Compton Polarimetry for ILC and CLIC

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Introduction & Overview

- requirements and goals
  - precision
  - spin precession and suitable locations
  - depolarisation issues
- Compton polarimetry basics
  - kinematics, spin-dependent cross sections, asymmetry
  - luminosity for pulsed lasers & laser parameters

specific polarimeter performance studies for

- **TESLA (2001 …)**
- **ILC (2005 …)**
- **CLIC (2008 …)**

summary & conclusion

requirements and goals

(inspired by earlier work at SLAC and DESY)

- dP/P = 0.25% or better (systematics limited) from physics requirments (see e.g. Moortgat-Pick et al., arXiv:hep-ph/0507011)
- polarimetry should be robust and fast for instant tuneup of spin-dependent machine parameters

spin precession and directional alignment tolerance

$$\theta^{spin} = \gamma \frac{g-2}{2} \theta^{orbit} = \frac{E_0}{0.44065\ GeV} \theta^{orbit}$$

$$\Delta P/P \leq 0.1\% \longrightarrow \Delta\theta^{spin} \leq 45\, mrad$$

ILC

$$\theta^{spin} = 567\ \theta^{orbit} \quad for\ E_0 = 250\ GeV$$

$$\rightarrow \Delta\theta^{orbit} \leq 80\ \mu rad$$

CLIC

$$\theta^{spin} = 3404\ \theta^{orbit} \quad for\ E_0 = 1.5\, TeV$$

$$\rightarrow \Delta\theta^{orbit} \leq 13\ \mu rad$$

ILC (RDR 2007): Polarimeter Locations

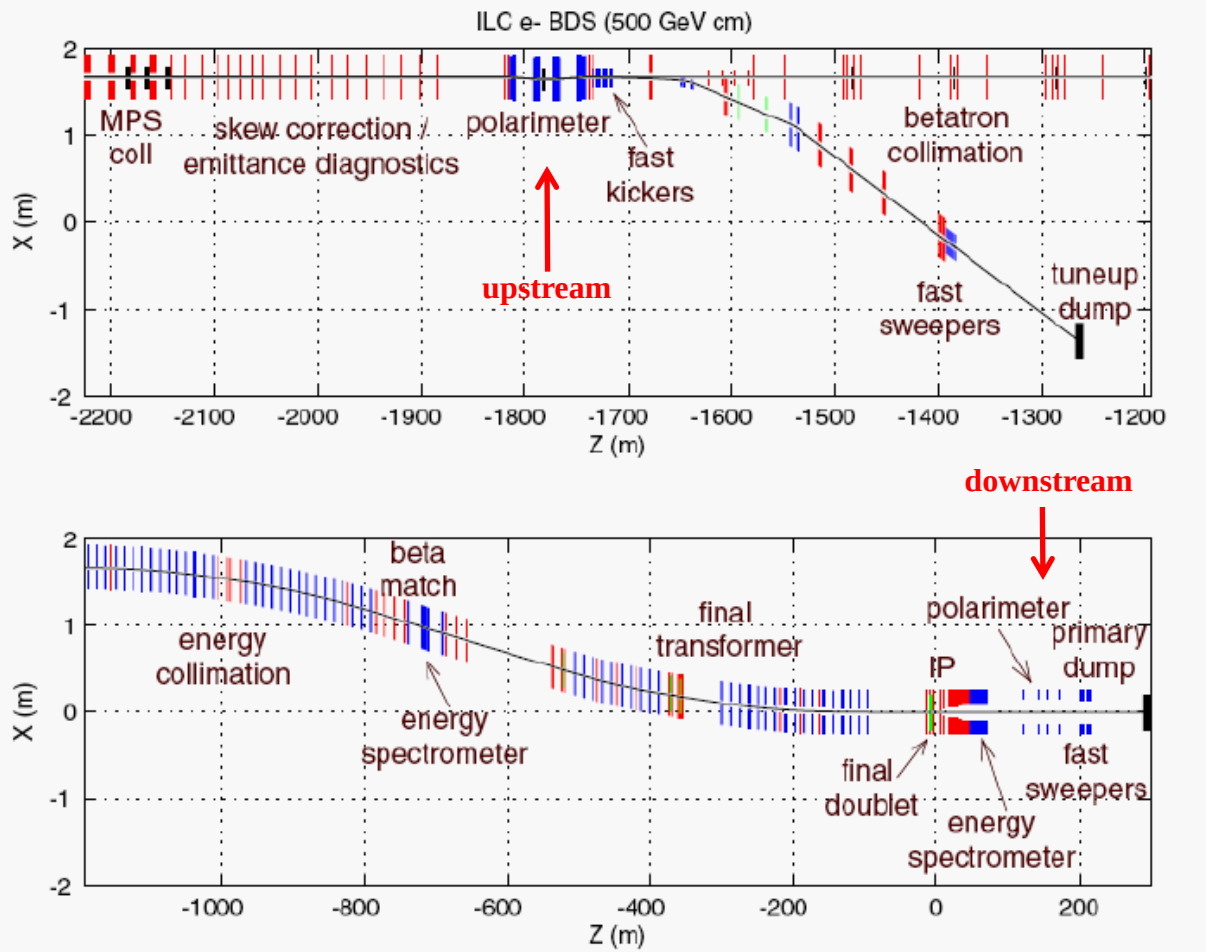
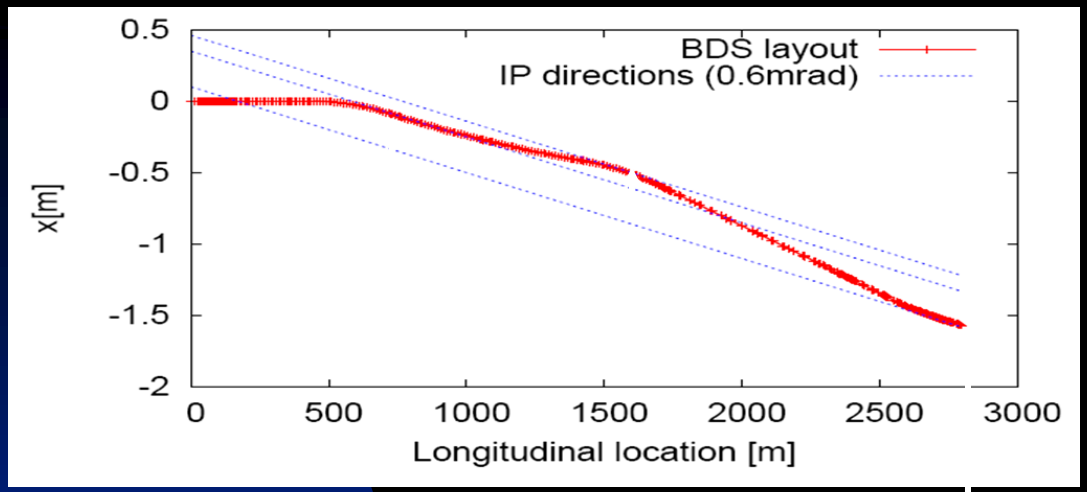
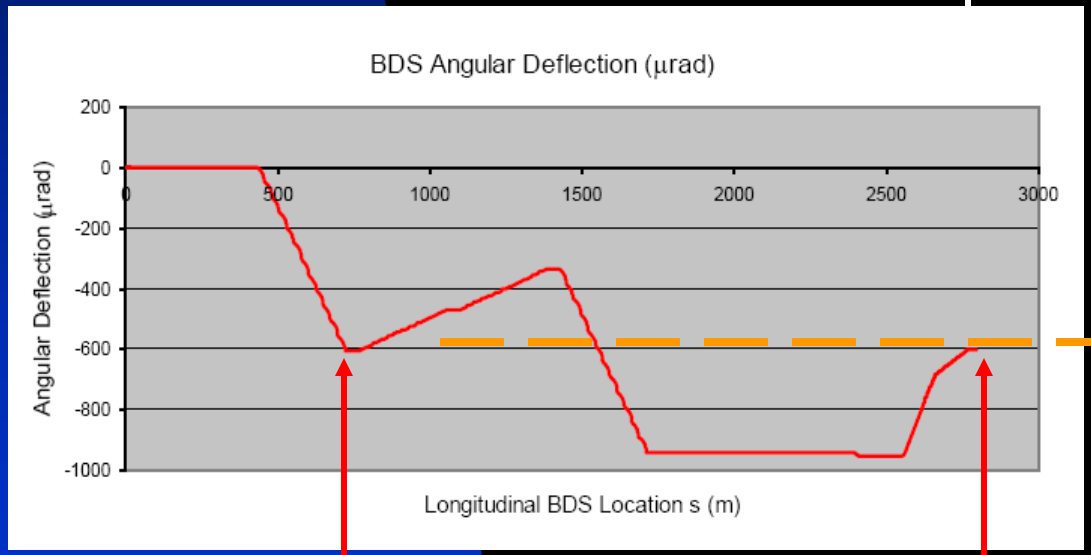


FIGURE 2.7-2. BDS layout showing functional subsystems, starting from the linac exit; X – horizontal position of elements, Z – distance measured from the IP.

CLIC: Suitable locations





Laser IP

End of BDS

alignment exists at two locations:

s = 742 m

(s = 1555 m)

but only the first one qualifies for polarimetry (upstream of energy collimation and sufficient free space for laser beam crossing)

(s is here distance from end of linac)

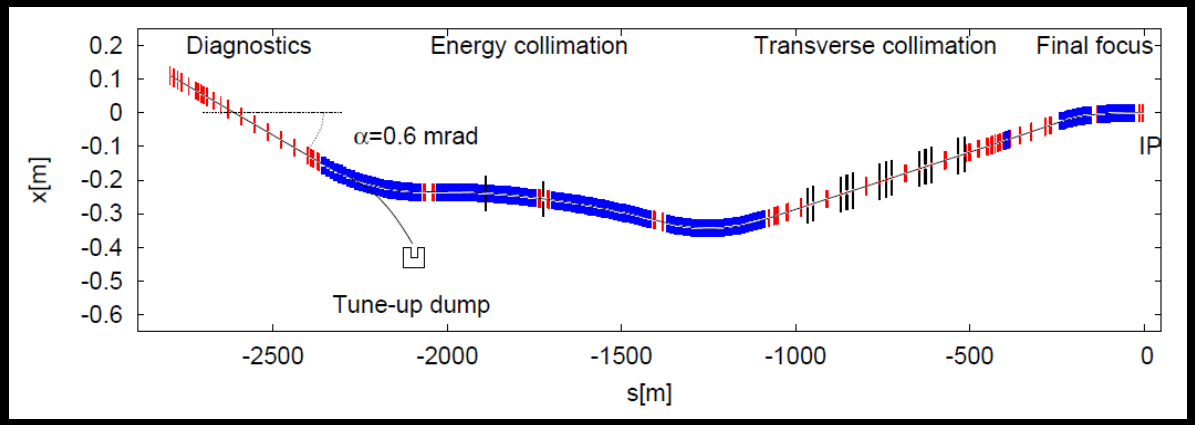
- 605.132 μrad (s = 742 m)

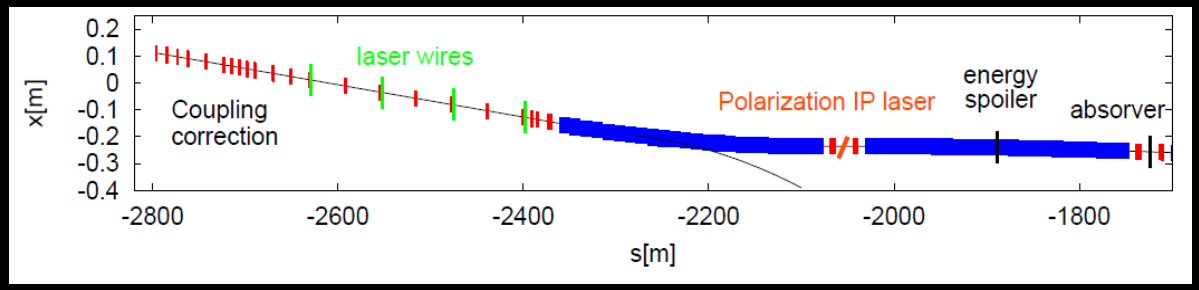
- 601.351 μrad (s = 2796 m)

aligned within **3.8 μrad**

CLIC BDS: polarimeter location

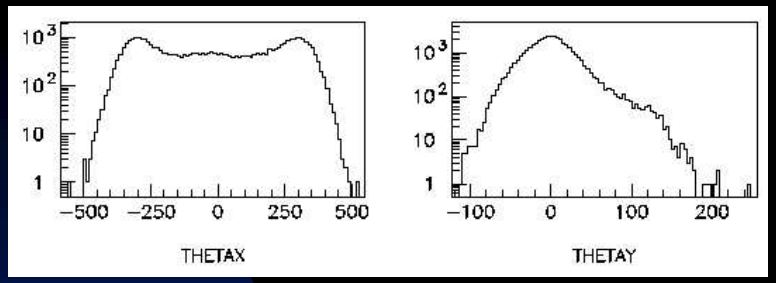
Parameter	Units	Value
Length (linac exit to IP distance)/side	m	2750
Maximum Energy/beam	TeV	1.5
Distance from IP to first quad, L*	m	3.5-6
Crossing angle at the IP	mrad	20
Nominal core beam size at IP, σ^*, x/y	nm	45/1
Nominal beam divergence at IP, θ^*, x/y	μrad	7.7/10.3
Nominal beta-function at IP, β^*, x/y	mm	10/0.07
Nominal bunch length, σ_z	μm	44
Nominal disruption parameters, x/y		0.15/8.4
Nominal bunch population, N		3.7×10^9
Beam power in each beam	MW	14
Preferred entrance train to train jitter	σ	< 0.2
Preferred entrance bunch to bunch jitter	σ	$<$?
Typical nominal collimation aperture, x/y	σ_x/σ_y	10/55
Vacuum pressure level, near/far from IP	nTorr	100/10





