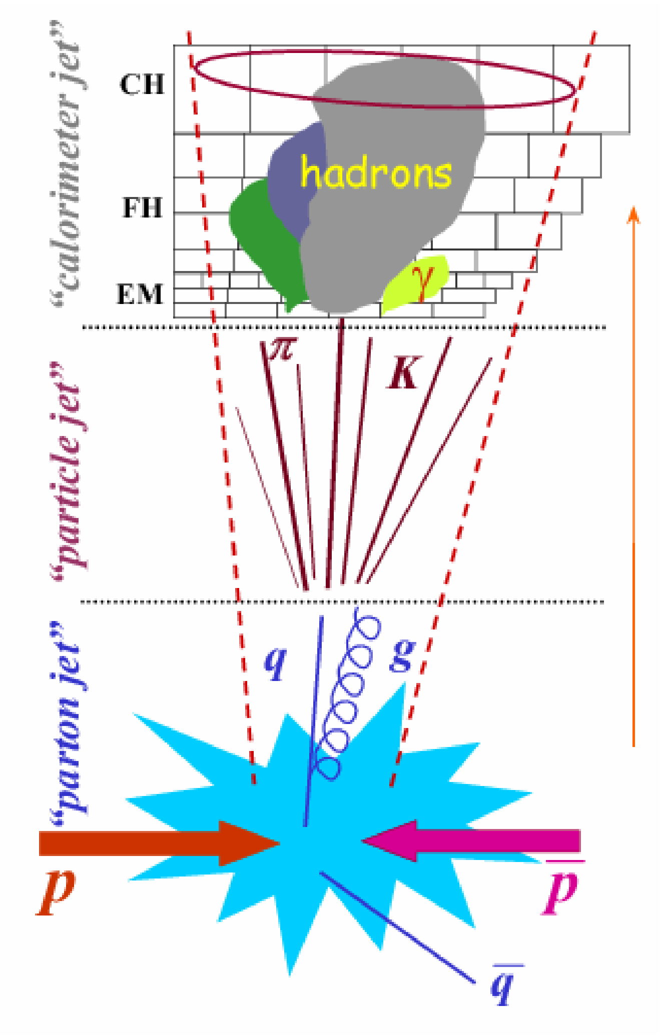
ATLAS Hadronic Calorimeters 101

First ATLAS Physics
Meeting of the Americas
20 August 2007

- Hadronic showers
- ATLAS Hadronic Calorimeters
  - Tile Calorimeter
  - Hadronic Endcap Calorimeter
  - Forward Calorimeter
- Noise and Dead Material

M. Lefebvre
University of Victoria

Hadrons in ATLAS

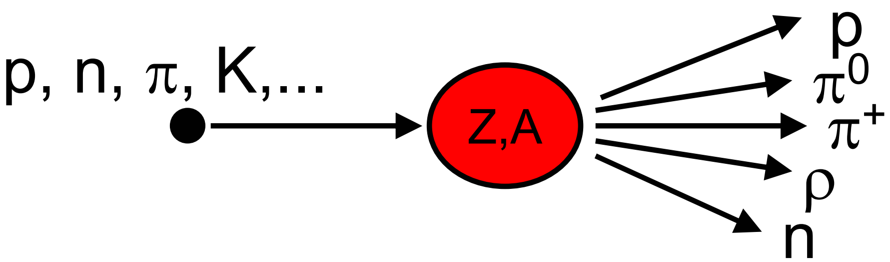


- hadronization of partons
  - and subsequent decays
- hadronic decays of taus

Nuclear interactions

Inelastic nuclear processes

- determines the interaction of energetic hadrons



$N \propto \ln(E_o)$

transverse momentum about 0.35 GeV/c

- Excitation and breakup of nucleus
  - nucleus fragments and secondary particles
- cross section depends ~only on A
  - $\sigma_{\text{inelastic}} \approx \sigma_\circ A^{0.7}$ $\quad \sigma_\circ \approx 35$ mb $\quad A$ in g/mol
- hadronic absorption length

$$\lambda_a = \frac{A}{N_A \sigma_{\text{inelastic}}}$$

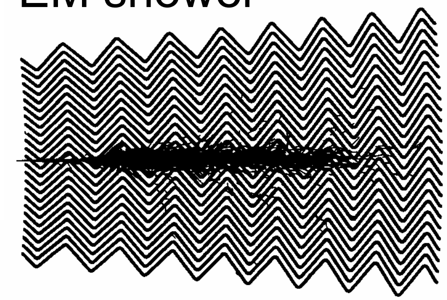
Interaction and hadronic absorption lengths

Material	Z	A	ρ [g/cm^3]	X_0 [g/cm^2]	λ_a [g/cm^2]
Hydrogen (gas)	1	1.01	0.0899 (g/l)	63	50.8
Helium (gas)	2	4.00	0.1786 (g/l)	94	65.1
Beryllium	4	9.01	1.848	65.19	75.2
Carbon	6	12.01	2.265	43	86.3
Nitrogen (gas)	7	14.01	1.25 (g/l)	38	87.8
Oxygen (gas)	8	16.00	1.428 (g/l)	34	91.0
Aluminium	13	26.98	2.7	24	106.4
Silicon	14	28.09	2.33	22	106.0
Iron	26	55.85	7.87	13.9	131.9
Copper	29	63.55	8.96	12.9	134.9
Tungsten	74	183.85	19.3	6.8	185.0
Lead	82	207.19	11.35	6.4	194.0
Uranium	92	238.03	18.95	6.0	199.0

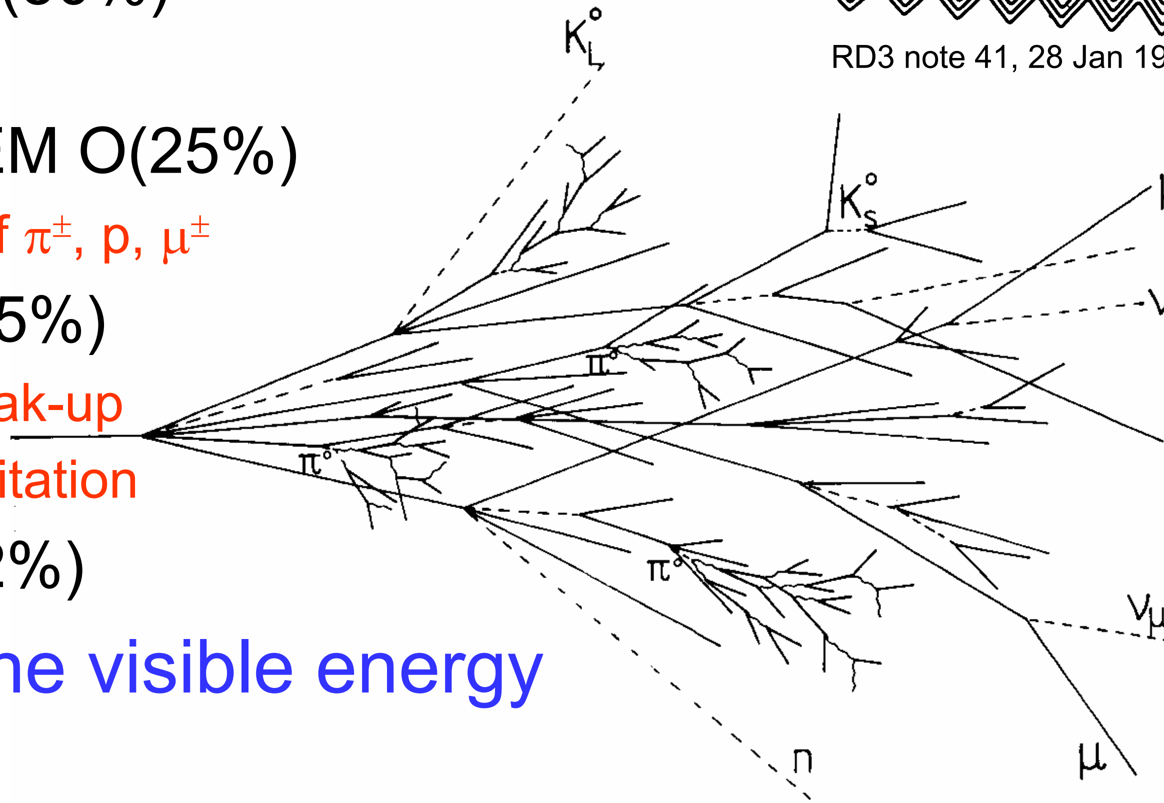
Hadronic Showers

- More complex than EM showers
  - visible EM O(50%)
    - $e^{\pm}$, γ, $\pi^{o} \rightarrow \gamma\gamma$
  - visible non-EM O(25%)
    - ionization of $\pi^{\pm}$, p, $\mu^{\pm}$
  - invisible O(25%)
    - nuclear break-up
    - nuclear excitation
  - escaped O(2%)
- Only part of the visible energy is sampled

EM shower



RD3 note 41, 28 Jan 1993



Grupen, Particle Detectors

Compensation

Each component fraction depends on energy

- visible non-EM fraction decreases with *E*

$$\left(\frac{E}{E_0}\right)^{m-1} \quad \begin{array}{l} 0.80 \le m \le 0.85 \\ E_0 \approx 1 \text{ GeV for } \pi^{\pm} \\ E_0 \approx 2.6 \text{ GeV for p} \end{array}$$

- pion (and jets) response non linear with *E*
  - "π" is the response to a pion
  - "e" is the intrinsic response to visible EM
  - "h" is the intrinsic response to visible non-EM

$$"\pi" = "e"\left[1-\left(\frac{E}{E_0}\right)^{m-1}\right] + "h"\left(\frac{E}{E_0}\right)^{m-1} \quad \Rightarrow \quad "\pi/e" = 1-(1-h/e)\left(\frac{E}{E_0}\right)^{m-1}$$

- in ATLAS, e/h > 1 for each sub-detector
  - invisible energy is the main source of e/h > 1
  - e/h = 1 is a compensating calorimeter

Hadronic Showers

- Large fluctuations of each component fraction
  - non-compensation amplifies fluctuations
- Hadronic calibration attempts to
  - provide some degree of software compensation
  - account for the invisible and escaped energy

Calorimeter types

- Homogeneous calorimeters
  - the detector is the absorber
  - good energy resolution
  - limited spatial resolution, especially longitudinal
  - only used for electromagnetic calorimetry
- Sampling calorimeters (as in ATLAS)
  - the detector and absorber are separated
  - only sample part of the shower
    - additional sampling fluctuations affect energy resolution
  - limited energy resolution
  - good spatial resolution

Energy Resolution

General parametrization

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

stochastic or sampling term

constant term

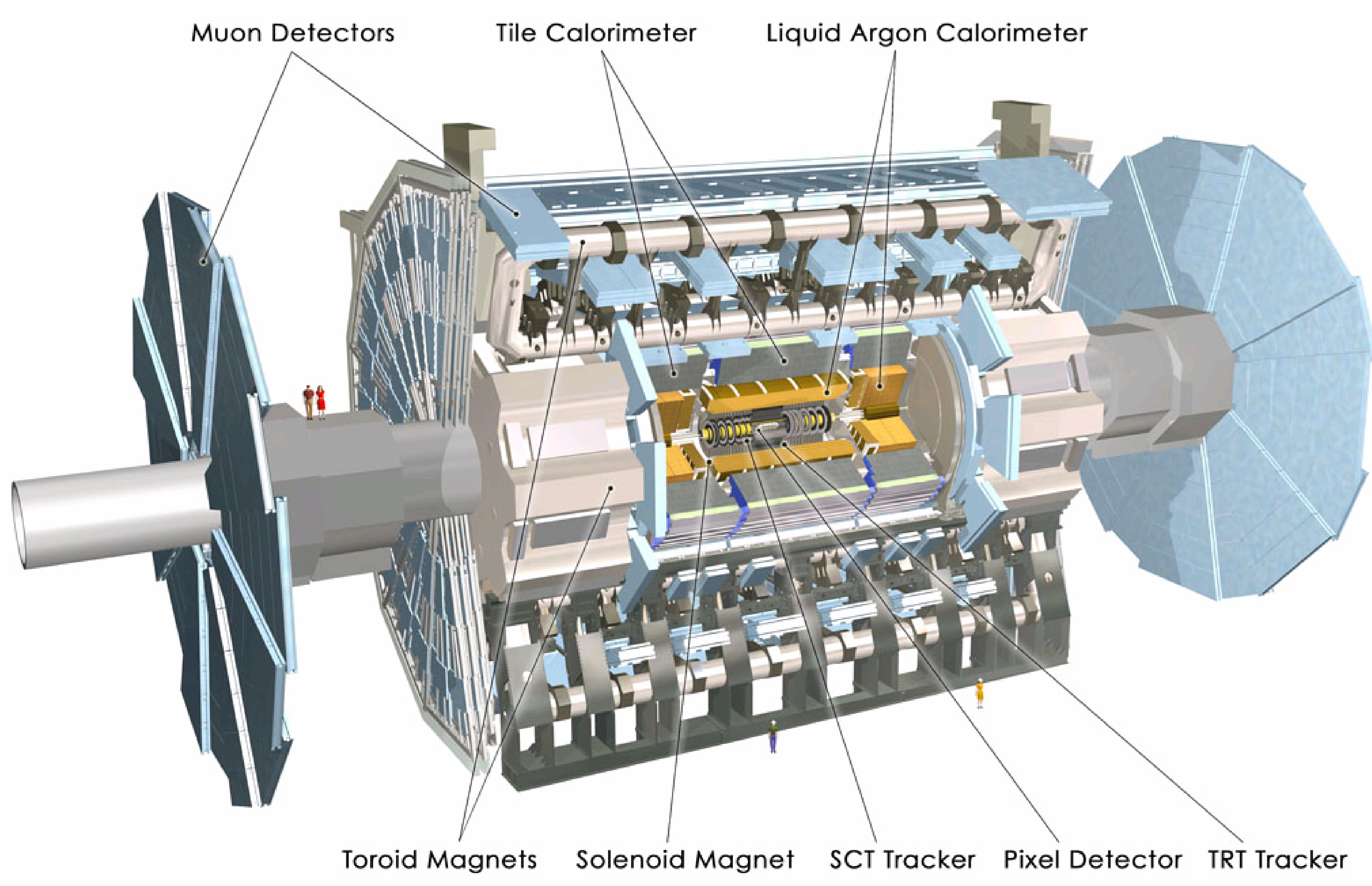
comes from inhomogeneity, bad calibration, non-linearity

noise term

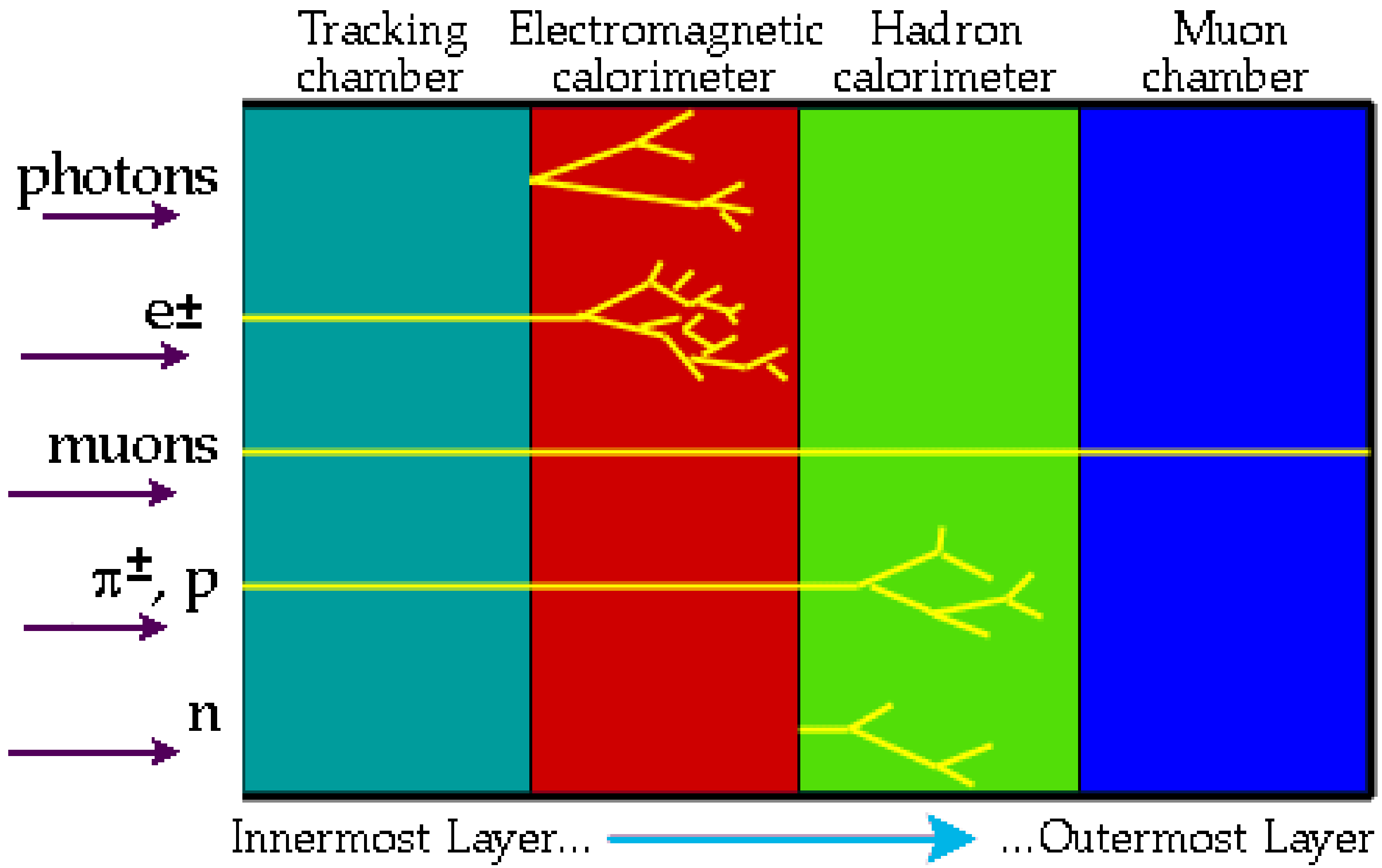
including electronic and pileup noise

- this is an approximation
  - *a*, *b* and *c* generally depend on η
- at high energy the constant term dominates!

