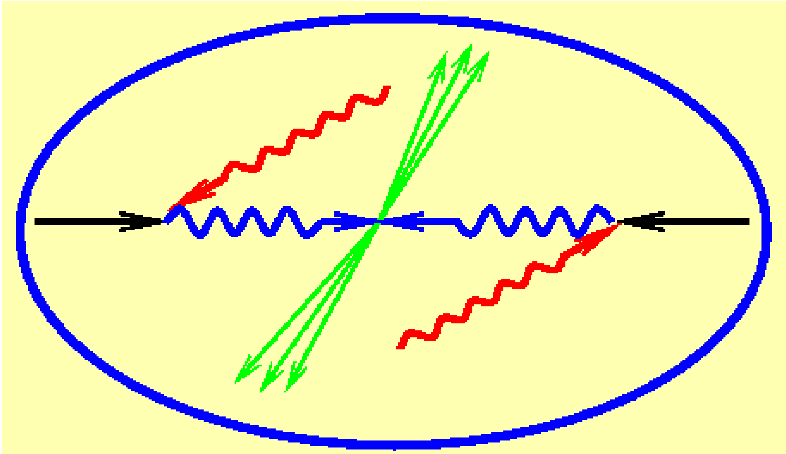


Photon Collider at ILC

Valery Telnov

Snowmass, Aug.16, 2005,

GG6 group session

Goal of the Global Group GG6

GG6: Options:

Understand requirements and configurational issues related to possible alternatives to e+e- collisions, including $\gamma\gamma$, γe, e-e-, GigaZ and fixed target; identify potential performance parameters.

Today $\gamma\gamma$, γe

Photon collider

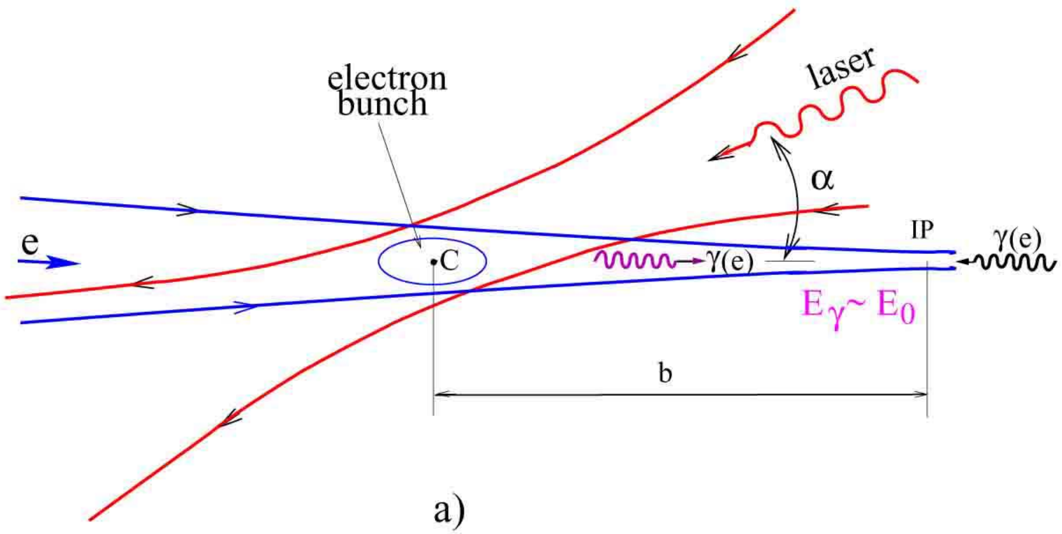
(mainly requirements and configurational issues)

Contents

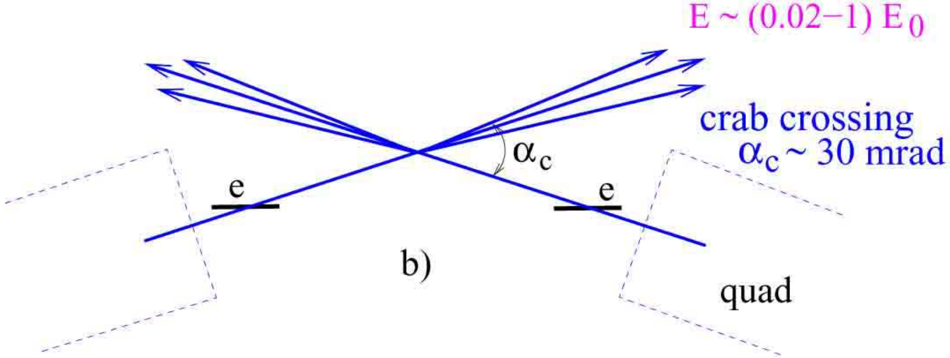
- Basic principles and parameters of the $\gamma\gamma$, γe collider
- Physics motivation (briefly)
- Interaction region
  - Factors limiting luminosities
  - Possible beams parameters and luminosities
  - Collision scheme, crab crossing angle
  - Effects of the detector field
  - Angle between tunnels, big band
  - Final quad
  - Problems of the beam removal, beam dump
- Lasers, optics
- Conclusion

Scheme of $\gamma\gamma$, γe collider

GKST,1981



a)



b)

$$\omega_m = \frac{x}{x+1} E_0$$

$$x \approx \frac{4E_0\omega_0}{m^2c^4} \simeq 15.3 \left[\frac{E_0}{\mathrm{TeV}}\right] \left[\frac{\omega_0}{\mathrm{eV}}\right]$$

$E_0 = 250$ GeV, $\omega_0 = 1.17$ eV
($\lambda = 1.06\ \mu$m) $\Rightarrow$
x=4.5, ω_m=0.82E_0=205 GeV

$x = 4.8$ is the threshold for $\gamma\gamma_L \to e^+e^-$ at conv. reg.

Due to the nonlinear effects in Compton scattering
$x_{th} \sim 4.8(1+\xi^2)$,
where $\xi \sim 0.3$ is acceptable.

Energy and luminosity of $\gamma\gamma,\gamma e$ collider based on TESLA (now ILC)

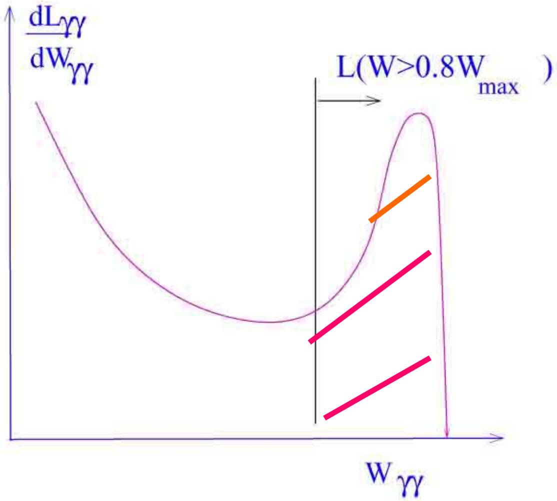
$\lambda_{laser} = 1.06\ \mu$m.

$2E_0$ (GeV)	200	500	800
$L_{geom}, 10^{34}$	4.8	12.0	19.1
$W_{\gamma\gamma,max}$ (GeV)	122	390	670
$L_{\gamma\gamma}(z > 0.8 z_{m,\gamma\gamma}), 10^{34}$	0.43	1.1	1.7
$W_{\gamma e,max}$ (GeV)	156	440	732
$L_{e\gamma}(z > 0.8 z_{m,\gamma e}), 10^{34}$	0.36	0.94	1.3
$L_{e^+e^-}, 10^{34}$	1.3	3.4	5.8

?

$$L_{\gamma\gamma}(z > 0.8 z_m) \sim \frac{1}{3} L_{e^+e^-}$$

where $z = W_{\gamma\gamma}/2E_0$.



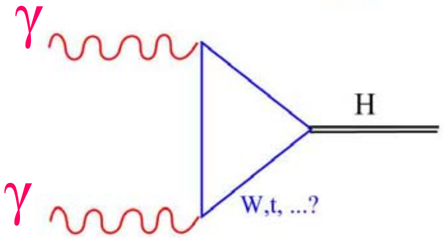
$W_{max} \sim 0.8 \times 2E_0$ in $\gamma\gamma$

($W_{max} \sim 0.9 \times 2E_0$ in $e\gamma$)

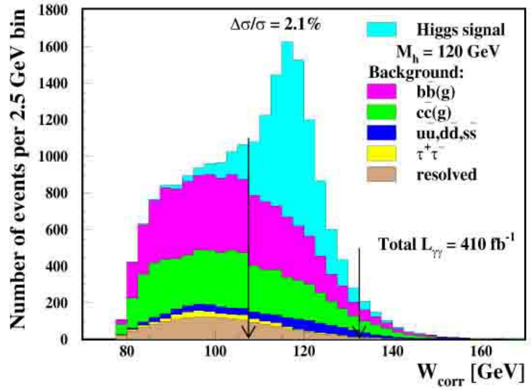
Some examples of physics

realistic simulation P.Niezurawski

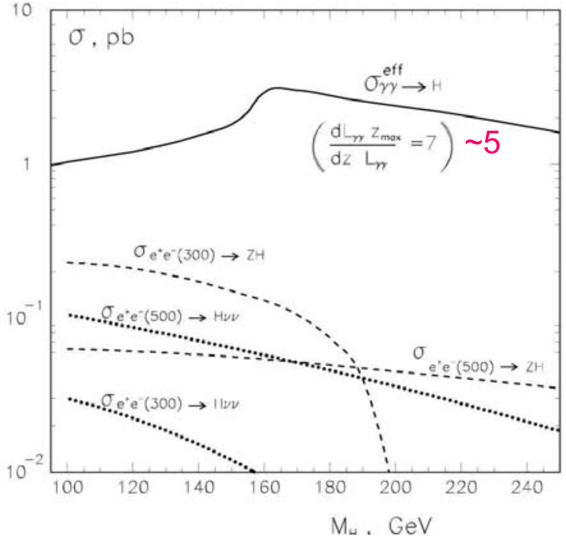
Higgs boson



Very sensitive to heavy charge particles in the loop.



Cross sections of the Higgs boson in $\gamma\gamma$ and e^+e^- collisions



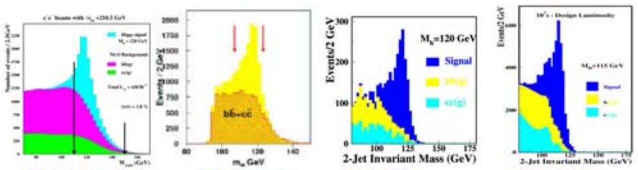
$$\dot{N}_{\gamma\gamma\to H} = L_{\gamma\gamma}\times\frac{dL_{\gamma\gamma}M_H}{dW_{\gamma\gamma}L_{\gamma\gamma}}\frac{4\pi^2\Gamma_{\gamma\gamma}(1+\lambda_1\lambda_2)}{M_H^3}$$

At TESLA

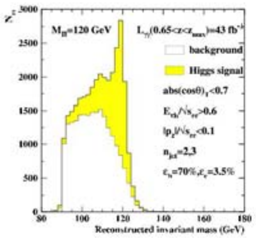
$$\frac{N(\gamma\gamma\to H)}{N(e^+e^-\to H+X)}\sim 1-10$$

for $M_H = 100-250$ GeV.

