Detectors for a Linear Collider

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DESY

Lyon, March 25th, 2008
The International Linear Collider (ILC)
- Status of the project
- Physics motivation
- Impact on detector design
- The detector concepts

Detector R&D for key components
- Vertex detectors
- Tracking
- Calorimetry
- Towards larger prototypes

Conclusions & Outlook
The International Linear Collider

- Electron-positron collider
  - centre-of-mass energy up to 1 TeV
  - centre-of-mass energy
  - luminosities > $10^{34}$/cm$^2$/s

- The next large High Energy Physics project (after the LHC)

- Designed in a global effort

- Accelerator technology:
  supra-conducting RF cavities

- Elements of a linear collider:
The International Linear Collider

- International organisation:
  - Global Design Effort (GDE), started in 2005
  - Chair: Barry Barish
  - representatives from Americas, Asia and Europe
  - all major laboratories and many people contributing
The International Linear Collider

- 2006: Baseline Configuration Document

Layout of the machine:

- 2 \times 250 \, \text{GeV}
- upgradable to 2 \times 500 \, \text{GeV}
- 1 interaction region
- 2 detectors (push-pull)
- 14 mrad crossing angle

Cost estimate:

4.87 \, \text{G$} \, \text{shared components}
+ 1.78 \, \text{G$} \, \text{site-dependent}
= 6.65 \, \text{G$} \ (= 5.52 \, \text{G€})

+ 13000 \, \text{person years}
The International Linear Collider

Next milestones:
- two stage Technical Design Phase (TDP I & II) as proposed by GDE

TDP I until 2010:
- concentrate on main technical and cost risks
  main linac, gradient, electron cloud, conventional facilities
  be prepared when LHC results justify the programme
- detectors: LOIs by March 2009
  update physics performance

TDP II until 2012:
- complete technical design
  siting plan or process
- detectors: react to LHC results
  complete technical designs

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ILC Physics Motivation

- ILC will complement LHC discoveries by precision measurements

- Here just two examples:

1) There is a Higgs, observed at the LHC
   - $e^+e^-$ experiments can detect Higgs bosons without assumption on decay properties
   - Higgs-Strahlungs process (à la LEP)

   - identify Higgs events in $e^+e^- \rightarrow ZH$ from $Z \rightarrow \mu\mu$ decay

   - count Higgs decay products to measure Higgs BRs
   - and hence (Yukawa)-couplings

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ILC Physics Motivation

- Measure Higgs self-couplings $e^+e^- \rightarrow ZHH$ to establish Higgs potential
  
  Note: small signal above large QCD background

2) There is NO Higgs (definite answer from LHC!)

- something else must prevent e.g. WW scattering from violating unitarity at $O(1 \text{ TeV})$
- strong electroweak symmetry breaking?
  
  → study $e^+e^- \rightarrow WW\nu\nu$, $Wze\nu$ and $ZZee$ events

- need to select and distinguish $W$ and $Z$ bosons in their hadronic decays!
  
  BR ($W/Z \rightarrow \text{hadrons}) = 68\% / 70\%$

- Many other physics cases: SM, SUSY, new phenomena, …

Need ultimate detector performance to meet the ILC physics case
Impact on Detector Design

- **Vertex detector:**
  - e.g. distinguish c- from b-quarks
  - goal impact parameter resolution
    \[ \sigma_{r\phi} \approx \sigma_z \approx 5 \oplus 10/(p \sin \Theta^{3/2}) \text{ } \mu m \]
    3 times better than SLD
  - small, low mass pixel detectors, various technologies under study
    \( O(20\times20 \text{ } \mu m^2) \)

- **Tracking:**
  - superb momentum resolution
    to select clean Higgs samples
  - ideally limited only by \( \Gamma_z \)
    \[ \rightarrow \Delta(1/p_T) = 5\cdot10^{-5} \text{ } /\text{GeV} \]
    (whole tracking system)
    3 times better than CMS

Options considered:
- Large silicon trackers (à la ATLAS/CMS)
- Time Projection Chamber with \( \approx 100 \text{ } \mu m \) point resolution
  (complemented by Si–strip devices)
Impact on Detector Design

- **Calorimeter:**
  distinguish W- and Z-bosons in their hadronic decays
  → $30\%/\sqrt{E_{\text{jet}}}$ jet resolution!

