• **Tracking Detectors**
  – Silicon Vertex Detectors
  – Silicon Tracking Detectors
  – Gaseous Detectors (Trackers and Muon Spectrometers)
• **Calorimeters**
  – ILC/CLIC R&D
  – HL-LHC R&D
• **Fast Timing and Particle Identification Techniques**
• **Read-out and Triggering**
• **Neutrino Detectors**
  – Technologies
  – Instrumenting Very Large Volumes
• **Conclusions**
Silicon Vertex Detector R&D for ILC/CLIC

Technologies

ILC Pixel Vertex R&D:
- CMOS MAPS
- DEPFET
- FPCCD
- 3D-pixel and integration

CLIC Pixel Vertex R&D:
- Hybrid Sensor +ASIC,
- HV-CMOS + ASIC

Challenges of ≤ 5µm precision, extremely low material and time-stamping given accelerator bunch train time structures

ILC-500 (1312 at 554ns every 200ms)
CLIC (312 at 0.5ns every 20ms)

→ Different on-detector data storage options, integration technologies and powering schemes
Hybrid Pixel Detector R&D for LHC Upgrades
(ECFA 13/284 [https://cds.cern.ch/record/1631032])

HL-LHC (3000fb⁻¹) implies doses up to \(2 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2\) and 1Grad (also up to 200 collisions per beam crossing). However n-in-n, n-in-p planar, 3D and diamond sensors still useable after such doses.

The mechanisms leading to larger than expected signals not completely understood but this can even be exploited (doping profile, trenches) to enhance signal after radiation.

Need fine lithography ASIC technology to allow pixel sizes of 55μm×55μm (LHCb VeLoPIX 130nm) or ~50μm×50μm (RD53).

Large format sensors prototyped with a number of potential suppliers.

(112 3D sensors installed on IBL in ATLAS)

Diamond (RD48)

3D at 150V (RD50)

Thin Planar (RD50) (RD50)

Diamond (RD48)

FE-I4 R/O Planar (RD50)

FE-T65-1 Single Pixel

26 planes of sensor 5.1mm to beam

CMS CNM 3D sensors

CMS Phase-II Pixel Module Concept

ATLAS VeLoPix Module Design

LHCb VeLoPix Module Concept

Phil Allport
Hybrid Pixel Detector R&D for LHC Upgrades

(ECFA 13/284 [https://cds.cern.ch/record/1631032])

- Irradiated single and quad n-in-p pixel modules (for higher radii) studied in test-beam with excellent performance

- Micro-channel in-silicon cooling (NA62, ALICE, LHCb)

- Need rad-hard, low power, fast opto-electronics

- Low mass structures, services (electrical link to optical for innermost layers), LV (serial powering for innermost layers, DC/DC elsewhere?), CO₂ cooling...

DC to DC converter to step down 10V→2.5V

ATLAS Phase-II Prototype Barrel Pixel Supports

ATLAS Forward Pixels

ATLAS Quad FE-I4 Module

Noise in 107,520 250μm×50μm irradiated pixels (5×10¹⁵ nₑq cm⁻²)

Noise in 107,520 250μm×50μm irradiated pixels (5×10¹⁵ nₑq cm⁻²)

ATLAS Phase-II Prototype Barrel Pixel Supports

ASICS: AMISS by CERN

L = 450mH

Rₑc = 40Ω

Toroidal inductor:

Vₑc < 3A

Vₑ out configurable; 2.4V(Vₑref) or 3.0V (Vₑref)

fₑ 1.5MHz

AC_PIX_V8_A: 2.8cm x 1.6cm, = 2.6g

GBTx, Versatile Link

→ GBTx, Versatile Link
MAPS/CMOS Detector R&D for LHC Upgrades

MAPS for ALICE
Priority is ultra-low radiation length due to the low $p_T$ of the decay products of interest.

Target:
- Pb-Pb $\geq 10$ nb$^{-1}$ → $8 \times 10^{10}$ events
- pp $\geq 6$ pb$^{-1}$ → $14 \times 10^{10}$ events
Read-out all Pb-Pb (50 kHz) ($L = 6 \times 10^{27}$ cm$^{-1}$s$^{-1}$)

Many different technology options (e.g. can consider “strip sensors” with z-encoding)

- For HL-LHC need to demonstrate radiation hardness also for large format devices
- HR/HV-CMOS need production experience with large format devices to determine yields and therefore better estimate expected costs

In HR/HV-CMOS charge collection through drift greatly improves speed and radiation hardness
Use at pp collision rates → HL-LHC Upgrades?
Can consider pixels with complex CMOS-based pixel electronics that process the particle signals or capacitively coupled pixel detectors (CCPDs) based on sensor implemented as a smart diode array with wafer bonding or glue to ASICs (no bumps)