(previous analyses)

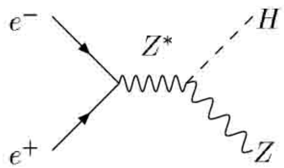


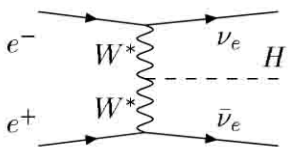
Niezurawski(TESLA) Rosca(TESLA) Asner(NLC) Asner(Cliche)



S.Soldner-Remboldt

H in e^+e^-



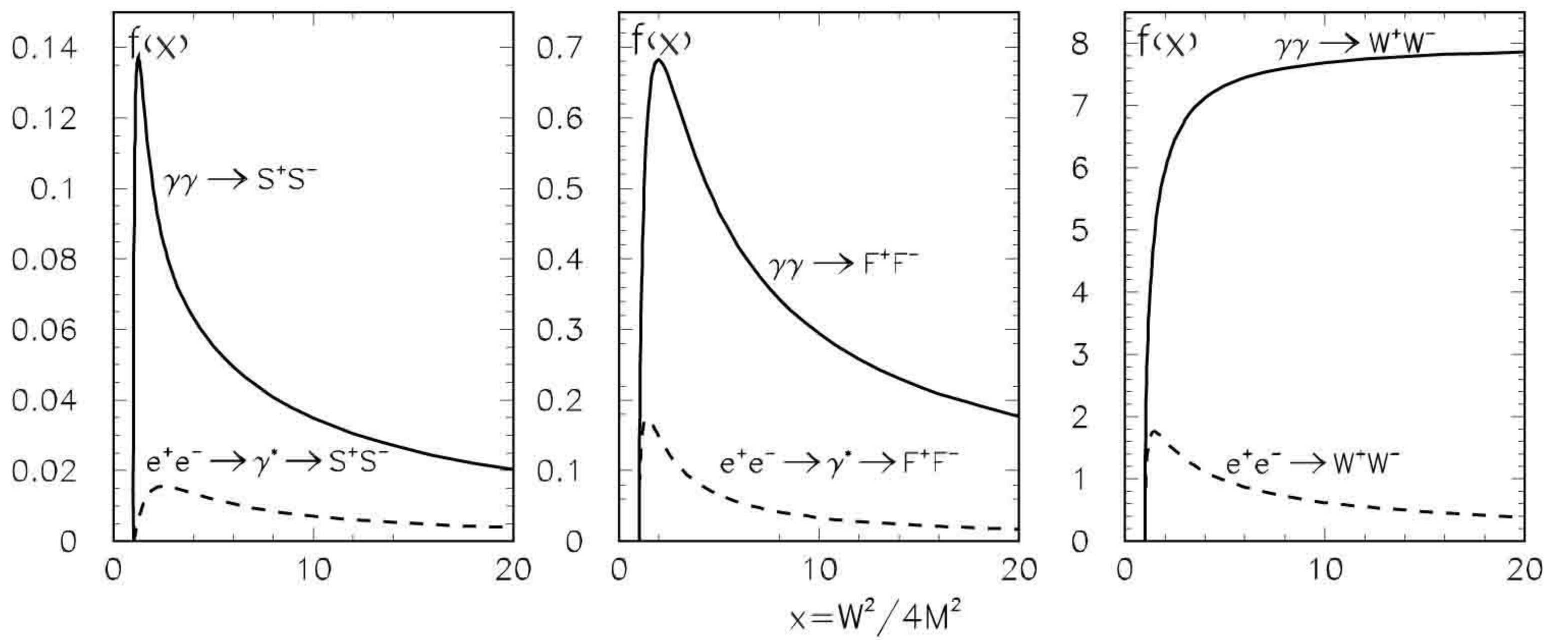


Some examples of Physics

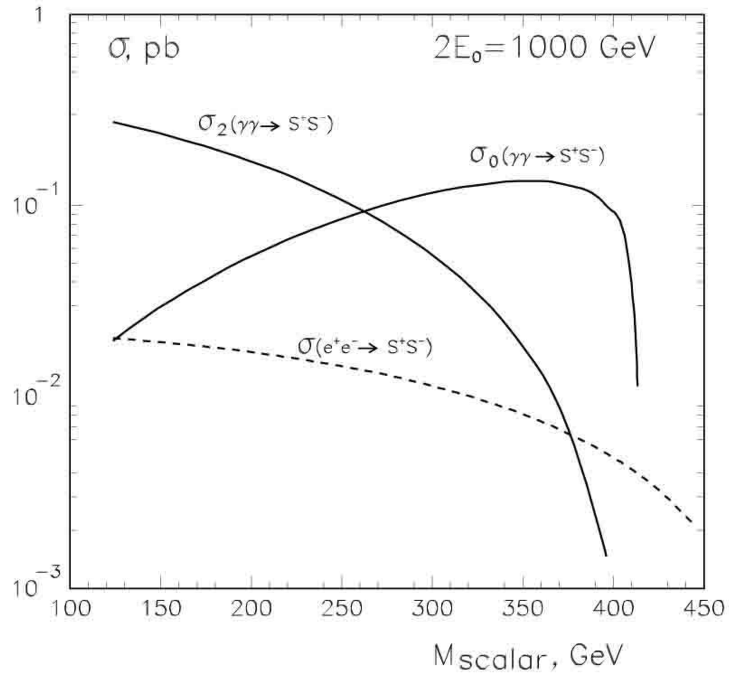
Charged pair production in e^+e^- and $\gamma\gamma$ collisions.

(S (scalars), F (fermions), W (W-bosons);
$\sigma = (\pi\alpha^2/M^2)f(x)$, beams unpolarized)

unpolarized
beams



Cross sections for charged scalars, $2E_0 = 1$ TeV



polarized
$\gamma\gamma$ beams

Resume:

- Typical cross sections of charged pair production in $\gamma\gamma$ collisions is higher than in e^+e^- by one order of magnitude.

- $\gamma\gamma$ reactions go via photons, while in e^+e^- Z-boson and t-exchange by some unknown particles also contributes, so reactions are complementary.

Supersymmetry in $\gamma\gamma$

In supersymmetric model there are 5 Higgs bosons:

h^0 light, with $m_h < 130$ GeV

H^0, A^0 heavy Higgs bosons;

H^+, H^- charged bosons.

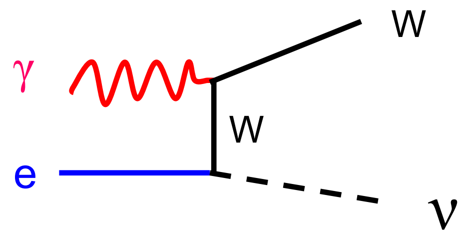
$M_H \approx M_A$, in e^+e^- collisions H and A are produced in pairs (for certain param. region), while in $\gamma\gamma$ as the single resonances, therefore:

in e^+e^- collisions $M_{H,A}^{max} \sim E_0$ ($e^+e^- \rightarrow H + A$)
in $\gamma\gamma$ collisions $M_{H,A}^{max} \sim 1.6 E_0$ ($\gamma\gamma \rightarrow H(A)$)

Supersymmetry in γe

At a γe collider charged particles with masses higher than in e$^+$e$^-$ collisions at the same collider can be produced (a heavy charged particle plus a light neutral one, such as a new W' boson and neutrino or supersymmetric charged particle plus neutralino):

$$m_{\tilde{e}^-} < 0.9 \times 2E_0 - m_{\tilde{\chi}_1^0}$$



Gold-plated processes at photon colliders

Reaction	Remarks
$\gamma\gamma \to h_0 \to \bar{\mathrm{b}}\mathrm{b}$	$\mathcal{SM}$ (or $\mathcal{MSSM}$) Higgs, $M_{h_0} < 160\mathrm{GeV}$
$\gamma\gamma \to h_0 \to WW(WW^*)$	$\mathcal{SM}$ Higgs, $140\mathrm{GeV} < M_{h_0} < 190\mathrm{GeV}$
$\gamma\gamma \to h_0 \to \mathrm{ZZ}(\mathrm{ZZ}^*)$	$\mathcal{SM}$ Higgs, $180\mathrm{GeV} < M_{h_0} < 350\mathrm{GeV}$
$\gamma\gamma \to h_0 \to \gamma\gamma$	$\mathcal{SM}$ Higgs, $M_{h_0} < 150\mathrm{GeV}$
$\gamma\gamma \to H, A \to \bar{\mathrm{b}}\mathrm{b}$	$\mathcal{MSSM}$ heavy Higgs, for intermediate $\tan\beta$
$\gamma\gamma \to \tilde{f}\bar{\tilde{f}},\ \tilde{\chi}_i^+\tilde{\chi}_i^-,\ H^+H^-$	large cross sections, possible observ. of FCNC
$\gamma\gamma \to S[\tilde{t}\bar{\tilde{t}}]$	$\tilde{t}\bar{\tilde{t}}$ stoponium
$\gamma\mathrm{e} \to \tilde{e}^-\tilde{\chi}_1^0$	$M_{\tilde{e}^-} < 0.9 \times 2E_0 - M_{\tilde{\chi}_1^0}$
$\gamma\gamma \to W^+W^-$	anomalous W interact., extra dimen.
$\gamma\mathrm{e}^- \to W^-\nu_e$	anomalous W couplings
$\gamma\gamma \to WW + WW(ZZ)$	strong WW scatt., quartic anom. W, Z coupl.
$\gamma\gamma \to t\bar{t}$	anomalous top quark interactions
$\gamma\mathrm{e}^- \to \bar{t}b\nu_e$	anomalous Wtb coupling
$\gamma\gamma \to$ hadrons	total $\gamma\gamma$ cross section
$\gamma\mathrm{e}^- \to e^-X$ and ν_eX	structure functions (pol. and unpol.)
$\gamma g \to \bar{\mathrm{q}}\mathrm{q},\ \bar{\mathrm{c}}\mathrm{c}$	gluon distribution in the photon
$\gamma\gamma \to J/\psi\, J/\psi$	QCD Pomeron

Physics motivation: summary

In $\gamma\gamma$, γe collisions compared to e^+e^-

1. the energy is smaller only by 10-20%
2. the number of events is similar or even higher
3. access to higher particle masses
4. higher precision for some phenomena
5. different type of reactions