(s is now distance from e+e- IP)

depolarization issues



angular spread of disrupted beam leads to corresponding spread of spin vector distribution

	$\Delta\theta_x^{orbit}(rms)$ (μrad)	$\Delta\theta_y^{orbit}(rms)$ (μrad)	$\Delta\theta_x^{spin}(rms)$ $(mrad)$	$\Delta\theta_y^{spin}(rms)$ $(mrad)$
250 GeV	245	27	139	15
400 GeV	153	17	139	15

Table 2: Disrupted beam rms angular spreads of orbit and spin angles.

depolarization estimate for TESLA:
disrupted beam: ~ 1 % (extracted beam)
beam at e+e- IP: ~ 0.25% (lumi-weighted)

ΔP (downstream)* ~ 4 x ΔP (lumi-weighted)
upstream value is much closer to lumi-weighted

Bailey et al. (EPAC08)

Parameter set	Depolarization ΔP_{lw}		
	ILC 100/100	ILC 80/30	CLIC-G
T-BMT	0.17%	0.14%	0.10%
S-T	0.05%	0.03%	3.4%
incoherent	0.00%	0.00%	0.06%
coherent	0.00%	0.00%	1.3%
total	0.22%	0.17 %	4.8%

*** directly behind IP**

(with suitable extraction line optics it is possible to reduce angular spread and depolarization at the location of the downstream polarimeter)

Compton polarimetry basics I: kinematics

E_0 (GeV)	λ (nm)	ω_0 (eV)	x	ω_{max} (GeV)	E_{min} (GeV)	ω_c (GeV)	E_c (GeV)
100	532	2.33	3.569	78.114	21.886	64.088	35.912
250	532	2.33	8.923	224.806	25.194	204.225	45.775
500	532	2.33	17.846	473.469	26.531	449.612	50.388
1000	532	2.33	35.692	972.746	27.254	946.939	53.061
1500	532	2.33	53.538	1472.496	27.504	1445.983	54.017

$$x = \frac{4E_0\omega_0}{m^2}\cos^2(\theta_0/2) \simeq \frac{4E_0\omega_0}{m^2}$$

$$\omega + E = \omega_0 + E_0 \simeq E_0$$

$$\omega_{max} = E_0\frac{x}{1+x}$$

$$E_{min} = E_0\frac{1}{1+x}$$

$$\omega_c = E_0\frac{x}{2+x}$$

$$E_c = E_0\frac{1}{1+x/2}$$

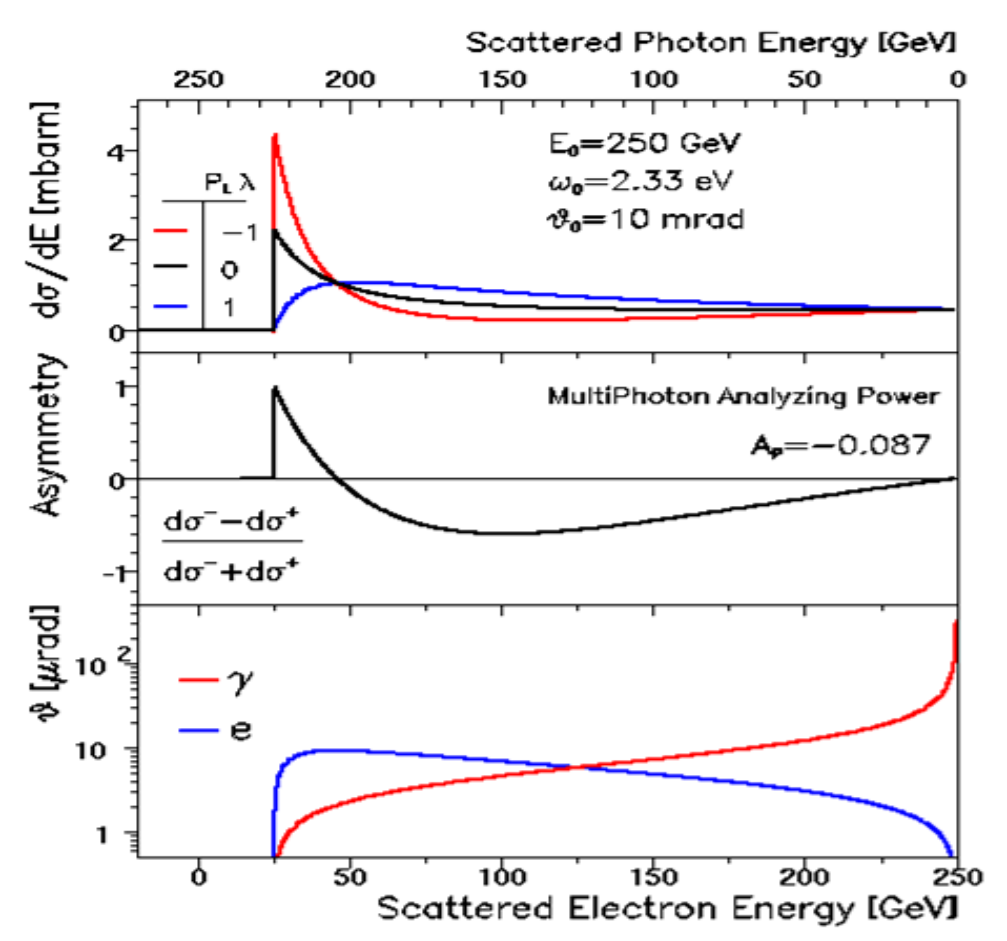
Compton polarimetry basics II :

cross sections, spin asymmetry, scattering angles

$-1 < P < +1$

$-1 < \lambda < +1$

$$\vartheta_e^{max} = 2\,\omega_o / m$$



$$A = \frac{d\sigma^- - d\sigma^+}{d\sigma^- + d\sigma^+}$$

$$\frac{d\sigma}{dy} = \frac{2\sigma_0}{x}\left[\frac{1}{1-y} + 1 - y - 4r(1-r) + P\lambda r x(1-2r)(2-y)\right]$$

scattering angles, cross sections at 1.5 TeV

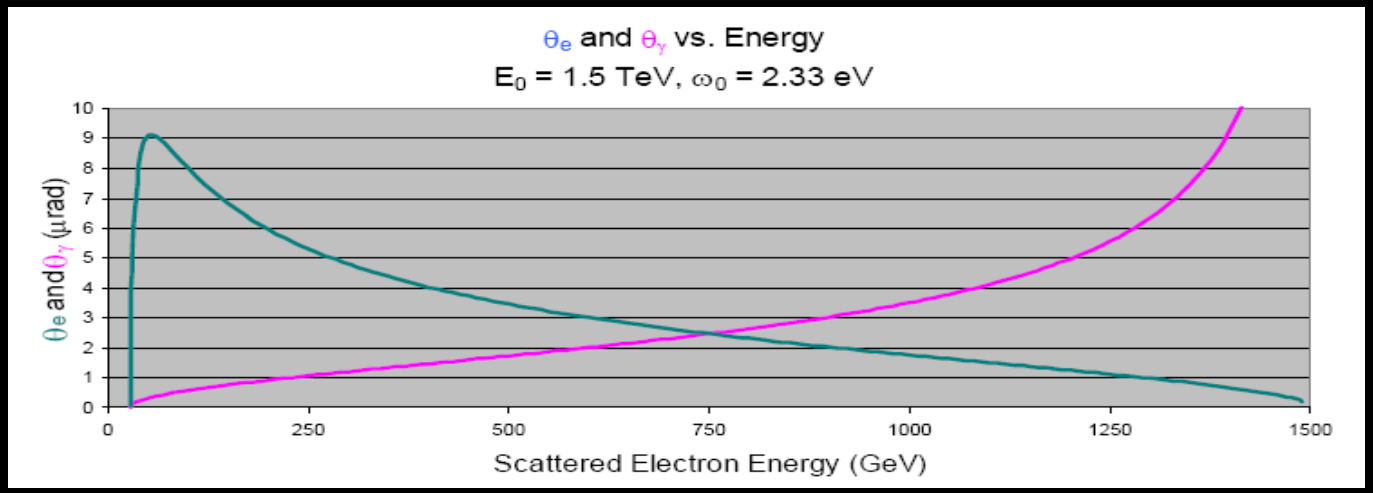
$$\theta_\gamma = \frac{m}{E_0}\sqrt{\frac{x}{y} - (x+1)}$$

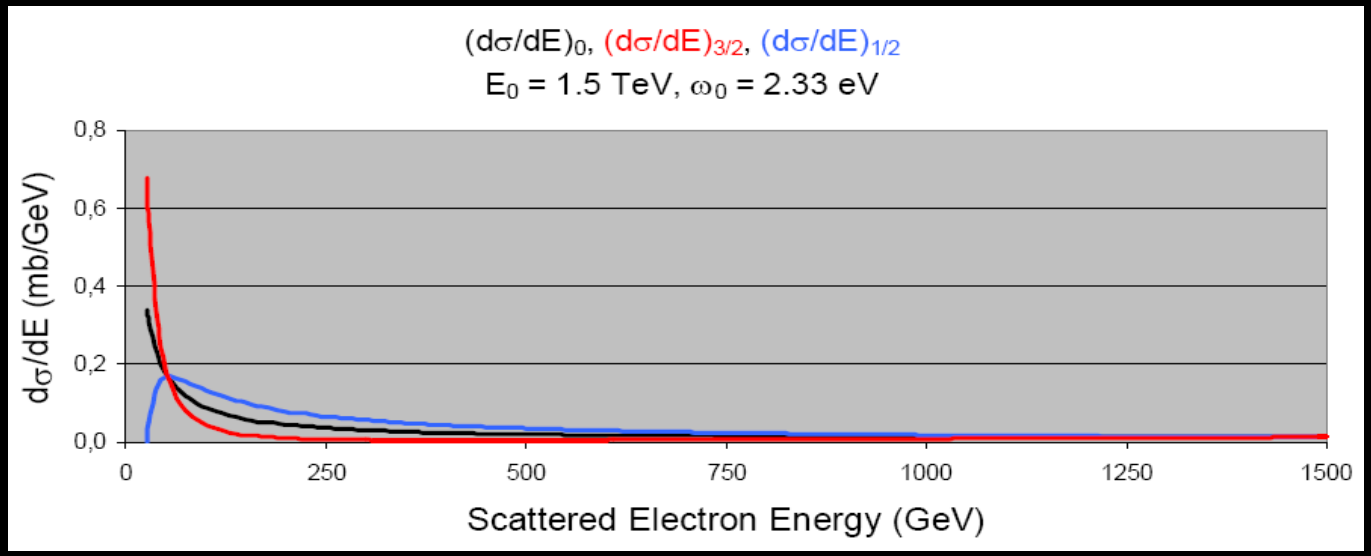
$$\theta_e = \frac{y}{1-y}\theta_\gamma$$

