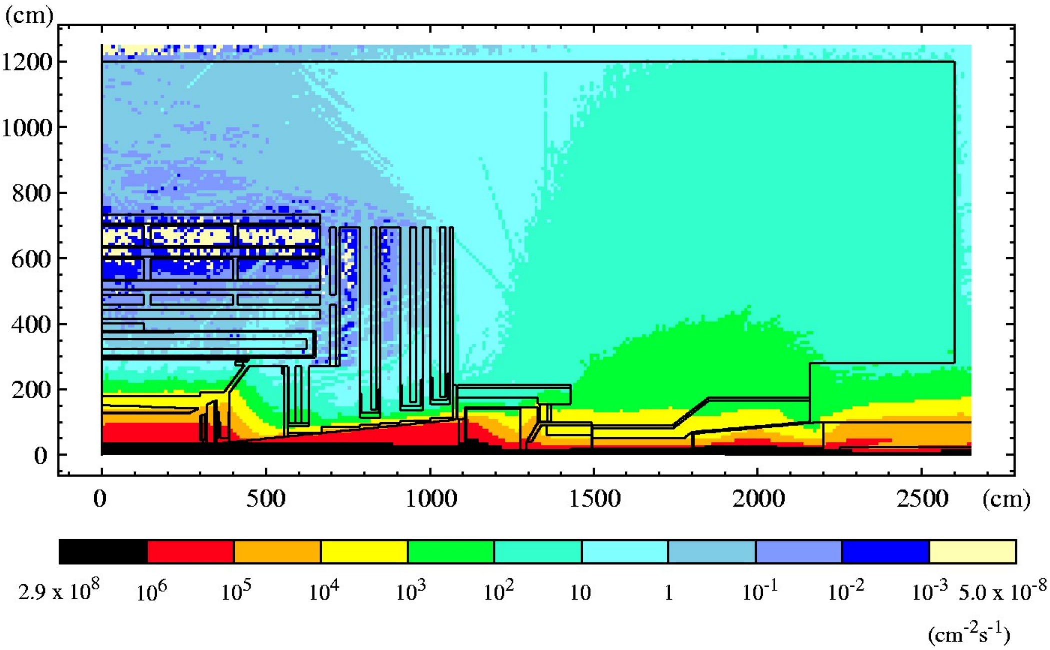
pp physics, RWTH, WS 2003/04, T.Hebbeker

2003-12-17

1.2.2. Detectors - general considerations

The high particle rate at proton colliders implies:

- Detectors (and electronics) must be radiation hard. The expected dose obviously depends very much on the location; it is highest close to the beam pipe in forward/backward direction. The exposure can be measured as deposited energy / mass of exposed material (unit $\mathbf{Gy = J/kg = 100\,rad}$)[1] or in terms of particle fluence (= integrated flux). Which quantity is better suited to characterize a potential damage depends on the type of detector.
  Example: At nominal LHC operation for one year some shielding elements near the detector regions suffer from neutron fluences of up to $\mathbf{10^{16}/m^2}$ *and* $\mathbf{100\,Gy}$*. In the detector itself the dose is lower by at least 2 orders of magnitude.*



The LHC background is particularly high, we will discuss only this case in the following[2]. The background stems mainly from $\mathbf{p\,p}$ collisions in the collision region ($\mathbf{10^{11}}$ particles / second), and not from beam-gas, beam-wall interations and not from synchrotron radiation.
Example: At both ends of the CMS detector two collimators are installed which absorb many particles created at large $\boldsymbol{\eta}$ *values. Each collimator absorbs per event on average* $\mathbf{2.1\,TeV}$ *(exposure from 'inside'!), corresponding to a power of* $\mathbf{2.1\,TeV \cdot 40\,MHz = 13\,W}$.

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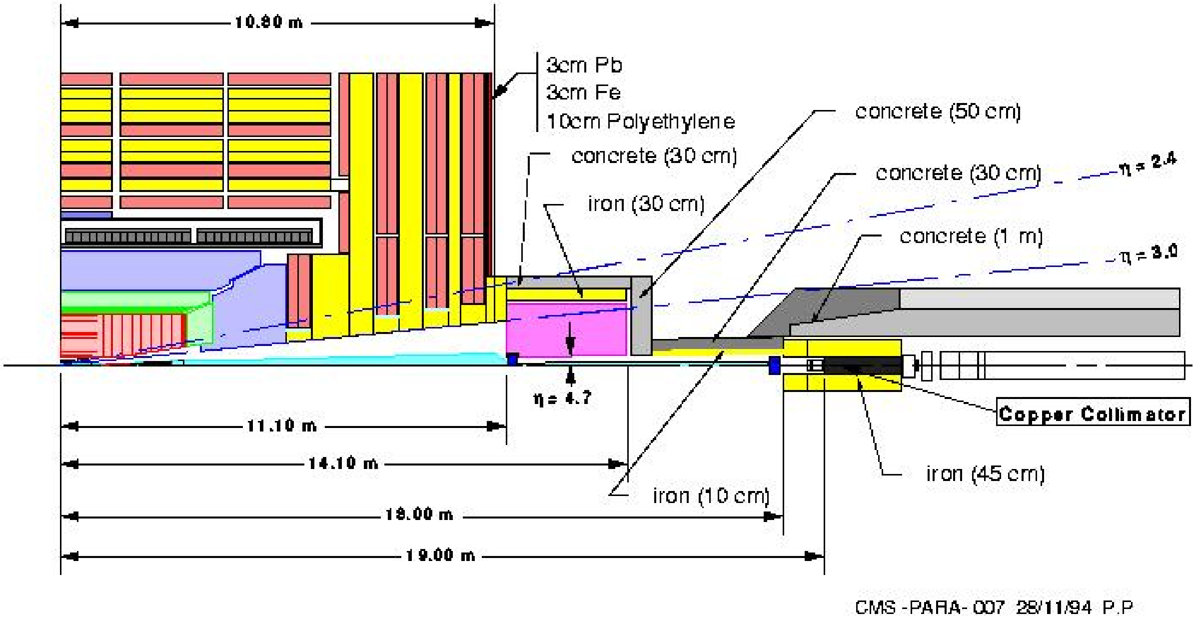
[1] 10 Gy = lethal

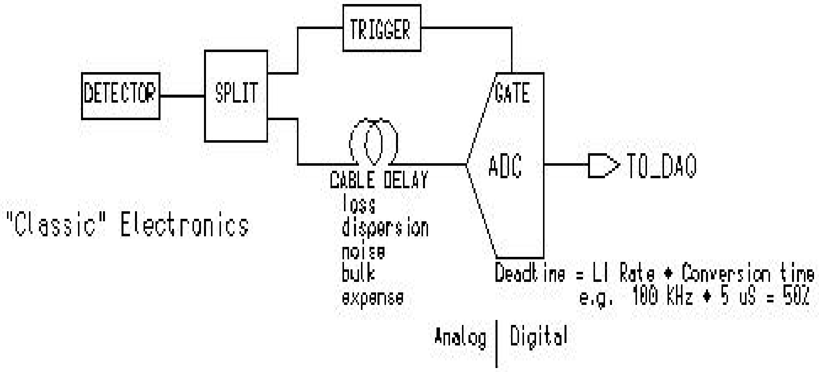
[2] Also at the Tevatron radiation damage plays an important role; the silicon track detectors have an estimated 'lifetime' of only a few $\mathbf{fb^{-1}}$! Even at the SPS detectors degradation due to radiation was an issue - for example the scintillators of the UA2 hadron calorimeter had to be replaced. . .