Wafer Bonding
Silicon Strip Detector R&D for LHC Upgrades
(ECFA 13/284 https://cds.cern.ch/record/1631032)

Need radiation hardness of current n-in-n pixel sensors at fraction of the cost

→ n-in-p technology

Many large area prototypes produced

Interest in larger (8”) wafers particularly for forward regions

ATLAS uses paired strip modules with small angle stereo (for z determination) around a central structure with embedded cooling (Trigger: Level-0 trigger objects from calorimeter and muon systems plus tracker information available to level-1 trigger)

CMS proposes paired layers for fast track $p_T$ filter for level-1

ATLAS

CO2 cooling based on pixel Phase 1 dev. 100kW power - common with ATLAS

SSA/MPA ASIC 65 nm being designed

DC-DC conversion based on pixel Phase 1 common dev. with ATLAS

Strip-Strip module

Concentrator ASIC 130 and/or 65 nm

Gbit 65 nm & Optical Link dev. low power, compact packaging w/ connector - based on common dev. for LHC experiments

CMS

Flex hybrid - Flip-Chip assembly - possibly TSV for inter-chip connection

Strip-Strip Module Prototype
Silicon Strip Detector R&D for LHC Upgrades
(ECFA 13/284 https://cds.cern.ch/record/1631032)

Need radiation hardness of current n-in-n pixel sensors at fraction of the cost
→ n-in-p technology

Many large area prototypes produced

10cm×10cm 4×1280 strip n-in-p sensor

Powering (DC/DC or Serial), HV multiplexing, CO₂ embedded cooling, low mass modular supports & services

For ILC/CLIC strip concepts (particularly SiD) developing large area thin sensors
Gaseous Tracking Detector R&D

Main R&D activities for ATLAS and CMS are for new muon chambers in the forward directions.

- Increased rate capabilities and radiation hardness
- Improved resolution (online trigger and offline analyses)
- Improved timing precision (background rejection)

Technologies

- Gas Electron Multiplier detectors (LHCb now, ALICE TPC - CMS forward chambers)
- Micro-pattern gas and Thin Gap Chambers (TGCs) (ATLAS forward chambers)
- Resistive Plate Chambers (RPCs) - low resistivity glass for rate capability - multi-gap precision timing (CMS forward chambers)

CERN RD51 common to GEM and Micro-Megas (does not include RPC R&D)

Developing commercial large-scale production capabilities

Report from the ILC R&D Liaison (AWLC, Fermilab, May 12 - 16, 2014)

ILC Technologies

- Laser-etched GEM
- Wet-etched GEMs
- Micromegas-based readout:
  - Resistive MM with dispersive anode
  - GEM or Micromegas + Timepix pixel readout
- GEM + pixel

InGrid

Micro-Megas Principle

GEM stack for ALICE TPC R/O

4 layer stack to minimise ion backflow given continuous readout at 50kHz

ILD TPC 4.6m×1.8m radius

Micro-Pattern Gas Detector

2.4m×1m Micro-Megas prototype for ATLAS New “Small” muon Wheel (1280m²)
Scintillating Fibre Tracker R&D
(ECFA HL-LHC Summary https://indico.cern.ch/event/252045/other-view?view=standard)

Large scale SciFi tracker for LHCb

3 stations of X-U-V-X scintillating fibre planes (≤5° stereo). Every plane is made of 5 layers of 2.5 m long Ø250 μm fibres.

Challenges
- Large size – high precision
- O(10,000 km) of fibres
- Operation of SiPM at -40°C

Crystal fibres with and without WLS for higher dose environments and fast R/O

SiPM location

F_n = 6·10^{11} cm^{-2}

N_{pe}

Σ = ~10-20 pe

7/9/2014
Phil Allport
Key Messages on Tracking

• Radiation and rate requirements for Upgrade/HL-LHC sensors at different radii look to be manageable, so attention more on material reduction, read-out, trigger, layout and cost optimisation including alternative technologies

• Different challenges with vertex detectors for $e^+e^-$ include ultimate low mass ($0.15\% X_0$/layer) with complex engineering and integration issues, precision time-stamp (~ns for CLIC) and $\leq 5\mu m$ spatial resolution

• ILC/CLIC trackers target very high resolution $\delta(1/p_T) \approx 2-5 \times 10^{-5}$ GeV\(^{-1}\)

• Services matter: low mass cooling and compact, radiation-hard optical+electrical links with HV/LV multiplexing (very large numbers of channels running at LV drawing high currents $\rightarrow$ big potential power loss in cables)

• Muon detectors with improved spatial resolution and enhanced rate capability: often using advanced micro-pattern gas detectors

• Large area detectors need close links with industry to develop processes for mass production

