# Electromagnetic Calorimeters

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JLab Summer Detector/Computer Lectures

https://userweb.jlab.org/~gen/talks/calor_lect_4.pdf

# Outline

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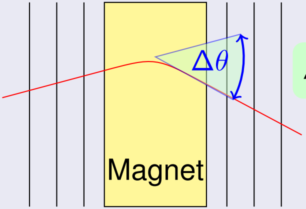
# What is a calorimeter?

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

## Magnetic spectrometers

- Coordinate detectors
- Magnetic field

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




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

Momentum resolution:

$\sigma(P)/P \propto P$ (for large $P$)

## 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. - $E_o$ (heat)
- "Pseudo" C. - $\mathcal{O}(E_o)$: ionization, Cherenkov light

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

# "True" Calorimeters

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

- High particle flux
  - History: W. Orthmann - 1$\mu$W sensitivity; 1930, with L. Meitner they measured the mean energy of $\beta$ from $^{210}$Bi (6% accuracy) $\Rightarrow$ W.Pauli's neutrino hypothesis.
  - 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 $\mathcal{O}(E_o)$: ionization, Cherenkov light

- 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 $\Rightarrow$ affordable ADC (Analog-to-Digital Converters). New accelerators - various types of calorimeters with $\sim 10 \rightarrow 10^5$ ADC channels.

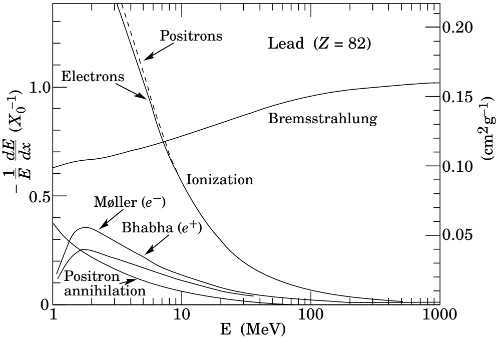
## Applications

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

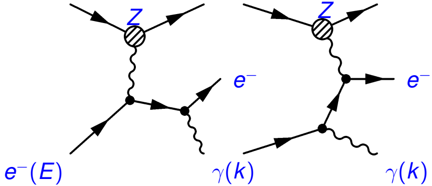
# $e^{\pm}$ interactions

## Energy loss in medium

- Bremsstahlung
  $e^{\pm}Z \rightarrow e^{\pm}\gamma Z$
- Ionization
- Bhabha/Møller scattering
  $e^{\pm}e^{-} \rightarrow e^{\pm}e^{-}$
- $e^{+}$ annihilation




## Bremsstrahlung



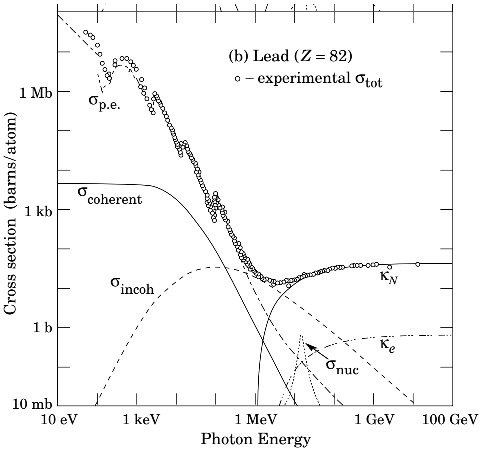

$$\sigma \propto \frac{Z^2}{m^2} \Rightarrow \frac{\sigma_{\mu}}{\sigma_e} \approx 2 \cdot 10^{-5}$$

$$\frac{dN_{\gamma}}{dk} \propto \frac{1}{k} \qquad \frac{dE_{\gamma}}{dk} = c(k)$$

# $\gamma$ interactions

## Interaction in medium

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



# Scaling of Material Properties

## Radiation length

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

$e^{\pm}$: $\frac{dE_{loss}}{dx} \simeq \frac{E}{X_0}$ $\quad$ $\frac{dE_{loss}}{E} \simeq \frac{dx}{X_0}$

