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Critical Issues in Linear Colliders *

Valery Telnov
Institute of Nuclear Physics, 630090 Novosibirsk, Russia

Abstract

Linear colliders (LC) on the energy 0.5–1 TeV are considered as the next step in the particle physics. High acceleration gradients, small beam sizes, precision tolerances, beam collision effects are main problems for linear colliders. In this paper we discuss physics motivation, parameters and status of current LC projects, e^+e^-, $\gamma\gamma$ and γe modes of operation, physical limitations on the energy and luminosity. Present technologies allow to reach energies about 5 TeV with adequate luminosities. Advanced technique based on plasma and laser method of acceleration can provide much higher accelerating gradients, however, perspectives of these methods for high energy colliders are still under big question. Linear colliders with energies above 10 TeV are hard for any acceleration technology. Speculations on possibility of PeV linear colliders based on ponderomotive laser acceleration are just not serious and contain several mistakes on conceptual level. It is shown that due to radiation in the transverse laser field, methods of acceleration based on laser bunch "pressure" do not work at high energies.

1 Introduction: next steps in particle physics

Progress in particles physics in the last several decades was connected with the increase of accelerator energies. Historically, two types of colliders co-existed and gave main results, $pp(p\bar{p})$ and e^+e^-. Proton colliders give access to higher energies, but e^+e^- colliders have simple initial state, smaller background and allow much better precision. At proton colliders c, b, t quarks and W, Z bosons have been discovered, while at e^+e^- colliders c-quark, τ-lepton, gluon. In addition, at e^+e^- colliders c, b, W, Z, τ physics has been studied with a high accuracy providing a precision test of the Standard Model.

The next proton collider LHC with the energy $2E_0 = 14$ TeV will start operation in about 2007. It will certainly bring new discoveries. But, as before, for detail study of new physics and it's *understanding* a e^+e^- collider is very desirable. Such projects on the energy $2E_0$ =0.5–1.5 TeV already exist, but, unfortunately, approval is delayed due to a high cost and necessity of international cooperation. According to present understanding the construction can start in about 2007.

As for long-term perspectives of particle physics, the future is even less clear. Three kind of facilities are under discussion: Very Large Hadronic Collider (VLHC) with pp beams on the energy up to 200 TeV, Compact e^+e^- Linear Collider CLIC on the energy $2E_0 = 3$–5 TeV and muon colliders which potentially can reach a c.m.s. energy even higher than in pp collisions.

Physics motivation for next generation of colliders (LHC, LC) is very strong, two examples are given below.

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If the Standard Model is valid a new particle, the Higgs boson, should exist. Direct search at LEP and measurements of loop corrections indicate that the Higgs boson mass lays in the region 115–200 GeV. Such a particle should have very special properties, their coupling constants with other particles are proportional to particle masses. Linear colliders allow us to measure Higgs branchings with a high accuracy, So, experiments at LHC and LC can shed a light on the origin of particle masses.

The second physics goal is a search of a supersymmetry which assumes the existence of a new class of particles, superpartners of known particles but with different spins: particles with the spin 1/2 have partners with the spin 0 and vice versa. It is possible that the dark matter in the universe consists of the lightest neutral supersymetrical particles. At colliders, one could produce any kind of such particles, charged and neutral. A discovery of a "parallel" world (which according to astronomical data has a density even higher than that of the barionic matter) would mean a new revolution in physics.

Below we consider existing projects of linear colliders, their problems, energy and luminosity limitations, prospects of advanced accelerator methods.

2 Projects of linear colliders

It was realized already 30 years ago that the energy of circular e^+e^- linear colliders is limited by synchrotron radiation losses at a level of 100–200 GeV and further progress is only possible using linear e^+e^- colliders [1]. At the end of 1980-th the 2-mile electron linac at SLAC has been transformed into a (semi)linear collider SLC with the c.m.s. energy of 90 GeV. It gave nice physics results and a great experience of work at the first linear collider.

At the same time an international study on linear collider lead by SLAC, KEK, DESY, CERN and BINP has been launched with ambitious goal to develop a linear collider with an energy about one TeV and a luminosity by a factor of 10^3–10^4 higher than it was at the SLC. Since that time a lot of developments have been done and now three projects TESLA (Europe) [2], NLC (US) [3], JLC (Japan) [4] are almost ready for construction. A fourth project CLIC(CERN) [5] is focused on multi-TeV energies and is considered as the next-to-next linear collider. Schemes of colliders are shown in Fig. 1, main parameters are presented in Table 1.

Each project has some distinctive features:

• TESLA: L band, 1.4 GHz, superconducting, $G_{max} \sim 35$ MeV/m, a good efficiency, a low wakefield, a relaxed alignment tolerances, a large distance between bunches;
• NLC/JLC: X-band, 11.4. GHz, warm cavities, a high gradient (55 MeV/m loaded);
• CLIC: 30 GHz, a two-beam accelerator (one of beams produces RF power), a very high gradient, 150 MeV/m, cost effective at multi-TeV energies.

So, there are three main technologies for LC developed by large teams, each project have certain advantages. It would be good to built two colliders almost simultaneously: TESLA for energies below 0.5 TeV, NLC/JLC for the energy region up to 1.5 TeV and a third collider, CLIC, on the energy 3–5 TeV one decade later. However, due to a high cost only one global linear collider is seen in the visible future.