$$y = 1 - \frac{E}{E_0} = \frac{\omega}{E_0}$$

$$r = \frac{y}{x(1-y)}$$

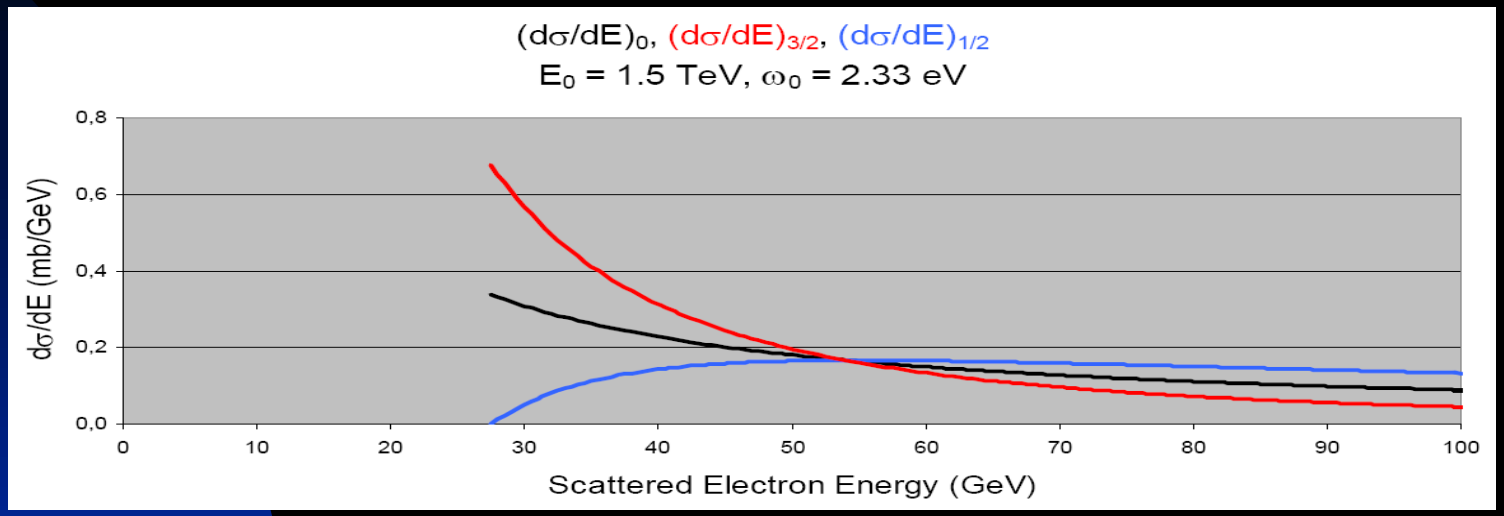
$$\sigma_0 = \pi r_0^2 = 0.2495\ barn$$

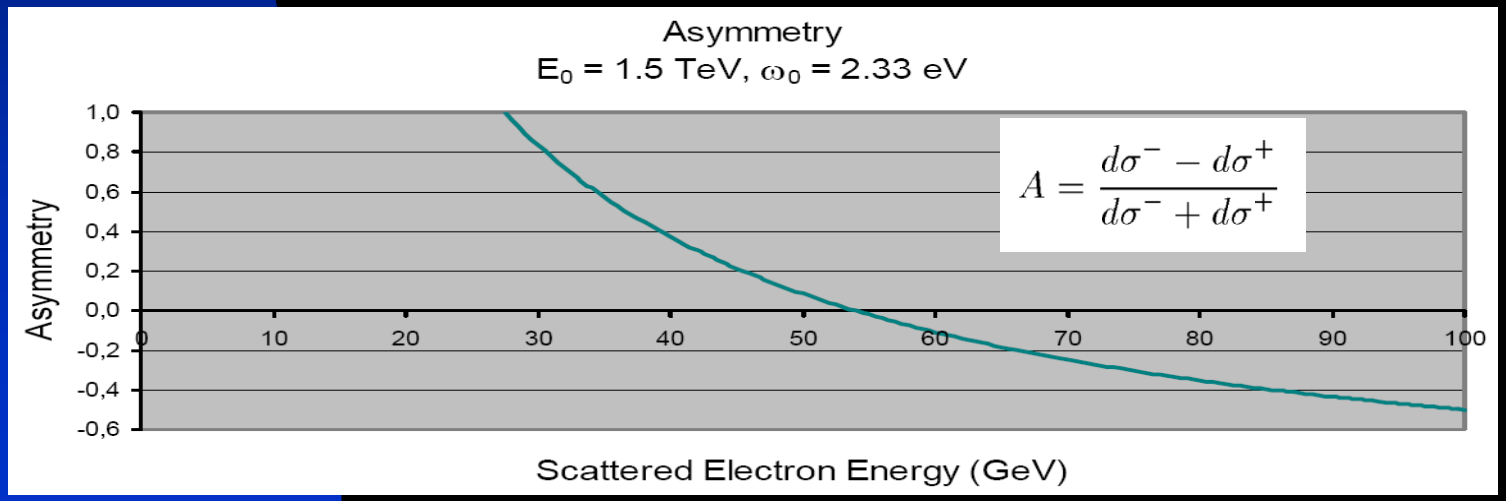




$$\frac{d\sigma}{dy} = \frac{2\sigma_0}{x}\left[\frac{1}{1-y} + 1 - y - 4r(1-r) + P\lambda r x(1-2r)(2-y)\right]$$

cross sections and spin asymmetry near the Compton edge





$$A = \frac{d\sigma^- - d\sigma^+}{d\sigma^- + d\sigma^+}$$

Compton polarimetry basics III: luminosity for pulsed lasers

$$\mathcal{L} = f_b \, N_e \, N_\gamma \, g$$

$$g = \frac{1}{2\pi \, \sigma_{x\gamma} \, \sigma_{y\gamma} \sqrt{1 + (0.5 \, \theta_0 \, \sigma_{z\gamma} \, / \, \sigma_{y\gamma})^2}}$$

f_b = bunch crossings per sec
N_e, N_γ = no. of e, γ per bunch
g = geometry factor
$\sigma_{x\gamma}$, $\sigma_{y\gamma}$ = transverse laser beam size
$\sigma_{z\gamma} = c \, \sigma_{t\gamma}$ = laser pulse length
θ_o = laser crossing angle

$$\mathcal{L} = \frac{\mathcal{L}_{max}}{\sqrt{1 + (0.5 \, \theta_0 \, \sigma_{z\gamma} \, / \, \sigma_{y\gamma})^2}}$$

$$\mathcal{L}_{max} = \frac{f_b \, N_e \, N_\gamma}{2\pi \, \sigma_{x\gamma} \, \sigma_{y\gamma}}$$

$\sigma_{t\gamma}$	$\sigma_{z\gamma}$	$\mathcal{L}/\mathcal{L}_{max}$		
(ps)	(mm)	$3\ mrad$	$10 mrad$	$30 mrad$
0	0	1.000	1.000	1.000
5	1.5	0.999	0.989	0.912
10	3.0	0.996	0.958	0.743
15	4.5	0.991	0.912	0.505
20	6	0.984	0.857	0.486
30	9	0.965	0.743	0.347
40	12	0.941	0.640	0.268
50	15	0.912	0.555	0.217
100	30	0.743	0.316	0.110
1000	300	0.110	0.033	0.011
10000	3000	0.011	0.003	0.001

$\Rightarrow$ effectiveness of laser degrades with increasing pulse length & crossing angle

Laser for TTF injector gun

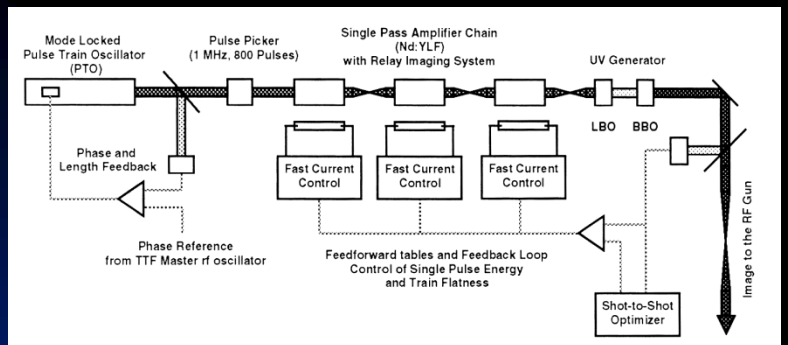
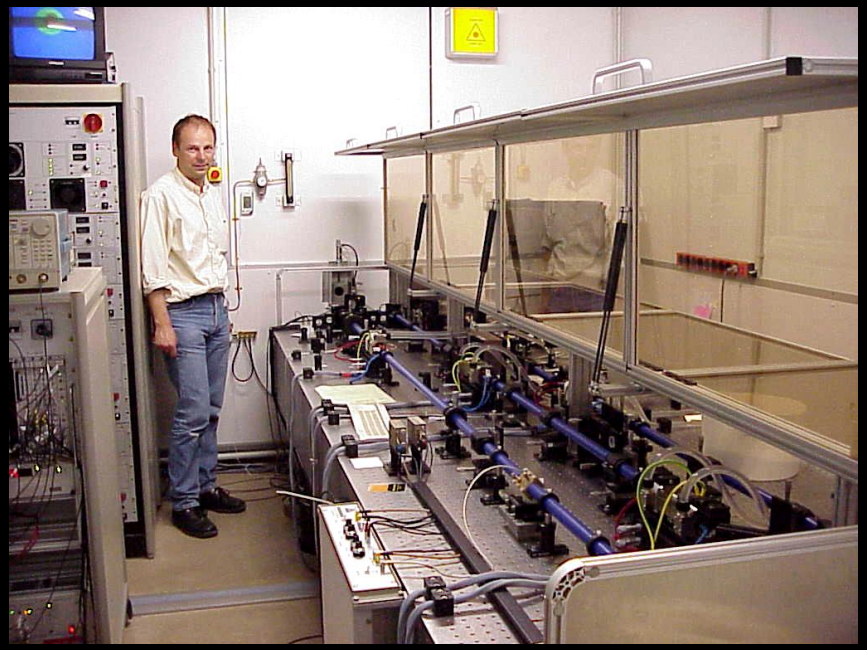
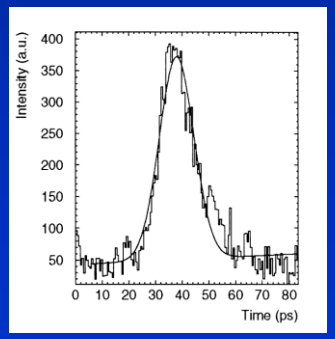


Fig. 1. Schematic overview of the TTF photoinjector laser system.



regen. multi-stage Nd:YLF ampl.
(built by Max-Born-Inst.)
operates at nominal pulse &
bunch pattern of TESLA

S. Schreiber et al.
NIM A 445 (2000) 427



$\sigma_t = 8$ ps

Laser parameters

for TESLA TDR (2001), we assumed TTF-style laser of variable wavelength:

configuration	E_0 (GeV)	$< I_e >$ (μA)	λ (nm)	ϵ_γ (eV)	$< P_L >$ (W)	j_γ (μJ)	$\mathcal{L}$ $(10^{32} cm^{-2}\, s^{-1})$	
TESLA-500	250	45	532	2.33	0.5	35	1.5	← green
TESLA-800	400	45	1064	1.165	1.0	71	6.0	← IR
Giga-Z	45.6	45	266	4.66	0.2	14	0.2	← UV

Table 9: Reference parameters for statistical tables.

