Detector needs for future collider experiments

Andy White
University of Texas at Arlington

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With thanks to the Instrumentation Frontier Topical Group Conveners who provided essential input
Future Colliders

Lepton Colliders
“Higgs Factories”

High Energy Lepton Colliders

High Energy Hadron Colliders

Snowmass’2021 AF-EF-TF: Collider Implementation Task Force Report
Detector needs for future collider experiments

Detector areas to be covered:

- IF03: Tracking
- IF05: MPGD
- IF06: Calorimetry
- IF04: Trigger/DAQ
- IF07: Electronics/ASICS

Input received from each of these Instrumentation Frontier Topical Groups.
Tracking

Tracking detector requirements

• Tracking detectors are of vital importance for collider-based HEP experiments
  • The performance requirements from the community require an evolution of tracking systems,

• Requirements for future trackers are significantly more demanding than currently available technologies
  • Precision timing resolution in a tracking environment
  • Segmentation and position resolution 2-4 times finer
  • Tolerance to fluences 1-2 orders of magnitude higher
  • Larger areas at lower costs
  • Radiation length per layer from 0.1-1% X₀
  • Advanced materials, fabrication techniques, edge-processing
Technology directions

- High granularity measurements: spatial and timing resolution
  - AC-LGADs, LGAD optimizations (buried layer, double-sided, etc)
  - 3D sensors, Induced Current sensors
  - Monolithic pixel sensors
- New materials, fabrication techniques
  - 4H-SiC, 3D silicon and diamond, 3D-sensors with gain, 3DIC SiPM, thin films, quantum dots
  - Advanced packaging, wafer-to-wafer bonding
- Light-weight support/cooling structures
  - Integrated services and cooling, novel materials, new cooling and composite manufacturing
- New approaches to front-end processing
  - Edge-computing, nanotechnologies to reduce power on the front-end, wireless
- Development of simulation tools
  - Invaluable in the development of new technologies
Technology priorities

• Developments of sensor technologies
  • Achieve 4D-capability from timing sensors with fine segmentation and able to cope with high occupancies and radiation tolerance
  • Large area sensors with improved uniformity, both traditional, LGADs, and wafer-scale MAPS
  • Major advances in ASIC development and approaches: bandwidth optimization, low noise, small area and low power dissipation
  • New materials for sensor and electronics: unified design of full systems

• Advanced packaging and edge-computing paradigms
  • Vertical integration of multi-tier processing electronics and sensors, optimization of detector thickness
  • Industry partnerships and adoption of new technologies

• Radiation hard technologies and more effective cooling

• Simulation tools
  • Unified radiation damage model, prescription for uncertainties in TCAD models
  • Measurements of damage factors
  • Feedback between full detector systems and per-sensor models
Tracking: MPGD

MPGDs have major roles in TPCs and large area muon detection systems. Essential features – large area, low material budget

**TPCs** – ILD/ILC, potential Belle II wire chamber replacement, for a detector at CEPC
MPGD readout – GEM, GridPix,…
Synergy with Si ASIC development – wafer post-processing, gas amplification on top of pixelized r/o chip
Negligible ExB effect with e.g. GEM due to ~100µm hole spacing

**Muon detection systems**
Precise muon tracking, trigger and tagger for collider detectors
Instrument large areas, high efficiency, in high background, high radiation environment

**Challenges**
Discharge protection (e.g. micro R-well), miniaturization of readout elements
FCC-hh very forward endcap regions
Multi-TeV Muon Collider – Fast Timing MPGD – use timing to mitigate beam-induced background.

NOTE: There is ongoing discussion about the need for a MPGD facility in the U.S. like the CERN GDD Group facility
Calorimetry – Techniques (PFA/DRO)

Particle Flow:
- Motivation: ultra-precise measurements of hadronic jets to discriminate between W, Z, and H bosons reconstructed in multijet final states
- Target performance: stochastic term of 30%/√E[GeV]