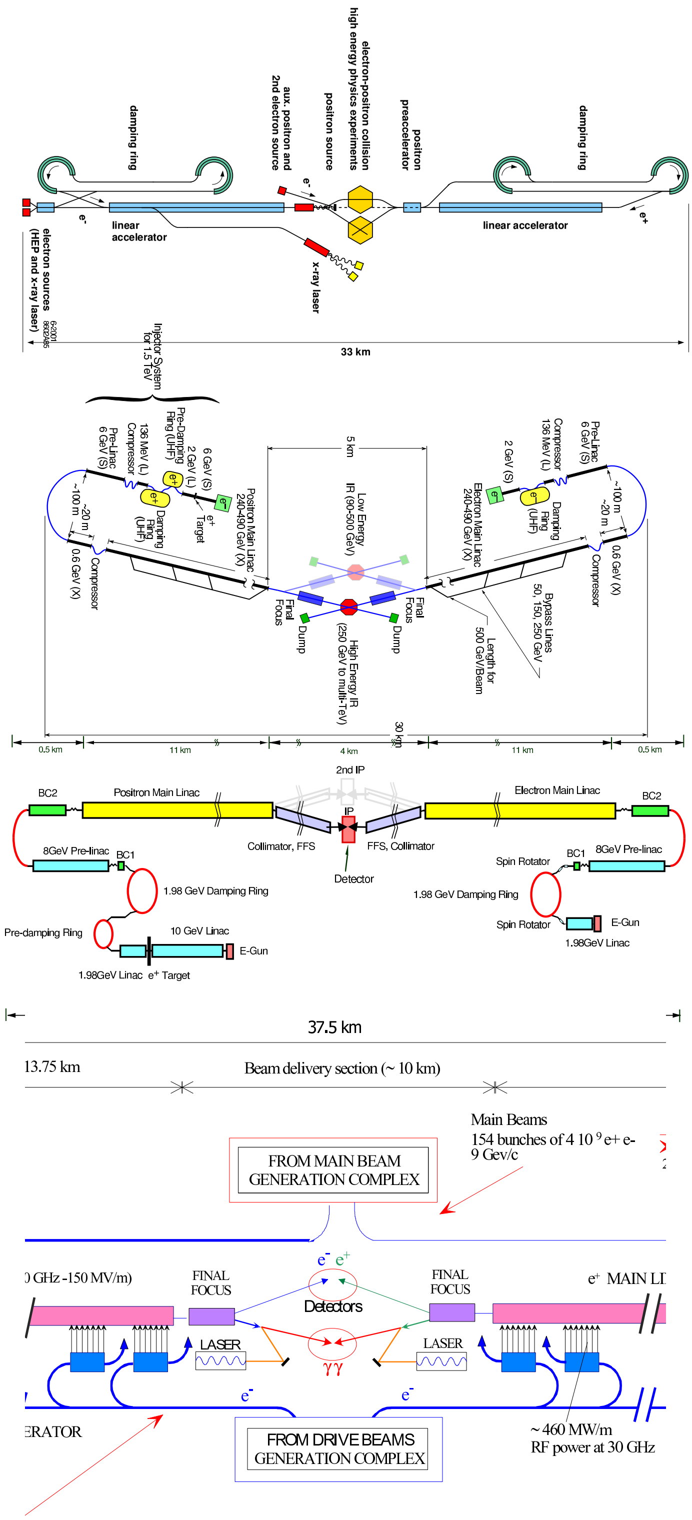

Figure 1: Schemes of linear colliders TESLA, NLC, JLC and CLIC (from up to down).

Table 1: Parameters of linear collider

		TESLA		JLC/NLC		CLIC	
$2E_0$	GeV	500	800	500	1000	500	3000
Site L	km	–	33	–	32	–	40
Two linac L	km	30	30	12.6	25.8	5	27.5
Beam del. L	km	3.2	3.2	3.8	3.8	5	5
G(un.l/load)	MeV/m	23.4	35	70/55	70/55	172/150	172/150
Total AC	MW	95	160	120	240	100	300
AC-beam eff.	%	23	21	10	10	8.5	8.5
RF freq.	GHz	1.3	1.3	11.4	11.4	30	30
Rep. rate	Hz	5	4	120	120	200	100
bunch/train		2820	4886	192	192	154	154
Coll. rate	kHz	14.1	19.5	23	23	30.8	15.4
Bunch separ.	ns	337	176	1.4	1.4	0.67	0.67
Train length	μsec	950	860	0.267	0.267	0.1	0.1
Part./bunch	10^{10}	2	1.4	0.75	0.75	0.4	0.4
σ_z	μm	300	300	110	110	30	30
$\varepsilon_{nx}/\varepsilon_{ny}$	mm·mrad	10/0.03	8/0.015	3.6/0.04	3.6/0.04	2/0.02	0.68/0.02
β_x/β_y	mm	15/0.4	15/0.4	8/0.11	13/0.11	10/0.15	8/0.15
σ_x/σ_y	nm	553/5	391/2.8	243/3	219/2.3	200/2.5	43/1
D_x/D_y		0.2/25	0.2/27	0.16/12.9	0.08/10	0.12/7.9	0.03/2.7
Υ_0		0.06	0.09	0.14	0.29	0.3	8.1
δ	%	3.2	4.3	4.7	8.9	3.8	31
n_γ/e		2	1.5	1.3	1.3	0.7	2.3
$n_{e^+e^-}$/e							0.17
L(with pin.)	10^{34} cm^{-2}s^{-1}	3.4	5.8	2	3	1.4	10.3
L(w/o pin.)	10^{34} cm^{-2}s^{-1}	1.6	2.8	1.2	1.9	?	?
L(1%)/L	%	66		64		67	25.5
L(5%)/L	%	91		85		86	40.8

3 General features of linear colliders

At storage rings, each bunch collides many times, the RF power is spent mainly for compensation of synchrotron radiation losses. At linear colliders, each bunch is used only once, radiation losses during the acceleration are negligible, but a lot of energy is needed for production and acceleration of bunches with a high rate. The total RF power consumption at LEP and at 0.5 TeV linear colliders are comparable, of the order of 100 MW from the wall plug.