ILC: employ similar laser for upstream chicane polarimeter, (operate only with green line at all ILC beam energies)

CLIC: assume standard Q-switched YAG laser for feasibilty study

laser for CLIC study

- will consider here only standard Q-switched YAG lasers
  with the following parameters:
  - 100 mJ pulse energy at 532 nm (2.33 eV)
  - 50 Hz operation (one laser pulse per CLIC bunch train)
  - ~3 ns pulse width (σ_t ~ 1 ns), will cover ~5 adjacent CLIC bunches
  - laser spot size $\sigma_x = \sigma_y = 50\ \mu m$
  - crossing angle of $\theta_0 = 10$ mrad
  - overlap efficiency with the ultra-short CLIC bunches will be poor, but sufficient for decent polarimetry

- other lasers
  with pulse length and repetition rate better matched
  to the peculiar bunch and pulse structure of the CLIC machine
  - can and should of course be considered
  - this will require in-depth examination with consultation of laser experts

CLIC study: luminosity for Q-switched YAG laser:

$$\mathcal{L} = f_b \, N_e \, N_\gamma \, g$$

For small crossing angle θ_0

$$g = \frac{1}{2\pi \sqrt{\sigma_{xe}^2 + \sigma_{x\gamma}^2} \sqrt{\sigma_{ye}^2 + \sigma_{y\gamma}^2} \sqrt{1 + \frac{\sigma_{ze}^2 + \sigma_{z\gamma}^2}{\sigma_{ye}^2 + \sigma_{y\gamma}^2} (\theta_0 / 2)^2}}$$

f_b = number of bunches per second hit by laser
N_e = number of particles per bunch
N_g = number of photons in laser puls
g = geometry factor

$$g = g_{max} \, \varepsilon$$

$$g_{max} = \frac{1}{2\pi \sqrt{\sigma_{xe}^2 + \sigma_{x\gamma}^2} \sqrt{\sigma_{ye}^2 + \sigma_{y\gamma}^2}}$$

$$\varepsilon = \frac{1}{\sqrt{1 + \frac{\sigma_{ze}^2 + \sigma_{z\gamma}^2}{\sigma_{ye}^2 + \sigma_{y\gamma}^2} (\theta_0 / 2)^2}}$$

$$f_b = 5 \cdot 50 = 250 \, Hz$$
$$N_e = 3.72 \cdot 10^9$$
$$N_\gamma = 0.100 \, J / \left(2.33 \, eV \cdot 1.602 \cdot 10^{-19} \, J / eV\right) = 2.68 \cdot 10^{17}$$

$$CLIC:$$
$$\sigma_{xe} = 300 \, \mu m = 0.03 \, cm$$
$$\sigma_{ye} = 27 \, \mu m = 0.0027 \, cm$$
$$\sigma_{ze} = 44 \, \mu m = 0.0044 \, cm$$

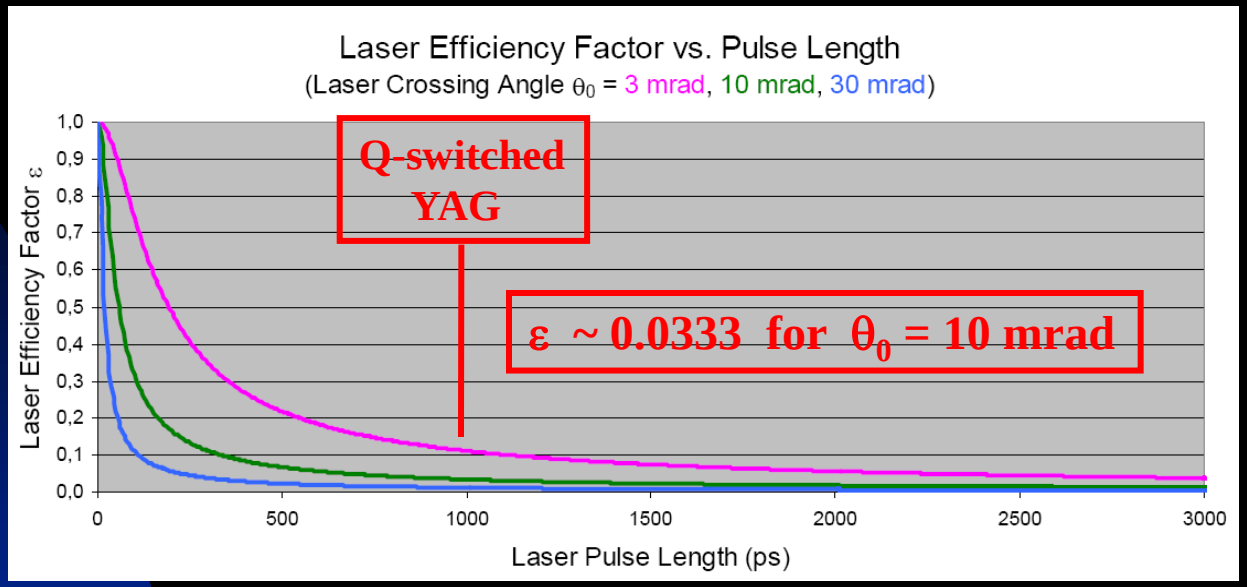
$$Laser:$$
$$\sigma_{x\gamma} = \sigma_{y\gamma} = 50 \, \mu m = 0.0050 \, cm$$
$$\sigma_{z\gamma} = 30 \, cm \, (1 \, ns)$$
$$\theta_0 = 10 \, mrad = 0.010 \, rad$$

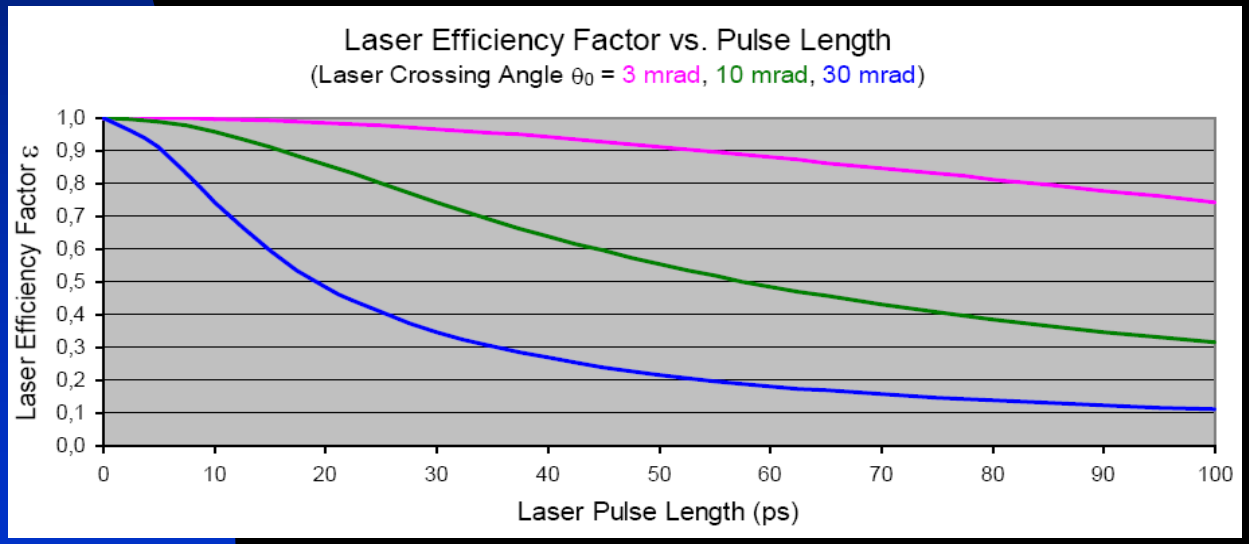
$$g_{max} = 921.2 \, cm^{-2}$$

$$\varepsilon = 0.333$$

$$L = 7.645 \cdot 10^{30} \, cm^{-2} \, s^{-1}$$

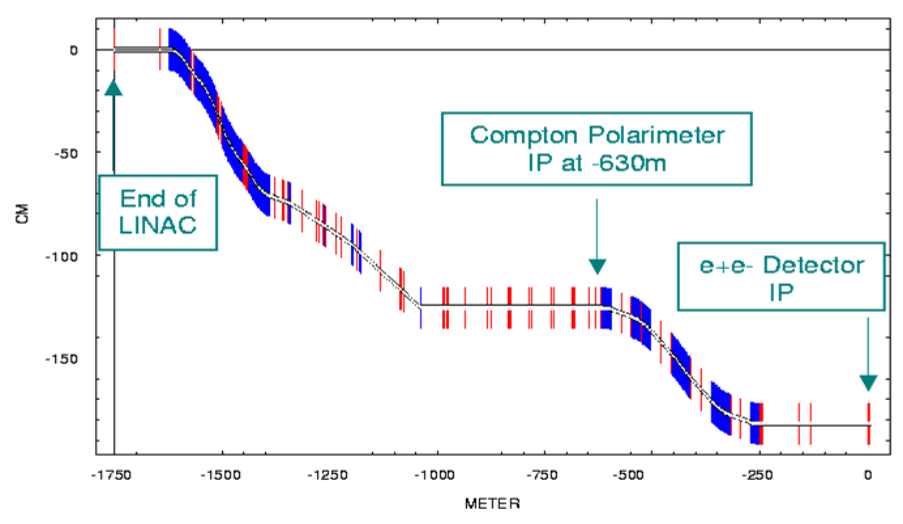
CLIC study: pulsed laser efficiency

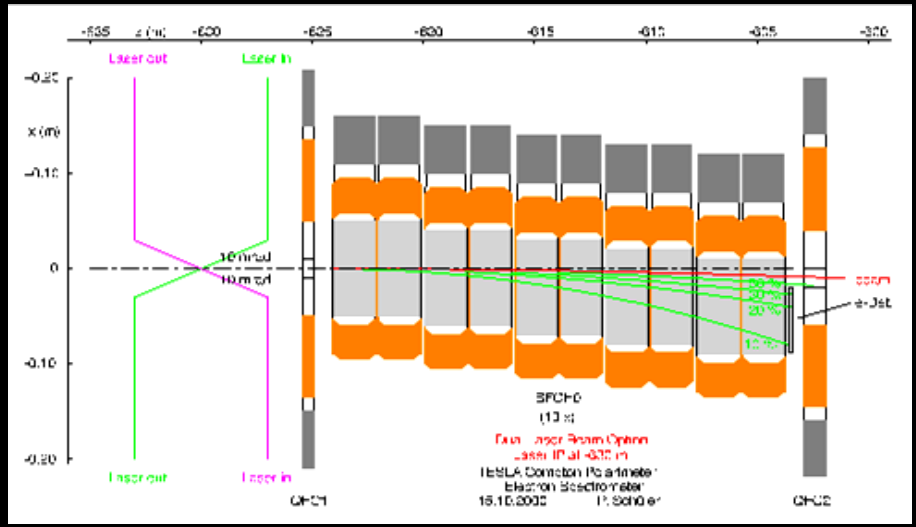




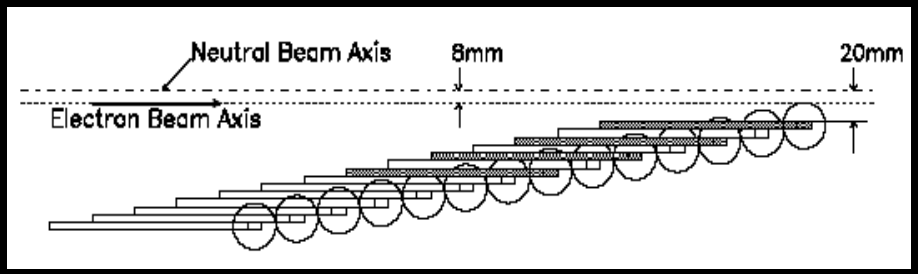
Tesla study

V. Gharibyan, N. Meyners, K.P. Schüler,
www.desy.de/~lcnotes/notes.html, LC-DET-2001-047



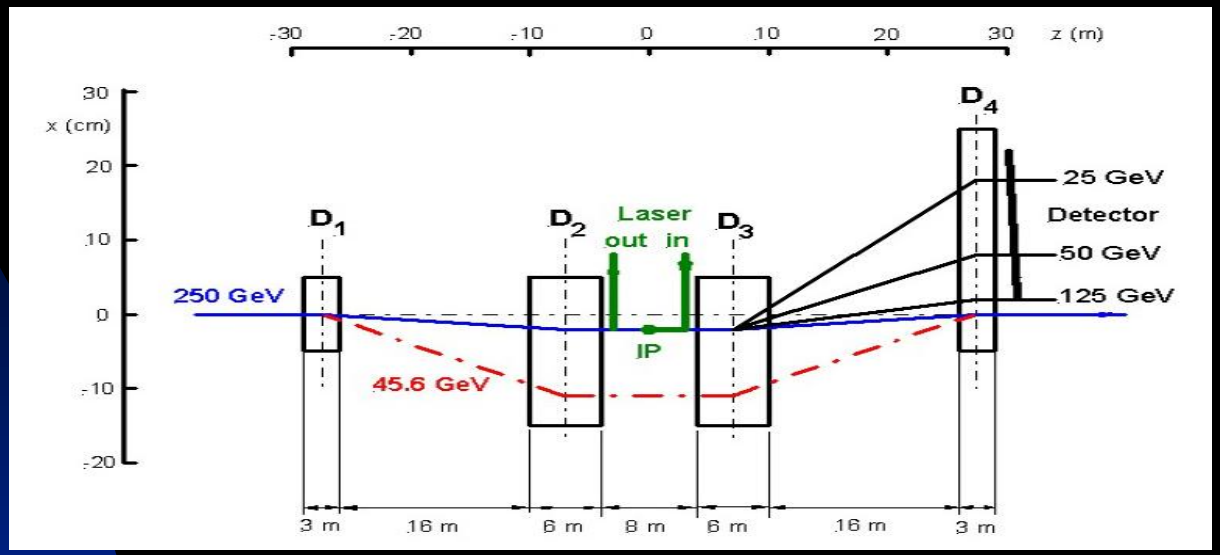


	e^+/e^- beam	laser beam
energy	250 GeV	2.3 eV
charge or energy/bunch	$2 \cdot 10^{10}$	35 μJ
bunches/sec	14100	14100
bunch length σ_t	1.3 ps	10 ps
average current(power)	45 μA	0.5 W
$\sigma_x \cdot \sigma_y$ (μm)	$10 \cdot 1$	$50 \cdot 50$
beam crossing angle	10 mrad	
luminosity	$1.5 \cdot 10^{32} cm^{-2} s^{-1}$	
cross section	$0.136 \cdot 10^{-24} cm^2$	
detected events/sec	$1.0 \cdot 10^7$	
detected events/bunch	$0.7 \cdot 10^3$	
$\Delta P/P$ stat. error/sec	negligible	
$\Delta P/P$ syst. error	$\sim 0.5\%$	