  2 times better than ZEUS

- **WW/ZZ → 4 jets:**

  → Particle Flow or Dual Readout calorimeter
Detector Challenges at the ILC

- Bunch timing:
  - 5 trains per second
  - 2820 bunches per train
  separated by 307 ns
  - no trigger
  - power pulsing
  - readout speed
- 14 mrad crossing angle
- Background:
  - small bunches
  - create beamstrahlung
  → pairs

background not as severe as at LHC but much more relevant than at LEP
Four detector concepts are being investigated
- GLD (Global Large Detector)
- LDC (Large Detector Concept)
- SiD (Silicon Detector)
- 4th concept

Merging into one concept:
(ILD) International Large Detector

Summer 2006: Detector Outline Documents (DOD)
evolving documents, detailed description

Summer 2007: Reference Design Reports (RDR)
comprehensive detector descriptions,
along with machine RDR

Prepared by international study groups
Detector Concepts

- **GLD**
  - TPC tracking
  - large radius
  - particle flow calorimeter
  - 3 Tesla solenoid
  - scint. fibre μ detector

- **LDC**
  - TPC tracking
  - smaller radius
  - particle flow calorimeter
  - 4 Tesla solenoid
  - μ detection: RPC or others

Both concepts are rather similar now merging into one (ILD)
- **SiD**
  - silicon tracking
  - smaller radius
  - high field solenoid (5 Tesla)
  - scint. fibre / RPC μ detector

- **Silicon tracker**

- **Magnet**
  - high field
  - but smaller volume
### Detector Concepts

- **4th concept**
  - TPC
  - multiple readout calorimeter
  - iron-free magnet, dual solenoid
  - muon spectrometer (drift tubes)

- **Dual solenoid**
  - iron return yoke replaced by second barrel coil and endcap coils

Average field seen by $\mu$:

$$\langle B \rangle \approx 1.5 \, \text{T}$$

$$\langle |B| \rangle \approx 3 \, \text{Tm}$$
### Detector Concept and R&D efforts

- R&D efforts for key detector elements
- Overlap with detector concepts:

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* silicon forward and auxiliary tracking also relevant for other concepts
Vertex Detector

- **Key issues:**
  - measure impact parameter for each track
  - space point resolution $< 5 \mu m$
  - smallest possible inner radius $r_i \approx 15 \, \text{mm}$
  - transparency: $\approx 0.1\% \, X_0$ per layer
    $= 100 \, \mu \text{m}$ of silicon
  - stand alone tracking capability
  - full coverage $|\cos \Theta| < 0.98$
  - modest power consumption $< 100 \, \text{W}$

- Five layers of pixel detectors
  - plus forward disks
  - pixel size $O(20 \times 20 \, \mu \text{m}^2)$
  - $10^9$ channels

- **Note:** wrt. LHC pixel detectors
  - $1/5 \, r_i$
  - $1/30$ pixel size
  - $1/30$ thickness
Critical issue is readout speed:
- Inner layer can afford $O(1)$ hit per mm$^2$ (pattern recognition)
  - once per bunch = 300 ns per frame too fast
  - once per train $\approx 100$ hits/mm$^2$ too slow
  - 20 times per train $\approx 5$ hits/mm$^2$ might work
  - 50 µs per frame of $10^9$ pixels!

→ readout during bunch train (20 times)
or store data on chip and readout in between trains
e.g. ISIS: In-situ Storage Image Sensor

- Many different (sensor)-technologies under study
  - CPCCD, MAPS, DEPFET, CAPS/FAPS, SOI/3-D,
  - SCCD, FPCCD, Chronopixel, ISIS, ...
  → Linear Collider Flavour Identification (LCFI) R&D collaboration

- Below a few examples

- Note: many R&D issues independent of Si-technology
  (mechanics, cooling, ...)
CP CCD

- CCD
  - create signal in 20 µm active layer
  - etching of bulk material to keep total thickness ≤ 60 µm
  - low power consumption
  - but very slow

→ apply column parallel (CP) readout

- Second generation CP CCD designed to reach 50 MHz operation
MAPS and DEPFET

- CMOS Monolithic Active Pixel detectors
  - standard CMOS wafer integrating all functions
  - no bonding between sensor and electronics
  - e.g. Mimosa chip

- DEPFET: DEPleted Field Effect Transistor
  - fully depleted sensor with integrated pre-amplifier
  - low power and low noise
Vertex Detector Support

- Mechanical support structure
  goal 0.1% $X_0$ per layer

- Example:
  - Reticulated Vitreous Carbon (RVC)
  - or Silicon Carbide SiC foams
    both good thermal match to Si

  $1.5 \text{ mm RVC foam} + 2\times25 \text{ µm silicon}$
  $= 0.09\% \ X_0$

  $1.5 \text{ mm SiC foam} + 25 \text{ µm silicon}$
  $= 0.16\% \ X_0$  (reducible, less dense foam) achieved

