Future e+e- Linear Collider Projects

Why?
Status of the SM
Very short overview on physics at future LC

How?
The ILC Project
The CLIC Project

You heard about….

- LHC Experiments
- LHC Theory
- Astroparticle Physics
- Accelerator Physics
- Electroweak Physics

→ You have an overview on the unanswered questions
→ You may know why the LHC and astroparticle physics experiments are not the end of the story
→ This lecture on future Linear e+e- colliders tries to summarize these points and to show the planning procedure for the next steps in high energy particle physics

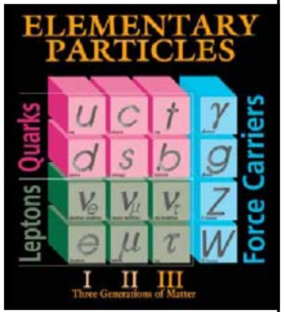
Status of the Standard Model

We learned over the last ~50 years:

The matter is composed of
Quarks and Leptons
+ anti-particles

interacting via
force carriers
(Gauge Bosons)

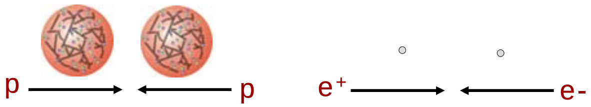
missing: Higgs boson



top-quark 1995
tau-neutrino 2000

Is the Standard Model valid up to the Planck Scale?

Hadron Collider or Lepton Collider ??



- **proton = composite particle:** unknown √s of partons, no polarization of partons, parasitic collisions
- **proton → strongly interacting:** huge SM backgrounds, highly selective trigger needed, radiation hard detectors needed

- **e = pointlike particle:** known and tunable √s of particles, polarization of particles possible, kinematic contraints can be used
- **e = electroweak interactions** low SM backgrounds, no trigger needed, detector design driven by precision

high energy ⇔ high precision

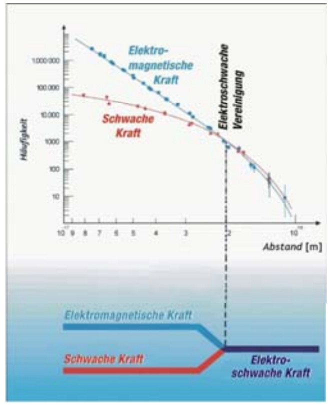
Both approaches are needed for a better understanding!

Forces:

- Electromagnetic, weak, strong
- gravitation
- different strengths depending on energy

Forces at high energy:
‚democratic' ⇔ unification

→ **situation immediately after creation of the Universe**



Standard Model of electroweak interaction

see lectures given by Wolfgang Lohmann

Matter particles

			T	T_3	Y	Q	
ν_{eL}	$\nu_{\mu L}$	$\nu_{\tau L}$	$1/2$	$+1/2$	$-1/2$	0	L-handed doublets
e_L	μ_L	τ_L	$1/2$	$-1/2$	$-1/2$	-1	
e_R	μ_R	τ_R	0	0	-1	-1	R-handed singlets
u_L	c_L	t_L	$1/2$	$+1/2$	$1/3$	$2/3$	L-handed doublets
d'_L	s'_L	b'_L	$1/2$	$-1/2$	$1/3$	$-1/3$	
u_R	c_R	t_R	0	0	$4/3$	$2/3$	R-handed singlets
d_R	s_R	b_R	0	0	$-2/3$	$-1/3$	

Weak hypercharge Y
Weak isospin T

$T_3 + Y/2 = Q$

Unification of electromagnetic and weak interaction

$$SU(2)_L \times U(1)_Y$$

$$\mathcal{L}_{\text{Fermion}} = i\bar{\psi}\gamma^\mu \mathbf{D}_\mu \psi$$

$$\mathbf{D}_\mu = \partial_\mu + ig_2 \mathbf{W}_\mu^a \mathbf{T}_a + ig_1 \mathbf{B}_\mu \mathbf{Y}$$

$$\frac{G_F}{\sqrt{2}} = \frac{g_2}{8m_W^2}$$

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} = \frac{g_1^2}{g_1^2 + g_2^2}$$

$$g_A^f = T_3^f$$

$$g_V^f = T_3^f - 2Q_f \sin^2\theta_W$$

$$e^2 = 4\pi\alpha = g_1^2 \sin^2\theta_W = g_2^2 \cos^2\theta_W$$

+ Higgs mechanism

$$m_W = \frac{1}{2} g_2 v$$

$$m_Z = \frac{1}{2} v \sqrt{g_1^2 + g_2^2}$$

$$m_\gamma = 0$$

$$m_H = v\sqrt{\lambda}$$

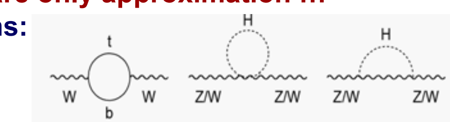
$$m_f = \frac{1}{\sqrt{2}} g_f v$$

$$v = \left(\frac{1}{\sqrt{2}G_F}\right)^{1/2} \approx 246\,\text{GeV}$$

+ Radiative corrections

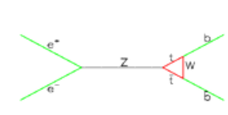
Born relations are only approximation !!!

Loop corrections:



$\delta_t \propto m_t^2$ $\delta_H \propto \ln \frac{m_H}{m_W}$

Vertex corrections



→ m_{top}

Precise measurements ➔ sensitive to top-quark and Higgs boson

Radiative corrections…

Electroweak corrections are summarized in
form factors → effective Born approximation

$$m_W = \frac{m_Z^2}{2}\left(1+\sqrt{1-\frac{4\pi\alpha}{\sqrt{2}G_F m_Z^2}}\right)$$

$$\cos\theta_W = \frac{m_W}{m_Z}$$

$$g_A^f = T_3^f$$

$$g_V^f = g_A^f\left(1-4|Q_f|\sin^2\theta_W\right)$$

→

$$m_W = \frac{m_Z^2}{2}\left(1+\sqrt{1-\frac{4\pi\alpha}{\sqrt{2}G_F m_Z^2}\frac{1}{1-\Delta r}}\right)$$

$$\cos\theta_W = \frac{m_W}{\rho\cdot m_Z}$$

$$g_A^{f,eff} = T_3^f\sqrt{1+\Delta\rho_f}$$

$$g_V^{f,eff} = g_A^{f,eff}\left(1-4|Q_f|\sin^2\theta_W\cdot\kappa_f\right)$$

→ All parameters depend on top quark and Higgs boson mass

Precision test of the Standard Model

→ **precise measurements** of SM parameters
at previous e+e- Colliders: LEP and SLC

→ Constraints from Tevatron, LHC (m_W, m_t)

→ consistency checks

→ Higgs boson

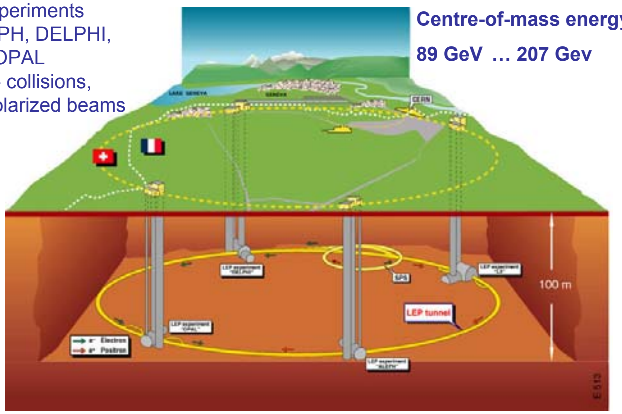
→ are there signatures beyond the SM ?

