Electromagnetic Calorimeters

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JLab Summer Detector/Computer Lectures
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Outline

1. Introduction

2. Calorimeters
   - Generic calorimeter
   - Light collecting calorimeters

3. Front-End Electronics

4. Procedures

5. Summary
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Calorimeters
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Front-End Electronics

Procedures

Summary
What is a calorimeter?

Particle detection main goal: measure 3-momenta $\vec{P}$

Magnetic spectrometers

- For charged particles
- Coordinate detectors
- Magnetic field

Charged particles ($e^\pm$, $\pi^\pm$ etc)

Momentum resolution:

$$\frac{\sigma(P)}{P} = \frac{\sigma(\Delta \theta)}{\Delta \theta} \propto P$$

(for large $P$)

$\Delta \theta \propto \frac{Bd\ell}{P}$

$P \propto \frac{Bd\ell}{\Delta \theta}$
What is a calorimeter?

Particle detection main goal: measure 3-momenta $\vec{P}$

**Magnetic spectrometers**

- For charged particles
- Coordinate detectors
- Magnetic field

**Calorimeters**

Detectors thick enough to absorb nearly all of the particle’s energy released via cascades (showers)

Neutral ($\gamma$, $n$) and charged particles

The energy goes mainly into heat.

- ”True” C. - $E_0$ (heat)
- “Pseudo” C. - $\mathcal{O}(E_0)$:
  - ionization, Cherenkov light

Poisson process: $N_e \propto E_0$, $\sigma N_e = \sqrt{N_e}$ and $\frac{\sigma E}{E} \propto \frac{1}{\sqrt{E}}$

Thickness needed for full absorption: $t \propto \ln(E)$

**Charged particles** ($e^\pm$, $\pi^\pm$ etc)

Momentum resolution:

\[
\frac{\sigma(P)}{P} = \frac{\sigma(\Delta\theta)}{\Delta\theta} \propto P
\]

(for large $P$)
"True” Calorimeters

"True” calorimeters measure the temperature change of the absorber:
\[ \Delta T = \frac{E_0}{c \cdot M} \sim \frac{1 \cdot 10^{10} \text{eV} \cdot 1.6 \cdot 10^{-19} \text{J/eV}}{10^3 \text{J/kg/K} \cdot 1 \text{kg}} \approx 10^{-12} \text{K} \text{ too low!} \]

- High particle flux
  - If the flux is well known - measure the mean particle energy:
    History: W. Orthmann - 1\(\mu\)W sensitivity;
    1930, with L. Meitner they measured the mean energy of \(\beta\) from \(^{210}\text{Bi}\) (6% accuracy) \(\Rightarrow\) W.Pauli’s neutrino hypothesis.
  - If the particle energy is well known - measure the flux:
    Precise beam current measurements (SLAC-1970s, JLab-2003)

- Ultra-cold temperatures (low C), superconductivity - new detectors for exotic particle search, like “dark matter” candidates.
“Pseudo” Calorimeters

"Pseudo" calorimeters detect $O(E_0)$: ionization, Cherenkov light

Calibration is needed!

- History: N.L. Grigorov 1954 - idea, 1957 - implementation in cosmic ray studies (Pamir, 3900 m). Layers of an absorber and layers of proportional counters - counting the number of particles in the shower (calibration needed).
- Starting in 1960s - revolution in compact electronics ⇒ affordable ADC (Analog-to-Digital Converters). New accelerators - various types of calorimeters with $\sim 10 \rightarrow 10^5$ ADC channels.

Applications

- detecting neutrals $\gamma$, $n$
- good energy resolution at high energies
- fast signals for trigger
- particle identification ($e^{\pm}/h$)
**e^\pm** interactions

### Energy loss in medium

- Bremsstrahlung
  \[ e^\pm Z \rightarrow e^\pm \gamma Z \]
- Ionization
- Bhabha/Møller scattering
  \[ e^\pm e^- \rightarrow e^\pm e^- \]
- \( e^+ \) annihilation