- can be adopted to all detector technologies
Silicon Tracking

- The SiD tracker:
  - 5 barrel layers
    - $r_i = 20\,\text{cm}$
    - $r_o = 125\,\text{cm}$
  - 10 cm segmentation in $z$
    - short sensors
  - measure $\phi$ only

- endcap disks
  - 5 double disk per side
  - measure $r$ and $\phi$

- critical issue:
  - material budget
    - (support, cooling, readout)
  - goal: 0.8% $X_0$ per layer

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Material budget complete tracking system

- $10\% \, X_0$
- beam pipe
- + main tracker
- + VTX
Silicon Tracking

- Alternative design: long ladder
  - Silicon tracking for the Linear Collider (SiLC) collaboration
  - for all-silicon tracker
    or silicon envelope (→TPC)

- Development of low noise electronics
  - amplification & pulse shaping
  - passive cooling
  - exploit low duty cycle

Prototype modules:

- 3 × CMS
- 10 × GLAST
Time Projection Chamber

- GLD, LDC and 4th: high resolution TPC as main tracker
  - 3 – 4 m diameter
  - $\approx 4.5$ m length
  - low mass field cage
    - $3\% \times X_0$ barrel
    - $< 30\% \times X_0$ endcap
  - $\approx 200$ points/track
  - $\approx 100\,\mu$m single point res.
  - $\Delta(1/p_T) = 10^{-4} /\text{GeV}$
    (10 times better than LEP!)

- Complemented by Forward Tracking
  - endcap between TPC and ECAL
  - Si strip, straw tube, GEM-based, …
    are considered

- TPC development performed in LCTPC collaboration
Time Projection Chamber

- New concept for gas amplification at end flanges:
  Replace proportional wires by Micro Pattern Gas Detectors (MPGD)

- GEM or MicroMegas
  - finer dimensions
  - two-dimensional symmetry
    \[ \rightarrow \text{no E} \times \text{B effects} \]
  - only fast electron signal
  - intrinsic suppression of ion backdrift

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Principle of MPGD based TPC established many small scale prototype experiments over the last \( \approx 5 \) years

- cosmics, testbeam
- magnetic field

under construction for experiments (MICE, T2K)

Example:

Single point resolution \( O(100 \, \mu m) \) established in
- small scale prototypes
- high magnetic fields
Time Projection Chamber

- Low mass fieldcage
  - large prototype under construction
  - using composite material

- Electronics
  - few $10^6$ channels on endplate (ILD)
  - low power to avoid cooling

- two development paths:
  - FADC based on ALICE ALTRO chip
  - and TDC chips

\[ \approx 1\% \, X_0 \]
TPC versus Silicon Tracking

- **TPC**
  - 200 space points (3-dim) \(\rightarrow\) continuous tracking, pattern recognition
  - low mass easy to achieve (barrel)

- **Silicon tracking**
  - better single point resolution
  - fast detector (bunch identification)
Silicon TPC Readout

- Combine MPGD with pixel readout chips
- 2-d readout with
  - Medipix2 0.25 µm CMOS
  - 256×256 pixel
  - 55×55 µm²

- Medipix (2-d) → TimePix (3-d)
- 50 - 150 MHz clock to all pixel
- 1st version under test

- Will eventually lead to
  - TPC diagnostic module
  - cluster counting to improve dE/dx
Calorimetry

- The paradigm of Particle Flow Algorithm (PFA) for optimum jet energy resolution:
  - try to reconstruct every particle
  - measure charged particles in tracker
  - measure photons in ECAL
  - measure neutral hadrons in ECAL+HCAL
  - use tracker + calorimeters to tell charged from neutral

- Jet resolution
  \[ \sigma = \sigma_{\text{charged}} \oplus \sigma_{\text{photons}} \oplus \sigma_{\text{neutral}} \oplus \sigma_{\text{confusion}} \]

- confusion term arises from misassignment, double counting, overlapping clusters, …

- minimizing confusion term requires highly granular calorimeter both ECAL and HCAL

- average visible energy in a jet
  - \( \approx 60\% \) charged particles
  - \( \approx 30\% \) photons
  - \( \approx 10\% \) neutral hadrons

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Calorimetry

- CALICE collaboration (Calorimeter for the Linear Collider Experiment)
  > 30 institutes from > 10 countries

  - performs R&D effort to validate the concept and design calorimeters for ILC experiments