$\gamma$: $\lambda_{e^+e^-} \simeq \frac{9}{7} \cdot X_0$

Derived from EM calculations:

$$X_0 \simeq \frac{716\ g{\cdot}cm^{-2}{\cdot}A}{Z(Z+1){\cdot}ln(287/\sqrt{Z})}$$

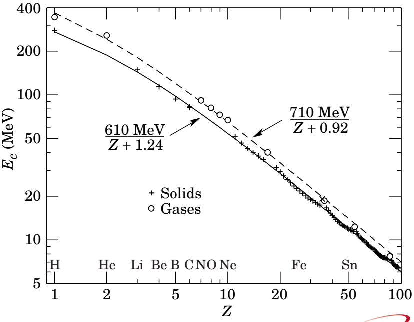
## Critical Energy

$E_c$: cascade stops

Losses: Ionization $=$ Radiation

B.Rossi: $\frac{dE_{ioniz}}{dx}\Big|_{E_c} \simeq \frac{E}{X_0}$

$E_c \simeq \frac{610(710)\ MeV}{Z+1.24(0.92)}$ solids(gasses)



# 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.

# Electromagnetic Shower: longitudinal development

Scaling variables:

$t = \frac{x}{X_0} \quad y = \frac{E}{E_c}$

## Simple model

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

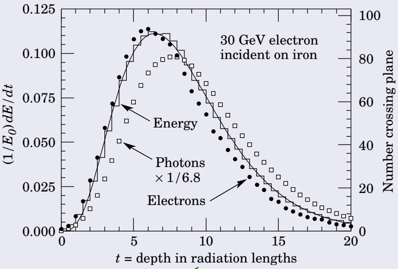
$E(t) = \frac{E_0}{2^t} \Rightarrow t_{max} = ln\frac{E_0}{E_c}/ln\,2$

$t_{max} \propto ln(\frac{E_0}{E_c})$

Detectable signal:

$L_{charged} \propto E_0/E_c$

## Simulation: EGS4, GEANT




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

$t(>95\%) \simeq t_{max} + 0.08Z + 9.6$

Fluctuations: mid of cascade

$\sigma N \simeq N \Rightarrow t_{calor} \sim t(>95\%)$



Jefferson Lab

# Electromagnetic Shower: transverse size

Molière radius: $R_M = \frac{X_0 \cdot 21 MeV}{E_c}$

$R < 2 \cdot R_M$ contains 95% of the shower

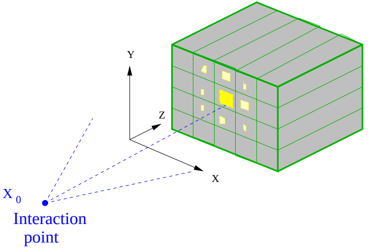
# Properties of Materials

| Material | Density $g/cm^3$ | $X_0$ $g/cm^2$ | $X_0$ $cm$ | $\lambda_I$ $g/cm^2$ | Molière $R_M cm$ | $E_{crit}$ $MeV$ | Refr. index |
|---|---|---|---|---|---|---|---|
| W | 19.3 | 6.5 | 0.35 | 185. | 0.69 | 10.6 | |
| Pb | 11.3 | 6.4 | 0.56 | 194. | 1.22 | 9.6 | |
| Cu | 8.96 | 13. | 1.45 | 134. | 1.15 | 26. | |
| Al | 2.70 | 24. | 8.9 | 106. | 3.3 | 56. | |
| C | 2.25 | 42. | 18.8 | 86. | 3.5 | 111. | |
| Plastic | 1.0 | 44. | 42. | 82. | 6.1 | | 1.58 |
| $H_2$ | 0.07 | 61. | 860. | 50. | 50. | 360. | |

