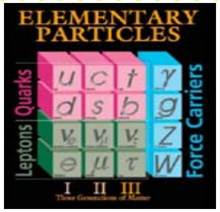
Outline

- Status SM
- What can a high energy e+e- collider contribute ?
  - **Physics items**
    - Higgs boson measurements
    - Top-quark
- The Linear Collider Projects
  - **Why linear ?**
  - **Key topics**
    - Energy
    - Luminosity
    - polarization
  - **Description and current status**
    - ILC project
    - CLIC project
- Summary

Status of the Standard Model



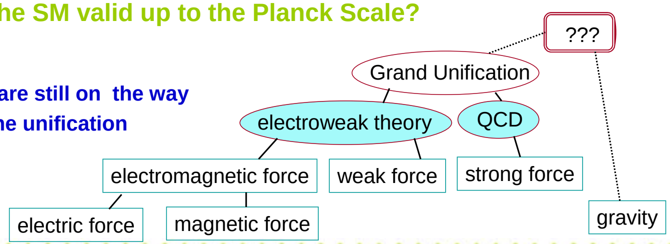
We know:

- **The matter is composed of Quarks and Leptons**
- **interacting via force carriers (Gauge Bosons)**

To be confirmed: Higgs boson

Is the SM valid up to the Planck Scale?

We are still on the way to the unification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Grand Unification

electroweak theory

QCD

electromagnetic force

weak force

strong force

electric force

magnetic force

gravity

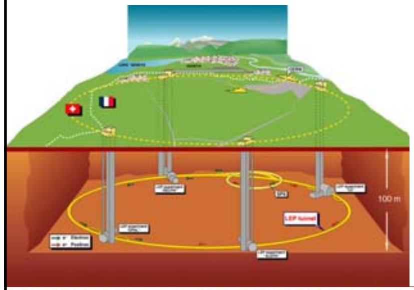
Precision electroweak measurements: e+e- colliders

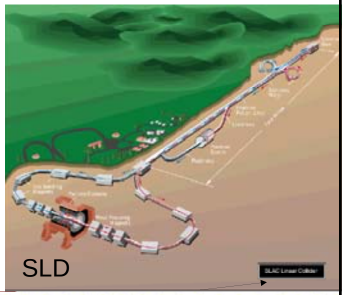
Last Electron Positron Collider LEP

- E_{cms} = 89 GeV … 208GeV
- unpolarized beams
- 4 experiments
- 1989 - 2000

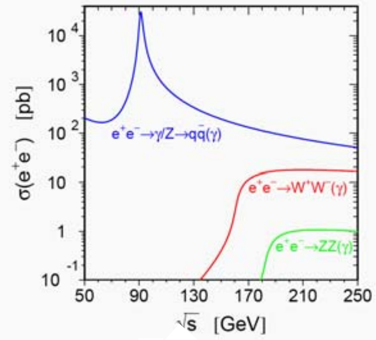
Stanford Linear Colllider SLC

- E_{cms} ~ 91 GeV
- polarized electron beam
- 1 experiment (SLD)
- 1989 - 1998

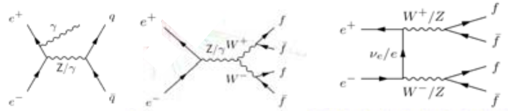




The nineties – precision physics at LEP and SLC



- LEP1 (1989-95)
  - **E_{cm} = 89-91-93 GeV**
  - **17x10^6 Z bosons**
- SLC (1989-1989)
  - **E_{cm} ≈ 91 GeV**
  - **5.5x10^5 Z bosons**
  - **Polarized e- beam**
- LEP2 (1995 – 2000)
  - **W physics**
  - **Searches: Higgs, SUSY**



Precision electroweak measurements

status of SM based on precision electroweak measurements
see: http://lepewwg.web.cern.ch/LEPEWWG/

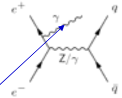
Fit of electroweak parameters:
- Measurements (LEP, SLD)
  - **cross sections, asymmetries**
  - **→ Z pole pseudo-observables**

	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	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26

Z Boson parameters (ee → $f\bar{f}$)

- Deconvolute electroweak kernel cross section:

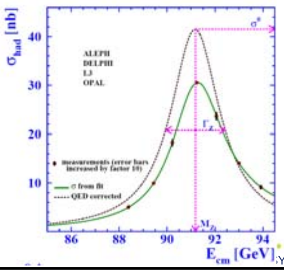
$$\sigma(s)=\int dz\, H_{QED}(z,s)\,\boxed{\sigma_{ew}(zs)}$$

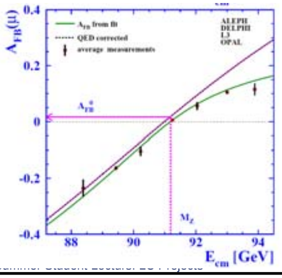


Mainly initial state radiation

- Extract Z pole pseudo-observables

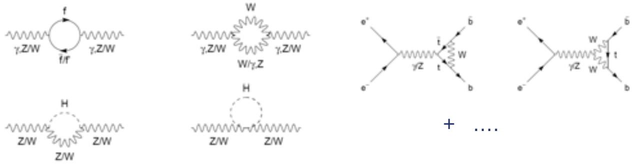
$$\boxed{\begin{array}{c} m_Z \\ \Gamma_Z \end{array}} \quad \boxed{\begin{array}{l} \sigma^0_{had} \equiv \dfrac{12\,\pi}{m_Z^2}\dfrac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2} \\ R^0_l \equiv \dfrac{\Gamma_{had}}{\Gamma_{ll}} \end{array}}$$





$$\boxed{\begin{array}{l} A^{0,f}_{FB} = \dfrac{3}{4}A_eA_f \\ A^0_{LR} = A_e \\ A^{0,f}_{LRFB} = \dfrac{3}{4}A_f \\ \left\langle P^0_\tau \right\rangle = -A_\tau \\ A^{pol,0}_{FB} = -\dfrac{3}{4}A_e \end{array}}$$

+ electroweak corrections



\+ ….

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

- Radiative correction described by formfactors ⇔ pseudo-observables correspond to improved Born
- Fit to pseudo-observables yields m_t
  - **Comparison with direct m_t measurements**
- Global fit to pseudo-observables + constraint from direct m_W and m_t measurement
  - **consistency check**
  - **Higgs mass**

Precision electroweak measurements

status of SM based on precision electroweak measurements
see: http://lepewwg.web.cern.ch/LEPEWWG/

Fit of electroweak parameters:
- Measurements (LEP, SLD)
  - **cross sections, asymmetries**
  - **→ Z pole pseudo-observables**
- Global fit of ew parameters (SM !!)
  m_Z, m_t, m_H, $\Delta\alpha^5_{had}(m_Z^2)$, $\alpha_s(m_Z^2)$
  - **Pseudo-observables + constraints from direct measurements**
    - Measurements of m_W, Γ_W (Tevatron, LEP2)
    - Measurements of m_t (Tevatron)
  - **→ Results:**
    - Excellent agreement of measurements with SM
    - Largest deviation: 3σ
    - Higgs mass

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
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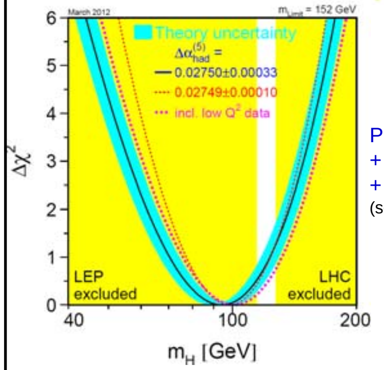
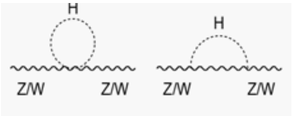
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26

SM Higgs Mass and precision measurements at LEP/SLD



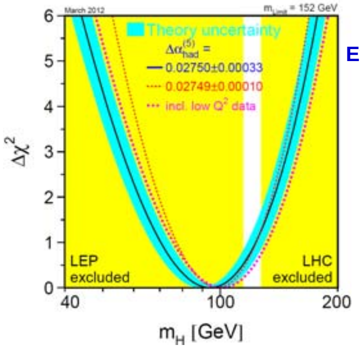


Precision measurements at LEP1/SLD
+ m_W from Tevatron and LEP2
+ m_t from Tevatron
(see http://lepewwg.web.cern.ch/LEPEWWG)

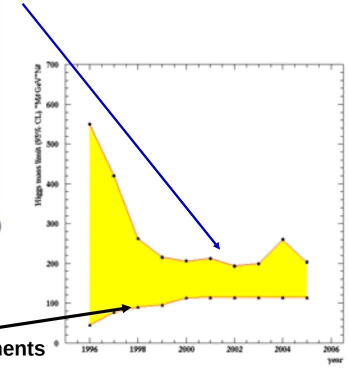
LEPEWWG(March'12): $m_H = 94^{+29}_{-24}$ GeV (ew + m_t + m_W)

m_H < 152 GeV (95% C.L.)