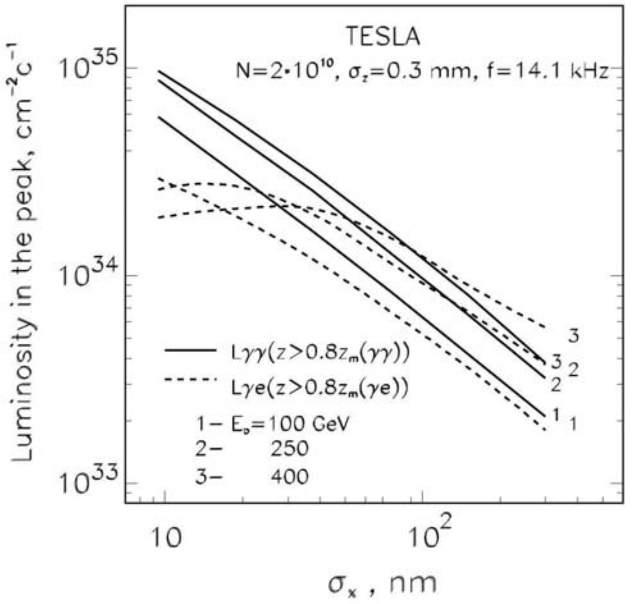
It is the unique case when the same collider allows to study new physics in several types of collisions at the cost of rather small additional investments

Factors limitting $\gamma\gamma$,γe luminosities

Collisions effects:

- Coherent pair creation
- Beamstrahlung
- Beam-beam repulsion
- Depolarization (not important)

On the right: dependence of $\gamma\gamma$ and γe luminosities in the high energy peak on the horizontal beam size:



For the TESLA electron beams $\sigma_x \sim 100$ nm at $2E_0 = 500$. Having beams with smaller emittances one could have by one order higher $\gamma\gamma$ luminosity.

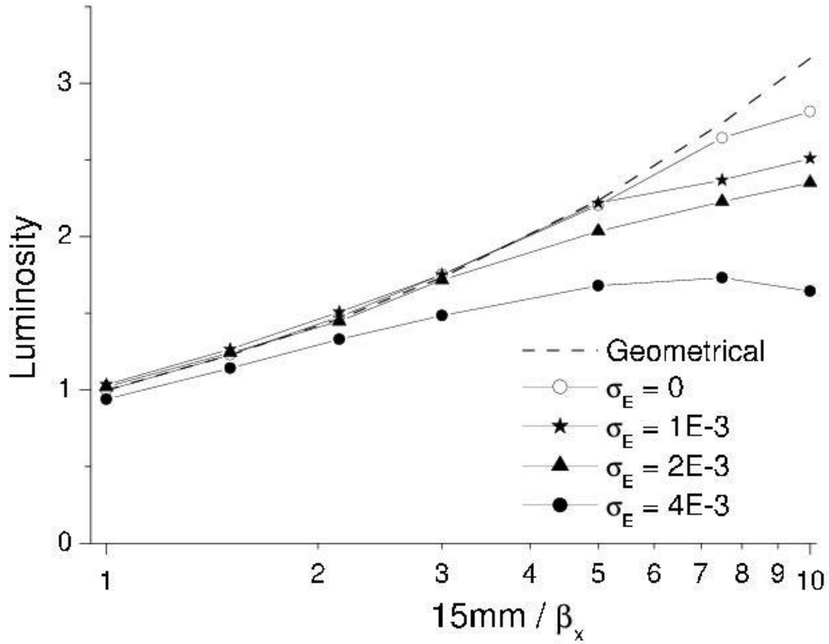
γe luminosity in the high energy peak is limited due to the beam repulsion and beamstrahlung

So, one need: ε_{nx}, ε_{ny} as small as possible and β_x , $\beta_y \sim \sigma_z$

β-functions

There is no problems to make $\beta_y=\sigma_z$ or even several times smaller, but there is a problem with reducing β_x due to chromo-geometric abberations.

In TESLA TDR we assumed β_x=1.5 mm (see A.Seryi figure) when there is about 20% loss of luminosity due to abberation. The minimum value of β_x depends on the emittances.



Emittances

Nominal ILC emittances (T.Raubemheimer table)

$\varepsilon_{nx}=10^{-5}$ m·rad, $\varepsilon_{ny}=4\times10^{-8}$ m·rad. Smaller emittances are not needed for *e+e-* due to beam-beam collision effects (beamstrahlung and instability).

For such emittances the minimum effective $\beta_x \sim 5$ mm (A.Seryi)

With TESLA damping ring optimized for $\gamma\gamma$ (W.Decking) we had at the IP $\varepsilon_{nx}=0.25\times10^{-5}$ m·rad, $\varepsilon_{ny}=3\times10^{-8}$ m·rad and min. effective $\beta_x \sim 2.2$ mm.

Similar emittances reported S.Mishra at LCWS04. With such emittances the geometric e^-e^- luminosity is larger than with the nominal ILC parameters by a factor of 3.5!

This is a large factor. If we plan the photon collider at ILC, we need to decrease emittances, especially ε_{nx} , as much as it is possible (at a reasonable cost). Such study has not been done yet.

A. Wolski gives a talk at this session on minimum emittances in damping rings.

Comparison of $L_{\gamma\gamma}$ and L_{e+e-}

At the nominal ILC parameters $L_{e+e-}=2\cdot10^{34}$ cm^{-2}c^{-1}. For same parameters, CP-IP distance b=1 mm and $t/\lambda_c=1$ $L_{\gamma\gamma}(z>0.8z_m)=3.4\cdot10^{33}$ or

$$L_{\gamma\gamma} / L_{e+e-} = 0.17$$

If one reduces somewhat emittances:

$\varepsilon_{nx}=10^{-5} \rightarrow 0.5\cdot10^{-5}$; $\varepsilon_{ny}=4\ 10^{-8} \rightarrow 3\cdot10^{-8}$ and $\beta_x=5 \rightarrow 3.7$ mm

then $L_{\gamma\gamma} / L_{e+e-} = 0.32$ (0.3 in TESLA TDR).

Optimistically, $\varepsilon_{nx}=10^{-5} \rightarrow 0.25\cdot10^{-5}$ ($\beta_x=5 \rightarrow 2.2$ mm)

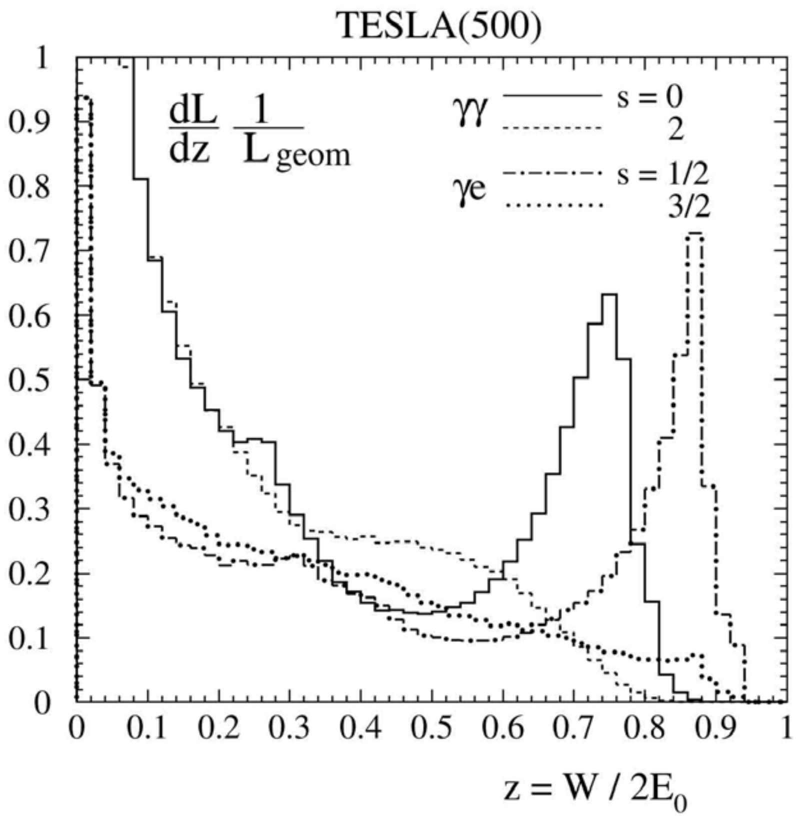
then $L_{\gamma\gamma} / L_{e+e-} = 0.59$

Note, cross section in $\gamma\gamma$ are larger then in e+e- by a factor of 10.

So, even in the worst case the number of events is $\gamma\gamma$ collisions is larger than that in e+e-, but it would be better, of course, to improve the luminosity by the additional factor 2 - 3.5, see above (which is not excluded).

Luminosity spectra

(decomposed in two states of J_z)



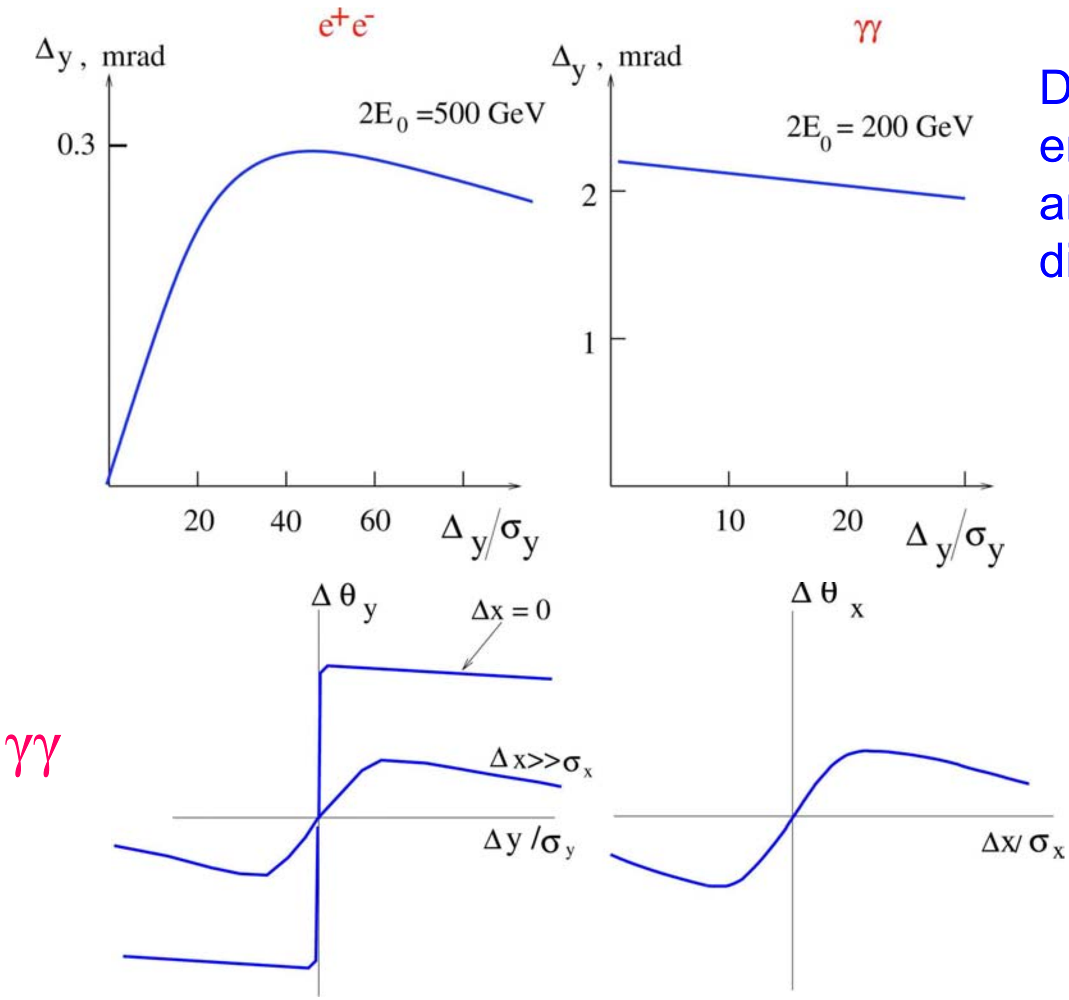
$\rho=b/\gamma\sigma_y=1$

(b=2.1 mm)