# Outline

# Generic Calorimeter

A matrix of separate elements:




$$E = \sum_{i \in k \times k} \mathcal{E}_i$$

Typically $k = 3, 5$

$\mathcal{E}_i = \alpha_i \cdot A_i$

$x|y = f(.., x_i|y_i, E_i, ..)$

$\vec{X}_0 \Rightarrow$ direction

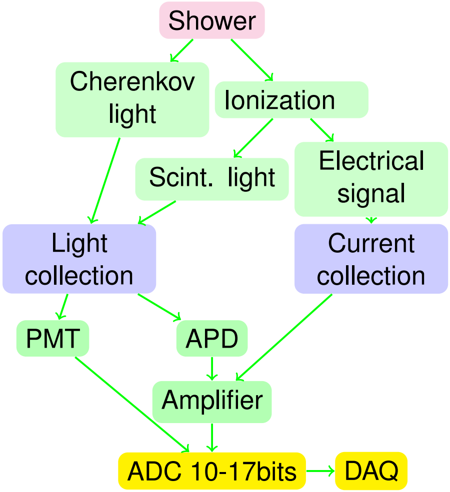
Measured:

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

## Important parameters

- Energy resolution $\frac{\sigma E}{E}$
- Linearity
- Coordinate resolution $\sigma x$
- Timing resolution
- Stability
- Specific requirements: radiation hardness. mag. field
- Cost

# Generic Calorimeter




## 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).

# Homogeneous and Sampling Calorimeters

Consider: EM shower in plastic scintillator
Needed length $\sim 15 \cdot X_0 = 600\ cm$ - not practical!

## Homogeneous calorimeters (EM)

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 $\frac{\sigma E}{E}$

# 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): $\frac{\sigma E}{E} \simeq \frac{0.005}{\sqrt{E}}$
- Statistics of the observed signal (EM): $\frac{\sigma E}{E} > \frac{0.01}{\sqrt{E}}$
- Sampling fluctuations (EM): $\frac{\sigma E}{E} \simeq \frac{\sqrt{E_c \cdot t}}{\sqrt{E}}$, where $t$ is the layer thickness in $X_0$ (B.Rossi),
  $\sim \frac{0.1 \cdot \sqrt{t}}{\sqrt{E}}$ 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

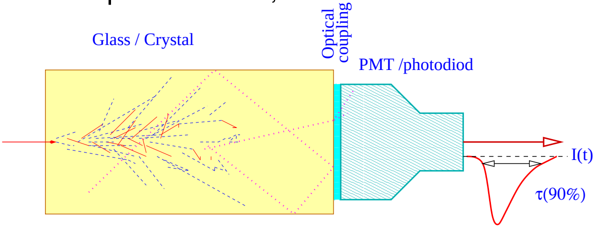
- Module lateral size $<$ shower size
- Calculating the shower centroid
- EM: $\sigma x > 0.05 \cdot R_M$

# Outline

# 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:

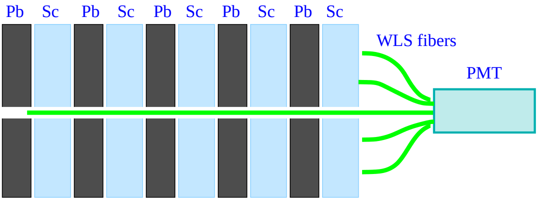
- Scintillation time
- Light bouncing
- Photodetector

Typically:
$\tau(90\%) \sim 100$ 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 (“shashlik”). The fibers are bundled to the PM. Good resolution. Easy to build.




Timing resolution:

- Scintillation time
- Photodetector time

Typically

$\tau(90\%) \sim 50$ ns

# Light Detectors

## Photomultiplier Tubes (PMT)

A vacuum vessel with a photocathode and a set of electrodes (dynodes) for electron multiplication.