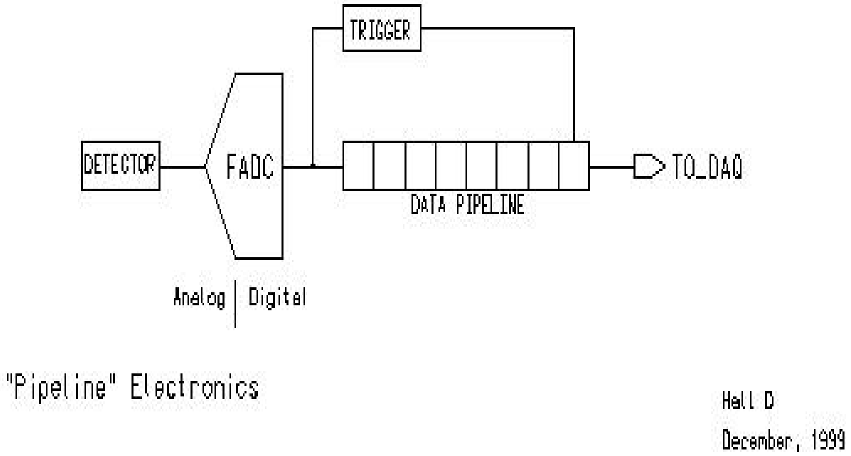


Even those detector elements, which are rather far away from the collision region see a high background rate.
Example: The background in the CMS muon chambers (up to $10\,\mathrm{MHz/m^2}$*) is dominated by low energy electrons from neutron capture and by charged hadrons (and not by muons!)*
In addition to 'normal' radiation a 'catastrophic beam loss' might (should not!) occur, in which case the exposed detector parts or collimators would be locally destroyed. Worst case: All protons ($3 \cdot 10^{14}$) are lost, corresponding to an energy deposit of $0.3\,\mathrm{GJ}$.

- Detectors (and electronics) must be fast; it is desirable to extract the signal before the next bunch crossing arrives. In general this is not possible; since signals overlapping in time can in general not be disentangled, the probability of such overlaps must be kept small. This is quantified by the 'occupancy' O of a given detector cell, this is the probability that at a given moment the cell (not the readout!) is 'busy'. Apart from the speed the cell size (detector granularity) influences the occupancy: the more cells, the better… Modern pp detectors must therefore avoid long drift- or relaxation times and need a huge number of independent detector cells.
  Example: In the CMS barrel muon system a single drift cell 'fires' with a rate of about $f = 10\,\mathrm{kHz}$ *(mainly charged particle background, not muons!). The maximum drift time amounts to* $t = 400\,\mathrm{ns}$*, thus* $O = f\,t < 1\%$*. (Note: ions drift much longer, so a small local E-field distortion will be felt even after a few 1000 bunch crossings!)*
  Counter example: In the TPC (Time Projection Chamber) of the Aleph experiment at LEP the maximum drift time is $55\,\mu\mathrm{s}$*, corresponding to 2000 bunch crossings.*
  Example: ATLAS pixel detector, estimate: The total number of pixel cells ($50\,\mu\mathrm{m} \times 400\,\mu\mathrm{m}$*) is* $\sim 10^8$*. It takes less than* $25\,\mathrm{ns}$ *for the electrons/holes to drift through the depletion layer. Since each bunch crossing produces 'only'* ~ 1000 *particles traversing the pixel detector, the cell occupancy is negligible.*

- The detector signals must be kept till a trigger decision has been made. This can last of the order of milliseconds, so a 'pipeline' storage system is needed:





1.2.3. Calorimeters

Important aspects:

- electromagnetic / hadronic
- sampling or homogeneous
- compensation (jets)
- readout (light, charge)
- speed

- energy resolution
- spatial resolution / transverse sampling (granularity)
- longitudinal sampling (electron-hadron separation)
- absolute energy scale

- η coverage, hermeticity

What matters in particular for the data analysis are energy and spatial resolution.
Example: Invariant mass of high energy particle pair:

$$m^2 = 2\,E_1\,E_2\,(1-\cos\theta_{12}) \quad \longrightarrow \;(\theta_{12} \ll 1) \quad \longrightarrow m^2 = E_1\,E_2\,\theta_{12}^2 \tag{1}$$

The energy resolution can be parametrised in the following way:

$$\frac{\Delta E}{E} = \frac{A}{\sqrt{E/\mathrm{GeV}}} \oplus \frac{B}{E/\mathrm{GeV}} \oplus C \tag{2}$$

The sampling constant A describes the intrinsic shower fluctuations (number of particles N etc.), the variation of the sampling fraction and the ionization/photoelectron statistics. Due to the statistical nature and the relation $N \sim E$, the sampling term decreases with $\sqrt{E}$. Electronic and other sources of noise effectively contribute an energy offset (B) with size independent of E, thus the relative influence drops with $1/E$. Calibration uncertainties and material inhomogeneities lead to a constant term C, which dominates at high energy.

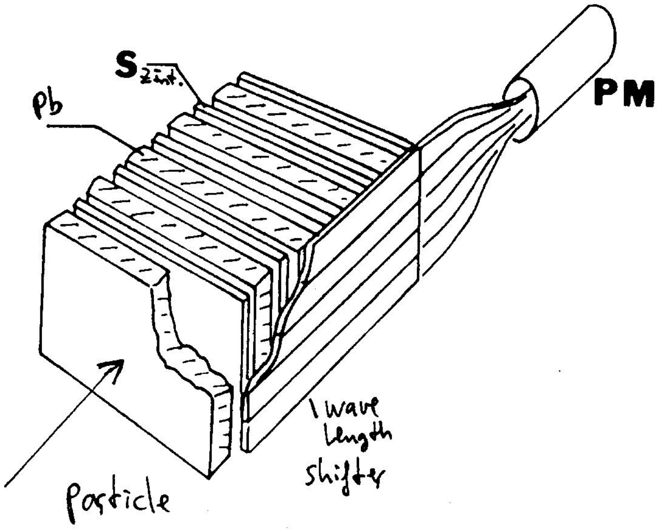
Good electromagnetic calorimeters reach $A \sim 10\%$, $B = 0.5$ (GeV !), $C = 1\%$.
Hadron calorimeters are considered good if $A \sim 50\%$, $B = 1$ (GeV !), $C = 5\%$.