The SM Higgs Mass history



Evolution from precision measurements



Lower limit from direct measurements

SM consistency check

	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
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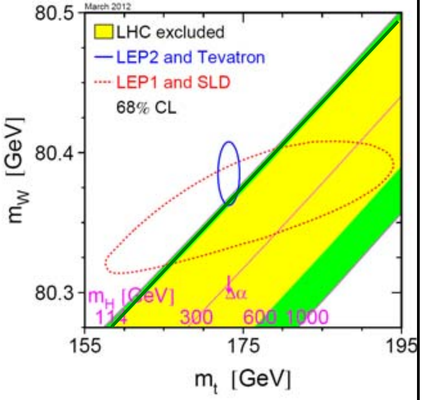
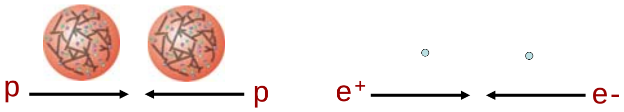
March 2012



So far, all measurements are in agreement with SM

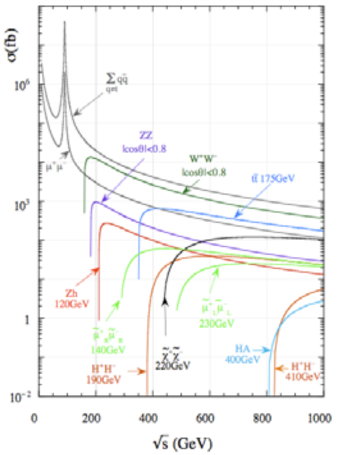
What could a high-energy e+e- collider contribute after years of

LHC running ?

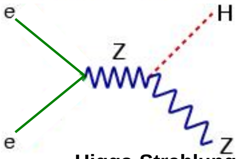


e+e- physics at highest energies

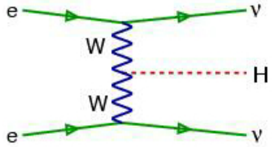
- Precision measurements
  - **Higgs physics**
  - **top quark physics**
  - **ZZ,WW**
  - **SUSY (?)**
- Searches
  - **Extra dimensions**
  - **Dark matter**
  - **...**
- Indirect searches
  - **precision measurements**
  - **→ Interprete deviations from SM predictions in terms of new physics models**



Production of the Higgs Boson

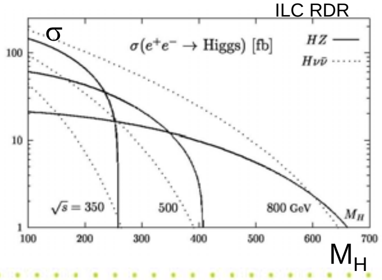


Higgs-Strahlung



WW-Fusion

ILC RDR



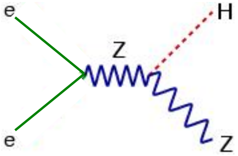
With high luminosity:

→Higgs factory !!

→ Higgs mass

→ Higgs coupling

Higgs Mass and Higgs Coupling to the Z

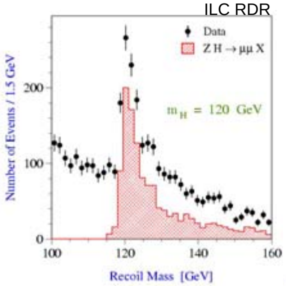


Select events:

e+e- → ZH and Z → μμ,ee

Fit to the spectrum of recoil mass of both leptons →

ILC RDR



Peak position	Peak height
Δm < 100 MeV	Δσ ~ 5 to 6%

$\sigma_{ZH} \sim g_Z^2$

→<u>model-independent</u> determinatin of ZH coupling g_Z

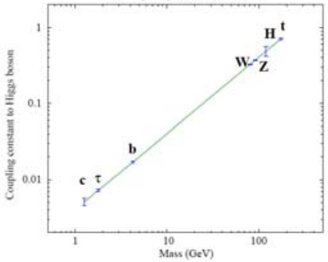
Δg~ 2-3%

Δm ~ 40 to 80MeV possible for full reconstruction of H decay

Higgs Boson

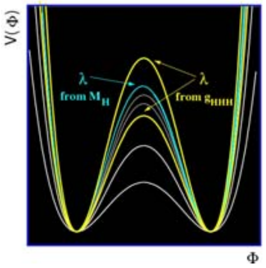
- Higgs boson mass
  - **in SM, it determines the couplings completely**
- Complete establishment of Higgs mechanism implies:
  - **Investigation of coupling - mass relations**
  - **Measurements of Higgs quantum numbers**
  - **Measurements of Higgs self-coupling**
    - **→ reconstruction of Higgs potential**
- Study the structure of the Higgs sector
  → single doublet of "Minimal SM" or extended Higgs sector (Beyond SM theory) ?

Coupling Mass Relation

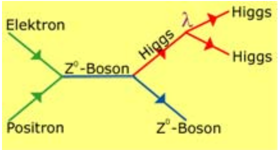


KEK-REPORT-2003-7

Higgs self-coupling

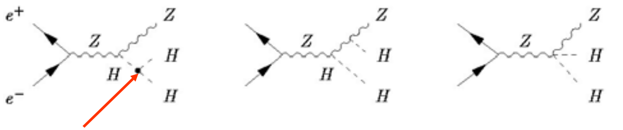


Reconstruction of Higgs potential ⇔
Measurement of Triple-Higgs coupling



$V(\Phi) = \lambda (\Phi^2 - 1/2\, \nu^2)^2$ with $\lambda > 0$ **$m_H^2 = 2 \lambda \nu^2$**

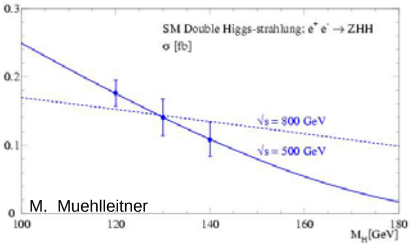
Higgs Self-Coupling



Sensitive to λ

Complex final state:
ZH→ZHH→qq bb bb
Huge SM background

tiny x-section: ~0.15 fb
→ need high luminosity



M. Muehlleitner

At 500GeV, 1ab-1: $\Delta\sigma/\sigma$=13 % → $\Delta\lambda/\lambda$=22%
At 1TeV, $\Delta\lambda/\lambda$=12% could be possible

(See ILC RDR and References therein)

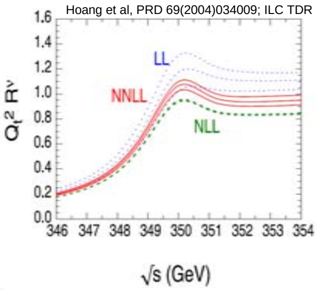
Higgs Boson

- LHC alone won't be able to provide a complete and comprehensive picture of Higgs mechanism
- precision of measurements at LHC insufficient to discriminate between different models
- model independent coupling measurements not possible
- Higgs-self coupling is very hard to access at LHC
- more than 10 years of detector and machine R&D and physics studies demonstrated high potential of a (sub)TeV e+e- machine and its complementarity to LHC

Top-quark physics

- heaviest quark, plays a key role in the understanding of flavour physics and requires precise determination of its properties
  - **Decay of t-quark 'before hadronization'**
  - **Top-polarization gets preserved to decay (similar to τ-lepton)**
  - **Important for quantum effects affecting many observables**
- Shape of ttbar cross section at energies around threshold is sensitive to top-quark mass and coupling
- Running at ttbar threshold
  - **→ statistical error Δm_t <100MeV (20MeV)**
  - **→ transition of measured mass to suitably defined top-mass (e.g. $\overline{\text{MS}}$ mass)**
  - **→ Δm_t ~100MeV dominated by theory error**