The status of the SM based on precision electroweak measurements

Details see: http://lepewwg.web.cern.ch/LEPEWWG/

LEP: Large Electron Positron Collider (1989 – 2000)

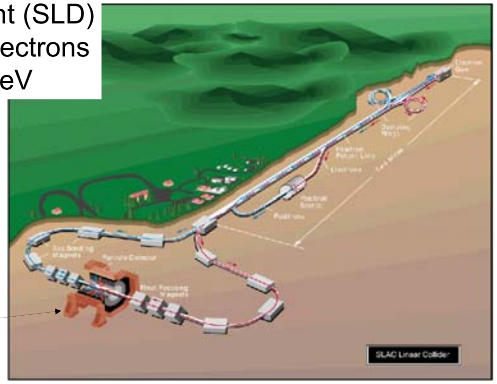
- 4 experiments ALEPH, DELPHI, L3, OPAL
- e+e- collisions, unpolarized beams



Centre-of-mass energy:
89 GeV … 207 Gev

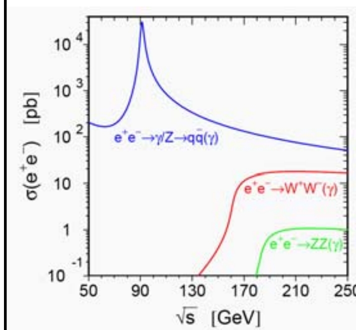
Stanford Linear Accelerator (SLC, 1989-1998)

- e+e- collisions
- 1 experiment (SLD)
- Polarized electrons
- E_{cms} ~ 91 GeV



SLD detector

The nineties – precision physics at LEP and SLC



LEP1 (1989 – 95, $\sqrt{s} \sim 89{-}91{-}93$ GeV)

- $\approx 17 \times 10^6$ Z bosons $\Rightarrow$ SM parameter
- heavy quark physics (b, c), τ physics
- QCD, measurement of α_s

SLC (1989 – 1998, $\sqrt{s} \approx m_Z$)

- polarized electron beam
- $\approx 5.5 \times 10^5$ Z bosons $\Rightarrow$ SM par.

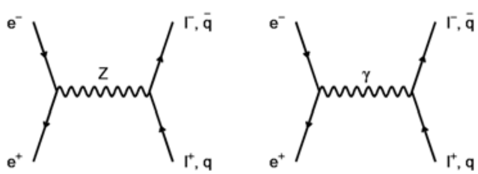
LEP2 (1995 – 2000, $\sqrt{s} \approx$ 130-209 GeV)

- SM tests $\to$ W physics
- Searches: Higgs, SUSY

Fermion Pair Production

Precision physics:

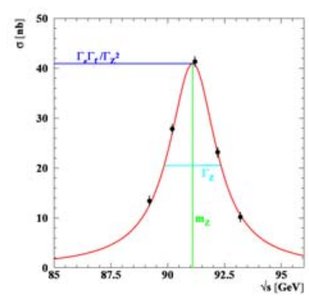
$$e^+e^- \to \gamma, Z \to f\bar{f}$$



$$|M|^2 = |M_Z + M_\gamma|^2$$

Cross section at the Z resonance

$$\sigma_Z^f(s) = \frac{12\pi}{m_Z^2} \frac{s\Gamma_e\Gamma_f}{\left(s - m_Z^2\right)^2 - \left(s/m_Z^2\right)^2 \Gamma_Z^2}$$

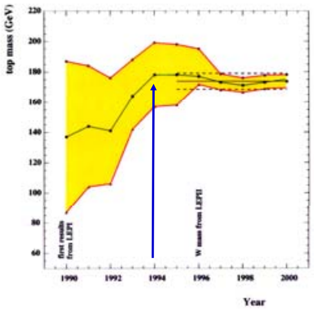


High statistics

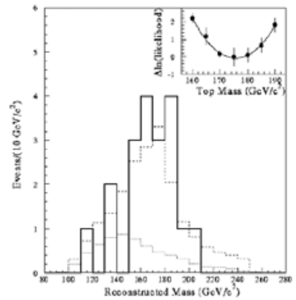
- **measure m_Z**
- **determine Γ**
- **determine couplings**

→ indirect information about m_t and m_H from electroweak corrections

Top mass predicted at LEP **BEFORE** top discovery

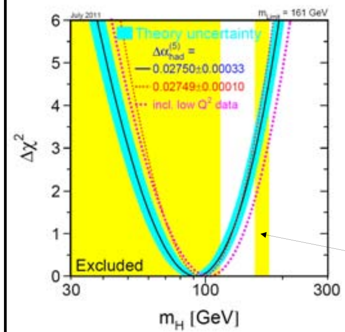


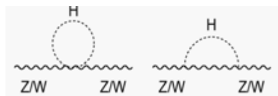
Precision measurements @ LEP/SLC



Discovery @ Tevatron, 1994
($p\bar{p}$ collisions)

SM Higgs Mass and precision measurements at LEP/SLD



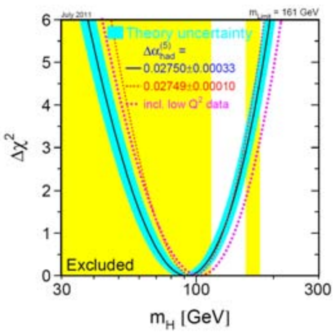


Precision measurements at LEP1/SLD
+ m_W from Tevatron and LEP2
+ m_t from Tevatron
(see LEPEWWG)

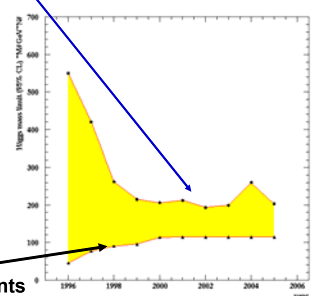
Tevatron exclusion for Higgs mass
156 GeV < m_H < 177 GeV (95% C.L.)

m_H = 92+35-26 GeV (ew + m_t + m_W)
m_H < 161 GeV (95% C.L.)
m_H < 185 GeV (incl. direct LEP limit)

The SM Higgs Mass history

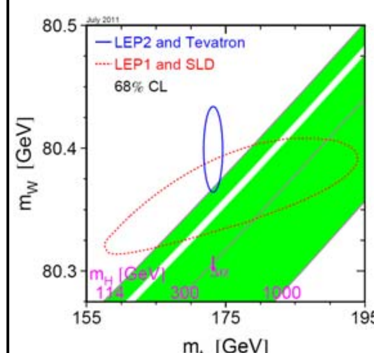


Precision measurements



Lower limit from direct measurements

SM consistency check



	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01646
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1482
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1039
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0743
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1482
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.378
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.27

July 2011

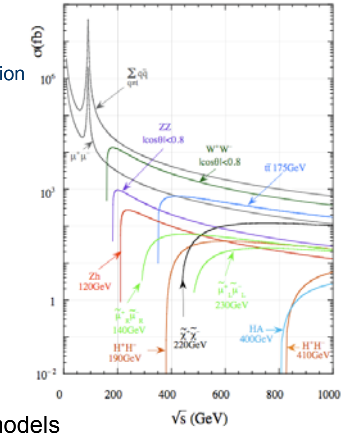
Up to now all measurements are in good agreement with SM

e+e- physics at highest energies

Precision measurements
- top quark physics
  - t decays before hadronization
- ZZ,WW
- Higgs pysics (mass, couplings)
- SUSY

Searches
- Extra dimensions
- Dark matter
- ...