- GLD, LDC, SID concepts based on PFA calorimeters

- ECAL:
  - SiW calorimeter
  - 23 $X_0$ depth
  - 0.6 $X_0$ – 1.2 $X_0$ long. segmentation
  - 5×5 mm$^2$ cells
  - electronics integrated in detector

- Alternative:
  W + Scintillating strips (GLD)
Calorimetry

- HCAL:
  2 options under consideration

- Analogue Scintillator Tile calorimeter
  - moderately segmented $3 \times 3 \text{ cm}^2$
  - use SiPM for photo detection

- Gaseous Digital HCAL
  - finer segmentation $1 \times 1 \text{ cm}^2$
  - binary cell readout
  - based on RPC, GEM or $\mu$Megas detectors
Calorimeter

- CALICE Testbeam at CERN (2006/07)

**ECAL 18×18 cm²**
- Si cells of 1×1 cm²
- (216 cells per layer)

**HCAL 100×100 cm²**
- scint.tiles of 3×3, 6×6, 12×12 cm²
- (216 tiles per layer)

**TCMT 100×100 cm²**
- scint.strips X or Y of 5×100 cm²
- (20 strips per layer)

Tail Catcher - Muon Tracker
Calorimeter

- CALICE Testbeam at CERN (2006/07)

- CALICE prototype now moving to FNAL, start test beam in summer 2008
Calorimeter

- Simulation of an ILC event

Event display to illustrate granularity

$\rho \rightarrow \pi^+ \pi^0$
**Dual Readout Calorimeter**

- **4th concept**
  - calorimetry based on dual/triple readout approach
  - complementary measurements of showers reduce fluctuations

- **Fluctuations of local energy deposits** → **Fine spatial sampling with SciFi every 2 mm**

- **Fluctuations in electromagnetic fraction of shower energy** → **clear fibres measure only EM component by Cerenkov light of electrons**
  - \( E_{th} = 0.25 \text{ MeV} \)

  
  Dual Readout Module (DREAM) in testbeam at CERN

- **Binding energy losses from nuclear break-up** → **try to measure MeV neutron component of shower**
  - (history or Li/B loaded fibres)

- **Like SPACAL (H1)**

- **Like HF (CMS)**

- **Triple readout**
**DREAM testbeam:**
- measure each shower twice

\[
\begin{align*}
 (e/h)_C &= \eta_C \approx 5 \\
 (e/h)_S &= \eta_S \approx 1.4 \\
 C &= \left[f_{em} + (1 - f_{em})/\eta_C\right]E \\
 S &= \left[f_{em} + (1 - f_{em})/\eta_S\right]E \\
 \therefore C/E &= 1/\eta_C + f_{em}(1 - 1/\eta_C)
\end{align*}
\]
Dual Readout Calorimeter

- From DREAM to an ILC calorimeter:

**DREAM module**

3 scintillating fibers
4 Cerenkov fibers

**ILC-type module**

2mm W, Pb, or brass plates;
fibers every ~2 mm

(Removes correlated fiber hits)
Forward Calorimetry

- Forward calorimeters needed
  - LumCal: precise luminosity measurement
    precision < 10^{-3}, i.e. comparable to LEP or better
  - BeamCal: beam diagnostics & luminosity optimisation

- Detector technology: tungsten/sensor sandwich
- Example: LDC design for zero cross angle
  to be adapted for 14 mrad ILC design
BeamCal

- **Challenges:**
  - \( \approx 15000 \, e^+e^- \) pairs per BX in MeV range, extending to GeV
  - total deposit \( O(10 \, \text{TeV})/\text{BX} \)
  - \( \approx 10 \, \text{MGy} \) yearly rad. dose

- identification of single high energy electrons to veto two-photon bkgd.

- **Requires:**
  - rad. hard sensors (diamond)
  - high linearity & dynamic range
  - fast readout (307 ns BX interval)
  - compactness and granularity
**Forward Calorimetry**

- Sensors tests at DALINAC (Darmstadt) current 1 – 100 nA (10 nA ≈ kGy/h)

  ![Diagram](image)

- **Diamond sensor after ≈ 7 MGy**

- **Alternative sensor materials**
  - GaAs
  - SiC
  - Radiation hard silicon

  ![Graph](image)
Muon Detectors

- GLD, LDC & SiD have muon detection only: RPC, scint. fibre detector momentum in central tracker
- 4th concept:
  - muon spectrometer between coils
  - high precision drift tubes

- low $p_T$-threshold for muons
- excellent $\pi/\mu$ separation
  also exploiting multiple readout calorimeter
Disclaimer:
- all in early design phase
- comparison difficult
- assume that R&D is successful and large scale detectors will keep performance

