8.882 LHC Physics

Experimental Methods and Measurements

Detectors: Tracking

[Lecture 7, February 25, 2009]

Physics
Colloquium Series

‘09

Spring

The Physics Colloquium Series

Thursday, February 26 at ***4:15 pm*** *in room* ***10-250***

Zoltan Fodor

University of Wuppertal, Eotvos University of Budapest, John von Neumann Institute for Computing, DESY-Zeuthen, and Forschungszentrum-Juelich

"The Origin of Mass of the Visible Universe"

For a full listing of this semester’s colloquia,
please visit our website at web.mit.edu/physics

Organizational Issues

Nothing from my side....

Remember though

- project 1 due March 12 (2.3 weeks)

Lecture Outline

Detectors: Tracking

- gas tracking detectors

Sauli paper CERN 77-09

- the Central Outer Tracker (COT) at CDF
- silicon detectors
- the silicon tracking system at CDF
- the tracker at CMS

To Remember: Gas Detectors

Design is complex.. or simply black magic

Things you should remember

- ionization, avalanche development
- gain
- proportional chamber, multi wire chamber
- outline of gas choices
- resolution

Pretty complete overview in Sauli's paper, impossible to copy in this lecture.

Ionization Reminder

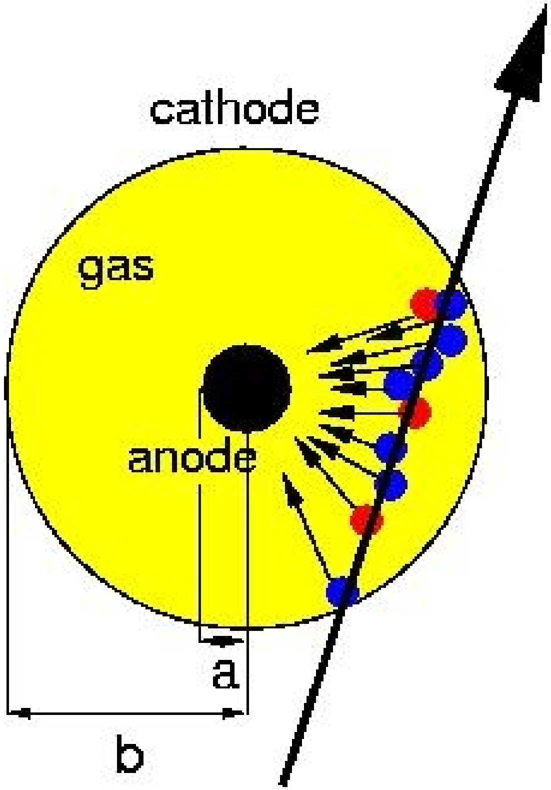
Ionization: process which causes $n_{\text{electrons}} \neq n_{\text{protons}}$

- usually kick electron out
- breaking ionization potential barrier

Charged particle causes ionization in detector

- ion-electron pair (called ion pair)
- separate ion and electron in electric field
- electron drifts to anode
- ion drifts to cathode
- round geometry:

$$E = \frac{V}{r \ln(b/a)}$$



Ionization continued

Factors for ionization

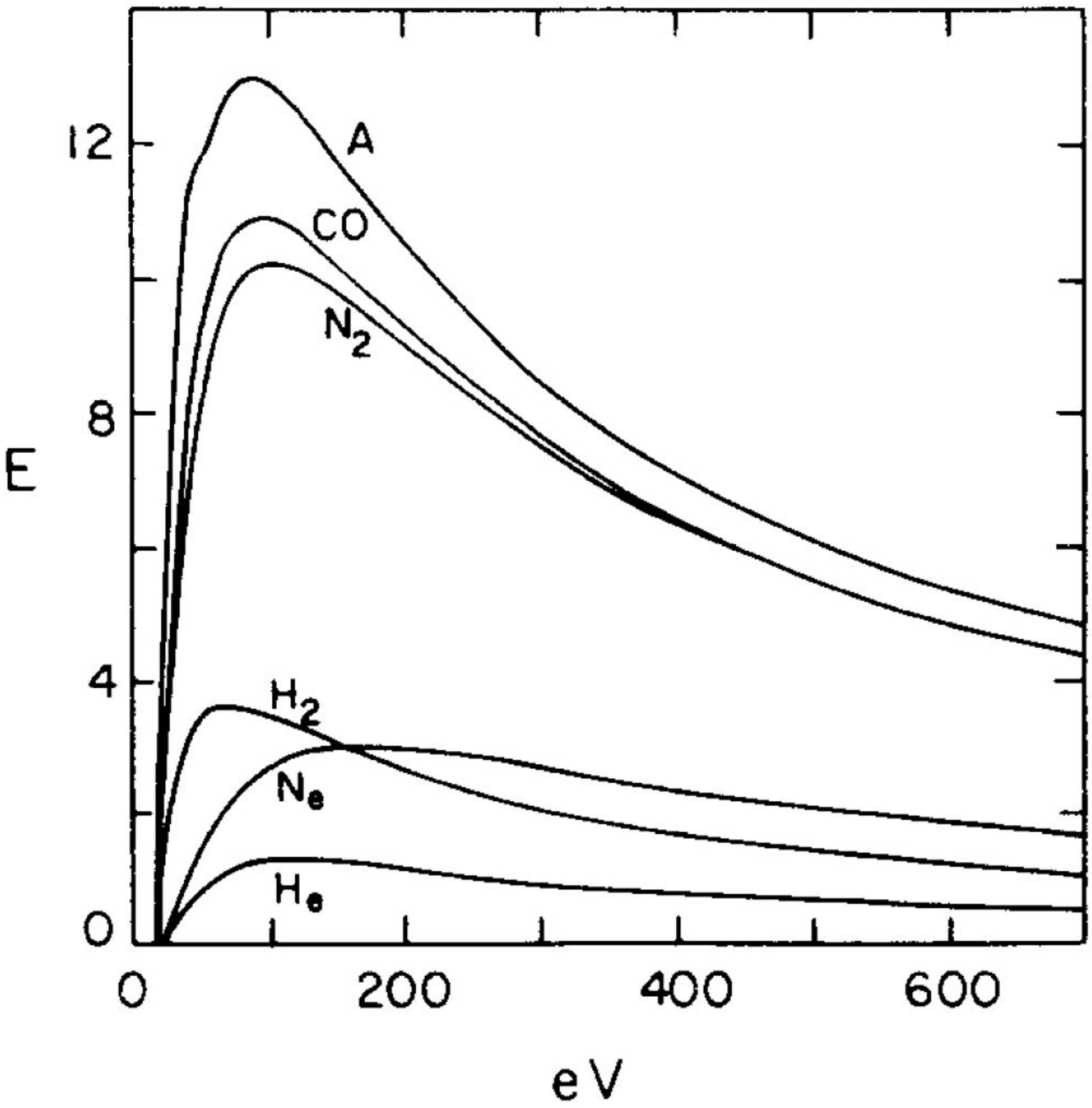
- electric field = “voltage”, but not only parameter
- affected by
  - gas temperature
  - gas pressure
  - electric field
  - gas composition
- mean free path an important parameter
- ionization depends on the material's ionization potential
- some gases eat up electrons (quenchers)

Ionization as a Function of Energy

Ionization probability quite gas dependent

General features

- threshold (≈20 eV)
- fast turnon
- maximum (≈100 eV)
- soft decline



Mean Free Path

Mean free path

- average distance an electron travels until it hits a target
- half of ionization is due to “last mean free path”

Some typical numbers

Vacuum range	Pressure [hPa]	Molecules/ccm	mean free path [m]
Ambient pressure	1013	2.7*1e19	68 1e-9
Low vacuum	300..1	1e19..1e16	1e-7 – 1e-4
Medium vacuum	1..1e-3	1e16..1e13	1e-4 – 1e-1
High vacuum	1e-3..1e-7	1e13..1e9	1e-1 – 1e3
Ultra high vacuum	1e-7..1e-12	1e9..1e4	1e3 – 1e8
Extremely high vacuum	<1e-12	<1e4	> 1e8

What Happens after Ionization?

