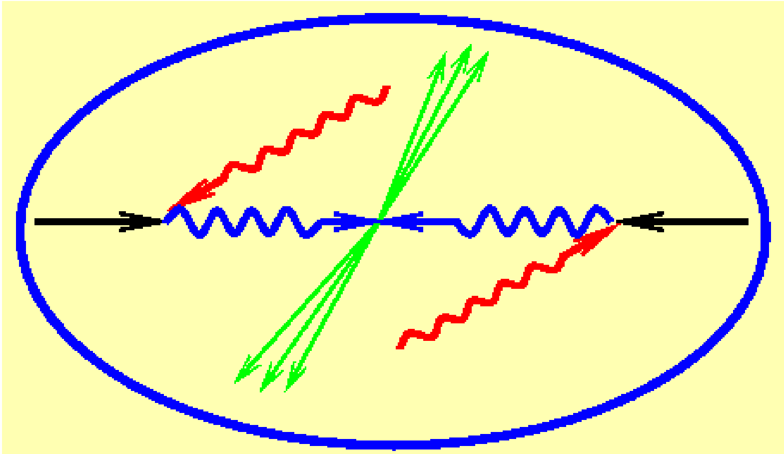


Gamma-gamma colliders:

status and perspectives

Valery Telnov

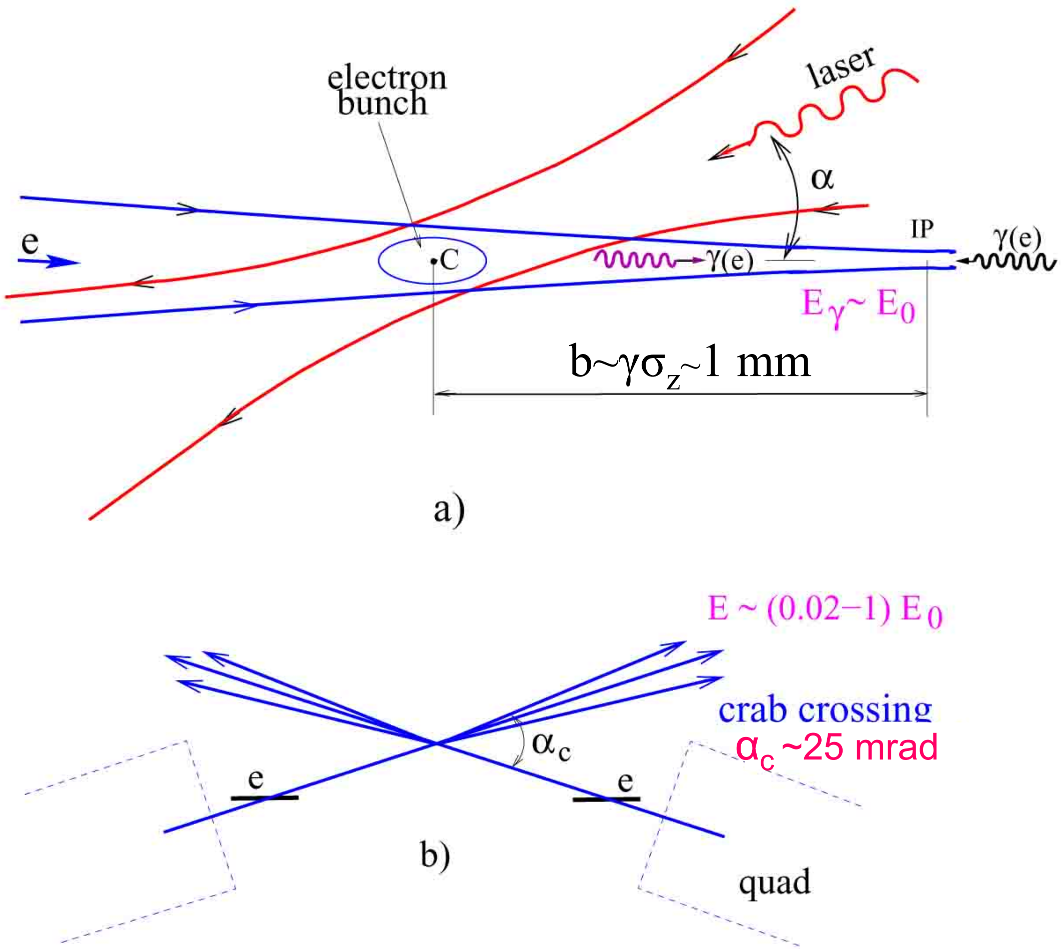
Budker INP, Novosibirsk

INFN miniworkshop, Como, Italy, May 16, 2013

Contents

Scheme of $\gamma\gamma$, γe collider

GKST 1981



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

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

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

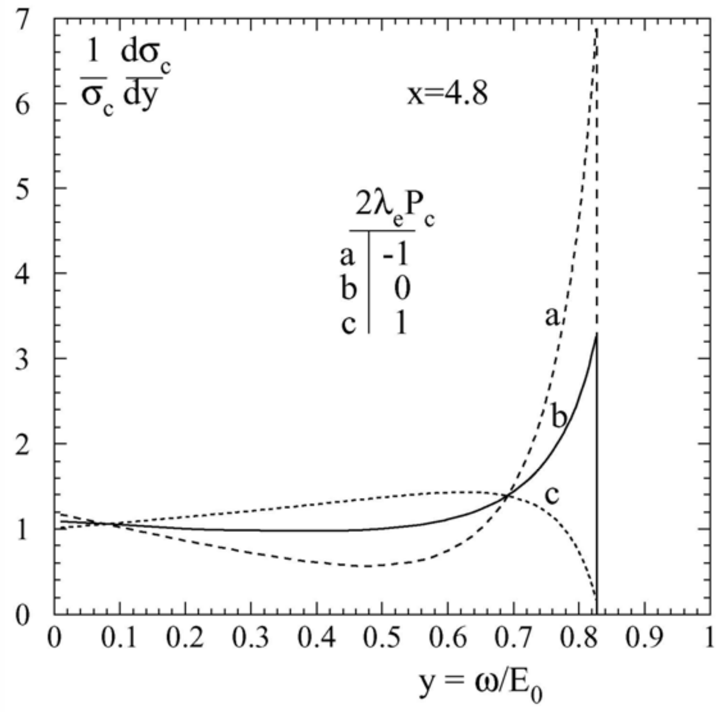
$x = 4.8$ is the threshold for
$\gamma\gamma_L \to e^+e^-$ at conv. reg.

$\omega_{max} \sim 0.8\ E_0$

$W_{\gamma\gamma,\ max} \sim 0.8 \cdot 2E_0$
$W_{\gamma e,\ max} \sim 0.9 \cdot 2E_0$

Electron to Photon Conversion

Spectrum of the Compton scattered photons



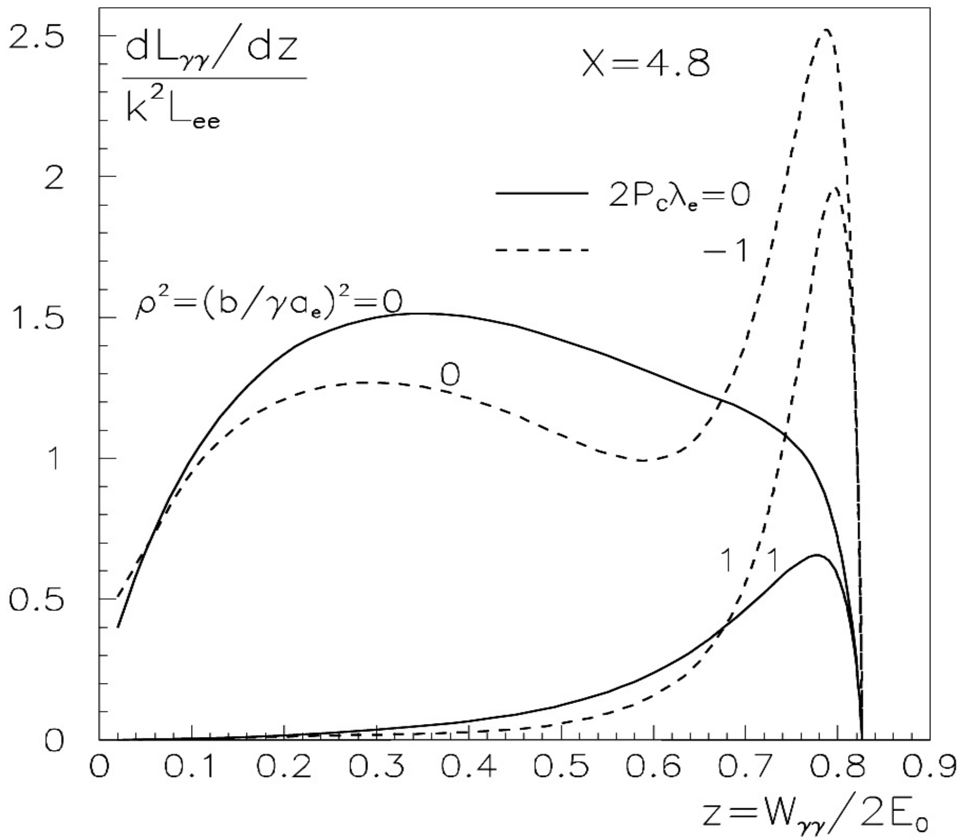
λ_e – electron longitudinal polarization

P_c – helicity of laser photons, $x \approx \frac{4E_0\omega_0}{m^2c^4}$

The electron polarization increases the number of high energy photons nearly by factor of 2).

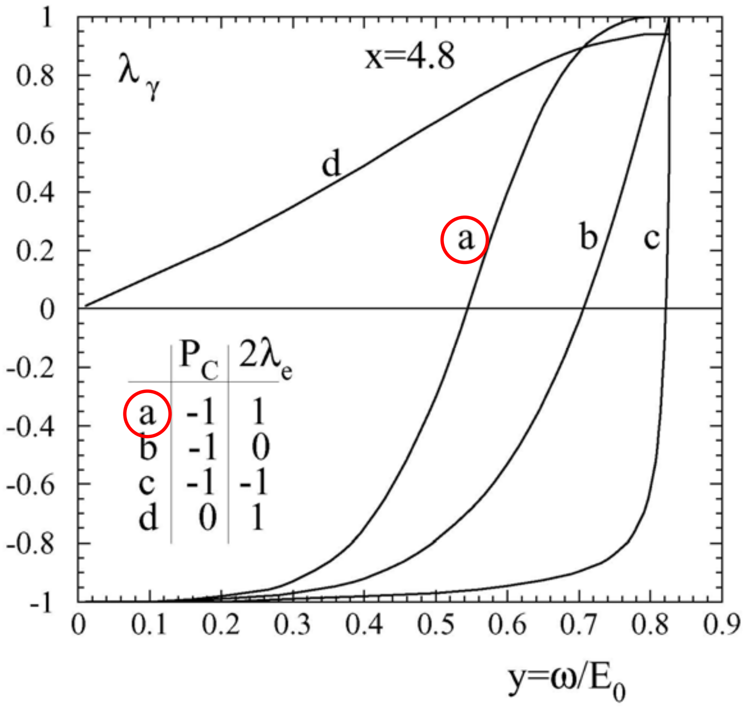
Ideal luminosity distributions, monohromatization

(a_e is the radius of the electron beam at the IP, b is the CP-IP distance)



Electron polarization increases the $\gamma\gamma$ luminosity in the high energy peak up to a factor of ~3-4 (at large x).

Mean helicity of the scattered photons ($x = 4.8$)



Highest energy scattered photons are polarized even at λ_e=0 (see (b))

(in the case a) photons in the high energy peak have $\lambda_\gamma \approx 1$)

The cross section of the Higgs production

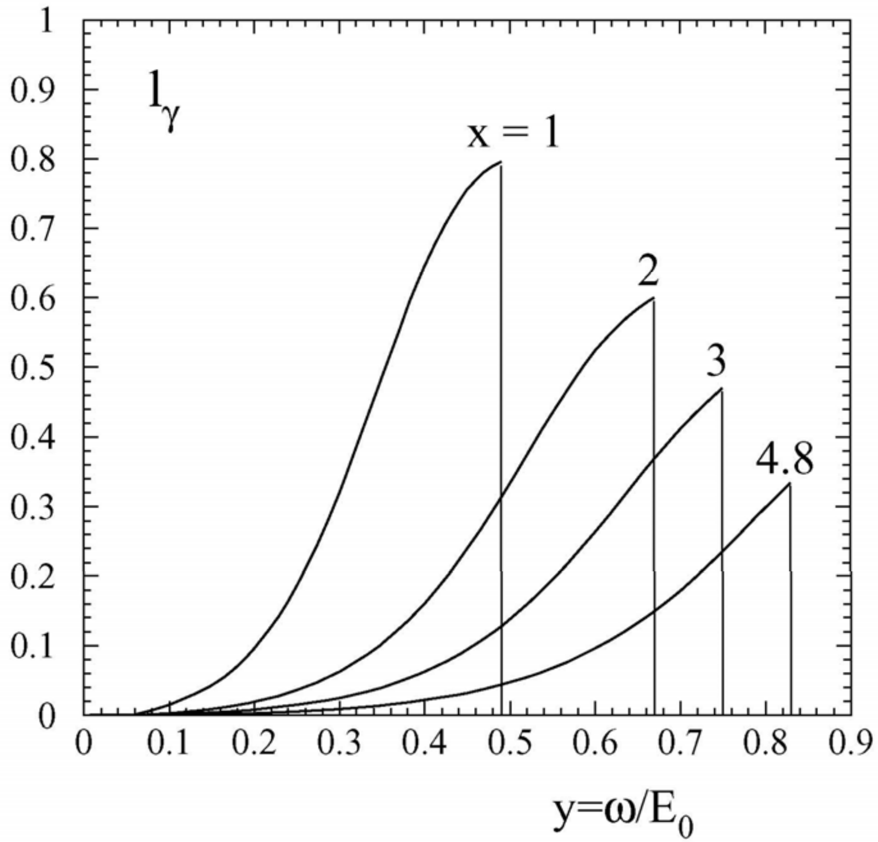
$$\sigma(\gamma\gamma \to h) \propto 1 + \lambda_1\lambda_2$$

The cross section for main backgound

$$\sigma(\gamma\gamma \to b\bar{b}) \propto 1 - \lambda_1\lambda_2$$

The electron polarization makes the region with a high polarization at $\omega\sim\omega_{m)}$ wider (compare a and b).