+Indirect searches
precision measurements ⇔ deviations from SM predictions, interpretation in terms of new physics models



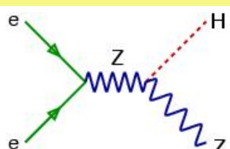
The Higgs Profile

➢ **Mass** (in SM mass determines the profile completely)
➢ **Higgs coupling**
- to Z and W: $M_W \sim g\,\nu$, $M_Z \sim g\,\nu$
  (g: gauge coupling, ν: vacuum expectation value)
- to fermions: $m_f \sim g_f\,\nu$
- Higgs self-coupling, Higgs potential

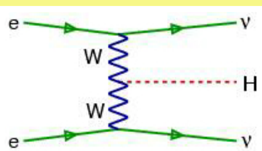
An important aim of future e+e- colliders:

Establish the Higgs Mechanism as responsible for mass creation and electroweak symmetry breaking

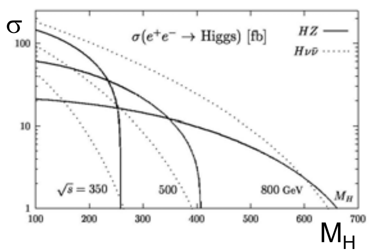
Production of the Higgs Boson



Higgs-Strahlung



WW-Fusion



$N_{Higgs} = \sigma\, L$

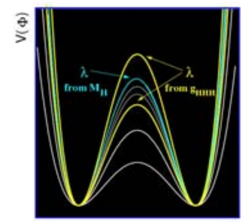
Expect ~17 Higgs events per hour

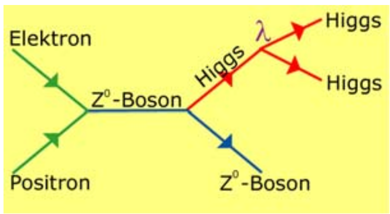
→Higgs factory !!

→ Higgs mass
→ $\sigma \sim$ (Higgs coupling)^2

Higgs Self-Coupling

Do we see the SM Higgs? The 'expected' ew symmetry breaking?
Reconstruction of potential ⇔ Measurement of Triple-Higgs coupl



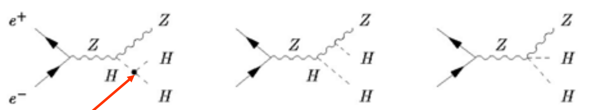


$V(\Phi) = \mu^2|\Phi|^2 + \lambda\,|\Phi|^4 \qquad \mu^2 < 0,\ \lambda > 0$

Vacuum expectation value $\nu^2 = -\mu^2/\lambda$

$V(H) = \lambda\,\nu^2 H^2 + \lambda\,\nu\, H^3 + \frac{1}{4}\lambda\, H^4 \qquad m_H^2 = 2\,\lambda\,\nu^2$

Higgs Self-Coupling

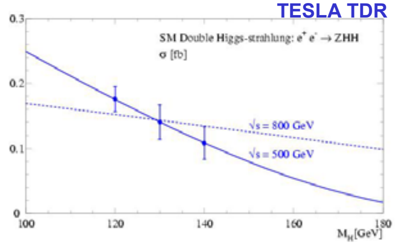


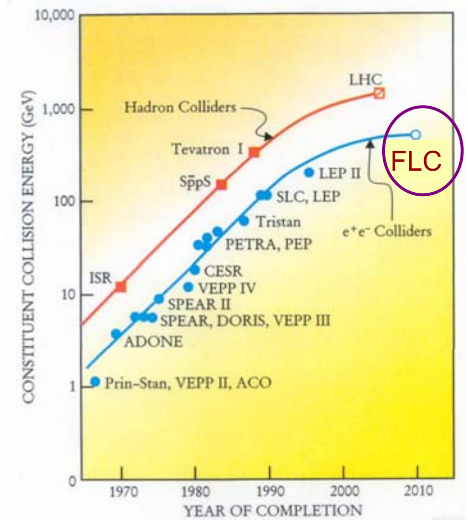
Sensitive to λ → $\Delta\sigma/\sigma$=13 % → $\Delta\lambda/\lambda$=23 %

TESLA TDR

tiny x-section: 0.15 fb
→ need high luminosity

Complex final state:
ZH→ZHH→qq bb bb





Future Linear Collider

Energy:
≥ 500 GeV
... 3-4 TeV

Summary 1 - Physics at e+e- colliders

fascinating physics potential of FLC cannot be shown completely in this lecture

Key word: Precision physics → Standard Model and beyond

→ high luminosity, high energy
→ excellent detectors
→ precise theoretical predictions

Top physics → mass and couplings (E_{cm} ≥ 340 GeV)

Based on LHC results to be tested at a high energy e+e- coll.:

→ Higgs boson: mass, couplings, gauge structure

→ new physics: extra dimensions, SUSY, strong ew symmetry breaking, …

The e+e- collider key issues

Energy
- Determined by technology
  - Gradient
  - → Length of accelerator

Luminosity
- High statistic for precision measurements

→Luminosity as high as possible

Beam polarization
- produce polarized e-, e+
- bring polarization to interaction point (IP)

+ precision measurements of these parameters (E, L, P)

ILC Baseline Machine (2007)

Physics between 200 GeV and 500 GeV
Electrons: Polarization P > 80%
Energy stability and precision below 0.1%

Luminosity:
Year 1-4: $L_{int} = 500\ fb^{-1}$:

→ expected statistics:

few 10^4	ee → HZ at 350 GeV (mH≈120 GeV)
10^5	ee → tt at 350 GeV
$5 \cdot 10^5$ ($1 \cdot 10^5$)	ee → qq ($\mu\mu$) at 500 GeV
10^6	ee → WW at 500 GeV

statistical cross section uncertainties at per-mille level !!

$$\Delta\sigma \propto \frac{1}{\sqrt{N}} \oplus \frac{\Delta L}{L} \oplus \frac{\Delta E}{E} \oplus \frac{\Delta P}{P} \longrightarrow O(10^{-3})$$

→ **Precision measurements**

Design of future e+e- Colliders

Design of future e+e- Colliders

- Which centre-of-mass energy ?
  - why **linear** collider?
- which luminosity ?
- accelerator components
  - ILC
  - CLIC

Which centre-of-mass energy??

Physics:

- **hint for light Higgs Boson < 200 GeV**
- **SUSY: s-particles < 1TeV, (~200 GeV ?)**
- **No Higgs: new strong interactions <1.3 TeV**
- **threshold for top-quark pair production: 350 GeV**

Scale of electroweak symmetry breaking : $v = 246\ \mathrm{GeV}$

Technology:

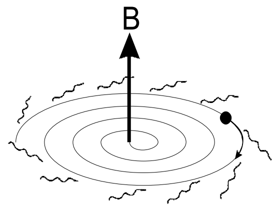
- **big steps are risky**

$\sqrt{s} = 500\ \mathrm{GeV}$ is "reasonable" first step
Upgrade to ~1 TeV must be possible
Multi-TeV accelerator to extend LHC search reach

Why linear colliders?