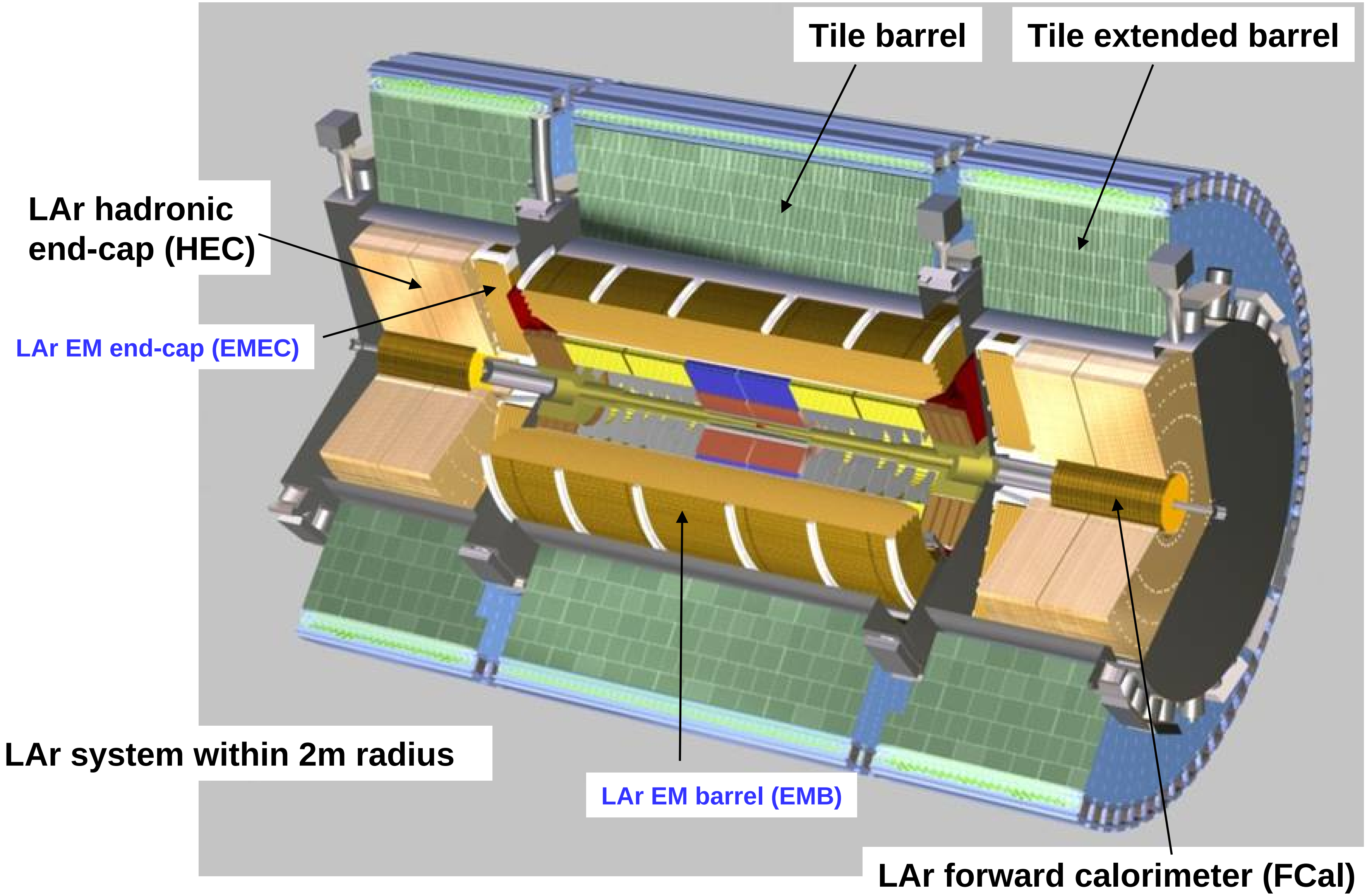
ATLAS Detector



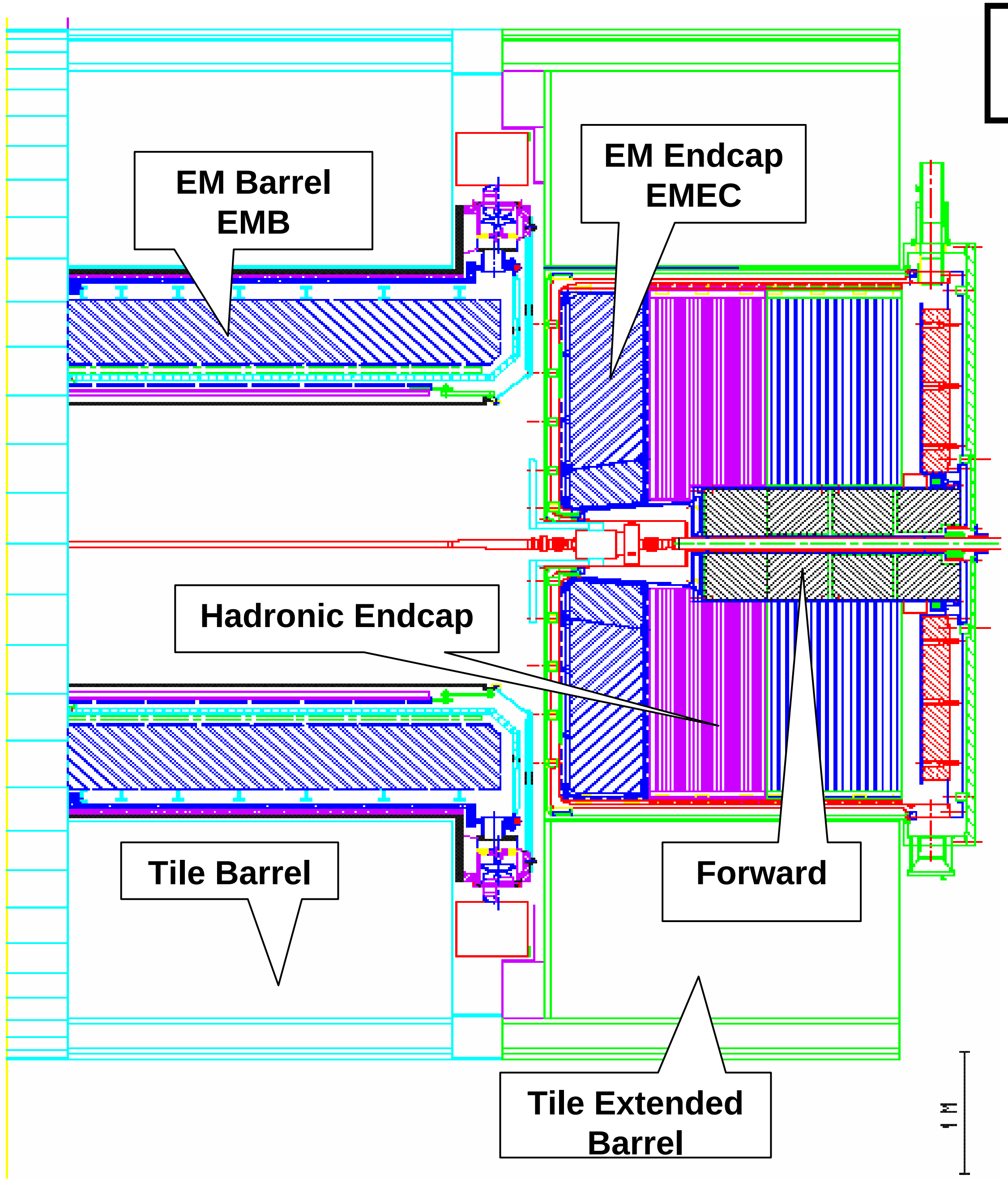
Typical Detector Components



ATLAS Calorimeters



Calorimeters



- EM Barrel
  - $|\eta| < 1.4$
- EMEC
  - $1.375 < |\eta| < 3.2$
- Tile
  - $|\eta| < 1.7$
- HEC
  - $1.5 < |\eta| < 3.2$
- FCal
  - $3.2 < |\eta| < 4.9$

varied granularity
varied techniques
many overlap regions

Physics Requirements

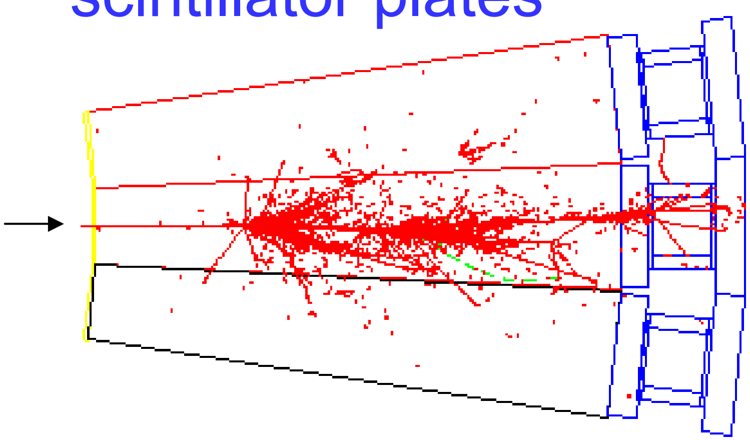
- Hadron and Forward Calorimeters
  - Benchmark channels $H \rightarrow WW \rightarrow$ jet jet X and Z/W/t require good jet-jet mass resolution
  - Higgs fusion $\rightarrow$ good forward jet tagging
  - EtMiss $\rightarrow$ calibration, jet resolution, linearity
- Design goals for jets (combined with EM calorimeter)
  - $\sigma(E)/E = 50\%/\sqrt{E} \oplus 3\%$ for $|\eta| < 3$ (E in GeV)
  - $\sigma(E)/E = 100\%/\sqrt{E} \oplus 5\%$ for $3 < |\eta| < 5$

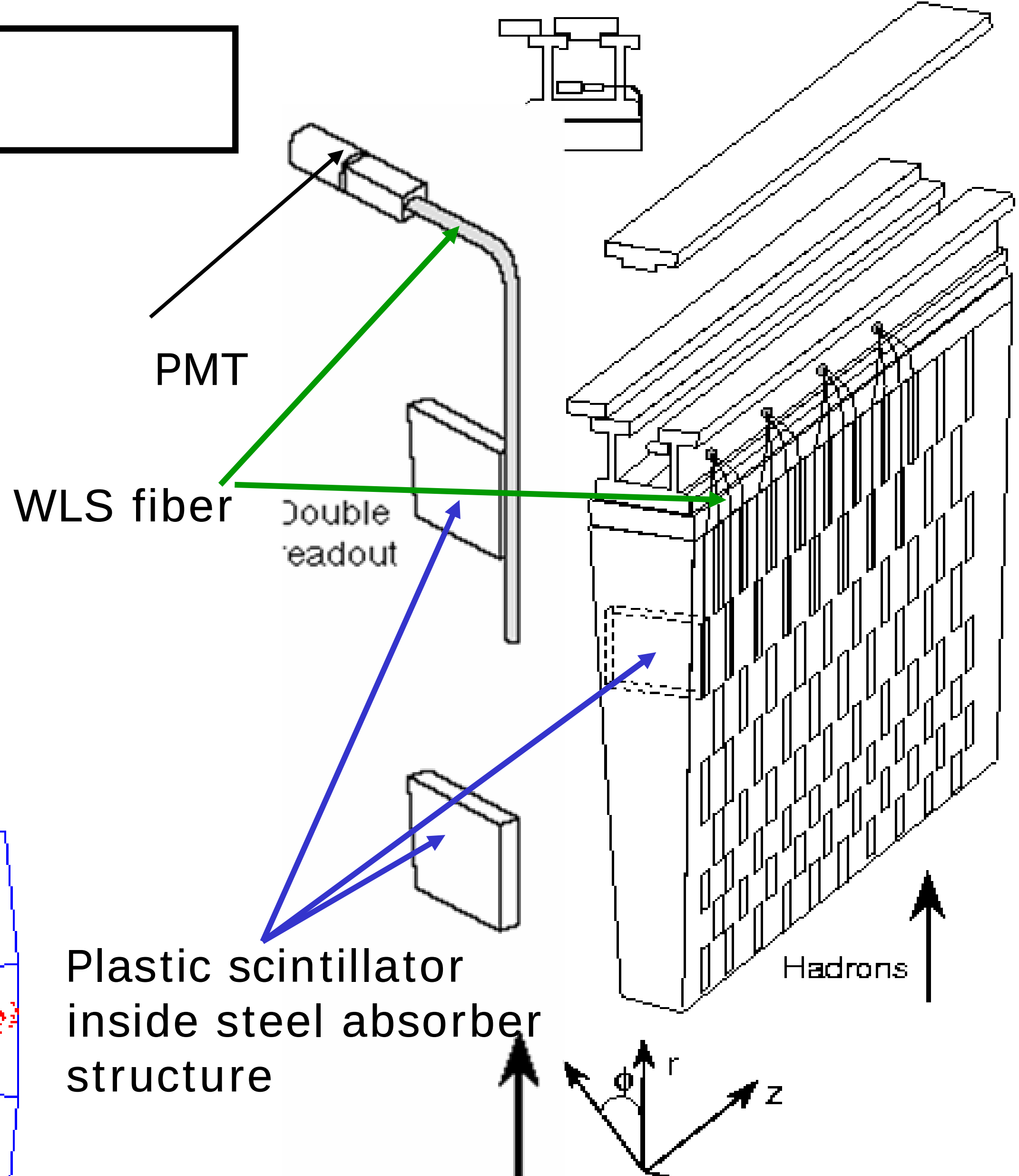
Tile Calorimeter

Sampling calorimeter made of plastic scintillator and steel

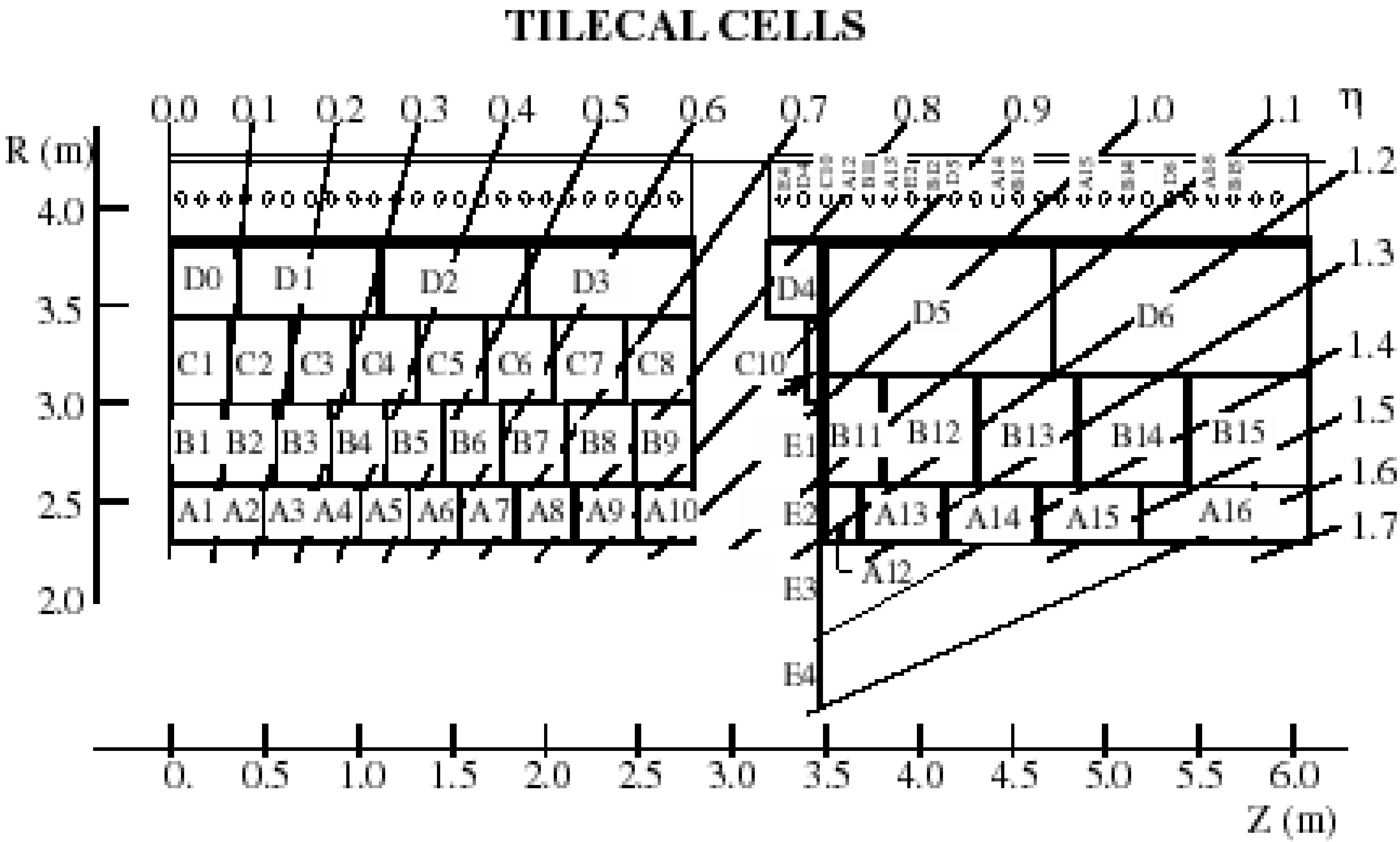
Light signal proportional to energy deposity in plastic