The number of accelerated particles is limited by total AC power which is proportional to the beam power P. Due to the dependence of cross sections on the energy as $\sigma \propto 1/E^2$ the luminosity should increase as E^2, as a result the required transverse beam sizes at TeV energies should be very small.

Beams with small sizes have very strong fields that lead to large radiation losses during beam collisions (beamstrahlung). This effect does not allow us to use beams with simultaneously small horizontal and vertical beam sizes (σ_x, σ_y) (only very flat beams) and to get the required luminosity the beam power should be additionally increased. This leads to the "energy crisis" at the beam energy of about $2E_0 \sim 5\,\text{TeV}$, see Sec. 4. In the $\gamma\gamma$ mode of operation (Sec. 5) only somewhat higher energies are possible due to conversion of high energy photons to e^+e^- pairs in the field of the opposing beam (coherent pair creation).

Beside traditional linear accelerators, there are ideas of using plasma and laser high gradient accelerator techniques for linear colliders. There are some speculations about colliders with 100 TeV and even PeV energies. Certainly, development of these techniques will lead to some practical applications, but obtaining colliding beams is very problematic due to required quality of beams and collision effects. Some considerations and critical remarks on plasma and laser acceleration are given Sec. 6.

4 Collision effects restricting luminosity and energy of linear colliders

In order to obtain a sufficient luminosity at linear colliders the beam sizes should be very small. This causes two sorts of problems: a) generation and acceleration of beams with very small emittances and focusing to a tiny spot, b) beam-beam collision effects which lead to degradation of the beam quality.

The first problem is very difficult but not fundamental, in principle, one can obtain emittance smaller than give damping rings using, for example, laser cooling. The second problem is even more severe: beam collision effects put restrictions on attainable luminosity and, correspondently, on the maximum energy of linear colliders.

In the absence of collision effects the luminosity of a collider

$$L \approx \frac{N^2 f}{4\pi\sigma_x\sigma_y} = \frac{P}{4\pi E_0} \times \frac{N}{\sigma_x\sigma_y}\,. \tag{1}$$

For $2P = 20$ MW (200 MW AC power), $N = 2\times10^{10}$, $\sigma_x = \sigma_y = 1$ nm it gives $L = 10^{37}/E_0[\text{TeV}]$, $\text{cm}^{-2}\text{s}^{-1}$, this luminosity is sufficient for production of 10^3 lepton pairs per 10^7 sec up to $2E_0 = 25$ TeV. Below we consider several limitations due to collisions effects.

4.1 Pinch effect and instability of beam collisions

During the collision beams attract (e^+e^-) or repulse (e^-e^-) each other. The characteristic disruption parameter [6, 7]

$$D_y = \frac{2Nr_e\sigma_z}{\gamma\sigma_x\sigma_y}\,. \tag{2}$$

For flat beam and $D_y \sim 10$, the attraction leads to increase of the e^+e^- luminosity by a factor of $H_D \sim 2$. At $D_y \geq 25$ beams become unstable, the corresponding luminosity

$$L \sim \frac{P}{mc^2 r_e\sigma_z}\,. \tag{3}$$

For $P = 10$ MW and $\sigma_z = 100\ \mu$m $L \sim 5\times10^{34}\ \text{cm}^{-2}\text{s}^{-1}$. So, this put limit on the luminosity for a given beam power and bunch length.

4.2 Beamstrahlung

A strength of a beam field is characterized by the parameter Υ [8, 7]

$$\Upsilon = \frac{2}{3}\frac{\hbar\omega_c}{E} = \gamma\frac{B}{B_0}, \quad B_0 = \frac{\alpha e}{r_e^2} = 4.4\times 10^{13}\mathrm{G}\,. \tag{4}$$

For flat beams

$$\Upsilon_{av} \approx \frac{5Nr_e^2\gamma}{6\alpha\sigma_x\sigma_z}\,. \tag{5}$$

The maximum value of σ_z is determined by disruption. Ideally, increasing σ_x to infinity and simultaneously decreasing σ_y to zero one can get arbitrary small Υ for any luminosity. However, if σ_y has some minimum value (there are many reasons), then $\Upsilon \propto L^2\gamma^2\sigma_y/P^2D_y$. As P is always limited, $D_y < 25$ and the required L increases with the energy as γ^2, the value of Υ increases rapidly with the energy. In the current LC projects at 1 TeV $\Upsilon = \mathcal{O}(1)$, at higher energies inevitably $\Upsilon \gg 1$.