<table>
<thead>
<tr>
<th>name</th>
<th>purpose</th>
<th>project</th>
<th>active material</th>
<th>channel size</th>
<th>readout</th>
<th># of layers (depth)</th>
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<td>ECAL</td>
<td>ILC*</td>
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<td>analog</td>
<td>30 (24X₀)</td>
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<td>ECAL⁶</td>
<td>HL-LHC</td>
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<td>analog</td>
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<td>CALICE Sci-ECAL</td>
<td>ECAL</td>
<td>ILC²</td>
<td>SiPM-on-tile</td>
<td>5 × 5 mm² ²/³</td>
<td>analog</td>
<td>30 (24X₀)</td>
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<tr>
<td>RADICAL</td>
<td>ECAL</td>
<td>FCC-hh</td>
<td>crystal + WLS²</td>
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<td>analog</td>
<td>29 (25X₀)</td>
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<tr>
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<td>ILC⁷</td>
<td>SiPM-on-tile</td>
<td>3 × 3 cm²</td>
<td>analog</td>
<td>40 (4λ₁)</td>
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<tr>
<td>HGCAL Scint</td>
<td>HCAL</td>
<td>HL-LHC</td>
<td>SiPM-on-tile</td>
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<td>analog</td>
<td>22 (7.8λ₁)</td>
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<tr>
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<td>HCAL</td>
<td>ILC</td>
<td>RPC</td>
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<td>digital</td>
<td>40 (4λ₁)</td>
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<tr>
<td>CALICE SDHICAL</td>
<td>HCAL</td>
<td>ILC</td>
<td>RPC</td>
<td>1 × 1 cm²</td>
<td>semi-digital</td>
<td>40 (4λ₁)</td>
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</tbody>
</table>

Extensive interest from e⁺e⁻ community, which has driven much R&D

First realization in HL-LHC, motivated by radiation hardness and pileup

- R&D continues to advance along many fronts
- Challenges remain:
  - Scaling to 10-100M channels at reasonable cost
  - Thermal and power management of front end ASICs
  - Compact design (minimizing gaps between sampling layers)
Calorimetry – Techniques (PFA/DRO)

Dual readout

- Shower-by-shower energy scale correction as a function of number of inelastic collisions.

- Total energy of all ionizing particles estimated from scintillation light (plastic or crystals).

- Energy due to relativistic ionizing particles estimated from Čerenkov light (clear fibers)

Examples

Spaghetti calorimeter with clear (Čerenkov) and scintillating fibers installed in a tower of passive material - IDEA (FCC-ee or CEPC)

Homogeneous scintillating crystals with two filter-SiPM readout assemblies, sensitive to either Čerenkov or scintillation light - SCEPCAL (FCC-ee or CEPC)

Challenges remain:

Mechanics, integration, and costing of a realistic spaghetti calorimeter

Red-sensitive SiPMs and novel optical materials to boost the Čerenkov signal/noise in homogeneous crystal setups
Particle flow and Dual readout

- **ADRIANO2** for proposed \( \eta \) factory
- Highly granular particle flow-like sampling **calorimeter**, but alternating lead glass absorber/scintillator (sensitive to Čerenkov) and plastic scintillator
- Discrimination between photons, neutrons, and \( \pi^0 \)s
- Spaghetti calorimeter with individual SiPM readout of each fiber
- **SCEPCAL** for CEPC or FCC-ee
  - Coarser longitudinal segmentation than CALICE-style particle flow
  - Tuned particle flow reconstruction algorithm + dual readout information yields better results than dual readout alone
- Both concepts being considered for a muon collider detector
Calorimetry - Precision Timing

Timing as an extra dimension to calorimeter systems

What can be achieved with $O(10 \text{ps})$, few-ps, or even sub-ps level timing?

**Higgs factories** – improving event reconstruction, 5-D ($x,y,z,E,t$), energy resolution, reduced uncertainties on Higgs BRs etc.

- Particle ID e.g. for $h \rightarrow \text{ssbar}$ and for long-lived particle searches

**Hadron colliders** – pile-up mitigation, reduction of confusion, improved event reconstruction

Implementing precision timing in calorimeters (volume/cell level, dedicated layers)

Technologies for precision timing
Higgs factories – improving overall precision of event reconstruction, particle ID

- e+e- -> ZH
  - Higgs to invisible analysis

Z -> μμ

Z-> qqbar

Particle ID
- Typical barrel layer

Calorimetry – Precision Timing

- Including timing information
- Study based on CALICE AHCAL (Scint tile/SiPM)

? How to use timing data in ML-based analyses?