Synchrotron radiation
→ Energy loss per turn
(radius R)

$$\frac{\Delta E}{\text{revolution}} \propto \frac{E^4}{Rm^4}$$



LEP (R_{eff} = 3.1km):

Bei E_{beam} = 50 GeV (E_{cms}=100GeV):
ΔE / Umlauf = 180 MeV
ΔE / t = 2 TeV/s

Bei E_{beam} = 100 GeV:
ΔE / t ~ 33 TeV/s !!!

Energy loss has to be compensated by RF system !

no problem at hadron colliders (m_p ~ 1GeV ~ 2000m_e) with synchrotron radiation

Scaling of costs at a circular collider

- 'Linear' costs (tunnel, magnets, etc.):
  $\$_{lin} \propto R$
- RF costs:
  $\$_{RF} \propto \Delta E \propto E^4 / R$
- Cost optimum if $\$lin = \$RF$
  → $R_{opt} \sim E^2$
- Total cost: $(\$_{lin} + \$_{RF}) \sim E^2$

For details check: B. Richter, NIM 136 (1976) pp. 47-60!

Scaling the costs of LEP ….

		LEP-II	Super-LEP	Hyper-LEP
E_{cm}	GeV	180	500	2000
L	km	27	200	3200
ΔE	GeV	1.5	12	240
$\$_{tot}$	10^9 SF	2	15	240

Circular e+e- collider for E_{CM} > 200 GeV is ineffective!

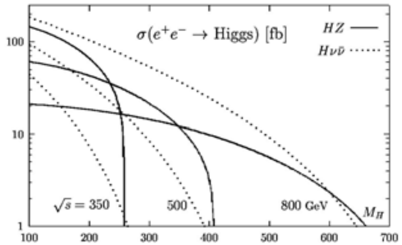
→ The e+e- future is linear: $\$_{LC} \sim E$

Luminosity of future e+e- colliders

N = Lσ. Design luminosity?

Physics argument:

- as much as possible, $\sigma \sim 1/E_{cm}^2 \rightarrow L \sim E_{cm}^2$
- precision measurement with uncertainty O(1%)
  >10000 events
- Example: SM-Higgs production ~20fb → need 500 fb^{-1}



5 years ⇔500 days

→ Per day > 1 fb^{-1} or

L >1 x 10^{34} $cm^{-2}s^{-1}$

Or more…..

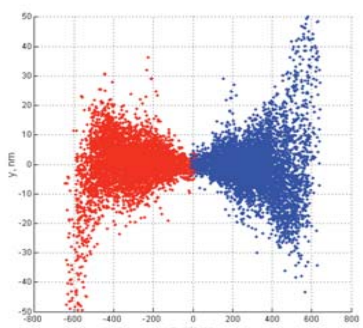
Luminosity

$$L = \frac{n_b N^2 f_{rep}}{4\pi\sigma_x^*\sigma_y^*} \times H_D$$

- Number of bunches per "train" (n_b)
- Number of particles per bunch (N)
- Repetition rate of "bunch trains" (f_{rep})
- Beam size at interaction point (IP) ($\sigma_x^*\sigma_y^*$)
- Beam enhancement factor (H_D)
  Beam-beam interaction → L increased by factor 1.5-2 due to "pinch effect"

Pinch effect

Electrons → ← positrons



Luminosity at linear collider

Beam Power, $P_{beam} = \eta_{RF \rightarrow beam} P_{RF}$

$$L = \frac{1}{4\pi E_{cm}} \left(E_{cm} f_{rep} n_b N\right) \frac{N}{\sigma_x^*\sigma_y^*} \times H_D$$

⇩

$$L = \frac{1}{4\pi E_{cm}} \left(\eta \cdot P_{RF}\right) \frac{N}{\sigma_x^*\sigma_y^*} \times H_D$$

η – efficiency to transfer power from RF →beam

Example:

Ecm = 500 GeV
N = 10^10
Nb = 100
frep = 100

→ Pbeam = 8 MW

Taking into account efficiency η, power > 100MW needed to accelerate and maintain luminosity

→ Repetition rate f_{rep} is power limited

Luminosity at linear collider

Beam Power, $P_{beam} = \eta_{RF \to beam} P_{RF}$

$$L = \frac{1}{4\pi E_{cm}} \left(E_{cm} f_{rep} n_b N\right) \frac{N}{\sigma_x^* \sigma_y^*} \times H_D$$

⇩

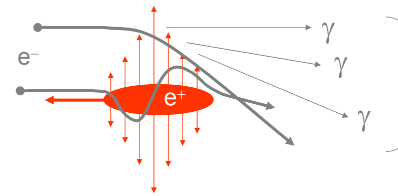
$$L = \frac{1}{4\pi E_{cm}} \left(\eta \cdot P_{RF}\right) \frac{N}{\sigma_x^* \sigma_y^*} \times H_D$$

η – efficiency to transfer power from RF → beam

- High RF power needed to accelerate beam, transferred with efficiency η
- Repetition rate f_{rep} is power limited in linear colliders
  → **less luminosity than with circular colliders**

➔ **Regain luminosity using small beam sizes**

Beamstrahlung



Radiation of hard photons in strong el-magn. field
= Beamstrahlung

$$\delta_{BS} = \frac{\Delta E}{E} \propto \frac{E_{cm}}{\sigma_Z}\left(\frac{N}{\sigma_X^* + \sigma_Y^*}\right)^2$$

→ Energy smearing + background in detector
→ **Limit: δ_{BS} ~ few %**

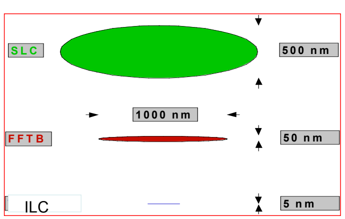
Flat beams:
- $\sigma_y << \sigma_x$ → minimal beamstrahlung
- small $\sigma_y \sigma_x$ → high luminosity

Maximize luminosity

Finally:

$$L \propto \frac{\eta \cdot P_{RF}}{E_{cm}} \left(\frac{\delta_{BS}}{\varepsilon_Y}\right)^{1/2}$$

- High transfer efficiency from RF to beam: η
- High RF power (klystrons)
- small vertical emittance: ε_y



Future e+e- projects

ILC
- Superconducting acceleration
- 31.5 MV/m, 1.3 GHz
  E_{cm} = 500 GeV
  (→ 1TeV)
- Technology at hand
  (XFEL)

CLIC
- Normalconducting acceleration
- 2-beam acceleration
- 100 MV/m, 12 GHz
  E_{cm} = 500 GeV – 3 TeV
- Still fundamental R&D phase

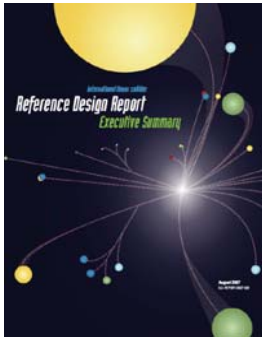
The International Collider Project (ILC)