---

**Bremsstrahlung**

\[
\sigma \propto \frac{Z^2}{m^2} \Rightarrow \frac{\sigma_\mu}{\sigma_e} \approx 2 \cdot 10^{-5}
\]

\[
\frac{dN_\gamma}{dk} \propto \frac{1}{k} \quad \frac{dE_\gamma}{dk} = c(k)
\]

\[
\theta_\gamma \sim \frac{m}{E_0}
\]
γ interactions

Interaction in medium

- Pair production
  \[ \gamma Z \rightarrow \alpha^+ \alpha^- Z \ (K_N) \]
- Pair production
  \[ \gamma \alpha^- \rightarrow \alpha^+ \alpha^- \alpha^- \ (K_e) \]
- Compton scattering
  \[ \gamma \alpha^- \rightarrow \gamma \alpha^- \ (\sigma_{incoherent}) \]
- Rayleigh scattering
  \[ (\sigma_{coherent}) \]
- Photonuclear absorption
  \[ (\sigma_{nuc}) \]
- Atomic photoeffect
  \[ (\sigma_{p.e.}) \]
Electromagnetic Showers

Photons and light charged particles ($e^\pm$) interact with matter:

- electrons radiate $e^\pm \rightarrow e^\pm \gamma$
- photons convert $\gamma \rightarrow e^+e^-$

A cascade develops till the energy of the particles go below a certain limit. The charged particles of the cascade ($e^\pm$) leave detectable signals.
Scaling of Material Properties

**Radiation length**

$X_0$ - the material thickness for a certain rate of EM:

\[ \frac{dE_{\text{loss}}}{dx} \sim \frac{E}{X_0} \quad \frac{dE_{\text{loss}}}{E} \sim \frac{dx}{X_0} \]

\[ \frac{dE_{\text{ioniz}}}{dx} \bigg|_{E_c} \approx \frac{E}{X_0} \]

\[ \lambda_{e^+e^-} \approx \frac{9}{7} \cdot X_0 \]

Derived from EM calculations:

\[ X_0 \approx \frac{716 \text{ g}\cdot\text{cm}^{-2}\cdot\text{A}}{Z(Z+1) \cdot \ln(287/\sqrt{Z})} \]

**Critical Energy**

$E_c$: cascade stops

Losses: Ionization $\approx$ Radiation

B. Rossi:

\[ \frac{dE_{\text{ioniz}}}{dx} \bigg|_{E_c} \approx \frac{E}{X_0} \]

\[ E_c \approx \frac{610 (710) \text{ MeV}}{Z + 1.24 (0.92)} \text{ solids(gasses)} \]

Graph showing $E_c$ vs. $Z$ for solids and gases.
Electromagnetic Shower: longitudinal development

Scaling variables: \( t = \frac{x}{X_0} \), \( y = \frac{E}{E_c} \)

Simple model

A simple example of a cascade: \( \times 2 \) at \( \Delta t = 1 \).

\[
E(t) = \frac{E_0}{2^t} \Rightarrow t_{\text{max}} = \ln \frac{E_0}{E_c} / \ln 2
\]

\( t_{\text{max}} \propto \ln \left( \frac{E_0}{E_c} \right) \)

Detectable signal:

\( L_{\text{charged}} \propto \frac{E_0}{E_c} \)

Simulation: EGS4, GEANT

\( t_{\text{max}} \approx \ln(y) + \begin{cases} -0.5 & e^- \\ +0.5 & \gamma \end{cases} \)

\( t(>95\%) \approx t_{\text{max}} + 0.08Z + 9.6 \)

Fluctuations: mid of cascade

\( \sigma N \approx N \Rightarrow t_{\text{calor}} \sim t(>95\%) \)
Electromagnetic Shower: transverse size

Molière radius: \( R_M = \frac{X_0 \cdot 21 \text{MeV}}{E_c} \)

\( R < 2 \cdot R_M \) contains 95% of the shower
<table>
<thead>
<tr>
<th>Material</th>
<th>Density $g/cm^3$</th>
<th>$X_0$ $g/cm^2$</th>
<th>$X_0$ $cm$</th>
<th>$\lambda_I$ $g/cm^2$</th>
<th>$\lambda_C$ $g/cm^2$</th>
<th>Molière $R_{Mc}cm$</th>
<th>$E_{crit}$ MeV</th>
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<td>W</td>
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<td>0.35</td>
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<td>0.93</td>
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<td>137.</td>
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<td>Plastic Sc.</td>
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## Properties of Materials

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Generic Calorimeter

A matrix of separate elements:

\[ E = \sum_{i \in k \times k} E_i \]