Linear polarization of photons

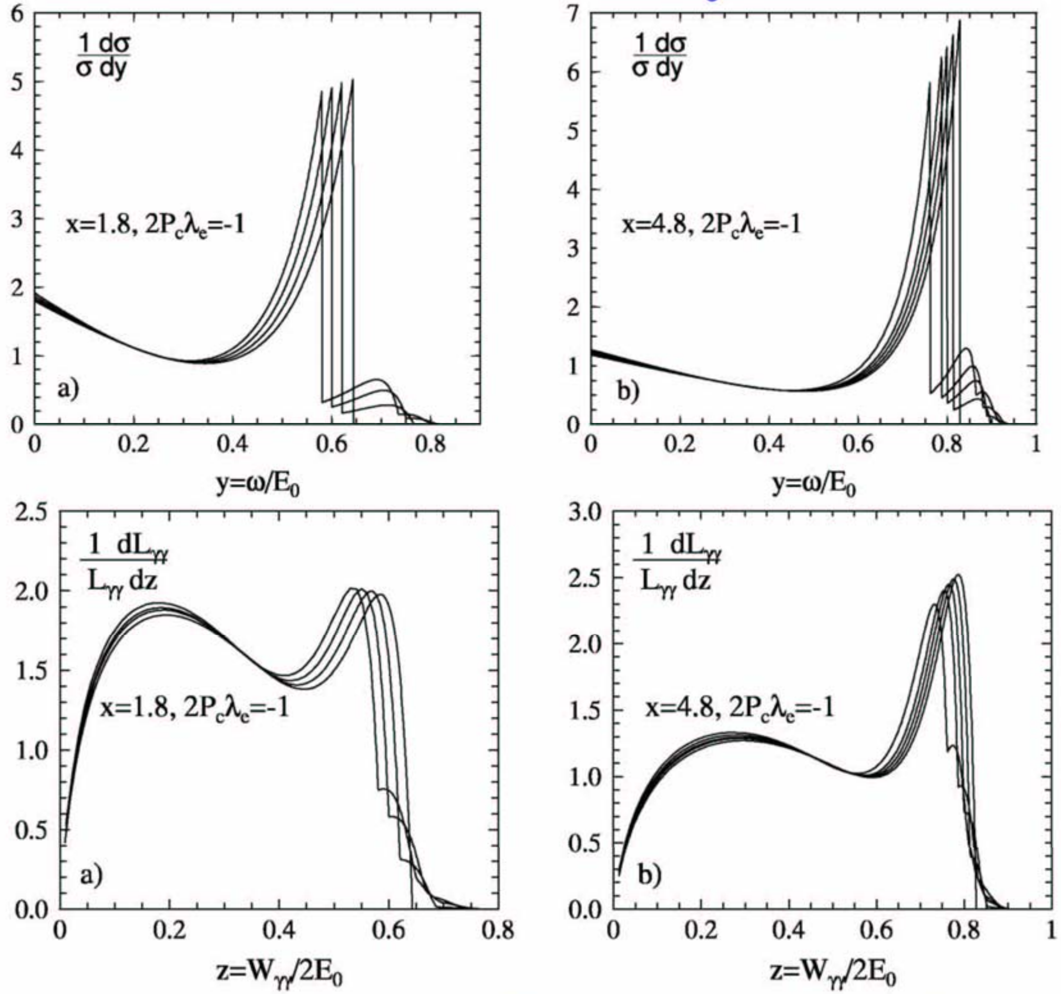


$\sigma \propto 1 \pm l_{\gamma 1} l_{\gamma 2} \cos 2\varphi$ $\qquad$ $\pm$ for CP=$\pm$1

Linear polarization helps to separate H and A Higgs bosons

Nonlinear effects in Compton scattering

$$\xi^2 = \frac{e^2 \bar{F}^2 \hbar^2}{m^2 c^2 \omega_0^2} = \frac{2 n_\gamma r_e^2 \lambda}{\alpha}$$



Photon spectra

$\gamma\gamma$ luminosity spectra

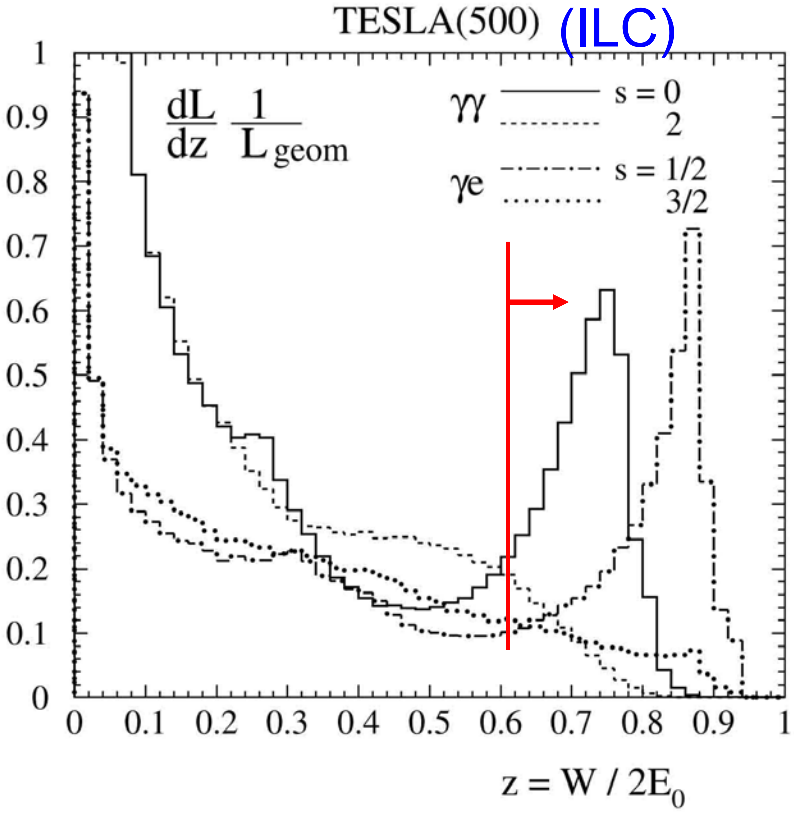
(Curves from right to left: $\xi^2 = 0, 0.1, 0.2, 0.3, 0.5$)

$\xi^2 \leq 0.2$-0.3 is required

Realistic luminosity spectra ($\gamma\gamma$ and γe)

(with account multiple Compton scattering, beamstrahlung photons and beam-beam collision effects)

(decomposed in two states of J_z)



Usually a luminosity at the photon collider is defined as the luminosity in the high energy peak, $z>0.8z_m$.

For ILC conditions

$L_{\gamma\gamma}(z>0.8z_m) \sim 0.1\ L_{e\text{-}e\text{-}}(geom)$

(but cross sections in $\gamma\gamma$ are larger then in e+e- by one order!)

Physics at PLC

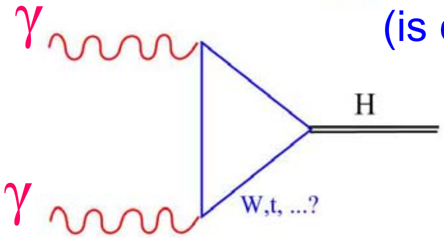
Physics at PLC was discussed so many times (>1000 papers) that it is difficult to add something essential. Most of examples are connected with production of the Higgs bosons or SUSY particles.

At present only light Higgs boson is discover.

Below I will just remind some gold-plated processes for PLC and model independent features.

Some examples of physics at PLC

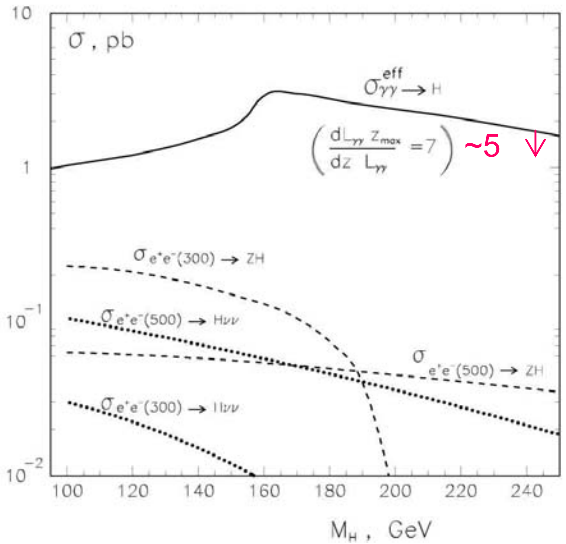
Higgs boson



(is considered for PLC since 1980th)

Very sensitive to heavy charge particles in the loop.

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



V.Telnov,1999

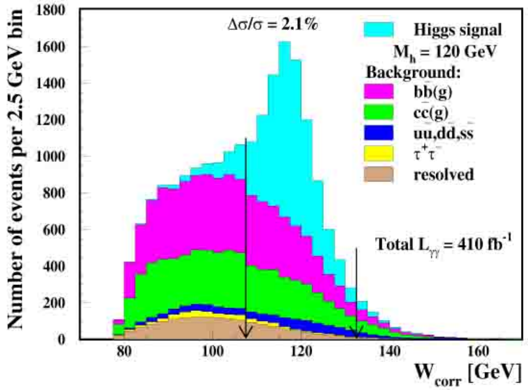
$$\dot{N}_{\gamma\gamma\to H} = L_{\gamma\gamma} \times \frac{dL_{\gamma\gamma} M_H}{dW_{\gamma\gamma} L_{\gamma\gamma}} \frac{4\pi^2 \Gamma_{\gamma\gamma}(1+\lambda_1\lambda_2)}{M_H^3}$$

At ILC

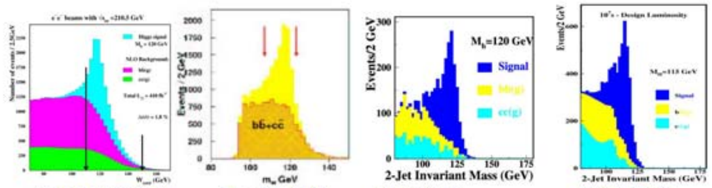
$$\frac{N(\gamma\gamma \to H)}{N(e^+e^- \to H+X)} \sim 1-10$$

For M_H=115-250 GeV

realistic simulation P.Niezurawski et al

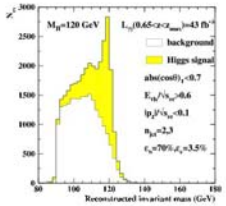


(previous analyses)



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

At nominal luminosities the number of Higgs in $\gamma\gamma$ will be similar to that in e+e-

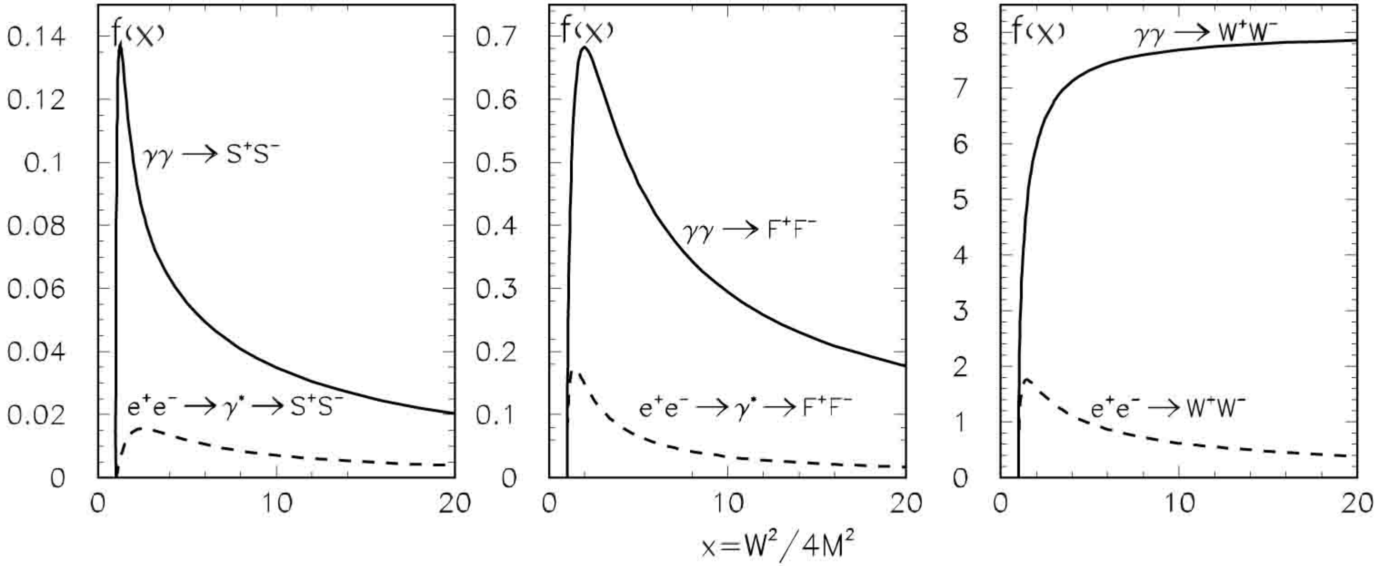


S.Soldner-Rembold
(thr first simulation)

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

So, typical cross sections for charged pair production in $\gamma\gamma$ collisions is larger than in e^+e^- by one order of magnitude

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:

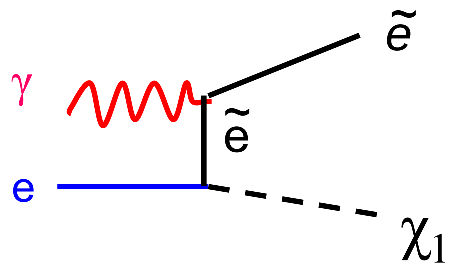
in e^+e^- collisions $M_{H,A}^{max} \sim E_0$ ($e^+e^- \rightarrow H + A$)
in $\gamma\gamma$ collisions $M_{H,A}^{max} \sim 1.6E_0$ ($\gamma\gamma \rightarrow H(A)$)

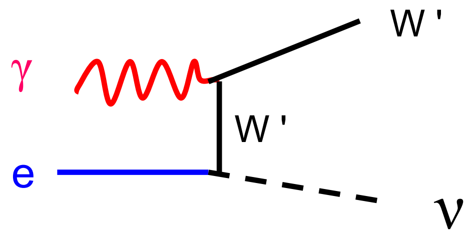
For some SUSY parameters H,A can be seen only in $\gamma\gamma$
(but not in e+e- and LHC)

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):

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





Physics motivation for PLC

(independent on physics scenario)

(shortly)

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 (H,A in $\gamma\gamma$, charged and light neutral SUSY in γe)
4. higher precision for some phenomena ($\Gamma_{\gamma\gamma}$, CP-proper.)
5. different type of reactions (different dependence on theoretical parameters)

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

Remark on Photon collider Higgs factories

Photon collider is attractive
for measurement of Br($H \to bb$)*Γ($H \to \gamma\gamma$),
but can not measure, Br(bb, cc, gg, $\tau\tau$, $\mu\mu$, invisible),
therefore PLC is the best motivated in combination with e+e-:
parallel work or second stage.

There were suggestions (H. Sugawara, 2009) to built a PLC Higgs factory as the ILC precursor, but it was not accepted by physics community mainly because a) e+e- physics case (for Higgs study) is stronger, 2) further delay of e+e-(~5 years)

Photon collider at ILC

The photon collider at ILC (TESLA) has been developed in detail at conceptual level, all simulated, all reported and published (TESLA TDR (2001), etc.

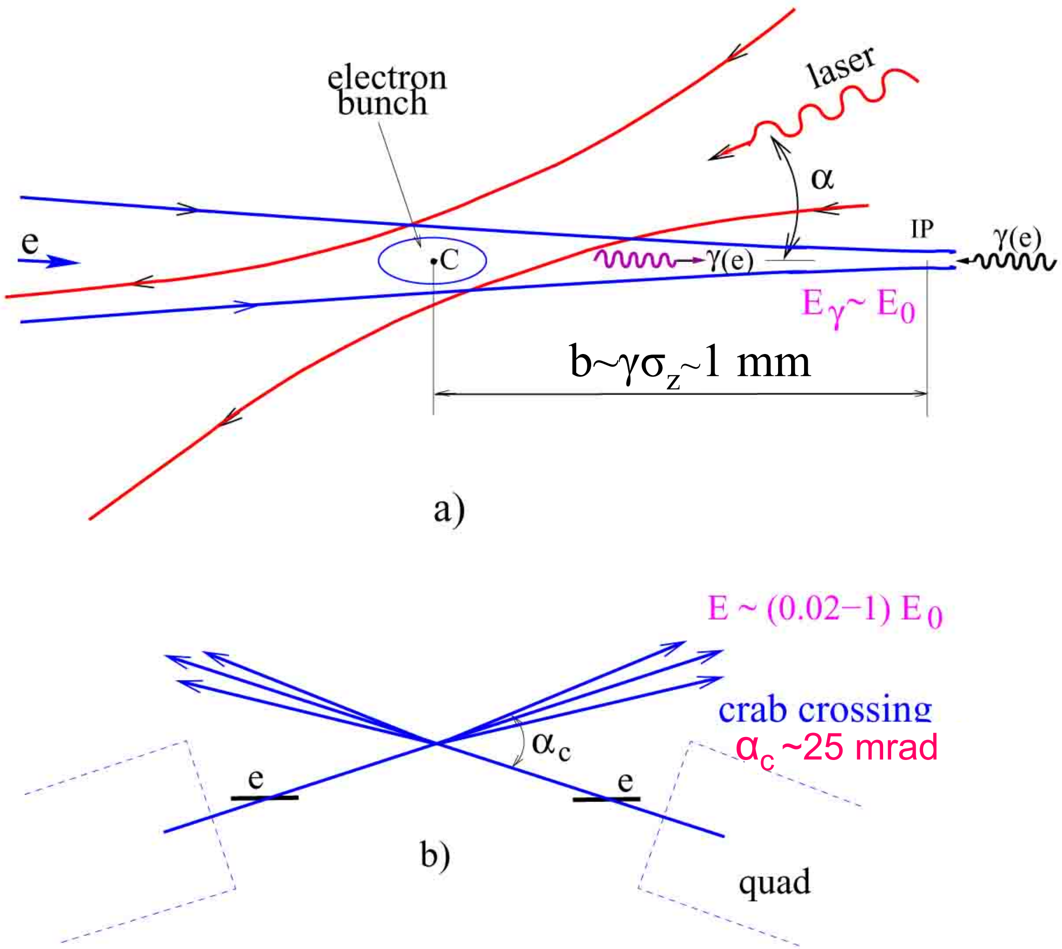
The conversion region: optimization of conversion, laser scheme.