Notice orientation of scintillator plates





Tile Calorimeter Cells

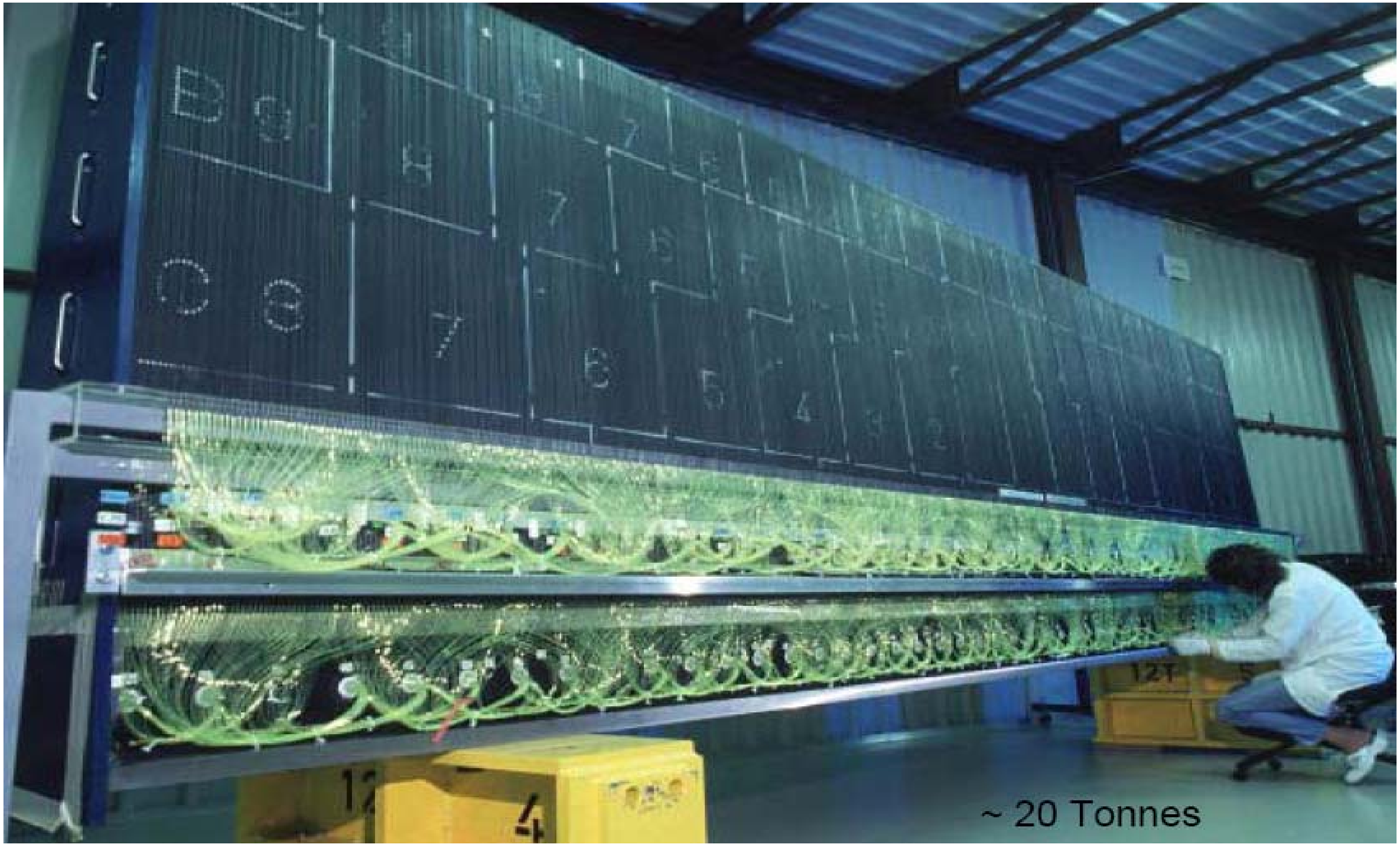


Tile Cell Count

offline/Calorimeter/CaloIdentifier/CaloIdentifier/TileID.h

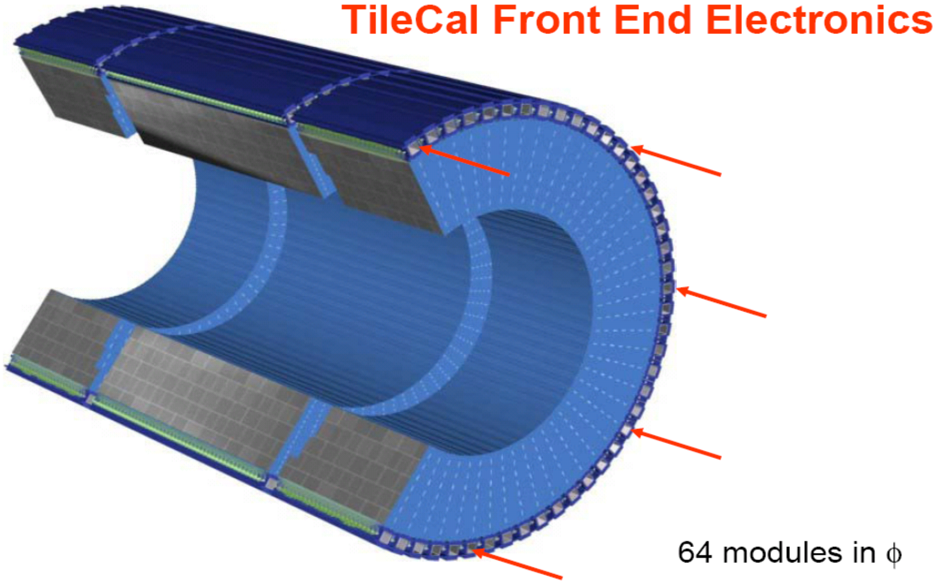
```
*  element      range      meaning
*  -------      -----      -------
*
*  section      1 to 15    section number  ( 1 = Barrel
*                                            2 = Extended Barrel
*                                            3 = Gap Detector
*                                                i.e. gap scin E1-E4 and ITC cells D4, C10
*                                            4 = Ancillary detectors )
*  side        -1 to 1     -1 = negative eta, 1 = positive eta, 0 = undefined (both sides)
*  module       0 to 63    module number by phi
*  tower(eta)   0 to 15    0-15 = tower number by pseudorapidity with 0.1 increment in eta
*                          Attention! in PhysTDR data last tower is 16
*  sample       0 to 15    0 = A, 1 = B = BC = C, 2 = D, 3 = special gap scin cells E1-E4
*                          4-15 = individual tiles, used in Cesium calibration data
*  pmt          0 to 1     PMT number in the cell (0 = side close to module with smaller number)
*  adc          0 to 1     ADC number for the PMT (0 = low gain, 1 = high gain)
```

One Tile Calorimeter Module



Tile Calorimeter Front End Electronics

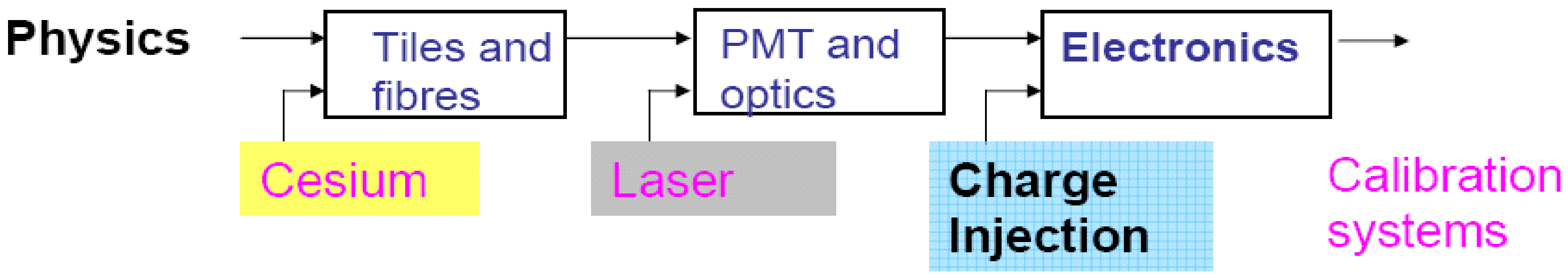
- Process 10000 PMT signals
- Effective 16 bit dynamic range
  - up to 2 TeV in a single cell
  - down to 30 MeV per cell
    - must see muons @ 350 MeV/cell for calibration, monitoring, electron identification
- Readout should not degrade calorimeter energy resolution
  - electronics noise low when merging cells into jets
- Radiation-tolerant > 10 years
- Provide level-1 trigger tower sums
- Electronics located in 256 “drawers”
  - each one 3 m long, 50 kg



Tile Calorimeter Calibration System

Every TileCal channel can be calibrated and monitored

with 3 systems



Cesium: single cell equalization

Electrons: setting of EM scale

Linearity including PMT

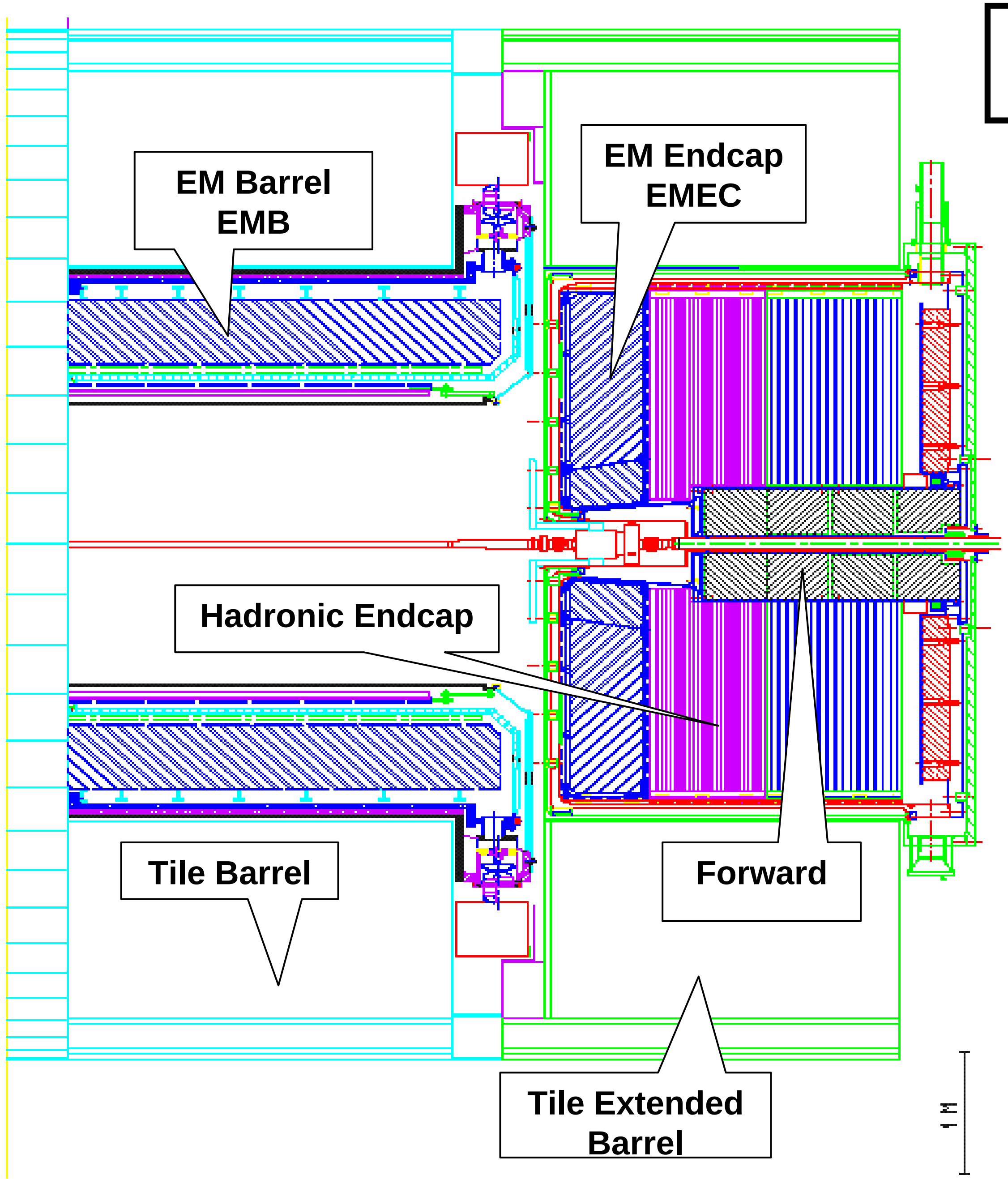
Calorimeter timing

Charge injection:
- **check linearity**
- **calibrate gain**

Dual gain 16 bit ADC

Energy = [30 MeV - 2 TeV]