For γe it is better to convert only one electron beam, in this case it will be easier to identify γe reactions and the γe luminosity will be larger.

Stabilization of $\gamma\gamma$ luminosity by beam-beam deflection

V.Telnov, ECFA, Montepellier,2003

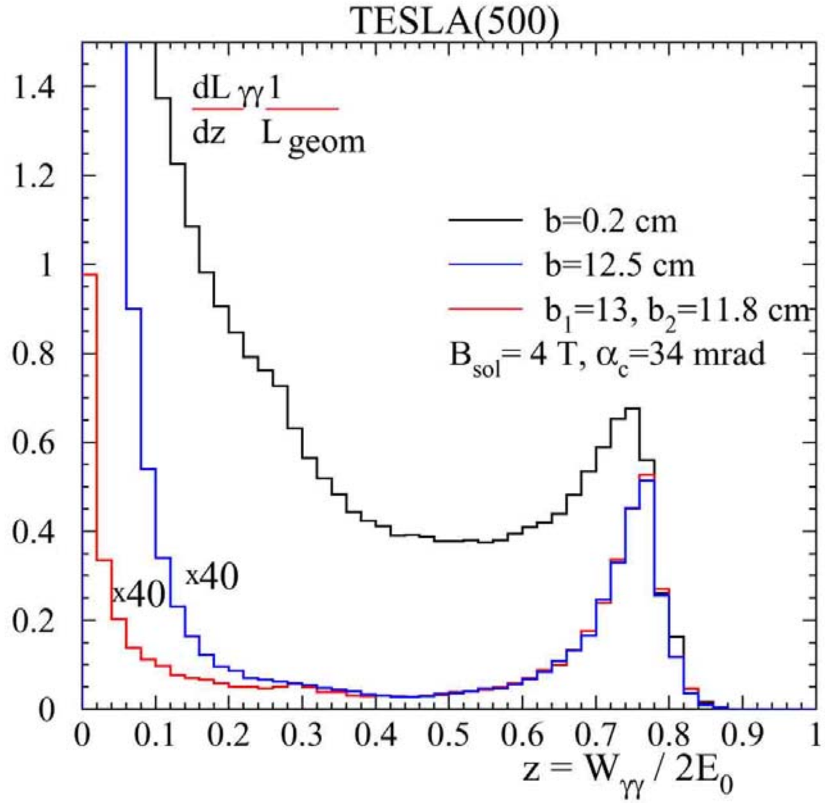


Due to smaller σ_x and lower average energy the kick in $\gamma\gamma$ is much larger and almost independent on the initial displacement

Prescription: the feedback system for γγ is similar to e+e- but uses different algorithm (for vertical displacement). Varying the beam position you finds the jump and then continuously go up and down by small steps ($\Delta y << \sigma_y$).
Zero point for pickups can be found by sending only one beam to the IP.

γ γ- luminosity spectrum for QCD study

For measurement of the total cross section or QCD study one needs lower luminosity (to decrease overlaping of events (about 1 hadronic event at the nominal luminosity), but more monochromatic. This can be achieved by increasing CP-IP distance.



Owing to the crossing angle and the detector field electron beams are deflected after the CP and do not collider, if b1≠b2 (red).

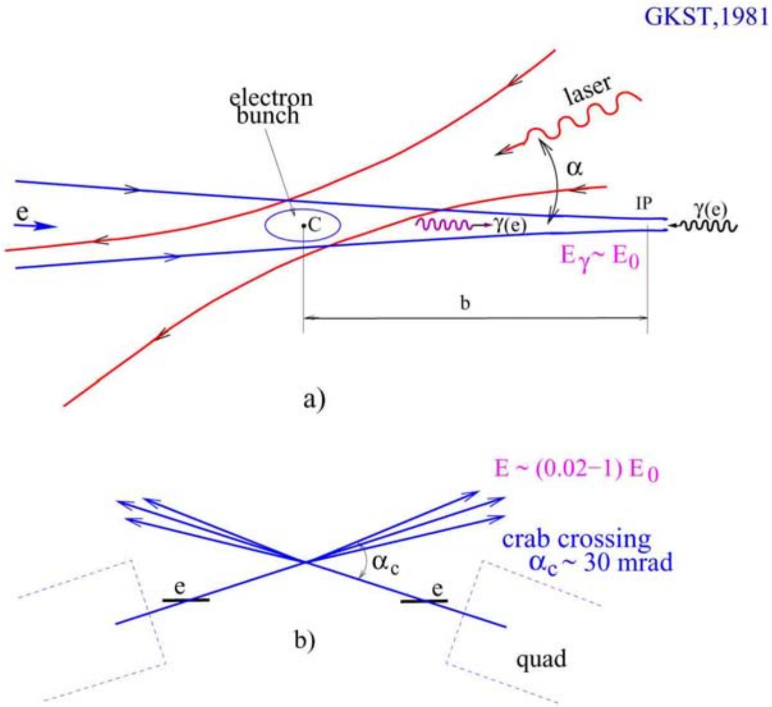
e^-e^- vs e^+e^-

Comparison was done in hep-ex/0507070 (V.Telnov's talk at LCWS05).

Conclusion:

e^+e are absolutely unusable for the photon collidere due to very serious problems with identification of $\gamma\gamma$ and e^+e^- reactions and a large low energy hadronic background.

Collision angle, crab-crossing scheme



After the collision the beams have a large energy spread: $E \sim (0.02-1)E_0$ and disruption angles $\theta_d \sim$ 10-12 mrad (the background from particles with larger angle is less than from unavoidable backgrounds).

The removal of disrupted beams need large crab-crossing angle:

$\alpha_c \sim R_{quad}/L^* + \theta_d$

$\sim 6/400 + 0.01 \sim 25$ mrad.

(For e^+e^- $\alpha_c = 20$ mrad is one of possible options.)

It is very desirable to have the crossing compatible with both collision modes, i.e. ≥ 25 mrads.

There are several problem due to crossing angle:

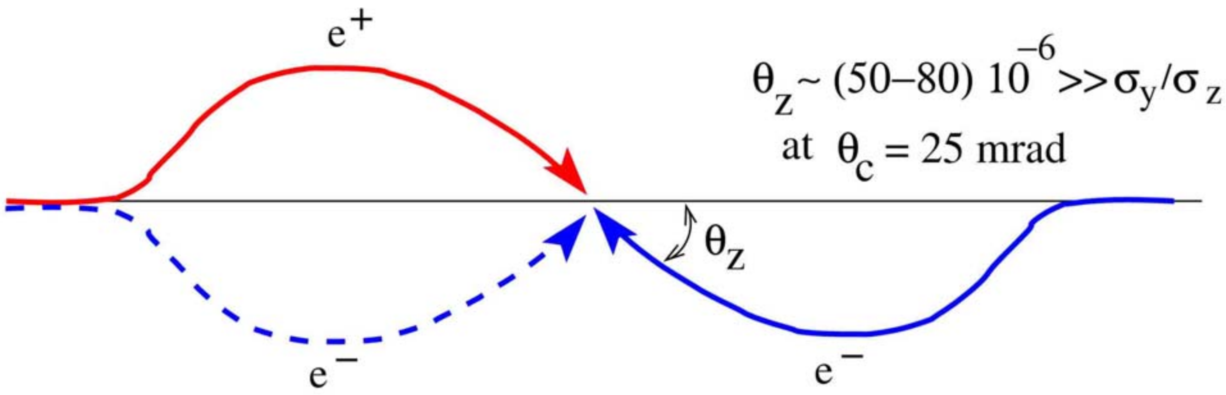
- Due to the detector field e^-e^- beam collide at a non-zero (unacceptably large) vertical collision angle;

- The increase of the vertical beam size due to radiation in the detector field, which depends strongly on α_c;

- The "big bend" length depends strongly on the bending angle;

- The additional vertical deflection of low energy particles

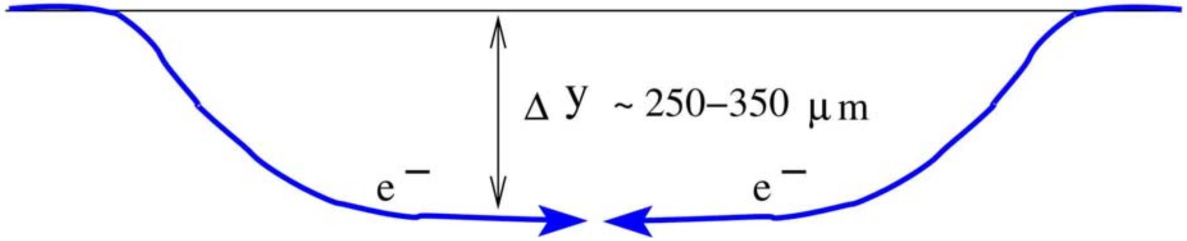
Trajectories in the detector field at $\alpha_c \neq 0$



OK for e+e−, but not OK for e−e−(gamma−gamma)

