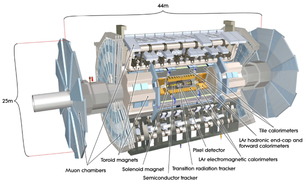
Everything You Always Wanted To Know About Particle Detectors

The ATLAS Detector

Jona Bortfeldt

Medical Physics
Ludwig-Maximilians-Universität Munich, Germany

Bacheloreinführungskurs SoSe 2019
April 29th 2019



Outline

What Can Particle Detectors Measure?

hit

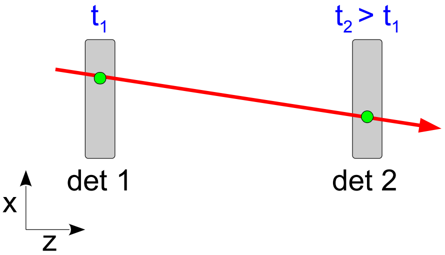
- presence

position

- tracking

timing

- trigger
- direction
- time-of-flight
  $\rightarrow$ velocity $\beta = \frac{\Delta z}{c\Delta t}$



energy loss $\Leftrightarrow$ pulse height

- particle identification
- particle energy $\beta\gamma$

Underlying Mechanisms of Particle Detection?

some kind of interaction of particle in detector!

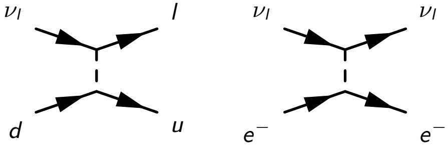
gravitation

- dark matter detection @ galactic dimension

$\rightarrow$ irrelevant in HEP

weak force

- ν: charged & neutral current interactions



$\rightarrow$ irrelevant in accelerator HEP

strong force

- hadrons & mesons
- dominant for neutrals
- calorimeters

electromagnetic force

- dominant for charged
- tracking, triggering, timing, calorimeters

Particle & Photon Interaction Processes

Electromagnetic Interaction of Particles With Matter

- excitation $\rightarrow$ light
- ionization $\rightarrow$ charge
- polarization (Cherenkov radiation) $\rightarrow$ light
- transition radiation $\rightarrow$ X-rays ($\rightarrow$ charge)
- bremsstrahlung $\rightarrow$ gammas ($\rightarrow$ charge)

charge detectors

- gaseous, liquid, solid
- often finely segmented
- tracking, triggering
- integrated particle counting (calorimeters)

light detectors

- transparent medium
- scintillation detectors: detect light from deexcitation & recombination
- Cherenkov detectors
- triggering
- integrated particle counting (calorimeters)

note: photons produce charged particles via photo effect, Compton effect and pair production

Photon Interaction With Matter

photo effect

- $E_\gamma < 100\,\text{keV}$
- $E_{e^-} = E_\gamma - E_b$
  $\rightarrow$ sharp energy deposit
  $\rightarrow$ detector calibration
- $\sigma_\text{photo} \propto Z^5$

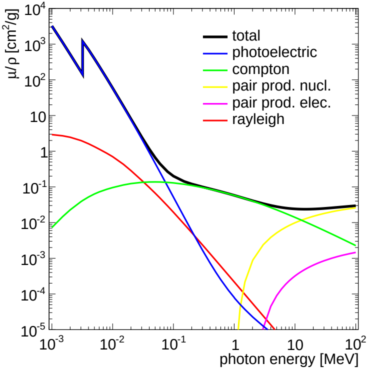
Compton effect

- $100\,\text{keV} < E_\gamma < 5\,\text{MeV}$
- $E'_\gamma = \frac{E_\gamma}{1+(1-\cos\vartheta)E_\gamma/m_e c^2}$

pair production

- $E_\gamma > 5\,\text{MeV}$
- $\sigma \propto \frac{\mu}{\rho} = \frac{7}{9}\frac{1}{X_0} \approx const(E_\gamma)$
  X_0: radiation length
  $\rightarrow P_\text{pair} = 1 - \exp(-7/9) \sim 54\%$
  for $x = X_0$

$$I(x) = I_0 \exp(-\mu d) = I_0 \exp(-\frac{\mu}{\rho}x)$$



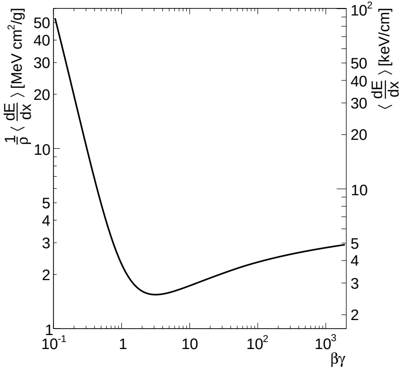
Bethe-Bloch-Formula

$$\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = -4\pi r_e^2 m_e c^2 \rho N_A \frac{Zz^2}{A\beta^2} \left(\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z} \right)$$

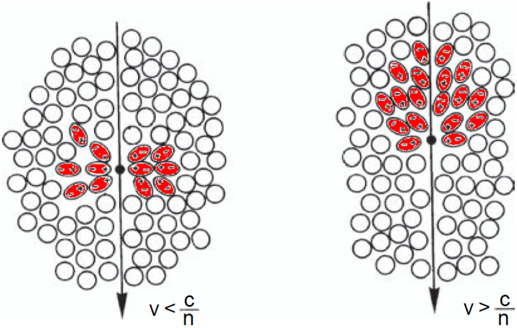
- includes ionization, excitation & polarization
- *mean* energy loss per unit length
- Photo Absorption Ionization model: Allison & Cobb, Ann. Rev. Nucl. Sci. 30 (1980) 253