SiD h -> inv, C. Potter et al.
Calorimetry – Precision Timing

Hadron colliders – pile-up mitigation, reduced confusion/backgrounds

Example: CMS HGCAL

**HL-LHC:**
Expect up to 200 simultaneous collisions

**FCC-hh:**
Expect O(1000) pile-up events

90% assigned tracks/central region – achieved with 5-10ps timing cut
-> keep effective pile-up below one/bunch crossing

Before/after cut on time of particles
(Hits > 12 fC, |Δt| > 90ps)
Technologies for layer and volume timing

**Timing layers**
- Low-Gain Avalanche Detectors (LGADs) ~30ps and 1mm spatial resolution
- Ultra-fast silicon monolithic sensors with integrated readout (CMOS) 10-20ps
- Micro-channel plate (MCP) detectors detection of single ionizing particles ~few ps
- 2-stage Micromegas detector + Cherenkov radiator equipped with a photocathode < 100ps
- LYSO crystals + SiPM few x10 ps
- Deep diffused avalanche photodiodes ~40ps
- Coherent microwave Cherenkov detectors ~0.3 – 3ps

**Volume timing**
- Silicon tiles e.g. LGADs few x10 ps
- Plastic scintillator tiles or strips with SiPM readout sub-ns -> few x10ps
- Multi-gap RPCs sub-100ps
- Highly granular crystal-based detectors, using a highly segmented readout

**Issues:** *R&D needed on electronics* to support timing resolution satisfying the constraints on power consumption associated with highly integrated systems with extreme channel counts

7/19/2022 A. White - Snowmass 2022 UW Seattle
Calorimeter Materials

- (Issues) stringent challenges to calorimeter materials in radiation tolerance, energy resolution, time response and project cost
  - Enhance calorimetry energy resolution for precision electroweak mass and missing energy measurements.
  - Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments.
  - Develop ultrafast media to improve background rejection in calorimeters and improve particle identification.
- WP summarized materials in the form of inorganic, liquid (oil- and water-based), and plastic scintillators from LOIs and consortiums
  - BaF$_2$:Y → feasible to TOF system; Mu2e-II, (also by RADiCAL)
  - LYSO:Ce or LuAG:Ce → best fit to radiation hardness; HL-LHC, FCC-hh (RADiCAL)
  - BGO, PWO, Glass → good EM and jet resolutions; Higgs-Factory, ILC and FCC-ee (CalVision and HHCAL)
  - Liquid (oil- and water-based) and plastics scintillators (from neutrino and other particle physics experiments)
- Inorganic scintillator crystals dominate the calorimetry applications
  - New glass materials (OGS) are promising
  - Organics scintillators are less selected, but could have usages in future large volume (cost) calorimeters
Calorimeter Materials

High density, good optical quality, high light-yield, fast decay time, good radiation hardness and low cost


<table>
<thead>
<tr>
<th>Materials (noble gas not included)</th>
<th>LY (ph/MeV)</th>
<th>Cost (per kg)</th>
<th>Time (ns)</th>
<th>General Comments</th>
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<tbody>
<tr>
<td>Inorganic Scintillator Crystals</td>
<td>1000~30000</td>
<td>$1000s</td>
<td>10s~100s²</td>
<td>High density, easy deployment, low optical, scale-up challenge (cost/volume); WLS³</td>
</tr>
<tr>
<td>Organic Scintillator Plastics</td>
<td>1000s</td>
<td>$10s</td>
<td>1s</td>
<td>Medium density, easy deployment, &lt;m-optical, scale-up challenge (3D-print?), WLS³</td>
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<tr>
<td>Organic Liquid Scintillator¹</td>
<td>9000-14000</td>
<td>$1s</td>
<td>Sub</td>
<td>~10m-optical, low density (mitigated by high-Z?), large volume; WLS-doped</td>
</tr>
<tr>
<td>Water-based Liquid Scintillator</td>
<td>1000s</td>
<td>&lt;$1s</td>
<td>Sub</td>
<td>~10m-optical, low density (mitigated by high-Z?), environmentally-friendly, large volume, WLS-doped</td>
</tr>
</tbody>
</table>

Optical and scintillation properties of candidate inorganic scintillators for CalVision and the HHCAL concept
“Fast” (<ms) machine learning is useful in many scientific domains, and many different kinds of detectors, to extract the science with increased TDAQ constraints on timing, bandwidth, etc:

- LHC detectors
- neutrino detectors
- dark matter detectors
- detectors at the EIC
- gravitational wave detection
- ...