• Scintillating fibres and straws (NA62, Mu2e) provide excellent alternatives for several key applications
PFA Calorimeter R&D for ILC/CLIC

Particle Flow Calorimetry (CALICE)

Particle flow analysis: need to associate energy deposits with charged particles → drives granularity requirements

Report from the ILC R&D Liaison (AWLC, Fermilab, May 12 - 16, 2014)

Technology

ILC ECAL R&Ds:
- Silicon ECAL
- MAPS ECAL
- Sci ECAL

ILC HCAL (AHCAL) R&Ds:
- Sci AHCAL

ILC HCAL ((s)DHCAL) R&Ds:
- RPC DHCAL
- RPC sDHCAL
- GEM DHCAL
- MM sDHCAL

CLIC HCAL R&Ds:
- Sci AHCAL

CLIC FCAL R&Ds:
- FCAL hardware

Si-ECAL: $\sigma/E \approx 17\%/\sqrt{E} \oplus 1.7$

Si-ECAL: $\sigma/E \approx 45\%/\sqrt{E} \oplus 1.7 \oplus 0.18/E$
**R&D for Sampling Calorimeters at HL-LHC**

**LHC Upgrades:**
ALICE new forward calorimeter (FoCal)
R&D on Tungsten-Silicon sampling
Electromagnetic Calorimeter

LHCb minor replacement in central part of ECAL due to radiation damage
ATLAS investigating sensitivity of forward calorimeter (LAr) to instantaneous rates
Possibly replace or new FCAL in front

CMS need to replace ECAL and HCAL end-cap calorimeters due to radiation damage

Limitation mostly from loss of transparency with radiation
LYSO or CeF$_3$ offer very high light yield. Use tungsten and WLS quartz wall capillaries or WLS quartz coated/doped rodsfibres for light transmission and GaInP/SiPM radiation-hard photo-sensors for ECAL

**DREAM (RD52):** Simultaneous readout of scintillator and Cherenkov signal signals using 2 types of fibres embedded in tungsten or brass.

**CMS PFA Upgrade Option high granularity calorimeter**
- Fine depth segmentation

**ECAL:** ~33cm, 25X0, 1λ 30 layers Si separated by lead/Cu

**HCAL:** ~66cm, 3.5 λ 12 planes of Si separated by absorber

660 m$^2$ Silicon: e/γ resolution $\sim 20\%/\sqrt{E} + 1\%$

Shashlik

$\Delta E/E \sim 10\%/\sqrt{E} + 1\%$

7/9/2014 Phil Allport
Timing Detectors and Particle ID

LHCb RICH system needs upgrades for triggerless operation at $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$

1920 (RICH 1) + 2560 (RICH 2)
new MaPMTs for 40MHz R/O
26.2 mm square, with 77%
active area: 8 x 8 pixels,
each 2.9 x 2.9 mm$^2$

RICH1 new optics, without aerogel: Time Of internally Reflected CHerenkov (TORCH)?

LHCb RICH system needs upgrades for triggerless operation at $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$

1920 (RICH 1) + 2560 (RICH 2)
new MaPMTs for 40MHz R/O
26.2 mm square, with 77%
active area: 8 x 8 pixels,
each 2.9 x 2.9 mm$^2$

RICH1 new optics, without aerogel: Time Of internally Reflected CHerenkov (TORCH)?

ATLAS AFP (MCP-PMT)
Timing Detector
6 independent quartz bars combined $\rightarrow$ 14ps

CMS crystal calorimeter shows 150ps in operation
(test beam down to 20ps)

High doped silicon (RD50), diamond (RD42), MG RPC, detector developments target similar timing resolution

Imaging Time of Propagation (iTOP) needs <50ps rad-hard single photon sensitivity in 1.5T field $\rightarrow$ 512 MCP-PMT

For 140 PU and "crab kissing", HL-LHC can deliver down to 0.7 event/mm (up to 1.45ns bunch length)
$\rightarrow$ Use 20-30ps timing to better associate high $p_T$ objects to vertices

7/9/2014
Phil Allport
Key Messages on Calorimetry, Timing and Particle ID

• For scintillator based systems, target higher light yield and better transparency (also for wavelength shifting fibres) after irradiation

→ Crucial development is advanced commercial photo-detector technologies with high sensitivity, radiation tolerance, high granularity and low cost

• Major challenge for PFA (very high granularity requirements over very large areas) is cost optimisation with many options for sensing components - plus need for extreme radiation hardness of all components if used at HL-LHC for forward calorimetry

• Fast timing detectors for PID/ToF and vertex ambiguity reduction (at hadron colliders). Need very fast photo-detectors ≤ 10-50ps (≈few mm)

→ Low cost, large area, fine granularity timing detector R&D needed
Read-out and Triggering