Typically \( k = 3, 5 \)

\[ E_i = \alpha_i \cdot A_i \]

\[ x|y = f(., x_i|y_i, E_i, ..) \]

\[ \vec{X}_0 \Rightarrow \text{direction} \]

Important Characteristics

- Energy resolution \( \frac{\sigma_E}{E} \)
- Coordinate resolution \( \sigma_X \)

Measured:
- \( A_i \) - measured amplitudes
- \( \alpha_i \) - calibration factors
  (slow variation)
- \( x_i|y_i \) - module coordinates
Generic Calorimeter

A matrix of separate elements:

\[ E = \sum_{i \in k \times k} \varepsilon_i \]

Typically \( k = 3, 5 \)

\( \varepsilon_i = \alpha_i \cdot A_i \)

\( x|y = f(\ldots, x_i|y_i, E_i, \ldots) \)

\( \vec{x}_0 \Rightarrow \text{direction} \)

**Important Characteristics**

- Energy resolution \( \frac{\sigma_E}{E} \)
- Coordinate resolution \( \sigma_x \)
- Linearity
- Timing resolution
- Stability
- Specific requirements: radiation hardness, mag. field
- Cost

Measured:
- \( A_i \) - measured amplitudes
- \( \alpha_i \) - calibration factors (slow variation)
- \( x_i|y_i \) - module coordinates

Interaction point

\( X_0 \)
Important procedures

- Calibration: \( A_i \) - measured
  \( \rightarrow E_i = \alpha_i \cdot A_i. \)
  \( \alpha_i \) have to be measured using particles of known energies.
- Monitoring of the calibration factors \( \alpha_i \) using detector response to a simple excitation (ex: light from a stable source).
Consider: EM shower in plastic scintillator
Needed length $15 \cdot X_0 = 600$ cm - not practical!

**Homogeneous calorimeters**

Heavy active material, no passive absorber
- Best energy resolution
- Higher cost

**Sampling calorimeters**

Heavy material absorber and the active material are interleaved.
Features:
- Compact
- Relatively cheap
- Sampling fluctuations $\Rightarrow$ impact on $\sigma_E / E$
Example: energy resolution of a sampling ECAL at ALICE

\[ J. \text{ Allen et al., NIMA 615, 6 (2010)} \]
Resolutions

Energy resolution

\[
\frac{\sigma E}{E} = \alpha \oplus \frac{\beta}{\sqrt{E}} \oplus \frac{\gamma}{E}
\]

- \( \alpha \) - constant term (calibration)
- \( \beta \) - stochastic term (signal/shower fluctuations)
- \( \gamma \) - noise

Spatial resolution

\[
\sigma X = \alpha_1 \oplus \frac{\beta_1}{\sqrt{E}}
\]
Energy resolution

- Fluctuations of the track length (EM): \( \frac{\sigma_E}{E} \sim \frac{0.005}{\sqrt{E}} \)
- Statistics of the observed signal (EM): \( \frac{\sigma_E}{E} > \frac{0.01}{\sqrt{E}} \)
- Sampling fluctuations (EM): Typically \( \frac{\sigma_E}{E} > \frac{0.05}{\sqrt{E}} \)
  \[
  \frac{\sigma_E}{E} \sim \frac{\sqrt{E_c \cdot t}}{\sqrt{E}}, \text{ where } t \text{ is the layer thickness in } X_0 \text{ (B.Rossi)},
  \sim \frac{0.1 \cdot \sqrt{t}}{\sqrt{E(\text{GeV})}} \text{ for lead absorber } (t > 0.2),
\]
- Noise, pedestal fluctuations \( \frac{\sigma_E}{E} < \frac{0.01}{E} \)
- Calibration drifts \( \frac{\sigma_E}{E} \sim 0.01 \) for a large detector
- Other ...
Spacial resolution

- Module lateral size $< \text{shower size}$
- Calculating the shower centroid
- EM: $\sigma x > 0.05 \cdot R_M$
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Light Collecting Homogeneous EM Calorimeters

Heavy transparent materials (small $X_0$) are preferable ⇒ compact, larger signal
- Heavy crystal scintillators: NaI, CsI, BGO, PbW etc: high light yield ⇒ good resolution, expensive
- Heavy crystal Cherenkov detectors: PbF, etc: compact, radiation hard
- Lead glass (SiO ⇌ PbO) Cherenkov detectors: medium performance, affordable

Light collection 20 - 50%

Timing resolution:
- Scintillation time
- Light bouncing
- Photodetector
- Readout electronics
- Typically: $\sim 1$ ns

Signal length:
$\tau(90\%) \sim 100$ ns for Cherenkov detectors
Light Collecting Sampling EM Calorimeters

Heavy absorber (Pb,Cu,W...) and a scintillator (plastic) or Cherenkov radiator (quartz fibers ...). Problem: how to collect the light? The most popular solutions for this moment:

- **SPACAL (Pb, sc. fibers).** The fibers can be bundled to the PM. Very good resolution. Difficult to manufacture.