Calorimeters

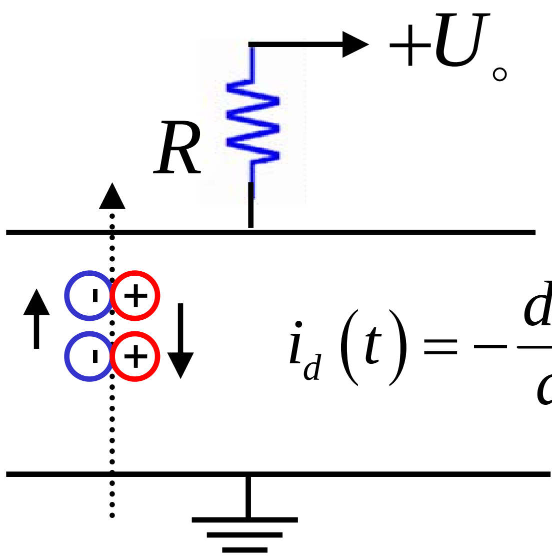


- EM Barrel
  - $|\eta| < 1.4$
- EMEC
  - $1.375 < |\eta| < 3.2$
- Tile
  - $|\eta| < 1.7$
- HEC
  - $1.5 < |\eta| < 3.2$
- FCal
  - $3.2 < |\eta| < 4.9$

varied granularity
varied techniques
many overlap regions

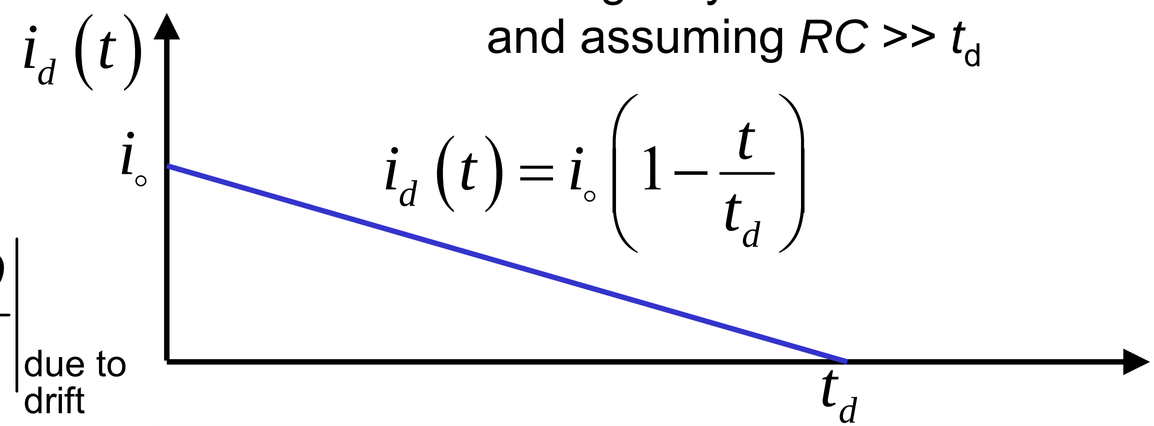
Liquid Argon Calorimetry

- LAr ionization chamber



$$i_d(t) = -\left.\frac{dQ}{dt}\right|_{\text{due to drift}}$$

considering only the electron drift and assuming *RC* >> t_d



$$i_d(t) = i_\circ\left(1 - \frac{t}{t_d}\right)$$

typical values:

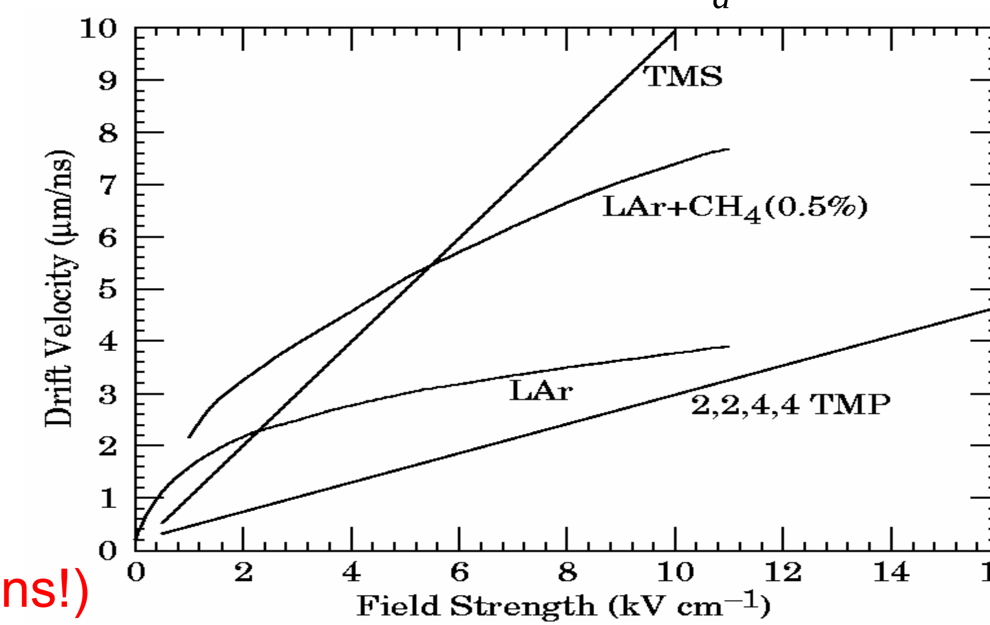
T = 87 K, ρ = 1.40 g/cm^3

X_0 = ρ 13.9 cm

W = 23.6 eV

U_0 = 2 kV over 2 mm gaps

$t_d \approx$ 450 ns (compare to LHC 25 ns!)



Particle Data Group

Liquid Argon Calorimeter Pulse Shape

- triangle current pulse, shaping, sampling

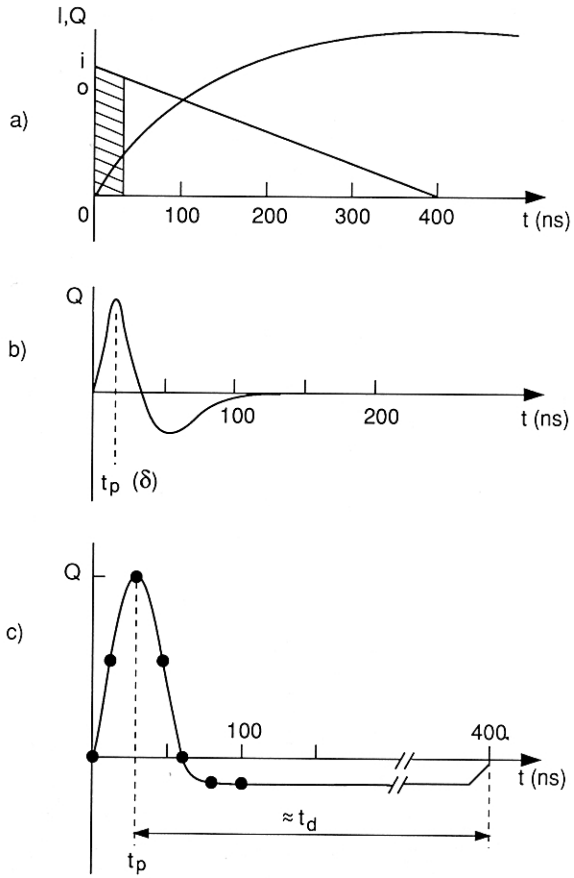
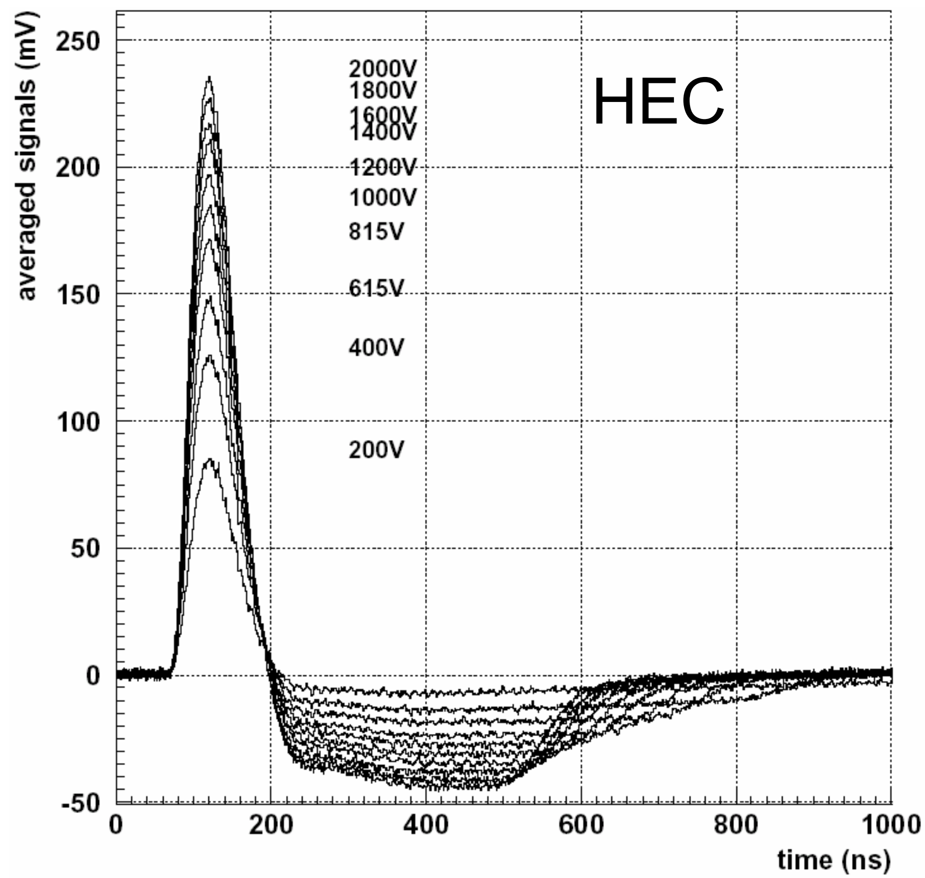


Fig. 1. (a) Drift current and integrated charge vs time for an ion chamber calorimeter. (b) Response of a shaping amplifier to a short current pulse (δ). (c) Response of a shaping amplifier to the current form shown in (a). The dots indicate where the beam crossings (every 15 ns) would appear if $t_p(\delta) = 20$ ns.

RD3 collaboration, NIM A309 (1991) 438-449

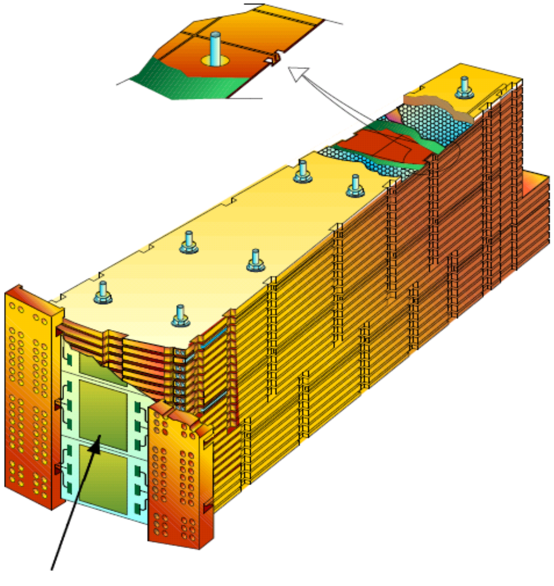


Hadronic Endcap Calorimeter

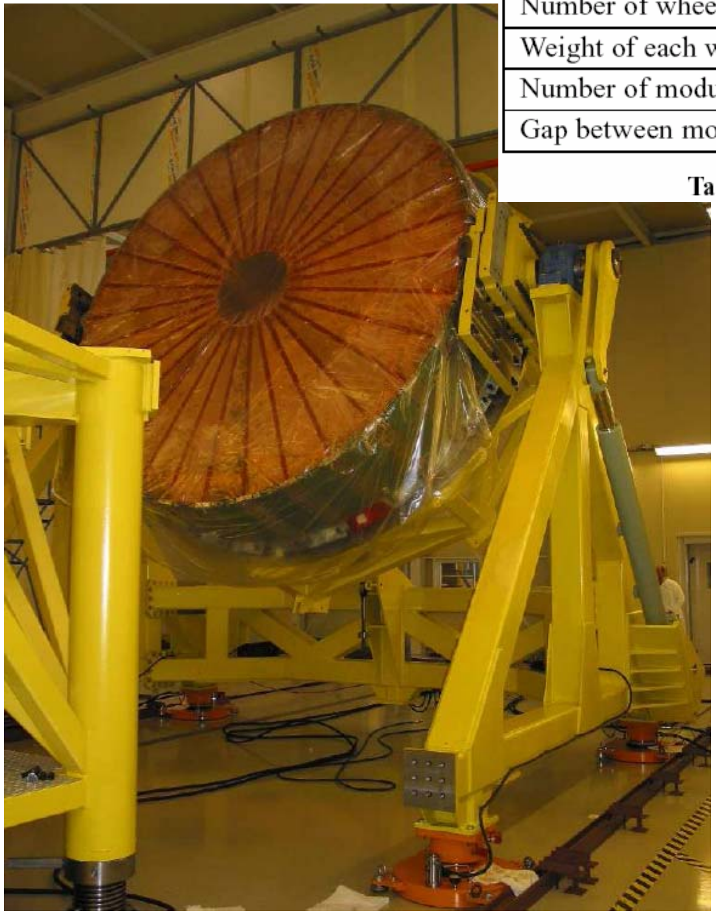
- D.M. Gingrich et al. (ATLAS Hadronic End-cap Calorimeter Group), **Construction, assembly and testing of the ATLAS hadronic end-cap calorimeter,** Journal of instrumentation, 2007_JINST_2_P05005.

Parameter	HEC1	HEC2
Number of wheels	2	2
Weight of each wheel	67,300 kg	89,900 kg
Number of modules per wheel	32	32
Gap between modules in azimuth	2 mm	2 mm

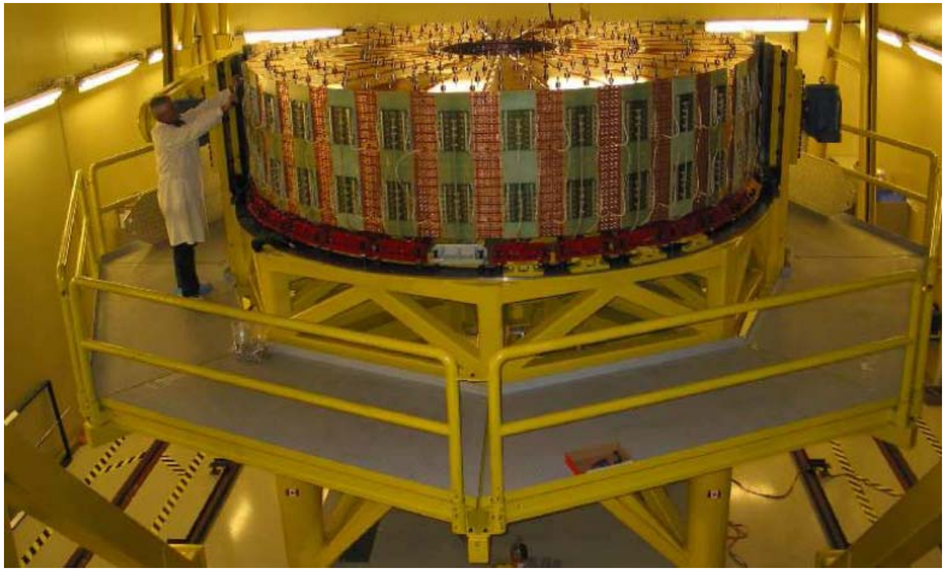
Table 1. HEC wheel parameters.