Also the position resolution improves with energy.

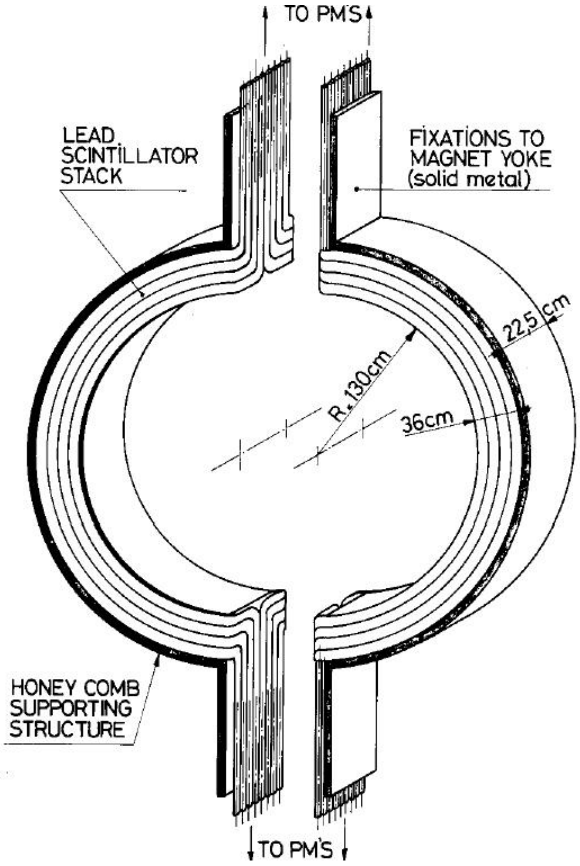
Electromagnetic (hadronic) detectors must have a thickness of approx. $20\,X_0$ $(10\,\lambda)$ in order to absorb the shower completely. X_0 (λ) denotes the radiation length (absorption length). These material constants should be small to allow for a compact calorimeter design. 'Classical' materials for the passive layers in sampling calorimeters are lead (high Z) and iron (high density, easy to handle).

In the following I will first describe the various calorimeter concepts used in the six pp detectors and then I try to compare and evaluate.

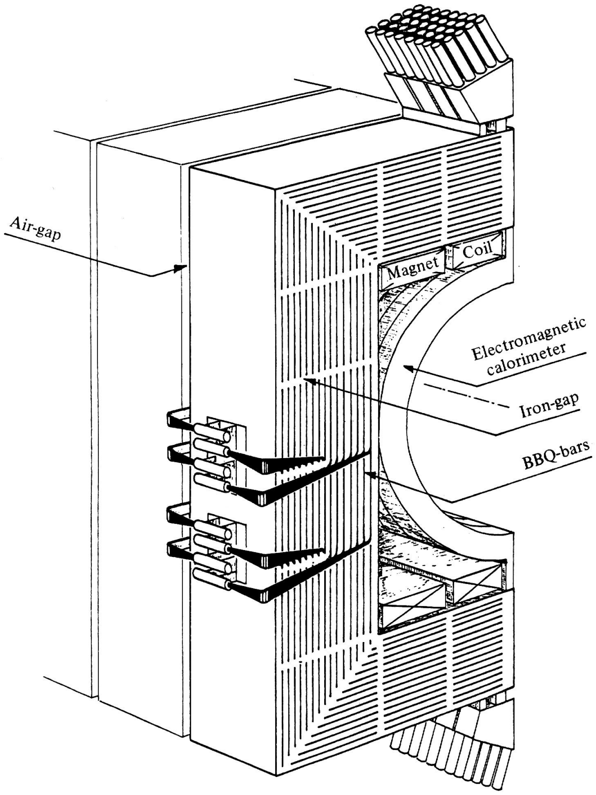
The **UA1** experiment uses 'classical' lead-scintillator and lead-iron (magnet yoke) sampling calorimeters with PM readout. New was at that time the light transport via wavelength shifting fibres, which avoids large dead regions:



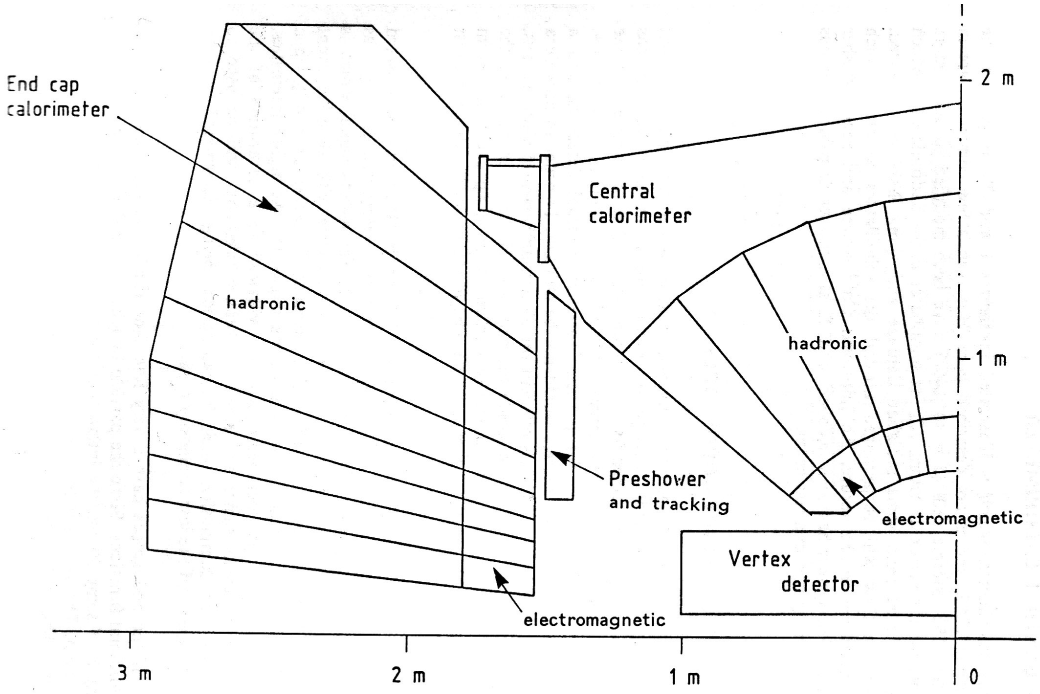
‘Gondolas’ (elm):

