New Technologies & Ideas for Collider Detectors

Summary

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@ LCWS, March 2021
Overview

- Brief recap of LC Detector design “philosophy”
- Ideas beyond the baseline - based on discussions last night
Key Drivers for Detector Design

Physics & Experimental Conditions

Physics

- Collision energy:
  - ILC: 250 GeV - 500 GeV - 1+ TeV
  - CLIC: 380 GeV - 1.5 TeV - 3 TeV

  - Leptons, jets, from a few 10 to many 100 GeV, heavy bosons / complex final states

- Small cross-section: High luminosity required, Statistics is precious:
  Excellent reconstruction of all final states
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Experimental conditions

- Extreme focussing: Beamstrahlung - tails in the luminosity spectrum, background from two-photon processes
- Pulsed operation in “bunch trains“:
  - $0(10 \text{ Hz})$ bunch train rate
  - $0.5 / \sim 550 \text{ ns bx separation}$
  - Enables power pulsing of detectors
Detector Performance Goals - Tracking

Motivated by key physics signatures

- **Momentum resolution**
  Higgs recoil measurement, $H \rightarrow \mu\mu$, BSM decays with leptons

  \[ \sigma(p_T) / p_T^2 \sim 2 \times 10^{-5} / \text{GeV} \]

  precise and highly efficient tracking, extending to 100+ GeV
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- **Impact parameter resolution, vertex charge**
  Flavour tagging: b/c/light tagging in Higgs decays, top physics, ...
  \[ \sigma(d_0) \sim [5 \oplus (10 - 15)/\text{psin}^{3/2}\theta] \ \mu\text{m} \]
Detector Performance Goals - Jets, Photons, PID

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- **Jet energy resolution**
  Recoil measurements with hadronic Z decays, separation of W, Z, H bosons, ...
  \[ \sigma(E_{\text{jet}}) / E_{\text{jet}} \sim 3\% - 5\% \text{ for } E_{\text{jet}} > 45 \text{ GeV} \]
  reconstruction of complex multi-jet final states.

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  Resolution not in the focus: \( \sim 15 - 20\%/\sqrt{E} \)
  Worth another look?
  Coverage to 100s of GeV important
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- **Hermetic coverage**
  Dark matter searches in mono-photon events, ...
  N.B.: Achievable limits do not depend strongly on \(\sigma(E_{\gamma})\)
The Linear Collider Detector Design - Main Features

Variations in terms of size, field and tracker / calorimeter details

- **A large-volume solenoid** 3.5 - 5 T, enclosing calorimeters and tracking

- **Highly granular calorimeter systems**, optimised for particle flow reconstruction, best jet energy resolution \([Si, Scint + SiPMs, RPCs]\)

- **Low-mass main tracker**, for excellent momentum resolution at high energies \([Si, TPC + Si]\)

- **Forward calorimeters**, for low-angle electron measurements, luminosity \([Si, GaAs]\)

- **Vertex detector**, lowest possible mass, smallest possible radius \([MAPS, thinned hybrid detectors]\)

- **Triggerless readout** of main detector systems
Ideas Beyond The Baseline

Just first thoughts and discussion starters

• Evolution of the current designs:
  Technological advances, reduction in cost, ...

• Additional Capabilities:
  Particle ID, additional dimensions in reconstruction, ...

• Revolutionising the current designs:
  Different approaches to key elements

Based on “flash talks” in session N2*, and open discussion - thanks to all who participated!

*session organizers: Sarah Eno, Philipp Roloff, FS
Evolution of the current design

Technology evolution, cost, scalability

• A central theme: semiconductor technology evolution

  • CMOS sensors for vertex, tracker, em calorimetry
    • industrial process with high throughput: scalable, cost advantage wrt high-resistivity Si
    • integration of “intelligence” - reduced complexity

An important element: power consumption
Eliminating the need for power pulsing in some detector regions may have significant benefits for stability, system design

Towards a common technology for all Si systems?
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- Pixelated readout planes for TPC endplates:
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- GaAs sensors with traces:
  reduced complexity, further compactness for forward calorimeters
Evolution of the current design