HEC1 wheel being rotated

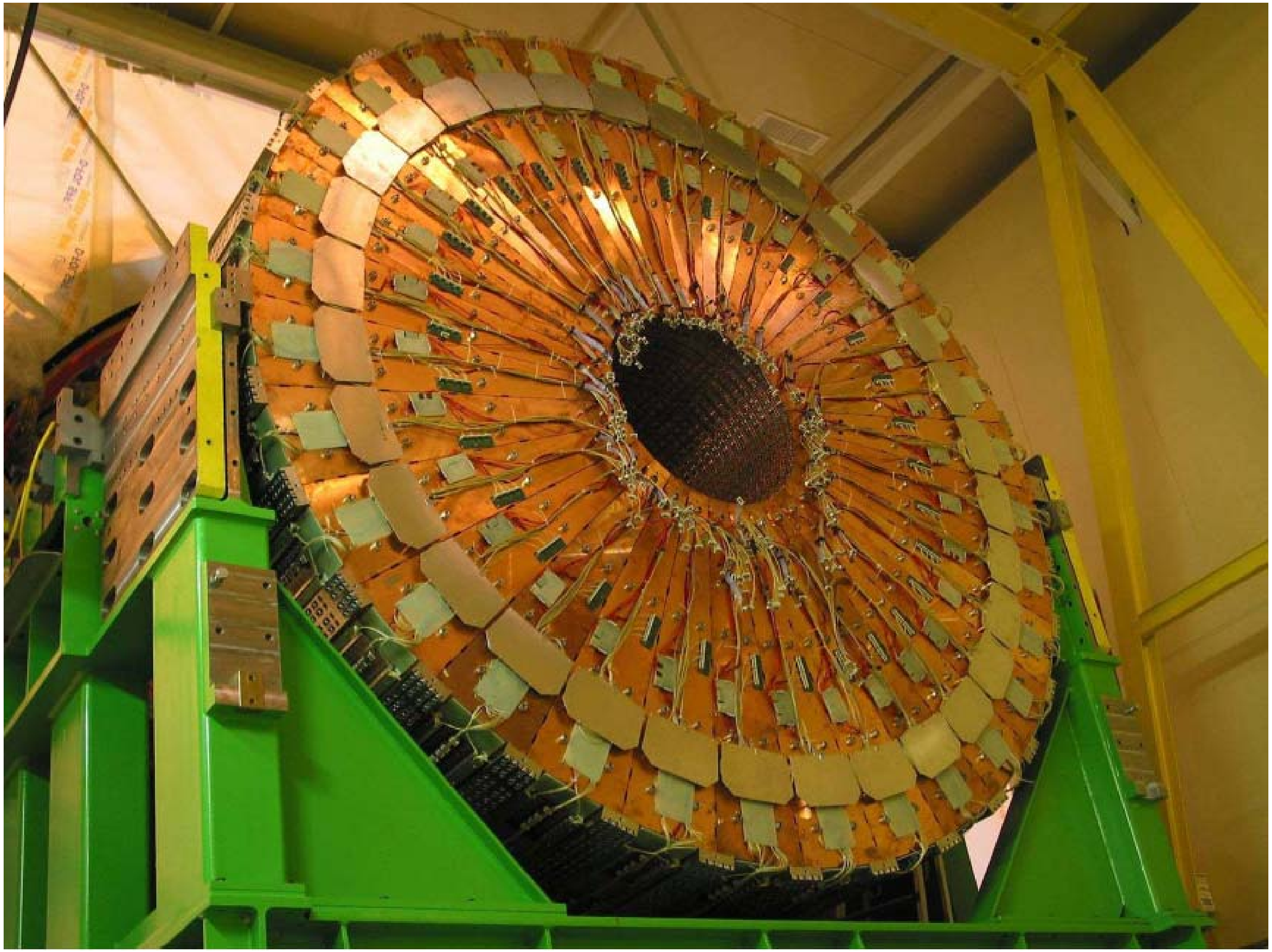


HEC wheel fully assembled on the assembly table



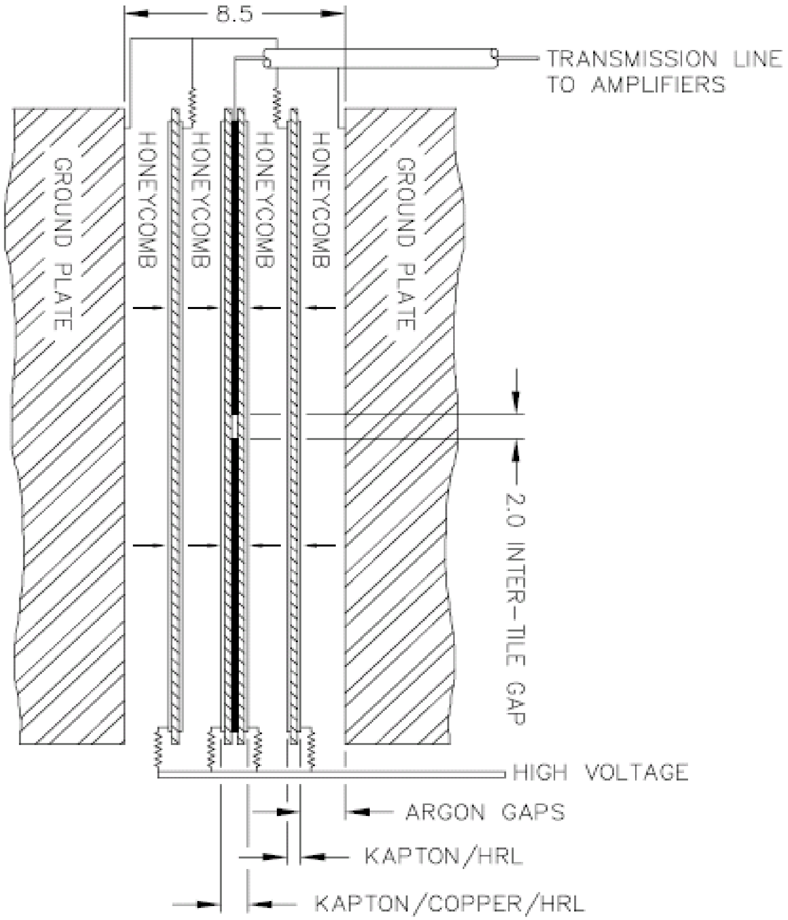
HEC Calorimeter

HEC2 A wheel on the insertion stand, August 2004



HEC Calorimeter

- Cu/LAr sampling calorimeter
- 2 wheels in each endcap
  - 32 phi modules each
  - 2 readout depths each
- HEC1 wheel
  - 25 mm Cu plates
- HEC2 wheel
  - 50 mm Cu plates
- Readout structure in the 8.5 mm LAr gaps forms an electrostatic transformer (EST)
  - optimize signal/noise
  - reduce HV requirement
  - limits effects of failure modes



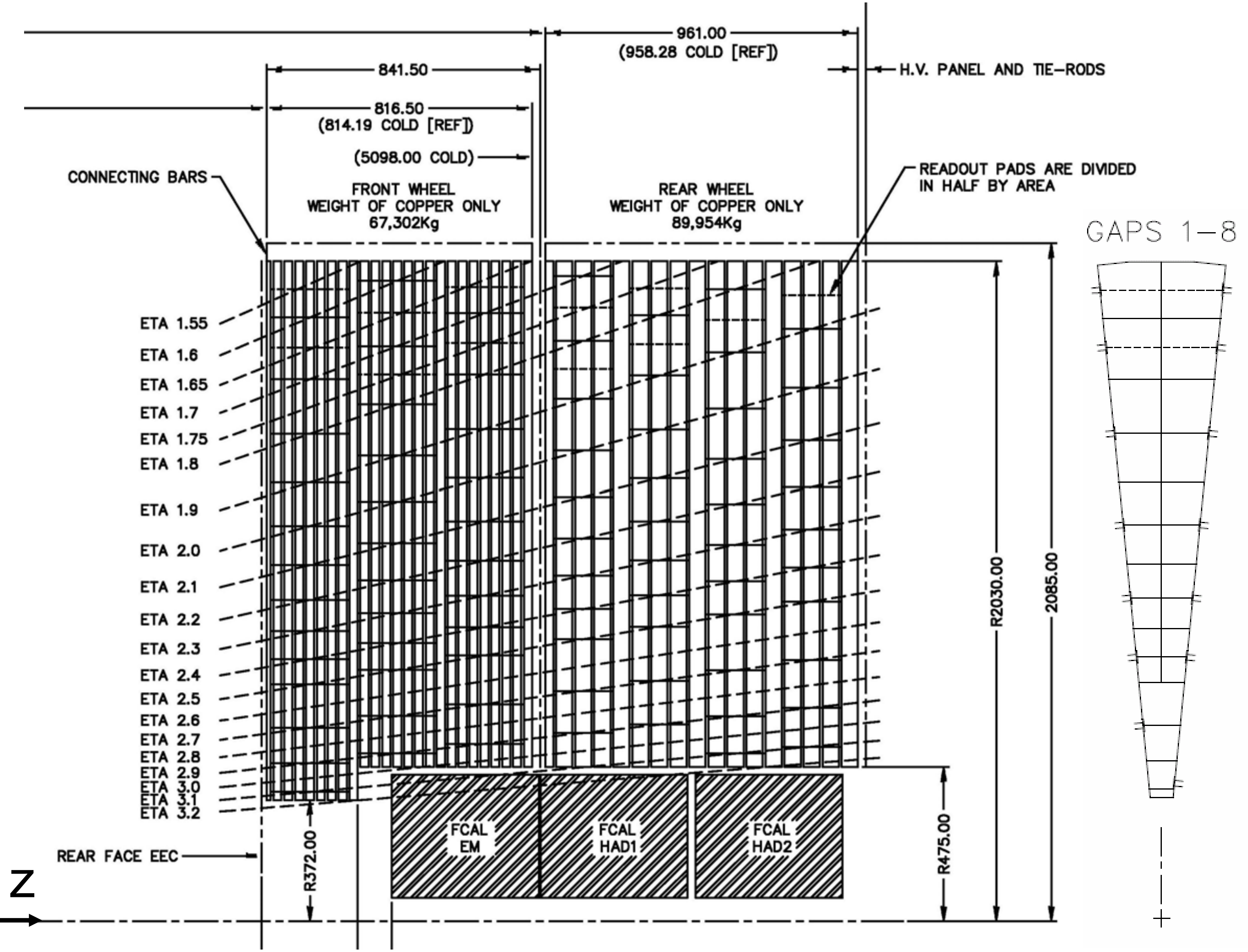
operating HV: 1800V

HEC Module Parameters

Parameter	Front modules	Rear modules
Number of copper plates	25	17
Thickness of first plate in module	12.5 mm	25.0 mm
Thickness of standard plates in module	25.0 mm	50.0 mm
Weight of standard plates	90 kg	180 kg
Module weight	2,103 kg	2,811 kg
Distance from copper plate to copper plate	8.500 mm	8.500 mm
Liquid argon subgaps	1.969 or 1.954 mm	1.969 or 1.954 mm
Honeycomb thickness	1.816 mm	1.816 mm
Total thickness of PAD and EST boards in gap	0.625 or 0.685 mm	0.625 or 0.685 mm
Number of read-out gaps	8+16 = 24	8+8 = 16
Number of read-out segments	2	2
Number of read-out towers	24+23 = 47	21+20 = 41
Number of preamplifier boards	3	2
Number of preamplifier chips	42	28
Number of low-voltage lines	12	8
Number of calibration distribution boards	1	1
Number of calibration lines	28	16
Number of high-voltage lines	4+4 = 8	4+4 = 8
Number of tie rods per module	7	7
Tie rod diameter	12 mm	16 mm
Tie rod stress	78 MPa	79 MPa
Tie rod thread root stress	125 MPa	118 MPa
Outside diameter of spacers for 8.5 mm read-out gaps	17 mm	23 mm
Maximum stress on the copper by the spacer	138 MPa	138 MPa

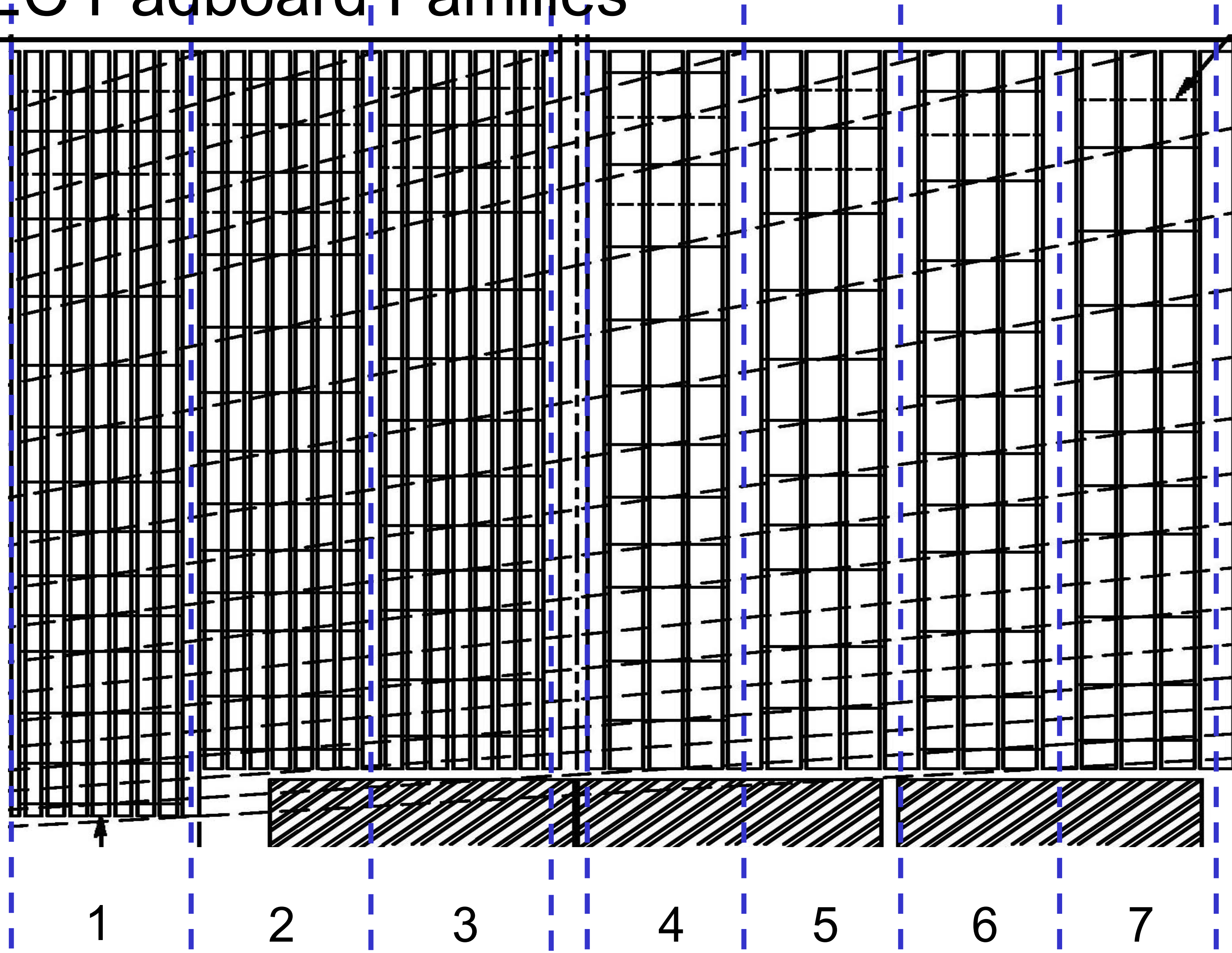
HEC module geometry

this drawing is in the plane of the middle φ of a HEC module and shows the 7 readout families and the η boundaries passing through the pad ρ boundaries at the middle z of pad board families

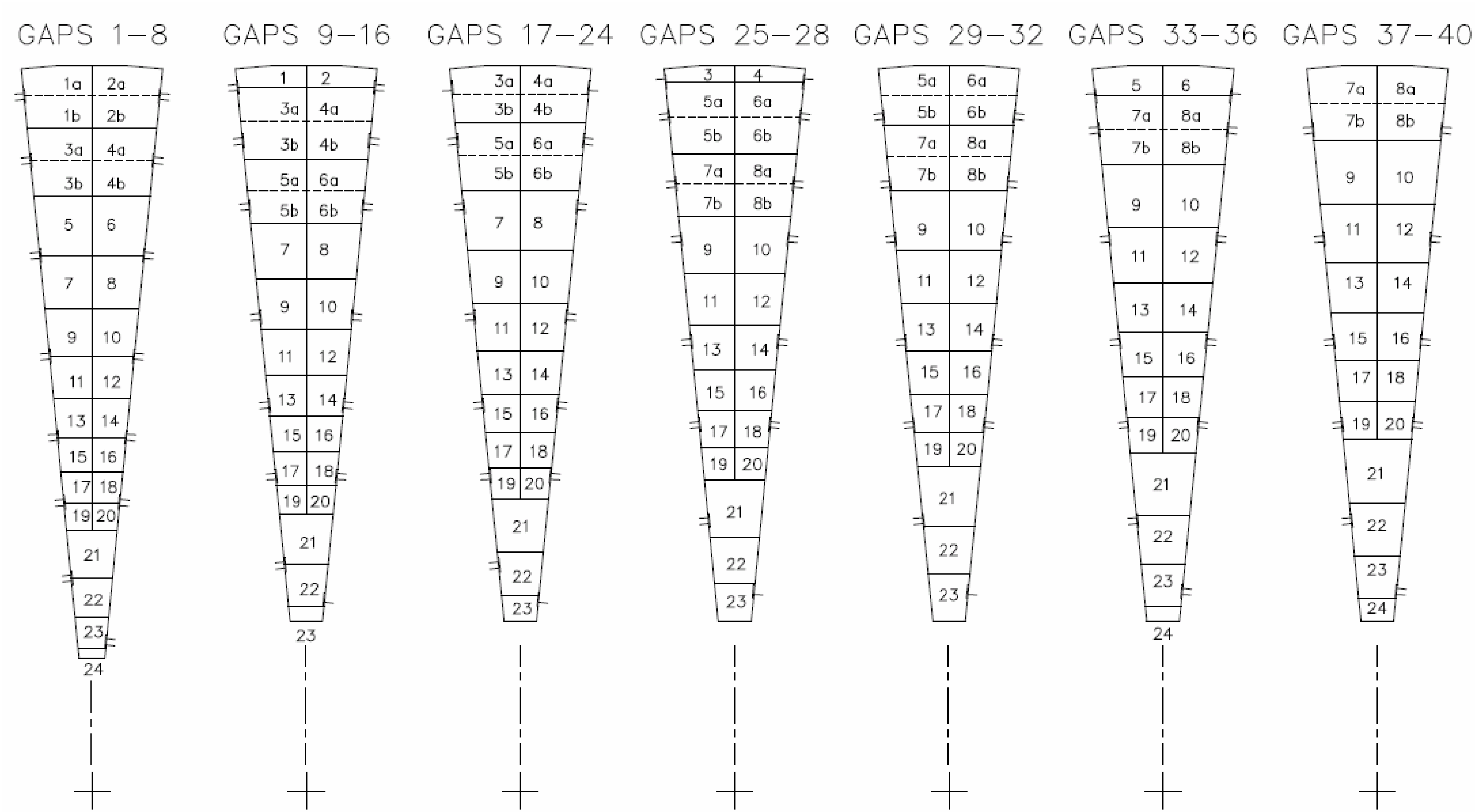


HEC Padboard Families

not to scale!