After collision ions/electrons thermalize quickly and travel until neutralized

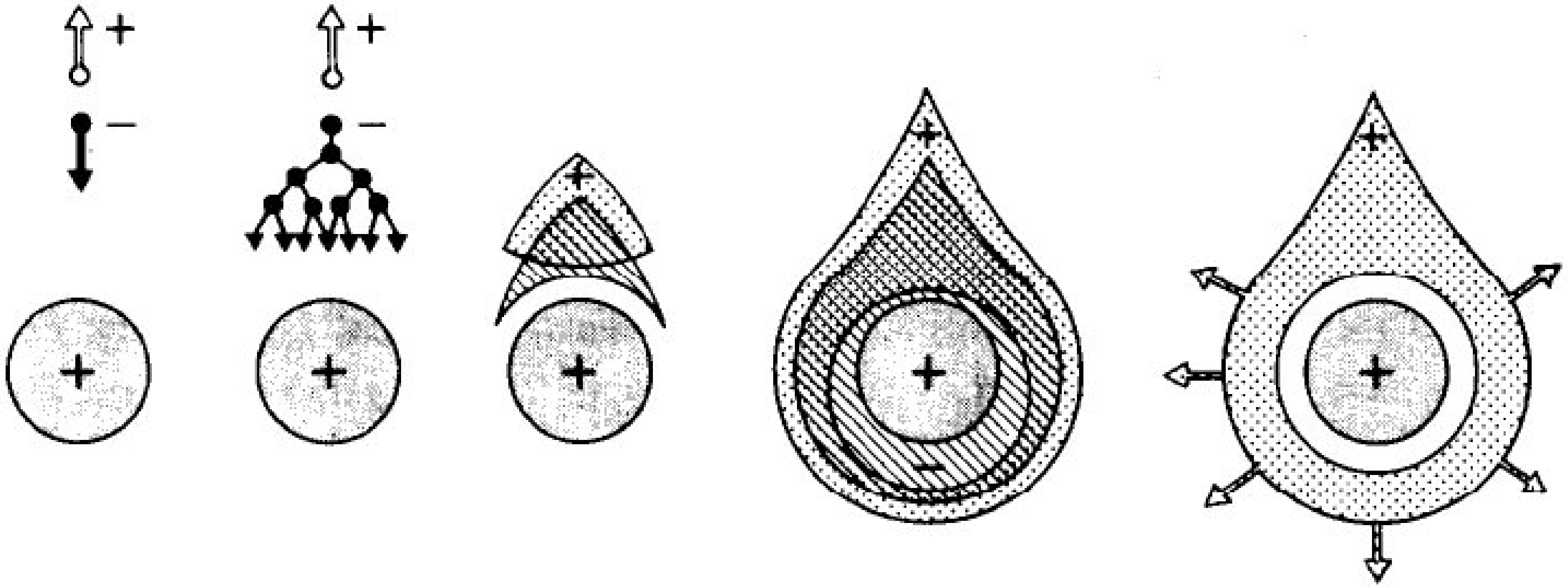
Ions

- neutralize through electron, wall, negative ion
- travel slowly through diffusion process
- diffusion velocity depends on gas, important for design

Electrons

- neutralize through ions, wall, attach to some molecules
- mean free path about 4 times longer than for ions
- diffuse very quickly, accelerate in E field (avalanche)
- drift velocity strongly depends on gas mixture

The Avalanche



Electrons diffuse to anode

- ionize atoms they hit
- spreading laterally
- electron drift fast about 1 ns ↔ ions slower (heavier)
- leave positive ion cloud behind

Gas Tracking Detectors

Ionization Chamber

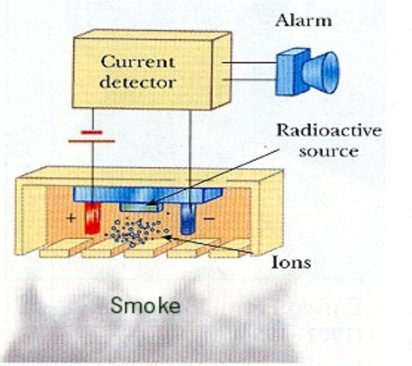
- lowest voltage
- no secondary ionization, just collect ions