The interaction region: luminosity spectra and their measurement, optimization of luminosity, stabilization of collisions, removal of disrupted beams, crossing angle, beam dump, backgrounds.

The laser scheme (optical cavity) was considered by experts, there is no stoppers. Required laser technique is developed independently for many other applications based on Compton scattering. Recently LLNL started work on LIFE lasers for thermonuclear plant which seems very attractive (one pass laser).

Further developments need political decisions and finances.

Scheme of $\gamma\gamma$, γe collider



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

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

$E_0 = 250$ 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.

ω_{max}~0.8 E_0

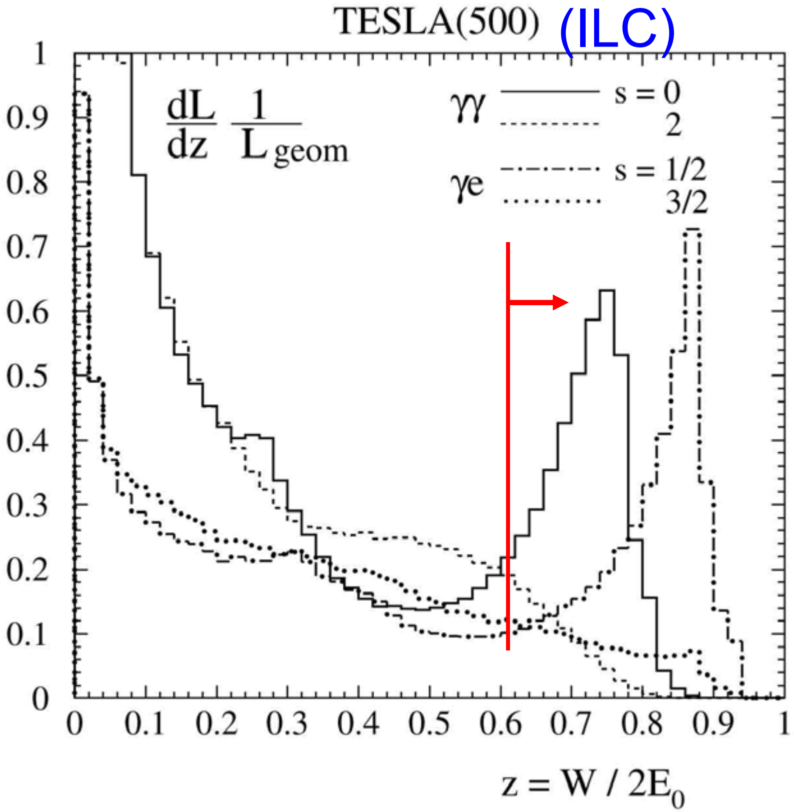
$W_{\gamma\gamma,\ max} \sim 0.8 \cdot 2E_0$
$W_{\gamma e,\ max} \sim 0.9 \cdot 2E_0$

Realistic luminosity spectra ($\gamma\gamma$ and γe)

(with account multiple Compton scattering, beamstrahlung photons and beam-beam collision effects)

(decomposed in two states of J_z)

(ILC)



Usually a luminosity at the photon collider is defined as the luminosity in the high energy peak, $z>0.8z_m$.

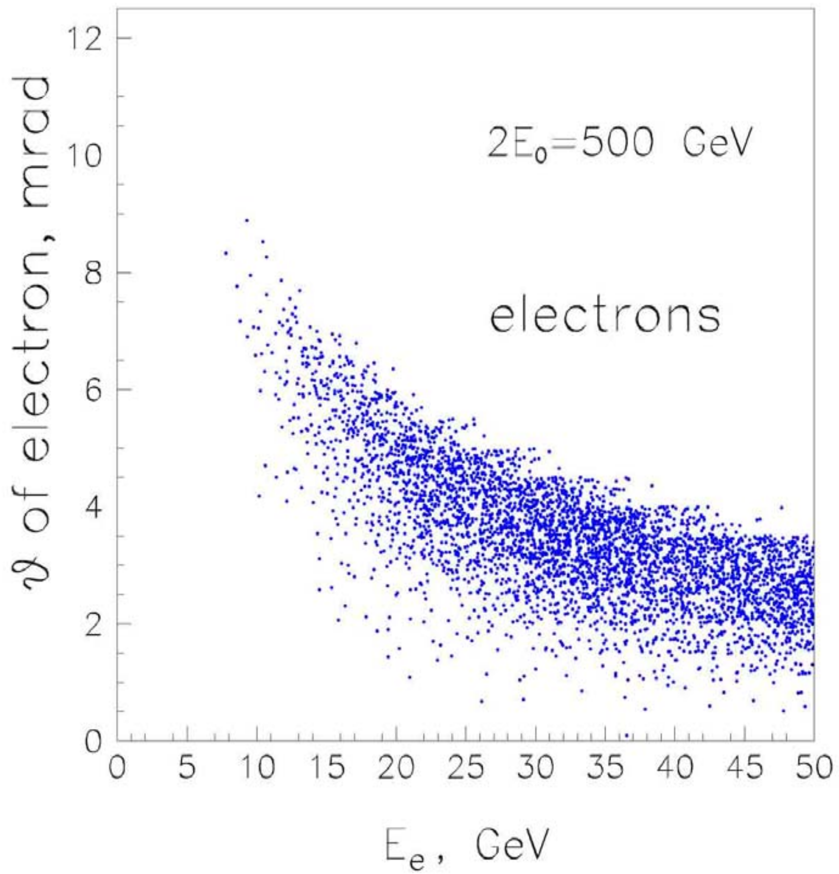
For ILC conditions

$L_{\gamma\gamma}(z>0.8z_m) \sim \ 0.1L_{ee} \sim 0.15L_{e+e-}$

(but cross sections in $\gamma\gamma$ are larger by one order!)

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

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

For low energy particles the deflection in the field of opposing beam

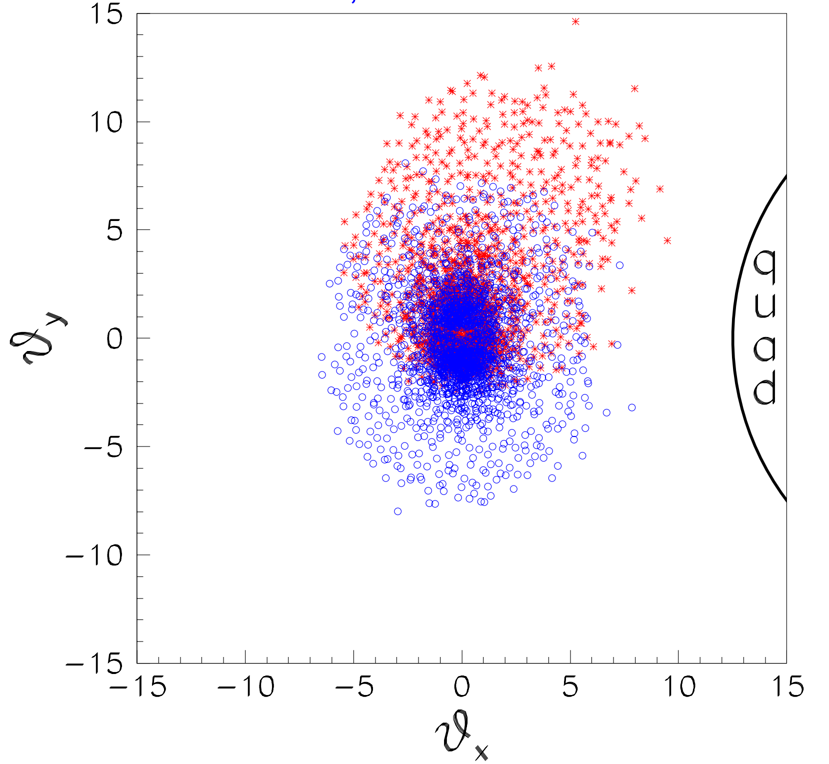
$$\vartheta \propto 1/\sqrt{E\sigma_z}$$

An additional vertical deflection, about ±4 mrad, adds the detector field

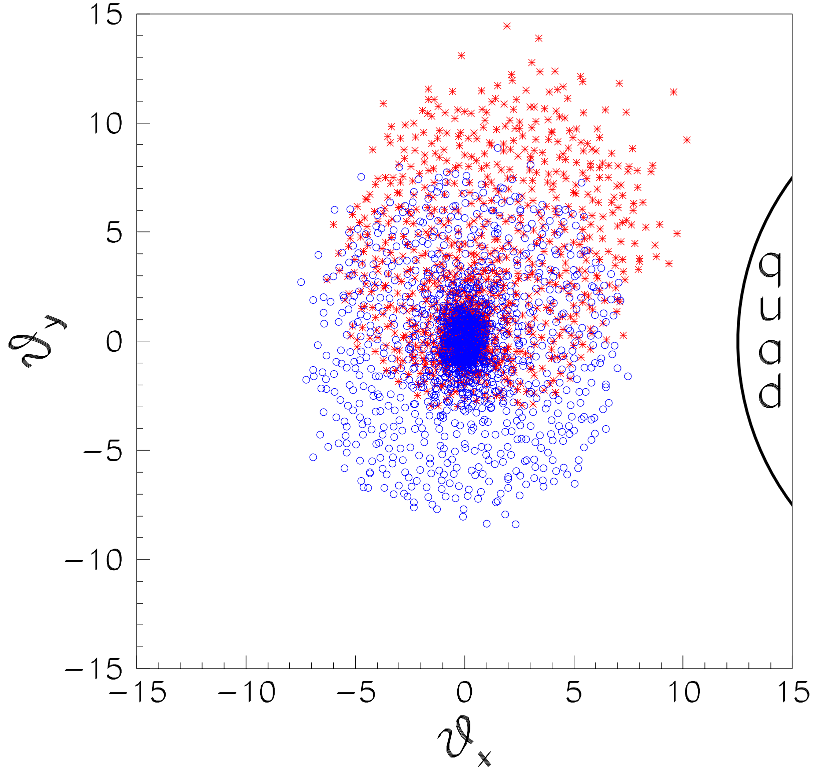
$$\alpha_c = (5/400)\ (\text{quad}) + 12.5 \cdot 10^{-3}(\text{beam}) \sim 25\ \text{mrad}$$

Disrupted beam with account of the detector field (at the front of the first quad, L~4 m)

$E_{e,\ min}$~6 GeV



$2E_0$=200 GeV



$2E_0$=500 GeV

With account of tails the save beam sizes are larger by about 20 %.

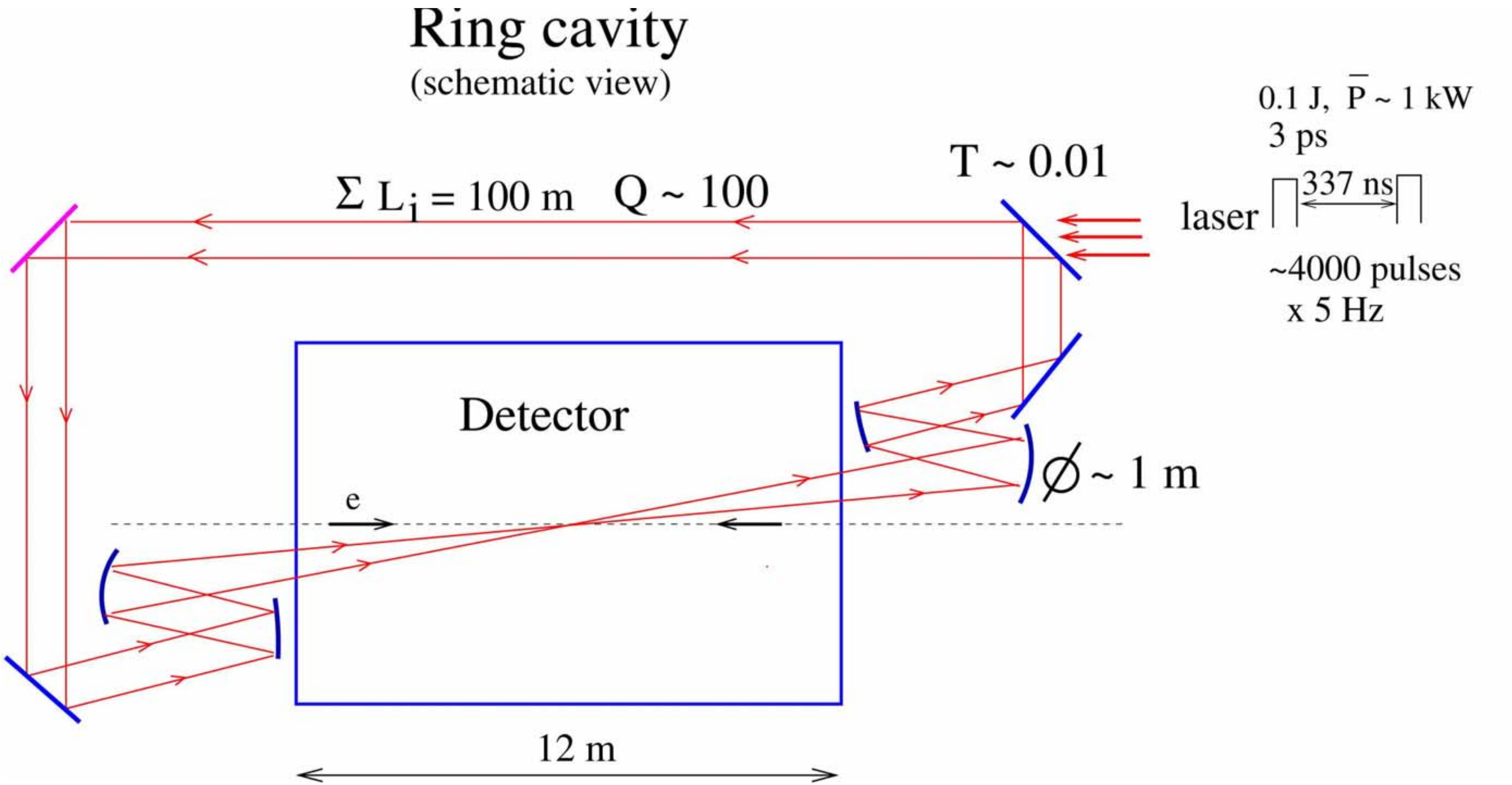
Requirements for laser

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

If a laser pulse is used only once, the average required power is P~150 kW and the power inside one train is 30 MW! Fortunately, 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 is the scheme with accumulation of very powerful laser bunch is an external optical cavity. The pulse structure at ILC (3000 bunches in the train with inter-pulse distance ~100 m) is very good for such cavity. It allows to decrease the laser power by a factor of 100-300.