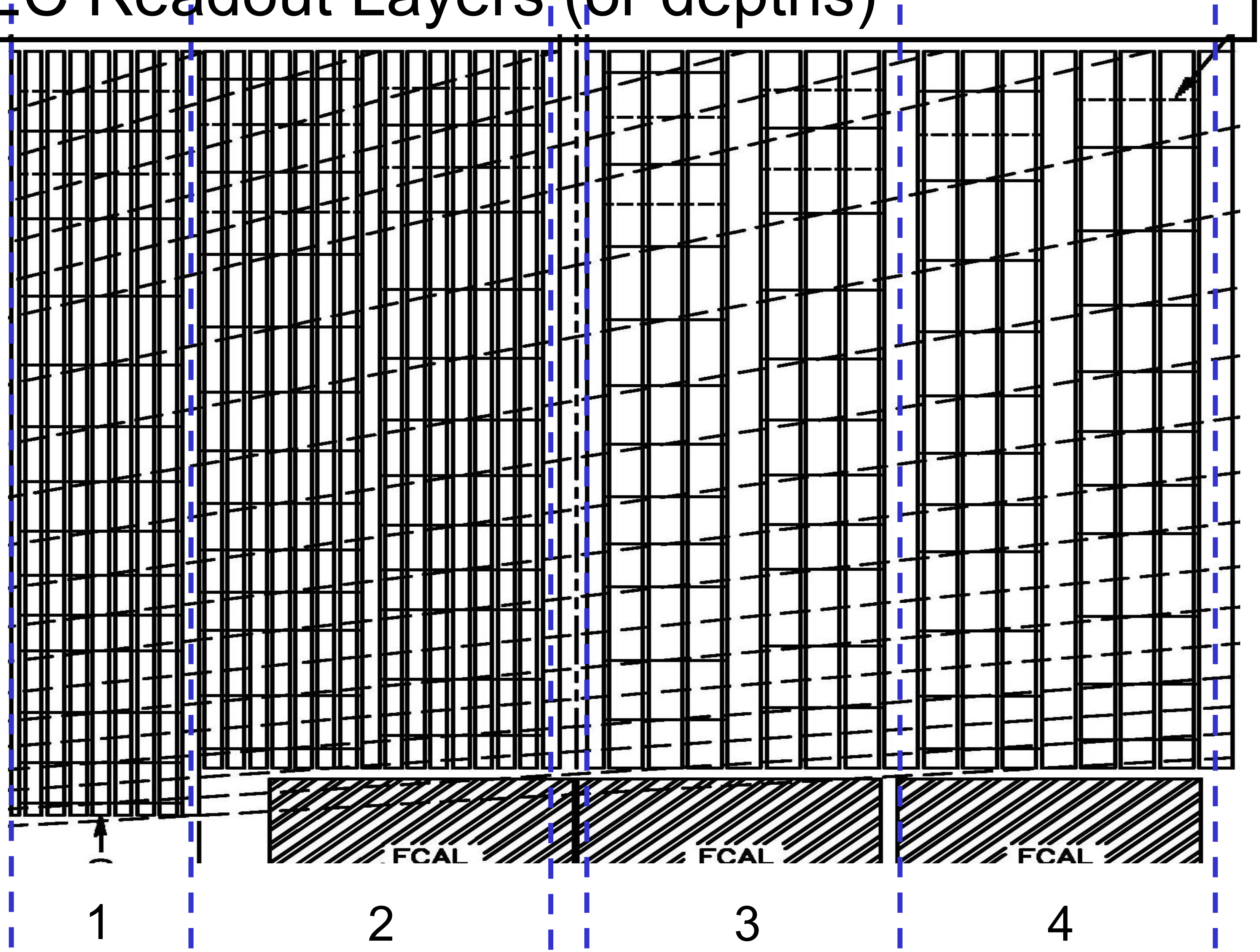


HEC Pad Board Families

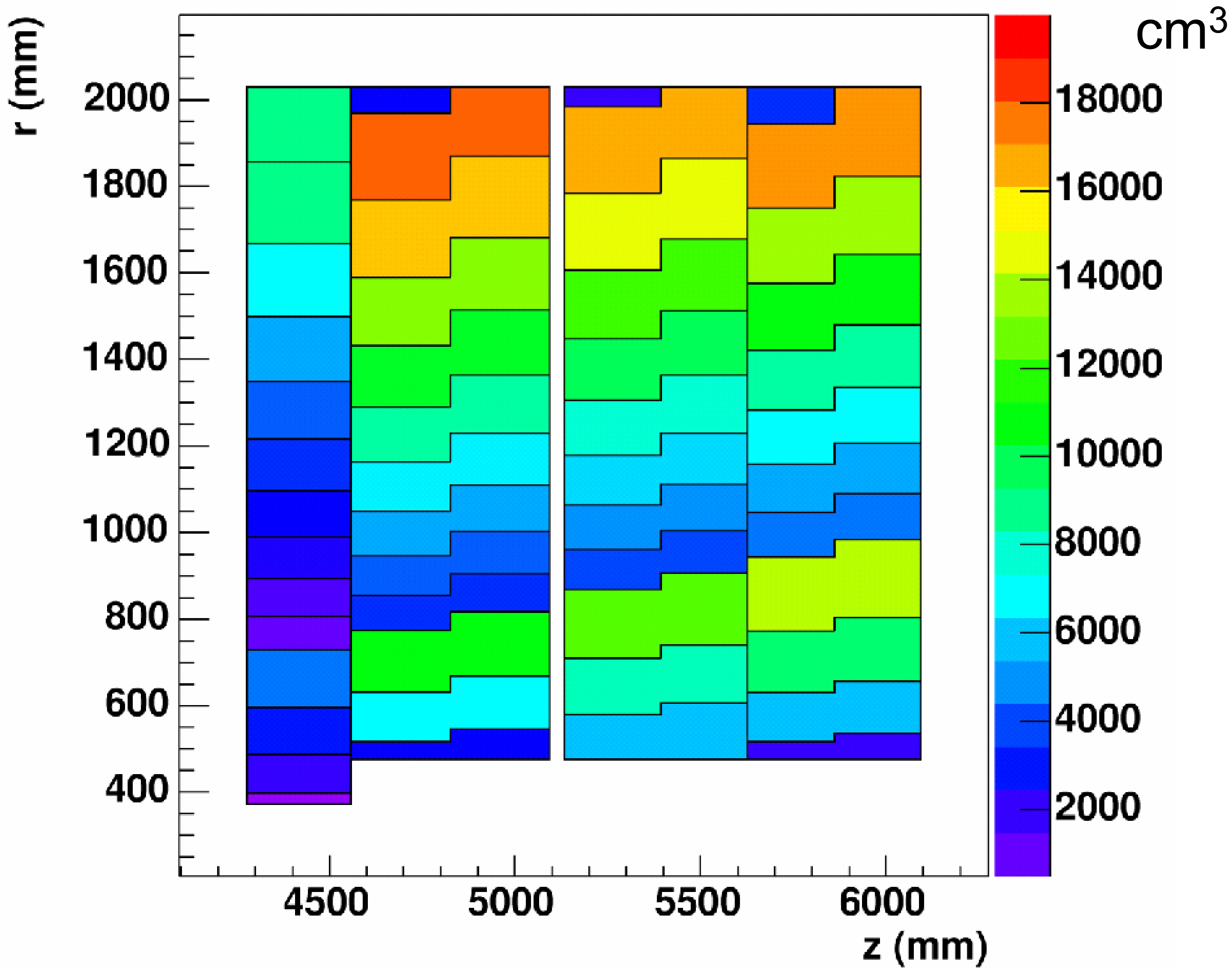


HEC Readout Layers (or depths)

not to scale!



HEC Readout Cell Volume

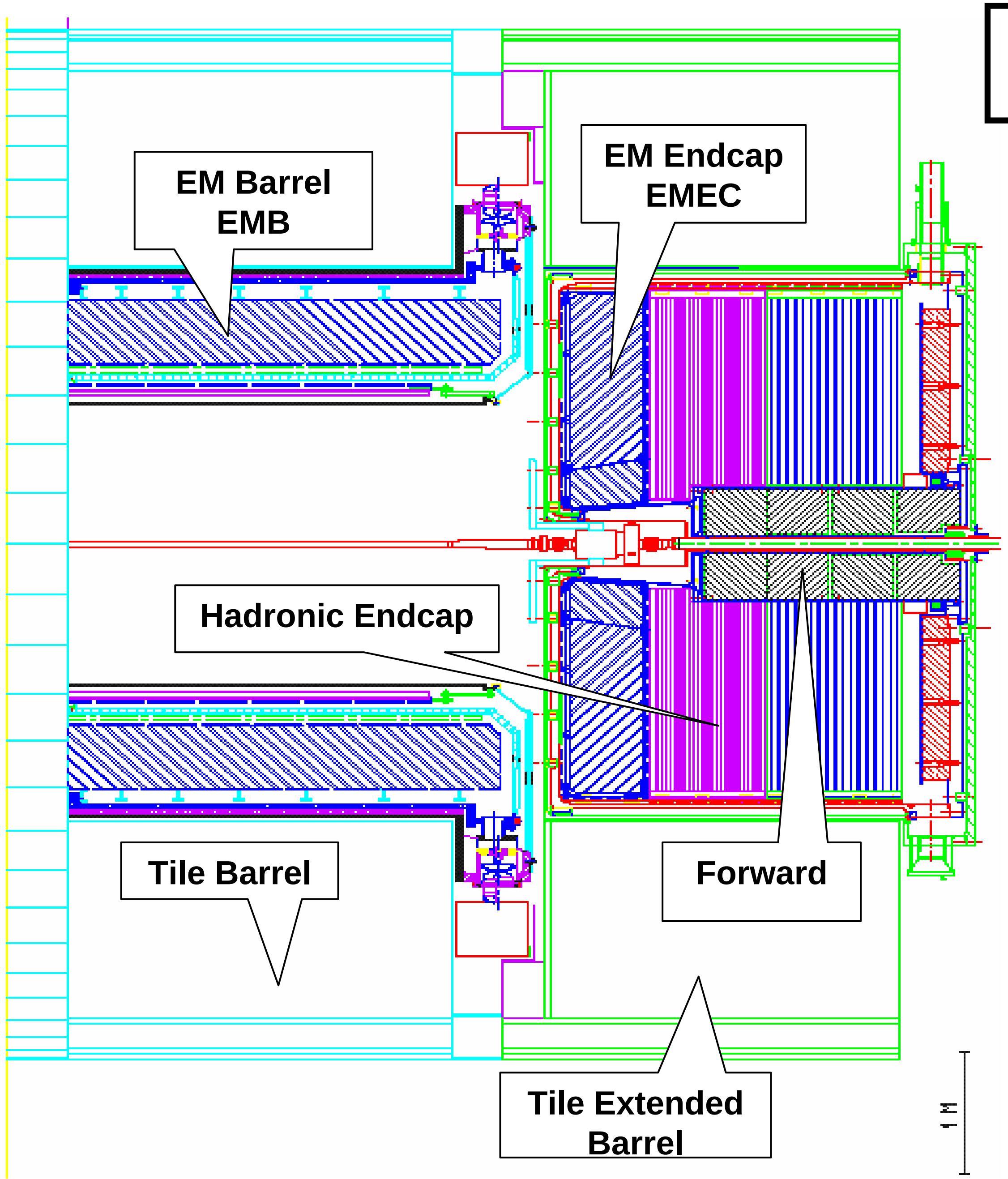


HEC Cell Count

offline/Calorimeter/CaloIdentifier/CaloIdentifier/LArHEC_ID.h

```
 *              Connected channels :
 *              ------------------
 * element            range              meaning
 * -------            -----              -------
 *
 * pos/neg           -2 or 2          -2 = negative HEC (C side), 2 = positive HEC  ( A side)
 *
 * sampling          [0,3]            [0,1] = first wheel, [2,3] = second wheel
 *
 * region            [0,1]            0 : outer part, 1 : inner part
 *
 * eta               [0,9]            Outer part region 0 , samplings 0 and 1 , 1.5< eta <2.5 , deta=0.1
 * "                 [1,9]            Outer part region 0 , samplings 2       , 1.6< eta <2.5 , deta=0.1
 * "                 [2,9]            Outer part region 0 , samplings 3       , 1.7< eta <2.5 , deta=0.1
 * "                 [0,3]            Inner part region 1 , samplings 0 and 3 , 2.5< eta <3.3 , deta=0.2
 * "                 [0,2]            Inner part region 1 , samplings 1 and 2 , 2.5< eta <3.1 , deta=0.2
 *
 * phi               [0,63]           Outer part, dphi=0.1
 * "                 [0,31]           Inner part, dphi=0.2
 *
 * 5632 active cells in the full HEC
```

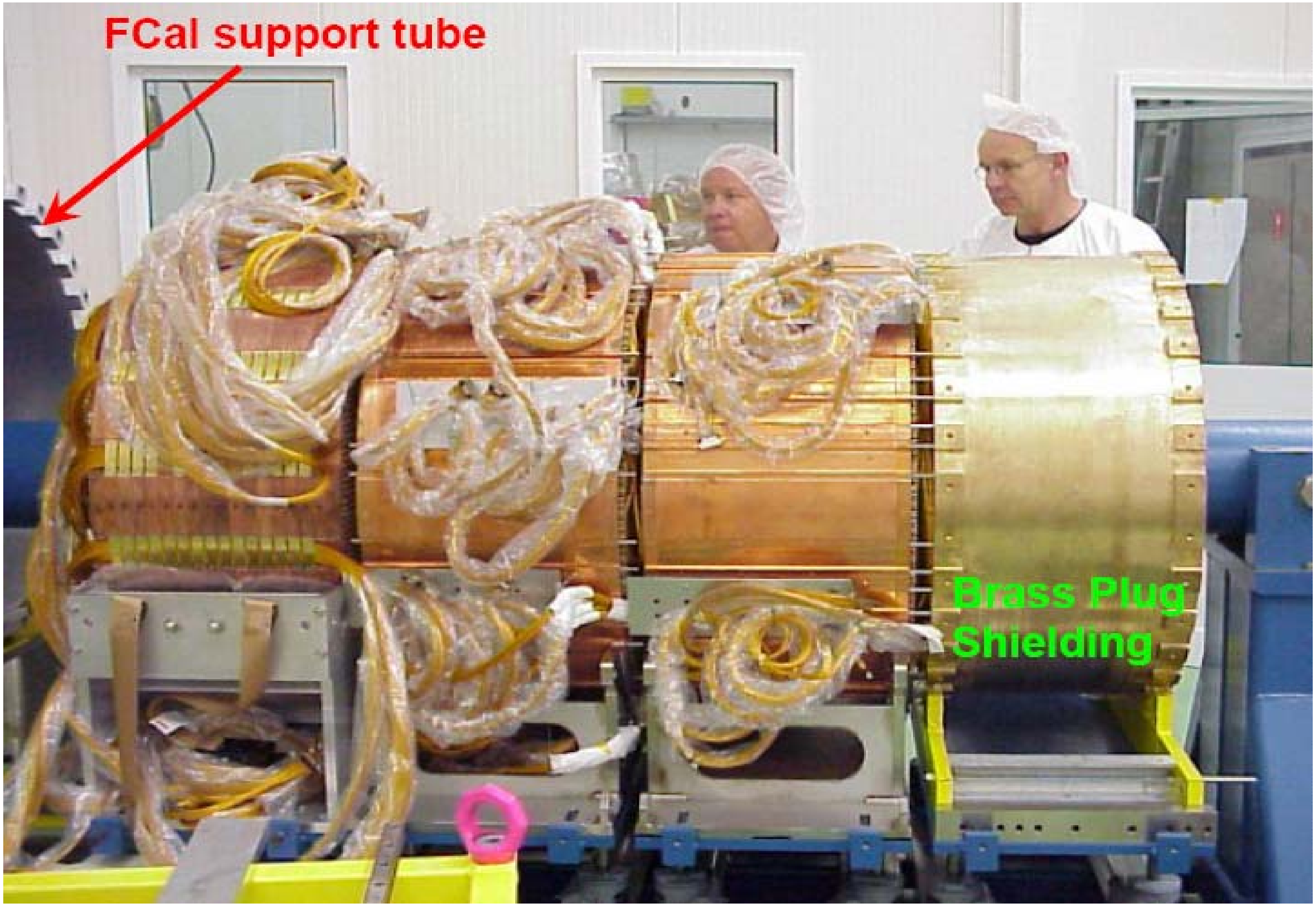
Calorimeters



- EM Barrel
  - $|\eta| < 1.4$
- EMEC
  - $1.375 < |\eta| < 3.2$
- Tile
  - $|\eta| < 1.7$
- HEC
  - $1.5 < |\eta| < 3.2$
- FCal
  - $3.2 < |\eta| < 4.9$