• Use of 65nm feature size ASICs (RD53) fast (10Gb/s) electrical+optical links with custom devices on-detector (low mass, compact and radiation-hard)
• Also need ever more powerful and more complex FPGAs for data handling
• Where possible send digitized data off-detector for every bunch crossing (40MHz at LHC) leading to $\sim 10^5$ Gb/s total bandwidths
• LHCb full triggerless (40MHz) operation, all data shipped to data acquisition
• HL-LHC operation $6-8 \times 10^9$ interactions per second in 25ns bunch crossings
• ATLAS & CMS hardware (L1) trigger $\rightarrow$ maintain low trigger thresholds
  • Track information for high momentum resolution - isolation - vertexing
    $\rightarrow$ Reduce rates of lepton triggers by a factor $\sim 10$
• Increased L1 bandwidth up to 400kHz in ATLAS and up to 1MHz in CMS
• Increased L1 latency 10 - 30 µs (CMS - ATLAS) - improved algorithms
• R&D on improved pattern recognition
  • Associative Memories ASICs and use of advanced FPGAs to achieve fast track fitting for L1

ATLAS L0/L1 Scheme
Read-out and Triggering

- Use of 65nm feature size ASICs (RD53) fast (10Gb/s) electrical+optical links with custom devices on-detector (low mass, compact and radiation-hard)
- Also need ever more powerful and more complex FPGAs for data handling
- Where possible send digitized data off-detector for every bunch crossing (40MHz at LHC) leading to $\sim 10^5$ Gb/s total bandwidths
- LHCb full triggerless (40MHz) operation, all data shipped to data acquisition
- HL-LHC operation $6-8 \times 10^9$ interactions per second in 25ns bunch crossings
- ATLAS & CMS hardware (L1) trigger $\rightarrow$ maintain low trigger thresholds
  - Track information for high momentum resolution - isolation - vertexing
  $\rightarrow$ Reduce rates of lepton triggers by a factor $\sim 10$
- Increased L1 bandwidth up to 400kHz in ATLAS and up to 1MHz in CMS
- Increased L1 latency 10 - 30 $\mu$s (CMS - ATLAS) - improved algorithms
- R&D on improved pattern recognition
- Associative Memories ASICs and use of advanced FPGAs to achieve fast track fitting for L1

![Extreme challenge: reconstruct O(100) tracks from $\sim 15000$ stubs at 40 MHz](image)
Neutrino Detectors

• The issue of scale associated with current and future neutrino experiments introduces a very different set of challenges (NOvA as an example)

896 alternating X-Y planes 16mx16mx55m “Largest Plastic Structure built by man”

• Hyper-Kamiokande at 48m×54m×248m (1 Mton water Cherenkov detector) illustrates the scale of detector to be instrumented with photo-detectors in the future: 100,000 if 1 per m² → Roughly half the total projected cost

7/9/2014

Phil Allport
Neutrino Detectors

*Photo sensors ~ R&D to improve the detector performance*

Better timing resolution ~ better vertex resolution
Higher quantum efficiency

### Baseline (reference)

- 20” Super-K PMT
  - R3600
  - Venetian blind dynode
  - Various drift path
  - Might miss dynode
  - Quantum eff.: 22%
  - Collection eff.: 80%
  - Timing res. (FWHM): 5.5 nsec

### Candidates (R&D phase)

- 20” Box&line PMT
  - R12860
  - Box&line dynode
  - Unique drift path
  - Large acceptance
  - Quantum eff.: 30%
  - Collection eff.: 93%
  - Timing res. (FWHM): 2.7 nsec

- 20” HPD
  - R12850
  - Avalanche diode (AD)
  - Short drift path
  - High first step gain (×1600)
  - Quantum eff.: 30%
  - Collection eff.: 95%
  - Timing res. (FWHM): 1 nsec

**Distinct R&D needed for Near-detectors**

First WATCHMAN/Hyper-K 11° ETEL/ADIT PMT envelopes prior to glass finishing.
Neutrino Detectors

• Photo-detector costs are critical but in many cases the purity of the large volume detecting medium is just as challenging

LBNE Liquid Argon TPC
GOAL: ≥34 kt fiducial mass
Volume: 18m x 23m x 51m x 2
Total Liquid Argon Mass:~50 kton

• < 200 / 10^{12} contamination for electron drift lifetime > 1.4ms
  (cf ICARUS τ_{electron} > 7 ms; ~40 / trillion [O_2]_{eq} ; see back-up)

• Modular design with 80 2.5m×7m anode plane assemblies and FE, ADC, FPGA operating in LAr with complex feed-through designs

• LAr scintillation light complements TPC with timing information using plastic bars with WLS coating and SiPM R/O (600 channels)
Neutrino Detectors

- But also the engineering challenges are unprecedented and a lot of highly innovative techniques are needed to deliver these vast arrays affordably.

eg JUNO with multiple reactor experiment at oscillation maximum for $\theta_{12}$ to determine mass hierarchy. Need 15-20m attenuation length at 430nm and 35% QE PMTs.