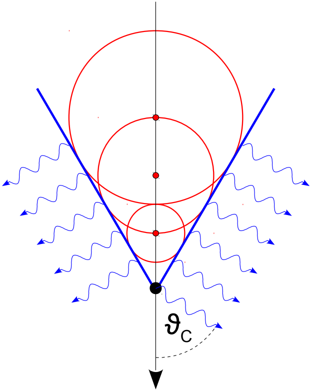
characteristics

- universal function of $\beta\gamma$
  $\rightarrow$ particle ID: $p = \beta\gamma mc$
- $\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle \propto \frac{1}{\beta^2}$ for $\beta\gamma < 1$
- $\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle$ minimal for $\beta\gamma \sim 4$
- $\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle \propto \ln \beta^2\gamma^2$ for $10 < \beta\gamma < 500$
- $\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle \sim$const. for $\beta\gamma > 500$
- universal: $\frac{1}{\rho} \left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = 2\,\mathrm{MeV\,cm^2/g}$



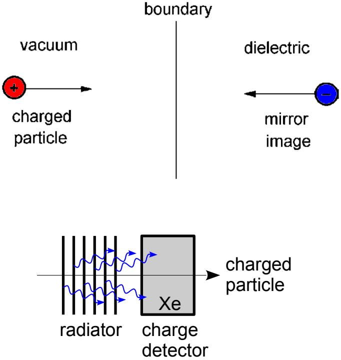
Cherenkov Radiation

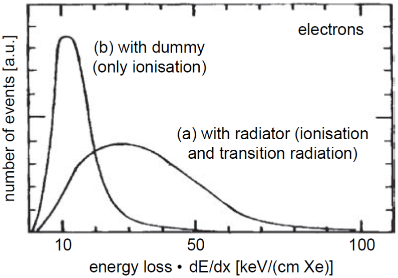




- charged particle in material → polarization
- $\beta > \frac{1}{n}$ = velocity of light in material
  → E-fields cannot follow
  → in-phase superposition of fields
  → emission of blueish light
  → optic analogon to sonic boom
- $\cos \vartheta_C = \frac{1}{\beta n}$
- $\frac{\mathrm{d}N}{\mathrm{d}x} = 490 \sin^2 \vartheta_C \,\mathrm{cm}^{-1}$

Transition Radiation





- charged particle at vacuum (gas)/solid boundary forms variable dipole with its mirror charge
  → emission of radiation (X-rays)
- radiated energy per boundary: $S = \frac{1}{3}\alpha z^2 \hbar\omega\gamma \propto \gamma$
- increase photon number
  → many layers
  → detect photons in high-Z gas detector together with Bethe-Bloch ΔE
- interference effects lead to saturation for $\gamma \sim 1000$

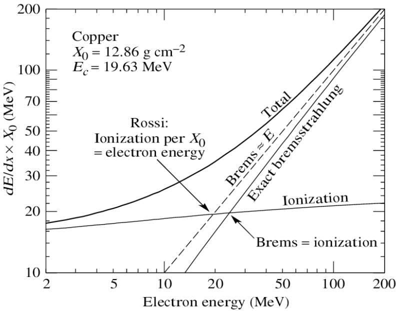
Bremsstrahlung

$$\frac{\mathrm{d}E}{\mathrm{d}x} = -4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{mc^2}\right)^2 \ln\frac{183}{Z^{1/3}} E$$

deceleration in coulomb field (nucleus, weaker also shell electron)
$\rightarrow$ emission of gammas

characteristics

- $\frac{\mathrm{d}E}{\mathrm{d}x} \propto \frac{1}{m^2}$
  $\rightarrow$ mostly relevant for electrons
- $\frac{\mathrm{d}E}{\mathrm{d}x} \propto E$
- $E^e(x) = E_0 \exp\left(-\frac{x}{X_0}\right)$,
  $X_0 = 4\alpha N_A \frac{Z^2}{A} z^2 r_e^2 \ln\frac{183}{Z^{1/3}}$: radiation length
- $\frac{\mathrm{d}E}{\mathrm{d}x}\Big|_{\mathrm{bethe-bloch}} = \frac{\mathrm{d}E}{\mathrm{d}x}\Big|_{\mathrm{brems}}$
  at critical energy E_c
- $E^e_{c,\mathrm{Fe}} \sim 21\,\mathrm{MeV}$ & $E^\mu_{c,\mathrm{Fe}} \sim 890\,\mathrm{GeV}$



How To Measure Energy Loss?

ionization yield in charge detectors

- $n_e = \frac{\Delta E}{W_I}$
  W_I: mean energy per creation of one electron-ion pair ($> E_{\mathrm{ionization}}$!)
- $W_{I,\mathrm{Ar}} = 26\,\mathrm{eV}$
- $W_{I,\mathrm{Si}} \sim 4\,\mathrm{eV}$

$\rightarrow$ gas detectors: $\sim 100\, e^-/\mathrm{cm}$
$\rightarrow$ amplification in detector necessary

$\rightarrow$ semiconductor detectors:
$\sim 22000\, e^-/300\,\mu\mathrm{m}$
$\rightarrow$ direct measurement

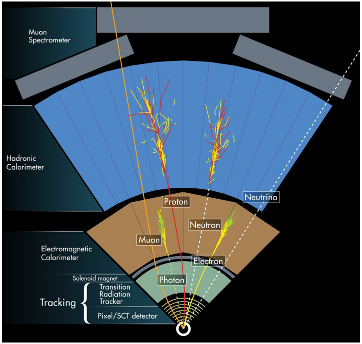
light yield in scintillation detectors

- $n_\gamma = \frac{\Delta E}{W_\gamma}$
  W_γ: mean energy per creation of one photon
- $W_\gamma \sim 100\,\mathrm{eV}$

$\rightarrow$ detect few to several ten thousand photons (possible)

What Info Are We Interested In?