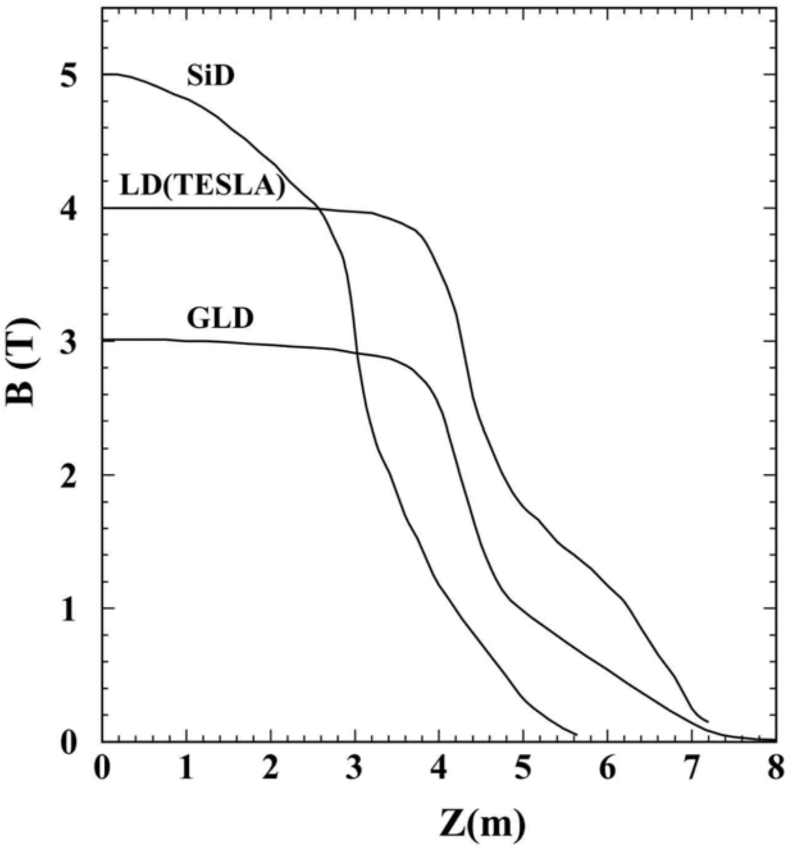
Vertical shifts of final qurds helps
for e−e−($\gamma\gamma$)

(or using correcting dipole coils)



Increase of σ_y due to SR

Detector field at the axis



Deflecting force which causes SR

$$F_y = e\frac{v}{c}(-B_z\,\theta_0 + B_r) = -e\frac{v}{c}\,\theta_0\left(B_z + \frac{\partial B_z}{\partial z}\frac{z}{2}\right).$$

where $\theta_0=\alpha_c/2$

Influence of SR on luminosity was found by full simulation
(V.Telnov, physics/0507134)

Results on $L(\alpha_c)/L(0)$

e^+e^- collisions

α_c(mrad)	0	20	25	30	35	40
LD	1.	0.98	0.95	0.88	0.83	0.76
SID	1.	0.995	0.985	0.98	0.95	0.91
GLD	1.	0.995	0.98	0.97	0.94	0.925

$\gamma\gamma$ collisions

α_c(mrad)	0	20	25	30	35	40
LD	1	0.99	0.96	0.925	0.86	0.79
SID	1	0.99	0.975	0.955	0.91	0.86
GLD	1	0.995	0.985	0.98	0.97	0.93

Statistical accuracy about $\pm 0.5\%$.

Conclusion: $\alpha_c = 25$ mrad is OK for all detectors.

For $\alpha_c = 30$ mrad the luminosity loss for LD is somewhat large, but possible can be optimized by proper shaping of the magnetic field (tails).

Configurations of tunnels

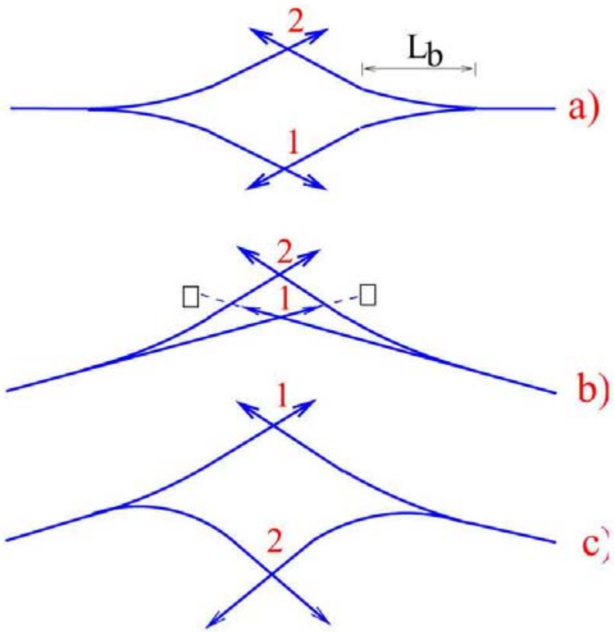


Figure 2: Possible configurations of tunnels at the ILC. The crab-crossing angle for e^+e^- (IP1) is about $\alpha_{c,1} =$ 0–20 mrad, smaller than that for $\gamma\gamma$ (IP2) which is $\alpha_{c,2} \sim$ 25 mrad.

Scheme a) the angle between tunnels is zero, it is the simplest configuration. The only problem: for maximum beam energies the bending length L_b required for a small emittance dilution may be too long.

Scheme b) there is non-zero angle between tunnels, bending angles are minimum, but may be problems with the space for detectors and for dumping of beams at the IP1.

Scheme c) the angle between tunnels is non-zero, as in the scheme a) the beams are bent in opposing directions, there is no problem with the space, but due to different bending angles the maximum energy for IP1 and IP2 are different. This scheme has sense only when tunnels will be used in future for other multi-TeV linear collider.

$$\Delta\epsilon_{nx} \propto \frac{E^6\alpha_b^5}{L_b^4}.$$

Taking the coefficient from the NLC ZDR one gets

$$\Delta\epsilon_{nx} = 1.8\times10^{-10}\left(\frac{2E_0}{\mathrm{TeV}}\right)^6\left(\frac{\mathrm{km}}{L_b}\right)^4\left(\frac{\alpha_b}{10\,\mathrm{mrad}}\right)^5\ \mathrm{m}$$

For $\epsilon_{nx} = 2\times10^{-6}$ m, $\alpha_b = 10$ mrad,
$\Delta\epsilon_{nx}/\epsilon_{nx} = 0.05$ at

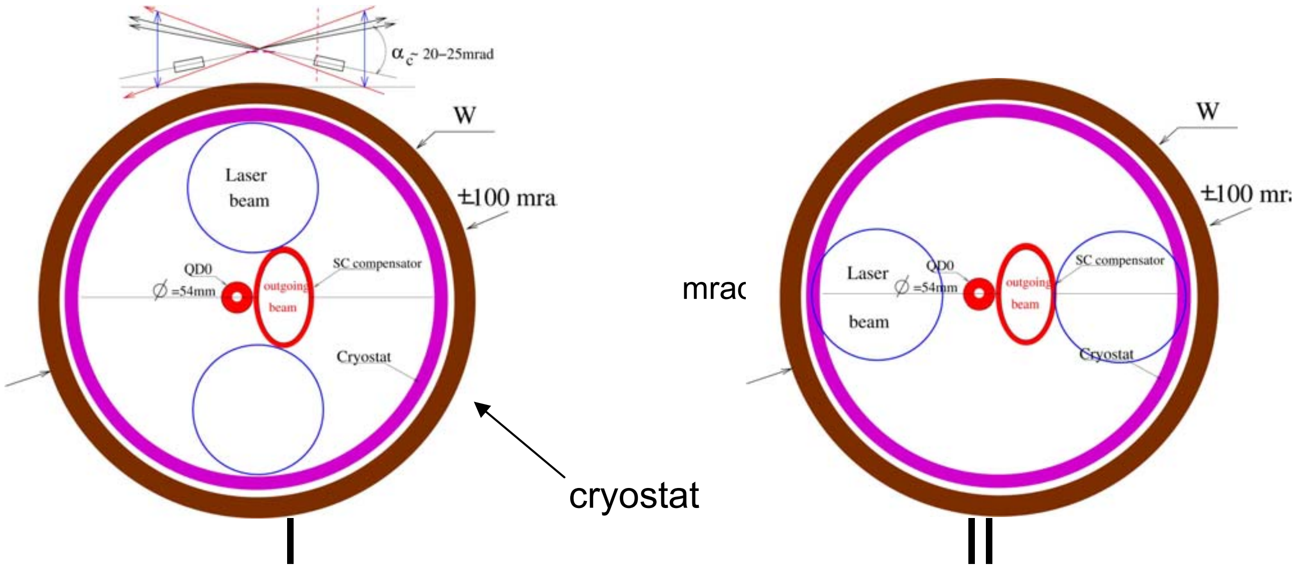
$2E_0$ TeV	1	2	3	5
L_b km	0.2	0.57	1.04	2.25

Optimum configuration depends on $E_{0,max}$

Final quads

The size of quads and the disruption angle determine the crossing angle.
Additional requirements:

- quad's field should be small in the region of low energy disrupted beams;
- quads should not stay on the way of laser beams

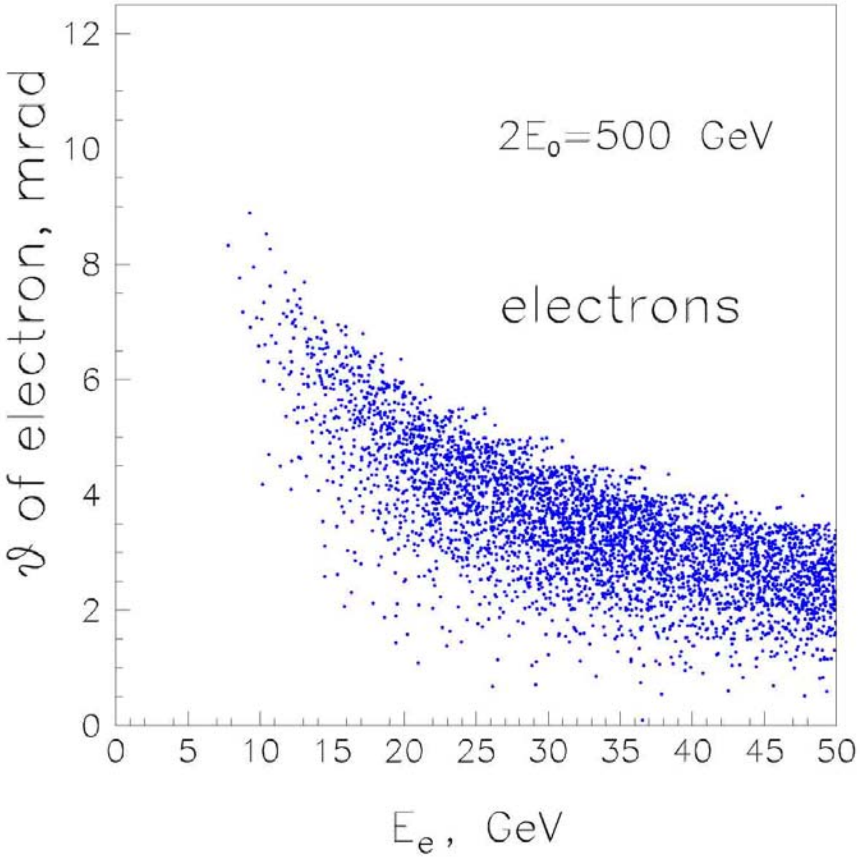


Details in B.Parker's talk.

