Detectors for a Linear Collider

Joachim Mnich
DESY

Annecy, July 4th, 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 $> 10^{34}/\text{cm}^2/\text{s}$

- 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:

J. Mnich, Detectors for a Linear Collider, Annecy, July 2008
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:
  - $2 \times 250$ GeV upgradable to $2 \times 500$ GeV
  - 1 interaction region
  - 2 detectors (push-pull)
  - 14 mrad crossing angle

- Cost estimate:
  - $4.87 \text{ G$} \text{ shared components}$
  - $1.78 \text{ G$ site-dependent}$
  - $= 6.65 \text{ G$} (= 5.52 \text{ G€})$

  + 13000 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

J. Mnich, Detectors for a Linear Collider, Annecy, July 2008
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

J. Mnich, Detectors for a Linear Collider, Annecy, July 2008
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?
  
  $\rightarrow$ 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!
  
  $\text{BR} (W/Z \rightarrow \text{hadrons}) = 68\% / 70\%$

- 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
    \[ \sigma_{r\phi} \approx \sigma_z \approx 5 + 10/(p \sin \Theta^{3/2}) \text{ } \mu m \]  
    3 times better than SLD
  - small O(20×20 µm²), low mass pixel detectors,
    various technologies under study

- **Tracking:**
  - superb momentum resolution
    to select clean Higgs samples
  - ideally limited only by \( \Gamma_Z \)
    \[ \Delta(1/p_T) = 5 \times 10^{-5} /\text{GeV} \]
    (whole tracking system)
  - 3 times better than CMS

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

- Calorimeter: distinguish W- and Z-bosons in their hadronic decays → 30%/√E 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 $\mu$ detector

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

Both concepts are rather similar now merging into one (ILD)
Detector Concepts

- **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 $\mu$:

$\langle B \rangle \approx 1.5 \, T$

$\langle B_l \rangle \approx 3 \, Tm$
### Detector Concept and R&D efforts

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

<table>
<thead>
<tr>
<th></th>
<th>GLD</th>
<th>LDC</th>
<th>SID</th>
<th>4th concept</th>
<th>Detector R&amp;D collaborations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vertex</strong></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>LCFI</td>
</tr>
<tr>
<td><strong>Tracking</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- TPC</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>LCTPC</td>
</tr>
<tr>
<td>- Silicon</td>
<td>*</td>
<td>*</td>
<td>X</td>
<td>*</td>
<td>SILC</td>
</tr>
<tr>
<td><strong>Calorimetry:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Particle Flow</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>CALICE</td>
</tr>
<tr>
<td>- Multiple Readout</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Forward region</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>FCAL</td>
</tr>
</tbody>
</table>

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

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

- **Five layers of pixel detectors**
  - plus forward disks
  - pixel size $O(20 \times 20 \ \mu$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 Carbid SiC foams
    both good thermal match to Si

  1.5 mm RVC foam + 2×25 µm silicon
  = 0.09% $X_0$

  1.5 mm SiC foam + 25 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

J. Mnich, Detectors for a Linear Collider, Annecy, July 2008
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
GLD, LDC and 4th:
high resolution TPC as main tracker
- 3 – 4 m diameter
- ≈ 4.5 m length
- low mass field cage
  - 3% X₀ barrel
  - < 30% X₀ endcap
- ≈ 200 points/track
- ≈ 100 µm single point res.
→ Δ(1/pₜ) = 10⁻⁴ /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
- 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 → no E×B effects
  - only fast electron signal
  - intrinsic suppression of ion backdrift
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 readout

J. Mnich, Detectors for a Linear Collider, Annecy, July 2008
TPC versus Silicon Tracking

- **TPC**
  - 200 space points (3-dim) → 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
  \[ \sigma = \sigma_{\text{charged}} + \sigma_{\text{photons}} + \sigma_{\text{neutral}} + \sigma_{\text{confusion}} \]

- average visible energy in a jet
  - ≈ 60% charged particles
  - ≈ 30% photons
  - ≈ 10% neutral hadrons