Proportional Chamber

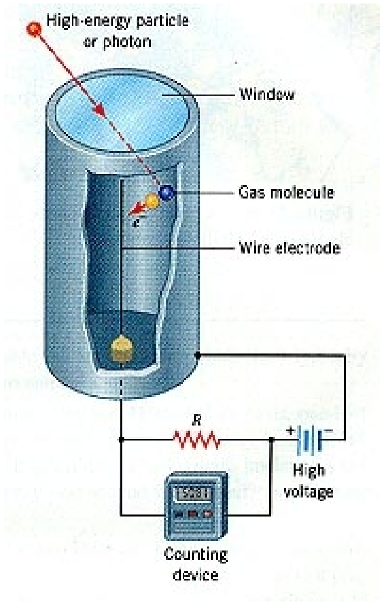
- higher voltage – tuned
- avalanches develop but independently
- total charge proportional to particle's kinetic energy

Geiger-Müller Counter

- highest voltage
- avalanche maximal, saturation



Smoke Detector



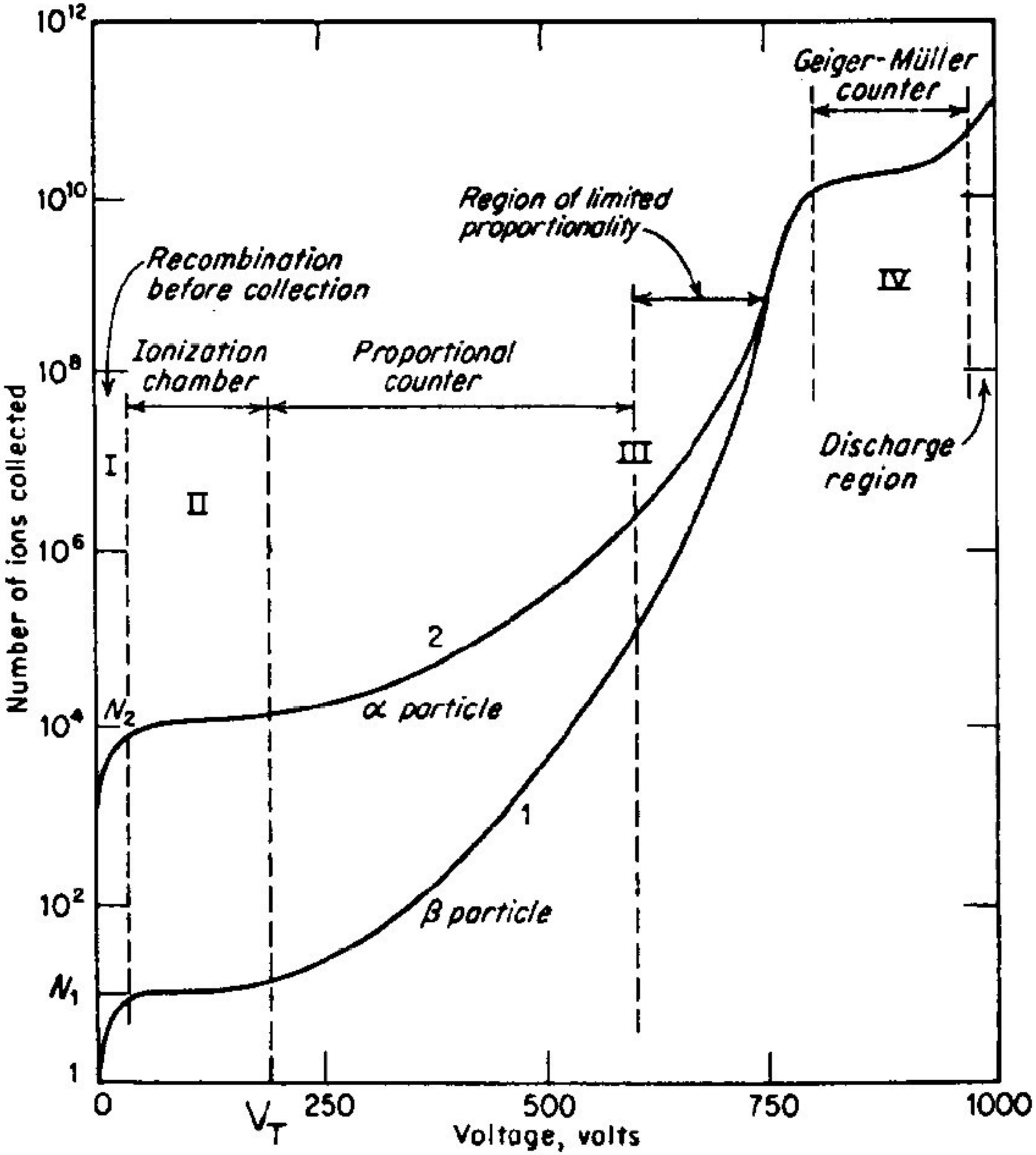
Geiger Counter

Regimes in a Tracking Chamber

Characteristics

- ionization
- proportional
- Geiger-Müller

Transitions not abrupt



Multiplication Factor / Gains

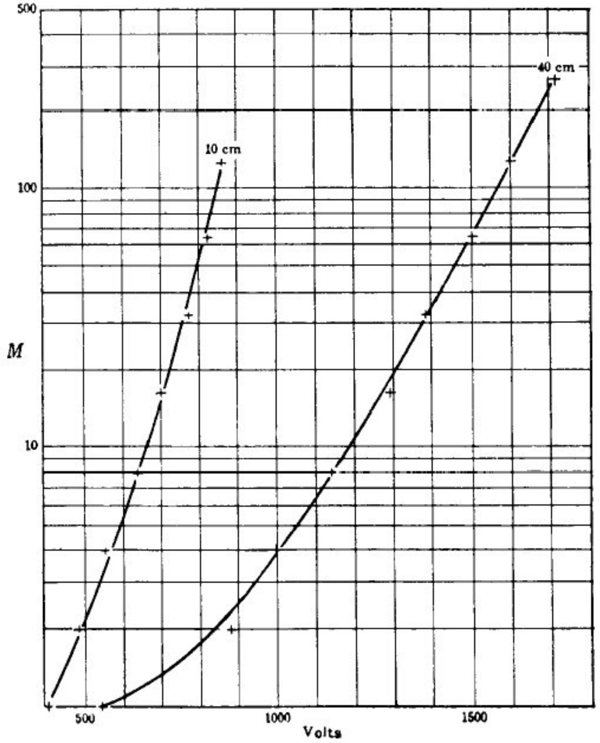
Strong signal is important

- detection efficiency