- Produce a design for the ILC that includes a
  - detailed design concept
  - performance assessments
  - reliable international costing
  - an industrialization plan
  - siting analysis
  - detector concepts and scope

www.linearcollider.org

- **Reference Design Report (RDR), 2007:**

- Executive summary
- Accelerator
- Physics at the ILC
- Detector



ILC Collaboration

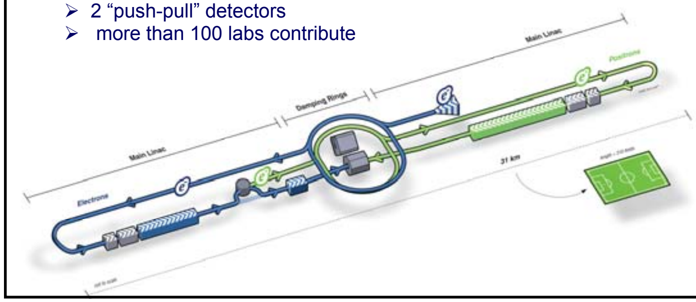
- ILC is most advanced future project for reasearch at high energy frontier
- International team: Global Design effort (GDE)
  - Joint effort of all leading accelerotor labs

The ILC (2007)

E_{cm} adjustable from 200 – 500 GeV (upgradeable to 1TeV):

- L ~ $2x10^{34}m^{-2}s^{-1}$, collect 500 /fb in 4 years
- Energy stability and precision below 0.1%

- Polarized electron source P > 80%
- (Polarized) positron source (P > 30%)
- two damping rings
- Main linacs: 16 000 SC cavities, 2000 cryomodules, 31km
- 2 "push-pull" detectors
- more than 100 labs contribute

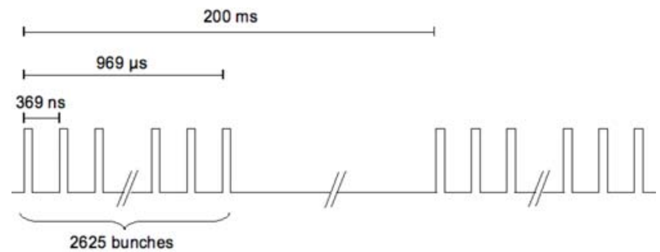


Towards the TDR in 2012

SB2009

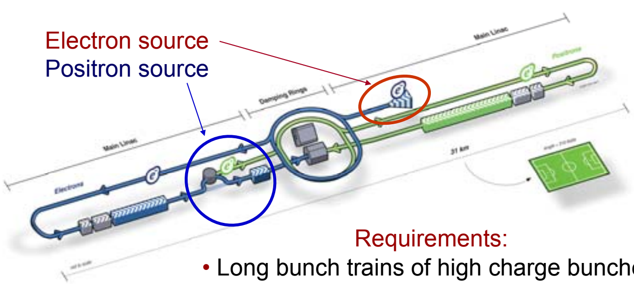
The ILC bunch structure

Superconductiong RF has small dissipation losses in cavity walls → long pulses with large bunch spacing are possible



(reduced by factor 2 in new baseline design SB2009)

ILC: Sources



Requirements:

- Long bunch trains of high charge bunches
  (~3000 bunches per train, 5 trains per second)
- Small emittances
- Beam polarisation
  - Mandatory for electrons
  - Desired for positrons

Electron Source (polarized)

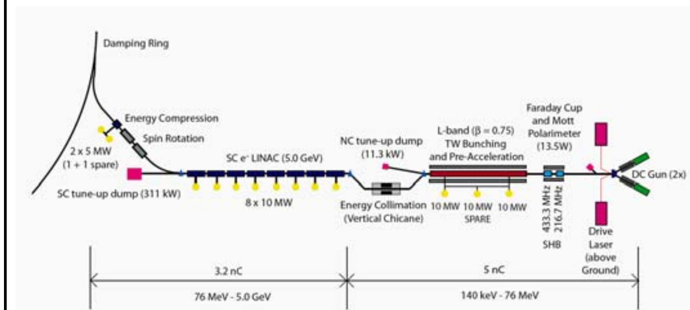
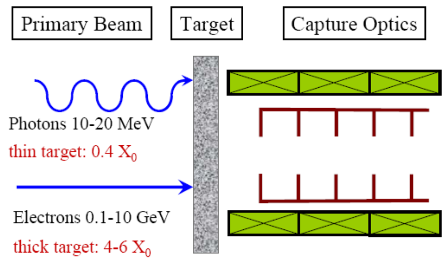
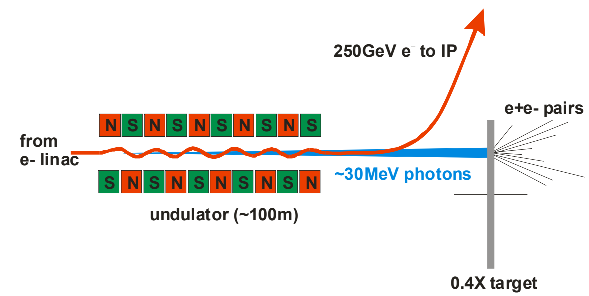


FIGURE 2.2-1. Schematic view of the polarized Electron Source.

Production of Positrons

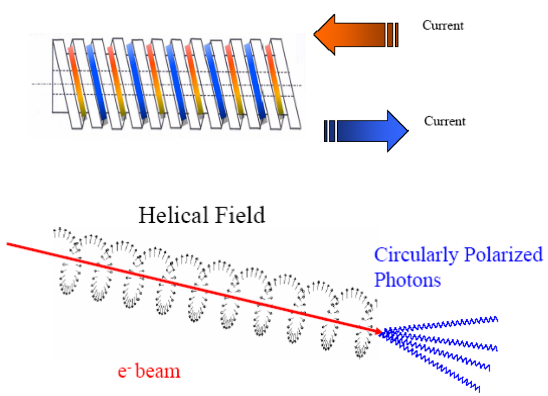


Positron source

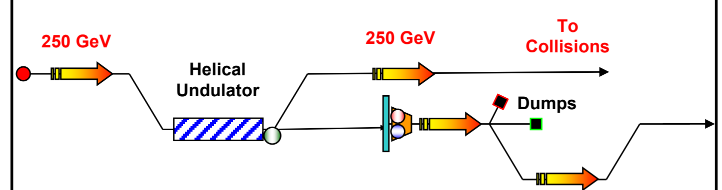


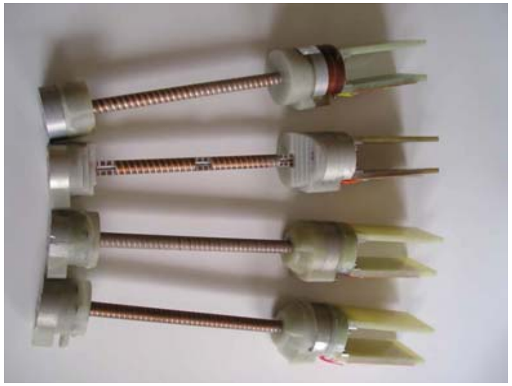
Polarized Positrons from helical undulator

- Ribbon-wire wound in a double helix



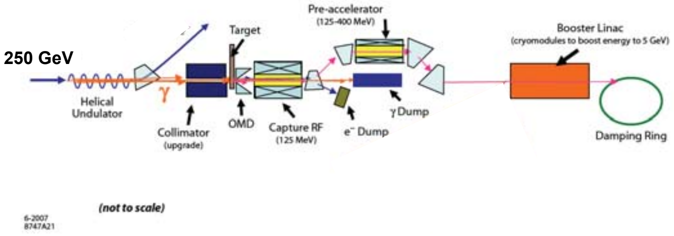
Undulator based positron source

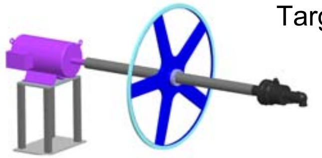




Short undulator prototypes

Positron Source Layout

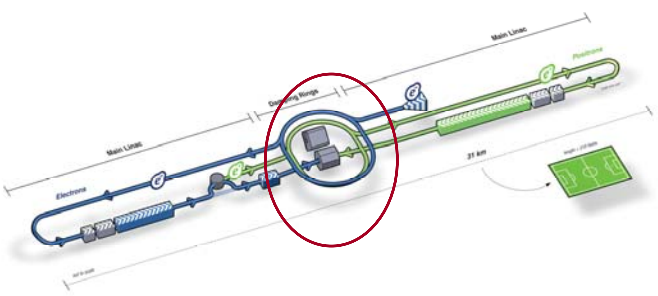




Target wheel (rotating to distribute heat load)

FIGURE 2.3-8. Target station layout.