Synchrotron radiation of electrons in the field of the opposing beam (beamstrahlung) put severe limitations on performance of linear colliders. Energy losses are given by approximate formulae [7]:

$$\frac{dN_\gamma}{dt} = \frac{5}{2\sqrt{3}}\frac{\alpha^2 c\Upsilon}{r_e\gamma}U_0(\Upsilon), \qquad U_0 \approx \frac{1}{(1+\Upsilon^{2/3})^{1/2}}, \tag{6}$$

$$-\frac{dE}{Edt} = \frac{2}{3}\frac{\alpha^2 c\Upsilon^2}{r_e\gamma}U_1(\Upsilon) \qquad U_1 \approx \frac{1}{(1+(1.5\Upsilon)^{2/3})^2}, \tag{7}$$

$$\frac{<\omega>}{E} = \frac{4\sqrt{3}}{15}\Upsilon\frac{U_1(\Upsilon)}{U_0(\Upsilon)} = 0.462\Upsilon \;\; (\Upsilon\to 0), \quad 0.254 \;\; (\Upsilon\to\infty), \tag{8}$$

$$\delta_E = \frac{\Delta E}{E} = 1.24\left[\frac{\alpha^2\sigma_z\Upsilon}{r_e\gamma}\right]\Upsilon U_1(\Upsilon); \tag{9}$$

$\Upsilon \ll 1$ is the "classic" regime; $\Upsilon \sim 0.2$–200 the "transition" regime ($\Upsilon U_1(\Upsilon) \approx 0.1$–$0.2 \sim 0.15$); $\Upsilon \gg 200$ the "quantum" regime. Colliders in the TeV region belong to the transition regime, multi-TeV LC with dense short bunches can reach the quantum regime.

The luminosity (1) can be expressed via δ_E. In the transition regime it does not depend on the bunch length σ_z:

$$L \sim \frac{6.45\delta_E}{4\pi\alpha r_e\gamma\sigma_y}\left(\frac{P}{mc^2}\right) = 1.5\times 10^{34}\frac{P[\mathrm{MW}]\delta_E}{E_0[\mathrm{TeV}]\sigma_y[\mathrm{nm}]}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}; \tag{10}$$

In the quantum regime

$$L \sim \frac{1.95}{4\pi\alpha^2\sigma_y}\sqrt{\frac{\delta_E^3}{r_e\sigma_z\gamma}}\left(\frac{P}{mc^2}\right) = 5\times 10^{34}\frac{P[\mathrm{MW}]}{\sigma_y[\mathrm{nm}]}\sqrt{\frac{\delta_E^3}{E_0[\mathrm{TeV}]\sigma_z[\mu\mathrm{m}]}}. \tag{11}$$

For example, for $P = 10$ MW per beam (about 200 MW from wall plug) $\sigma_y = 1$ nm, $2E_0 = 5$ TeV, $\delta_E = 0.2$ we get (accuracy is about factor of 2–3) $L = 1.2\times 10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in the transition regime (does not depend on σ_z) and $L = 3\times 10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in the quantum regime (for $\sigma_z = 1$ μm), an additional factor of ~ 1.5 can give the pinch effect. We see that the quantum regime (short bunches) helps but not too much.

In order to produce 10^3 characteristic reactions $e^+e^- \to \mu^+\mu^-$ per 10^7 sec at the energy $2E_0 = 5$ TeV the required luminosity is 3×10^{34}, that is close to the above limit due to beamstrahlung. So, if $\sigma_{y,min} \sim 1$ nm (see Sec. 4.5), the maximum reasonable energy of linear colliders is about $2E_0 \sim 5$ TeV.

In principle, there is a possibility to cancel beam fields by colliding four beams (e^+e^- from each side), then beamstrahlung is absent. The beams instability threshold remains at the same level of luminosity or may be only somewhat higher. This scheme can give some gain in luminosity, but technically it looks unrealistic.

4.3 Coherent e^+e^- pair creation

At $\kappa = (\omega/E_0)\Upsilon > 1$ a beamstrahlung photon can convert into e^+e^- pairs in the field of the opposing beam [9]. At $\kappa \gg 1$ the ratio of beamstrahlung/pair creation probabilities is about 3.8. The number of beamstrahlung photons at linear colliders $N_\gamma \sim N_e$ (in order to increse luminosity the horizontal size is decreased until each electron emit about one photon). Therefore the number of e^+e^- pairs at $\kappa \gg 1$ (or $\Upsilon \gg 1$), $N_{e^+e^-}/N_e = \mathcal{O}(0.1)$. For example, at CLIC(3000) $N_{e^+e^-}/N_e \sim 0.085$. The minimum energy of produce particles (important from a background point of view) $E_{min} \sim 0.05 E_0/\Upsilon$.

4.4 Deflection of soft particles

The lowest energy charged particles produced in process of coherent pair creation with the same sign of the charge as that of the opposing beam are deflected by the opposing beam on the angle [9]

$$\theta \sim \left(\frac{4\pi N e^2}{\sigma_z E_{min}}\right)^{1/2} \sim 170 \frac{N}{\sigma_z}\left(\frac{r_e^3}{\sigma_x}\right)^{1/2}. \tag{12}$$

For example, at CLIC $\theta \sim 15$ mrad. To avoid background from these large angle particles one should use the crab-crossing scheme [10]. Below we will see that crab-crossing angles below 20–30 mrad are acceptable, but larger angles lead to the increase of the vertical beam size.