- presence
- timing
- position

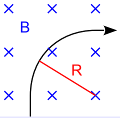


identity

- specific interactions
- $\frac{\mathrm{d}E}{\mathrm{d}x}$ measurement + p
- charge: from p
- via mass: $E^2 - p^2c^2 = m^2c^4$ (difficult)

momentum

- $p = \beta\gamma mc$
- magnetic field: $p = qRB$



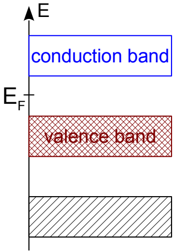
energy

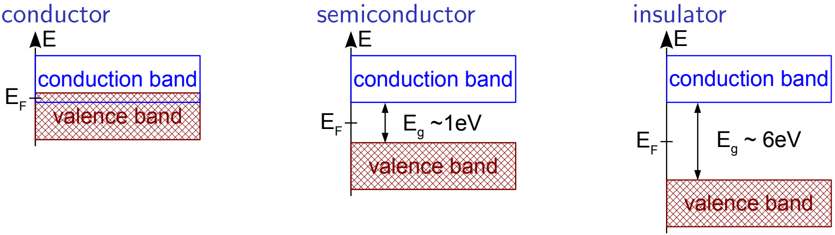
- $E = \gamma mc^2$
- identity + p
- range measurement
- measure complete energy deposition

ATLAS – Inner Detector

Reminder: Band Model & Semiconductors

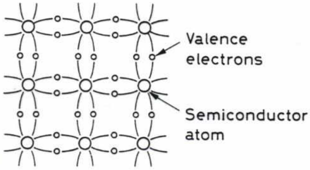
- Schrödinger equation for electron energy in periodic lattice
  $\rightarrow$ quasi-continuous energy bands
- valence band: fully occupied @ $T = 0\,\mathrm{K}$, e^- bound to atoms
- conduction band: empty @ $T = 0\,\mathrm{K}$, e^- could move within lattice





Conductivity of Semiconductors

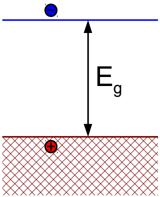
$T = 0\,\text{K}$

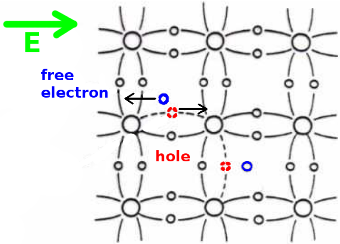


- valence band completely occupied
- conduction band empty

$\rightarrow \sigma = 0$
$\rightarrow$ insulating

$T > 0\,\text{K} + E$-field



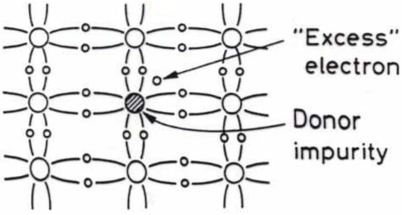


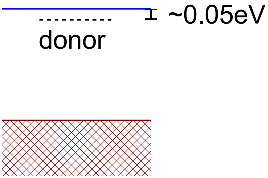
- $\sigma = e(n_n\mu_n + n_p\mu_p)$
  $\rightarrow$ electrons (n) & holes (p) contribute to conductivity
- $n_n = n_p \sim 5 \times 10^{15}\, T^{3/2} \exp(-\frac{E_g}{2kT})$
- strong temperature dependence
- 300 K: $\rho_{\text{Si}} = 1/\sigma_{\text{Si}} \sim 10^5\,\Omega\text{cm}$
  $\rightarrow$ low conductivity
  $\rightarrow$ strong dependance on impurities

Doping of Semiconductors $\rightarrow \rho \sim 10^3\ \Omega$cm

n-type

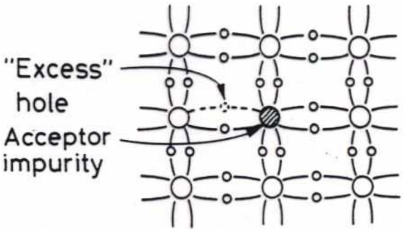
- add quinquevalent impurity (e.g. P)

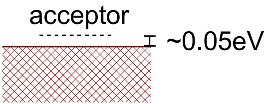




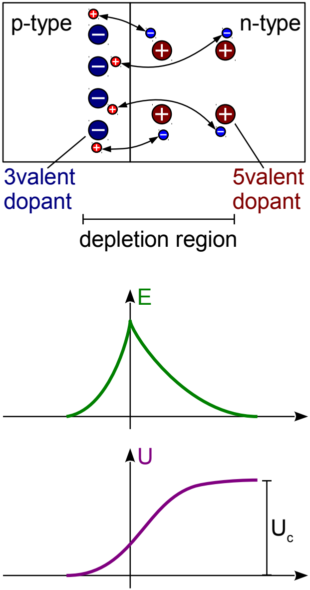
p-type

- add trivalent impurity (e.g. B)





P-N Junction



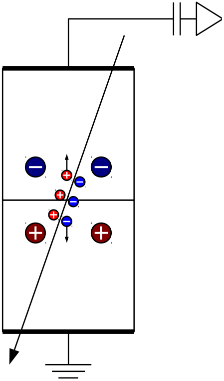
- electrons diffuse into p-type
- holes diffuse into n-type

