi^2} \approx 0.43\,. \tag{3}$$

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

$$0.6 \cdot 10^{10} \nu/s \;\; with \;\; E_\nu = \langle E_\nu^h \rangle \approx 30 \; GeV, \quad \text{and} \quad 0.6 \cdot 10^{10} \nu/s \;\; with \;\; E_\nu = \langle E_\nu^\ell \rangle \approx 9 \; GeV. \tag{4}$$

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 τ neutrino are produced mainly in PP. Two mechanisms were discussed in this respect, the Bethe-Heitler process $\gamma N \to \tau\bar{\tau} + X$ [4] and process $\gamma N \to D_s X$ [5]. The second process is dominant, with cross section $\sigma(\gamma N \to D_s X) \approx 2 \cdot 10^{-33}$ cm^2 [5]. This cross section is 5 orders less than $\sigma(\gamma N \to X)$. Mean transverse momentum of ν_τ is given by m_τ, which is more than 3 times higher than that for ν_μ. Therefore for flux density (per second and mrad^2) we have (factor 4 is due to fraction 1/4 of ν/pi ratio connected to small length of NT)

$$N_{\nu_\tau} \lesssim 4 \cdot 10^{-6} N_{\nu_\mu}. \tag{5}$$

The ν_τ energy is typically higher than that of ν_μ by factor $2 \div 2.5$.

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

3.6. 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 absorbtion is

$$\sigma(\bar{\nu} N \to \mu^+ h) = 0.1 \frac{m_p E_{\bar{\nu}}}{\pi v^4} \approx 10^{-37} cm^2, \qquad \sigma(\nu N \to \mu^- h) = 0.22 \frac{m_p E_\nu}{\pi v^4} \approx 2 \cdot 10^{-37} cm^2. \tag{6}$$

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

$$\begin{array}{c} 3 \div 6 \;\; events \;\; with \;\; \mu \;\; production \;\; per \;\; \textbf{second} \;\; (with \;\; \langle E_\mu \rangle \sim 30\, GeV); \\ 200 \div 400 \;\; events \;\; with \;\; \tau \;\; production \;\; per \;\; \textbf{year} \;\; (with \;\; \langle E_\tau \rangle \sim 50\, GeV) \end{array} \tag{7}$$

(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.

• **Additional opportunity for using NBD.**

High rate of $\nu_\mu N \to \mu X$ processes expected in NBD allows to study new problems of high energy physics. The simplest example is the opportunity to study with high precision charged and axial current induced diffraction ($\nu N \to \mu N' \rho^\pm N$, $\nu N \to \mu N' b_1^\pm N$,...). Measurements of charged current induced structure function are the second example.

3.7. Far Distance Detector (FDD)

• *Main goal of FDD* — **study of neutrino oscillations.**

We consider $\nu_\mu - \nu_\tau$ oscillations and oscillations with sterile neutrino. In our estimates we assume that the length of oscillations is [6]

$$L_{osc} \approx E_\nu / (50\ GeV) \cdot 10^5\ km\,. \tag{8}$$

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 $\alpha = \arcsin[L_F/(2R_E)]$ below horizon with the aid of beam turning magnet (here R_E is Earth radius). We consider separately the potentials of two possible positions of FDD.

• **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 $\nu_\mu \to \nu_\tau$ oscillation. Oscillations 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 (7) for $\nu N \to \mu X$ reactions with high energy neutrino. We also expect the rate of $\nu_\tau N \to \tau X$ events to be another 10^5 times lower (that is about 10 times higher than the background given by initial ν_τ flux,

$$N(\nu_\mu N \to \mu X) \approx (3 \div 6) \cdot 10^6/year, \qquad N(\nu_\tau N \to \tau X) \approx (30 \div 60)/year \;\; in \;\; FDDI. \tag{9}$$

For neutrino of lower energies effect increases. Indeed, $\sigma(\nu N \to \tau X) \propto E_\nu$ 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 $\nu_\tau N \to \tau X$ reaction with low energy neutrino (with $\langle E_\nu \rangle = 9$ GeV) cannot be estimated so simply, but rough estimates give numbers similar to (9).

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 $\nu_\tau N \to \tau X$ 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 $L_F \approx 10^4$ 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 $\nu_\mu \to \nu_\tau$ or $\to$ *sterile* ν.

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

$$N(\nu_\mu N \to \mu X) \approx (3 \div 6) \cdot 10^5/year, \qquad N(\nu_\tau N \to \tau X) \approx 10^4/year \;\; in \;\; FDDII. \tag{10}$$

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.

Acknowledgments

I am thankful to D. Naumov, L. Okun, V. Saveliev, A. Sessler, A. Skrinsky, 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. N. Skrinsky, *Sov. Phys. Uspechi* **25** (1982) # 9
[5] V. I. Telnov, *Talk at SLAC seminar* (1992), unpublished.
[6] M. Vysotsky, private communication.