“Fusing powerful ML techniques with experimental design decreases the ‘time to science’ and can range from embedding real-time feature extraction to be as close as possible to the sensor all the way to large-scale ML acceleration across distributed grid computing datacenters.”
• Early-stage triggers based on tracking information can preserve interesting events for study.
  • Emphasis to expand capability to include long-lived low momentum particles, very-short-lived high momentum particles, ...

• Hardware-based tracking explored and/or used in multiple previous detectors (at Tevatron, LHC, at future experiments...)

• Multiple approaches: associated memory/pattern bank, use of different kinds of machine learning techniques

Example from contributed Snowmass white paper, highly-parallelized graph computing architecture using FPGAs.

**Figure 4-1.** (left) An example of the point cloud generated by 100 particles in an azimuthal sector of the silicon pixel detector of width one radian. The silicon sensors are placed in concentric circles with radial separation of 5cm. (right) The reconstruction of 100 tracks from the point cloud. [1]
TDAQ-Readout Technologies

• Improvements in readout technologies are necessary to handle high data rate of future detectors
  • Reduce the data rate close to the detector
  • Increase data bandwidth per material/power cost

• Wireless communication
  • Could enable designs with localized readout and fast analysis/triggering to reduce data volumes
  • Microwave-based technologies have strong momentum, but reaching upper physical limit in bandwidth
  • Free-space optics operating in mid-IR regime show promise for Tb/s bandwidths

• Next-generation Rad-hard links
  • Move beyond current bandwidth-limited VCSEL-based links
  • Silicon photonics can integrate directly to chips, and offer ~x2 bandwidth at less power
  • Wavelength Division Multiplexing (WDM) can reduce data aggregation layers by transmitting individual serial links at different wavelengths

• See readout technologies white paper: https://arxiv.org/abs/2203.14894
Higher Collisions Rates & Channel counts \(\rightarrow\) Huge Increase in Sensor Data

- **Control Data Content**
  - Implement data reduction techniques for low and moderate occupancy sensors.
  - Utilize High Level Feature extraction techniques (eg. Hough transforms for groups of sensors) on detector to increase physics content/bit transferred off detector.
  - Sparsify readout applying trigger selection .. utilize AI/ML techniques etc.

- **Increase off Detector Data Throughput**
  - Implement high speed Rad hard Optical links @ rates \(tx > 10\text{Gbps}\) \(rx \sim 1\text{Gbps}\) (in 28nm technology)
  - Reduce footprint/Minimize Power of Optical modules.
  - Investigate/Implement direct ASIC to fiber transceivers. (Bi-CMOS – Optical ASICs)
Challenges for Next Generation Collider Detector Systems

• Tracking
  • 4D Silicon strips and Pixels with data concentrators to provide tracklet 4 vectors instead of hit data. ~50um geometric resolution & 2-3mm time derived track association.
    • Geometric resolution from pixel position sensor thickness
    • ~10-15ps hit time resolution (dependent on clock distribution jitter)

• Calorimetry
  • Dual Readout high transverse granularity with precision timing for shower readout.
    • Simultaneous low latency readout of Scintillation and Cherenkov signals with precision timing information
      • More than Doubles the Data of traditional Calorimeter readout
      • Challenges for analog front end / data storage / trigger selection
Workforce & Infrastructure Support

- Ensure Institutional Retention of >2 decades of collider detector Instrumentation Design & Development experience:
  - System Design $\rightarrow$ moving towards Co-design/Co-simulation
  - Hierarchical Approach to Design & Simulation of High Channel detector sub-systems
  - Integrated sensors & readout on single / multiple parallel substrates eg. MAPS
  - Engage designers in building Radiation Tolerant ASIC blocks for Future Systems On a Chip (SoC) $\rightarrow$ to maintain State of Art Readiness
    - Front End Readout
    - Local Memory
    - On Chip Supply conversion DCDC and LDO’s
- Maintain HEP specific (Rad Tolerant/Cryo) Web Resource for Tutorials/Examples/References
- Future Designs will require broad (multi-institutional) access to:
  - Advanced Technology Nodes for ASIC fabrication
  - CAD Design and Design management tools and training
  - Hierarchical System Simulation tools
### Basic Research Needs for High Energy Physics Detector Research & Development