- **Sandwich with WLS fibers crossing through ("shashlyk").** The fibers are bundled to the PM. Good resolution. Easy to build.

![Diagram of light collection system]

**Timing resolution:**
- Scintillation time
- Photodetector time
- Electronics
- Typically: $< 1$ ns

**Signal length:**
$\tau(90\%) \sim 50$ ns
Resolution of Sampling Calorimeters

R.Wigmans Prog.Part.Nucl.Phys. 103, 119 (2018): $\beta \propto \sqrt{d_{\text{act}}/f_{\text{samp}}}$, where:

- $\beta$ - stochastic term of the energy resolution $\frac{\sigma_E}{E} = \alpha \oplus \frac{\beta}{\sqrt{E}} \oplus \gamma_E$
- $d_{\text{act}}$ - thickness of 1 layer of the active material (in mm)
- $f_{\text{samp}}$ - sampling fraction, fraction of the full energy released in the active material

Approximately $d_{\text{act}}/f_{\text{samp}} \propto d_{\text{absorber}}$ - thickness of the absorber layer

![Graph showing energy resolution stochastic term $\beta$ vs $\sqrt{d_{\text{act}}/f_{\text{samp}}}$ for various experiments.]
## Light Detectors

### Photomultiplier Tubes (PMT)
A vacuum vessel with a photocathode and a set of electrodes (dynodes) for electron multiplication.
- Very high gain $\sim 10^5 - 10^7$
- Very low electronic noise
- Size: diameter 2-40 cm
- Radiation hard
- Sensitive to magnetic field
- Slow drift of the gain
- Relatively low QE $\sim 20\%$

### Avalanche Photodiodes (APD)
A silicon diode in avalanche mode and an electronic amplifier
- Not sensitive to magnetic field
- High QE $\sim 75\%$ at 430 nm
- Gain $\sim 50 - 300$
- High electronic noise
- Size: $1 \times 2$ cm$^2$
- Sensitive to the bias voltage
- Temperature sensitive -2%/K
- Radiation hardness may be a problem

### Silicon Photomultiplier (SiPM)
- Not sensitive to magnetic field
- High gain $\sim 10^6$
- Radiation hardness
- Non linear
Detector technology: Silicon Photomultiplier (SiPM)

**Introduction**

- Silicon Photo Multiplier (SiPM) is a new type of photon-counting device made up of multiple Avalanche Photo Diode (APD) pixels operating in Geiger mode. Each APD pixel outputs a pulse signal when it detects one or more photons, and the output of the SiPM is the total sum of all these pulses.

**New Popular Photosensor:** planned to be used at many projects instead of PMTs

- Matrix of pixels: APDs in the Geiger mode
- PDE (QE \times packing factor) \sim 20\%
- Gain \sim 10^6
- Immune to magnetic field
- Timing resolution < 100 ps
- Noise (temperature dependent)
- Small size, now \sim 12 \times 12 \text{ mm}^2
- Limited range of the gain
- Non-linearity
- Radiation hardness

**Damage Curve**

- Radiation damage does NOT depend on temperature
- Radiation damage does NOT depend on previous irradiations

**Extensive study of Rad. hardness**

- Affected by neutron radiation
- Noise increase \propto \text{ eff. fluence}
- No other serious effects
- Self-annealing: a factor of 0.5
- Self-annealing - better at higher temperature
Crystals in big experiments