Hoang et al, PRD 69(2004)034009; ILC TDR

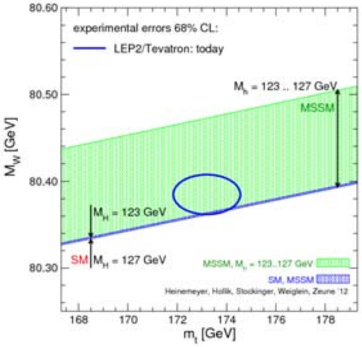


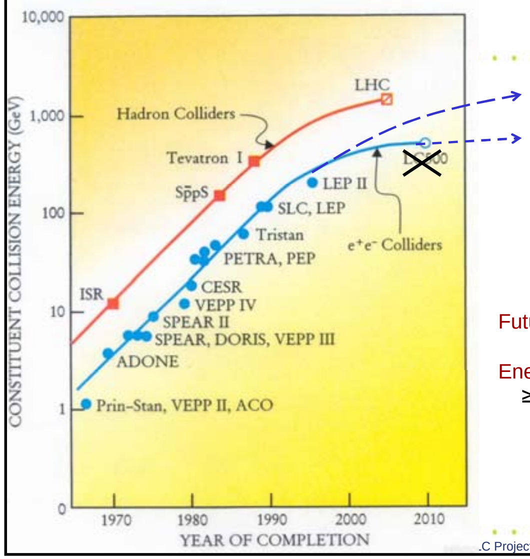
Top-quark mass

- At hadron colliders, the mass of top-quark decay products is compared with MC template → fit to get pole mass
- Tevatron
  - **m_t = 173.2±0.9 GeV**
- LHC:
  - **Direct measurements already dominated by systematic error**

  σ_{tt} used to determine m_t
  - **Precision seems to be limited:**

    $\Delta\sigma_{tt}/\sigma_{tt} \sim 5\ \Delta m_t/m_t$
- m_t already very precise – but precise enough?
  - **uncertainty is correlated to theory parameters**
  - **Precision tests (m_t enters quadratically)**





CLIC

ILC

Future e+e- Collider:

Energy:
≥ 500 GeV... 3-4 TeV

Summary 1 - Physics at e+e- colliders

Comprehensive overview of the fascinating physics potential at high-energy e+e- Colliders: TESLA TDR, ILC RDR, ILC TDR, CLIC CDR (*)

Precision physics to test Standard Model and beyond at energies >200 GeV

→ Top physics: mass and couplings ($E_{cm} \geq 340$ GeV)
→ Higgs boson: mass, couplings, gauge structure
→ New physics: extra dimensions, SUSY, …
LHC will show the path

(*) TDR = Technical Design Report, CDR = Conceptual Design Report

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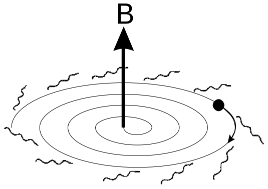
The e+e- Linear Collider Projects

- Why linear colliders
- Key parameters:
  - **Energy**
  - **Luminosity**
  - **Polarization**

Why linear colliders?

Synchrotron radiation
→ Energy loss per revolution
(radius R)

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



LEP (R_{eff} = 3.1km):

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

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

Energy loss has to be compensated by RF system

Scaling of costs at a circular collider

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

From LEP2 to 500GeV ⇔ cost increase by factor ~15

From LEP2 to 3 TeV ⇔ cost increase by factor ~280

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

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

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

Storage rings
- Accelerate and collide every turn
  → 're-use' of RF structures
  → 're-use' of particle beam
- efficient

Linear Colliders
- One-pass acceleration
- One-pass collision
- no bending magnets, but lots of RF structures
  → High gradient to limit length of the machine

The e+e- collider key parameters

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+**

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

Which centre-of-mass energy??

Physics:

- Higgs Boson mass ~125GeV
- Vacuum expectation value ν = 246GeV
- SUSY: s-particles ? <1TeV ??
- threshold for top-quark pair production: 350 GeV
- new discoveries at LHC ⇔ E_{cm} = ??

Technology:

- big steps are risky

Conclusion for energy range

- E_{cm} = 500GeV is "reasonable" first step
- Upgrade to ~1 TeV must be possible
- Multi-TeV accelerator to cover and extend LHC search reach
- Also a Z factory (GigaZ), i.e. running at the Z resonance, should be possible if desired

---

The e+e- collider key parameters

Energy

- Determined by technology
  - Gradient
  - → Length of accelerator

Luminosity

- High statistic for precision measurements
- → Luminosity as high as possible

Beam polarization

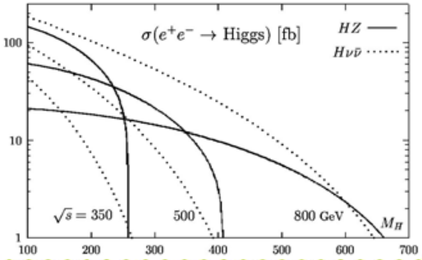
- produce polarized e-, e+

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

Design luminosity?

N = Lσ

- as much luminosity as possible, $\sigma \sim 1/E_{cm}^2$ → $L \sim E_{cm}^2$
- precision measurement with uncertainty O(1%)
  $>10^4$ events required
- Example: SM-Higgs production σ ~ 20fb → need $L_{int} = 500\ fb^{-1}$

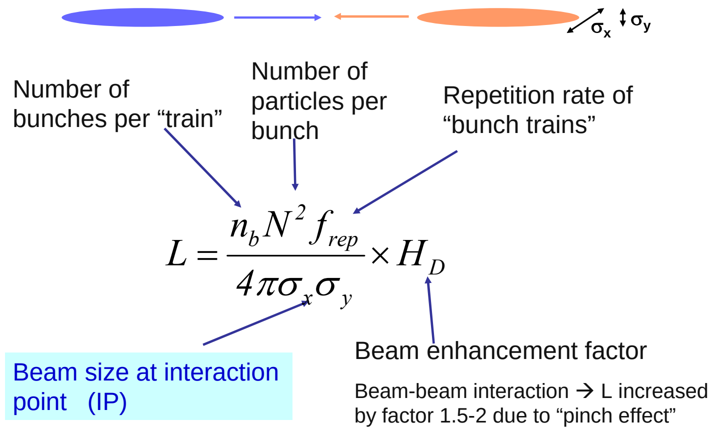


4-5 years ⇔ ~500 days

→ per day ≈1 fb^{-1} or

$L = 1 \times 10^{34}\ cm^{-2}s^{-1}$

Luminosity



Number of bunches per "train"

Number of particles per bunch

Repetition rate of "bunch trains"

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

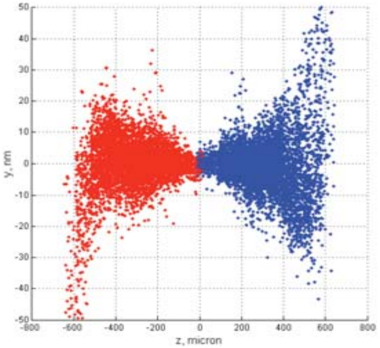
Beam size at interaction point (IP)

Beam enhancement factor

Beam-beam interaction → L increased by factor 1.5-2 due to "pinch effect"

Pinch effect

Electrons → ← positrons



Luminosity

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

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

$$\Downarrow$$

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

η – efficiency to transfer power from RF →beam

Example:

E_{cm} = 500 GeV
N = 10^{10}
N_b = 100
f_{rep} = 100

→ P_{beam} = 8 MW

Taking into account efficiency η, power >100MW needed to accelerate particles and maintain luminosity
→ Repetition rate f_{rep} is power limited

Luminosity

Beam Power, $P_{beam} = \eta_{RF \rightarrow beam} P_{RF}$
(typically 5-8MW)

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

$$\Downarrow$$

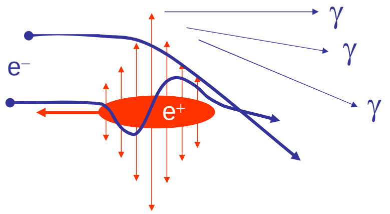
$$L = \frac{1}{4\pi E_{cm}} \left(\eta \cdot P_{RF}\right) \frac{N}{\sigma_x \sigma_y} \times H_D$$

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

→ Pinch effect

$$\delta_{BS} = \frac{\Delta E}{E} \propto \frac{E_{cm}}{\sigma_z} \left(\frac{N}{\sigma_x + \sigma_y} \right)^2$$

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

Optimize beam size for luminosity

Choose flat beams ($\sigma_y \ll \sigma_x$):

$$\frac{N}{\sigma_x} \propto \sqrt{\frac{\sigma_z \delta_{BS}}{E_{cm}}}$$

+ luminosity law:

$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \left(\frac{N}{\sigma_x} \right) \frac{1}{\sigma_y}$$

yields

$$L \propto \frac{\eta \cdot P_{RF}}{E_{cm}^{3/2}} \frac{\sqrt{\delta_{BS} \sigma_z}}{\sigma_y}$$

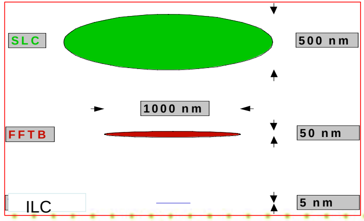
Optimize luminosity

Finally:

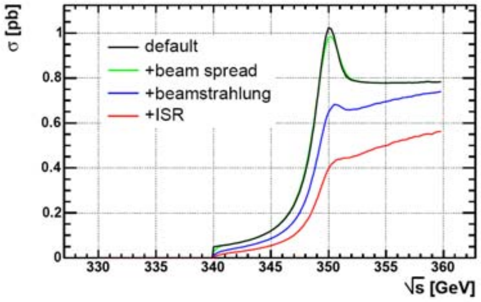
$$L \propto \frac{\eta \cdot P_{RF}}{E_{cm}^{3/2}} \left(\frac{\delta_{BS} \sigma_z}{\sigma_y} \right)^{1/2}$$

- High transfer efficiency from RF to beam: η
- High RF power P_{RF} (klystrons) (~100MW)
- small vertical beamsize σ_y
- Relatively large bunch length σ_z
- (x,y) beam dimensions

(for comparison:
LHC σ ~ 15 μm)



Beamstrahlung at the ttbar threshold



S. Boogert, Snowmass 2005, ILC RDR:
Smearing of the theoretical ttbar cross section (default)
by beam effects and initial state radiation
➔ important for m_t measurement

The e+e- collider key parameters

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+**

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

Beam polarization

Lessons from LEP/SLD: Measurement of $\sin^2\theta_W^{eff}$

- **LEP: Unpolarized beams, 17x10^6 Z events**
  - **➔ leptonic weak mixing angle measured with relative precision of 1.3x10^{-3}**
- **SLD: Polarized electron beam, 5x10^5 Z events**
  - **➔ leptonic weak mixing angle measured with relative precision of 1.1x10^{-3}**

→ Electrons must be polarized

→ Even better if also positrons are polarized

The e+e- collider key parameters

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+**

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

Linear Collider - Requirements

Physics between 200 GeV and 500 GeV up to 1-3TeV
Polarized electrons: 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
5·10^5 (1·10^5) ee → qq (μμ) 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 of observables and E, L, P

Summary (2)

- High-energy e± colliders beyond (E_{cms}>200GeV) must be linear
- Key parameters of high-energy linear colliders:
  - **High energy, flexible choice of E_{cm}**
    - Higgs physics ⇔ E_{cm} ~250GeV
    - Top physics at threshold ⇔ E_{cm} ~350GeV
    - Beyond SM measurements depend strongly on LHC results
  - **High luminosity ⇔ 'flat' beams**
    - L ≥ 1x10^{34}/cm^2/s
  - **Beam polarization, desired for both beams**
    - P(e-) ≥ 80%
  - **Precision diagnostics of E,L, P**

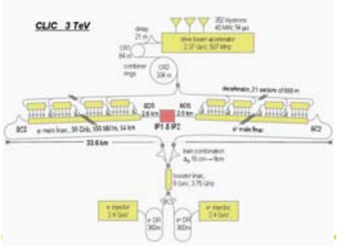
Future e+e- projects

ILC (International Linear Collider)
- Superconducting acceleration

- 31.5 MV/m, 1.3 GHz
  E_{cm} = 500 GeV (1TeV)
- Technology at hand (XFEL)
  TDR end 2012

CLIC (Compact Linear Collider)
- Normalconducting acceleration
- 2-beam acceleration

- 100 MV/m, 12 GHz
  E_{cm} = 500 GeV – 3 TeV
- Still fundamental R&D phase
  CDR 2012



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www.linearcollider.org

- ILC Reference Design Report (RDR), 2007:
  http://www.linearcollider.org/about/Publications/Reference-Design-Report
  - Executive summary
  - Accelerator
  - Physics at the ILC
  - Detector
- ILC Interims Report (2011)
  http://ilcdoc.linearcollider.org/record/32863/files/ilc_interim_report_2011-lores.pdf
- TDR: end 2012

The Compact Linear Collider (CLIC)

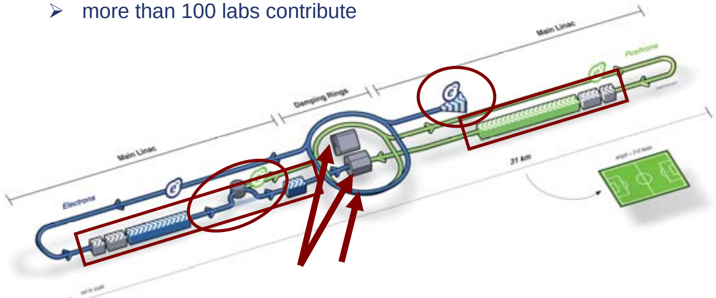
Develop technology to extend e-/e+ linear colliders into the **Multi-TeV** energy range
- http://clic-study.org/

Physics motivation:
- "Physics at the CLIC Multi-TeV Linear Collider" by CLIC Physics Working Group: CERN 2004-5

CLIC CDR
- In preparation (partially final), to be finalized this year
- Includes machine (Vol 1) and physics and detector (Vol 2)

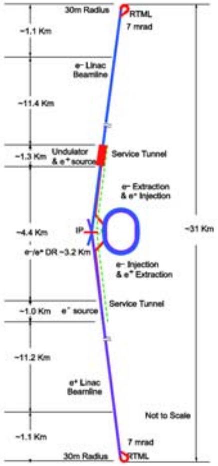
The ILC (RDR)

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



ILC layout

TDR:



E_{cm}	500 GeV
e- polarization	80%
e+ polarization	30%
Peak luminosity	$1.5x10^{34}cm^{-2}s^{-1}$
Acc. gradient	31.5 MV/m
Bunch length	0.3mm
Beam size at IP	$474x5.9nm^2$
Beam power	10.8 MW
Total AC power consumption	230 MW

Corresponding tables for 250 …350GeV, 1TeV

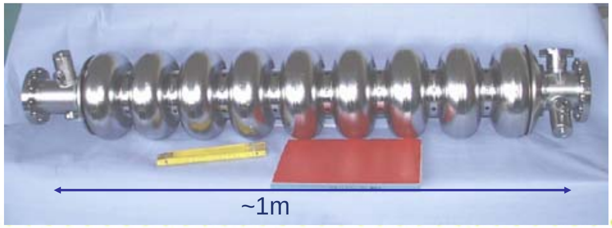
Towards the TDR in 2012

SB2009

Not to scale

Workhorse: main linac

- TESLA superconducting 9-cell Niobium cavity
  - Working at 2K
- Gradient:
  - 31.5MV/m (500GeV)
  - fundamental limit at 55 MV/m:
    - cavity becomes normal conducting above ~55MV/m



Why a 'cold machine'

Advantage of superconducting RF Technology

- Low RF losses in resonator walls
  - Niobium cavities: $Q_0 \approx 10^{10}$ (compared to Cu $\approx 10^4$)
  - High efficiency $\eta_{RF \rightarrow beam}$
  - Long beam pulses (many bunches within one pulse) are possible → lower RF peak power

    Remember: $P_{beam} = E_{cm} f_{rep} n_b N = \eta_{RF \rightarrow beam} P_{RF}$

  - Larger bunch spacing ⇔ corrections within bunch train are possible

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:

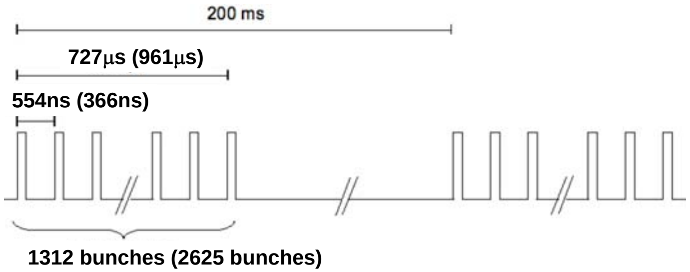
$$Q = \frac{\text{stored energy}}{\text{energy loss per cycle}}$$