- precision of pulse height / energy relation

Multiplication factor, M ($N_{\text{p.i.}} * M$)

full derivation Sauli paper

$$M = \exp\left[2\sqrt{\frac{kNCV_0 a}{2\pi\varepsilon_0}}\left(\sqrt{\frac{V_0}{V_T}} - 1\right)\right]$$



For $V_0 >> V_T$ expression can be approximated as

$$M = k \exp CV_0$$

Quantities from Equation

k - material constant (avalanche development)

N - number of molecules per unit volume

C - system capacitance (ne/V)

a - wire radius

ε_0- dielectric constant of gas (≈8.85 pF/m)

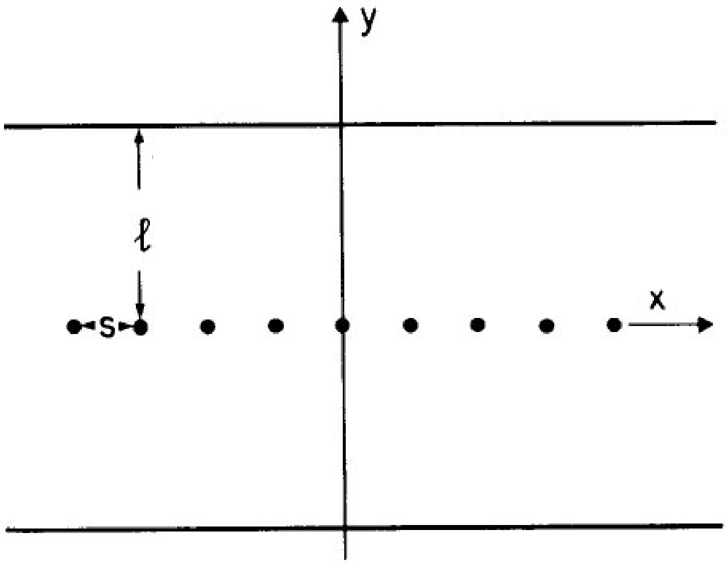
V_0 - operating voltage between anode and cathode