Laser system

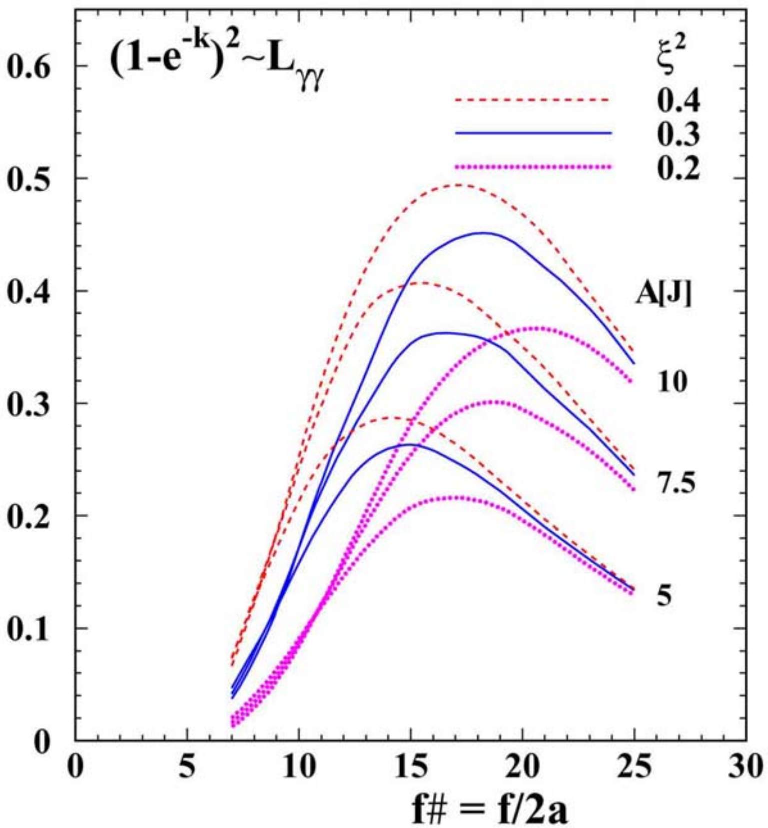


The cavity includes adaptive mirrors and diagnostics. Optimum angular divergence of the laser beam is ±30 mrad, A≈9 J (k=1), $\sigma_t \approx 1.3$ ps, $\sigma_{x,L}$~7 μm

Nonlinear effects in CS are important for optimization

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

T.V.



f- focal distance

a – mirror radius

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

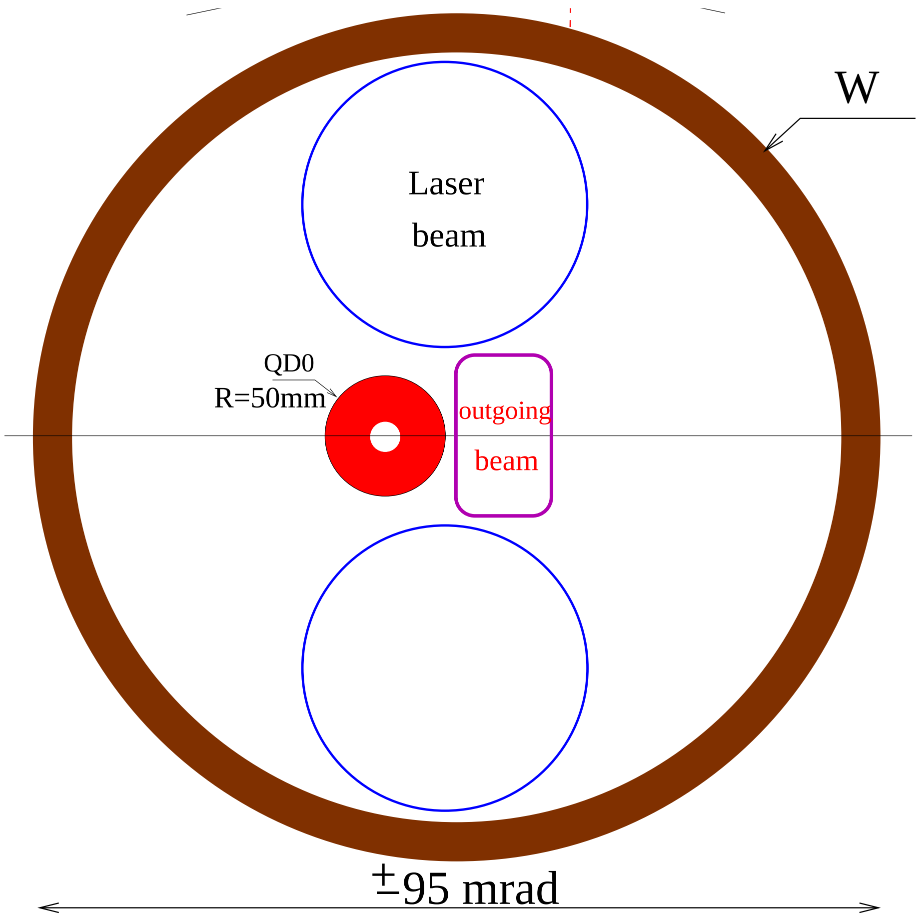
characterizes the probability of Compton scattering on several laser photons simultaneously, it should be kept below 0.2-0.4, depending on the par. x)

For ILC beams, α_c=25 mrad, and θ_{min}=17 mrad (see fig. with the quad) the optimum $f_{\#}$ =f/2a ≈ 17, A≈9 J (k=1), σ_t ≈ 1.3 ps, $\sigma_{x,L}$~7 μm.

So, the angle of the laser beam is ±1/2$f_{\#}$ = ±30 mrad,

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

Layout of the quad, electron and laser beams at the distance 4 m from the interaction point (IP)

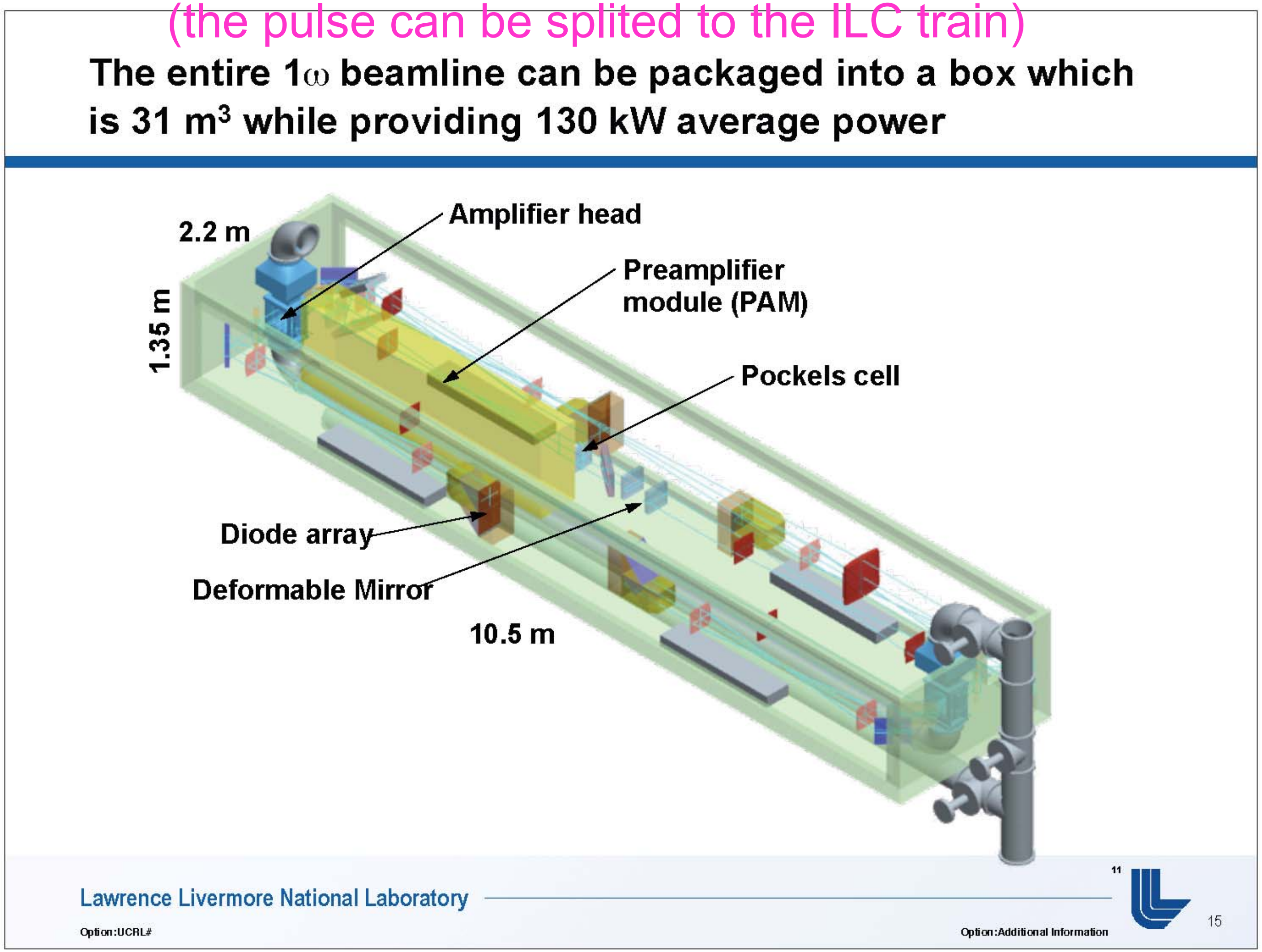


Recently new option has appeared, one pass laser system, based on new laser ignition thermonuclear facility

Project LIFE, LLNL

16 Hz, 8.125 kJ/pulse, 130 kW aver. power

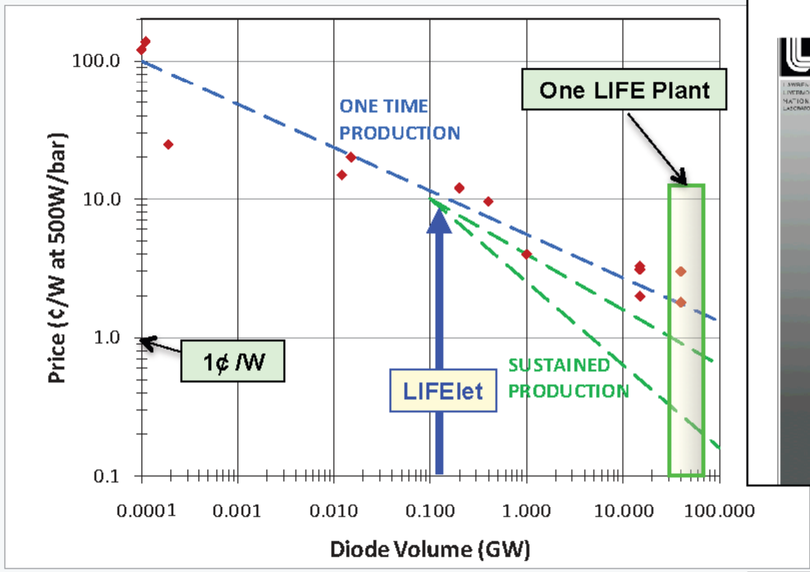
(the pulse can be splited to the ILC train)

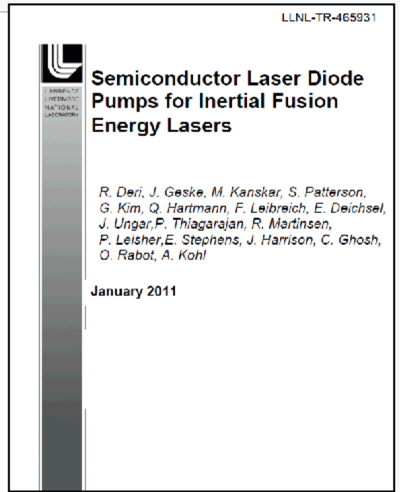


Laser diodes cost go down at mass production, that makes one pass laser system for PLC at ILC and CLIC realistic!

Diode costs are the main capital cost in the system

- White paper co-authored by 14 key laser diode vendors
- 2009 Industry Consensus: 3¢/W @ 500 W/bar, with no new R&D




LLNL-TR-465931

Semiconductor Laser Diode Pumps for Inertial Fusion Energy Lasers

R. Deri, J. Geske, M. Kanskar, S. Patterson, G. Kim, Q. Hartmann, F. Leibreich, E. Deichsel, J. Ungar, P. Thiagarajan, R. Martinsen, P. Leisher, E. Stephens, J. Harrison, C. Ghosh, O. Rabot, A. Kohl

January 2011

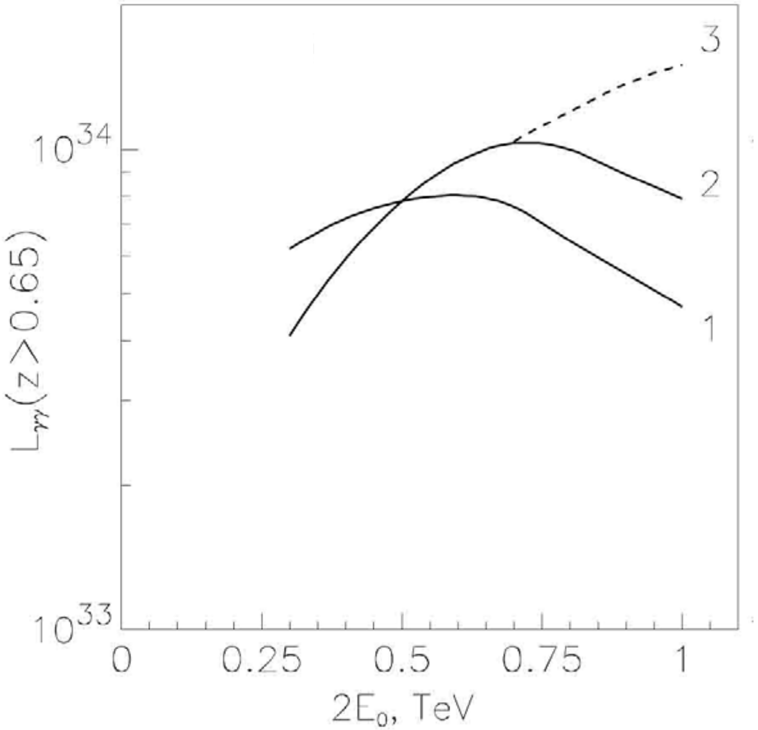
- Power scaling to 850 W/bar provides \$0.0176/W (1st plant)
- Sustained production of LIFE plants reduces price to ~\$0.007/W
- Diode costs for first plant: \$880M
- Diode costs for sustained production: \$350M

Diode costs for 1 beamline ~ \$2.3M

LIFElet (1st beamline) \$0.1/W
diodes for 1 beamline \$13M

Dependence of the $\gamma\gamma$ 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

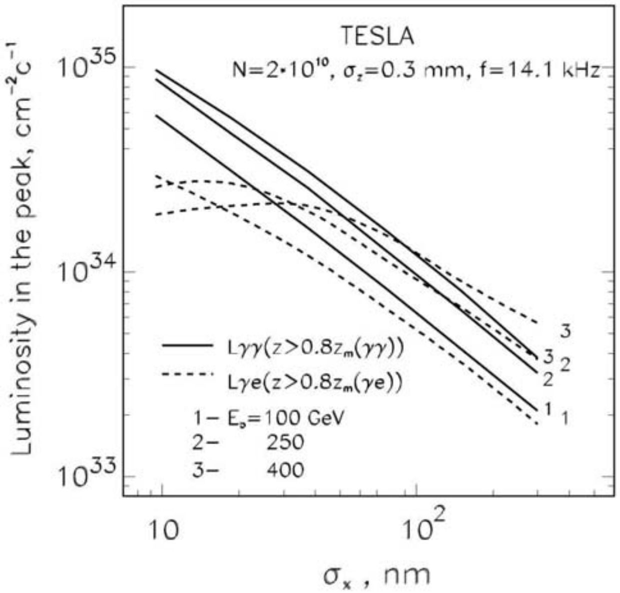
3- k=0.64 at all energies, $\xi^2 \propto A$, λ =1.47 μm (to avoid pair creation)

Laser system with $\lambda\sim1.06$ μm is suitable for 2E=200-700 GeV

Factors limiting $\gamma\gamma$,γe luminosities

Collisions effects:

- Coherent pair creation
- Beamstrahlung
- Beam-beam repulsion



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

For the ~~TESLA~~ ILC electron beams $\sigma_x \sim$ ~~100~~ 300 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

At e^+e^- the luminosity is limitted by collision effects (beamstrahlung, instability), while in $\gamma\gamma$ collsions only by available beam sizes or geometric e^-e^- luminosity (for at $2E_0$<1 TeV).

Photon collider at CLIC

CLIC main parameters

parameter	symbol		
centre of mass energy	E_{cm} [GeV]	500	3000
luminosity	$\mathcal{L}$ [10^{34} cm^{-2}s^{-1}]	2.3	5.9
luminosity in peak	$\mathcal{L}_{0.01}$ [10^{34} cm^{-2}s^{-1}]	1.4	2
gradient	G [MV/m]	80	100
site length	[km]	13	48.3
charge per bunch	N [10^9]	6.8	3.72
bunch length	σ_z [μm]	70	44
IP beam size	σ_x/σ_y [nm]	200/2.26	40/1
norm. emittance	ϵ_x/ϵ_y [nm]	2400/25	660/20
bunches per pulse	n_b	354	312
distance between bunches	Δ_b [ns]	0.5	0.5
repetition rate	f_r [Hz]	50	50
est. power cons.	P_{wall} [MW]	240	560

Comparison of ILC and CLIC parameters (important for PLC)

Laser wave length $\lambda \propto E$

for ILC(250-500) λ~1μm, for CLIC(250-3000) λ~ 1 - 4.5 μm

Disruption angle $\theta_d \sim (N/\sigma_z E_{min})^{1/2}$

For CLIC angles θ_d is larger on 20%, not important difference.