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

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

The ILC bunch structure

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

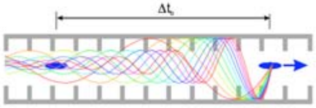


(baseline design 2012: reduced by factor 2 → 1312 bunches. Numbers in brackets correspond to the 'high luminosity' option)

Why a 'cold machine'

Advantage of superconducting RF Technology

- Low-frequency accelerating structures:1.3 GHz
  (Cu: 6…30GHz)



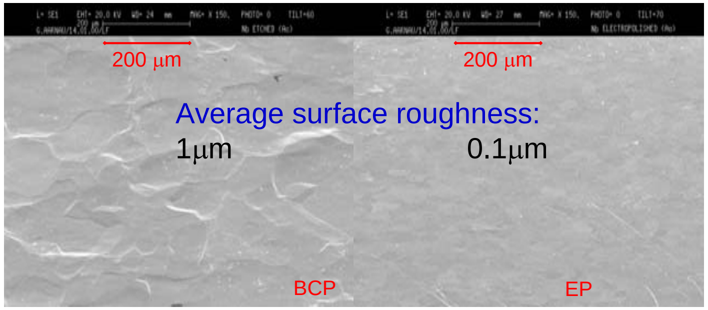
  - **small wakefields**
    - bunch travels through a structure with a transverse offset with respect to the structure axis
    - the bunch induces transverse modes which act back on the beam.
    - single bunches: the modes deflect the tail of the bunch
    - Multibunches: modes generated by earlier bunches deflect the later ones.

    →Compensation or correction, otherwise beam breaks
  - **Relaxed alignment tolerances**
  - **High beam stability**

Gradient

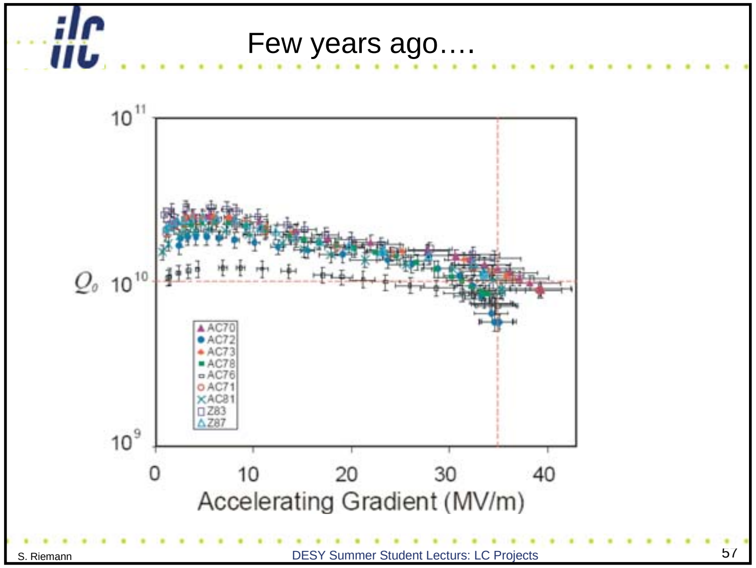
In practice: Limitation due to quality of surface and niobium

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

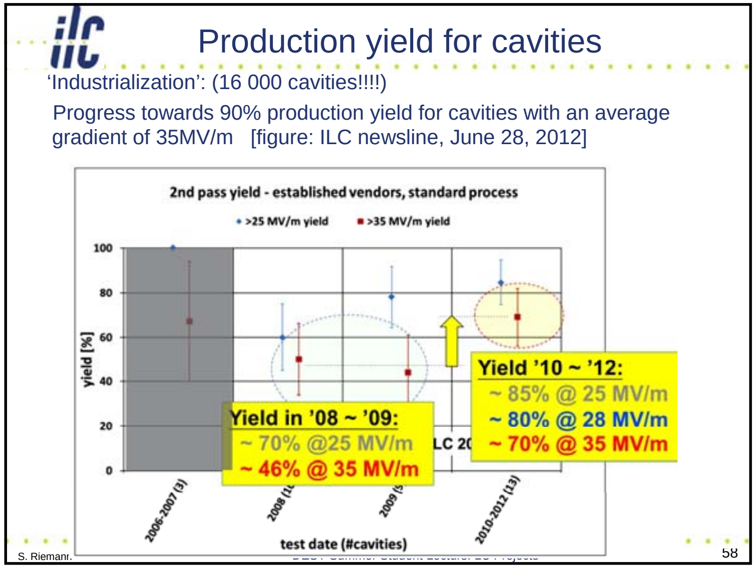


Average surface roughness:
1μm 0.1μm

etching - "buffered chemical polish" electro-polishing



Few years ago….



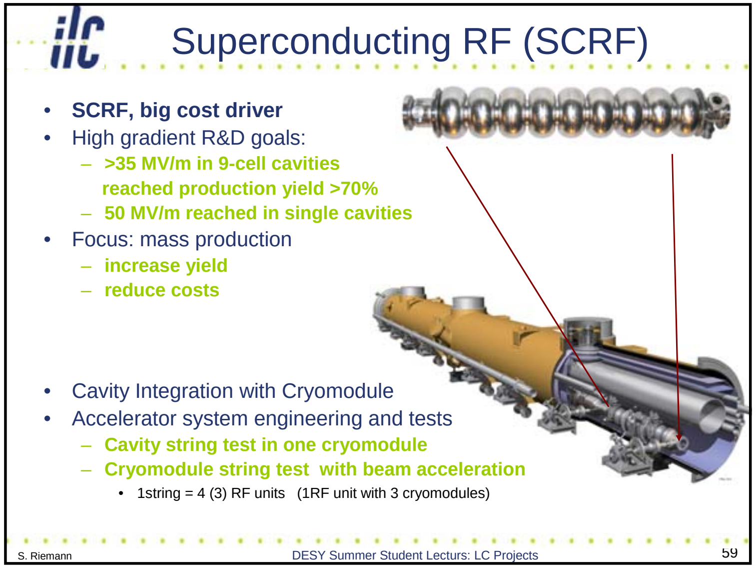
Production yield for cavities

'Industrialization': (16 000 cavities!!!!)

Progress towards 90% production yield for cavities with an average gradient of 35MV/m [figure: ILC newsline, June 28, 2012]

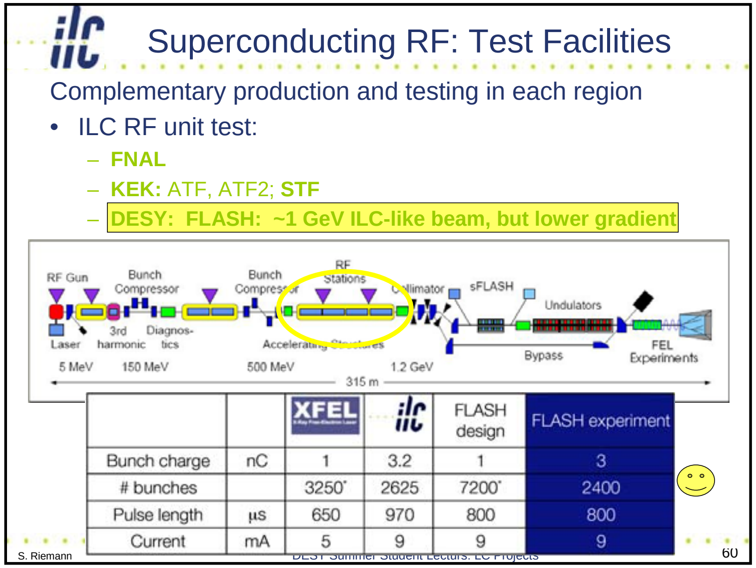
Yield in '08 ~ '09:
~ 70% @25 MV/m
~ 46% @ 35 MV/m

Yield '10 ~ '12:
~ 85% @ 25 MV/m
~ 80% @ 28 MV/m
~ 70% @ 35 MV/m



Superconducting RF (SCRF)

- **SCRF, big cost driver**
- High gradient R&D goals:
  - **>35 MV/m in 9-cell cavities reached production yield >70%**
  - **50 MV/m reached in single cavities**
- Focus: mass production
  - **increase yield**
  - **reduce costs**
- Cavity Integration with Cryomodule
- Accelerator system engineering and tests
  - **Cavity string test in one cryomodule**
  - **Cryomodule string test with beam acceleration**
    - 1string = 4 (3) RF units (1RF unit with 3 cryomodules)