So, deflection of soft particles put an additional constraint on the beam parameters. Beamstrahlung and instabilities may be OK (in case of very short bunches), but disruption angles are too large.

4.5 Minimum value of σ_y

The minimum vertical beam size at the interaction point (at $\beta_y \sim \sigma_z$) $\sigma_y = \sqrt{\varepsilon_{ny}\sigma_z/\gamma}$. Limitations:

- Attainable value of the normalized vertical emittance from an injector;
- Radiation in final quadrupoles (Oide effect) [11]. Minimum achievable beam size $\sigma_{min}[\mathrm{m}] \approx 1.7 \times 10^{-4} \varepsilon_{ny}[\mathrm{m}]^{5/7}$. For ε_{ny} considered in the current LC projects $\sigma_{min} \sim 0.5$ nm;
- Radiation in the detector solenoid field due to the crab crossing [12, 13, 14]

$$\sigma_y^2 = \frac{55 r_e^2}{480\sqrt{3}\,\alpha}\left(\frac{eB_s\theta_c L}{2mc^2}\right)^5. \tag{13}$$

For $B_s = 4$ T, $L = 4$ m $\sigma_y = 0.74$ nm for $\theta_c = 20$ mrad and 2 nm for $\theta_c = 30$ mrad. More accurate simulation of this effect (the number of emitted photon is about one) was done in Refs [13, 14]. As a linear collider without a detector has no sense this effect put a limit on a minimum vertical beam size at the interaction point at the level of 0.5 nm at $\theta_c = 20$ mrad.

4.6 Resume on maximum energies of linear colliders

For a reasonable wall plug AC power 100–300 MW the maximum energy of linear e^+e^- colliders with a luminosity sufficient for experiments, according to present understanding, is limited by collision effects at the level of $2E_0 = 5$–10 TeV.

5 Photon colliders

In addition to e^+e^- physics, linear colliders provide a unique opportunity to study $\gamma\gamma$ and γe interactions at high energies and luminosities [15, 16]. High energy photons can be obtained using Compton backscattering of laser light off high energy electrons. This option is foreseen in all other project of linear colliders [2, 3, 4, 5, 18]. The maximum energy of photons after Compton scattering

$$\omega_m = \frac{x}{x+1}E_0; \quad x \approx \frac{4E_0\omega_0}{m^2c^4} \simeq 15.3\left[\frac{E_0}{\mathrm{TeV}}\right]\left[\frac{\omega_0}{\mathrm{eV}}\right]. \tag{14}$$

For example: $E_0 = 250$ GeV, $\omega_0 = 1.17$ eV ($\lambda = 1.06$ μm) $\Rightarrow x = 4.5$ and $\omega_m = 0.82E_0 = 205$ GeV. The value $x = 4.8$ is the threshold for the process $\gamma\gamma_L \to e^+e^-$ in the conversion region. This determine the optimum laser wavelength: $\lambda_{opt} \sim 4E_0[\mathrm{TeV}]$ μm [19]. Nonlinear effects in Compton scattering increase the threshold value of x by a factor of $(1+\xi^2)$, where a parameter of nonlinearity $\xi^2 \sim 0.5$ is acceptable [18]. Most powerful solid state laser with $\lambda \sim 1.05$ μm can be used upto the energies $2E_0 \sim 800$ GeV. Detailed discussion of physics, and technical problem of photon colliders can be found elsewhere [18, 3, 28]. Below we consider only the most critical issues: luminosity, energy, laser system.

5.1 Current projects of photon colliders

Parameters of the photon colliders at TESLA [18] (as an example) are presented in Table 2, for comparison the luminosity in e^+e^- collisions is also given. Other parameters, constant for all energies, are: $\lambda = 1.06$ μm, $N = 2\times10^{10}$, $\sigma_z = 0.3$ mm, $f_{rep}\times n_b = 14.1$ kHz, $\varepsilon_{nx}/\varepsilon_{ny} = 2.5/0.03\times10^{-6}$ m·rad, $\beta_x/\beta_y = 1.5/0.3$ mm.

For the same energy the $\gamma\gamma$ luminosity in the high energy peak of the luminosity spectrum

$$L_{\gamma\gamma}(z > 0.8z_{max}) \approx (1/3)L_{e^+e^-}, \tag{15}$$

where $z = W_{\gamma\gamma}/2E_0$. Note, that cross sections in $\gamma\gamma$ collisions are typically larger then in e^+e^- by one order of magnitude. A more universal relation $L_{\gamma\gamma}(z > 0.8z_m) \approx 0.1L_{ee}(geom)$ (for $k^2 = 0.4$). Expected $\gamma\gamma$, γe luminosity spectra at TESLA can be found elsewhere [20, 18, 21].

Table 2: Parameters of the photon collider at TESLA

$2E_0$, GeV	200	500	800
$W_{\gamma\gamma,max}$	122	390	670
$W_{\gamma \mathrm{e},max}$	156	440	732
$\sigma_{x/y}$ [nm]	140/6.8	88/4.3	69/3.4
b [mm]	2.6	2.1	2.7
L_{ee}(geom) [10^{34}]	4.8	12	19
$L_{\gamma\gamma}(z > 0.8 z_{m,\gamma\gamma})[10^{34}]$	0.43	1.1	1.7
$L_{\gamma e}(z > 0.8 z_{m,\gamma \mathrm{e}})[10^{34}]$	0.36	0.94	1.3
$L_{ee}(z > 0.65)[10^{34}]$	0.03	0.07	0.095
$L_{\mathrm{e}^+\mathrm{e}^-}$, [$10^{34}$]	1.3	3.4	5.8

The $\gamma\gamma$ luminosity at TESLA is limited by attainable electron beam sizes. Having beams with smaller emittances (especially the horizontal one) one would get a higher luminosity. In order to increase the geometric luminosity one should decrease the β-functions as much as possible, down to about a bunch length. In the current scheme of the final focus it was not possible to make β_x below 1.5 mm due to chromo-geometric abberations [18]. It is not clear whether this is a fundamental or just a temporary technical problem.