Laser flash energy A~10 J for ILC, A~5J for CLIC

Duration of laser pulse τ~1.5 ps for ILC, τ~1.5 ps for CLIC

Pulse structure

ILC Δct~100 m, 3000 bunch/train, 5 Hz (f_{col}~15 kH)

CLIC Δct~0.15 m, ~300 bunch/train, 50 Hz (f_{col}~15 kH)

Laser system ILC – a ring optical cavity with Q>100

CLIC –one pass system

(or short linear cavity?)

Laser system for CLIC

Requirements to a laser system for a photon collider at CLIC

Laser wavelength	~ 1 μm
Flash energy	A~5 J
Number of bunches in one train	354
Length of the train	177 ns=53 m
Distance between bunches	0.5 nc
Repetition rate	50 Hz

The train is too short for the optical cavity, so one pass laser should be used.

The average power of one laser is 90 kW (two lasers 180 kW).

Possible approaches to CLIC laser system

•FELs based on CLIC drive beams.

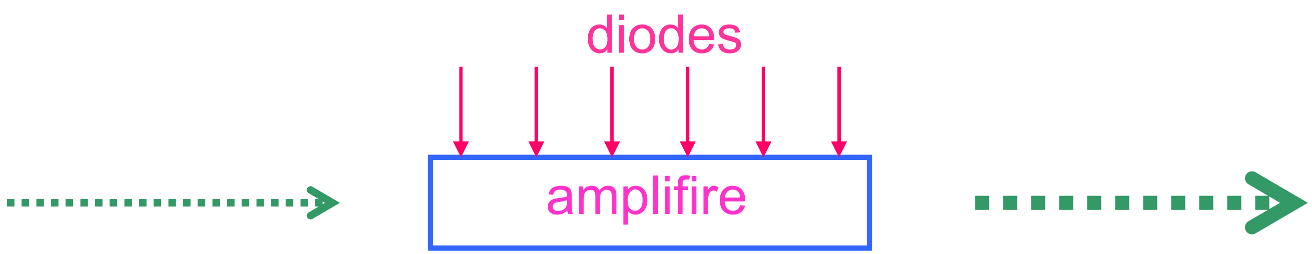
There were suggestions to use CLIC drive beams to generate light flashes (FEL), but they have not enough energy to produce the required flashes energy. In addition, the laser pulse should be several times shorter than the CLIC drive bunch.

For any FEL, the laser power inside 177 ns train should be about 20 GW! While the average power 200 kW. The problem is due to very non uniform pulse structure.

Solid state lasers pumped by diodes.

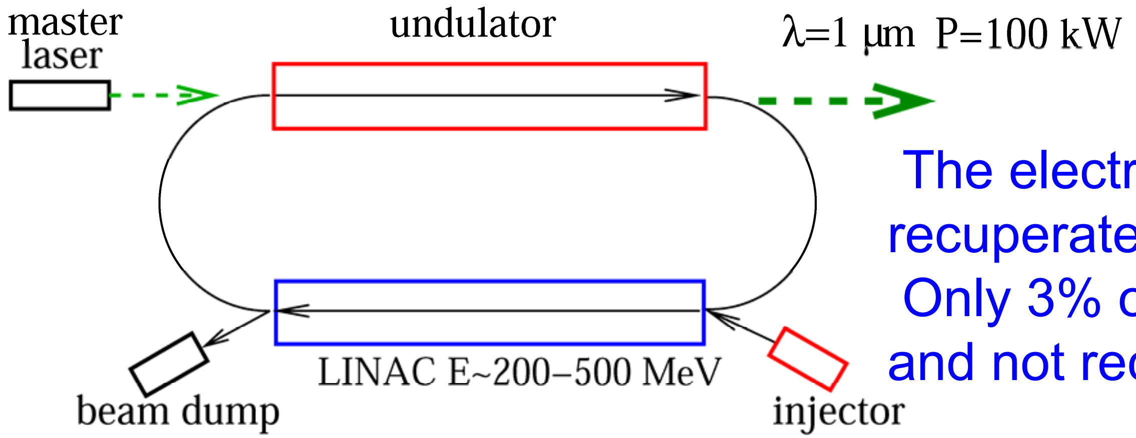
One can use solid state lasers pumped by diodes. There are laser media with a storage time of about 1 ms. One laser train contains the energy about 5x534=2000 J. Efficiency of the diode pumping about 20%, therefore the total power of diodes should be P~2*2000/0.001/0.20~20 MW.

LLNL system LIFE based on diode pumping, page 27, is very close to CLIC requirements and can be reconfigured for CLIC (and ILC) (talk at HF2012, see Gronberg's at this meeting)



Another suggestion (Telnov,2010):

to use FELs with the energy recuperation instead of diodes for pumping the solid state laser medium.



The electron beam energy can be recuperated using SC linac.
Only 3% of energy is lost to photons and not recuperated.

With recuperation and 10% wall plug RF efficiency the total power consumption of the electron accelerator from the plug will be about 200 kW/ 0.1 = 2 MW only.

The rest past of the laser system is the same as with solid state lasers with diode pumping.

The FEL pumped solid state laser with recuperation of electron beam energy is very attractive approach for short train linear colliders, such as CLIC.

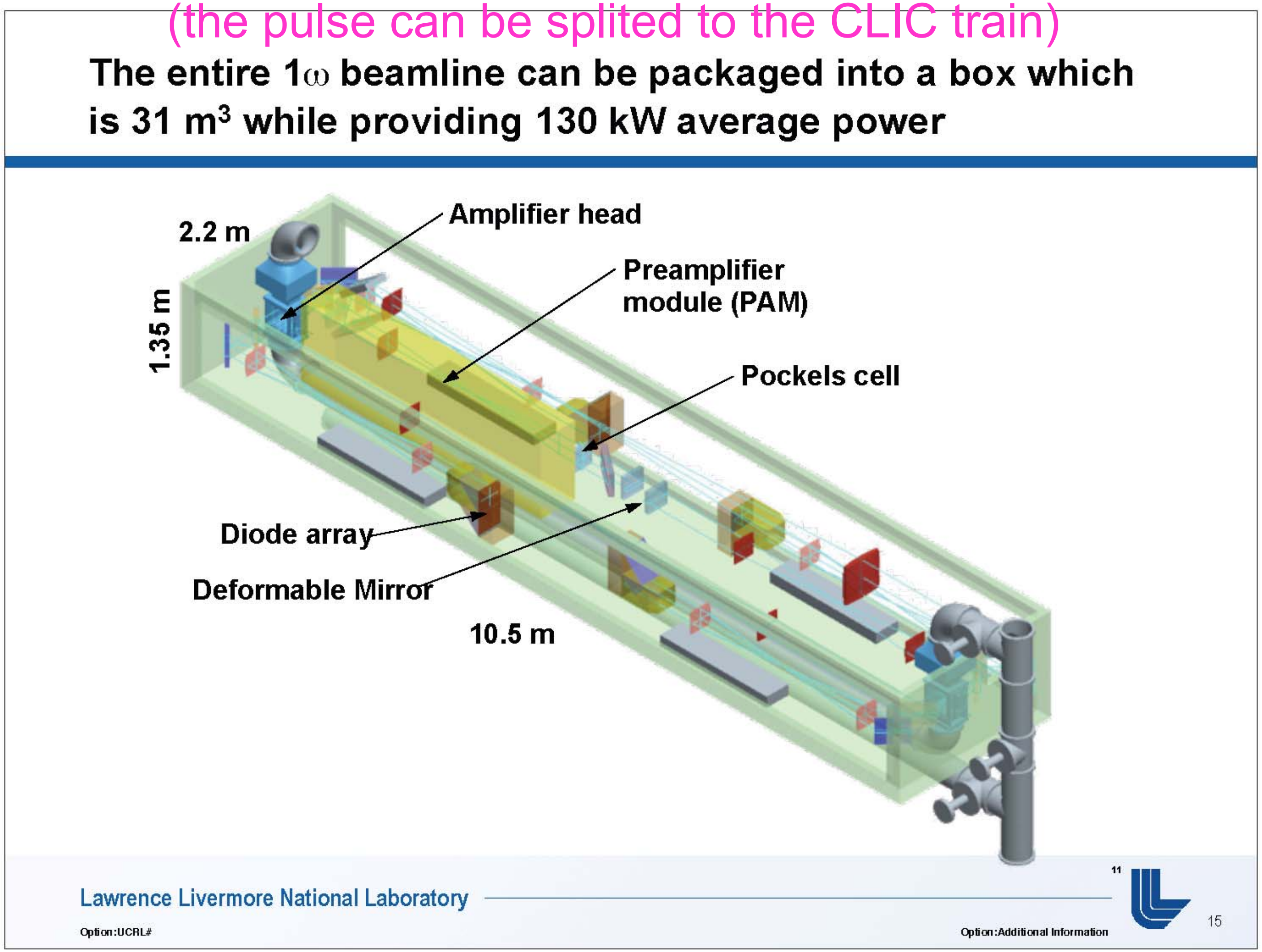
Storage of the pumping energy inside solid-state laser materials reduces the required FEL power inside the CLIC train by a factor 1 ms/ 177 ns=5600!

Such FEL can be built already now.

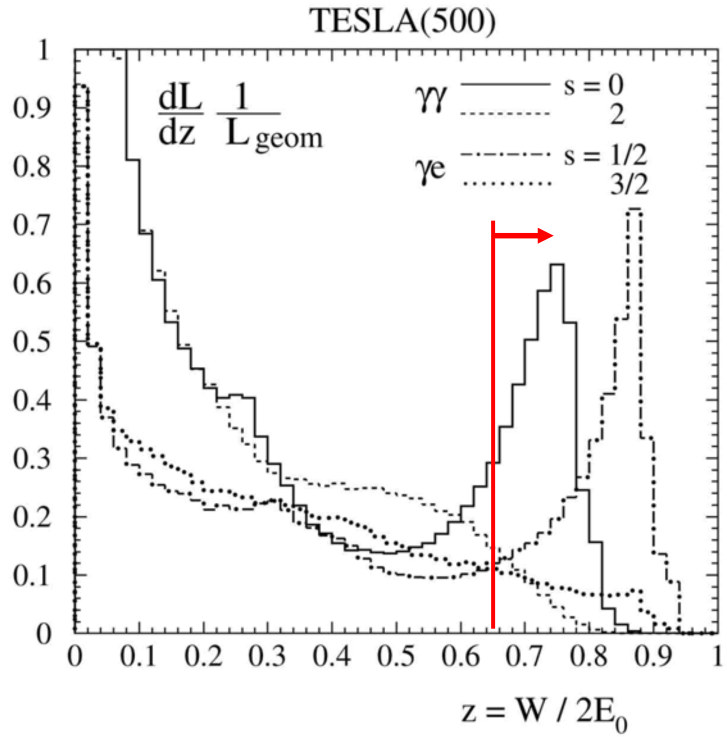
One pass laser system, developed for LIFE (LLNL) is well suited for CLIC photon collider

Project LIFE, LLNL 16 Hz, 8.125 kJ/pulse, 130 kW aver. power

(the pulse can be splited to the CLIC train)



Luminosity



Usually a luminosity at the photon collider is defined as the luminosity in the high energy peak, $z>0.8z_m$.

At energies 2E<1 TeV there no collision effects in $\gamma\gamma$ collisions and luminosity is just proportional to the geometric e-e- luminosity, which can be, in principle, higher than e+e- luminosity.

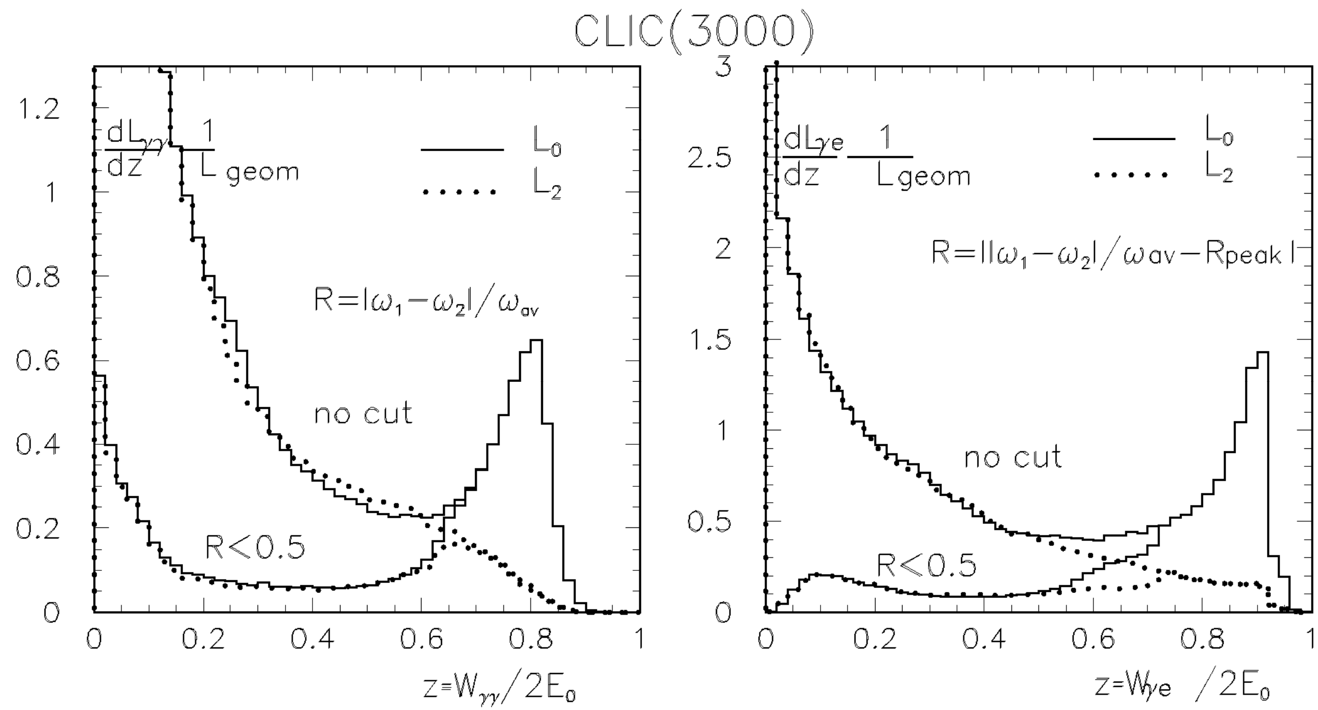
$L_{\gamma\gamma}(z>0.8z_m) \sim 0.1L(e^-e^-,geom)$

(this is not valid for multi-TeV colliders with short beams(CLIC) due to coherent e+e- creation)

For CLIC(500) $L_{\gamma\gamma}(z>0.8z_m) \sim 3\cdot 10^{33}$ for beams from DR

Luminosity spectra for CLIC(3000)

Here the $\gamma\gamma$ luminosity is limitted by coherent pair creation (the photon is converted to e+e- pair in the field of the opposing beam). The horizontal beam size can be only 2 times smaller than in e+e- collisions.