The total angular size of the quad is somewhat larger for the scheme II. The required flash energy is also larger for the scheme II. So, the scheme I is better.

There are other ideas on quad designs. A compact quad without the field compensators and with a small diameter cryostat is not excluded. The work is just in the beginning.

Properties of the beams after CP,IP



Electrons:

E_{min}~6 GeV,
$\theta_{x\ max}$~8 mrad
$\theta_{y\ max}$~10 mrad

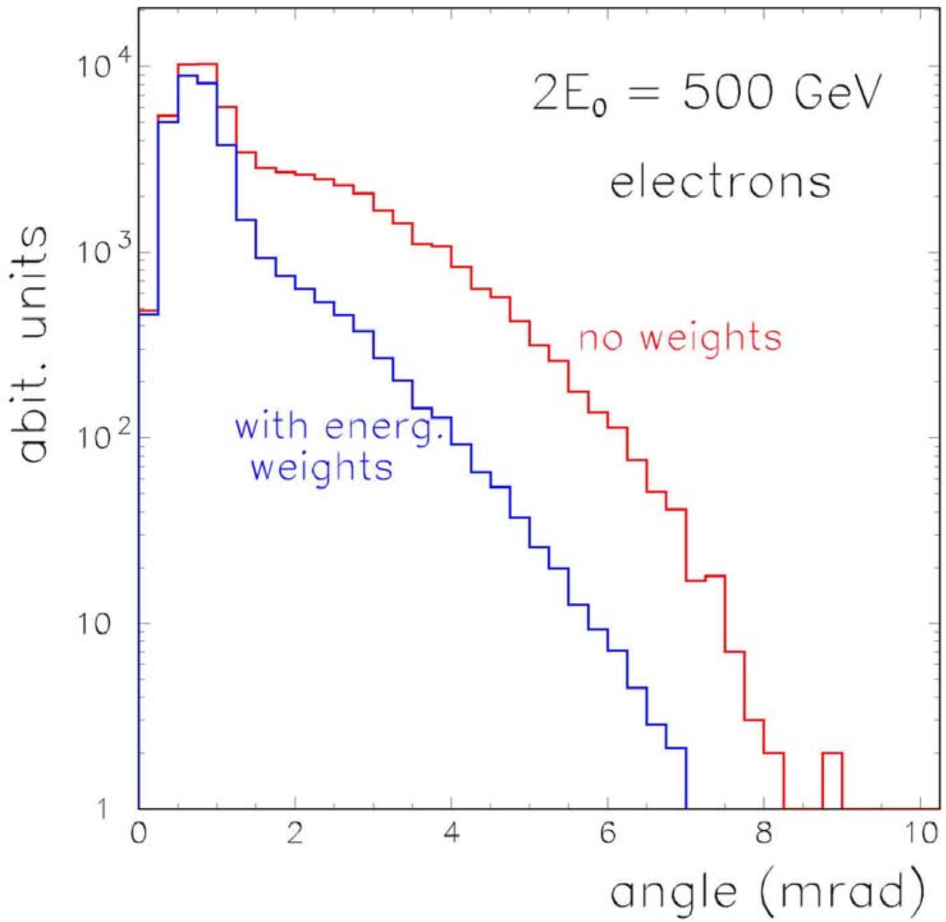
practically same for
E_0=100 and 250 GeV

low energy particles the deflection in
field of opposing beam

$$\vartheta \propto 1/\sqrt{E}$$

additional vertical deflection,
ut ±4 mrad, adds the detector field

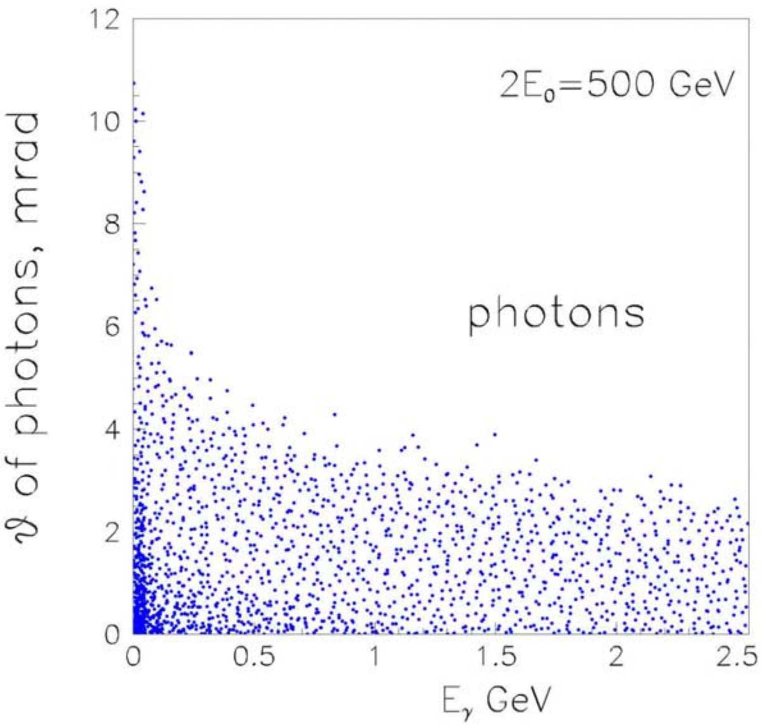
The angular distribution of electrons

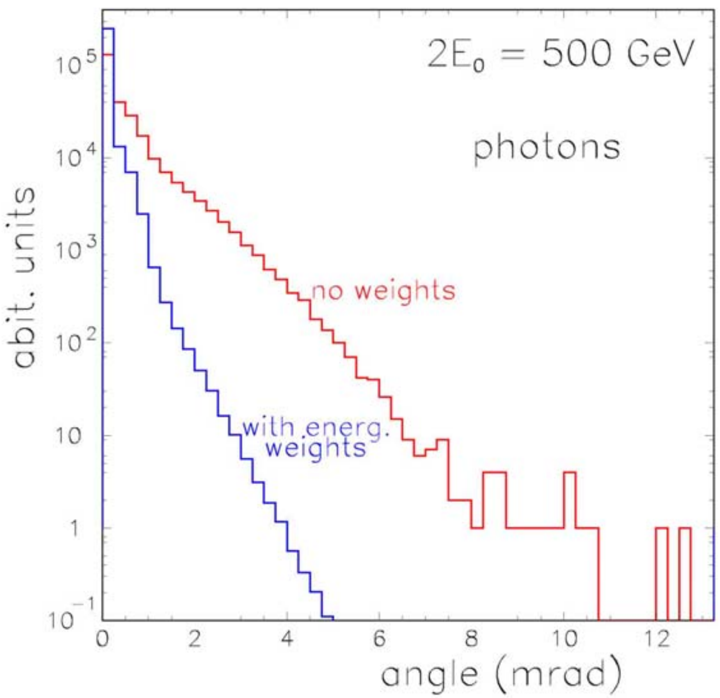


If the beam dump is situated at L=250 m, than for particles with θ=7 mrad r~1.8 m, too much. Some focusing of electrons will be useful in order to decrease the radius of the tube and to reduce the energy deposition (rad. activation on the way to the beam dump).

Angular distribution of photons

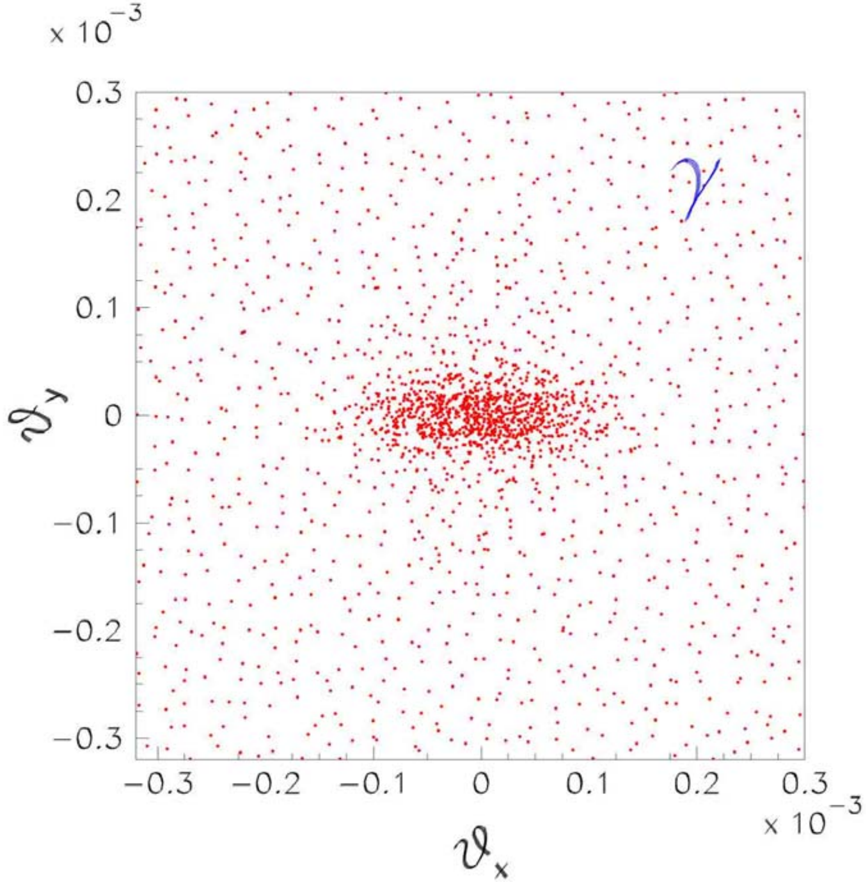
Large angle photons are radiated by low energy electrons, therefore they are soft