Also INO 50-100kt: RPCs in magnetized iron.

- Much larger neutrino detector systems can observe using water or ice (Cherenkov, radio, acoustic).

eg atmospheric neutrinos to access mass hierarchy.

- Cosmic ray studies using the atmosphere as target.
Dark Matter and $0\nu2\beta$ Decay

- Huge variety of DM experiments with small and rare signals as ionisation, scintillation light, phonons or combinations thereof: (see talk yesterday by Henrique Araújo)

- Many techniques also for neutrinoless double-beta decay involving many different techniques (SuperNEMO, EXO200, LUMINEU, MAJORANA, KamLAND-ZEN, NEXT, GERDA, SNO+, LUCIFER, CUORE, ...) but all again with the requirement of high radio-purity and many needing isotope enrichment
Some General Comments on R&D

• Resources for R&D are severely limited in many countries and also, in some, young people working in detector development can face difficulties with career progression → possible changes in academic culture to address this?

• R&D timescales are long and lead-times before large-scale production can start, even once resources are identified, are seldom fully appreciated (market surveys, agree specifications and QA with suppliers, tendering, pre-series production, qualification, tooling, time to first series delivery, batch scheduling, …) → R&D for the next generation of facilities is already urgent

• Coordinated R&D is vital and prototyping should encompass all aspects (not just sensors and FE electronics) if surprises are to be avoided (particularly where extreme environments are anticipated)

• Activation (LHC) and other accessibility issues once inside the experiment, make it important to commission the final system thoroughly prior to installation

• Many technology developments to address the unique challenges of high energy physics lead to significant opportunities for applications in other fields, to the major benefit of particle physics → important to also nurture this aspect
Conclusions

- Failed to do justice to a broad range of topics, especially but not only: fixed target, lower energy, dark matter and astro-particle detector systems. Also missing are many developments in electronics, data acquisition, monitoring, alignment, global engineering, radiation protection …

- Progress with detector technology is just about keeping pace with the requirements for future facilities but resources are very tight despite much better coordination of effort between experiments

- **Sizeable and highly dedicated community engaged in detector R&D**

  a testament to this being the excellent talks and posters at this conference

(Detector R&D in particle physics is an area where each sub-topic fills a conference series in itself, so this survey was very superficial. Some links to where recent material outside this Conference can be found below:


  ACES 2014: [https://indico.cern.ch/event/287628/other-view?view=standard](https://indico.cern.ch/event/287628/other-view?view=standard)

  CALOR 2014 [http://indico.uni-giessen.de/indico/conferenceTimeTable.py?confId=164#20140407.detailed](http://indico.uni-giessen.de/indico/conferenceTimeTable.py?confId=164#20140407.detailed)

  AWLC 2014: [https://agenda.linearcollider.org/conferenceOtherViews.py?view=standard&confId=6301](https://agenda.linearcollider.org/conferenceOtherViews.py?view=standard&confId=6301)

  Neutrino 2014: [https://indico.fnal.gov/conferenceOtherViews.py?view=standard&confId=8022](https://indico.fnal.gov/conferenceOtherViews.py?view=standard&confId=8022)


  … and of course the very high quality presentations at this conference)
Back-up
## $e^+e^-$ Beam Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ILC 500</th>
<th>1000</th>
<th>CLIC 3 TeV</th>
<th>( \times 10^{10} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrons/bunch</td>
<td>2</td>
<td>2</td>
<td>0.37</td>
<td>( \times 10^{10} )</td>
</tr>
<tr>
<td>Bunches/train</td>
<td>1312</td>
<td>2450</td>
<td>312</td>
<td></td>
</tr>
<tr>
<td>Bunch separation</td>
<td>554</td>
<td>366</td>
<td>0.5</td>
<td>ns</td>
</tr>
<tr>
<td>Train length</td>
<td>727</td>
<td>897</td>
<td>0.156</td>
<td>us</td>
</tr>
<tr>
<td>Train repetition rate</td>
<td>5</td>
<td>4</td>
<td>50</td>
<td>Hz</td>
</tr>
<tr>
<td>Horizontal IP beam size</td>
<td>474</td>
<td>335</td>
<td>40</td>
<td>nm</td>
</tr>
<tr>
<td>Vertical IP beam size</td>
<td>6</td>
<td>3</td>
<td>1</td>
<td>nm</td>
</tr>
<tr>
<td>Longitudinal IP beam size</td>
<td>300</td>
<td>224</td>
<td>44</td>
<td>( \times 10^{34} )</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2</td>
<td>5</td>
<td>6</td>
<td>( \times 10^{34} )</td>
</tr>
</tbody>
</table>