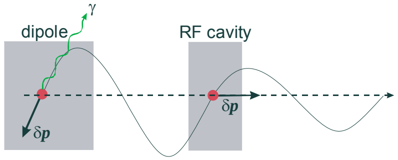
ILC: Damping Ring



- Damping rings reduce emittances of e- and e+ from source

Damping rings (DR)

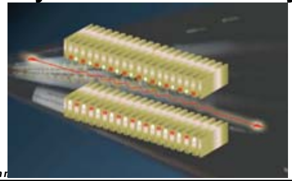
- Emittances of e- and e+ from source are too high



DR: Acceleration in longitudinal direction

Energy loss by radiation

- **Interplay between radiation and acceleration reduces transverse emittance**
- **Reduce damping time from synchrotron radiation by damping wigglers**
  (SR due to dipoles is not not sufficient)
- **~100 ms damping time**

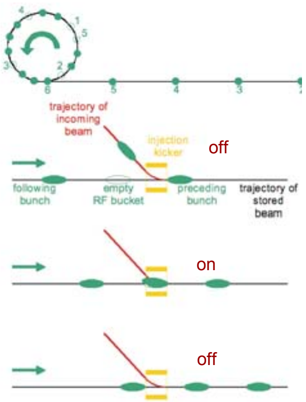


Damping rings

Long pulses:
1ms×c = 285km!

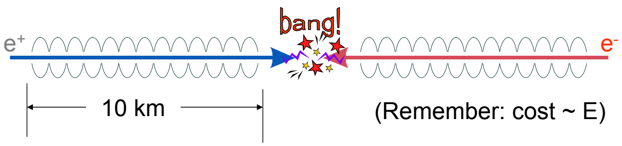
→compress whole bunch train to DR with O(10km)

→ Injection & extraction



ILC: Energy and Gradient

Energy of the ILC



➔ high gradient

For E_{cm} = 500 GeV:
Gradient G = 250 GV / 10 km= 25 MV/m

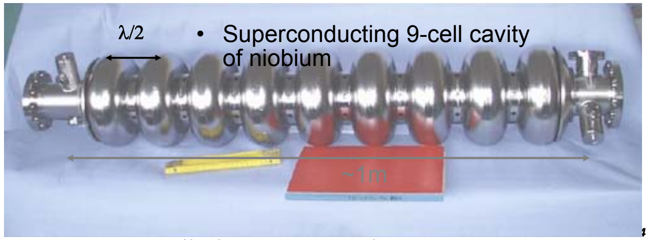
(L=28.8km: 550 GeV → G=23.4 MV/m
800 GeV → G =35 MV/m)
(LEP2 cavities ~ 7MV/m)

➔ and high efficiency to transfer primary power to the beam

Gradient in ILC cavities

★ **fundamental limit at 55 MV/m**
higher fields → critical B field of superconduction is exceeded
★ superconducting cavities experience: FLASH

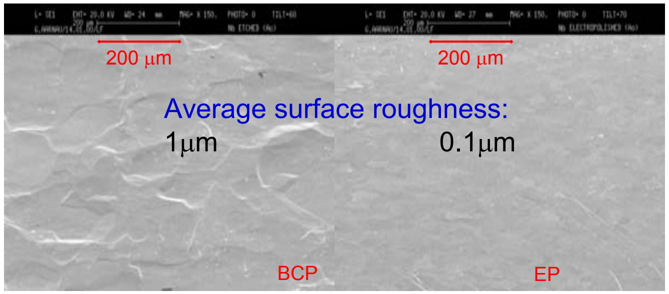
Challenge
1. Increase gradient
2. Reduction of costs
3. Mass productions



Gradient

In practice: Limitation due to quality of surface and niobium

Gradients > 35 MV/m reached after “electro-polishing” of the surface



etching - “buffered chemical polish“ electro-polishing

The quality factor Q

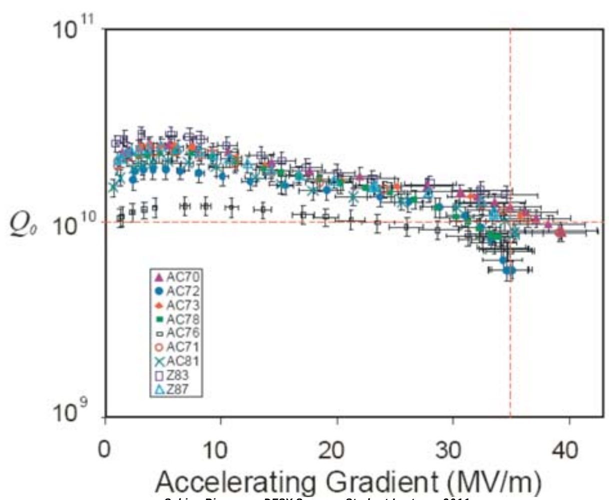
- Primary AC power → beam
- **Key number for cavities: Quality factor Q**

  Q is a measure of how much energy the cavity stores divided by how much it loses on each oscillation of the RF electric field:

$$Q = \frac{\text{stored energy}}{\text{energy loss per cycle}}$$

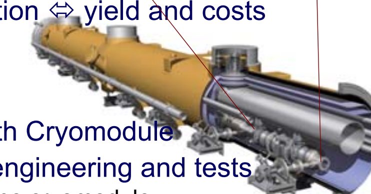
ILC goal: $Q = 10^{10}$

A church bell (2000 Hz) with Q of 10^{10} would ring for several months after being struck.



Superconducting RF

- **SCRF, big cost driver**
- High gradient R&D goals
  - >35 MV/m in 9-cell cavities reached production yield >80%
  - 50 MV/m reached in single cavities
- Focus: mass production ⇔ yield and costs



- Cavity Integration with Cryomodule
- Accelerator system engineering and tests
  - Cavity string test in one cryomodule
  - Cryomodule string test with beam acceleration

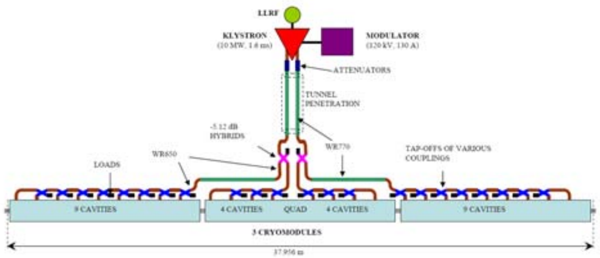
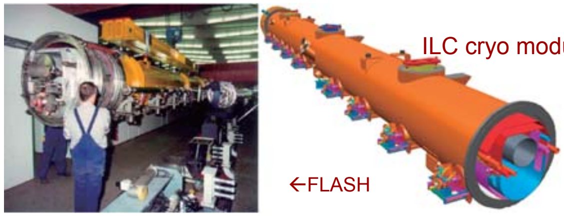


FIGURE 1.3-5. RF unit layout.