BaBar CsI(Tl) $\sim 10000$

L3 BGO $\sim 11000$

CMS PbWO $\sim 80000$

0 cm

20 cm
EM calorimeters with optical readout

<table>
<thead>
<tr>
<th>Material</th>
<th>Density $g/cm^3$</th>
<th>$X_0$ cm</th>
<th>$R_M$ cm</th>
<th>$\lambda_f$ cm</th>
<th>Refr. index</th>
<th>$\tau$ ns</th>
<th>Peak $\lambda$ nm</th>
<th>Light yield</th>
<th>$N_{p.e.}$ GeV</th>
<th>rad</th>
<th>$\sigma E/E$</th>
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<td>Crystals</td>
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<td>NaI(Tl)**</td>
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<td>41.4</td>
<td>1.85</td>
<td>250</td>
<td>410</td>
<td>1.00</td>
<td>$10^6$</td>
<td>$10^2$</td>
<td>1.5%/E$^{1/4}$</td>
</tr>
<tr>
<td>CsI *</td>
<td>4.53</td>
<td>1.85</td>
<td>3.8</td>
<td>36.5</td>
<td>1.80</td>
<td>30</td>
<td>420</td>
<td>0.05</td>
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<td>CsI(Tl)*</td>
<td>4.53</td>
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<td>BGO</td>
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<td>22.0</td>
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<td>300</td>
<td>480</td>
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<td>$10^5$</td>
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<td>2.0%/E$^{1/2}$</td>
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<td>PbWO$_4$</td>
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<td>0.89</td>
<td>2.2</td>
<td>22.4</td>
<td>2.30</td>
<td>5/39%</td>
<td>420</td>
<td>0.013</td>
<td>$10^4$</td>
<td>$10^6$</td>
<td>1.5%/E$^{1/2}$</td>
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<td>LSO</td>
<td>7.40</td>
<td>1.14</td>
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<td>1.81</td>
<td>40</td>
<td>100/01%</td>
<td>440</td>
<td>0.7</td>
<td>$10^6$</td>
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<td>PbF$_2$</td>
<td>7.77</td>
<td>0.93</td>
<td>2.2</td>
<td>1.82</td>
<td>Cher</td>
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<td>0.001</td>
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<td>Lead glass</td>
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</table>

* - hygroscopic
## EM calorimeters with optical readout

<table>
<thead>
<tr>
<th>Material</th>
<th>Density $g/cm^3$</th>
<th>$X_0$ cm</th>
<th>$R_M$ cm</th>
<th>$\lambda_I$ cm</th>
<th>Refr. index</th>
<th>$\tau$ ns</th>
<th>Peak $\lambda$ nm</th>
<th>Light yield</th>
<th>$N_p,e.$ GeV</th>
<th>rad</th>
<th>$\sigma E/E$</th>
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<tbody>
<tr>
<td><strong>Crystals</strong></td>
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<td>NaI(Tl)**</td>
<td>3.67</td>
<td>2.59</td>
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<td>1.85</td>
<td>250</td>
<td>410</td>
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<td>1.5%/E$^{1/4}$</td>
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<td>1.85</td>
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Crystal Ball (SLAC, DESY, Mainz)

- ~ 600 NaI crystals
- $\gamma$ detection
- Charmonia spectra $\Rightarrow$ QCD tune!
Crystal Ball (SLAC, DESY, Mainz)

Now at Mainz

- ~ 600 NaI crystals
- $\gamma$ detection
- Charmonia spectra $\Rightarrow$ QCD tune!
- ~ 10000 CsI(Tl) crystals
- $\sigma E/E \approx 2.3%/E^{1/4} + 1.9%$
JLab: big projects using PbWO$_4$ crystals

PrimeX PRAD Hall B

PrimeX
1000 crystals
$\sigma E/E \approx 2.0\% \sqrt{E} + 0.5\%$
600 lead glass blocks

NPS Hall C

NPS
1080 crystals
Very high intensity

FCAL2 Hall D

FCAL2
1600 crystals $2 \times 2 \times 20\text{cm}^3$ $20X_0$
2400 lead glass blocks
$4 \times 4 \times 45\text{cm}^3$ $14.5X_0$

E.Chudakov
July 2024

Electromagnetic Calorimeters
The crystals provide:

- Twice better energy and spacial resolution
- Better radiation hardness
4.1 Description of the ECAL

- ~70000 PbWO₄ crystals
- 4500 photons/GeV
- APD readout
Scintillating fibers / lead matrix

- Fibers/lead 50% / 50% in volume
- $X_0 = 1.2$ cm
- 5 g/cm$^3$

- CERN - original R&D
- KLOE (DAFNE) - 5000 PMTs
- KLOE $\sigma E/E \approx 5.7\%/E^{1/2}$
- KLOE $\sigma_T \approx 50/E^{1/2} + 50$ ps
Barrel Calorimeter in Hall D