---

*P.N. Burrows*
**VERTEX** “flavour tag, IP resolution” (H $\rightarrow$ bb, cc $\tau\tau$)

$\sim 1/5 \ r_{\text{beampipe}}, 1/30$ pixel size, $\sim 1/10$ resolution (ILC vs LHC)

vtx 1-2 cm (ILC) vs vtx 2-3 (CLIC)

$$\sigma_{IP} = 5 \oplus \frac{10}{\rho \sin^{3/2} \theta} (\mu m)$$

**TRACKING** “recoil mass to Higgs” (e+e- $\rightarrow$ Zh $\rightarrow$ llX)

$\sim 1/6$ material, $\sim 1/10$ resolution (ILC vs LHC)

$B = 3.5 – 5T$ (CLIC and ILC)

$$\sigma(1/\rho) = 2 \times 10^{-5} (\text{GeV}^{-1})$$

**CALO** “particle flow, di-jet mass resolution”

1000x granularity, $\sim 1/2$ resolution (ILC vs LHC);

Detector coverage down to very low angle

$$\sigma_E / E = 0.3 / \sqrt{E} (\text{GeV})$$

Key detector R&D technologies have been demonstrated with prototypes in test beams

Physics performance has been studies in full simulations

Major engineering R&D efforts and optimization of detector concepts are still needed
Tracking Systems – ILC Example

Large TPC
R~1.8m
Z/2~2.0m

Central and forward Si tracking system

Vertex detector
Inner radius~1.6cm
Outer radius~ 6 cm

Low mass for tracking & vertexing
- Thin silicon sensors
  ~50 µm for pixel vertex detectors
- Light support structures
e.g. advanced endplate for TPC

Alice
Belle
ATLAS
ILC

p_T [GeV]
Vertex Detector System

State-of-the-art pixel technologies: CMOS MAPS, DEPFET, FPCCD, 3D, Chronopixel, SOI

Motivation:
- high efficiency & purity flavor tagging (bottom, charm, tau, jet-flavor → e.g. b/c-quark separation for Higgs decays, b-quark charge measurement)

Approach:
- 2-sided ladders concept, very low power
- unprecedented granularity & material budget (ultra-thin ~ 50μm sensors)

A complex set of highly correlated issues:
- pixel sensors
- staves/ladders: thermo-mechanical aspects and services
- need careful thinking in terms of material budget and power cycling, besides the usual speed/resolution/data flow requirement

CMOS MAPS: Spatial Resolution and Time Stamping

~ 3μm track resolution achieved:

DEPFET: Mechanical ladder tested for power pulsing

Ultrathin ladder - PLUME

0.6%X₀ (0.35X₀ for ILC)
Central Tracking – Time Projection Chamber

ILCTPC with MPGD-Readout
→ spatial resolution < 100 µm @ 4T
(precise momentum: e+e→ZH→ll/H)

➢ Wet-etched triple GEMs
➢ Laser-etched GEMs 100µm thick ("Asian")
➢ GEM + pixel readout

➢ Resistive MM with dispersive anode
➢ InGrid (integrated Micromegas grid with pixel readout)

Resistive Micromegas @ DESY Test-Beam:

Resistive MM: B=1 T \( C_d = 94.2 \, \mu m/\sqrt{cm} \) (Magboltz)

Goal for final TPC can be reached:

➢ GEM / MM performance similar
→ both extrapolate to better than 100 µm at B=3.5 T & drift length 2.25 m
Continuation of the R&D Support for the LHC Upgrades

**MM for the ATLAS Muon System Upgrade:**
R&D Started in 2007 within the RD51 collaboration:

Standard Bulk MM suffers from limited efficiency at high rates due to discharges induced dead time

Solution: Resistive Micromegas concept

- 2.4 x 1m² MM resistive chamber constructed and characterized at CERN RD51 lab

- Resolution for inclined tracks (μTPC method) better than 80 µm

- MM can operate in magnetic field

NSW Technical Design Report (TDR) approved by LHCC (October 2013) →

~ 1280 m² of resistive MM will be installed (LS2) in ATLAS → the largest MM system, ever built

→ FOSTER INDUSTRIAL PRODUCTION NEEDS

**GEMs for the CMS Muon System Upgrade:**
R&D Started in 2009 within the RD51 collaboration:

Single-mask GEM technology (instead of double-mask) → Reduces cost / allows production of large-area GEM

Self-stretching technique: assembly time reduction from 3 days → 2 hours

<table>
<thead>
<tr>
<th>GE1/1-I</th>
<th>GE1/1-II</th>
<th>GE1/1-III</th>
<th>GE1/1-IV</th>
<th>GE1/1-V</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>2011</td>
<td>2012</td>
<td>2013</td>
<td>2014</td>
</tr>
</tbody>
</table>