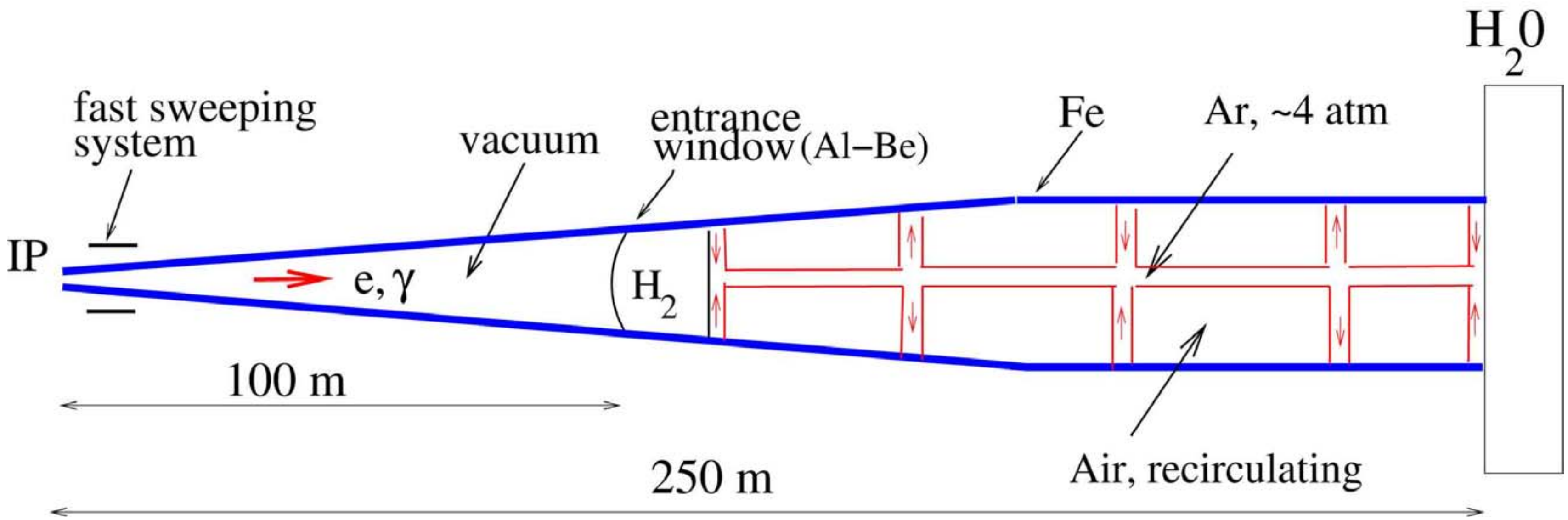
For photons the clear angle about 3 mrad will be sufficient, that is 75 cm at L=250 m.

On the contrary, the angular distribution of photons after Compton scattering is very narrow, equal to the angular divergence of electron beams at the IP: $\sigma_{\theta x} \sim 4 \cdot 10^{-5}$ rad, $\sigma_{\theta x} \sim 1.5 \cdot 10^{-5}$ rad, that is 1 x 0.35 cm^2 and beam power about 10 MW at the beam dump. No one material can withstand with such average power and energy of one ILC train.



Possible scheme of the beam dump for the photon collider

V.Telnov, L.Shektman



The photon beam produces a shower in the long gas (Ar) target and its density at the beam dump becomes acceptable. The electron beam without collisions is also very narrow, its density is reduced by the fast sweeping system. As the result, the thermal load is acceptable everywhere. The volume with H_2 in front of the gas converter serves for reducing the flux of backward neutrons.

In the previous scheme (V.Telnov,LCWS04 proceedings) Ar filled all diameter, in the present scheme off axis particles do not scatter therefore less energy reaches the tube.

Requirements for laser

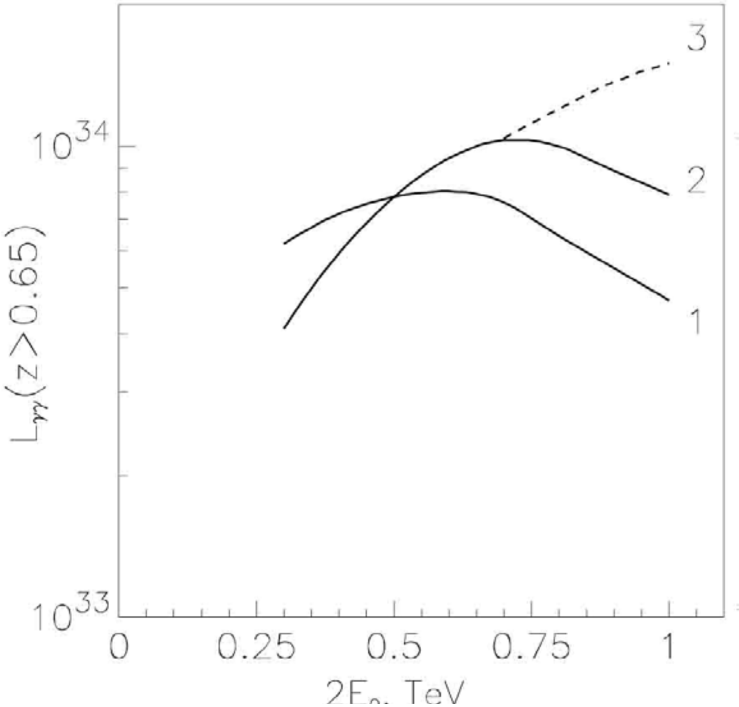
- Wavelength ~1 μm (good for 2E<0.8 TeV)
- Time structure Δct~100 m, 3000 bunch/train
- Flash energy ~5-10 J
- Pulse length ~1-2 ps

If a laser pulse is used only once, the required power is P~150 kW. Only 10^{-9} part of the laser photons is knocked out in one collision with the electron beam, therefore the laser bunch can be used many times.

The best scheme with storage and recirculation of very powerful laser bunch is an external optical cavity.

Dependence of the γγ luminosity on the energy due to laser parameters

V.Telnov, LCWS04, physics/0411252



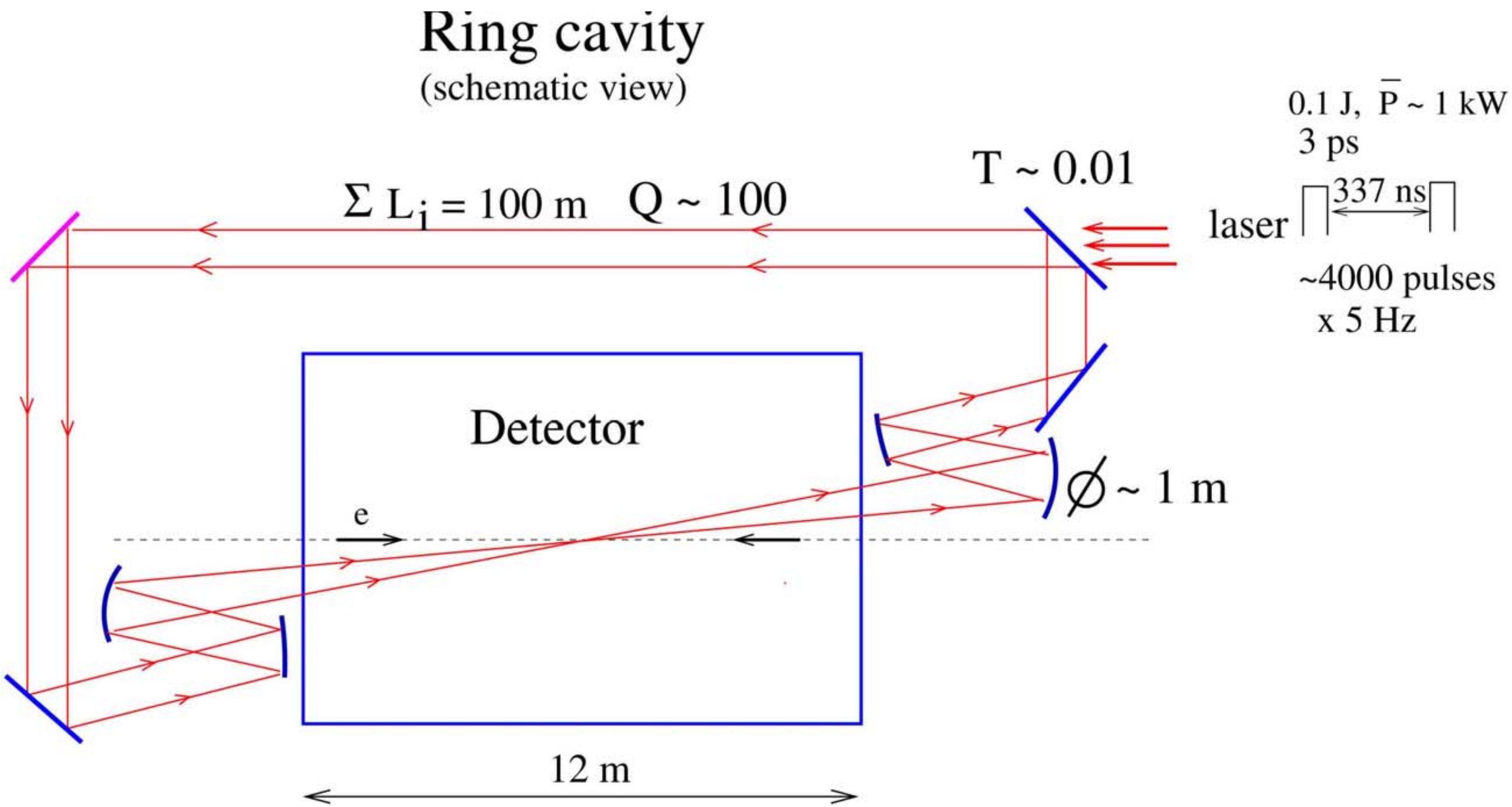
1- k=0.64 at 2E=500, A = const, ξ^2 = const, λ = 1.05 μm

2- k=0.64 at all energies, $\xi^2 \propto$ A, λ =1.05 μm

3- k=0.64 at all energies, $\xi^2 \propto$ A, λ =1.47 μm (to avoid pair creation)

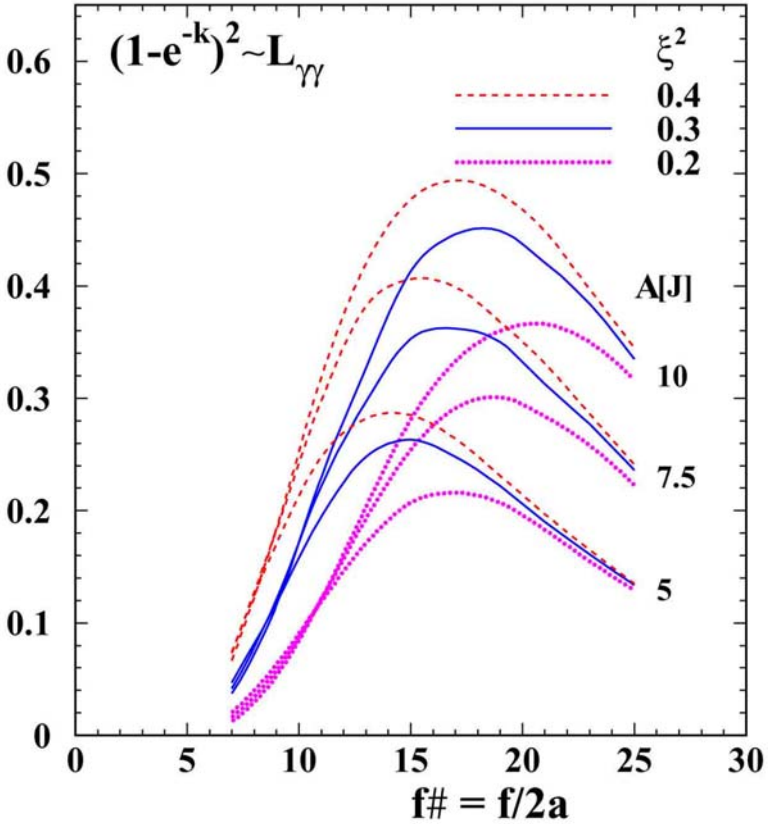
If the laser wave length is fixed, the Compton cross section decreases with increasing the energy, consequently the conversion coefficient decreases. Moreover for $x > 4.8$, the e^+e^- pair creation in the conversion region is possible which leads to large decrease of the conversion coefficient at large x. Laser with $\lambda \sim 1.05$ μm (most developed powerful lasers) can be used up to the energy of about $2E_0 = 750 - 800$ GeV. For $2E_0 = 1$ TeV it is desirable to use lasers with $\lambda \sim 1.5$ μm.