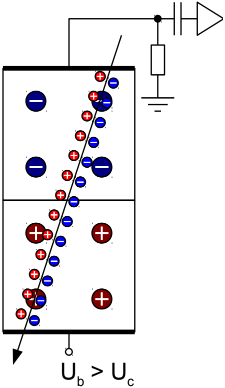
→ recombine
→ dopant trunks produce space charge
→ space charge prevents further diffusion

formation of depletion region: no free charge carriers
→ no current in reverse bias direction (diode behavior)

in reality: leakage current due to thermal excitation of semiconductor or contaminants and defects
→ strong reduction by cooling

P-N Junction as Particle Detector



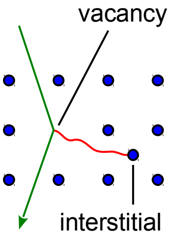


- charged particle
  → **ionization** & excitation
- charge separation only in depletion region
  → current pulse

- reverse bias voltage $U_b \sim 100\,\text{V}$
  → increase depletion region
  → increase current pulse & active volume

Aging of Semiconductor Detectors

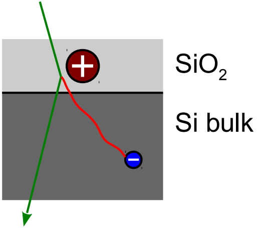
bulk damage



- higher leakage current
- capturing of e^{-} or holes
  $\rightarrow$ charge collection efficiency
- space charge
- type inversion: n-type bulk $\rightarrow$ p-type bulk
  $\rightarrow$ p-n junction at n^{+}-bulk interface

$\rightarrow$ adapt U_b accordingly

surface damage



- surface leakage current
- space charge

Annealing of Semiconductor Detectors

- empiric: damage $\propto$ integrated dose Φ
- interstitials and vacancies diffuse within warm semiconductor

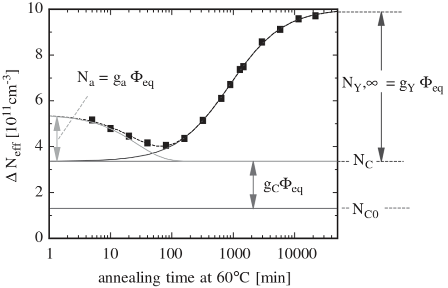
beneficial annealing

- recombination of single interstitions & vacancies
- short term

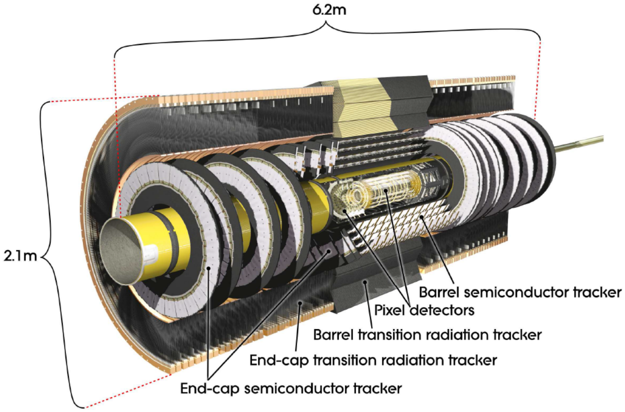
reverse annealing

- undesired
- long term

stable damage



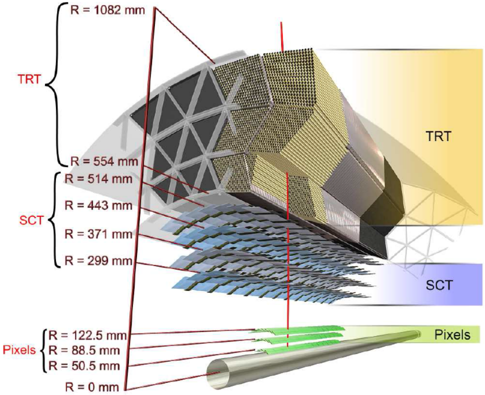
Inner Detector



- momentum measurement with high resolution
  → whole ID in 2 T solenoidal B-field
- primary & secondary vertex reconstruction
- pattern recognition
- electron identification

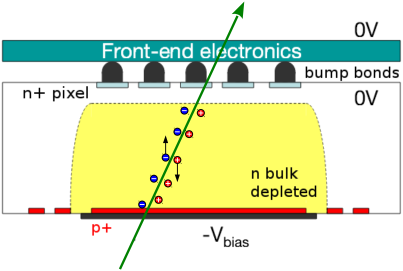
- high spatial resolution
- high granularity
- transition radiation detector

Inner Detector Components

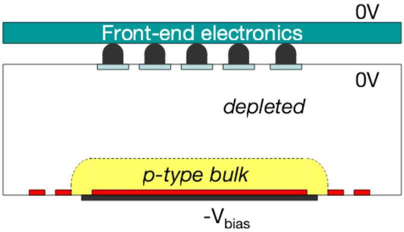


- transition radiation tracker
  - many layers 4 mm straw tubes $\rightarrow$ at least 36 individual position measurement points
  - embedded in TR radiator (polypropylene fibres (barrel) and foils (endcap)) $\rightarrow$ especially electrons produce TR X-rays, 7 to 10 detected TR photons with much higher pulse height per traversing electron
- four double-layers silicon microstrip detectors ($\sim 80\mu\mathrm{m} \times 12\,\mathrm{cm}$)
- four layers silicon pixel detectors
  - insertable B-layer: $50\mu\mathrm{m} \times 250\,\mu\mathrm{m}$ (planar and 3D pixels, not treated in this talk)
  - three outer layers: $50\mu\mathrm{m} \times 400\,\mu\mathrm{m}$