varied granularity
varied techniques
many overlap regions

Forward Calorimeter Assembly

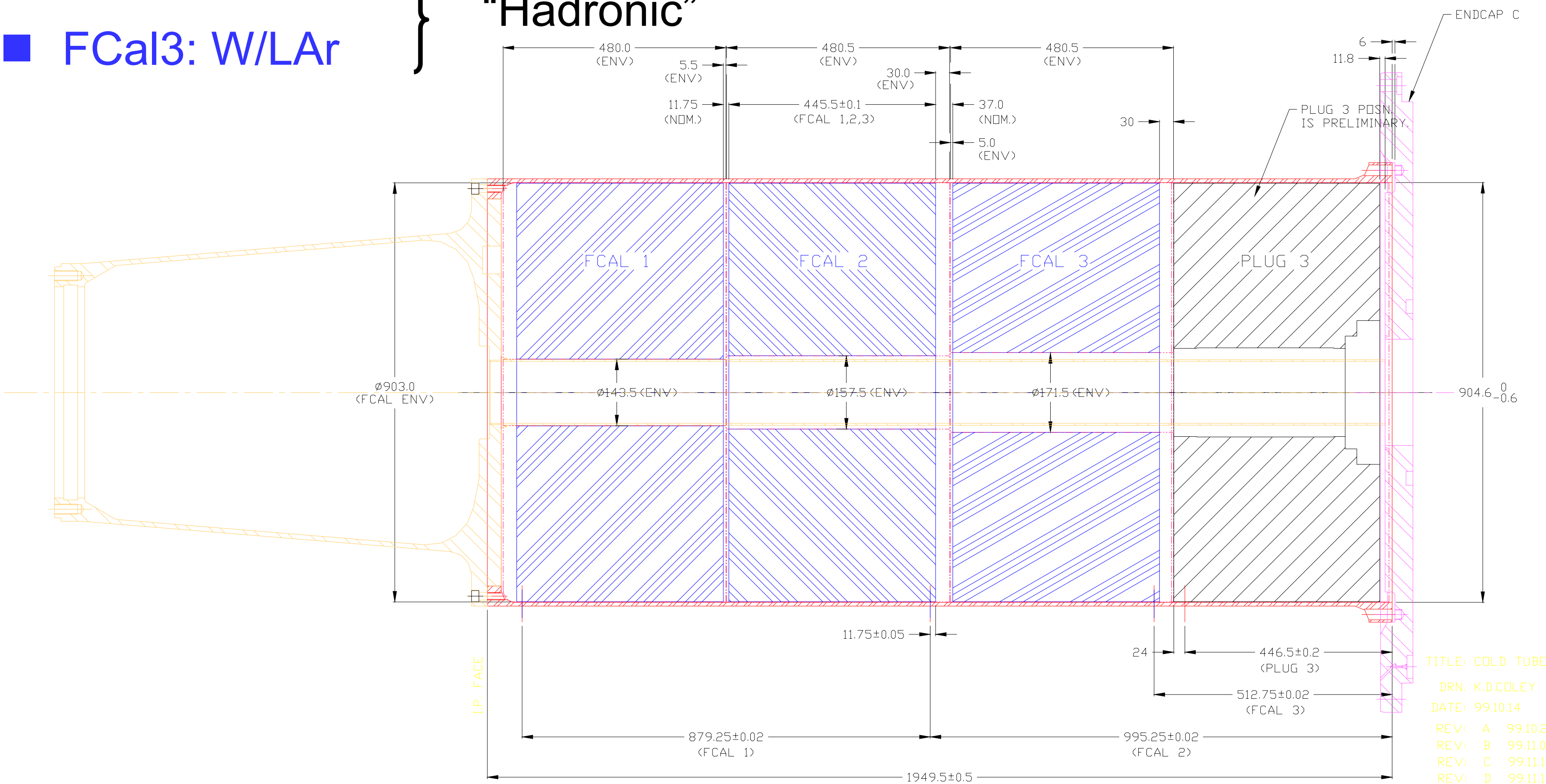


FCal

- 3 modules
  - 0.9 m diameter
  - 0.45 m long
- FCal1: Cu/LAr → "EM"
- FCal2: W/LAr
- FCal3: W/LAr

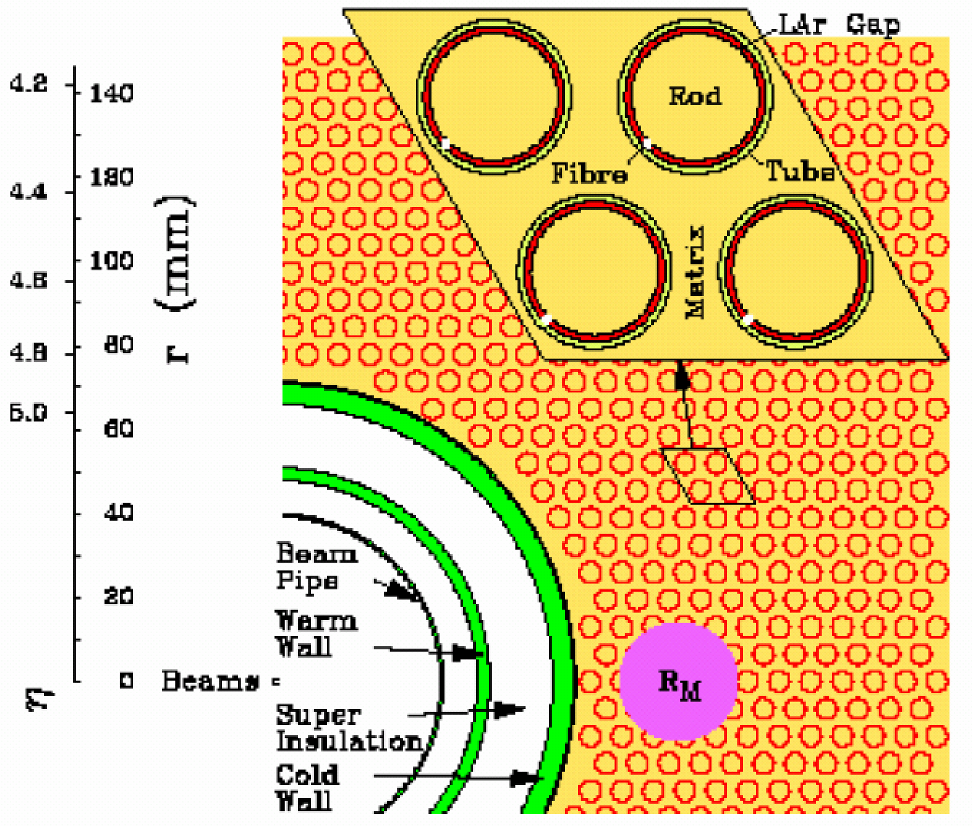
} "Hadronic"

- recessed to reduce neutron albedo in the central cavity
- not much room left for 9.5λ



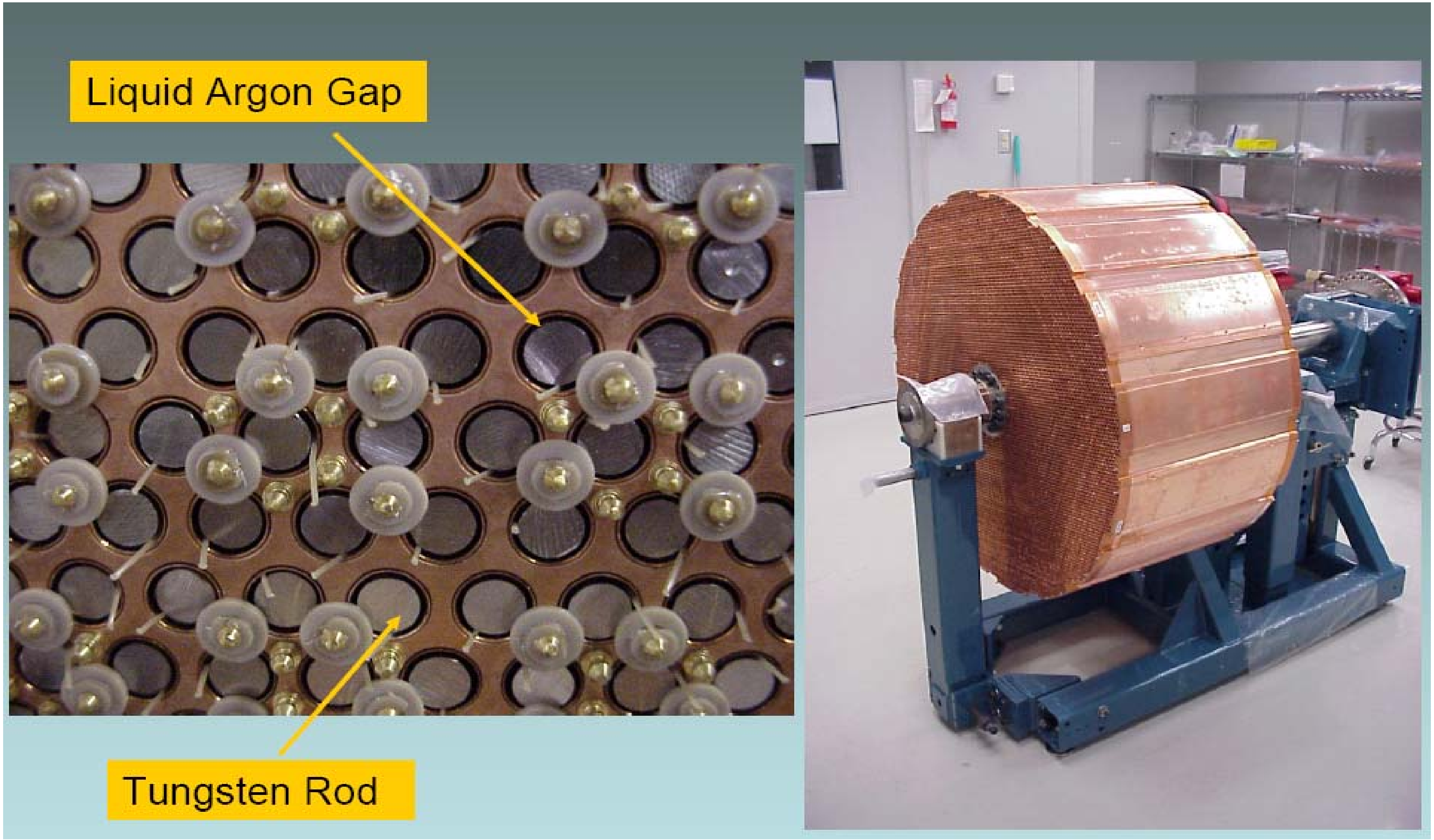
FCal

- Novel electrode structure
  - thin annular gaps form by tubes in an absorber matrix, which are filled with anode rods of slightly smaller radius
- Electrodes along z
  - not pointing!
- All radiation hard materials
- Small gap thickness
  - short drift times
    - reduce ion buildup
  - small HV needed



	Type	Absorber	Gap (μm)	Number of Electrodes
FCal1	EM	copper	250	12000
FCal2	HAD	tungsten	375	10000
FCal3	HAD	tungsten	500	8000

FCal 2/3 Structure and Assembled Modules

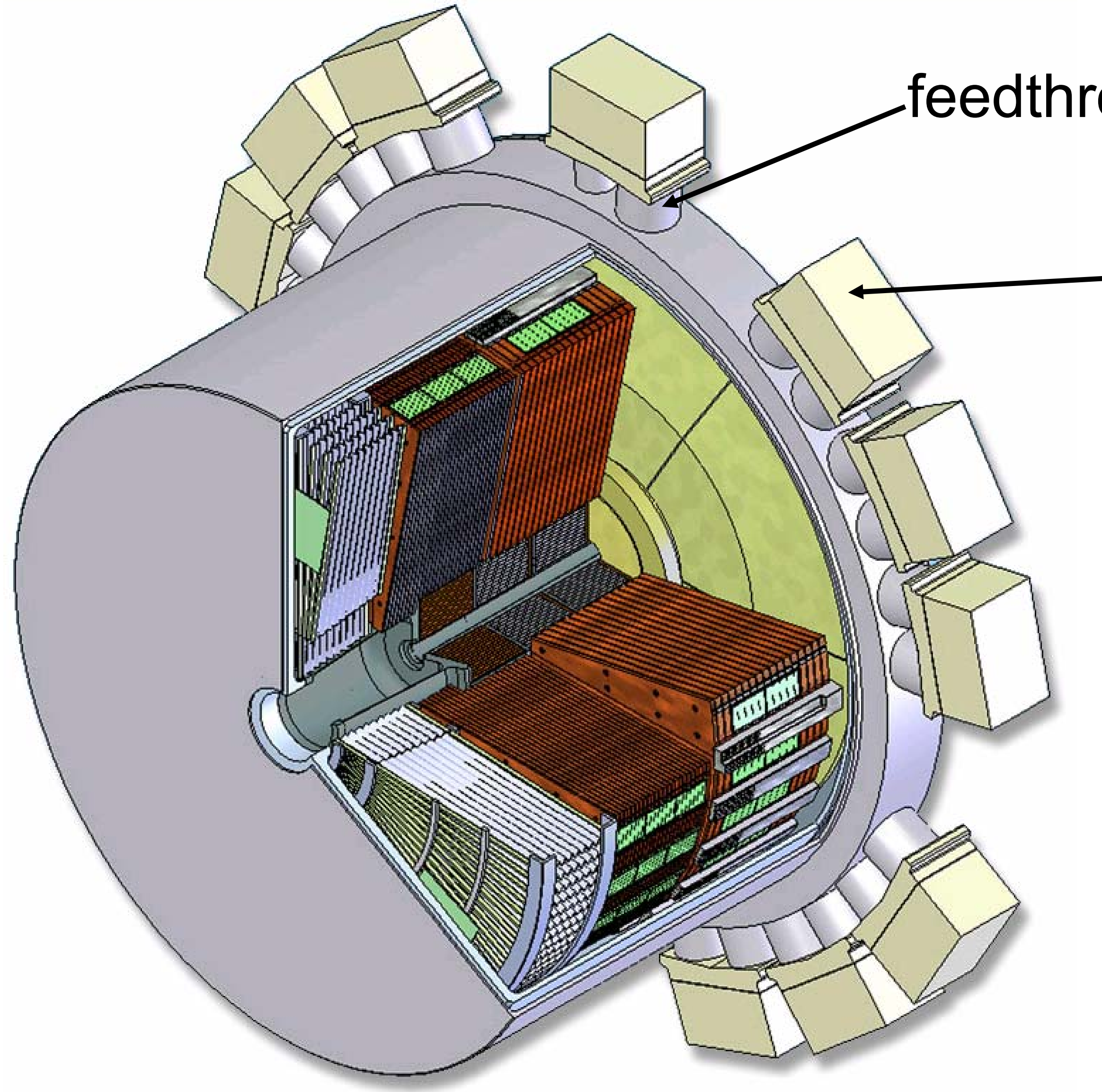


FCal Cell Count

offline/Calorimeter/CaloIdentifier/CaloIdentifier/LArFCAL_ID.h

```
*               Connected channels :
*               ------------------
* pos_neg = +/- 2 (A/C side)<br><br>
*
* module = [1,3] : 1 EM , 2-3 Hadronic <br><br>
*
* phi = [0,15] <br><br>
*
* eta = [0,62] module 1 ; <br>
* eta = [0,31] module 2, except phi=3,4,11,12: eta = [0,30] and phi=0,7,8,15: eta = [0,29]
* eta = [0,15] module 3, except phi=2,10: eta = [0,14]    (old FCAL desciption) <br>
*                        except phi=5,13: eta = [0,14]    (new FCAL desciption) <br><br>
*
* 3524 connected cells in total  <br>
```