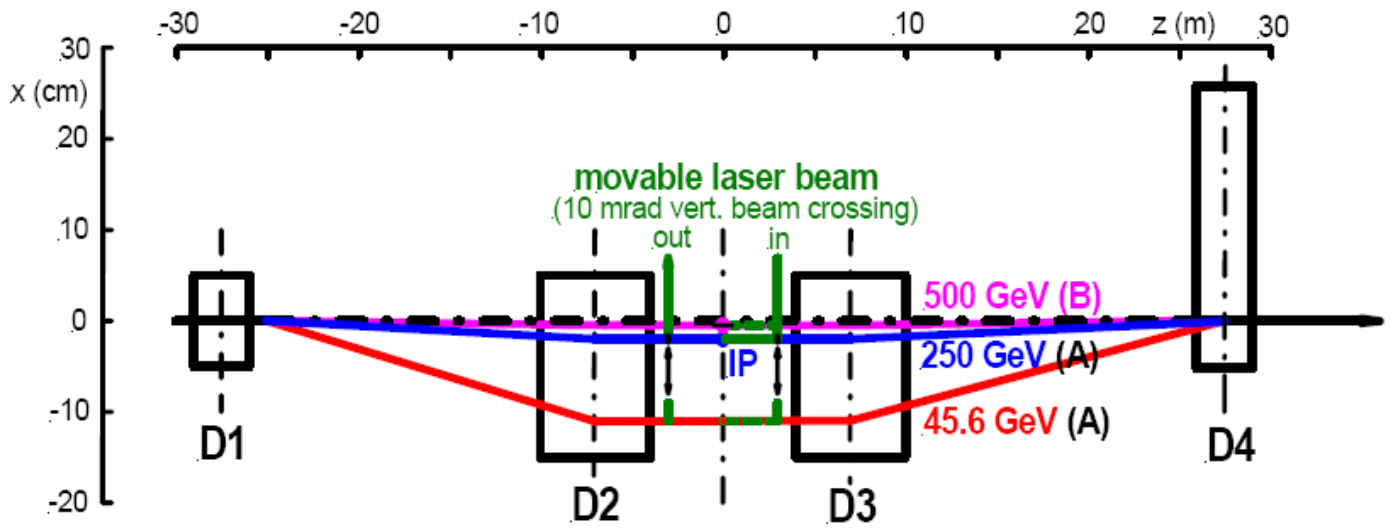
- **minimal space & no special magnets**
- **need to change laser wavelength to UV for z-pole running**

Chicane Design



- essential for downstream polarimetry (separates Compton electrons from low-energy disrupted beam background), but adventageous also for upstream polarimetry
- requires ~ 60 meters length
- constant field settings ∫ B dl over wide range of energies
- good acceptance of Compton spectrum at all energies without changing laser wavelength
- laser crossing (Compton IP) at mid-chicane

4-Magnet Chicane: general layout

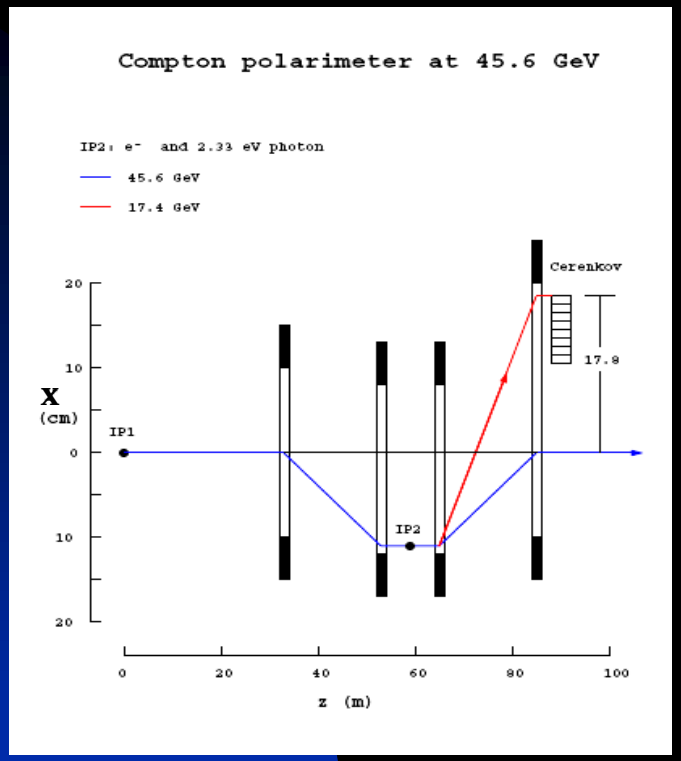


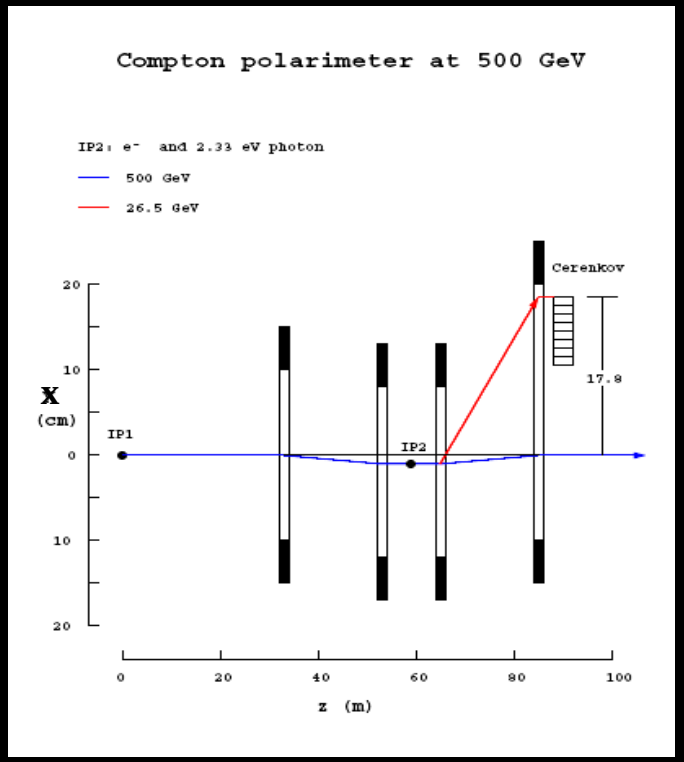
Chicane Magnet	D1	D2	D3	D4
cntr. z-pos. (m)	-27.5	-7	+7	+27.5
L (m)	3	6	6	3
hor. width (cm)	10	20	20	30
B_T (T)	0.272	0.136	0.136	0.272
$B_T L$ (Tm)	0.815	0.815	0.815	0.815
P (GeV/c)	0.245	0.245	0.245	0.245

Beam Energy (GeV)	Beam Defl. Angle per magnet (mrad)	Hor. Dispersion at IP (mm)
45.6	5.366	110
100	2.447	50
250	0.979	20
500	0.489	10

Chicane properties

(W. Oliver, MDI workshop, SLAC, 2005)