- 48 modules 4 m long
- very regular matrix
Shashlyk: Experiment KOPIO

- $\sigma E / E \approx 2.0 \oplus 3.0\% / E^{1/2}$
- $\sigma_T \approx 70 / E^{1/2} \oplus 14 / E$ ps
## Front-End Electronics

### Requirements

- Resolution $\sim 10^{-3}$
- Dynamic range $> 10^2$: needed to measure the shower profile and the coordinates
- Differential linearity $< 1\%$
- Digitization speed ($> 1$ MHz)
- Readout speed ($> 100$ kHz)
- Cost

### Existing generic solutions

- Charge integrating ADC
- Flash ADC
Many products on the market
- Precise: 12-15 bits
- Gate must come in time $\Rightarrow$ long (>300-500 ns) delay for each channel is needed (cables)
- Slow conversion time $> 10 \, \mu s \Rightarrow$ not suitable for trigger logic
- Problems at very high rate: pileup, deadtime
- Pedestal
Flash ADC

- Cost $\times 10$ of the QDC (250 MHz, 12 bits)
- Huge memory buffers needed
- Resolution $n$ bits $\Rightarrow 2^n$ comparators
- Pipeline readout - no dead time
- No delay cables needed
- Pileup can be partially resolved
- Timing resolution without extra discr.& TDCs
- FPGA computing - trigger logic
- Became the mainstream

JLab: 12 bit fADC-250MHz, 16ch in a VXS/VME module

E.Chudakov July 2024 Electromagnetic Calorimeters
The detector has to be calibrated at least once.

- Test beam
- Better: in-situ, using an appropriate process:
  - $e^+e^- \text{ collider: Bhabha scattering } e^+e^- \rightarrow e^+e^-$, $e^+e^- \rightarrow e^+e^-\gamma$
  - LHC: $Z \rightarrow e^+e^- \ (1 \text{ Hz at low luminosity})$
  - $h+h \rightarrow \pi^0+X, \pi^0 \rightarrow \gamma\gamma$
  - RCS (JLab): $e^-p \rightarrow e^-p$

Procedure: for event $n$:

$$E^{(n)} = \sum_{i \in k \times k} \alpha_i \cdot A_i^{(n)}$$

$$\chi^2 = \sum_n \frac{(E^{(n)} - \sum_{i \in k \times k} \alpha_i \cdot A_i^{(n)})^2}{\sigma_n^2}$$

- System of linear equations
- $\Rightarrow N \times N \text{ matrix - nearly diagonal}$
- Easy to solve
Monitoring

Instabilities:
- All avalanche-type devices tend to drift (PMT, gas amplification ...)
- Optical components may lose transparency
- Temperature dependence
- Many other sources of instability ...

Calibration is typically done once per many days of running ⇒ signal monitoring in between is needed.
**Light collecting devices**

- **Stable pulsed light source:**
  - Xe flash lamp: 1% stability, $>100$ ns pulse
  - Laser: 2-5% stability, $\ll 1$ ns pulse
  - LED: 1-3% stability in thermostat, $>30$ ns pulse
- Usually the light source has to be monitored
- Light distribution
- Material transparency: not easy to monitor ($\lambda$-dependence)
- Scintillation yield - no monitoring this way
Calorimeters are used for:

- Detecting neutrals
- Energy and coordinate measurements
- Trigger
- Separation of hadrons against $e^\pm$, $\gamma$ and muons

The calorimeters are of increasing importance with higher energies. They became the most important/expensive/large detectors in the current big projects (LHC etc).
There are various techniques to build calorimeters for different resolution, price, radiation hardness and other requirements.

The typical energy resolutions are:

- **EM:** from $\frac{\sigma E}{E} \sim \frac{2\%}{\sqrt{E}} \oplus 0.3\%$ for scintillating crystals to about $\frac{\sigma E}{E} \sim \frac{10\%}{\sqrt{E}} \oplus 0.8\%$ for sampling calorimeters.
- **HD calorimeters:** $\frac{\sigma E}{E} \sim \frac{30-50\%}{\sqrt{E}} \oplus 3\%$

The coordinate resolutions could be about 1-3 mm for EM calorimeters and 20-30 mm for HD ones.