ILC: Beam delivery system

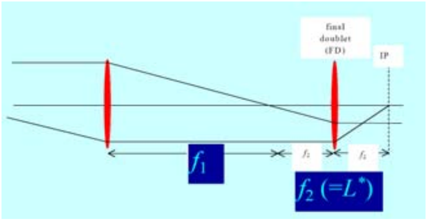
Tasks of the beam delivery system

- Collimation
  - Remove beam halo to reduce background
- Beam diagnostics
  - Measurement upstream and downstream the interaction point
- Final Focus System
  - Sqeeze the beams to nm sizes ⇔ high luminosity
- Beam Dumps
  - Dispose spent beams after collision

Final focus

Telescope optics to de-magnify beam by factor $m = \frac{f_1}{f_2} = \frac{f_1}{L^*}$

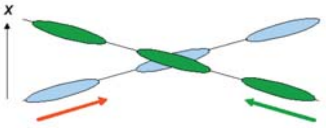
Typically, m=300 needed
With L* = 2m ⇔ f_1 = 600m



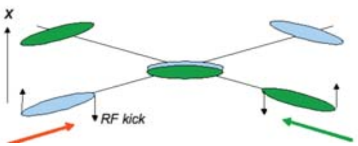
However, also corrections for large chromatic and geometric aberrations needed (life is much more complicated than depicted here…)

Interaction Point

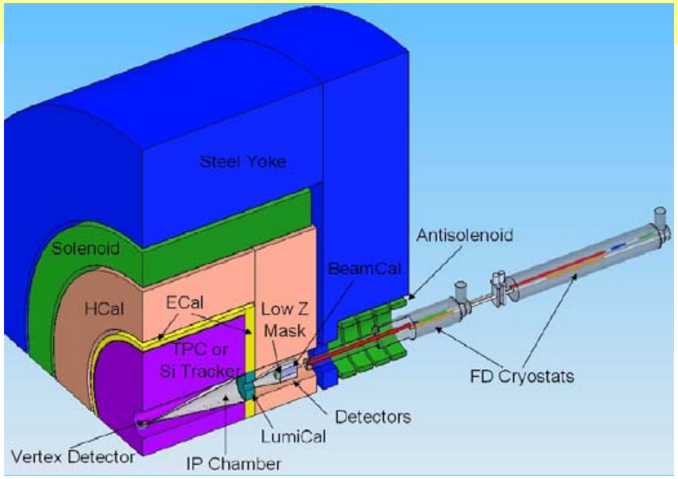
Crossing angle at interaction point



Reduction of luminosity by factor ~10

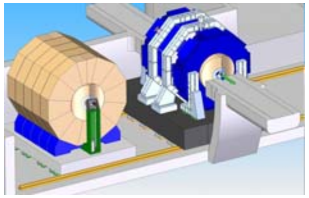


Need transverse (crab) RF cavity to tilt the bunch for collision

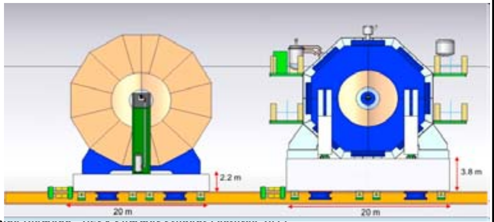


Detectors and Interaction Region (IR)

- Desired: at least 2 experiments
- At linear colliders, the integrated luminosity does NOT scale with the number of interaction regions
- ILC proposal: only one IR, but 2 detectors



Solution:
Push-Pull system, both detectors on platform
(but different size of detectors)



Sample sites

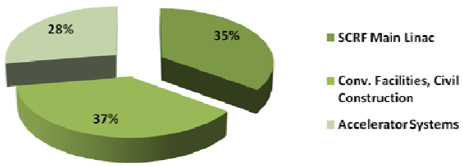
- Under study:
- Deep sites:
- Americas: Fermilab
- Asia: Japan
- Europe: CERN

- Shallow sites:
- DESY
- Dubna

- Choice of real site
- will be a political decision!

The cost estimate in 2007

- Estimated cost (2007) ~6.7 Billion ILCU*
  - 4.87 BILCU shared
  - 1.78 BILCU site-specific



- ~10,000 person-years "implicit" labour
  - Engineering design, preparation activities, prototypes
  - Surface acquisition, underground easement costs
  - Detectors
  - Contingency for risks, escalation (inflation)
- * 1 ILCU = 1 US Dollar (2007) =0.83 Euro = 117 Yen

ILC Technical Design R&D Plans

- ILC could be built now – if money was available
- Budget cuts (black Dezember 2007)

- schedule delayed
  - Technical Design Phase 1 (till summer 2010)
  - Critical R&D demonstrations
    - ➔ 're-baseline' document
  - Technical Design Phase 2 (till end 2012)

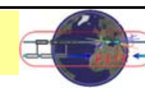
→Ready for construction / decision to politicians

ILC Timeline

- 2012: Technical Design Report

LHC results

CLIC feasibilty study



ILC ⇔ CLIC ?

0.5 TeV ?

1TeV ??

3 TeV??

Decision will be driven by
- Physics requirements
- LHC results
- Technology success
- Feasibility

The Compact Linear Collider (CLIC)

The Compact Linear Collider (CLIC)

- Develop technology to extend e-e+ linear colliders into the **Multi-TeV** energy range
  http://clic-study.web.cern.ch/CLIC-Study/
- Physics motivation:
  - http://clicphysics.web.cern.ch/CLICphysics
  - "Physics at the CLIC Multi-TeV Linear Collider" by CLIC Physics Working Group:CERN 2004-5

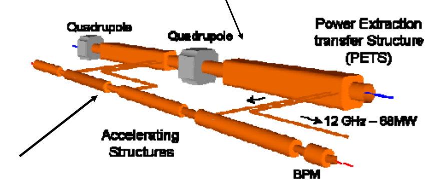
COMPACT LINEAR COLLIDER (CLIC)

E_{cm} energy range
- from ILC to LHC: E_{cm} = 500 GeV - 3 TeV
  - acceleration gradient: ~100 MV/m
  - "Compact" collider: total length ~50 km at 3TeV
- L > few 10^{34} $cm^{-2}s^{-1}$
- E_{cm} and L to be reviewed when LHC physics results available

Total power consumption <500MW
  - (LEP in 1998: ~240 MW)

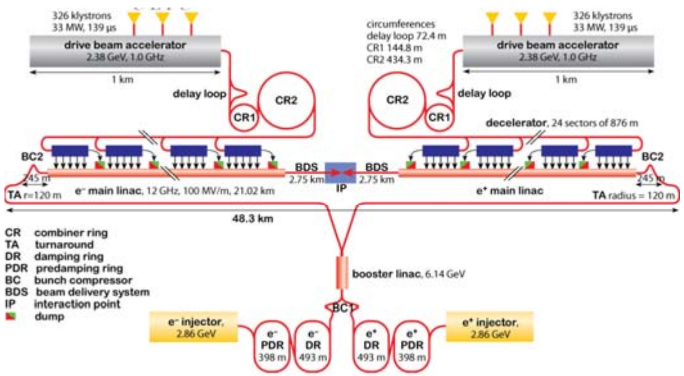
CLIC: Two beam scheme

- Drive Beam supplies RF power
  - low energy (2.4 GeV - 240 MeV)
  - high current (100A)