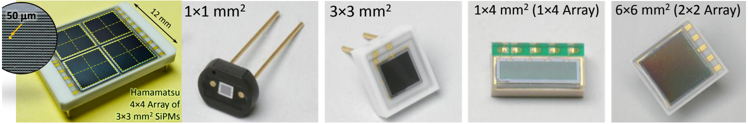
- Very high gain $\sim 10^5 - 10^7$
- Very low electronic noise
- Size: diameter 2-40 cm
- • Slow drift of the gain
- • Sensitive to the magnetic field
- • Relatively low QE$\sim$20%
- Radiation hard

## Avalanche Photodiods (APD)

A silicon diod in avalanche mode and an electronic amplifier

- Gain $\sim 50 - 300$
- • High electronic noise
- • Size: $1 \times 2$ $cm^2$
- • Very sensitve to the bias voltage
- Not sensitive to the magnetic field
- High QE$\sim$75% at 430 nm
- • Temperature sensitive -2%/K
- • Radiation hardness may be a problem

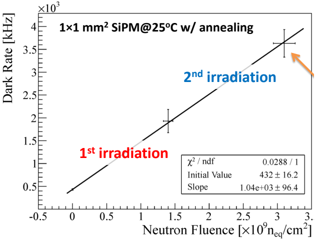
# Detector technology: Silicon Photomultiplier (SiPM)




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

- Matrix of pixels: APDs in the Geiger mode
- PDE (QE × packing factor) ∼20%
- Gain ∼ $10^6$
- Immune to magnetic field
- Timing resolution <100 ps

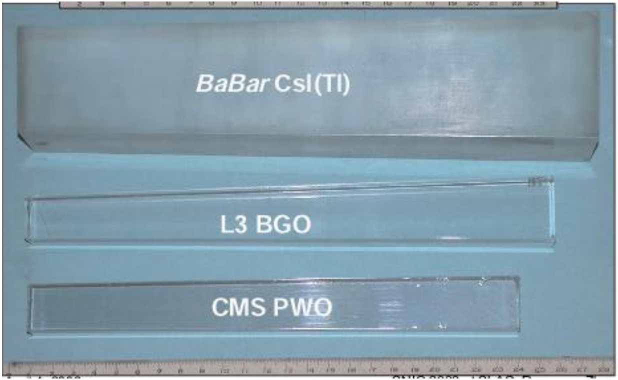
- Noise (temperature dependent)
- Small size, now $<12\times12$ mm$^2$
- Limited range of the gain
- Non-linearity
- Radiation hardness




Extensive study of Rad. hardness

- Affected by neutron radiation
- Noise increase ∝ 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