5.2 Ultimate luminosity of photon colliders

Though photons are neutral, $\gamma\gamma$ and γe collisions are not free of collision effects. Electrons and photons are influenced by the field of the opposite electron beam that leads to the following effects [19]:

- in $\gamma\gamma$: conversion of photons into $\mathrm{e}^+\mathrm{e}^-$ pairs (coherent pair creation);
- in γe: coherent pair creation; beamstrahlung; beam displacement.

Beam collision effects in $\mathrm{e}^+\mathrm{e}^-$ and $\gamma\gamma$, γe collisions are different. In particular, in $\gamma\gamma$ collisions there are no beamstrahlung and beam instabilities which limit the horizontal beam size in $\mathrm{e}^+\mathrm{e}^-$ collisions on the level 550 (350) nm for TESLA (NLC/JLC). A simulation, which includes all collision effects has shown that in $\gamma\gamma$ mode at TESLA one can use beams with the horizontal size down to $\sigma_x = 10$ nm (at smaller σ_x may be problems with the crab–crossing scheme) and influence of collision effects will be rather small [22, 20, 18]. The $\gamma\gamma$ luminosity (in the high energy part) can reach 10^{35} cm^{-2}s^{-1}. Note that now in TESLA project $\sigma_x \approx 500$ nm in $\mathrm{e}^+\mathrm{e}^-$ collisions and about 100 nm in the $\gamma\gamma$ collisions. Having electron beams with much smaller emittances one could build a photon collider factory with production rate of new particles by a factor of 10–50 higher than at $\mathrm{e}^+\mathrm{e}^-$ colliders. A laser cooling of electron beams is one of the possible methods of reducting beam emittances at photon colliders [23, 24], but this method is not easy.

Note that small rate of coherent $\mathrm{e}^+\mathrm{e}^-$ pair production at TESLA energies is partially explained by the beam repulsion which reduces the field acting on the photons. For multi-TeV energies and short bunches such suppression is absent and photon colliders reach their energy limit (with adequate luminosity) approximately at the same energies as $\mathrm{e}^+\mathrm{e}^-$ colliders [25, 26, 27].

5.3 Technical aspects of photon colliders

A key element of photon colliders is a powerful laser system which is used for the $e \to \gamma$ conversion. Required parameters are: a few Joules flash energy, a few picosecond duration and 10–20 kHz repetition rate.

To overcome the "repetition rate" problem it is quite natural to consider a laser system where one laser bunch is used for the $e \to \gamma$ conversion many times. At the TESLA, the electron bunch train contains 3000 bunches with 337 ns spacing, here two schemes are feasible: an optical storage ring and an external optical cavity [20, 18, 21]. With the optical cavity a required laser power can be lower than in the case of a one-pass laser by factor of 50–100. There is no detailed scheme of such laser system yet.

At NLC, the electron bunch train consists of 96 bunches with 2.8 sec spacing therefore exploiting of the optical cavity is not effective. A current solution is a one-pass laser scheme based on the Mercury laser developed for the fusion program. The laser produces 100–200 J pulses which after splitting to 96 pulses can be used for $e \to \gamma$ conversion of one train [3, 21].

A laser system for a photon collider can certainly be built though it is not easy and not cheap.

6 Advanced accelerator schemes

Conventional RF linear colliders have accelerating gradients up to 150 MeV/m, corresponding lengths about 30–40 km and attainable energies up to 5 TeV (Sec.2). On the other hands, people working on plasma and laser methods of acceleration have obtained gradients of 100 GeV/m! Some people are thinking already about 100 TeV and even 1 PeV linear colliders or about 1–5 TeV LC with less than one km length.

Certainly, new methods of acceleration will make further progress and find certain applications, but it is less clear about possibility of super high energy colliders based on these technologies.

First of all, collision effects restrict the energy of linear colliders at about 10 TeV (Sec.4); secondly, the quality of electron beams should be very high; and thirdly, it is very likely that in considerations of very high acceleration gradients some important effects are just missed. Driven by my curiosity and for self-education I have spent some time for random check of these conceptions and some remarks are presented below. Situation in this field is not bad, but some of existing proposals are certainly wrong.

6.1 Plasma acceleration

Laser or particle beams can excite waves in plasma with a longitudinal electrical field [29]. The accelerating gradient

$$G \sim mc\omega_p \sim 10^{-4}\sqrt{n_p[\mathrm{cm}^{-3}]}\left(\frac{\mathrm{MeV}}{\mathrm{m}}\right). \qquad (16)$$

Typical parameters considered: $n_p \sim 10^{15}$ cm^{-3}, $G \sim 2$ GeV/m.