Silicon Pixel Modules



before irradiation:
p-n junction between
p+ and n-type bulk

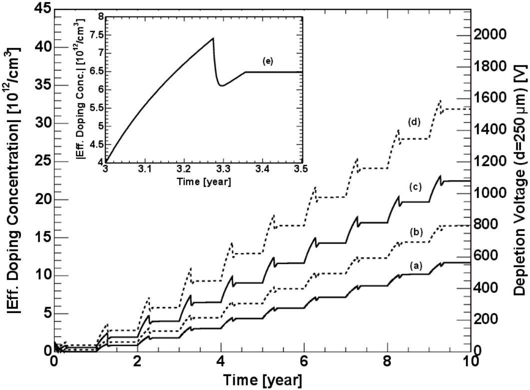


after irradiation & type inversion:
p-n junction between p-type bulk
and n+ pixels

- 250 μm thick n-type bulk
- readout electronic directly bonded onto sensor
- 50$\mu\mathrm{m} \times 400\,\mu\mathrm{m}$ pixel size
  $\rightarrow$ spatial resolution 10 μm & 115 μm
- type inversion & ageing anticipated
  $\rightarrow$ n$^+$ pixels
  $\rightarrow$ U_b from 150 V to 600 V
- cooled to -10° idle, 0° in operation

Aging of Pixel Modules

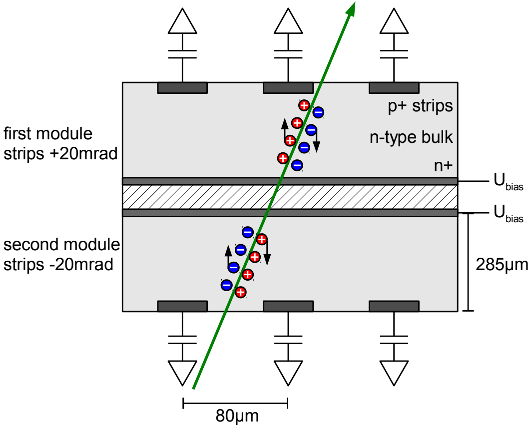
- aging: increase of effective dopant concentration
- increase bias voltage to reach full depletion
- 100 days operation @ 0°
- 30 days maintenance @ 20° → annealing
- rest: idle @ -10°
- $U_b = 600\,\mathrm{V}$ maximum!



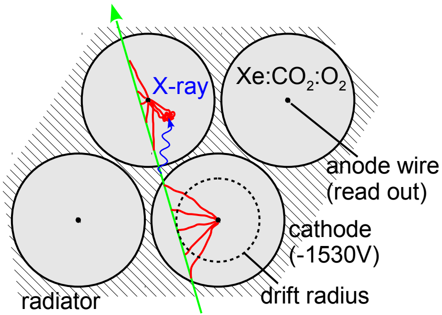
a: $R = 88\,\mathrm{mm}$ layer for nominal dose
c: $R = 50\,\mathrm{mm}$ layer for nominal dose
b & d: same as a and c but for 1.5 nominal dose

Silicon Microstrip Modules

- two layers per module, stereo angle 40 mrad
- conventional p-in-n-type: large area & cost
- readout electronic wire bonded to sensor
- spatial resolution 17 μm & 580 μm (from stereo angles)
- type inversion & ageing anticipated
  $\rightarrow U_b$ from 150 V to 500 V, sufficiently large margin
- cooled to -7° for reduced leakage current and reverse annealing



Transition Radiation Tracker



- radial E-field in straw tube
  $\rightarrow$ strong close to wire
- ionization along particle track (100 e)
- charge amplification around wire (25k)
- measure earliest arrival time
- $t_{\mathrm{drift}} = \frac{r_{\mathrm{drift}}}{v(r_{\mathrm{drift}})}$
  $\rightarrow$ drift radius
  $\leftrightarrow$ position $O(130\,\mu\mathrm{m})$
- TR: $E_\gamma \sim 20\,\mathrm{keV} \rightarrow 900\,e$
- Why Xe ($Z = 54$, extremely expensive)? remember: $\sigma_{\mathrm{photo}} \propto Z^5$

ATLAS – Calorimeter

Measurement Principle: Electromagnetic Sampling Calorimeter

dominant interaction of

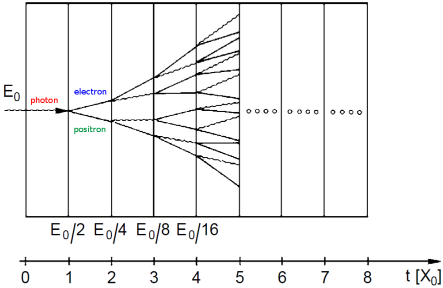
- high energy electrons: bremsstrahlung $\rightarrow$ photons
- high energy photons: pair production

remember: after $1X_0$:

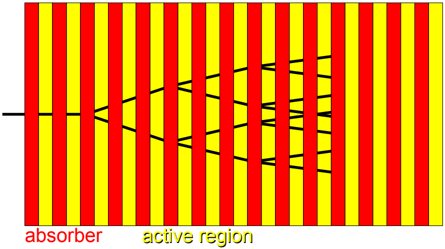
- $P_{\mathrm{brems}} \sim 63\%$
- $P_{\mathrm{pair}} = 1 - \exp(-7/9) \sim 54\%$