Endcap Cryostat



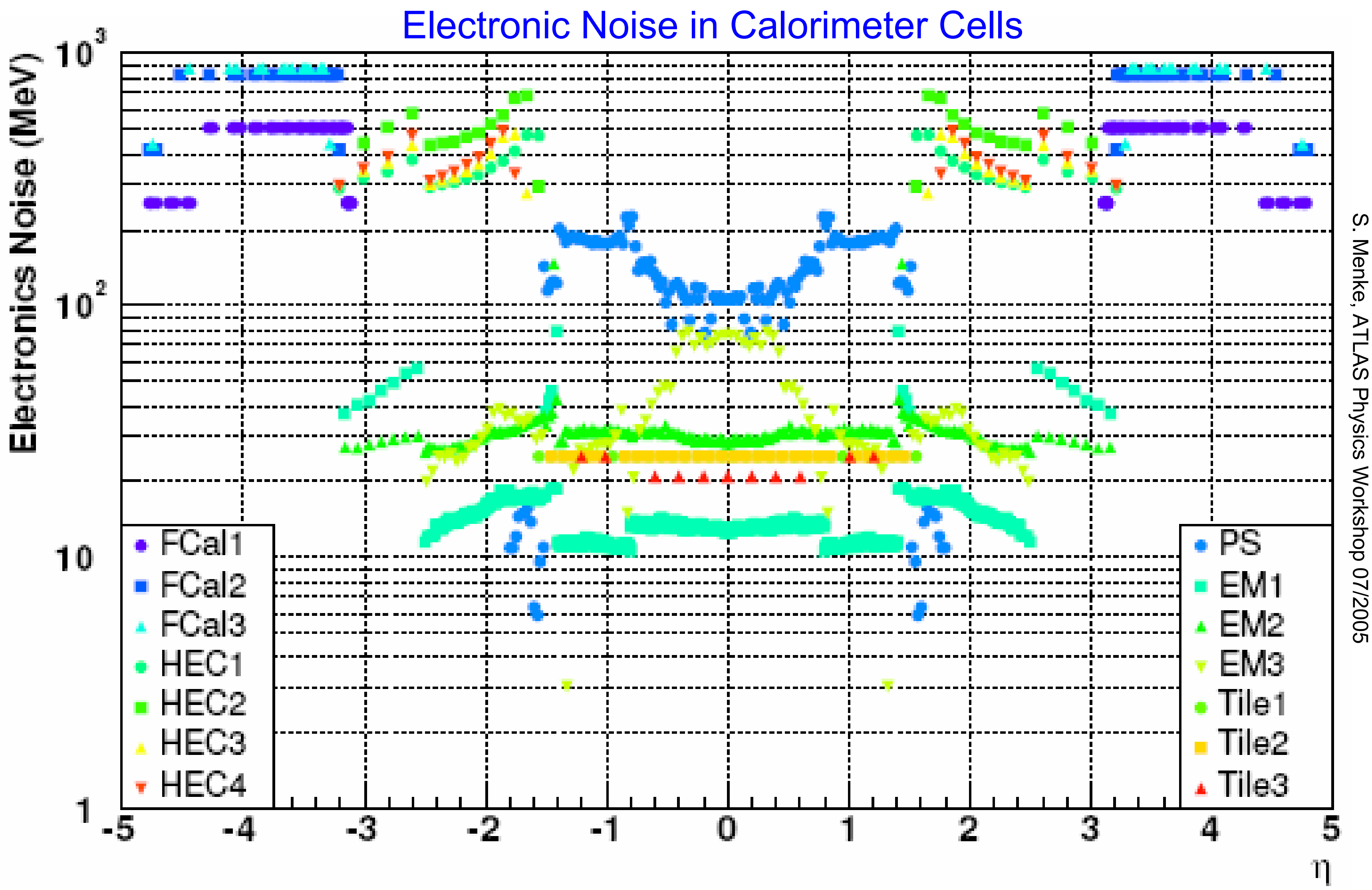
- Only HEC has active electronics in the LAr
  - preamp + sums
- Front End Boards
  - 3 gain readout
    - 10 bit ADC
    - effective 16 bit
  - SCA pipeline

Equipped endcap cryostat C being lowered into position

Calorimeters: Signal Noise (Incoherent)

- Electronic noise
  - unavoidable basic fluctuation on top of each calorimeter cell signal, typically close to Gaussian (symmetric)
  - ranges from ~10 MeV (central region) to ~850 MeV (forward) per cell
  - independent of physics collision environment
  - coherent noise contribution in cells generated in the calorimeter and/or in the readout electronics typically much smaller than incoherent cell electronic noise
    - “fake” pile-up noise avoided

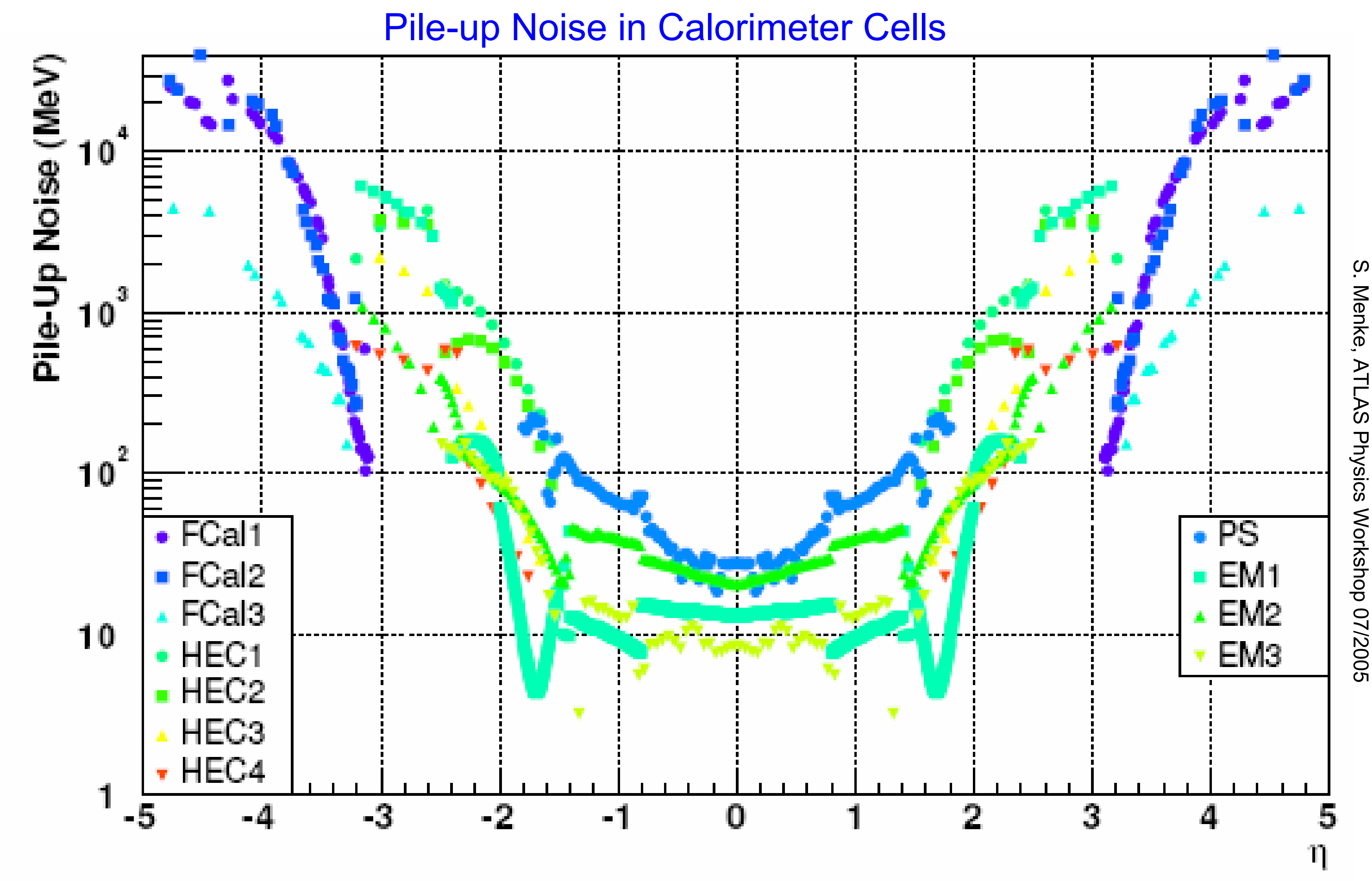
Calorimeters: Signal Noise (Incoherent)



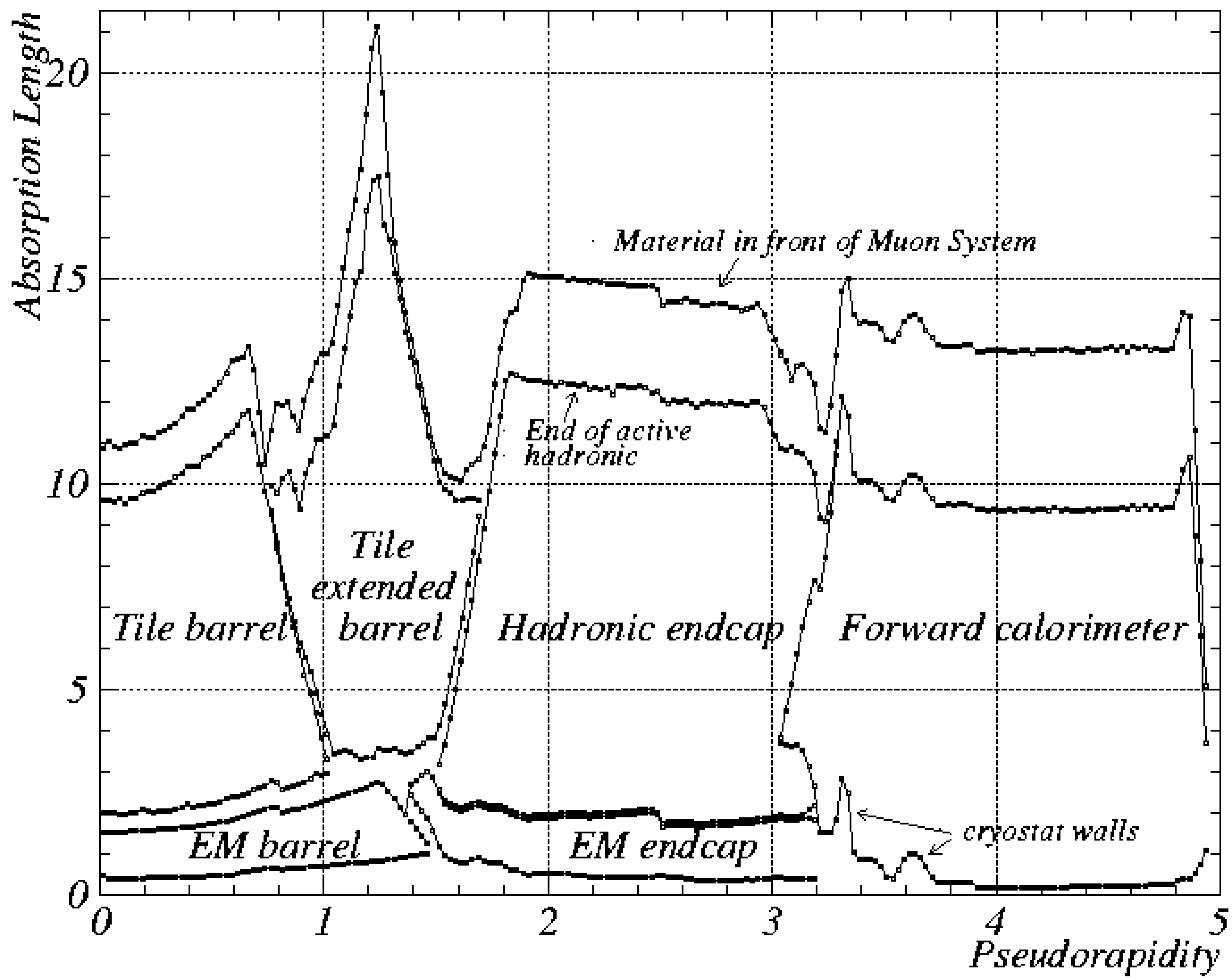
Calorimeters: Signal Noise (Coherent)

- Pile-up noise
  - generated by (many) minimum bias events (MB) in physics collisions
  - depends on instantaneous luminosity
  - illuminates basically the whole calorimeter
  - major contribution to out-of-time signal history due to calorimeter shaping functions (total of ~625 MB/triggered event affect the signal @ $10^{34}cm^{-2}s^{-1}$)
    - slow charge collection in LAr calorimeters (~500 ns) versus high collision frequency (25 ns bunch crossing to bunch crossing) generates signal history in detector
  - Introduces asymmetric cell signal fluctuations from ~10 MeV (RMS, central region) up to ~40 GeV (RMS, forward) similar to coherent noise
    - "real" showers generated by particles in pile-up event introduce cell signal correlation leading to (large) coherent signal fluctuations

Calorimeters: Signal Noise (Coherent)

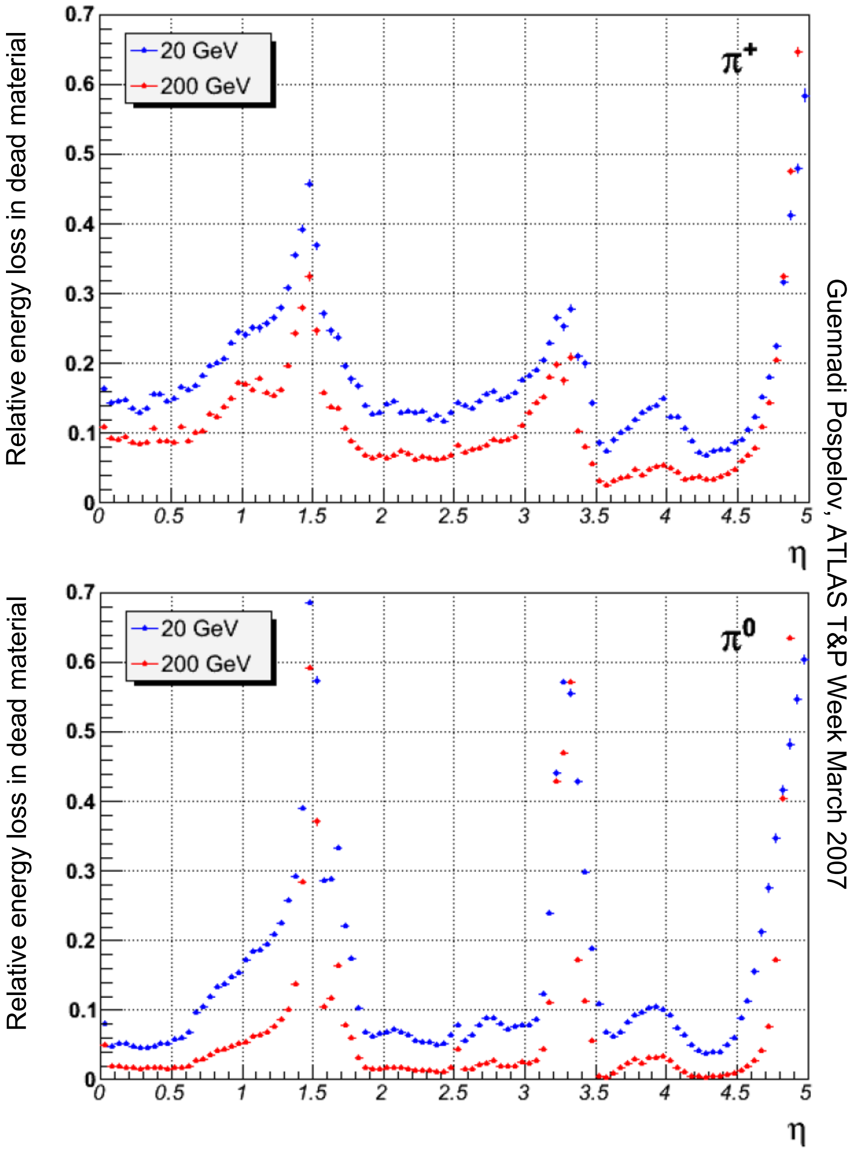


ATLAS Absorption Length Budget (TDR)



Calorimeters: Dead Material

- Dead material
  - Energy losses not directly measurable
    - Signal distribution in vicinity can help
  - Introduces need for signal corrections up to O(10%)
    - Exclusive use of signal features
    - Corrections depend on electromagnetic or hadronic energy deposit
  - Major contributions
    - Upstream materials
    - Material between LAr and Tile (central)
- Cracks
  - dominant sources for signal losses
    - |η| ≈ 1.4 - 1.5
    - |η| ≈ 3.2
  - Clearly affects detection efficiency for particles and jets
    - already in trigger!
    - Hard to recover jet reconstruction inefficiencies
  - Generate fake missing E_T contribution
    - Topology dependence of missing E_T reconstruction quality



Summary of (some) Calorimeter Beam Tests