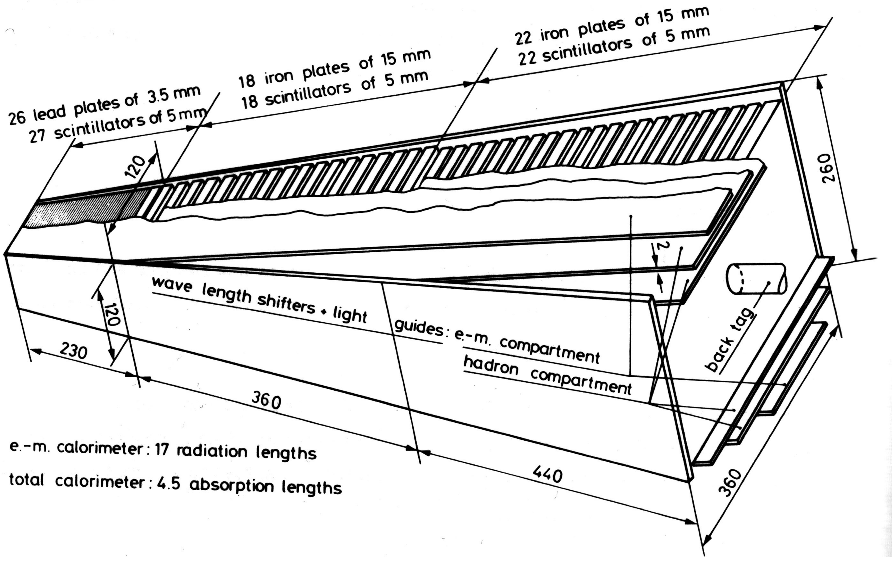


Hadron calorimeter:



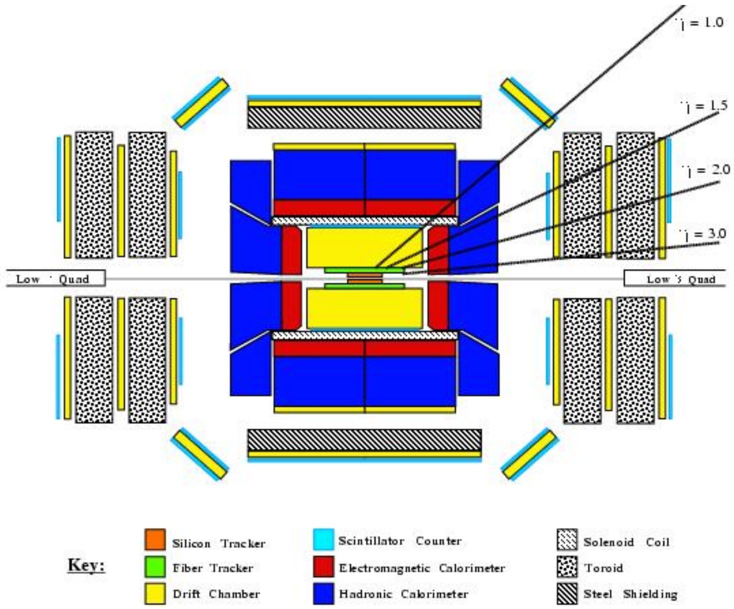
The **UA2** detector employs similar techniques:



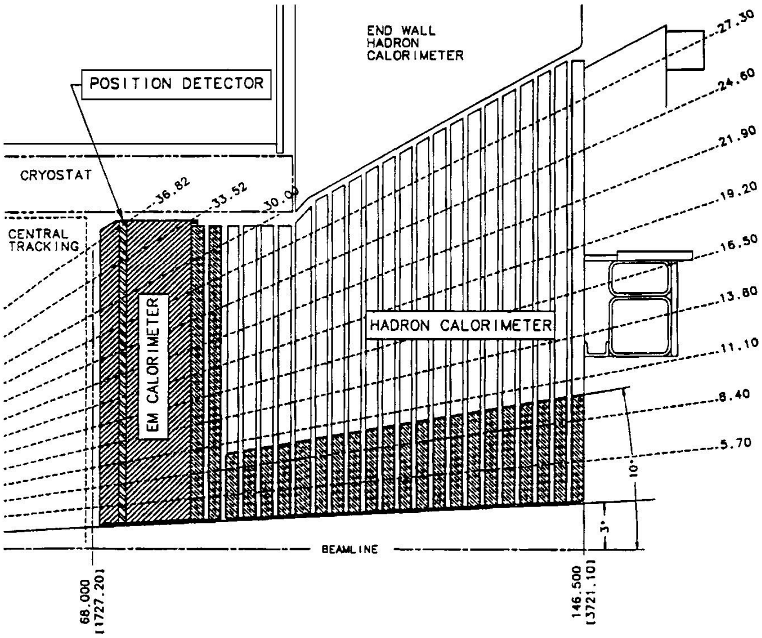


Some numbers about the structure:
electromagnetic endcap calorimeter: 33 alternating layers of lead (3 mm) and scintillator (4 mm).
hadronic endcap calorimeter: 38 alternating layers of iron (25 mm) and scintillator (4 mm).

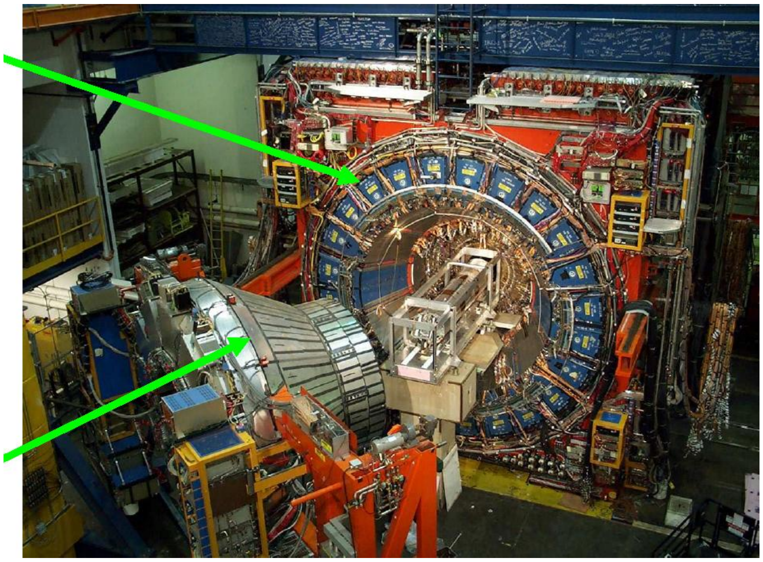
Also the **CDF** experiment



uses sampling calorimeters based on lead/iron and scintillators, both in the central and in the endcap regions, the latter is shown here:



The photo shows both parts:

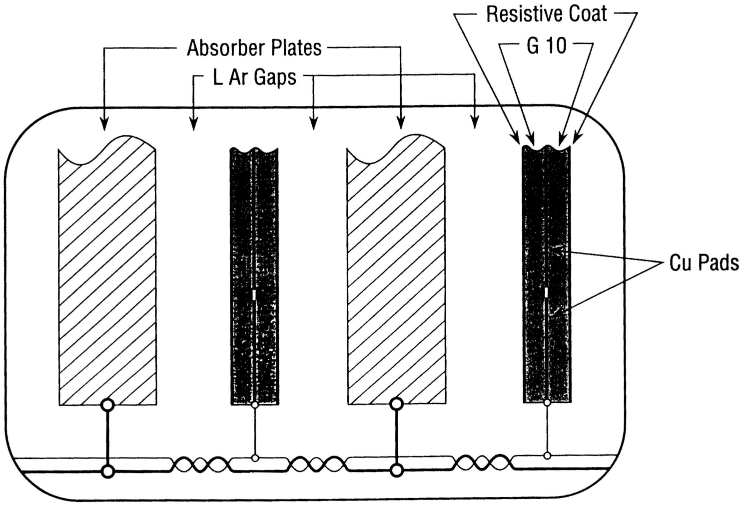


The light is collected by wavelength shifting plates and measured with PMs. In the endcap calorimeter wavelength shifting fibres are used (more on this technique see below, CMS).

Both the central and the endcap calorimeters have one position detector (chamber, scintillator strips) inserted where electromagnetic showers reach their maximum energy deposit, in order to separate π^0's and single photons.

Note that the endcap calorimeter is new, the older version used chambers for the readout, but they were too slow for Tevatron run II.

The **D0** calorimeter is quite different from the detectors discussed so far: It uses the ionization in liquid argon. Principle:



The liquid argon gaps are only $\mathbf{2.3\,mm}$ thick. The electric field between absorber and signal boards ($\sim \mathbf{2.5\,kV}$) leads to electron drift times $< \mathbf{450\,ns}$[3] ($\approx \boldsymbol{\Delta t}$ between bunch crossings!).

(Dis-)Advantages of this technique:

- \+ high number of electron-ion pairs $(\mathbf{5 \cdot 10^4/MeV})$[4] → small fluctuations → good energy resolution
- \- requires cryostat $(\boldsymbol{T} < \mathbf{87\,K})$
- \+ excellent homogeneity and hermiticity
- \+ high granularity possible
- \- slow
- \- repair difficult
- \+ radiation hard

In principle one could use other liquids, either other noble gases or maybe substances which are liquid at room temperature. However, the latter ones require a very high purity (to avoid absorption of the electrons), which is technically difficult to achieve.

D0 calorimeter:

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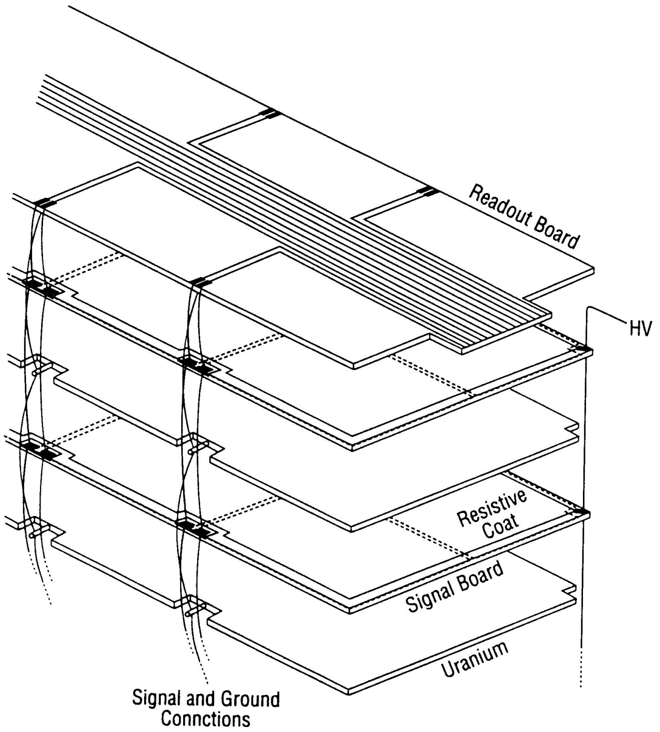
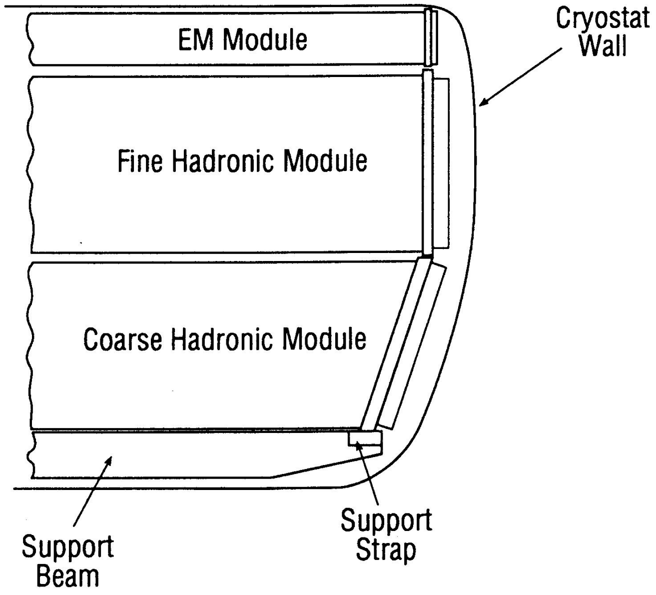
[3] scintillators: few $\mathbf{ns}$!

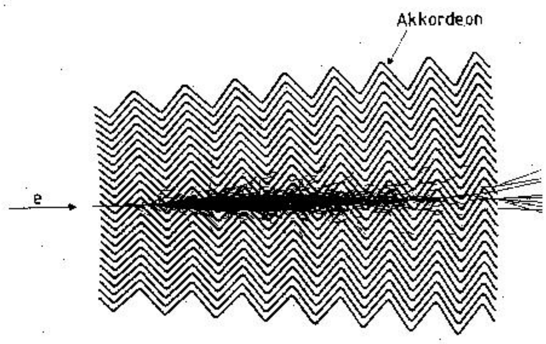
[4] compare scintillators: $\mathbf{10^4}$ primary photons $/\mathbf{MeV}$.