Superconducting RF: Test Facilities

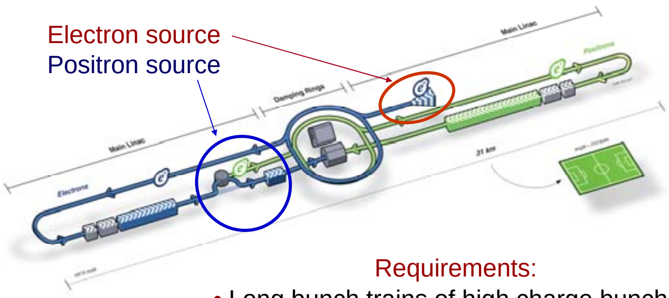
Complementary production and testing in each region

- ILC RF unit test:
  - **FNAL**
  - **KEK:** ATF, ATF2; **STF**
  - **DESY: FLASH: ~1 GeV ILC-like beam, but lower gradient**

		XFEL	ilc	FLASH design	FLASH experiment
Bunch charge	nC	1	3.2	1	3
# bunches		3250*	2625	7200*	2400
Pulse length	µs	650	970	800	800
Current	mA	5	9	9	9

ILC: Sources

Electron source
Positron source



Requirements:

- Long bunch trains of high charge bunches
  1312 (2625) bunches per train, 5 trains per second)
- Small emittances
- Beam polarisation

Electron Source (polarized)

Concept of the e- source

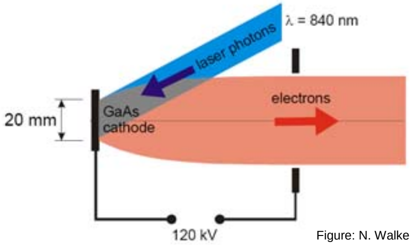


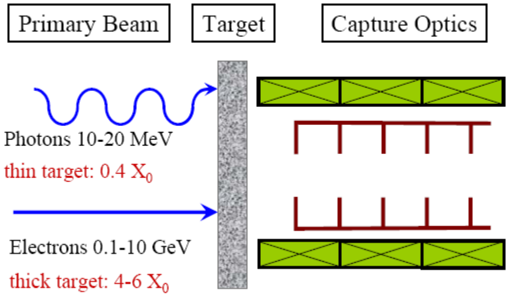
Figure: N. Walker, USPAS lectures, June 2003

Polarization (similar as at SLC) >80%:

- strained lattice GaAs cathode

Electrons are collected and pre-accelerated (~5GeV)

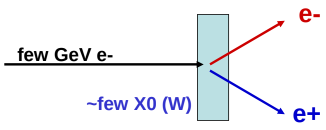
Production of Positrons



Courtesy: K. Floettmann

Generation of Positrons using e-

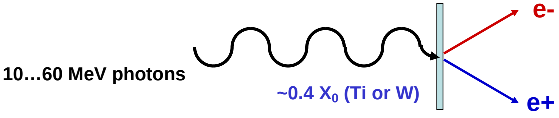
- Conventional source:



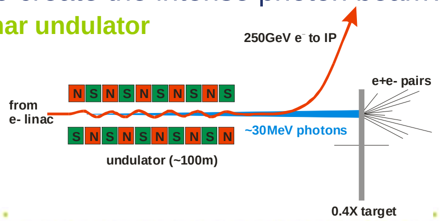
- Huge heat load on target to create enough positrons
  → use photons to produce e+

Generation of Positrons using photons

- photons produce positrons and electrons

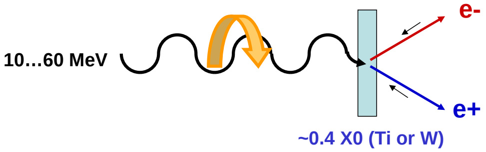


- How to create the intense photon beam?
  - Planar undulator



Generation of polarized positrons

- Circularly polarized photons produce longitudinally polarized positrons and electrons



- Methods to produce polarized photons
  - Radiation from **helical undulator**
  - **Compton backscattering** of laser light off an electron beam

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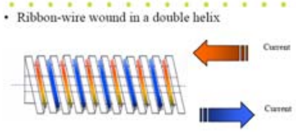
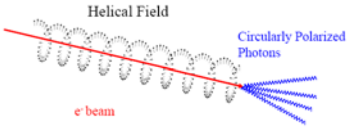
Polarized Photons from Helical Undulator

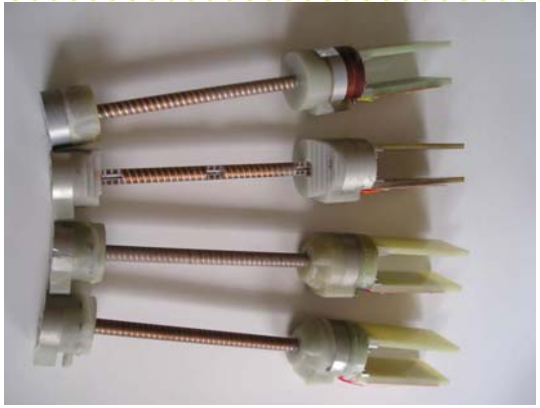
- Rotating dipole field in the transverse planes



- Electrons follow a helical path
- Emission of circularly polarised radiation
- Polarization sign is determined by undulator (direction of the helical field)

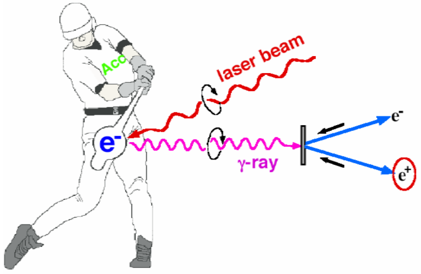


- Photon yield in a helical undulator is about 1.5…2 higher than that in a planar undulator
  - → **ILC design with helical undulator**
  - → **polarized e+ at ILC**



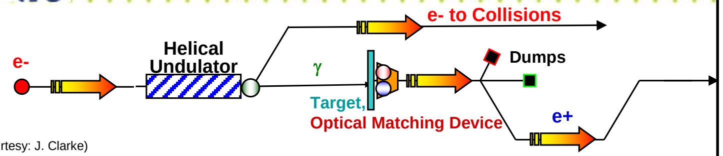
Short undulator prototypes

The Compton scheme



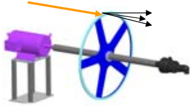
Compton backscattering of laser light off an electron beam.
This scheme is suggested for CLIC ('update option')

ILC Positron Source

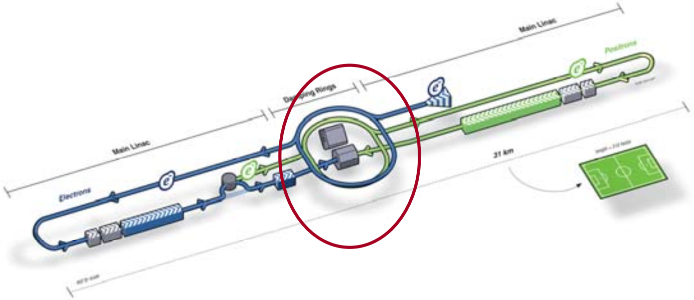


(courtesy: J. Clarke)

- Superconducting helical Undulator
  - → **Electron beam is used to produce circularly polarized photons**
  - **positron beam is polarized**
- Photon-Collimator → to remove part of photon beam with lower polarization
- e+ Production Target
  - **Ti alloy wheel, radius 1m, thickness 1.4cm**
  - **Rotating speed 100m/s (1000rpm)**
  - **Prototyp design and test ongoing**
- OMD (Optical Matching Device)
  - **Pulsed flux concentrator (prototyping ongoing)**
- Polarization:
  - **Spin rotation, rapid helicity reversal**



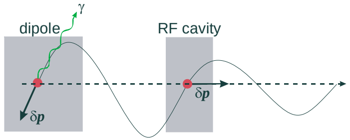
ILC: Damping Ring



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

Damping rings (DR)

- Emittances of e- and e+ from source are too high
  - **Emittance⇔ particles are confined close together with ~equal momentum**

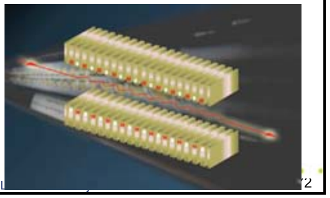


RF: Acceleration in longitudinal direction

Dipol: Energy loss by radiation

- Interplay between synchrotron radiation and acceleration reduces transverse emittance
- However, this takes time – and the bunch train has to be damped within <200ms
- Reduce damping by using damping wigglers
  (SR due to dipoles is not not sufficient)

→ ~100 ms damping time



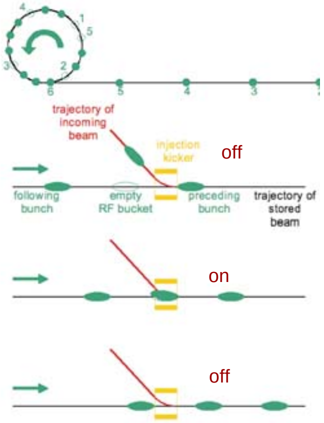
Damping rings

Long pulses:

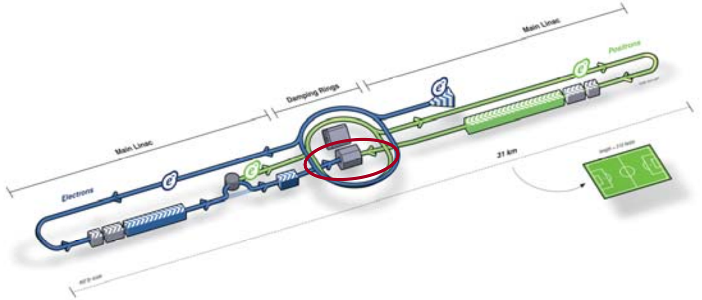
1ms×c = 285km!