- A few DOD plots on performance from simulation studies

4th concept:
- muon spectrometer
  \[ \sigma(1/p_T) \approx 4 \cdot 10^{-4} /\text{GeV} \]
Detector Performance

- **SiD Tracking:**
  - 143 GeV selectron at 1 TeV mass measurement from end point
  - 0.1% beam energy spread
  - 100 MeV error not limited by tracker

- **GLD calorimetry:**
  - test of PFA with Z-pole events
  - $Z \rightarrow \text{hadrons}$
  - 38% mass resolution improvements are still possible
Detector R&D in Europe

- Next step:
  from small scale proof-of-principle experiments
to larger scale prototypes

- Example:
  the EUDET programme in Europe
  - improvements of infrastructures for
    larger scale detector prototypes
    (not only ILC)
  - devised in close cooperation with the
    international R&D collaborations

- Transnational Access:
  - support for (European) groups
    - DESY testbeam
    - usage of EUDET infrastructures

- Project started in 2006
  for 4 years duration

- More information at [www.eudet.org](http://www.eudet.org)
Detector R&D in Europe

European infrastructure projects are based on three pillars:

- Detector R&D Network:
  - Information exchange and intensified collaboration
  - Common simulation and analysis framework
  - Validation of simulation
  - Deep submicron radiation-tolerant electronics

- Test Beam Infrastructure:
  - Large bore magnet
  - Pixel beam telescope

- Calorimeter:
  - ECAL
  - HCAL
  - Very Forward Calorimeter
  - FE Electronics and Data Acquisition System

Activities split up into several tasks:

- Detector R&D Network:
  - Information exchange and intensified collaboration
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- Test Beam Infrastructure:
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- Calorimeter:
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  - FE Electronics and Data Acquisition System
The EUDET Map

- EUDET partners
- EUDET associates

Novosibirsk
Protvino
ITEP
MPHI
MSU
Obninsk

KEK (Japan)
Dalian (China)
Beam Telescope

- 1st version of pixel beam telescope:
  - analogue readout, reduced speed
  - tested & commissioned at DESY
  - now in CERN testbeam
- 2nd version in preparation
  - digital readout

- Performance:
  - test with DEPFET detectors
  - 3.4 µm resolution (intrinsic + telescope)
  - in good agreement with expected DEPFET resolution (3 µm)
- **Fieldcage design**  
  based on light small prototype TPC

- **Prototype electronics**  
  - FADC based on ALTRO  
  - TDC type readout

- **Well defined interfaces to readout plane**  
  - mechanics  
  - electronics

- **Dimensions:**  
  - 60 cm length  
  - 80 cm diam.

- **Few 1000 channels under construction**

- **TPC in PCMAG**

Both, with pad and Si readout
Calorimeter

- Design of the EUDET module
  - ECAL (see right)
  - and HCAL

- Design and prototypes of readout ASICs
  - ECAL, DHCAL & AHCAL

DHCAL board
Transnational Access

- Call for applications
  - see advertisement in CERN courier

- EUDET can supply travel funds
  - for DESY testbeam
  - for use of EUDET infrastructures (beam telescope etc.)

- Conditions & requirements:
  - European institute
  - not from country of infrastructure

- send short scientific proposal to Joachim.Mnich@desy.de

- + some forms to fill …

TO APPLY FOR EC FUNDED ACCESS

visit our web site http://www.eudet.org to get more information about the modalities of application.
EUDET Summary

- EUDET is an EU funded infrastructure programme for detector R&D
  - well defined programme
  - embedded in international detector R&D collaborations such as CALICE, LCTPC etc.

- Provides additional funds for European institutes
  - to help in the next phase of ILC detector R&D from small to larger prototypes

- Even more important
  - EUDET fertilises collaboration between institutes („community building“)
  - EUDET can help to raise additional funds at national agencies

- Can provide some support for other European groups
  → Transnational Access

- EUDET is now at mid-term
  - project is on track with major milestones achieved
  - more exciting work ahead of us
  - still open for contributions from new interested groups

More information at www.eudet.org
Conclusion & Outlook

- ILC: 500 → 1000 GeV Linear Collider
  next large collider project

- Requires detectors with unprecedented performances
  - challenges different than at the LHC

- 4 (now 3) detector concepts under development
- R&D on detector technologies
  - candidate technologies
    - identified & verified in small scale experiments

- Many questions still to be answered

- Next steps:
  - engineering designs for machine and detectors
  - detector R&D move to larger scale prototypes
  - requires intensified international collaboration

- Need to increase efforts to have ILC and two detectors ready next decade

Simulated ee → ZZ