Roger Rusack – The University of Minnesota

CALORIMETER BRN
Conveners – Francesco Lanni (BNL) and Roger Rusack (Minnesota)

Sub-conveners –
- Nural Akchurin (Texas Tech)
- Sarah Eno (Maryland)
- Paolo Rumerio (Alabama)
- Renyuan Zhu (Caltech)

With input from: Marty Bradenbach, Vitaliy Fadeyev, Jim Brau, Marcello Mannelli, Paul Lecoq, Jim Hirschauer, Craig Woody, Stephen E. Derenzo David Hitlin, Sasha Ledovskoy, Charles L. Melcher, Adam Para, Gaudio Gabriella, Lorenzo Pezotti, Franco Bedeschi, Roberto Ferrari, Paolo Giacomelli, Artur Apreysian, Maria Spiropolou, Alessandro Tricoli, Martin Aleska, Hong Ma.

Not a complete representation of the field, but broad input from multiple sub-disciplines of the field.
Our focus was on calorimeters for future collider experiments as they set the most stringent requirements.

*And we don’t know what the future holds for us:*

*But we can guess.*

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**Timeline:**

- 12/11/19 Calorimetry BRN 3

- Based on Ursula Bassler’s timeline presented at Granada Symposium.

- To do: add technology timelines in coordination with technology groups

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**Collider scenarios beyond HL-LHC**

- Linear e⁺e⁻:
  - 250–380 GeV
  - 0.5–1.5 TeV
  - 1–3 TeV
  - $L = 1.4 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ at Higgs threshold

- Circular e⁺e⁻:
  - 90–250 GeV
  - 350 GeV
  - $L = 9 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ at Higgs threshold

- Circular pp:
  - 100 TeV
  - $L = 3 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$, 1000 PU

- Staged e⁺e⁻ → pp:
  - 90–250 GeV e⁺e⁻
  - 100 TeV pp
Recent detector paradigm shifts

**Particle Flow:**
Calorimeters and tracker information combined to understand the event.

**Precision Timing**
Precision measurement of the time of arrival of a shower to better than 30 ps

**5D Calorimetry:**
Measure position, energy and time of shower as it develops.

**UV sensitive photodetectors**
Developments in neutrino and dark matter detectors.

**MAPS Technology**
Development of integrated sensor and readout technology.
PRD #1 High precision 5D calorimetry with a resolutions of $\sim 15\%/\sqrt{E}$ EM and $\sim 35\%/\sqrt{E}$ hadronic and shower $\Delta T < 30$ ps for linear and circular $e^+e^-$ machines. *Timescale ready in 10 years.*
Electron Positron machines are low energy, zero pile-up machines. We can hope for 2 – 4 different detectors.

Energy scale is set by Z-boson and Higgs decay (50 – 60 GeV) at rest at start top-quark later (~150 GeV).

Key physics goal: Z + H production, tag H with Z-hadronic decay.

Technology needs:
- Simple low-cost construction designed for particle flow
- High bandwidth intelligent readout for complex events
- Low power electronics or pulsed power.
- Timing precision ~ 25 ps to identify long-lived particles.
Priority Research Direction - 2

PRD #2 High precision 5D calorimetry for $hh$ machines with an EM resolution of $< 10\%/\sqrt{E}$ and $< 30\%/\sqrt{E}$ hadronic $\Delta T < 5$ ps in an irradiation environment of $> 10^{17}$ n/cm$^2$. Timescale ready in 20 years.

Ready by 2035
Detectors at 100 TeV $hh$ machines will have to cope with high-energy jets, pile-up $\sim$1000, irradiation levels, $\sim$ 1 GigaGy and $>10^{17}$ neutrons/cm$^2$.

Energy scale is from $<1$ GeV to $>20$ TeV $\Rightarrow$ Dynamic range of $10^6$

**Key physics goal:**
H-self-coupling, new physics searches, Higgs invisible, Precision Higgs coupling.

**Technology needs:**
- Construction designed for high radiation tolerance.
- High bandwidth readout for complex events
- Radiation hard low-power intelligent electronics
- Timing precision $\sim$ 1 ps for pile-up suppression and particle id.
Priority Research Directions - 3

PRD #3 Ultrafast calorimetry media with order 1 ps precision for low-energy electrons and photons.

Physics motivation:
   Cope with ultra-high rate CLFV experiments.
   Special detectors at colliders.
We have identified three major detector research areas where the US can contribute to future high energy physics program needs.

**PRD #1** High precision 5D calorimetry with a resolutions of \(\sim 15\%/\sqrt{E}\) EM and \(\sim 35\%/\sqrt{E}\) hadronic and shower \(\Delta T < 30\) ps for linear and circular e\(^+\)e\(^-\) machines.  
*Timescale ready in 10 years.*

**PRD #2** High precision 5D calorimetry for hh machines with an EM resolution of < 10\%/\sqrt{E}\) and <30\%/\sqrt{E}\) hadronic \(\Delta T < 5\) ps in an irradiation environment of > 10\(^{17}\) n/cm\(^2\).  
*Timescale ready in 20 years.*

**PRD #3** Ultrafast calorimetry media with order 1 ps precision for low-energy electrons and photons.
Backup
Noble Liquids at FCC hh

Radiation levels will be ten times larger than HL-LHC and pileup ~ 1,000!

Inspired by ATLAS and HGCAL
FCC–hh Calorimeter

EM Barrel

EM and Hadronic EndCap

Electromagnetic calorimeter barrel

- 2 mm absorber plates inclined by 50° angle;
- LAr gap increases with radius: 1.15 mm–3.09 mm;
- 8 longitudinal layers (first one without lead as a presampler);
- $\Delta \eta = 0.01$ (0.0025 in 2nd layer);
- $\Delta \phi = 0.009$;

FCC-hh simulation EMB+HB

100 GeV $\pi^-$ $\emptyset \eta = 0.36$, topo-cluster 4-2-0 PU0

12/11/19 Calorimetry BRN
Fast Timing: Metascintillators

**High stopping power**
- L(Y,G)SO,
- (La,Ce)Br3,
- BGO,
- CsI

**Prompt emission**
- Quantum confined (bi)-excitons in nanocrystals

**Meta-material**

**Light transport to SiPM**
- Photonic crystals, photonic fibers

- **CdSe/CdS nanoplatelets**
- ZnO:Ga powder
- ZnO:Ga in PS