$\rightarrow$ shower develops

- shower stops when $E(t) < E_c$
- number of $e^{\pm}\&\gamma$: $N(t) \sim 2^t$
- mean particle energy: $E(t) \sim E_0/N(t) = E_0 2^{-t}$
- at maximum depth: $E(t) = E_c$ $\rightarrow E_0 2^{t_{\mathrm{max}}} = E_c$
- total particle path $\Leftrightarrow$ number of $e^{\pm}$: $S = \sum_{t=0}^{t_{\mathrm{max}}} \frac{2}{3} N(t) \sim \frac{2}{3} 2^{t_{\mathrm{max}}+1} = \frac{4}{3} \frac{E_0}{E_c}$
- note: for constant ionization: $S \propto Q$



sampling calorimeter

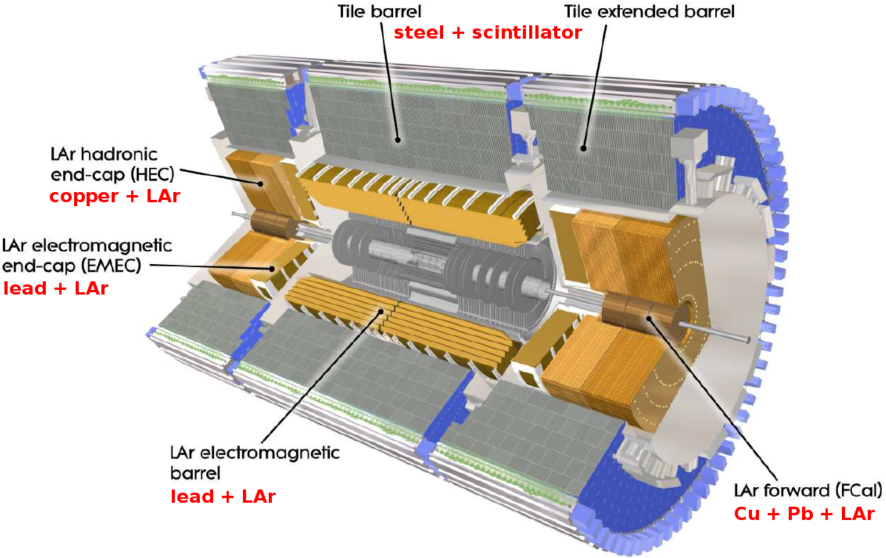


Hadronic Sampling Calorimeter

- equivalent to EM calo but hadronic interaction $\leftrightarrow$ bremsstrahlung/pair production
- nuclear interaction length $\lambda \gg X_0$
  $\rightarrow$ much thicker absorber plates than in EM
- hadron cascades: more particles with difficult energy determination (ν & μ leave calo, $\pi^0 \rightarrow \gamma\gamma$ are lost in absorber, slow nuclear fragments ionize strongly)
  $\rightarrow$ energy resolution worse than in EM calo

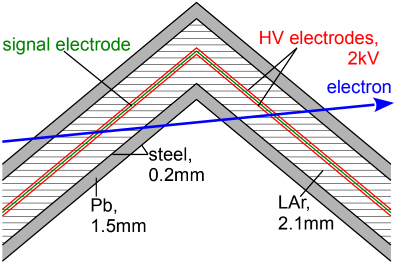
material	λ[cm]	X_0 [cm]
LAr	85.8	14.0
Fe	16.8	1.76
Cu	15.3	1.44
Pb	17.6	0.56
W	9.95	0.35

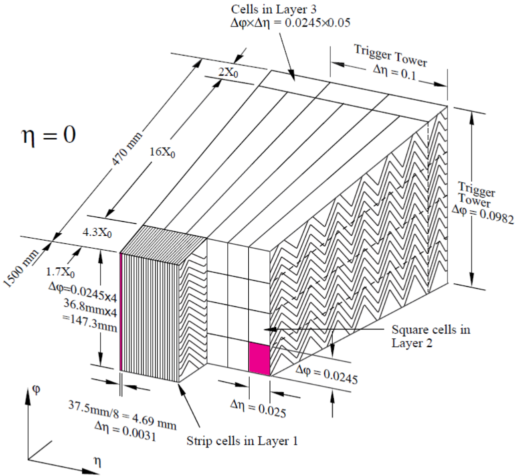
ATLAS Calorimeter System



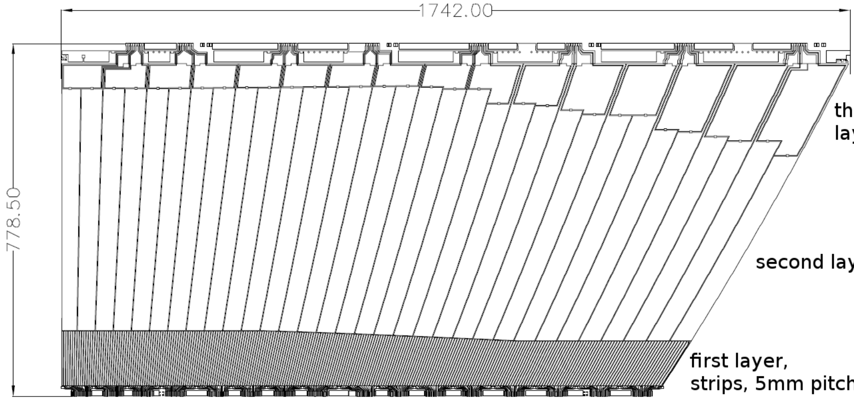
Electromagnetic Barrel Calorimeter

- absorber: lead (1.5 mm & 1.1 mm for $\eta > 0.8$) between 0.2 mm steel
- active layer: twice 2.1 mm LAr
- two HV electrodes for electron-ion-separation
- charge signal collected by electrode
- three layers in depth: segmentation of signal electrode