Future work will focus on stability and uniformity of GEMs, and development of electronics, …

During the LHC End-Year stop of 2016/2017, two GEM super-chamber demonstrators will be installed
ALICE TPC Upgrade
→ replace MWPC with GEM

- Continuous TPC readout at 50 kHz
- Physics requirement: IBF < 1%, energy: \( \sigma(E/E) < 12\% \) achieved

Energy resolution vs IBF (4-GEM detector):

Special ALICE TPC / RD51 workshop will be organized on June 18th, 2014 (during the RD51 Collaboration Week)
The main objective is to advance MPGD technological development and associated electronic-readout systems, for applications in basic and applied research.”

A fundamental boost is offered by RD51: from isolate MPGD developers to a world-wide net

World-wide Collaboration for the MPGD Developments → RD51 (91 institute, > 500 people):

- Large Scale R&D program to advance MPGD Technologies
- Access to the MPGD “know-how”
- Foster Industrial Production

Advances in photolithography → Large Area MPGDs (~ m² unit size)

http://rd51-public.web.cern.ch/rd51-public
R&D in Calorimetry is an LC driven effort → a marriage with “Particle Flow Algorithm” (pioneering work) has delivered a proof of principle and been established experimentally.

Goal is $\Delta E_{jet}/E_{jet} - 3-4\%$:
(separate hadronic W/Z decays)

- **PFA Algorithm (jet energy carried by ...):**
  - Charged particles ($e^\pm, h^\pm, \mu^\pm$): 65% - most precise measurement by tracker up to 100 GeV
  - Photons: 25% - measurement by ECAL
  - Neutral Hadrons: 10% - measurement by HCAL and ECAL

- Overlap between showers compromises correct assignment of calo hits (“Confusion Term”):
  → control by highly pixelised calorimeter readout
  → new technologies (Si, SiPM, MPGD, RPC, etc …)

Detector cost is driven by instrumented area rather than channel count

ILD/SiD Calorimeter Concepts:

<table>
<thead>
<tr>
<th>#ch</th>
<th>ECAL</th>
<th>HCAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILC (ILD)</td>
<td>100M</td>
<td>10M</td>
</tr>
<tr>
<td>LHC</td>
<td>76K (CMS)</td>
<td>10K (ATLAS)</td>
</tr>
</tbody>
</table>
**Calorimeter Technologies: Towards Final Systems**

**Physics Prototype**
- Proof of principle
- 2003 - 2011

**Technological Prototype**
- Engineering challenges
- 2010 - ...

**CALICE (SiW ECAL):**
- From first prototypes to full calorimeter systems
- Technological integration (power pulsing, compact design, scalability)
- R&D oriented towards LC but synergies with other projects (e.g. CMS ECAL Endcap Upgrade)

**Forward Calorimetry (FCAL):**
- LumiCal provides integrated luminosity measurement
- BeamCal provides instant luminosity measurement and assists beam tuning

**BeamCal Sensors:**

**Large Scale Prototypes:**

**Sci tiles + SiPM:**

**1m³ abs.: steel or W**

**Hadron Calorimetry (HCAL):**
- Excellent hadronic energy resolution by software compensation

**Number of channels:**
- **CALICE:** 45360
- **Physics Prototype:** 9720
- **Technological Prototype:** 45360

**Pixel size:**
- **CALICE:** 0.55x0.55 cm²
- **Physics Prototype:** 1x1 cm²
- **Technological Prototype:** 0.55x0.55 cm²

**Weight:**
- **CALICE:** ~700 Kg
- **Physics Prototype:** ~200 Kg
- **Technological Prototype:** ~700 Kg
- **Total Weight:** ~130 t
ICARUS T600 LAr purity offline analysis: new results

- ICARUS has operated with $\tau_{\text{ele}} > 7$ ms (~40 p.p. trillion $[O_2]_{eq}$) corresponding to a 12% maximum charge attenuation at longest drift distance!

- New pump has been installed on East cryostat since April 4th, 2013: $\tau_{\text{ele}}$ exceeding 12 ms and still rising!