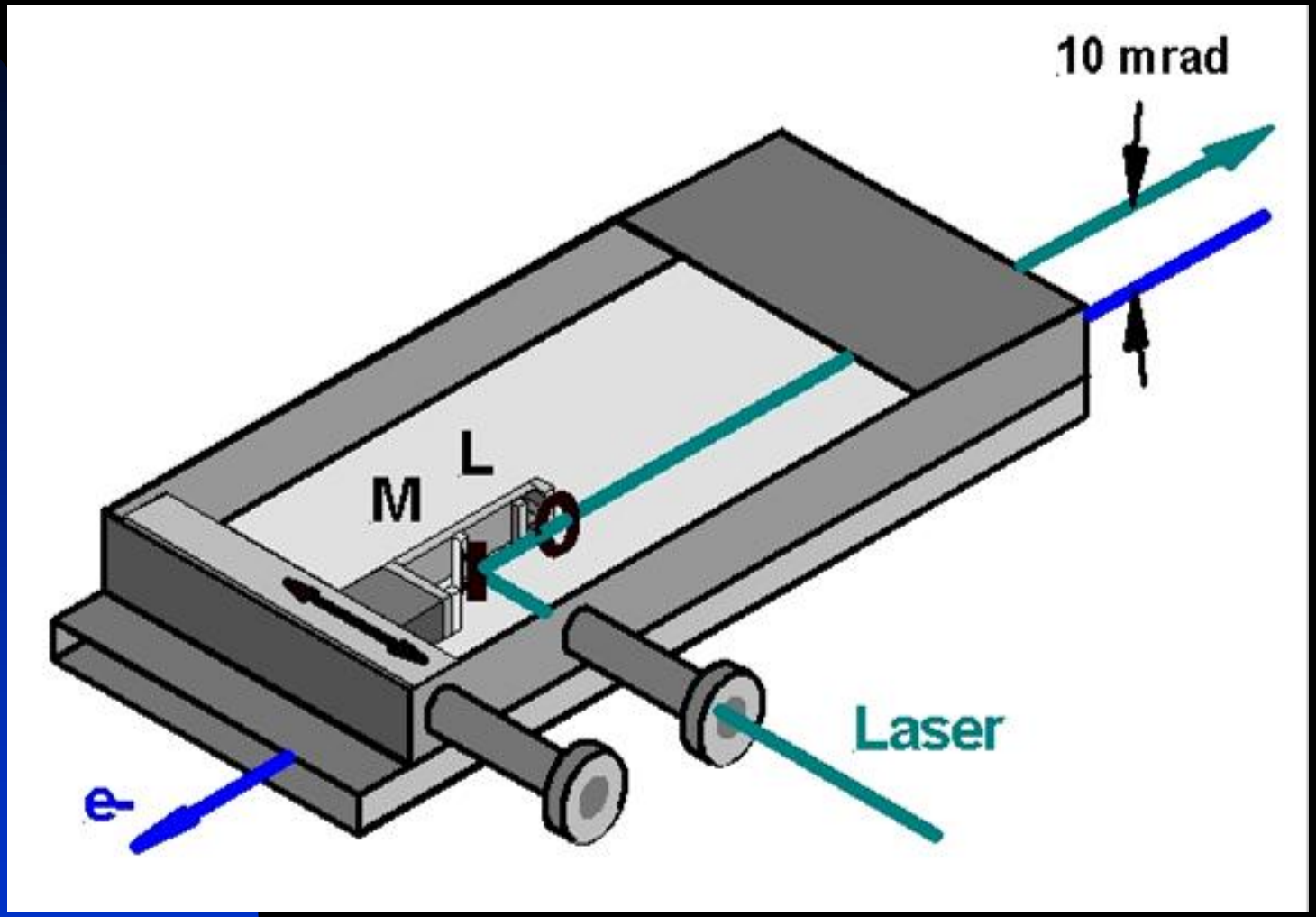




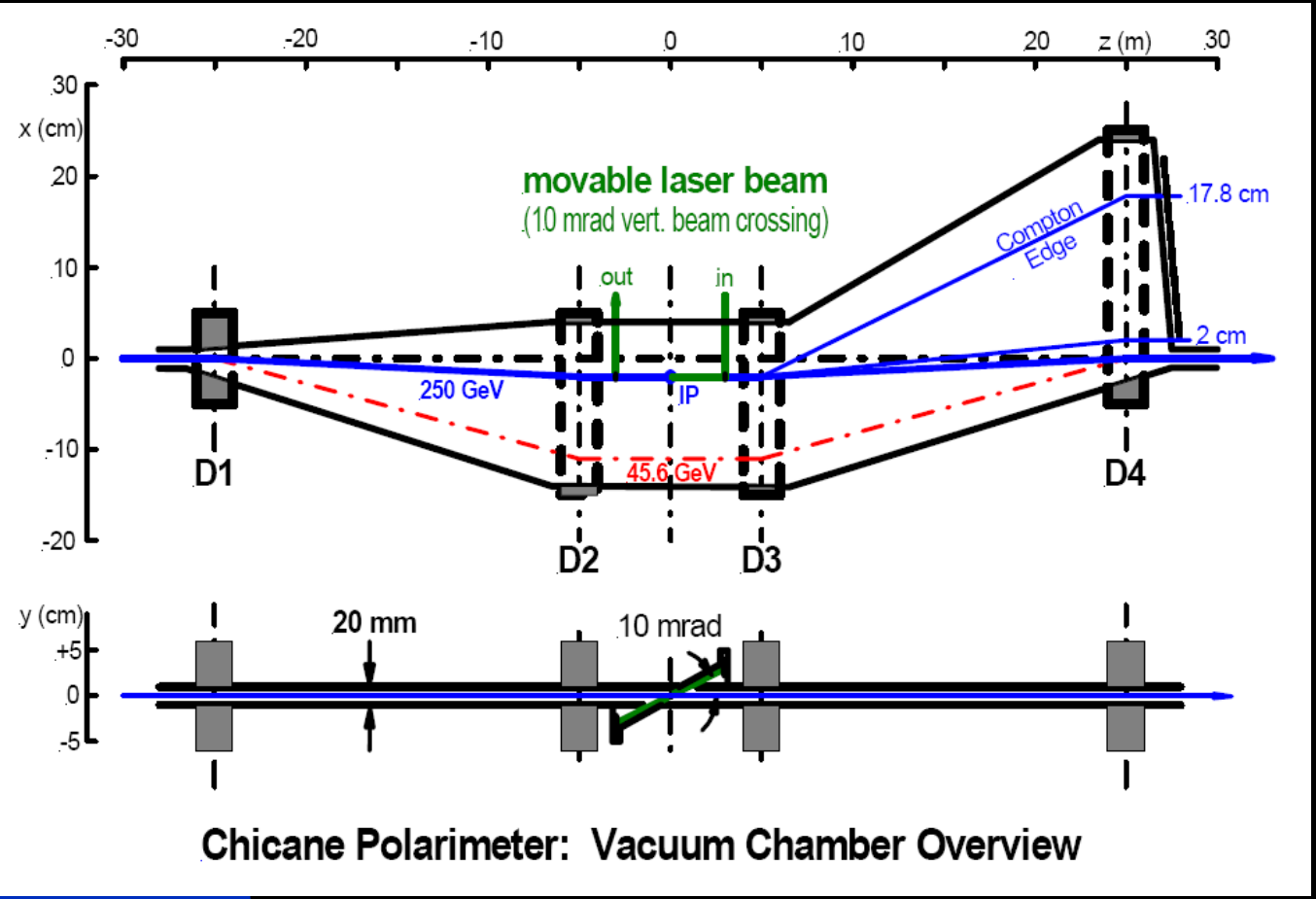
$X_{max} = 4\,\omega_0\, p_T\, L / m^2$ ← position of Compton edge is independent of beam energy

e.g. $X_{max} = 17.8$ cm for $\omega_0 = 2.33$ eV, $P_T = 0.25$ GeV/c, L = 20 m

movable laser beam

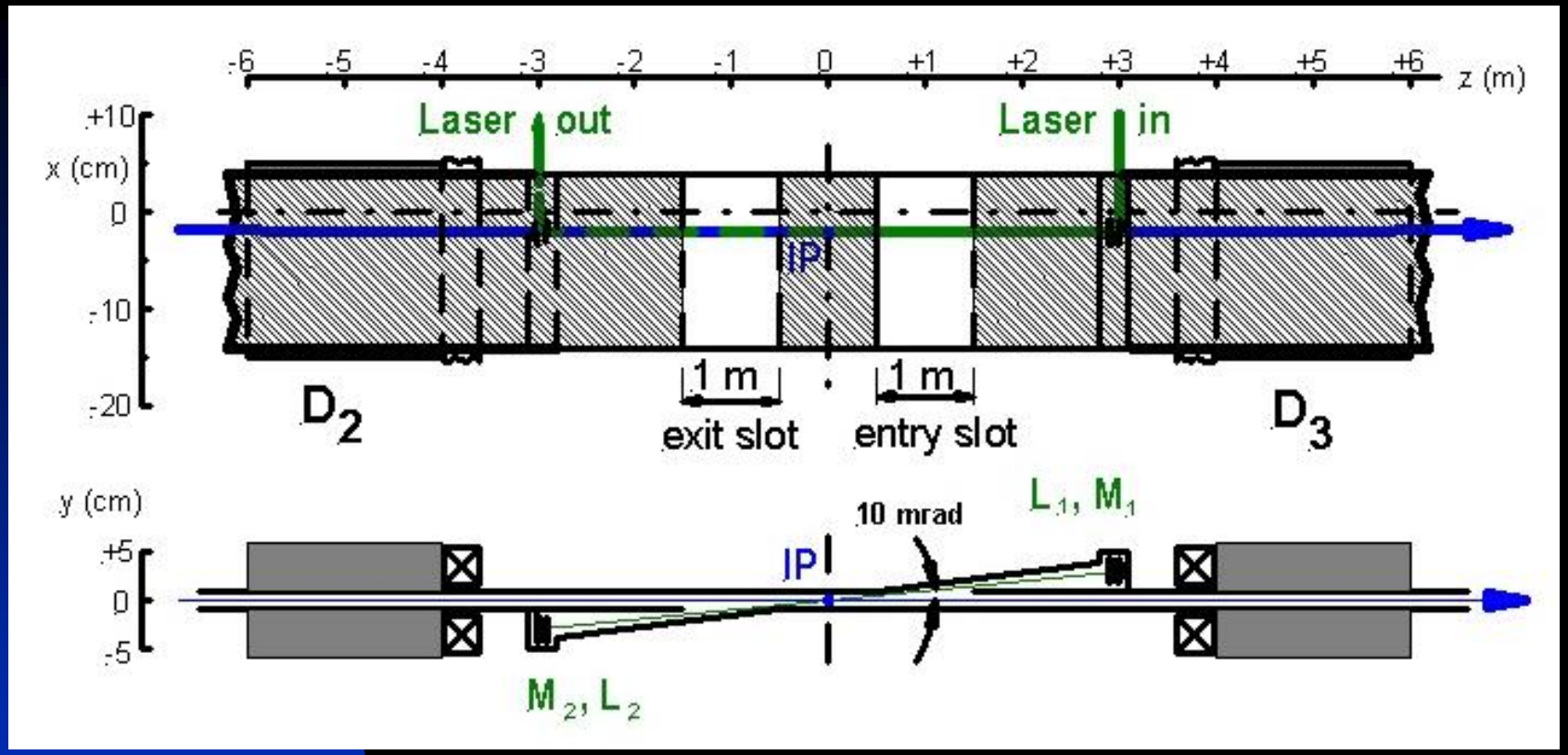


vacuum chamber overview



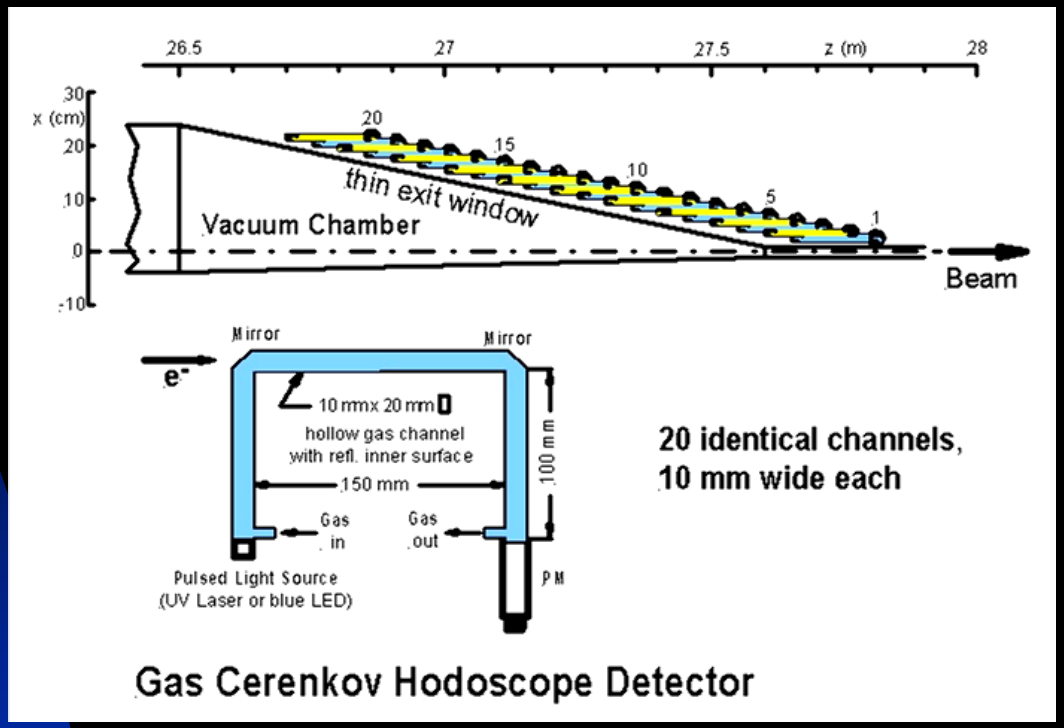
chambers are tapered to minimize wake fields

vacuum chamber detail



laser beam crossing requires ~ 1 m long insertion/exit slots along z
(wake field effects have been studied and were found to be harmless)

electron detector



- design similar to gas Cerenkov employed in SLD Compton polarimeter
- C_4F_{10} gas (~10 MeV threshold)
- detector will be immune against low-energy and diffuse background (syn. rad.)
- 20 channels, 10 mm wide each, will cover a large fraction of the Compton spectrum
- Cerenkov photon detection with conventional PMs, but other technologies are also explored

some simulation results

input parameters

0.5 x 10^6	no. of Compton evt's per polarity	
676749.	random seed	
2.33	laser photon energy	(eV)
250.	electron energy	(GeV)
10.	crossing angle	(mrad)
1.50	luminosity	(10^32 / cm² / sec)
0.250	chicane transv. mom. kick	(GeV/c)
2.	magnet length	(m)
20.	cntr. dist. magnets 1&2 (3&4)	(m)
10.	cntr. distance magnets 2&3	(m)
0.7	dist. mag. 4 edge to det. ch. n	(m)
20	no. of det. channels (max. 100)	
10.	det. channel x-size (hor.)	(mm)
20.	det. channel y-size (vert.)	(mm)
150.	det. channel length along z	(mm)
20.	distance det. ch. 1 to beam	(mm)
50.	z-dist. btw. det. channels	(mm)
1.	meas. time for stat. error	(sec)
0.80	beam pol. to calculate stat. error	

E_0 = 250 GeV

ω_0 = 2.33 eV (green laser)