Electromagnetic Barrel Calorimeter – Signal Electrode

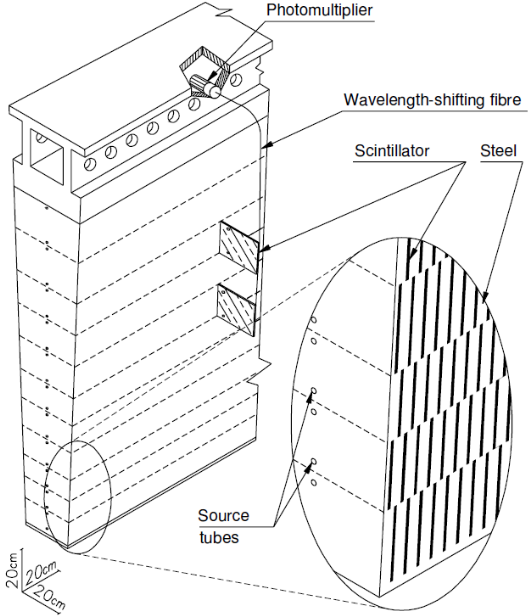


seve

signal electrodes from adjacent LAr-gaps are grouped to form cells

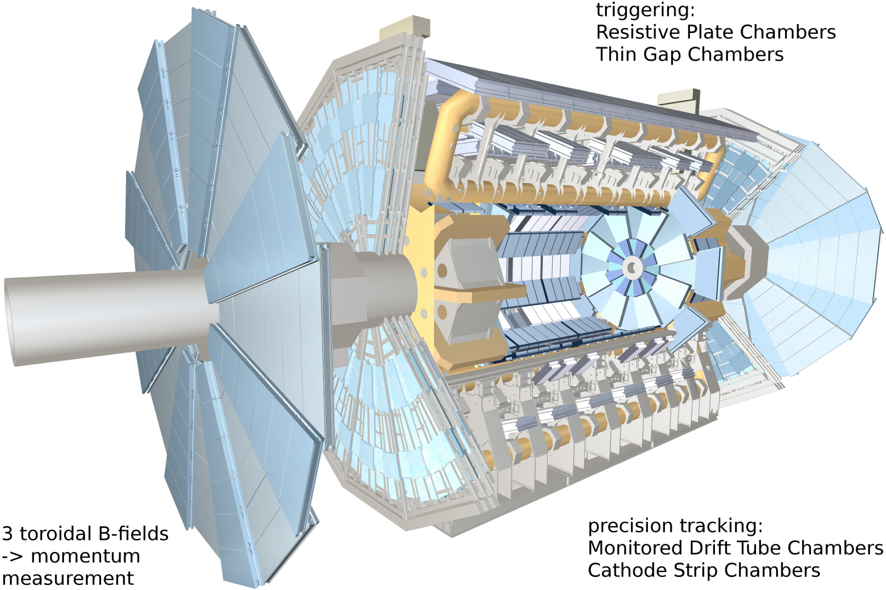
Hadronic Barrel Calorimeter

- absorber: steel ($5\,\text{mm}\times 97\,\text{mm}\times 200\,\text{mm}$ to $5\,\text{mm}\times 187\,\text{mm}\times 400\,\text{mm}$)
- active layer: 3 mm plastic scintillator tiles
- scintillation light from both sides decoupled via wavelength-shifting fibers
- fibers grouped & read out via photomultiplier
- three layers in depth



ATLAS – Muon System

Quarter of the ATLAS Muon System

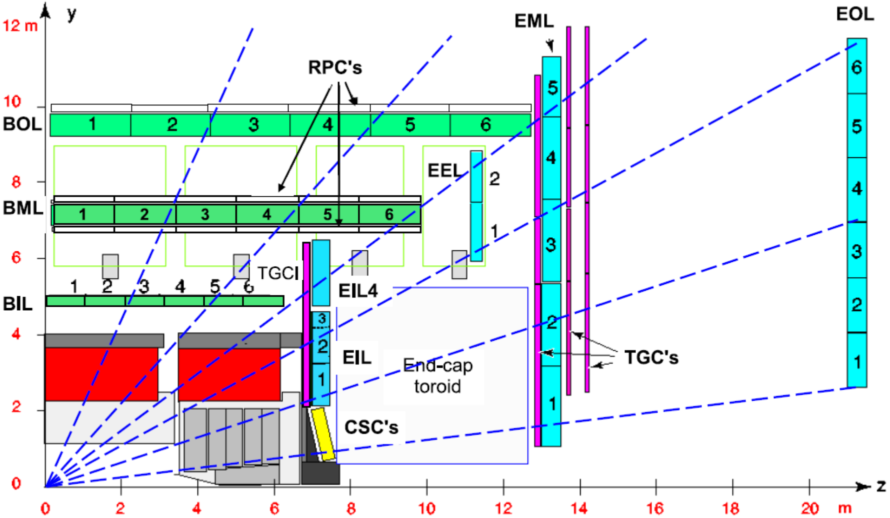


triggering:
Resistive Plate Chambers
Thin Gap Chambers

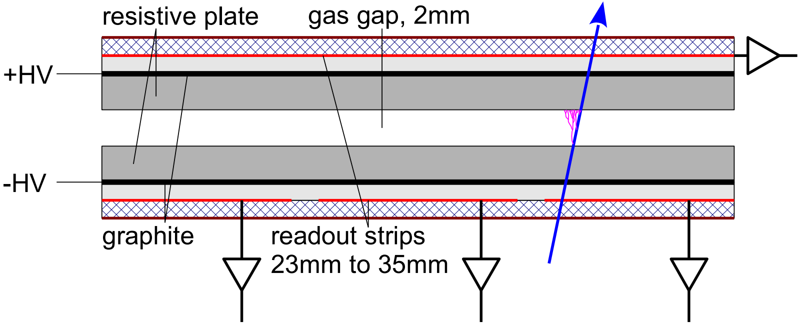
3 toroidal B-fields
-> momentum
measurement

precision tracking:
Monitored Drift Tube Chambers
Cathode Strip Chambers

ATLAS Muon System



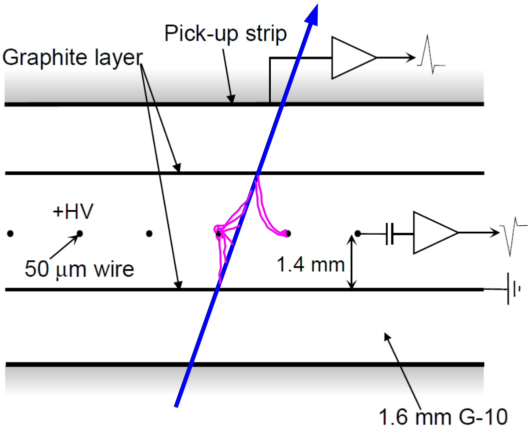
Trigger Barrel: Resistive Plate Chambers