6.1.1 Multiple scattering

Let us consider the case $n_b \gg n_p$ when all plasma electrons are pushed out from the accelerated beam. The beams travel through ions with density n_p and experience a plasma focusing with the β-function [30] $\beta \sim \sqrt{2\pi\gamma/r_e n_p} = \sqrt{2\gamma}\lambda_p$. The r.m.s. angle due to multiple scattering

$$\Delta\theta^2 \approx \frac{8\pi Z^2 r_e^2 n dz}{\gamma^2}\frac{d\rho}{\rho}, \quad \rho_{min} \sim R_N, \quad \rho_{max} \sim R_D, \tag{17}$$

where $R_D = (kT/4\pi ne^2)^{1/2}$ is the Debai radius. The increase of the normalize emittance $\Delta\varepsilon_n{}^2 = \gamma^2 r^2 \Delta\theta^2 = \varepsilon_n\ \gamma\beta\Delta\theta^2$. After integration on the energy we get the final normalized emittance

$$\varepsilon_n \sim 8\pi\sqrt{2\pi}Z^2(n_p r_e^3 \gamma_f)^{1/2}(mc^2/G)\ L, \tag{18}$$

where $L = \ln\rho_{max}/\rho_{\min} \sim 20$. Substituting $n = 10^{15}$ cm^{-3}, $G = 2$ GeV/m, $Z = 1$, $\gamma_f = 5\times10^6$ ($2E_0 = 5$ TeV) we get $\varepsilon_n \sim 3\times10^{-7}$ cm. Note that the result does not depend on the plasma density because $G \propto \sqrt{n_p}$ (Eq.16). In present LC designs the minimum vertical emittance $\varepsilon_{ny} = 2\times10^{-6}$ cm, so multiple scattering in an *ideal* plasma accelerators look acceptable. It is assumed that sections with plasma have small holes for beams since any windows will give too large scattering angles.

6.1.2 Synchrotron radiation

Due to a strong focusing by ions (plasma electrons are pushed out from the beam), beam electrons lose their energy to radiation, the radiation power $P = (2/3)cr_e^2\gamma^2E_\perp^2$, where $E_\perp = 2\pi e n_p Z r$ (as before we assume $n_b \gg n_p$), $r \sim \sqrt{\varepsilon_n\beta/\gamma}$, $\beta = \sqrt{2\pi\gamma/r_e n_p}$. After integration on the energy we find the difference of energies for the particle on the axis (no radiation) and one at the r.m.s distance form the axis

$$\Delta E/E \sim 25 r_e^{5/2} n_p^{3/2} Z^2 \gamma_f^{3/2}(mc^2/G)\varepsilon_n\ . \tag{19}$$

For $G = 2$ GeV/m, $n_p = 10^{15}$ cm^{-3}, $\varepsilon_{nx}\ \sim 10^{-4}$ cm (emittance from damping rings or from photo-guns), $\gamma_f = 5\times10^6$ ($2E_0 = 5$ TeV) we get $\Delta E/E \sim 10^{-3}$, that is acceptable. For several times larger energy spreads there are chromaticity problems in final focus systems. Note, that $G \propto \sqrt{n_p}$, therefore the energy spread is proportional to the plasma density. In Ref. [31] the case of the overdense plasma ($n_b < n_p$) was also investigated with the conclusion that it is not suited for TeV colliders.

So, synchrotron radiation puts a limit on a maximum plasma density (and acceleration gradient). A 10 TeV collider with a gradient 10 times larger that at CLIC is still possible.

6.1.3 Some other remarks on plasma acceleration

Though plasma accelerators pass the simple criteria discussed above, there are many other question.

At $E_0 = 1$ TeV, $n_p = 10^{15}$ cm^{-3}, ε_{ny}=10^{-6} cm the transverse electron beam size in plasma is about 0.1 μm ! This means that the accelerating sections should have relative accuracy better than $0.1\sigma_y \sim 10^{-6}$ cm !

The beam axis is determined in large extent by the drive beam. The transverse size of the drive beam (of it's head which is focused by external quadrupoles) is of the order of 10^{-2} cm. Small fluctuations in the beam profile will lead to dilution of the accelerated beam emittance.

To avoid radiation of the high energy accelerated beam in the field of kickers during the injection of the drive beam, the kickers should be very fast, in 100 GHz frequency range [32]. Then the required stability of the horizontal angle is about $\sim 0.1\sigma_x/L \sim 0.1\times 10^{-4}/100 \sim 10^{-7}$ rad. If the kick angle is 10^{-2} rad, the required time stability is about $\sim \Delta x/c \times 10^{-5} \sim 10^{-16}$ sec.

In summary: a plasma acceleration is a perspective technique, it can find certain applications, but technical feasibility of plasma based linear colliders is not clear now.

6.2 Laser acceleration in vacuum

There are many ideas on this subject. [1] In general, in a space with some boundaries the accelerating gradient is proportional to the electric field, $G \propto E$, and $G \propto E^2$ in an open space. This is because the charged particle extracts the energy from the field due to interference of the external and radiated field:

$$\Delta\mathcal{E} \ \propto \int (E+E_{rad})^2\, dV - E^2\, dV \propto EE_{rad}\, dV, \tag{20}$$

where $E_{rad} \sim const$ when a particle radiates in a given structure without any field and in a free space the radiated field is proportional to a particle acceleration: $E_{rad} \propto E$.