<table>
<thead>
<tr>
<th>Experiments</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
<th>2040</th>
<th>2045</th>
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<tbody>
<tr>
<td>Calorimetry</td>
<td>PRD 1: Enhance energy resolution</td>
<td>PRD 2: Advance spatial &amp; timing resolution &amp; radiation hardness</td>
<td>PRD 3: Develop ultrafast media for improved background rejection/particle identification</td>
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<tr>
<td>Photodetectors</td>
<td>PRD 7: Extend wavelength range &amp; develop new single-photon counters</td>
<td>PRD 8: Adapt photosensors for extreme environments</td>
<td>PRD 9: Devices/architectures for picosecond timing &amp; event separation</td>
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<td></td>
<td>PRD 10: Develop optical coupling paradigms for enhanced light collection</td>
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<td>PRD 11: Developing optical coupling paradigms for enhanced light collection</td>
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<td>Readout &amp; ASICS</td>
<td>PRD 16: Process evaluation/modeling for ASICS in extreme environments</td>
<td>PRD 17: Create building blocks for Systems-on-Chip for extreme environments</td>
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<td>SSD &amp; Tracking</td>
<td>PRD 18: Pixel detectors with high spatial/ per-pixel time resolution for high-collision-density environments</td>
<td>PRD 19: Adapt new materials and fabrication/integration techniques for particle tracking</td>
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<td>TDAQ</td>
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<td>PRD 21: Achieve on-detector, real-time, continuous data processing and transmission</td>
<td>PRD 22: Develop timing distribution with picosecond synchronization</td>
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</table>
The Detector R&D Roadmap Process

- US participation in new DRDC groups
- Avoiding duplication of R&D across regions
The Energy Frontier also supports the possibility of a Higgs factory in the US. Given global uncertainties, consideration should also be given to the timely realization of a possible domestic Higgs factory, in case none of the currently proposed global options are realized. To enable the realization of a Higgs factory in the shortest possible timescale, a targeted program on detector R&D for Higgs factories should be supported. In order for the US to build a strong community of young physicists engaged in Higgs factory research, the EF community supports the case for the establishing a program for detector R&D that covers the range of proposed accelerator facilities, with initial emphasis on areas that are applicable across facilities.

- A Higgs Factory is emerging as a strong medium-term priority
- The US needs to build a strong community to participate in the e+e-experiments/physics
- Significant investments already made elsewhere (esp. Europe)
- Urgent need for a detector R&D program directed towards Higgs Factory participation by U.S. HEP.
Conclusions

- There are many challenges to be met to have successful detector designs and implementation for future collider detectors.

- Challenges in spatial and timing precision, channel counts, radiation hardness, high data volumes/rates, power requirements, materials and material profiles, high speed low noise electronics,…

- Many new approaches to solving these challenges!

- Significant Detector R&D support will be needed in the U.S. to ensure effective participation in future collider programs.

- Essential that these Detector R&D needs are effectively communicated in the Snowmass Report and conveyed to P5.
Extra slides
Implementing precision timing in calorimeters

Various possible schemes for timing – timing resolution/performance/cost considerations

**Volume timing** – timing for all active cells in calorimeter
- 5-D (x, y, z, E, t) in highly granular calorimeter
- benefits for pattern recognition, shower reconstruction/separation, energy measurement
- BUT – potentially high cost
- Explore benefits of full digital calorimetry – needs much R&D

**Timing layers** – small number of dedicated timing layers
- e.g. before/after Electromagnetic calorimeter
- layers in Hadron Calorimeter
Future directions:

- application of Machine Learning (ML) to TDAQ systems, particularly considering co-design of hardware and software to apply ML algorithms to real-time hardware and in other novel uses of ML to make future experiments more operationally efficient while increasing sensitivity for new physics;

- the design of TDAQ system architectures to enable more intelligent aggregation, reduction, and streaming of data from detectors to higher-level trigger systems and offline data processing; and,

- the development of improved readout technologies to increase data bandwidth, that are capable of operating in extreme environments while fitting the material and power budgets of future experiments.