- 2 mm gas gap, $C_2H_2F_4$:iC_4H_{10}:SF_6
- highly resistive plates, contacted by graphite layers
- charged particle $\rightarrow$ ionization
- homogenous E-field (49 kV/cm) $\rightarrow$ gas amplification & electron-ion separation
- fast signal on perpendicular readout strips (1.5 ns resolution, 5 ns duration)
- coarse position information $O(35\,\mathrm{mm})$ per module
- two modules per chamber

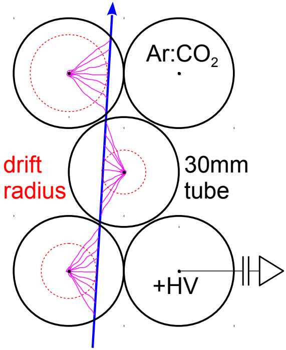
Trigger Endcap: Thin Gap Chambers

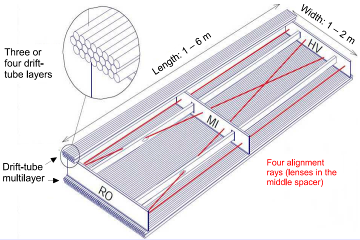
- 2.8 mm planar gas gap, CO_2:nC_5H_{12}
- 50 μm wires, pitch 1.8 mm, 2.9 kV
- charged particle $\rightarrow$ ionization
- electrons drift to wires $\rightarrow$ saturated gas amplification
- signal on wire
- signal on perpendicular readout strips
- spatial resolution $O(5\,\mathrm{mm})$ per layer, timing resolution 4 ns



Tracking Barrel/Endcap: Monitored Drift Tube Chambers

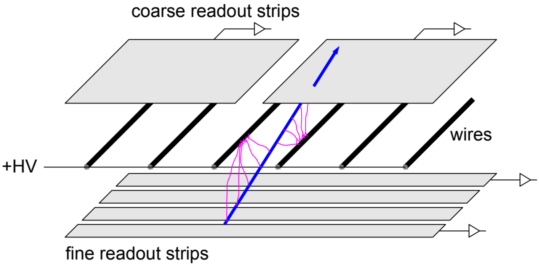
- 30 mm aluminum tube, Ar:CO_2 93:7, 3 bar
- central 50 μm wire, 3 kV
- charged particle → ionization
- electrons drift to central wire (max 700 ns)
  → gas amplification
- measure earliest arrival time of electrons
  → drift radius
- combine 6 to 8 tube layers
  → particle track $O(35\,\mu\mathrm{m})$
- $2 \times 5\,\mathrm{m}^2$ max size → deformation: temperature gradients, mounting position
  → wire position has to be known with $O(30\,\mu\mathrm{m})$
  → monitor relative position and internal deformation via optical system





Tracking Inner Endcap: Cathode Strip Chambers

- 5 mm planar gas gap, Ar:CO_2
- 30 μm wires, pitch 2.5 mm, 1.9 kV, not read out
- charged particle $\rightarrow$ ionization
- electrons drift to wires $\rightarrow$ gas amplification
- mirror signal on two layers of perpendicular readout strips
- precision coordinate: 1.85 mm pitch, every third read out $\rightarrow$ spatial resolution $O(60\,\mu\mathrm{m})$ per layer
- coarse coordinate: 21 mm & 13 mm pitch $\rightarrow$ spatial resolution $O(5\mathrm{mm})$ per layer



Summary

Summary

- charged particles & photons: EM interaction dominant
  - excitation
  - ionization
  - Cherenkov radiation
  - transition radiation
  - bremsstrahlung

  (excitation, ionization, Cherenkov radiation: } Bethe-Bloch)
- neutral hadrons: strong interaction
- charge detectors $\leftrightarrow$ light detectors
- detectors: presence, timing, position
- momentum measurement (track radius in B-field), energy (range or calorimetric), identity
- ATLAS:
  - transition radiation tracker
  - electromagnetic lead-LAr calorimeter
  - hadronic steel-scintillator calorimeter
  - resistive plate chambers
  - thin gap chambers
  - monitored drift tube chambers
  - cathode strip chambers

  (resistive plate chambers, thin gap chambers: } muon trigger)
  (monitored drift tube chambers, cathode strip chambers: } muon track)

Summary

- charged particles & photons: EM interaction dominant
  - excitation
  - ionization
  - Cherenkov radiation
  - transition radiation
  - bremsstrahlung

  (excitation, ionization, Cherenkov radiation } Bethe-Bloch)
- neutral hadrons: strong interaction
- charge detectors $\leftrightarrow$ light detectors
- detectors: presence, timing, position
- momentum measurement (track radius in B-field), energy (range or calorimetric), identity
- ATLAS:
  - transition radiation tracker
  - electromagnetic lead-LAr calorimeter
  - hadronic steel-scintillator calorimeter
  - resistive plate chambers
  - thin gap chambers
  - monitored drift tube chambers
  - cathode strip chambers

  (resistive plate chambers, thin gap chambers } muon trigger)
  (monitored drift tube chambers, cathode strip chambers } muon track)

Thank you!