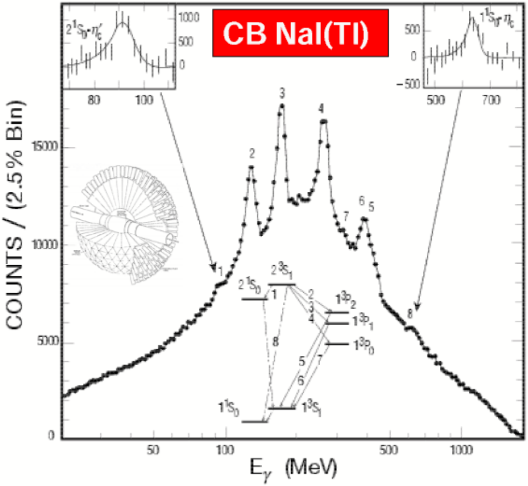
CMS PbWO - $\sim$ 80000

# EM calorimeters with optical readout

| Material | Density $g/cm^3$ | $X_0$ $cm$ | $R_M$ $cm$ | $\lambda_I$ $cm$ | Refr. index | $\tau$ $ns$ | Peak $\lambda$ $nm$ | Light yield | $\frac{N_{p.e.}}{GeV}$ | rad | $\frac{\sigma E}{E}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Crystals | | | | | | | | | | | |
| NaI(Tl)** | 3.67 | 2.59 | 4.5 | 41.4 | 1.85 | 250 | 410 | 1.00 | $10^6$ | $10^2$ | $1.5\%/E^{1/4}$ |
| CsI * | 4.53 | 1.85 | 3.8 | 36.5 | 1.80 | 30 | 420 | 0.05 | $10^4$ | $10^4$ | $2.0\%/E^{1/2}$ |
| CsI(Tl)* | 4.53 | 1.85 | 3.8 | 36.5 | 1.80 | 1200 | 550 | 0.40 | $10^6$ | $10^3$ | $1.5\%/E^{1/2}$ |
| BGO | 7.13 | 1.12 | 2.4 | 22.0 | 2.20 | 300 | 480 | 0.15 | $10^5$ | $10^3$ | $2.\%/E^{1/2}$ |
| $PbWO_4$ | 8.28 | 0.89 | 2.2 | 22.4 | 2.30 | 5/39% | 420 | 0.013 | $10^4$ | $10^6$ | $2.0\%/E^{1/2}$ |
| | | | | | | 15/60% | 440 | | | | |
| | | | | | | 100/01% | | | | | |
| LSO | 7.40 | 1.14 | 2.3 | | 1.81 | 40 | 440 | 0.7 | $10^6$ | $10^6$ | $1.5\%/E^{1/2}$ |
| $PbF_2$ | 7.77 | 0.93 | 2.2 | | 1.82 | Cher | Cher | 0.001 | $10^3$ | $10^6$ | $3.5\%/E^{1/2}$ |
| Lead glass | | | | | | | | | | | |
| TF1 | 3.86 | 2.74 | 4.7 | | 1.647 | Cher | Cher | 0.001 | $10^3$ | $10^3$ | $5.0\%/E^{1/2}$ |
| SF-5 | 4.08 | 2.54 | 4.3 | 21.4 | 1.673 | Cher | Cher | 0.001 | $10^3$ | $10^3$ | $5.0\%/E^{1/2}$ |
| SF57 | 5.51 | 1.54 | 2.6 | | 1.89 | Cher | Cher | 0.001 | $10^3$ | $10^3$ | $5.0\%/E^{1/2}$ |
| Sampling: lead/scintillator | | | | | | | | | | | |
| SPACAL | 5.0 | 1.6 | | | | 5 | 425 | 0.3 | $2\cdot10^4$ | $10^6$ | $6.0\%/E^{1/2}$ |
| Shashlyk | 5.0 | 1.6 | | | | 5 | 425 | 0.3 | $10^3$ | $10^6$ | $10.\%/E^{1/2}$ |
| Shashlyk(K) | 2.8 | 3.5 | 6.0 | | | 5 | 425 | 0.3 | $4\cdot10^5$ | $10^5$ | $3.5\%/E^{1/2}$ |

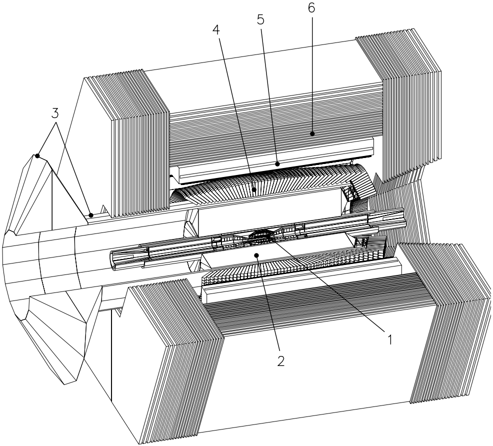
$*$ - hygroscopic

# Crystal Ball (SLAC, DESY)

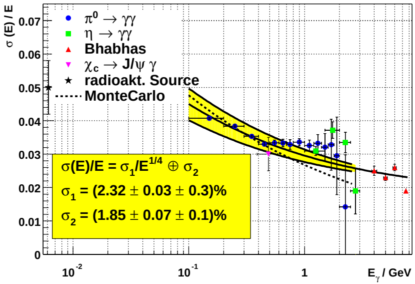



- $\sim$ 600 NaI crystals
- $\gamma$ detection
- Charmonia spectra $\Rightarrow$ QCD tune!