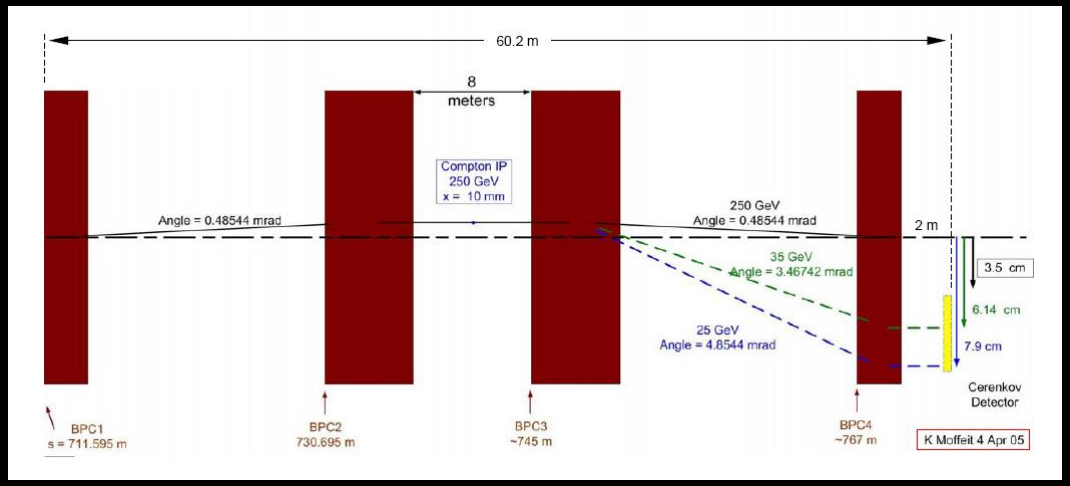
$\mathcal{L}$ = 1.5 x 10^{32}/cm²/sec

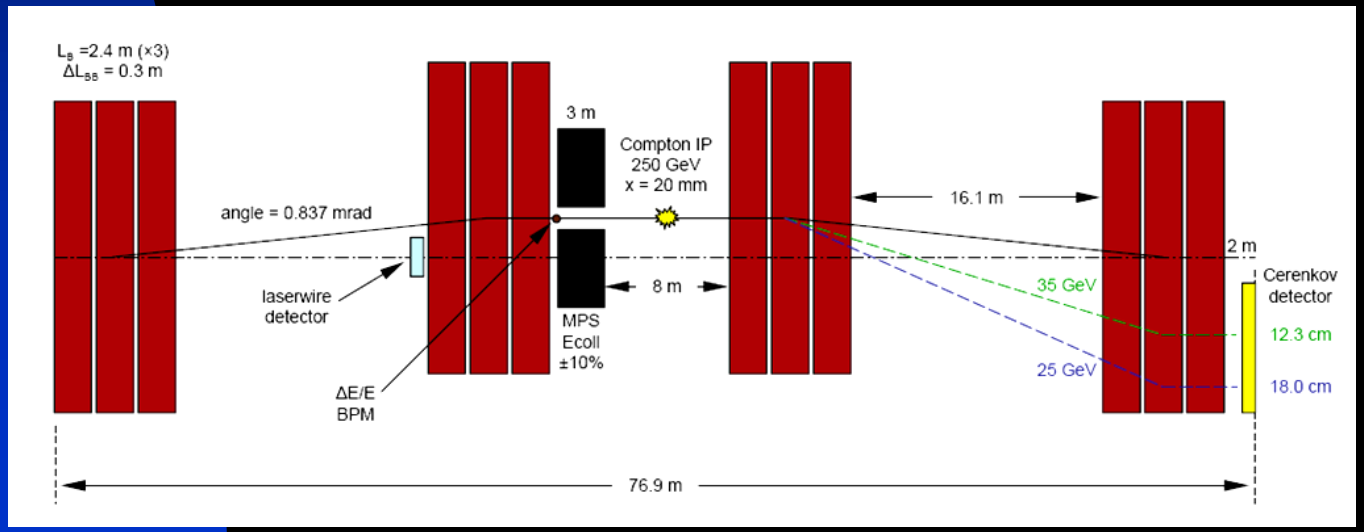
results

Ch. #	x [mm]	N+	N-	A	Rate*A²	Rate [MHz]	dP/P [%]
1	25	60,682	23,368	-0.444	0.337	1.710	0.228
2	35	45,868	17,348	-0.451	0.262	1.287	0.260
3	45	35,673	16,012	-0.380	0.152	1.052	0.335
4	55	28,337	16,029	-0.277	0.069	0.903	0.486
5	65	22,996	16,956	-0.151	0.019	0.813	0.924
6	75	18,333	17,876	-0.013	0.000	0.737	11.521
7	85	15,248	18,744	0.103	0.007	0.692	1.466
8	95	12,025	19.818	0.245	0.039	0.648	0.646
9	105	9,881	20,480	0.349	0.075	0.618	0.473
10	115	7,815	21,525	0.467	0.130	0.597	0.370
11	125	6,246	21,961	0.557	0.178	0.574	0.324
12	135	4,849	22,795	0.649	0.237	0.562	0.289
13	145	3,479	23,315	0.740	0.299	0.545	0.266
14	155	2,385	23,821	0.818	0.357	0.533	0.250
15	165	1,346	24,171	0.895	0.416	0.519	0.238
16	175	457	20,900	0.957	0.398	0.435	0.249
17	185	0	0				
18	195	0	0				
19	205	0	0				
20	215	0	0				

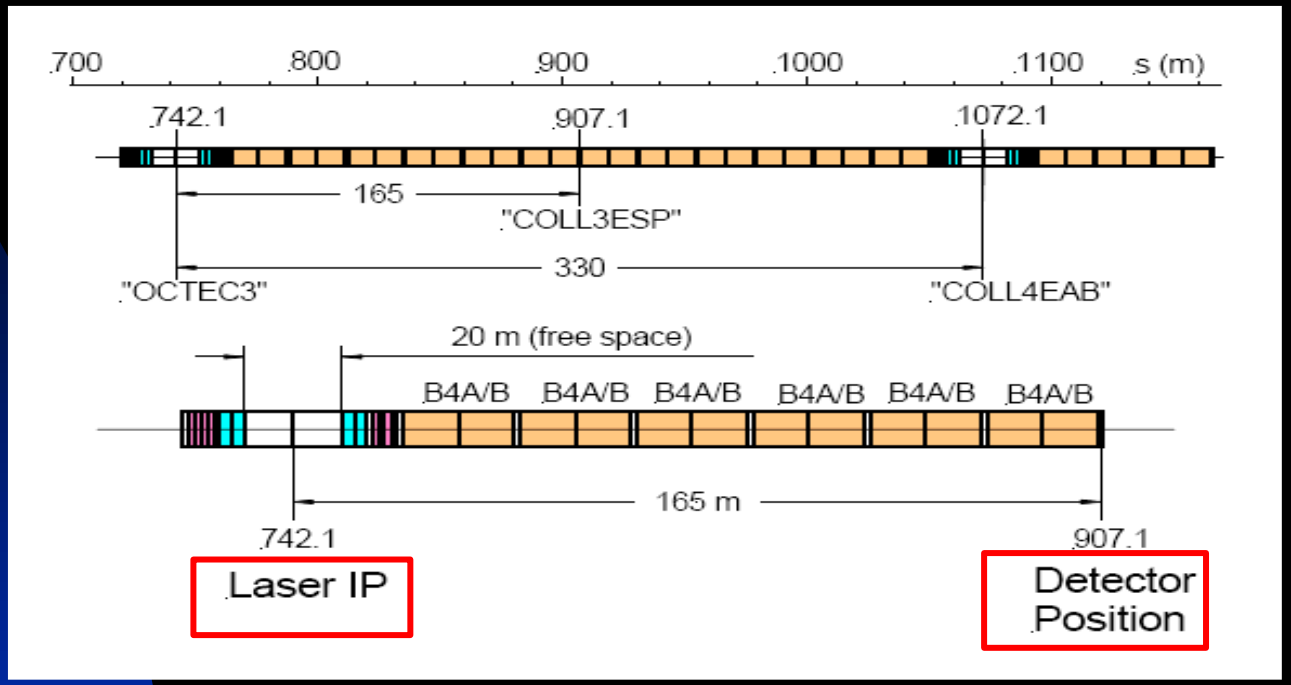
overall stat. error: dP/P = 0.082%
for dT = 1 sec (very fast!)

ILC polarimeter chicane: some nasty historic detour





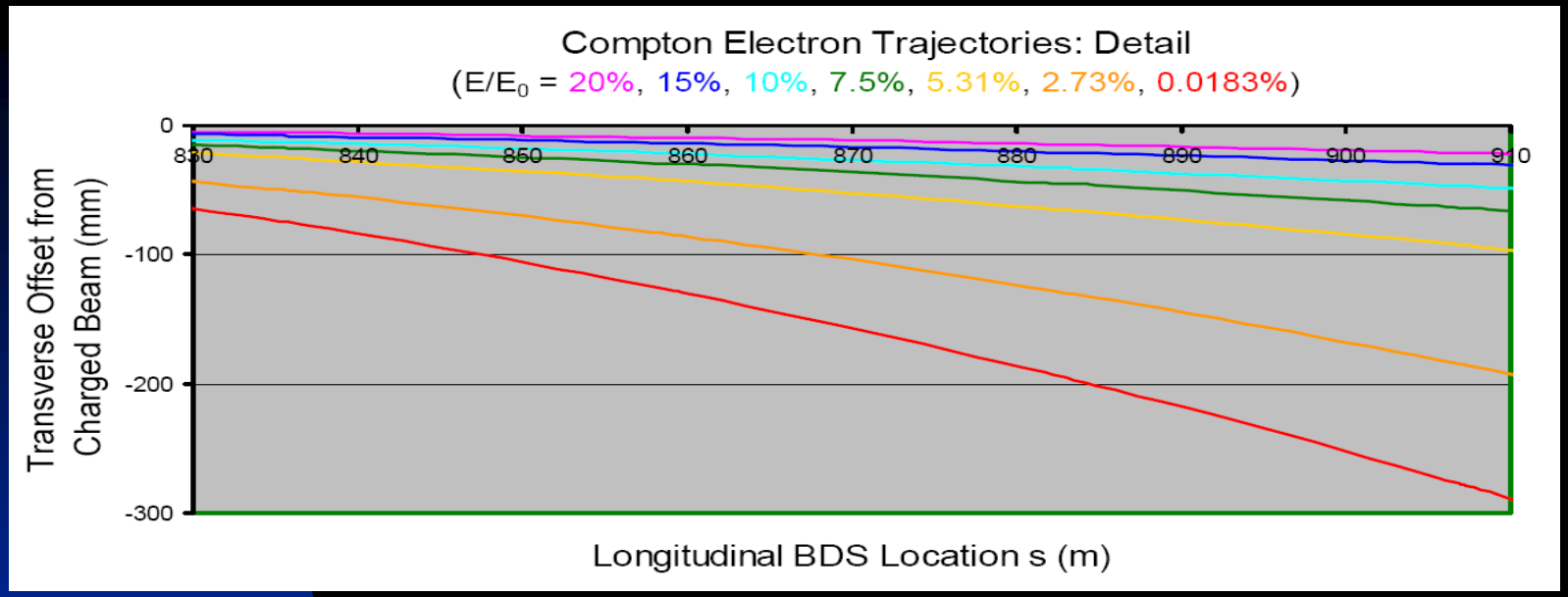
electron spectroscopy at CLIC



BDS detail behind s = 742 m

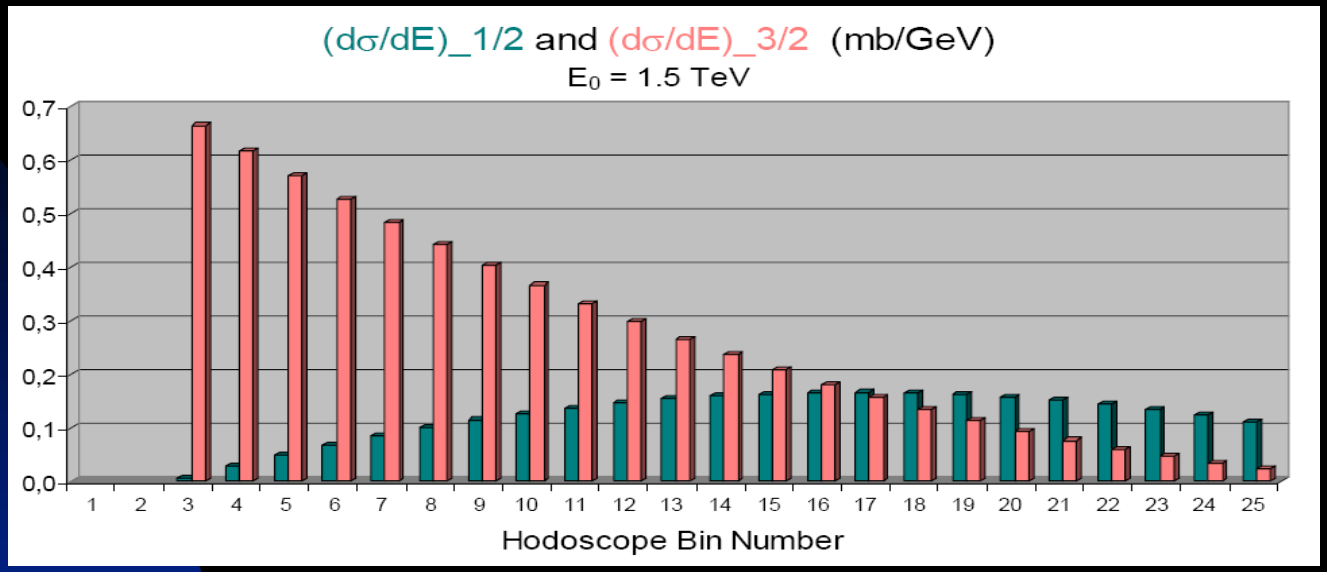
Laser IP at s = 742 m, Compton electron detector at s = 907 m
(behind 12 dipoles, as shown, or behind a lesser number of dipoles, but with reduced performance)