$L_{\gamma\gamma}(z>0.8z_m) \sim 8\cdot 10^{33}$

Photon collider Higgs factory SAPPHiRE

Submitted to the European Particle Physics Strategy Preparatory Group

SAPPHiRE: a Small $\gamma\gamma$ Higgs Factory

S. A. Bogacz[1], **J. Ellis**[2,3], **L. Lusito**[4], **D. Schulte**[3], **T. Takahashi**[5], **M. Velasco**[4], **M. Zanetti**[6] and **F. Zimmermann**[3]

Aug. 2012

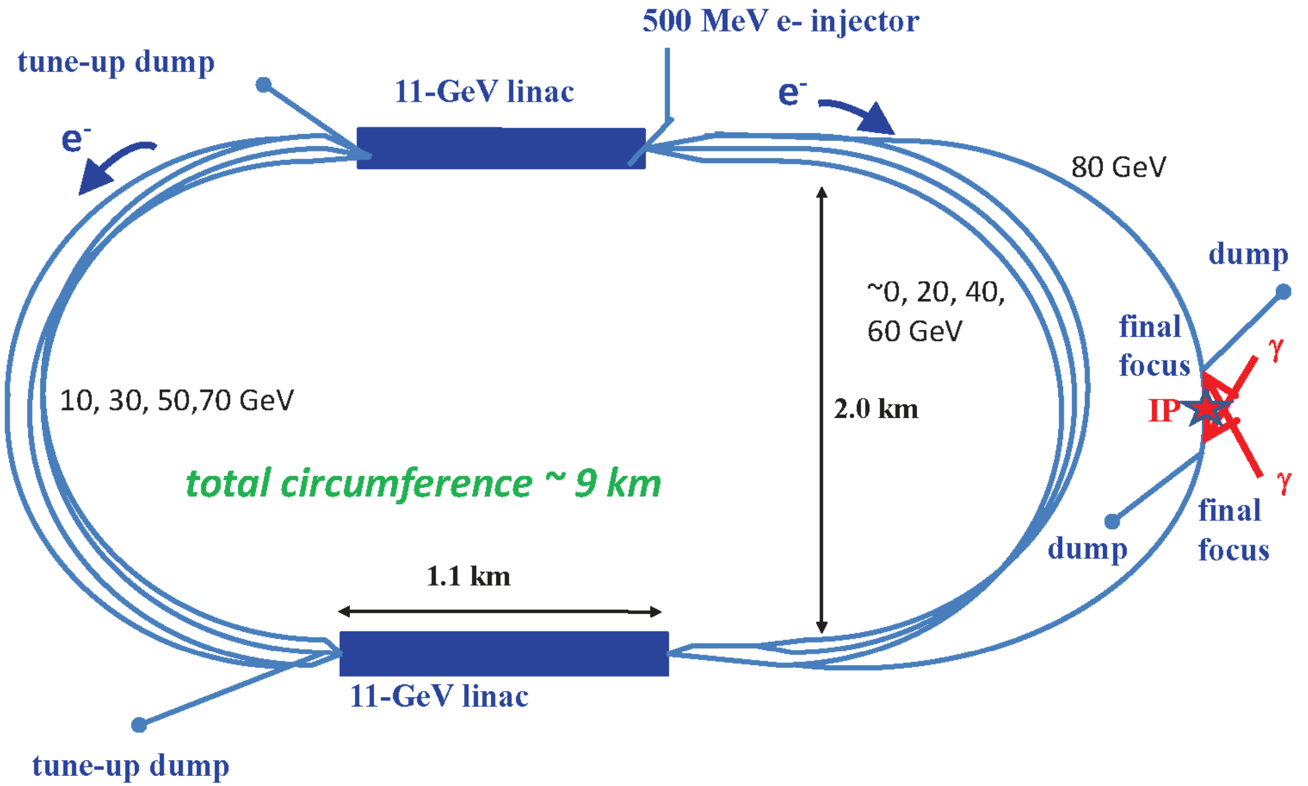


Figure 3: *Sketch of a layout for a $\gamma\gamma$ collider based on recirculating superconducting linacs – the SAPPHiRE concept.*

The scheme is based on LHeC electron ring, but shorter beams (σ_z = 30μm)) and somewhat higher energy, 80 GeV

Table 1: *Example parameters for $\gamma\gamma$ colliders based on CLIC-1 (CLICHE, left column), as optimized for $M_h \sim 115$ GeV [3], and a pair of recirculating superconducting linacs (SAPPHiRE, right column) optimized for $M_h \sim 125$ GeV.*

Variable	Symbol	CLICHE [3]	SAPPHiRE
Total electric power	P	150 MW	100 MW
Beam energy	E	75 GeV	80 GeV
Beam polarization	P_e	0.80	0.80
Bunch population	N	4×10^9	10^{10}
Number of bunches per train	n_b	154	—
Number of trains per rf pulse	n_t	11	—
Repetition rate	$f_{\rm rep}$	100 Hz	cw
Average bunch frequency	$\langle f_{\rm bunch} \rangle$	169 kHz	200 kHz
Average beam current	$I_{\rm beam}$	0.11 mA	0.32 mA
RMS bunch length	σ_z	30 μm	30 μm
Crossing angle	θ_c	≥ 20 mrad	≥ 20 mrad
Normalised horizontal emittance	ϵ_x	1.4 μm	5 μm
Normalised vertical emittance	ϵ_y	0.05 μm	0.5 μm
Nominal horizontal beta function at the IP	β_x^*	2 mm	5 mm
Nominal vertical beta function at the IP	β_y^*	20 μm	0.1 mm
Nominal RMS horizontal IP spot size	σ_x^*	138 nm	400 nm
Nominal RMS vertical IP spot size	σ_y^*	2.6 nm	18 nm
Nominal RMS horizontal CP spot size	$\sigma_x^{C,*}$	154 nm	400 nm
Nominal RMS vertical CP spot size	$\sigma_y^{C,*}$	131 nm	180 nm
e$^-$e$^-$ geometric luminosity	$\mathcal{L}$	4.8×10^{34} cm^{-2}s^{-1}	2.2×10^{34} cm^{-2}s^{-1}

200 kHz!!!

!!!

Table 2: *Example parameters for the CLICHE mercury laser system [3], and for the SAPPHiRE laser system, assuming $\mathcal{L}_{ee} = 4.8 \times 10^{34}\,$cm^{-2}s^{-1} and $\mathcal{L}_{ee} = 2.2 \times 10^{34}\,$cm^{-2}s^{-1}, respectively.*

Variable	Symbol	CLICHE [3]	SAPPHiRE
Laser beam parameters			
Wavelength	λ_L	0.351 μm	0.351 μm
Photon energy	$\hbar\omega_L$	3.53 eV = 5.65×10^{-19} J	3.53 eV
Number of laser pulses per second	N_L	169400 s^{-1}	200000 s^{-1}
Laser peak power	W_L	2.96×10^{22} W/m^2	6.3×10^{21} W/m^2
Laser peak photon density		5.24×10^{40} photons/m^2/s	1.1×10^{40} photons/m^2/s
Photon beam			
Number of photons per electron bunch	N_γ	9.6×10^9	1.2×10^{10}
$\gamma\gamma$ luminosity for $E_{\gamma\gamma} \geq 0.6 E_{CM}$	$\mathcal{L}_{\gamma\gamma}^{peak}$	3.6×10^{33} cm^{-2}s^{-1}	3.6×10^{33} cm^{-2}s^{-1}

!

Main critical remarks on SAPPHIRE

1. The emittance dilution in arcs is too optimistic, compared to LHeC it was suggested to decrease the dipole section length by a factor of 4 and thus to decrease the dilution by a factor of 64! However, in this case the quads gradient should be 42=16 times larger! (May be OK?)
2. The initial beam normalized emittances, 5 and 0.5 mm mrad in X and Y directions corresponds to best emittances of unpolarized RF guns. PLC needs polarized electrons. Present polarized DC guns (polarized RF guns do not exist yet) have emittances > 20 times larger! It means that the luminosity will be 20 times smaller. That is why PLC at ILC assumes damping rings. However, several labs. are working on low emittance polarized RF guns, there is a good progress and results will appear soon. That would be great for any PLC!
3. Conservation of polarization in rings is a problem (due to the energy spread, too many spin rotation).
4. The bunch length (σ_z = 30 μm) is very close to condition of coherent radiation in arcs.

4. The length of the ring 9 km (2.2 km linac, 30 km arcs). The LC with G=30 MeV/m would have L=6 km total length (with the final focus) and can work with smaller emittances and thus can have a higher luminosity. Where is profit?

5. The PLC with E=80 GeV and λ=1.06/3 μm have very low energy final electrons with energies down to E=2 GeV. Besides the electron bunch length is very short. This courses very large disruption angles ($\theta \sim 1/(E\sigma_z)^{1/2}$ in the field of opposing beam and due to deflection in the solenoid field (due to crab crossing). Namely due to this reason TESLA (ILC) always considered the Higgs factory with E>100 GeV and λ=1.06 μm.

The Higgs factory with λ=1.06/2 μm is still may be possible, but this requires higher Sapphire energy, which is not possible due do to unacceptable emittance dilution and energy spread.

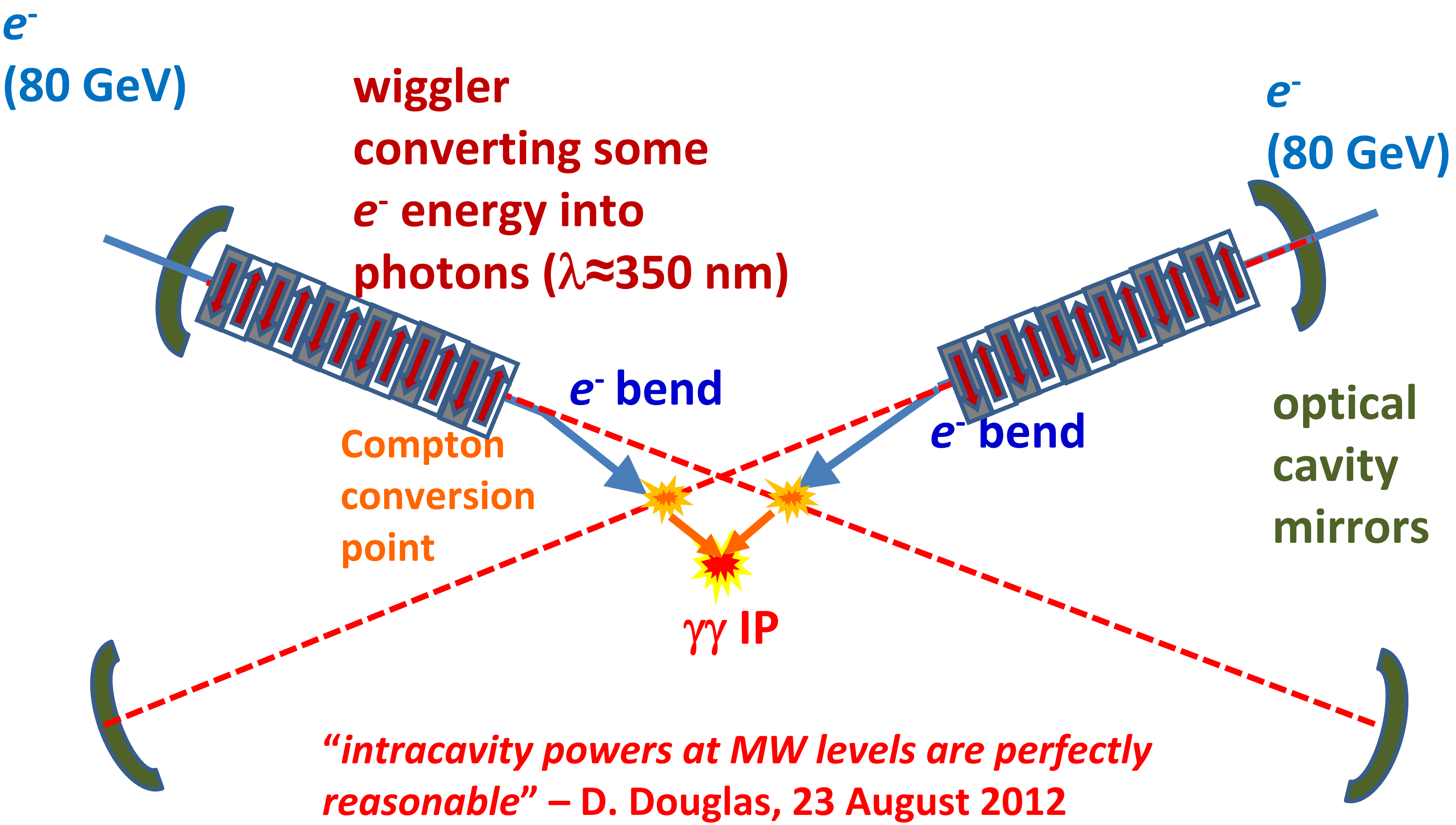
6. Ring colliders (Sapphire) have no possibility for increasing energy.

7. The repetition rate 200000 is very uncomfortable for laser system, optical cavity can help, but it is much more demanded than for ILC.

7. It is obvious that e+e- is better for the Higgs study, there is no chance to get support of physics community, if this collider is instead of e+e-(worse that precursor).

option: self-generated FEL γ beams (instead of laser)?

(I do not believe, there is no space near IP!)



***"intracavity powers at MW levels are perfectly reasonable"* – D. Douglas, 23 August 2012**

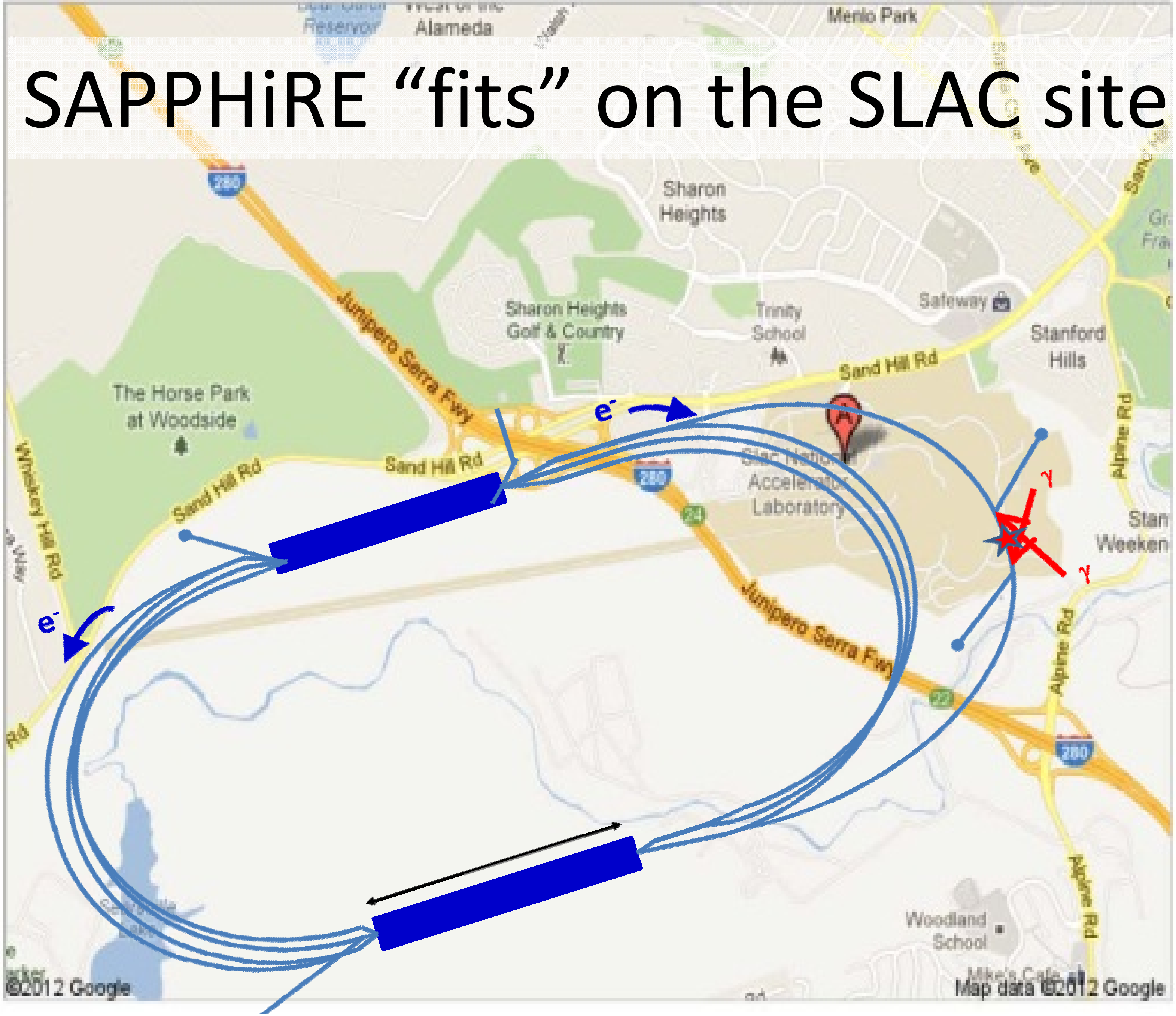
example:

λ_u=200 cm, B=0.625 T, L_u=100 m, $U_{0,SR}$=0.16 GeV, 0.1%P_{beam}≈25 kW

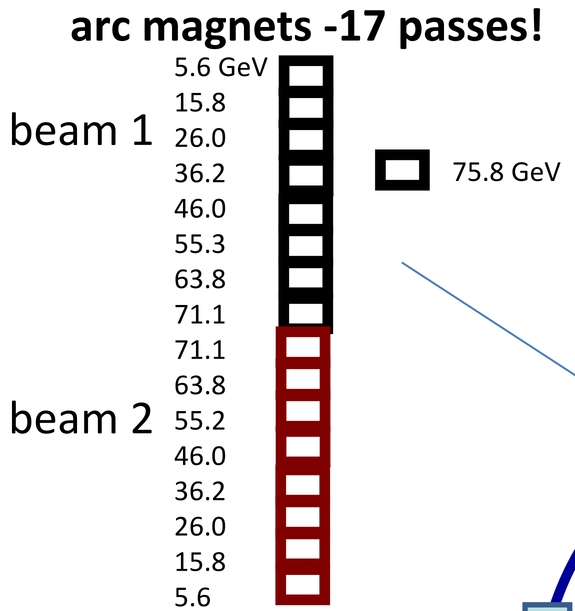
scheme developed with Z. Huang

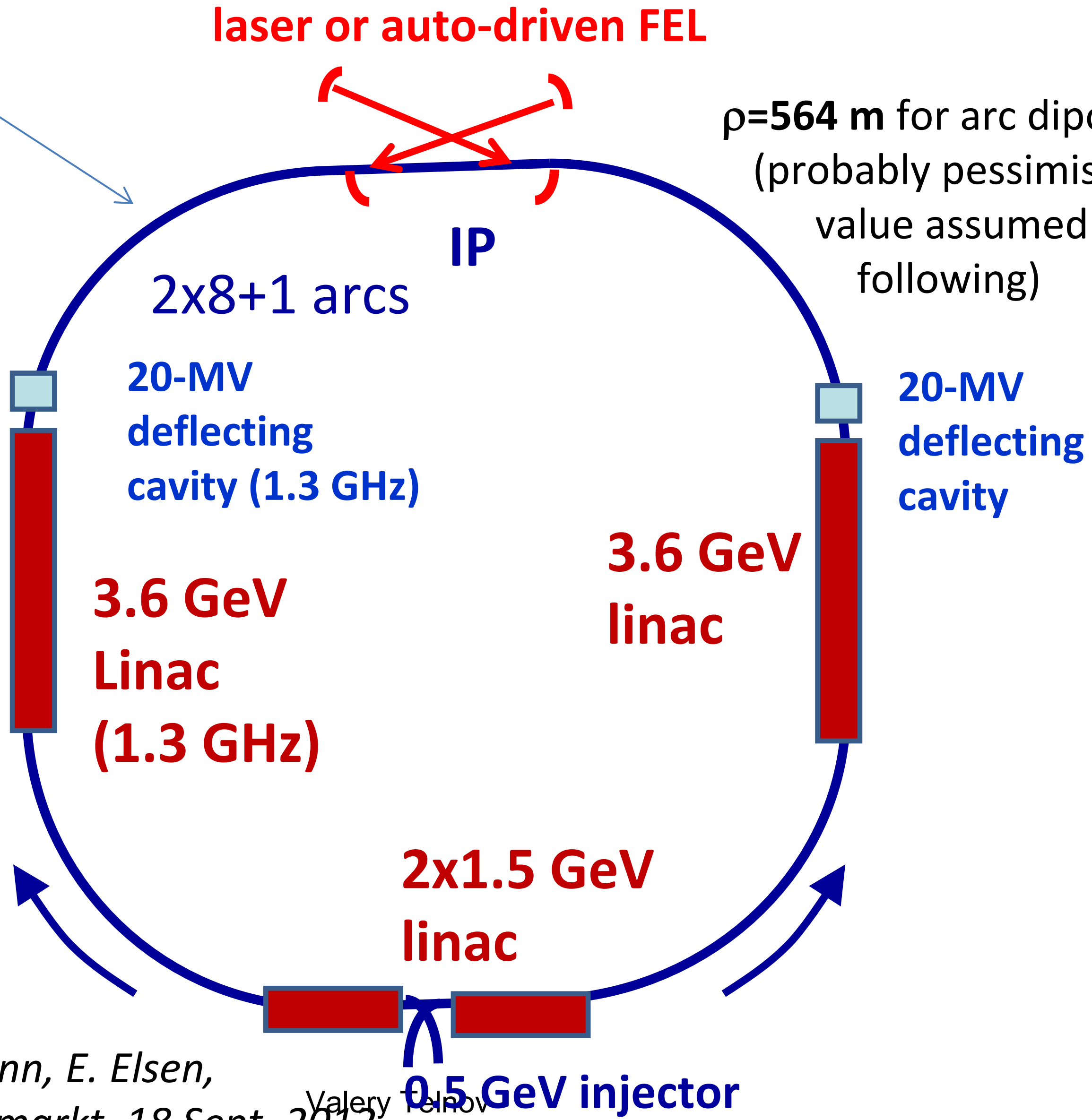
Below are several examples of Sapphire followers, stimulated by the need of some Higgs factory.

SAPPHiRE "fits" on the SLAC site



HERA Tunnel Filler





ρ=**564 m** for arc dipoles (probably pessimistic; value assumed in the following)

real-estate linac Gradient ~ 10 MV/m

total SC RF = 10.2 GV

F. Zimmermann, R. Assmann, E. Elsen, DESY Beschleuniger-Ideenmarkt, 18 Sept. 2012

Edward Nissen

Town Hall meeting Dec 19 2011

Possible Configurations at JLAB

85 GeV Electron energy
γ c.o.m. 141 GeV

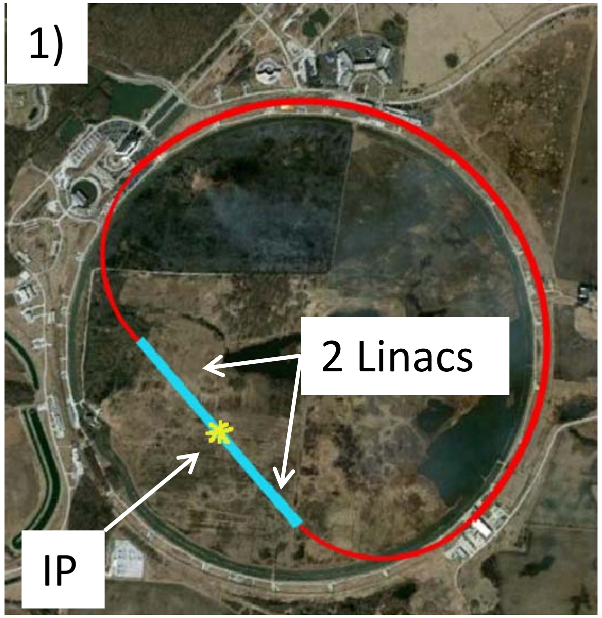
103 GeV Electron energy
γ c.o.m. 170 GeV

Possible Configurations at FNAL

Edward Nissen

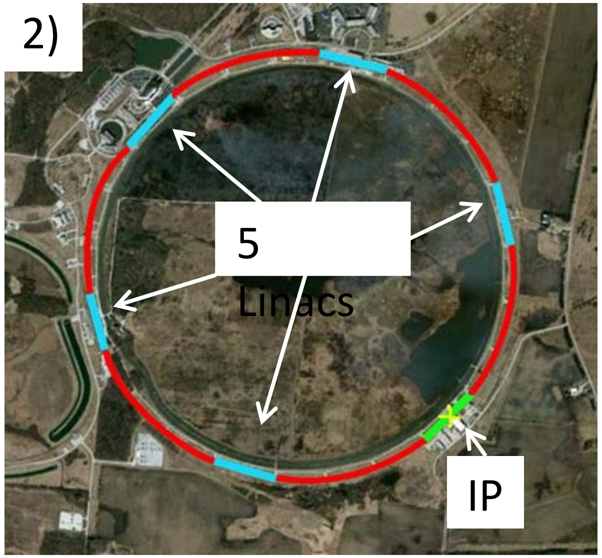
Tevatron Tunnel Filler Options

1)



Top Energy	80 GeV	80 GeV
Turns	4	5
Avg. Mag. ρ	661.9 m	701.1 m
Linacs (2)	10.68GeV	8.64GeV
δp/p	8.84×10^{-4}	8.95×10^{-4}
ϵ_{nx} Growth	2.8μm	2.85μm

2)



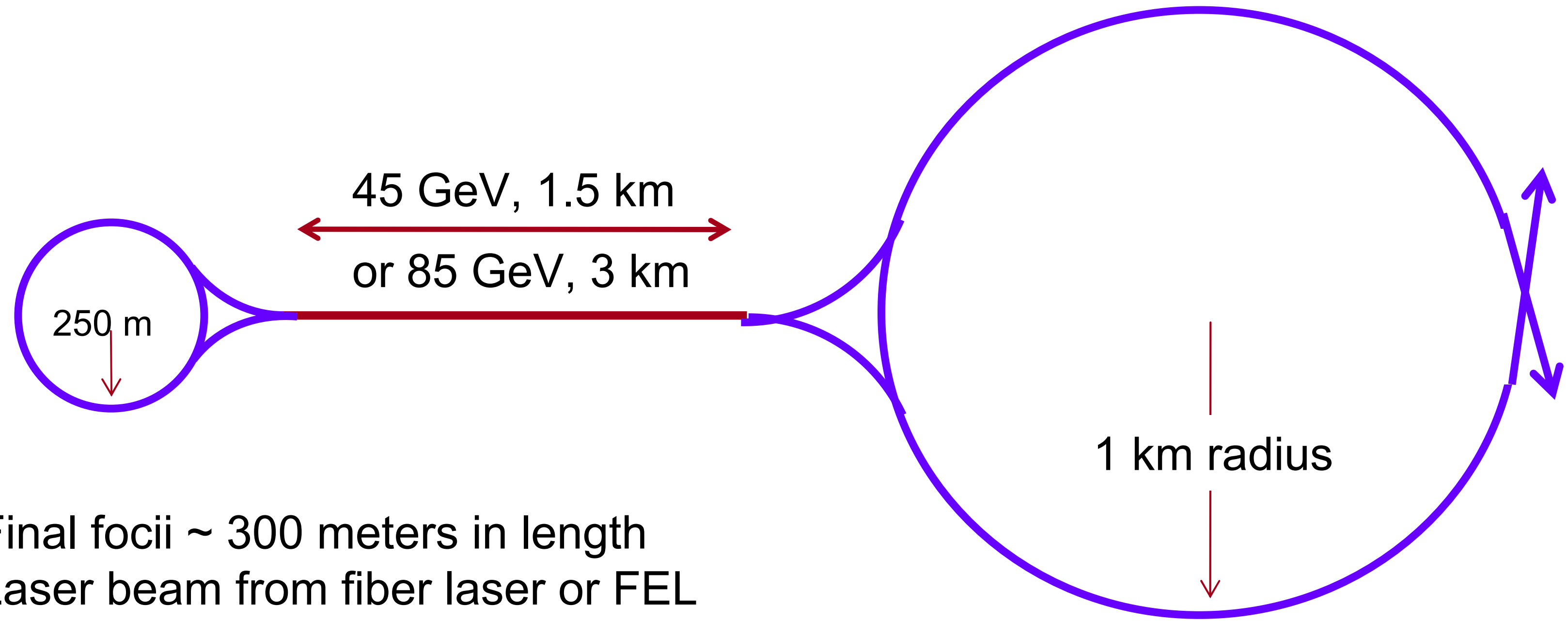
Top Energy	80 GeV	80 GeV
Turns	3	4
Magnet ρ	644.75 m	706.65 m
Linacs (5)	5.59GeV	4.23GeV
δp/p	6.99×10^{-4}	7.2×10^{-4}
ϵ_{nx} Growth	1.7μm	1.8μm

- Both versions assume an effective accelerating gradient of 23.5 MeV/m
- Option 1: would require more civil construction, but would only require two sets of spreader /recombiner magnets, and only two linacs, for greater simplicity.
- Option 2: would require 10 sets of spreader /recombiner magnets and 5 linacs but would achieve better beam parameters

SLC-ILC-Style (SILC) Higgs Factor

(T. Raubenheimer)

- Some challenges with 2-pass design!



Final focii ~ 300 meters in length
Laser beam from fiber laser or FEL
2 x 85 GeV is sufficient for $\gamma\gamma$ collider
Upgrade with plasma afterburners to reach 2 x 120 GeV. Then final ring should have R=3.5 km (to preserve emittance).

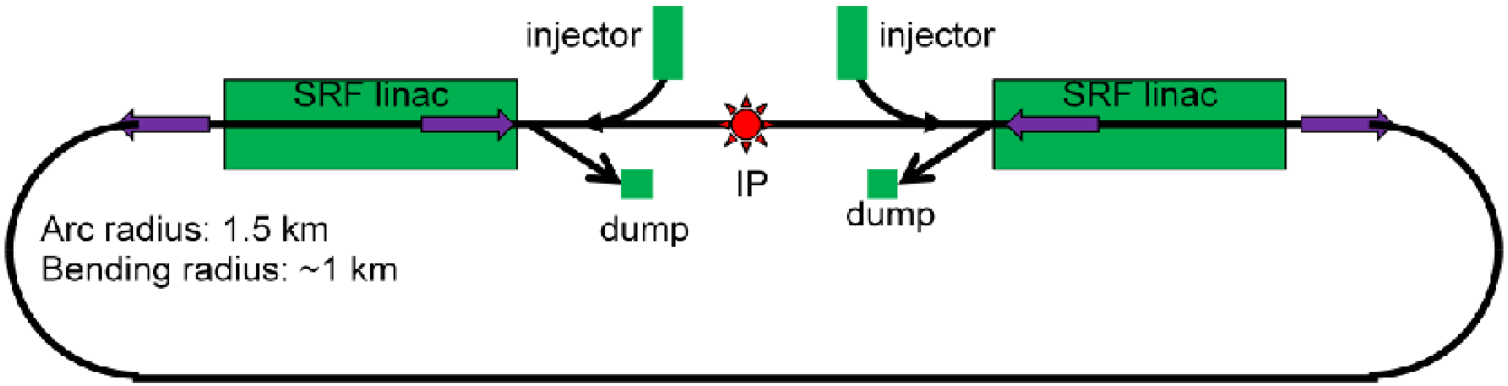
55

Jefferson Lab Technote JLAB-TN-12-053 October 31,2012

Design Concept of A γ-γ Collider-Based Higgs Factory Driven by a Thin Laser Target and Energy Recovery Linacs

Yuhong Zhang

Thomas Jefferson National Accelerator Facility
12000 Jefferson Avenue, Newport News, VA 23607 USA



Main idea: smaller conversion coefficient e→γ, but higher beam current due to recuperation of unscattered electrons energy.

It does not work:

a) electrons experience strong beamstrahlung and are not suited for recuperation due to the energy spread,

b) there is no improvement of luminosity, only decrease, because emittance increases with the increase of N. Maximum L for k~1.

Dreams of $\gamma\gamma$ factories

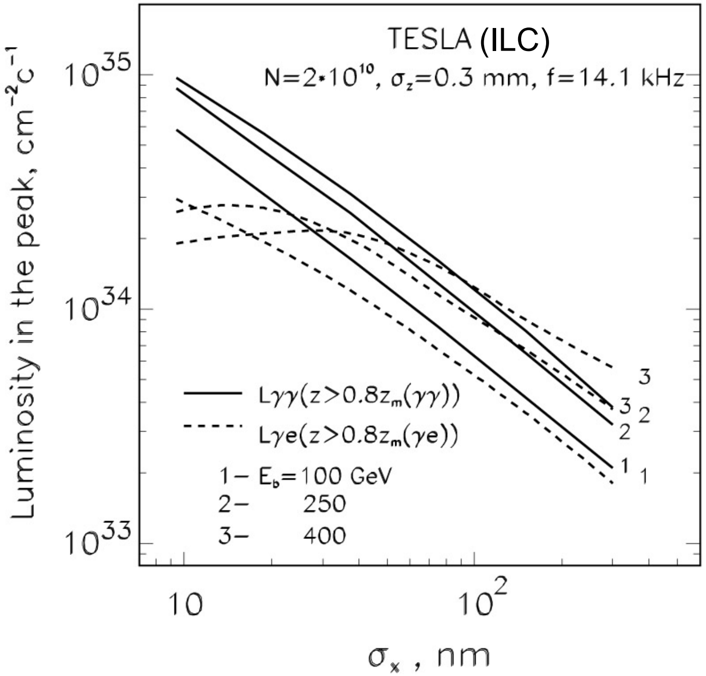
Factors limiting $\gamma\gamma$,γe luminosities

Telnov,1998

Collision effects:

- Coherent pair creation ($\gamma\gamma$)
- Beamstrahlung (γe)
- Beam-beam repulsion (γe)

On the right figure:
the dependence of $\gamma\gamma$ and γe luminosities in the high energy peak vs the horizontal beam size (σ_y is fixed).