Damping ring circumference is 3.2km

→compress whole bunch train to DR with injection & extraction



Beam Delivery System



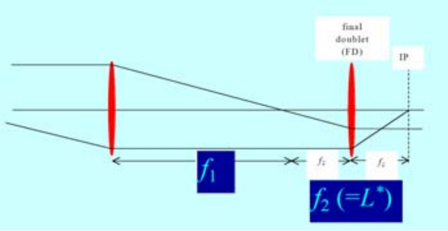
Tasks of the beam delivery system

- Collimation
  - **Remove beam halo to reduce background**
- Beam diagnostics (E, P, dL/dE)
  - **Measurements of energy and polarisation**
- 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 $m = \frac{f_1}{f_2} = \frac{f_1}{L^*}$

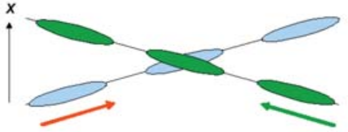
Typically, m=300 needed
With L* = 2m ⇔ f_1 = 600m



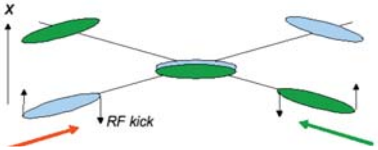
However, also corrections for large chromatic and geometric aberrations needed (life is much more complicated than depicted here…)

Interaction Point

Crossing angle at interaction point



Reduction of luminosity by factor ~10

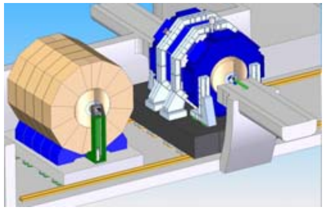


Need transverse (crab) RF cavity to tilt the bunch for collision

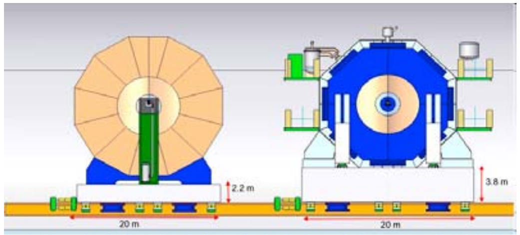
---

Detectors and Interaction Region (IR)

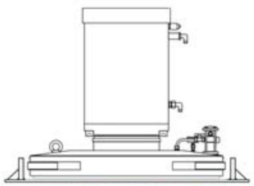
- Desired: at least 2 experiments
- At linear colliders, the integrated luminosity does NOT scale with the number of interaction regions
- ILC proposal: only one IR, but 2 detectors, ILD and SiD

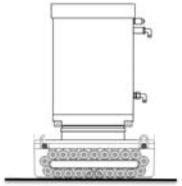


Solution:
Push-Pull system, both detectors on platform



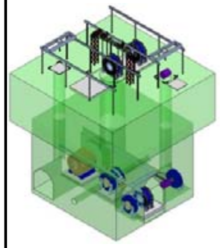
Platform Motion System



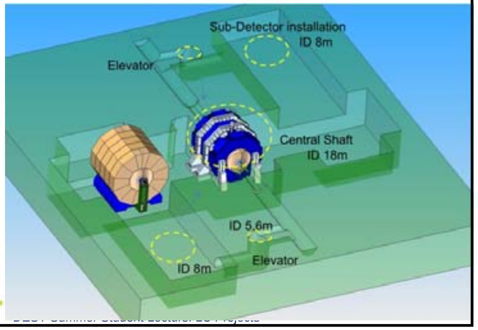


- Airpads (left) or rollers (right)

Push-pull detectors



If the ILC is not built in a mountainous region:
A heavy-duty crane on the surface will transport the assembled detector slices to the hall below.



Z shape – one detector in parking position, one taking data.

Graphics: Marco Oriunno

Sample sites

Under study (technical reasons, costs):

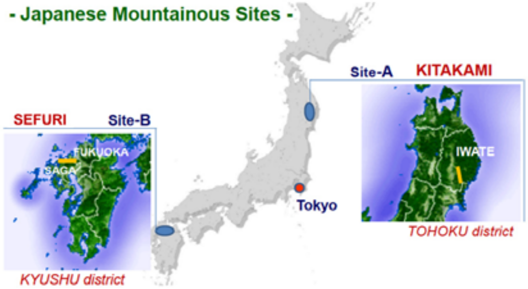
- Deep sites:
  - **Americas: Fermilab**
  - **Asia: Japan**
  - **Europe: CERN**

Example: Dubna

- Shallow sites:
  - **DESY**
  - **Dubna**

Choice of real site will be a political decision!

ILC in Japan ??



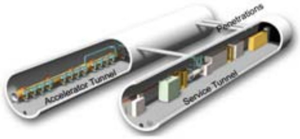
The two candidate sites

- are located in mountainous regions where the geology for tunnelling is stable granite rock without active faults or volcanoes
- There are good access roads and high-voltage transmission lines nearby.
- The local governments and community are supportive and cooperative towards developing these sites for a possible ILC project.

ILC Tunnel layout

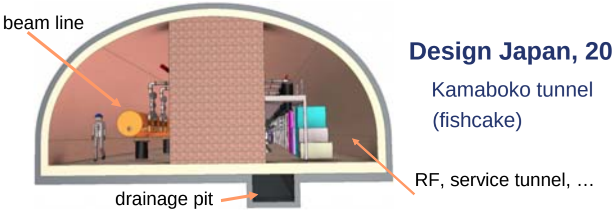
Reference Design (2007)

2 tunnels (accelerator + service)



Design 2009

1 tunnel ⇔ cost reduction



Design Japan, 2011

Kamaboko tunnel (fishcake)

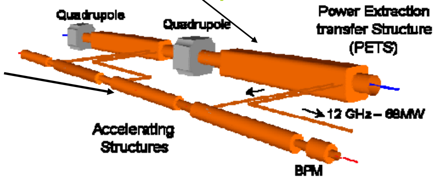
- ILC:
  - **Technical Design Report 2012 (including cost estimate)**
  - **1TeV option under study (highest priority) to be optimized**
  - **Post-TDR work**
    - Improve gradient
    - Positron source
    - Reduce power consumption
    - Cost effective production
    - High flexibility to operate at energies as suggested by LHC

COMPACT LINEAR COLLIDER (CLIC)

- 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 should be below <500MW
  - **LEP in 1998: ~240 MW**

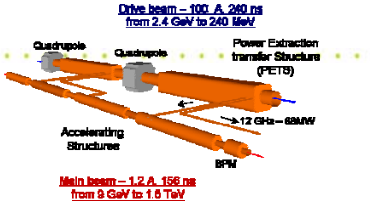
CLIC: Two beam scheme

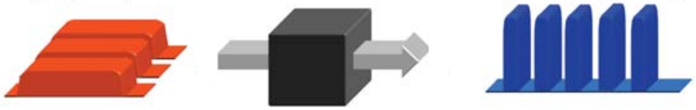
- Drive Beam supplies RF power
  - **12 GHz bunch structure**
  - **low energy (deceleration 2.4 GeV → 240 MeV)**
  - **high current (100A)**



- Main beam for physics
  - **high energy (9 GeV → 1.5 TeV)**
  - **current 1.2 A**
- PETS
  - **extract power from drive beam**
  - **Transfer to main beam accelerating strucures**
- No individual RF power sources (“CLIC itself is a 50km long klystron”)