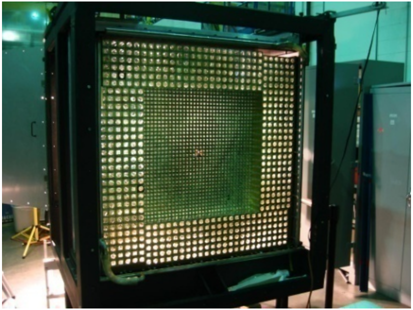
# BaBar (SLAC)




- ∼ 10000 CsI(Tl) crystals
- $\sigma E/E \approx 2.3\%/E^{1/4} + 1.9\%$



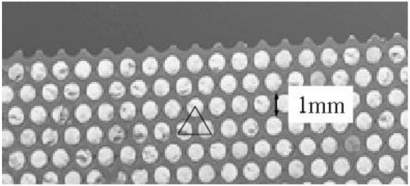
# Primex (JLab)



- $\sim$1000 $PbWO_4$ crystals + $\sim$600 lead glass blocks
- $\sigma E/E \approx 2.0\%\sqrt{E} + 0.5\%$

# SpaCal (CERN, Frascatti, JLab)

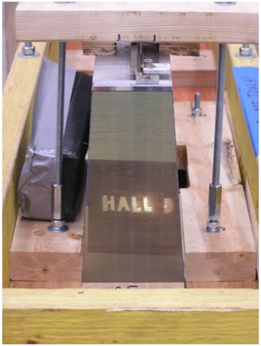
scintillating fibers / lead matrix

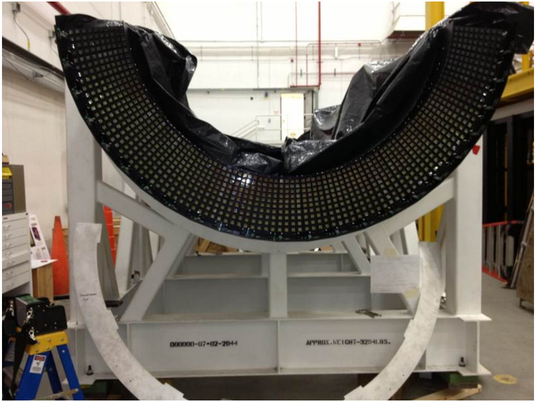



- Fibers/lead 50% / 50% in volume
- $X_{\circ} = 1.2$ cm
- 5 g/cm$^3$

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

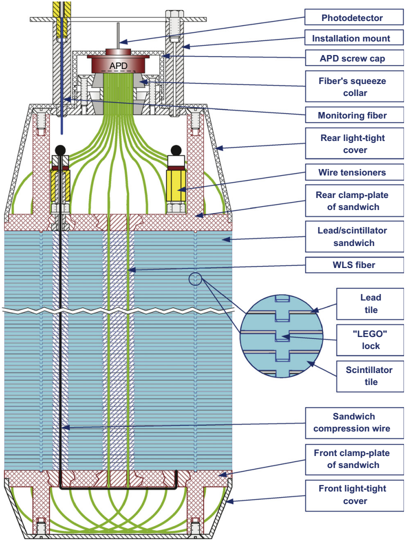
# Barrel Calorimeter in Hall D

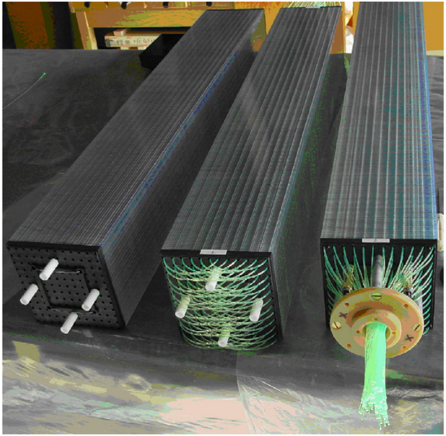


- 48 4 m long modules
- very regular matrix

# Shashlyk: Experiment KOPIO



- $\sigma E/E \approx 2.0 \oplus 3.0\%/E^{1/2}$
- $\sigma\tau \approx 70/E^{1/2} \oplus 14/E$ ps