At the ILC nominal parameters of electron beams σ_x ~ 300 nm is available at $2E_0$=500 GeV,
but PLC can work even with ten times smaller horizontal beam size.

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

Having electron beams with smaller emittances one could dream on photon colliders with the γγ-luminosity up to $L \sim 5 \times 10^{34}$ in the high energy peak.

Collision effects do not restrict the luminosity at 2E<1 TeV.

The cross section for the Higgs in γγ is higher than in e+e- by a factor of 5, for any charged pair by a factor of 5-10, so the number of interesting events could be higher by a factor of 20-50 times.

The problem – transverse emittances. Damping rings emittances are already near physics limits (due to SR). RF guns give larger product of horizontal and vertical emittances than DRs (determined by the space charge). Moreover, polarized RF guns do not exist yet (but may be appear soon).

Are there ways to small emittances without damping rings?

Comparizon of transverse emittances in damping rings and photo-guns

The ILC DR (polarized): $\varepsilon_{nx}=10^{-3}$ cm, $\varepsilon_{ny}=3.6\cdot10^{-6}$ cm, $\beta_x\sim4$ mm

RF guns (3 nC, unpolarized): $\varepsilon_{nx}=3\cdot10^{-4}$ cm, $\varepsilon_{ny}=3\cdot10^{-4}$ cm, $\beta_x\sim2$ mm

DC guns (polarized): $\varepsilon_{nx}=7\cdot10^{-3}$ cm, $\varepsilon_{ny}=7\cdot10^{-3}$ cm, $\beta_x\sim4$ mm

$L_{geom}\sim \quad F_{(pol.ench.)}/(\varepsilon_{nx}\varepsilon_{ny}\beta_x\beta_y)^{1/2}$ $\quad F_{pol.ench}\sim 2\text{-}3.5$ (depends on the energy)

Very approximately with account of β_x variation (chromo-geom.aberrations):

L(DR)/ L(RFguns,unpol)~ 7-12

L(DR)/ L(DCguns,pol) ~ 100

Therefore until now DRs were considered as a preferable source of electrons for the PLC.

Let us assume further that we have polarized guns with emittances similar to that for unpolarized guns. What can be done in this case?

Method based on longitudinal emittances

V.Telnov, LWLC10, CERN

Let us compare longitudinal emittances needed for ILC with those in RF guns.

At the ILC $\sigma_E/E \sim 0.3\%$ at the IP (needed for focusing to the IP),
the bunch length $\sigma_z \sim 0.03$ cm, $E_{min} \sim 75$ GeV
that gives the required normalized emittance

$$\varepsilon_{nz} \approx (\sigma_E/mc^2)\sigma_z \sim 15 \text{ cm}$$

In RF guns $\sigma_z \sim 0.1$ cm (example) and $\sigma_E \sim 10$ keV, that gives $\varepsilon_{nz} \sim 2 \cdot 10^{-3}$ cm, or 7500 times smaller than required for ILC!

So, photoguns have much smaller longitudinal emittances than it is needed for linear collider (both e+e- or $\gamma\gamma$).

How can we use this fact?

A proposed method

Let us combine many low charge, low emittance beams from photo-guns to one bunch using some differences in their energies. The longitudinal emittance increases approximately proportionally to the number of combined bunches while the transverse emittance (which is most important) remains almost constant.

It is assumed that at the ILC initial micro bunches with small emittances are produced as trains by one photo gun.

Each gun is followed by round-to-flat transformer (RFT). RFT does not change the product of transverse emittances, but it is easier to conserve emittances manipulating with flat beams in the horizontal plane.

Below the scheme for the ILC case is considered.

Round to flat transformer (RFT)

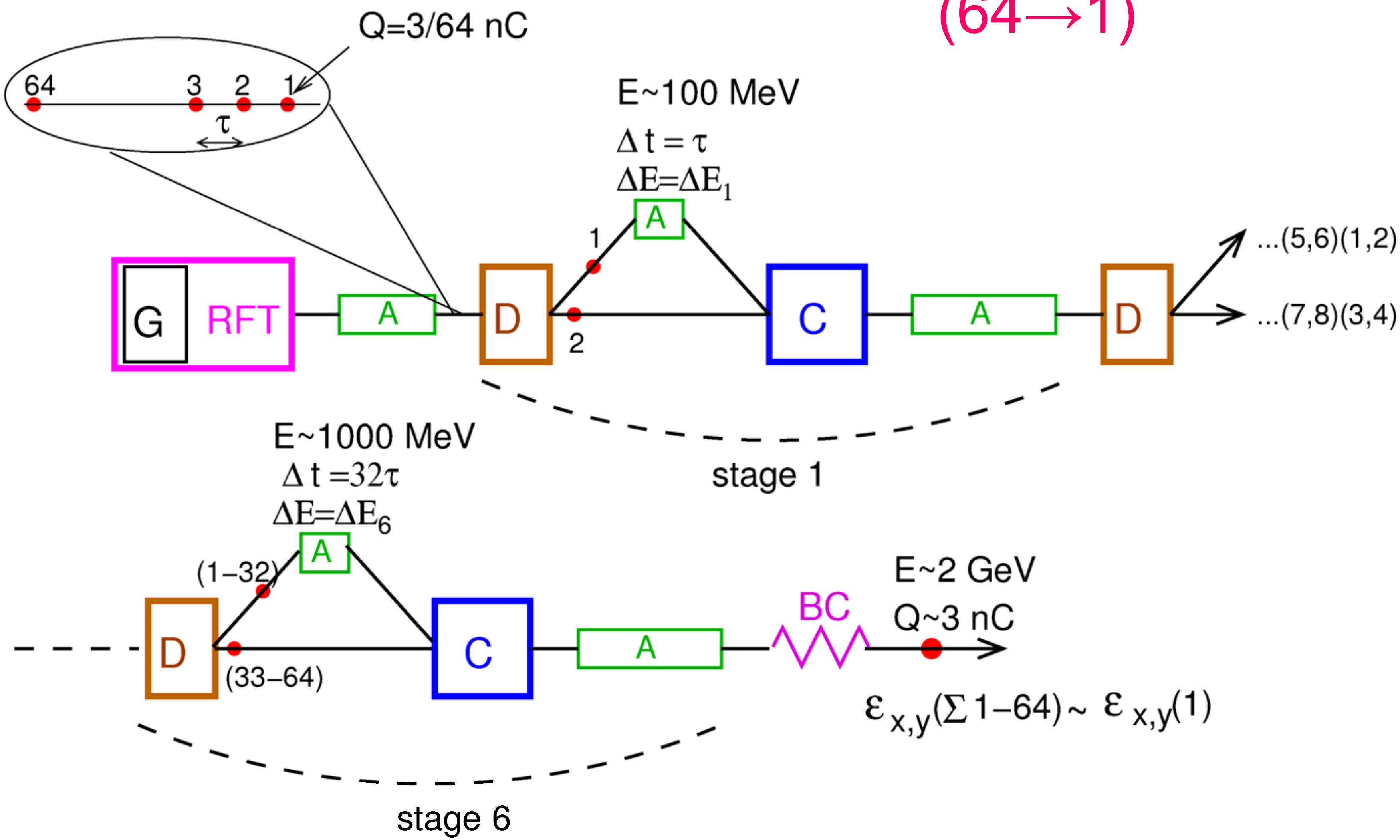
In 1998 Ya. Derbenev has found that using the RF gun inside the solenoid and following skew quadrupoles one can transform a round beam (from an electron gun) to a flat beam with an arbitrary aspect ratio.

After such transformation $\varepsilon_{nx}\varepsilon_{ny}=\varepsilon^0_{nx}\varepsilon^0_{ny}=(\varepsilon^G_n)^2=const$

The ratio R=100 was demonstrated at FNAL and this is not the limit. The initial goal of the R-F-transformer was the e+e- linear collider, but now there are much wider applications.

Scheme of combining one bunch from the bunch train (for ILC)

(64→1)

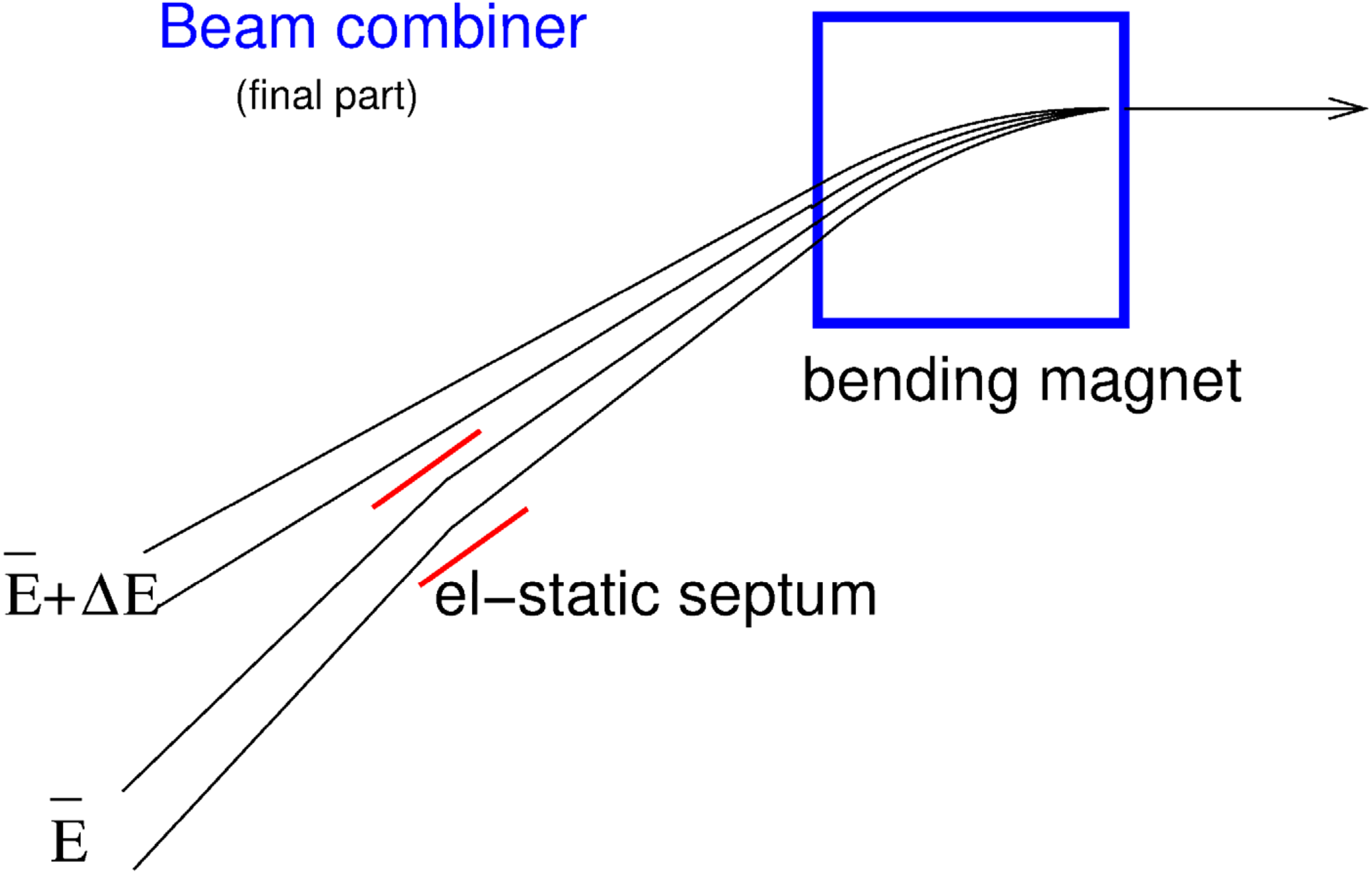


G –photogun, A –RF–cavities (accel), RFT –round to flat transformer,

D –deflector, C –beam combiner, BC –bunch compressor

Beam combiner

(final part)



Description of the scheme

After the gun and RFT the train passes several stages of deflectors-combiners. Each two adjacent bunches are redirected by the deflector (D) (transverse RF-cavity) into two beamlines which have difference in length equal to distance between bunches. One of these beamlines contains a weak RF-cavity which adds ΔE to the beam energy. Further these two beams are combined in a dispersion region of the combiner (C) using the difference in beam energies.

In order to combine the whole train to one bunch the procedure is repeated $m=\log_2 n_b$ times. The scheme shown above assumes $n_b=64$, that needs 6 stages. The energy between stages is increased by linacs in order to avoid emittance dilution due to the space charge effects. At the end, the final bunch is compressed down to required bunch length by a standard bunch compressor.

For more details see the talk at LWLC10.

Emittances in RF-guns

There are two main contribution to transverse emittances in RF guns:

1. Space charge induced normalize emittance;
2. Thermal emittance.

The space charge emittance $\varepsilon_{sc} \sim 10^{-4}$ Q[nC] cm

The thermal emittance $\varepsilon_{th} \sim 0.5 \cdot 10^{-4}$ R[mm], cm (for polarized different)

Assuming $R^2 \propto Q$ and R=1 mm at 1 nC, we get for Q=3/64 nC

$$\varepsilon_{sc} \sim 0.5 \cdot 10^{-5} \text{ cm}, \ \varepsilon_{th} \sim 10^{-5}$$

$$\rightarrow \varepsilon_{n,\,tot} \sim 10^{-5} \text{ cm}$$

After RFT with the ratio 100

$$\varepsilon_{nx} \sim 10^{-4} \text{ cm}, \ \varepsilon_{ny} \sim 10^{-6} \text{ cm}.$$

Luminosities

Beam parameters: $N=2\cdot10^{10}$ (Q~3 nC), $\sigma_z=0.4$ mm

Damping rings(RDR): $\varepsilon_{nx}=10^{-3}$ cm, $\varepsilon_{ny}=3.6\cdot10^{-6}$ cm, $\beta_x=0.4$ cm, $\beta_y=0.04$ cm,

RF-gun (Q=3/64 nC) $\varepsilon_{nx}\sim10^{-4}$ cm, $\varepsilon_{ny}=10^{-6}$ cm, $\beta_x=0.1$ cm, $\beta_y=0.04$ cm,

The ratio of geometric luminosities

$$L_{RFgun}/L_{DR}=12\sim10$$

So, with polarized RF-guns one can get the luminosity ~10 times higher than with DR.

Summary on low emittances with guns

Polarized RF-guns

Having polarized RF guns with emittances similar to existing unpolarized guns we could obtain the $\gamma\gamma$ luminosity ~10 times higher than that with ILC DRs (all polarization characteristics are similar).

Possible technical problems in suggested technique

1. Dilution of the emittance due to wakefields in combiner sections.
2. All parameters of beamlines should be continuously adjusted in order to perfectly combine all 64 bunches.

The above ideas should be proved by realistic consideration-optimization.

There is even more effective method of obtaining very low emittance electron beams, laser cooling (Telnov, 1997), but it need a laser system much more powerful than for PLC. This is next-to-next step.

Conclusion

- Photon colliders have sense as a very cost effective addition for e+e- colliders: as the LC second stage or as the second IP (preferable).
- PLC at ILC is conceptually clear, the next step is the design and construction of the laser system prototype. Now, due to LIFE project it seems that one pass scheme becomes very attractive.
- PLC at CLIC is more difficult due to much shorter trains. However LIFE help here as well.
- PLC SAPPHIRE proposal is does not look realistic due to technical problems, restriction on energy and absence of e+e- collisions.

  The PLC for Higgs without e+e- has not sufficient physics case.
- PLC without damping rings is possible, could have even higher (or much higher) luminosity, needs further study. That could open the way to γγ factories, to precision measurement of the Higgs self coupling etc (if there is any new physics in the sub-TeV region).

Conclusion (contin.)

- The ILC is close to approval (in Japan). It is very important to make the final ILC design compatible with the photon collider (as was required by the ILC scope document many years ago)