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

- minimizing confusion term requires highly granular calorimeter both ECAL and HCAL
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\( \times \)5 mm\(^2\) cells 
  - electronics integrated in detector

- Alternative: 
  W + Scintillating strips (GLD)

J. Mnich, Detectors for a Linear Collider, Annecy, July 2008
Calorimetry

- **HCAL:**
  - 2 options under consideration
  - Analogue Scintillator Tile calorimeter
    - moderately segmented $3 \times 3$ cm$^2$
    - use SiPM for photo detection
  - Gaseous Digital HCAL
    - finer segmentation $1 \times 1$ cm$^2$
    - binary cell readout
    - based on RPC, GEM or $\mu$Megas detectors
Calorimeter

- CALICE Testbeam at CERN (2006/07)

ECAL $18 \times 18 \text{ cm}^2$
- Si cells of $1 \times 1 \text{ cm}^2$
- (216 cells per layer)

HCAL $100 \times 100 \text{ cm}^2$
- scint.tiles of $3 \times 3$, $6 \times 6$, $12 \times 12 \text{ cm}^2$
- (216 tiles per layer)

TCMT $100 \times 100 \text{ cm}^2$
- scint.stripes X or Y of $5 \times 100 \text{ cm}^2$
- (20 strips per layer)

Tail Catcher - Muon Tracker

TCMT

ECAL

HCAL
Calorimeter

- CALICE Testbeam at CERN (2006/07)

- CALICE prototype moved to FNAL, 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
- like SPACAL (H1)

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

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

Dual Readout Module (DREAM) in testbeam at CERN
Dual Readout Calorimeter

- DREAM testbeam:
  - measure each shower twice

\[ (e/h)_C = \eta_C \approx 5 \]
\[ (e/h)_S = \eta_S \approx 1.4 \]

\[
C = \left[ f_{em} + (1 - f_{em})/\eta_C \right] E
\]
\[
S = \left[ f_{em} + (1 - f_{em})/\eta_S \right] E
\]

\[ \rightarrow C/E = 1/\eta_C + f_{em}(1 - 1/\eta_C) \]

200 GeV $\pi^-$ beam at CERN

raw data

using C and S

incl. leakage correction (using $E_B$)
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
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:
  - $\approx 15000 \text{ e}^+\text{e}^- \text{ pairs per BX}$ in MeV range, extending to GeV
  - total deposit $O(10\text{ TeV})$/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

Energy deposit per BX:

Electron ID efficiency:
Forward Calorimetry

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

Diamond sensor after ≈ 7 MGy

10 MeV

- Alternative sensor materials
  - GaAs
  - SiC
  - radiation hard silicon
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 $Z \rightarrow$ 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
  - Project started in 2006 for 4 years duration

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

- More information at www.eudet.org
European infrastructure projects are based on three pillars:

- **EUDET**
  - **Network**
    - Management
    - Detector R&D Network
  - **Transnational Access**
    - Access to DESY Test Beam
    - Access to Detector R&D Infrastructures
  - **Joint Research Activities**
    - Test Beam Infrastructures
    - Tracking Detectors
    - Calorimeter

Activities split up into several tasks:

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

**Tracking Detectors:**
- Large TPC prototype
- Silicon TPC readout
- Silicon tracking

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

**Calorimeter:**
- ECAL
- HCAL
- Very Forward Calorimeter
- 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
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 …

CERN Courier May 2007:

EUDET is a project supported by the European Union in the Sixth Framework Programme (FP6) structuring the European Research Area. This project aims at creating a coordinated European effort towards research and development for the next generation of large-scale particle detectors. EUDET comprises 23 European partner institutes and 24 associated institutes working in the field of High Energy Physics.

EUDET provides in the framework of the Transnational Access scheme travel support for groups from the EU and countries associated to FP6 using the following infrastructures:

TA1: Experiments at DESY testbeam (http://testbeam.desy.de)
TA2: Experiment using infrastructure developed in the EUDET project: high precision beam telescope; large, low mass TPC field cage; silicon based TPC readout system; infrastructure for development of SI-Stripdetectors; infrastructures for development of granular calorimeters.

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