Laser system



Parameters of the laser system

The figure shows how the conversion efficiency depends on the f# of the laser focusing system for flat top beams in radial and Gaussian in the longitudinal directions



The parameter $\xi^2 = \frac{e^2F^2}{m^2c^2\omega^2} = \frac{2n_\gamma r_e^2\lambda}{\alpha}$

characterizes the probability of Compton scattering on several laser photons simultaneously, it should be kept below 0.2-0.4, depending on the energy (par. x)

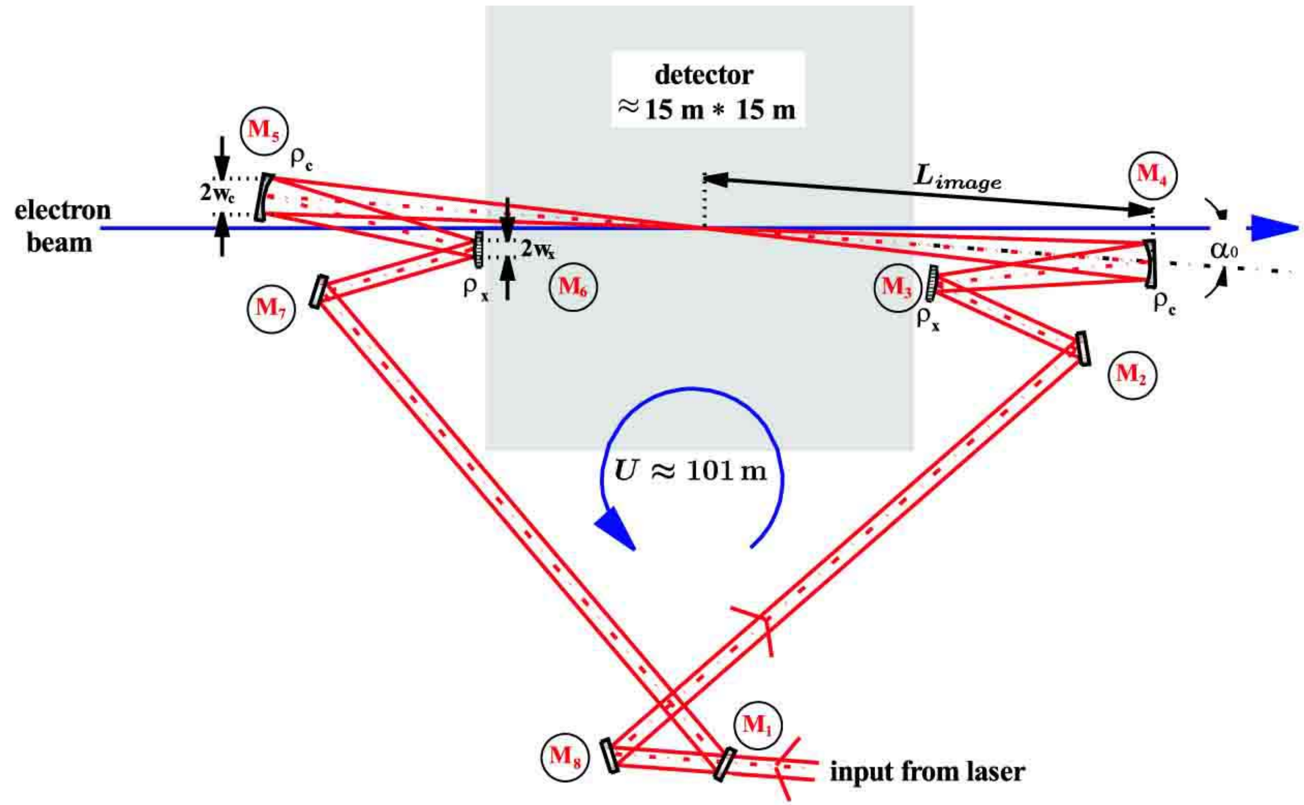
For ILC beams, α_c=25 mrad, and θ_{min}=17 mrad (see fig. with the quad) the optimum $f_\# \approx 17$, A≈9 J (k=1), $\sigma_t \approx 1.3$ ps.

So, the angle of the laser beam is $\pm 1/2f_\# = \pm 30$ mrad.

The diameter of the focusing mirror at L=15 m from the IP is about 90 cm.

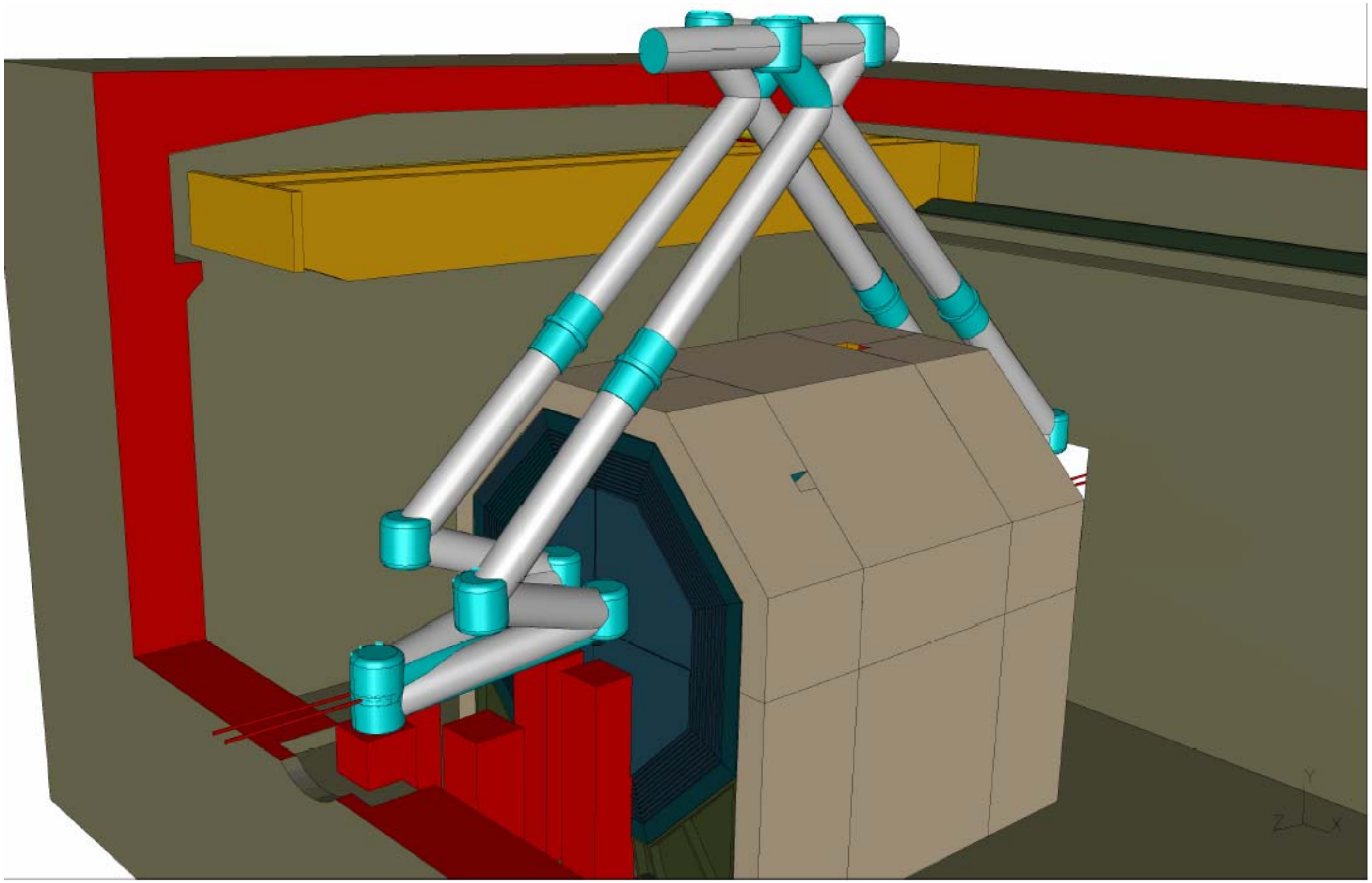
Simulation of the ring optical cavity in DESY-Zeuthen

Optimization was done at the wave level. The cavity was pumped by a truncated Gaussian beam with account of diffraction losses (which are negligibly small). Obtained numbers are close to that for flat-top beams (sho



View of the detector with the laser system

(the pumping laser is in the building at the surface)



For easier manipulation with bridge crane and smaller vibrations it may be better to hide the laser tubes under the detector

Conclusion

- The ILC has an unique possibility to study new phenomena in $e^+e^-, \gamma\gamma, \gamma e, e^-e^-$ collisions.
- In order to increase $L_{\gamma\gamma}$ it is desirable to decrease emittances in the DRs.
- The required crab crossing angle α_c=20-25 mrad is fully compatible with e^+e^-, decrease of L_{e+e-} is small. In order to fix the angle, detailed designs of the quad, compensator and simulation of beam losses are required.
- The non-zero vertical collision angle can be compensated by the shift of quads (or dipole coils).
- There are ideas on the beam dump for the photon collider, detailed consideration is necessary.
- There are some considerations of the laser optical cavity for the photon collider, next steps needs participation of laser experts (needs money).
- At the photon collider, the angle ±100 mrad is occupied by laser beams; it should be taken into account in a design of one of detectors.
- The photon collider should be developed now, because it influences many ILC systems; development of the laser system should be started without further delay.
- For success of the photon collider it should be considered as an integral part of the ILC project.