- Main beam for physics
  - high energy (9 GeV – 1.5 TeV)
  - current 1.2 A

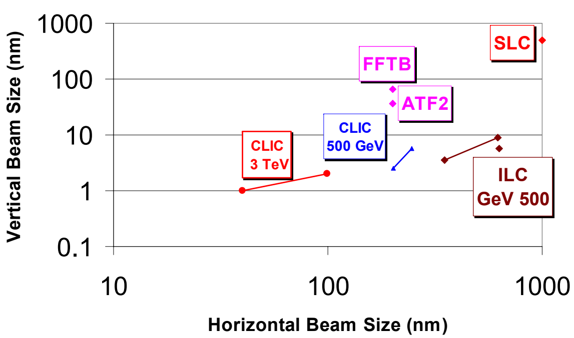
CLIC layout



CLIC parameters

	ILC 500 GeV	CLIC 500 GeV	CLIC 3 TeV
Lumi [$10^{34}cm^{-2}s^{-1}$]	2	2.3	5.9
Repetition rate [Hz]	5	50	
Bunch separation [ns]	370	0.5	
Beam pulse duration	950μs	177ns	156ns
Beam size [nm] horizontal / vertical	~600 / 6	200 / 2.3	40 / 1.0

Beam sizes in linear colliders



→ High level of beamstrahlung at CLIC (3TeV)

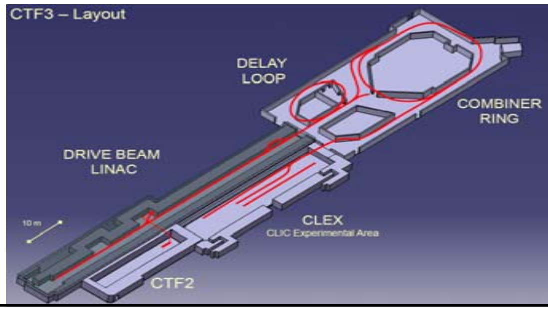
CLIC accelerator program

- Organisation
  - Strong CLIC/CTF3 collaboration (32 institutes involving 19 funding agencies of 17 countries)
- Up to end 2010:
  - Demonstrate feasibility of CLIC technology (CTF3)
  - LC design based on CLIC technology
    - Estimation of its cost in the CERN area
    - Conceptual Design Report including cost by 2010
- ~End 2015
  - Technical design report

Approval ? First beam (~2023) ???

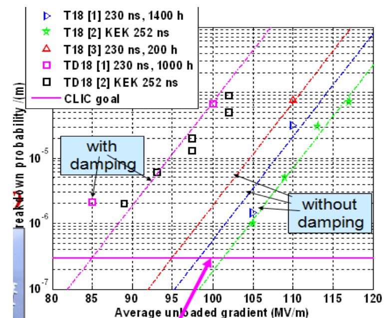
CLIC Test Facility (CTF3)

- Addressing all major CLIC technology key issues in CTF3
  - Drive Beam generation (fully loaded acceleration, bunch frequency multiplication)
  - CLIC accelerating structures
  - CLIC power extraction transfer structures (PETS)



Nominal CLIC structure performance demonstrated

Example of fruitful collaboration:
Design@CERN, built/tested @KEK, SLAC



CLIC goal:100 MV/m loaded with BR<3 10-7/m

CLIC:

breakdown rate vs. gradient

improvement by RF conditioning

Summary 2: Accelerator design

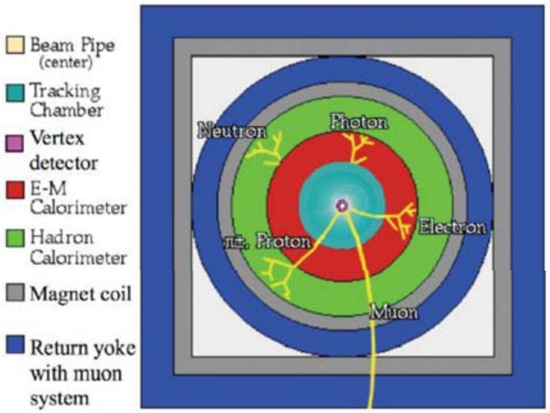
Scientific case for a LC is strong and convincing, a world consensus exists on its importance and on its timing w.r.t. the LHC

Two projects – ILC and CLIC

- The SC technology for the ILC is well developed
- 2012 ILC Technical design will be ready
  → Technical Report (TDR)
- CLIC Conceptual Design Report ~2011
  Technical Design Report ~2015
- Politicians are following the process
  (technical decision, joint global design..)

Detectors

Generic Detector



Basic detector design concept

! Precision measurements !

Performance goal (common for all detector concepts)

- Vertex detector: $\delta(IP) \leq 5 \oplus 10 / p \sin^{3/2}\theta [\mu m]$
  excellent point resolution <4μm (5x better than LEP)
- Tracking: $\frac{\delta p_t}{p_t^2} \leq 5 \times 10^{-5} [GeV^{-1}]$
  (10x better than LEP)
- Jet energy resolution $\frac{\delta E}{E} \leq \frac{0.3}{\sqrt{E}} [E \text{ in GeV}]$
  (2x better than LEP)

→ Detector optimized for particle flow algorithm (PFA)

The Particle Flow Concept

- Typical jet:
  - 65% visible jet energy from charged hadrons
  - 25% photons (from $\pi \rightarrow \gamma\gamma$)
  - 10% neutral hadrons
- Traditional calorimetric approach:
  - Measure total visible jet energy in ECAL and HCAL
  - But 70% of energy are measured in HCAL ⇔ problem: large fluctuations, poor resolution
- PFA:
  Use the sub-detector with the best resolution for the energy measurement
  - Charged particles measured in tracker (essentially perfectly)
  - Photons in ECAL
  - Neutral hadrons in HCAL
  - Only 10% of jet energy from HCAL → substantially improved resolution

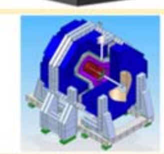
Validated ILC concepts

ILD: International Large Detector

"Large" : tracker radius 1.8m
B-field : 3.5 T
Tracker : TPC + Silicon
Calorimetry : high granularity particle flow
ECAL + HCAL inside large solenoid

SiD: Silicon Detector

"Small" : tracker radius 1.2m
B-field : 5 T
Tracker : Silicon
Calorimetry : high granularity particle flow
ECAL + HCAL inside large solenoid



CLIC detector concepts will be based on SiD and ILD.
Modified to meet CLIC requirements

http://www.cern.ch/lcd Lucie Linssen, 13/11/2009 67

More details see: http://www.ilcild.org/, www.linearcollider.org/physics-detectors/Detectors

Summary

- The LHC results will need to be complemented by precision measurements at a e+e- collider
- The parameter for the FutureLC will be constrained by the LHC results
- ILC and CLIC – both have a strong programme
  - ILC is the far most advanced collider design
  - CLIC ⇔ high energy option
- ILC and CLIC: Synergy and competition
- Both ILC and CLIC demand high-tech solutions on yet untested scales

More information: http://www.linearcollider.org/

CLIC & ILC roadmaps