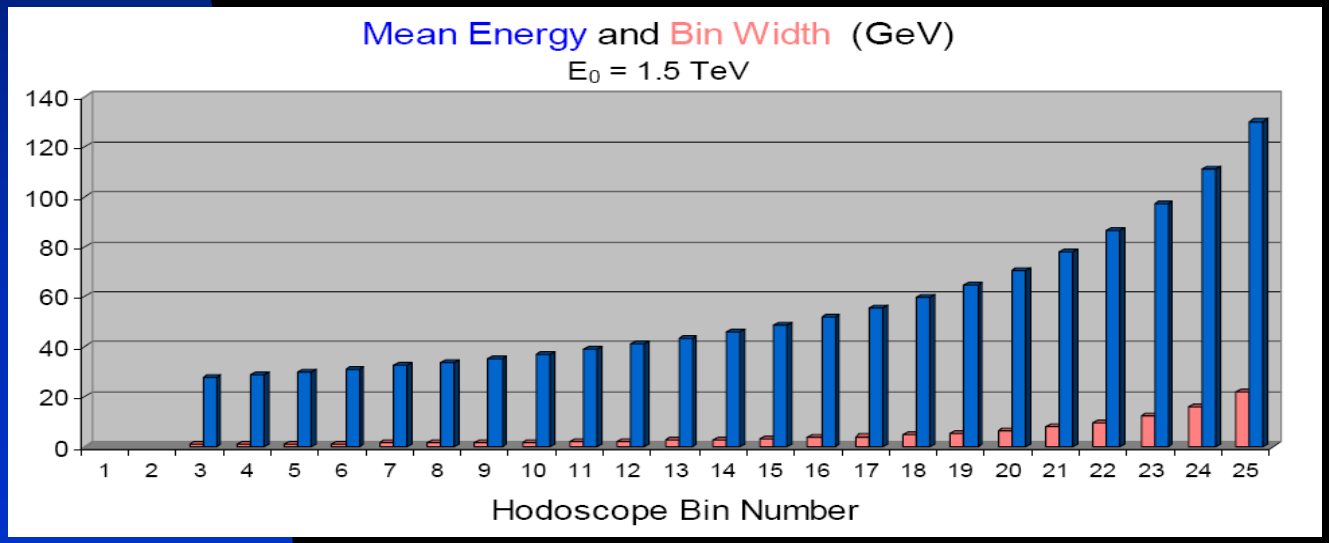
CLIC detector hodoscope: where to place it?



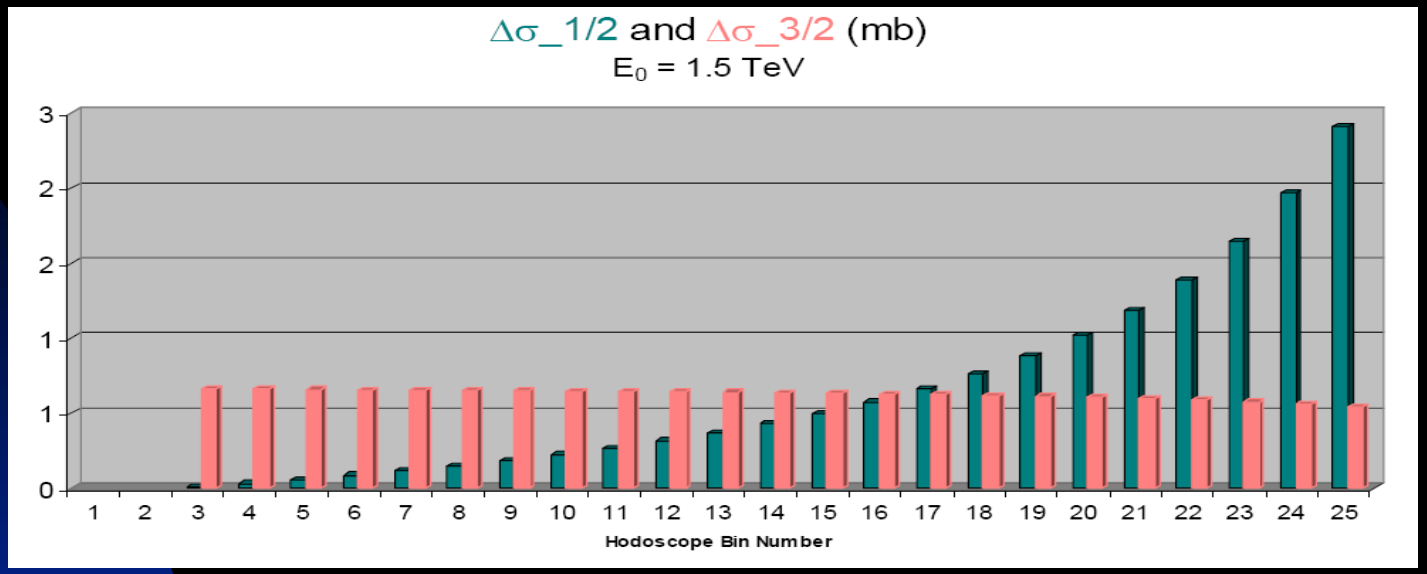
- trajectories shown indicate Compton electrons in the range of interest: red, orange and yellow trajectories correspond to the Compton edge for beam energies of 1.5 TeV, 1.0 TeV and 0.5 TeV.
- a detector position behind 12 dipoles (at s = 907 m) would give excellent coverage for beam energies from 1.5 TeV down to 135 GeV, but would require several wide-aperture dipoles
- a detector position behind 6 dipoles (at s = 835 m) would work only for beam energies down to 511 GeV.

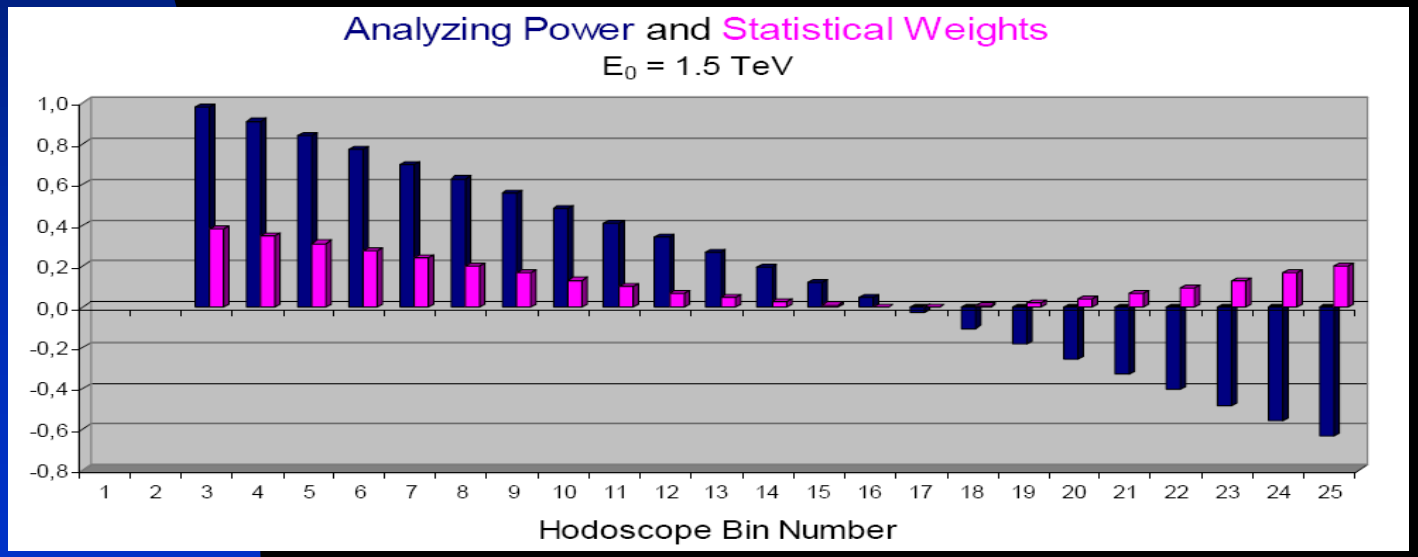
CLIC study: expected performance



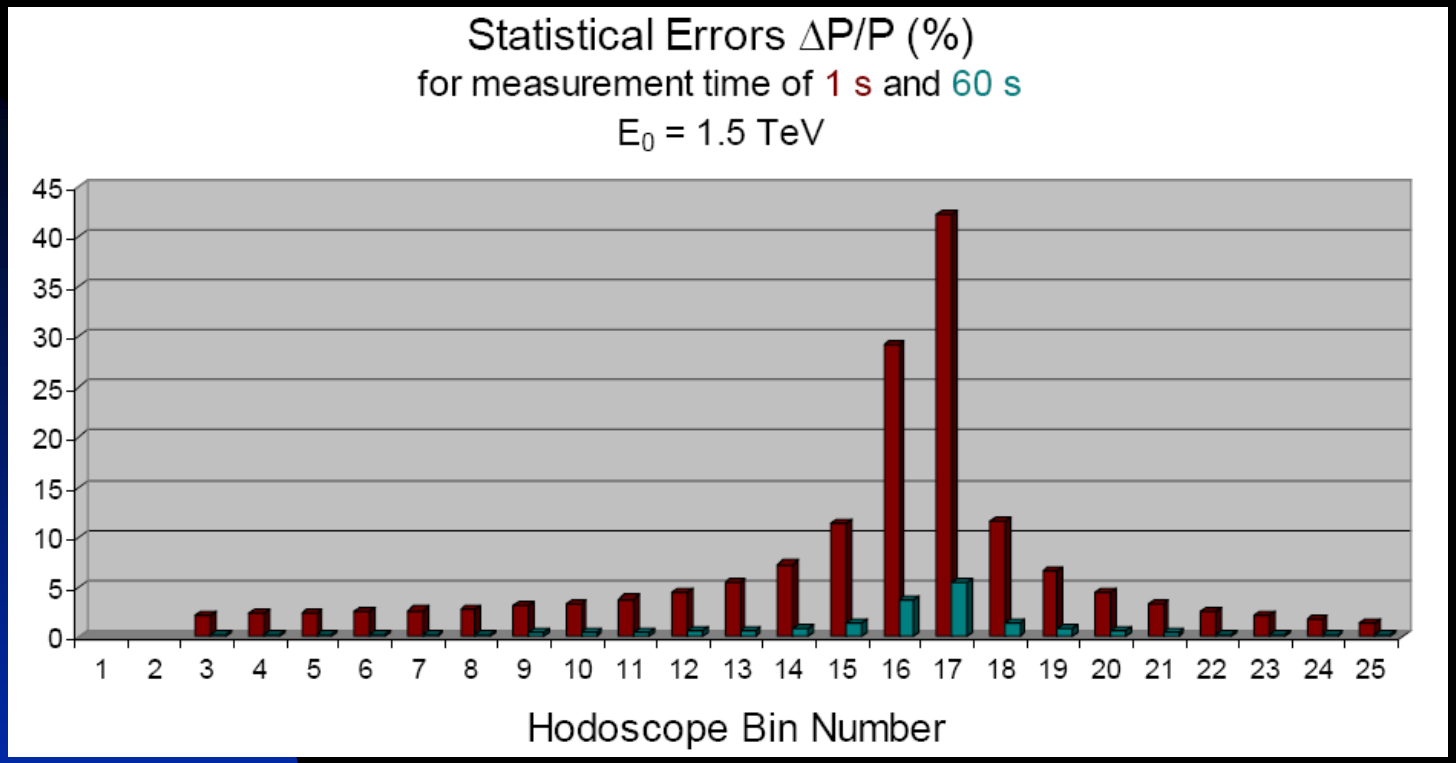


CLIC study: expected performance





CLIC study: statistical errors



measurement time	1 s	60 s
statistical error	ΔP/P	ΔP/P
bins 1-10 (edge region) combined	0.89%	0,11%
all 25 bins combined	0.61%	0.08%

summary & conclusion

- laser-based Compton scattering provides a powerful tool for high-energy electron and positron beam polarimetry
- with suitable lasers matched to the bunch and pulse pattern of the machine, measurements will be very fast, allowing instant feedback for spin control elements in the machine
- overall errors for ILC will be limited by systematics to the level of ~ 0.2% which is comparable to the degree of depolarization of the incoming beams from beam-beam interaction up to the lumi-weighted interaction point
- comparison of upstream polarimetry with downstream polarimetry (not covered here) and physics-based polarization analysis will check the control of systematics
- detailed studies have been carried out for TESLA and for ILC, based on a dedicated TTF-style laser
- a feasibility study has also been carried out for CLIC, assuming a standard Q-switched YAG laser