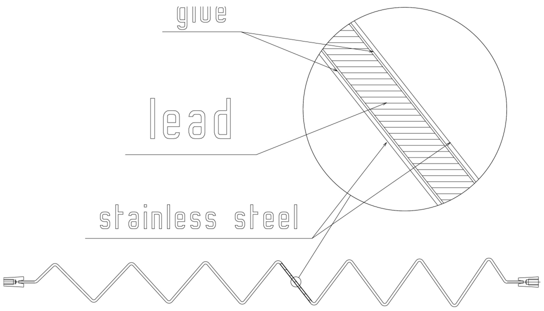




The electromagnetic and the first hadronic compartment are made out of uranium absorber, the coarse hadronic module uses copper and stainless steel.

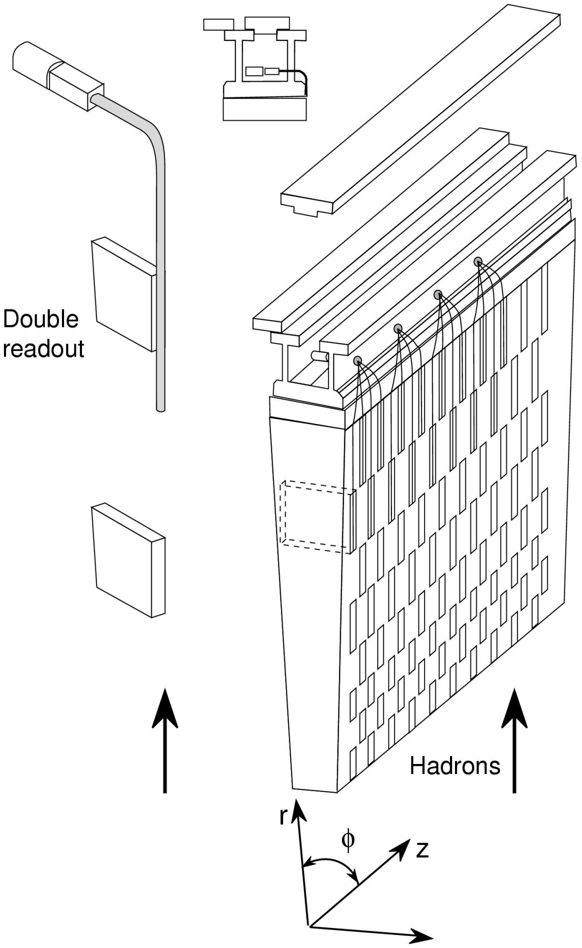
Also the **ATLAS** electromagnetic calorimeter is of liquid Argon (LAr) type, with accordion geometry:





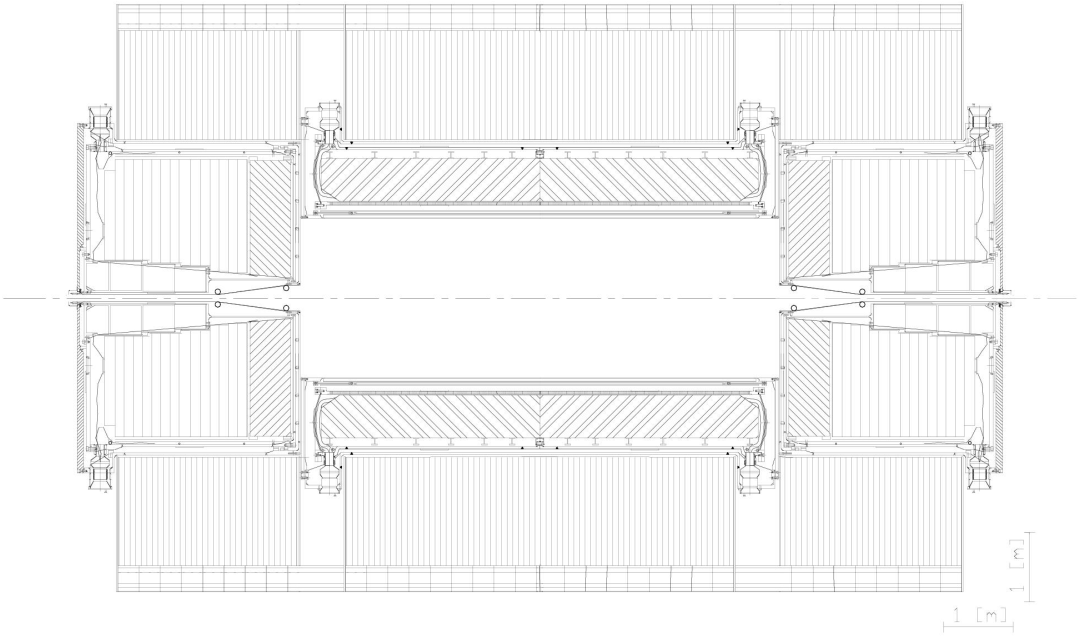
Absorber material is lead. The endcap hadron calorimeter is made of iron plates and LAr.

The barrel hadron calorimeter uses iron absorber plates (parallel to incoming particles) and scintillator plates, read out via wavelength shifting fibres and PMs:

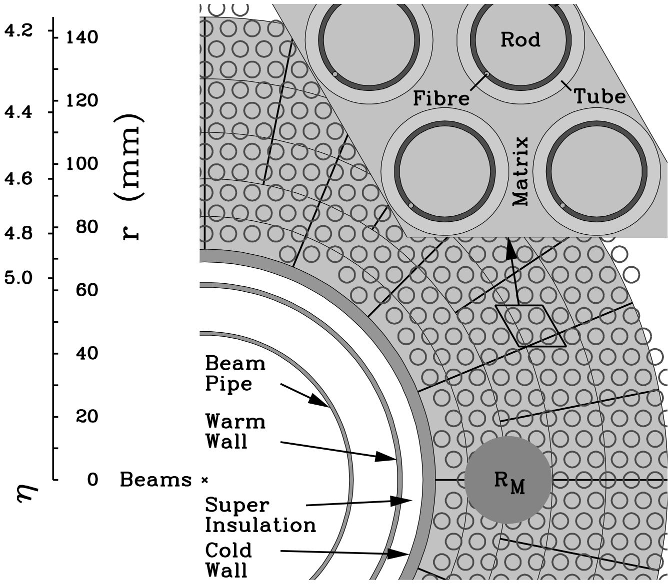


This is called a ‘tile calorimeter’; note that the incoming particles move parallel to the scintillator plates. The light yield is approximately 40 photoelectrons per GeV.