*Its not only sensors*

- Mechanical systems: Ultra-light materials, additive manufacturing - reducing material, increasing stability, reducing cost?
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- Alternatives for data transmission: wireless in regions with extreme space constraints?
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- Detector design and reconstruction tools form a symbiosis - Particle Flow paradigm a great example

*For best results:*
- Careful integration and optimisation of all components together (hard- and software)
- Design for "understanding": a uniform and understood response may ultimately be a more important figure of merit for many measurements than the ultimate resolution
Adding Capabilities

The main trend: Timing

- Timing detectors with few 10 ps resolution now feasible - pioneered for HL-LHC upgrades

**Optical:**
Fast scintillators, SiPMs

![Image of scintillator and SiPM modules]
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**Silicon:**
LGADs and variants

Newer ideas: AC-coupled LGADs, deep-junction, trenches, …
Potential for fine pixilation
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⇒ Dedicated timing systems, but also potential in trackers, calorimeters, …
Also here: interesting optimisation questions: A balance between time resolution, spatial resolution, data rate and power consumption
Adding Capabilities

Additional Dimensions: Timing and others

• Timing: What would we need?
  (note: Bgd rejection at LCs needs ~ns - level only)

• A clear use case: PID via time-of-flight.
  In the focus: π/K separation - important
  for example for flavour tagging.

• Typical momenta in the ~ 5 GeV
  region - depending on collision energy

• Resolutions today: < 10 ps with multiple layers
  - but system challenges to scale this up are
  formidable
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• Can provide an additional dimension in
  calorimetry: Separation of electromagnetic and
  hadronic processes based on time evolution

• Also: Dual readout - signal-based separation of em and
  hadronic components - now moving towards high granularity

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Available time resolution with calos

Difference in ToA at ILD Calos

Available “now”

Doable with Intensive R&D in 5-10 years

Requires a new breakthrough

Figure G. Wilson

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p[GeV]

3x3 cm² Glass tile 3x3 cm² Plastic Tile
Revolution of the current design

Is it worth revisiting established choices?

- The fundamental design choices for the current LC detector concepts were made ~15 years ago
- The sequence of energy stages has changed - at least for ILC: Now a first phase at 250 GeV (and below)

⇒ For some speculation on experiment staging, see Karsten Büßer this morning
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New ideas in jet reconstruction - emphasising electromagnetic resolution:

A fresh look at high-resolution ECALs?

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Also other areas - technology of gaseous tracking (TPCs vs DCs) as an example.
In general: many parameters to consider - no straight-forward answers
Summary

... and Outlook

• The current LC detector concepts are well-established - and have been studied in realistic simulations, in many areas validated by testbeam measurements of realistic prototypes
• Technology has evolved, enabling reduction of cost and complexity, and the addition of new capabilities

• Evolution of concepts has started, using advances of silicon technology and others
• Additional Capabilities are studied - first and foremost the use of precision timing (<< 100 ps) - benefits and technological and system-based boundary conditions still need to be understood
• Revolutionising of designs is not excluded - New ideas studied in the context of circular colliders may also have merits for LCs.
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*The time is right for this process*: Technological solutions are becoming available, and final technology choices are still a while off.

This will be exciting - In many cases no immediately obvious answers - and many “dimensions” to consider from technological aspects to running and staging scenarios and sociological aspects.
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*To be continued...* In October in Tsukuba - hopefully in person!
Extras
The Time Line for ILC Detectors

To provide some background

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<th>Timeline for the ILC experiments</th>
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- Funding agencies will not provide dedicated ILC detector R&D funds before the Pre-lab being established.
- For some EoIs, R&D would be needed to make LolIs.
  → driving the timing for the Lol submission
- Selection process starts with the LolIs.
  → driving the timing for the Lol decision
- Experiments are formally approved based on TPs.
- The ILC-lab is needed for approvals.
- Availability of resources is part of the approval criteria.
  → driving the timing for the TP decision
- These considerations are for the initial set of experiments. There could be more experiments proposed at later time.

From Hitoshi Murayama, yesterday

Bottom line (my interpretation):

- **2023**: Detector concepts
- **2025**: Technical layout with options
- **2027**: Proceed to TDRs, final technology choices

There is (some) time to explore new ideas!