- A remarkable purity has been achieved on ~1 kt scale detector, to be compared with $\approx 1$ ms longest electron drift time, approaching the LAr lifetime of $\tau_{\text{ele}} \approx 21$ ms previously observed with a ~100 litres prototype

**ICARUS has demonstrated the effectiveness of the single phase LAr-TPC technique, paving the way to huge detectors/~5 m drift as required for LBNE project**
New LHC schedule beyond LS1

Only EYETS (19 weeks) (no Linac4 connection during Run2)

**LS2**
- starting in **2018 (July)**
- 18 months + 3 months BC (Beam Commissioning)

**LS3**
- LHC: starting in 2023 =>
- 30 months + 3 BC
- injectors: in 2024 => 13 months + 3 BC
CMS Phase 2 Upgrades

Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to $\eta \sim 4$

Muons
- Replace DT FE electronics
- Complete RPC in forward region with new technology
- Investigate Muon-tagging up to $\eta \sim 4$

Endcap Calorimeters
- Radiation tolerant - higher granularity
- Investigate coverage up to $\eta \sim 4$

Barrel ECAL
- Replace FE electronics

Trigger/DAQ
- L1 (hardware) with tracks and rate up $\sim 500$ kHz to 1 MHz
- Latency $\geq 10\mu$s
- HLT output up to 10 kHz

Integrated radiation levels (up to $2 - 3 \times 10^{16} n_{\text{eq}}/\text{cm}^2$) and plan to cope with up to 200 interactions every 25ns.

Implications of this include:
- New Inner Detector (strips and pixels)
- Trigger and data acquisition upgrades
- L1 Track Trigger
- New LAr front-end and back-end electronics
- Possible upgrades of HEC and FCal
- New Tiles front-end and back-end electronics
- Muon Barrel and Large Wheel trigger electronics
- Possible upgrades of TGCs in Inner Big Wheels
- Forward detector upgrades
- TAS and shielding upgrade
- Various infrastructure upgrades
- Common activities (installation, safety, ...)
- Software and Computing
Baseline layout of the new ATLAS inner tracker for HL-LHC Aim to have at least 14 silicon hits everywhere (robust tracking)
HV/HR-CMOS R&D

Potential technologies under study to bring some of the advantages of monolithic active pixel sensor (MAPS) technology to the ITk.

Already installed at STAR (RHIC) and proposed for ALICE and ILC.

- Hybrid Pixels with “smart” diodes
  - HR- or HV-CMOS as a sensor (8”)
  - Standard FE chip
  - Ex: CCPD on FE-I4

- CMOS Active Sensor + Digital R/O chip
  - HR- or HV-CMOS sensor + CSA (+Discriminator)
  - Dedicated “digital only” FE chip

- Monolithic Active Pixel Sensor on a fully depleted substrate (DMAPS)
  - HR-CMOS process

Could also envisage using the “smart diode” approach to propose a single-sided strip replacement with z encoding.

Many technologies under investigation for potential use in pixel system at higher radii or allowing less expensive 5th layer.

Cost evaluation depends critically on yield estimates for large format detectors.
IBM announced (Feb 2014) foundries for sale
New CERN contract with TSMC until end 2017
Both 65 nm and 130 nm
Mixed signal design kit available for the 65 nm
2 metal stacks: 6+1 and 9+1
130 nm could be used as an alternative to IBM
Design kit being developed
Radiation hardness tests to be completed

RD53 Summary

- Highly focused ATLAS-CMS-LCD/CLIC RD collaboration to develop/qualify technology, tools, architecture and building blocks required to build next generation pixel chips for very high rates and radiation
- Synergy with other pixel projects when possible
- Centered on technical working groups
- Baseline technology: 65nm
  - CERN frame contract/NDA/design kit
  - Will evaluate alternatives ("emergency" plan)
- 17 Institutes, 100 Collaborators
- Initial work program of 3 years
  - Goal: Full pixel chip prototype 2016
    - Working groups have gotten a good start.
    - Common or differentiated final chips to be defined at end of 3 year R&D period
New All-silicon Inner Tracker

Strip Detector

- Thin build FR4 hybrid made quickly
  - 10 ABCi30 attached, 5 off “FIBd” and 5 off “non-FIBd”
  - All 10 ABCi30s linked serially (for data readout) with common TTC bus
- Wire-bonding much simpler/faster
  - Benefit of collaborating withasic designers to fix geometry
- Hybrid/module behaves as expected:
  - Data Passing at 80MHz RCLK works
  - Hybrid draws ~810mA when configured (PTOTAL ~ 1.2W/hybrid)
  - Total power consumption of ~3W/module (inc.HCC)
  - Current ABCN-25 module power consumption is ~20W
  - Output noise as expected and extremely regular

12 Module full length 250nm ASIC stave with 61440 channels
Simulation studies show that including a track trigger complements muon and EM triggers

- Improves muon $p_T$ resolution
- Improves EM identification by matching to track

Implemented as 2-level scheme to accommodate legacy electronics and reduce links from strip tracker → reuses Phase-I L1 trigger improvements for new L0 LOA scheme and buffering fully integrated in ABCn130 ASIC

FTK technology could be used to perform fast track fit in L0 defined Region of Interest (RoI)

Note this scheme impacts the electronics in all systems and provides possibilities to exploit the L0/L1 structure to have more extensive information from all sub-detectors at L1