CLIC scheme





Klystrons
Low frequency
High efficiency

Power stored in electron beam

Power extracted from beam in resonant structures

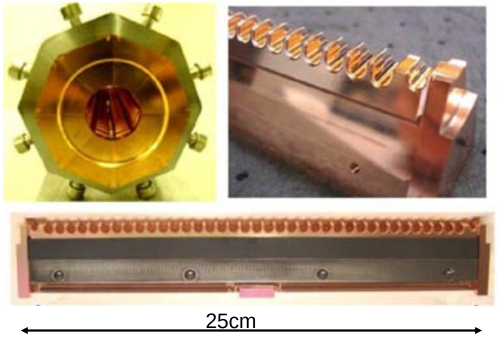
Accelerating Structures
High Frequency - High field

Long RF Pulses

Electron beam manipulation
Power compression
Frequency multiplication

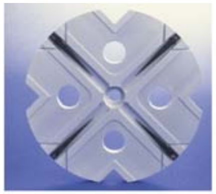
Short RF Pulses

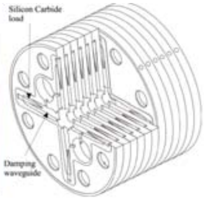
PETS



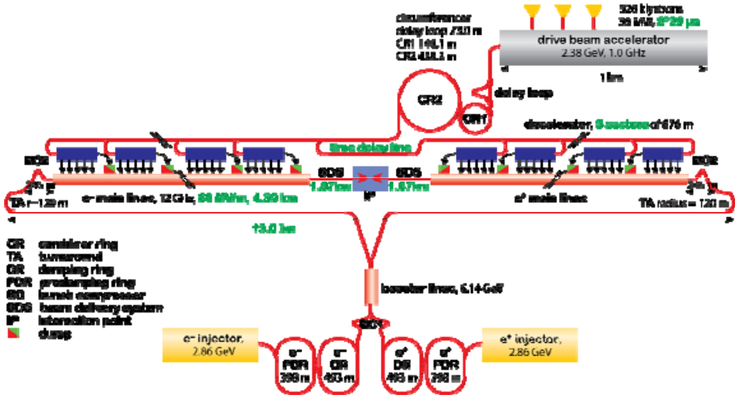
CLIC accelerating structures

- Structures are built from discs

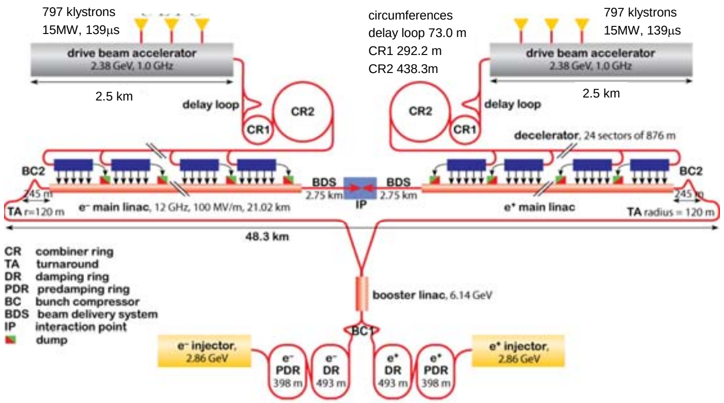




CLIC layout 500 GeV (not to scale)



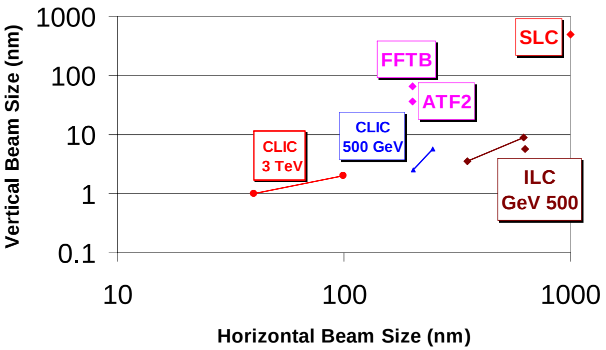
CLIC layout 3TeV (not to scale)



ILC/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	~474 / 6	200 / 2.3	40 / 1.0
Power consumption [MW]	230	240	560

Beam sizes in linear colliders

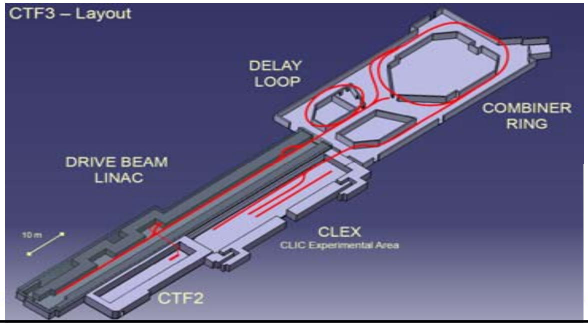


→ High level of beamstrahlung at CLIC (3TeV)

CLIC Test Facility (CTF3)

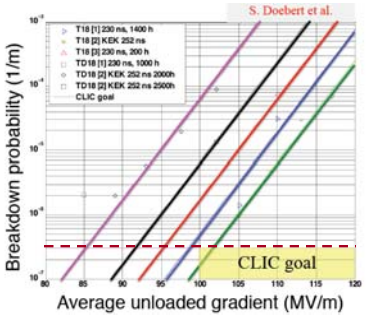
Addressing all major CLIC technology key issues in CTF3

- Drive Beam generation (acceleration, bunch frequency multiplication)
- CLIC accelerating structures
- CLIC power production structures (PETS)



Nominal CLIC structure performance demonstrated

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



CLIC:

breakdown rate vs. gradient

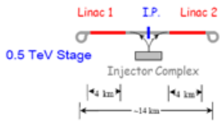
goal: 100MV/m,
breakdown rate < 10^{-7}

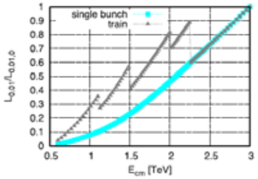
CLIC Implementation – in Stages?

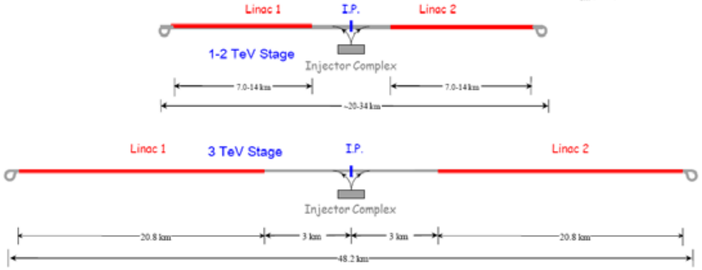
Daniel Schulte

CLIC two-beam scheme compatible with energy staging to provide the optimal machine for a large energy range

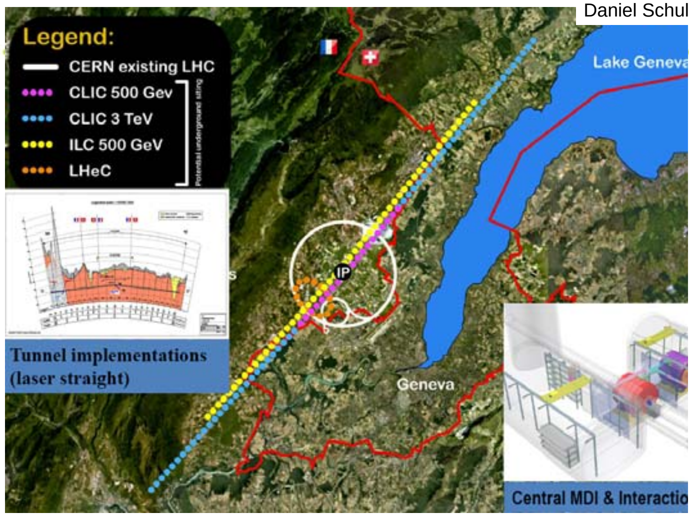
Lower energy machine can run most of the time during the construction of the next stage. Physics results will determine the energies of the stages







Daniel Schulte



Summary: ILC & CLIC Projects

- The SC technology for the ILC is well developed and tested, ILC could be built; ILC Technical Design Report 2012
- CLIC Conceptual Design Report 2012 (500GeV-3TeV)
- collaboration between ILC and CLIC exists
  - **Accelerator components (sources, damping ring, interaction region)**
  - **Detectors**
  - **physics**
- worldwide Linear Collider Organization