6.2.1 $\mathbf{G \propto E}$

In this case, a particle is accelerated by the axial electrical field E_z of a focused laser. For a radially polarized Gaussian beam $E_z \sim E(\lambda/\pi w_0)$, where E is the transverse laser field, w_0 is the radius of the focal spot.

The electron is in the accelerating phase of the wave on the length $\sim Z_R$ (Rayleigh length). In order to get a net acceleration one has to put some screen with a small hole to restrict the interaction length. The damage threshold of the optical components is a limiting factor of the method. For the damage threshold 5 TW/cm^2 the maximum energy gain $\Delta E(\mathrm{MeV}) \sim 20[P(\mathrm{TW})]^{1/2}$, that is about 50 MeV for P = 10 TW [33]. There is a proposal to study this method at SLAC [34].

One of the other approaches uses small cavities pumped by a laser [35]. This method needs very small beam sizes (emittances) and severe tolerances.

There are many laser accelerating schemes of such kind under development.

6.2.2 $\mathbf{G \propto E^2}$

There are many fantasies on this subject.

1. Light pressure. If an electron is in the rest, a plane electromagnetic wave pushes it with a force $F = \sigma_T \times (E^2/4\pi)$, where σ_T is the Thomson cross section. This is because laser photons scatter isotropically and momenta of laser photons incident onto σ_T are transfered to the electron. At $I = 10^{28}$ W/cm^2 (in Ref.[36]), the accelerating gradient $d\mathcal{E}/dx = 1$ TeV/cm.

[1] In Secs 6.2, 6.3 $\mathcal{E}$ denotes an electron energy and E is the strength of a laser field.

Unfortunately, in a real wave, laser photons have the divergence $\theta \sim \sqrt{\lambda/4\pi Z_R}$. Therefore, if the electron has $\mathcal{E}/mc^2 > 1/\theta$, then in the electron rest frame laser photons come from the forward hemisphere and therefore the electron is deaccelerated! For $\lambda = 1$ μm and $Z_R = 100$ μm, $E_{max} \sim 15$ MeV only!

2. Ponderomotive acceleration. In a strong laser field an electron experiences a collective force from the whole laser bunch, so called a ponderomotive force [37, 38, 39],

$$F_i \sim \frac{mc^2}{\gamma}\frac{d\xi^2}{dx_i}, \quad \xi^2 = \frac{e^2\overline{E^2}}{m^2c^2\omega_0^2} = \frac{2n_\gamma r_e^2\lambda}{\alpha}. \tag{21}$$

This opens a way to transfer the energy from large body (laser beam) to one microscopic particle (electron). There is an idea [40] to collide the laser pulse propagating in a rare gas (to have $v^* < c$, large effective γ^*) with the oncoming electron bunch with a relativistic factor γ_0, so that after elastic reflection the electron will have $\gamma = (\gamma^*)2/\gamma^0$. According to above Refs, for the laser power 4.3 EW (EW=10^{18} W) $\gamma^* = 1.6 \times 10^6$ and $\gamma_0 = 1400$, the energy of reflected electrons in the laboratory system is 1 PeV $\equiv$ 1000 TeV! The length of the collider is the laser bunch length or almost ZERO!

Unfortunately, the idea is wrong due to many reasons:

- The interaction length is not the bunch length but $L_{int} \sim l_{laser}/(1 - v^*/c) \sim l_{laser} \times (\gamma^*)^2 \sim 10^{-2} \times 10^{12} \sim 10^5$ km !
- Radiation of electrons (see below), and many other "NO".

6.2.3 Radiation during a ponderomotive acceleration

During the ponderomotive acceleration electrons radiate in the transverse laser field. This can be treated as Compton scattering. Radiated energy per unit length: $d\mathcal{E}/dx \sim \bar{\epsilon}\, n(1-\cos\theta)\sigma_T$. Substituting $\theta^2 \sim \lambda/(2\pi Z_R)$, $\bar{\epsilon} \sim \omega_0\gamma^2\theta^2$, $n = \alpha\xi^2/(2r_e^2\lambda)$ we get

$$\frac{d\mathcal{E}}{dx} \sim \frac{\xi^2\gamma^2 r_e}{Z_R^2}mc^2. \tag{22}$$

For example: $\mathcal{E}_0 = 1$ TeV, $Z_R = 100$ μm, and $\xi^2 = 100$ (flash energy $\sim$ 100 J), $d\mathcal{E}/dx = -200$ GeV/cm. For the mentioned 1 PeV project with $\xi^2 = 2 \times 10^6$, $d\mathcal{E}/dx = -10^9$ PeV/cm!

So, ponderomotive acceleration can be useful for low energy application, but not for linear colliders due to the decrease of the force with the increase of the energy and a huge radiation.

7 Conclusion

Linear e^+e^-, e^-e^-, $\gamma\gamma$, γe colliders are ideal instrument for study of matter in the energy region $2E_0 \sim$ 100–1000 GeV. Three projects are almost ready for construction, a wise choice and political decision are needed.

A linear collider is not a simple machine, very high accuracies, stabilities and cleaver beam diagnostics are needed. Many critical elements have been tested experimentally.

According to present understanding a maximum attainable energy of linear colliders with adequate luminosity is about $2E_0 \sim 5$ TeV. There is technology for such "last" LC, that is CLIC.

Advance technologies (plasma, laser) can give higher accelerating gradients but their application for high energy linear colliders is under big question. Further complex studies of new accelerating methods in this context are needed.

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