Global view of the ATLAS calorimeter:

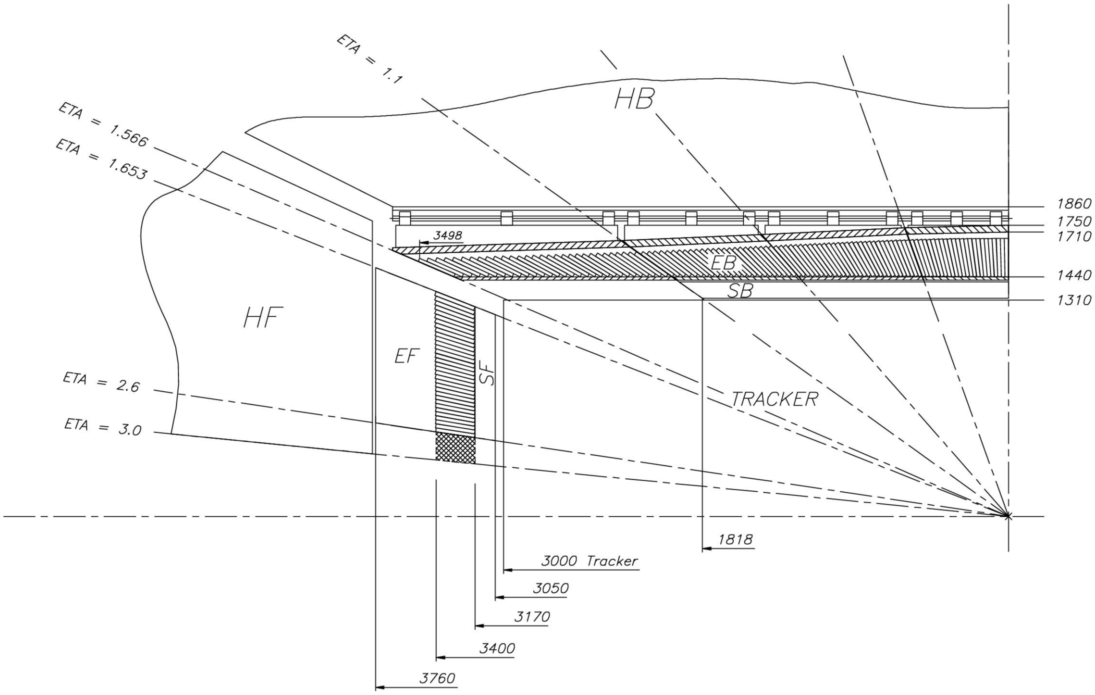


Near the beam pipe the forward calorimeter can be seen, which is also an LAr type detector, but of another geometry:



Only the small gaps between ‘rod’ and ‘tube’ are filled by Liquid Argon. Absorber Materials are copper (elm.) and tungsten alloy (hadr.). This calorimeter is compact and fast.

Quite different is the **CMS** electromagnetic calorimeter. It is *not* a sampling device built out of about 93,000 $\boldsymbol{PbWO_4}$ crystals and thus allows for a very good energy resolution.


ETA = 1.1
ETA = 1.566
ETA = 1.653
ETA = 2.6
ETA = 3.0
HB
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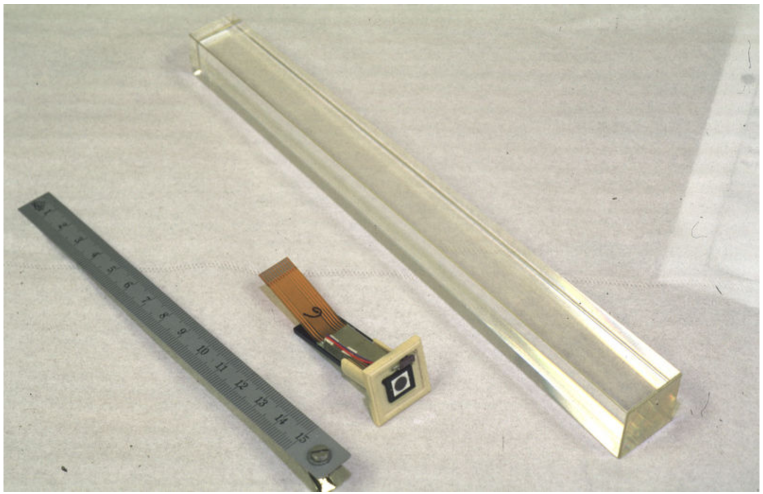

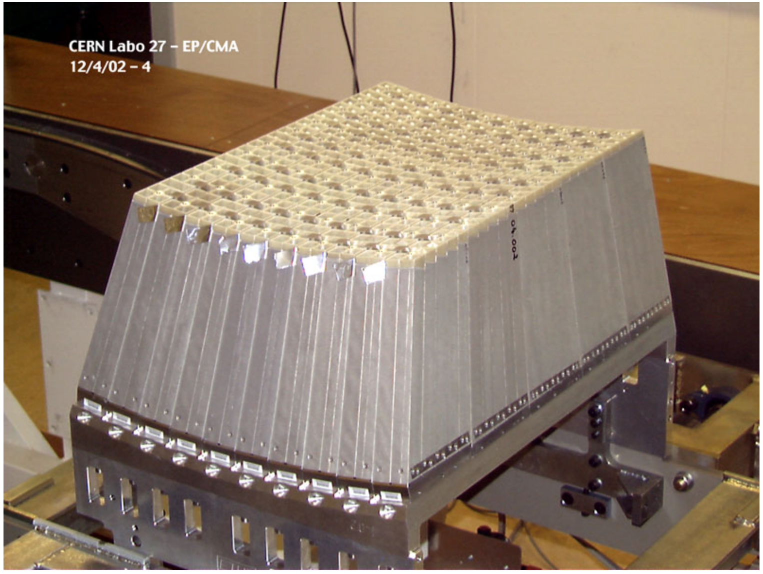
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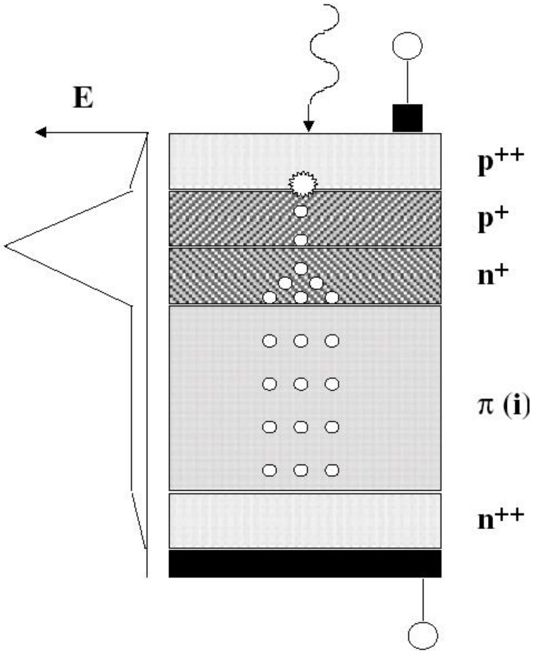
Lead-tungstate is a transparent scintillating material with a very short radiation length of $0.89\,\mathrm{cm}$, allowing for a very compact calorimeter (thickness $\sim\ 23\mathrm{cm}$). The (dis)advantage of $PBWO_4$ compared to other suitable anorganic scintillators are:

+ small radiation length
+ radiation hardness
+ short decay constant (scintillation light pulse) $\sim\ 10\,\mathrm{ns}$
- light yield: $\sim\ 100$ photons $/\mathrm{MeV}$

The latter disadvantage can be overcome by using novel photodetectors[5] with a high quantum efficiency of $>\ 60\%$, 'Avalanche PhotoDiodes' (APD) (of which two are used per crystal):



The strong magnetic field can not deteriorate the performance, since the detectors are very thin (first layer $<\ 100\mu\mathrm{m}$).
Disadvantage of the crystal design: no longitudinal sampling (along shower axis)!