# Front-End Electronics

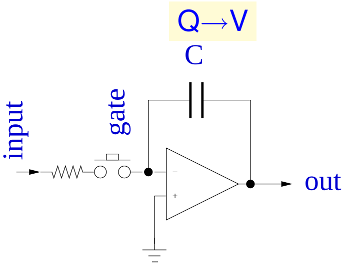
## Requirements

- 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

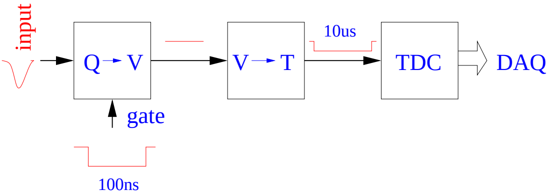
- Charge integrating ADC
- Flash ADC
- Combinations (pipeline ADC)

# Charge Integrating ADC

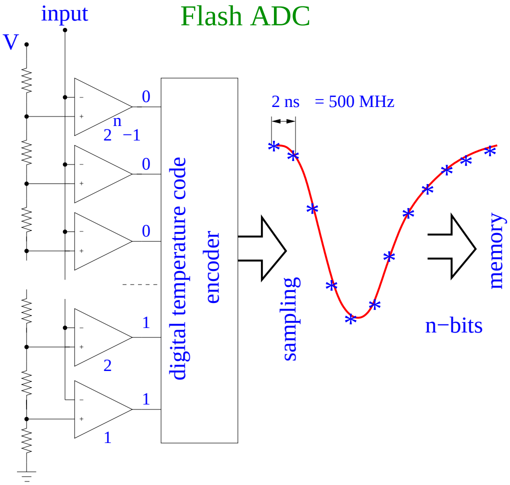



- Many products on the market
- Precise: 12-15 bits
- Gate must come in time ⇒ long (>300-500 ns) delay for each channel is needed (cables)
- Slow conversion time > 10 $\mu s$ ⇒ not suitable for trigger logic
- Problems at very high rate: pileup, deadtime
- Pedestal

Integrating ADC



# Flash ADC




- Cost ×10 of the QDC (250 MHz, 12 bits)
- Huge memory buffers needed
- Resolution n bits ⇒ $2^n$ 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

# Calibration

The detector has to be calibrated at least once.

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

Procedure: for event $n$:

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

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

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

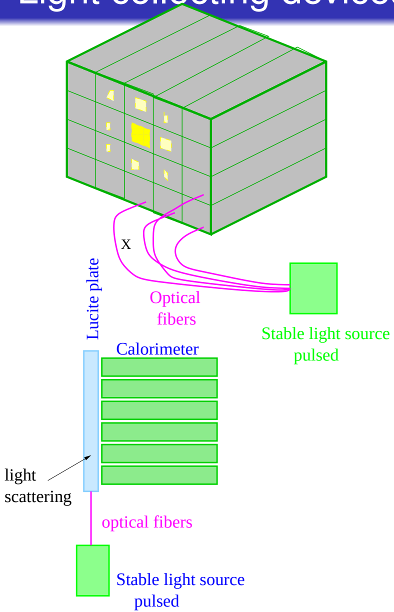
# Monitoring

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 thermostate, $>$30 ns pulse
- Usually the light source has to be monitored
- Light distribution
- Material transparency: not easy to monitor ($\lambda$-dependence)
- Scintillation yield - no monitoring this way

# Summary

**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).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# Summary (continued)

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.