There is another important difference between the ATLAS and CMS calorimeters: In ATLAS the solenoid coil sits in front of the electromagnetic calorimeter, thus degrading the resolution, while in CMS both the elm. and hadr. calorimeters are inside the solenoid coil.

The CMS hadronic calorimeter is made of copper and scintillating tiles:

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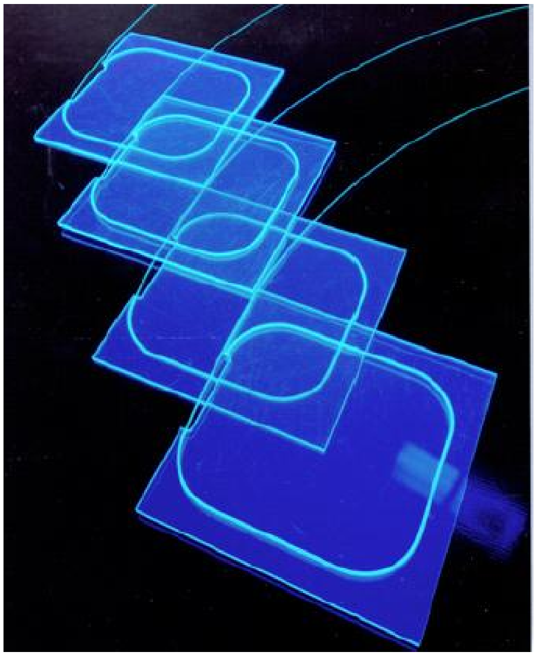
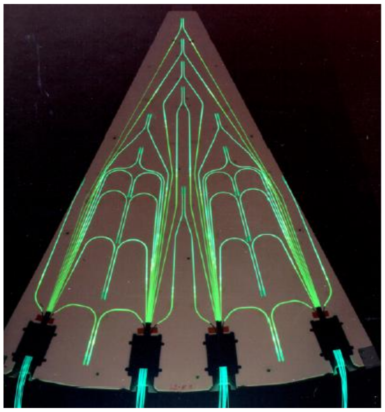
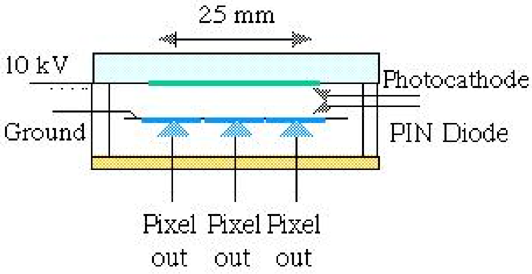
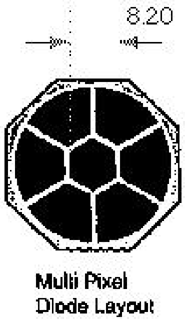
[5] barrel only; endcap: vacuum triodes





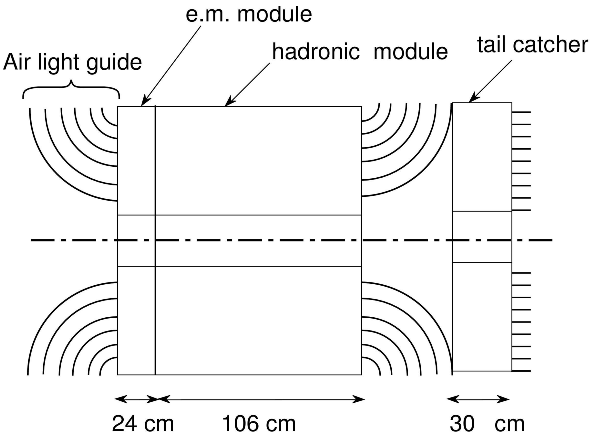
Advantage of this design: light extraction needs very little space ! As absorber material copper is used. The light is converted into an electrical signal with Hybrid PhotoDiodes (HPD's):





This combination of a thin (few millimeters) electrical field region and a silicon detector can operate in strong magnetic fields. The photocathode is segmented, so that one device can read out several fibres independently.

In addition to the barrel and endcap calorimeters there are forward hadron calorimeters made out of steel with quartz fibres, where *Cerenkov light* is generated. This detector is extremely radiation hard:



The light is read out via photo multipliers. Special: Cerenkov light is emitted only from ultra relativistic particles - so this detector ’sees’ mainly electrons and is quite insensitive to hadronic ‘background’.

Comparison of electromagnetic calorimeters:

detector	type	E-resol. A	E-resol. C	channels	long. sampling
UA1	scint	10%	2%	$\sim 1200\ PM$	4
UA2	scint	14%	$\sim 1\%$	$\sim 500\ PM$	1
CDF	scint	14%	$< 1\%?$	$\sim 1000\ PM$	1
D0	LAr	15%	0.3%	~ 20000	4
ATLAS	LAr	10%	0.5%	~ 180000	3
CMS	$PBWO_4$	6%	0.5%	$\sim 100000\ APD$	1

The angular resolution for both the ATLAS and the CMS central elm. calorimeters (incl. preshower) can be parametrised by

$$\sigma_\theta = \frac{0.05}{\sqrt{E/\mathrm{GeV}}}$$

Comparison of hadronic calorimeters:

detector	type	E-resol. A	E-resol. C	channels	long. sampling
UA1	scint	$\sim 110\%$	?	$1000\ PM$	1
UA2	scint	$\sim 100\%$	?	$\sim 1000\ PM$	2
CDF	scint	$\sim 50\%$	4%	$\sim 1400\ PM$	1
D0	LAr	50%	4%	~ 30000	$4-6$
ATLAS	scint	50%	2%	$\sim 10000\ PM$	3
CMS	scint	110%	5%	$\sim 20000\ HPD$	2

The resolution values are given for charged hadrons (pions). For jets (mixture of neutral hadrons (π^0!) and charged hadrons) the energy resolution becomes somewhat worse - for most detectors.