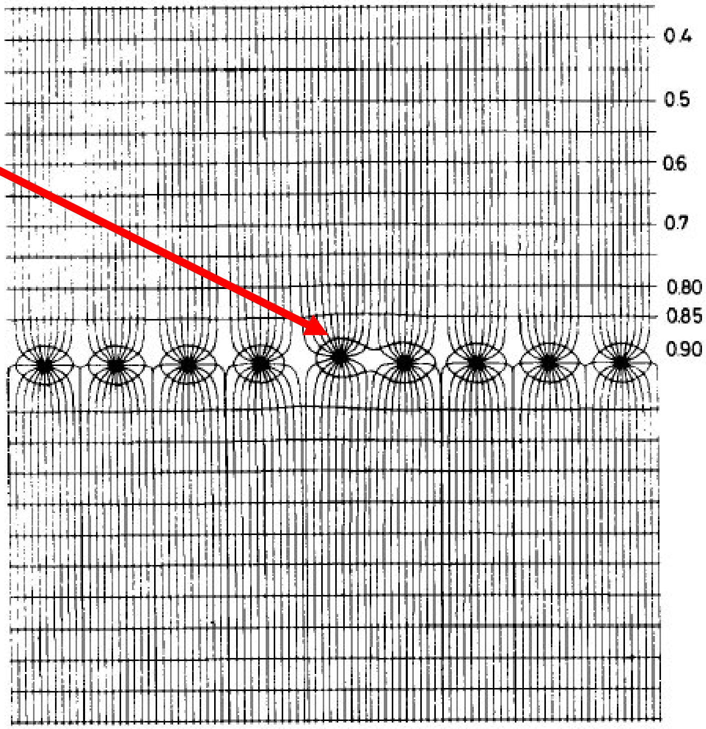
V_T - voltage threshold for proportional amplification

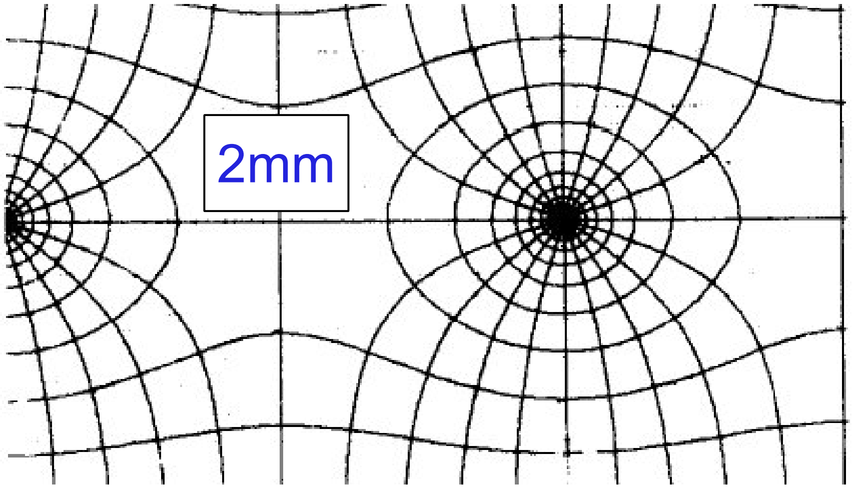
(Multi) Wire (Proportional) Chamber

Principle design

- single anode wire → wire plan
- cathode plane: mostly foils
- forces homogeneous field, sufficiently far from anode wire
- field around wires very sensitive to positioning of the wires
- 25 µm wire







What Measures a Wire Chamber?

Running in “Geiger” amplification

- pulse time & drift velocity → position, ambiguous
- brings up issue of t_0 calibration (per event)
- remove ambiguity with another wire under angle, stereo
- axial wires and stereo wires

Running in proportional amplification

- in addition measure pulse height
- determines energy and thus allows *dE/dx* measurement
- talk more about this in another lecture
- momentum of track more precise from curvature in *B*

Resolution: $\sigma(p_T) \propto \sigma(\rho)/L^2$ use large radius

with $L = r_{outer} - r_{inner}$

Wire Chamber Design

Constraints

- precise position measurements require precise and wire spacing and small wire spacing
- homogeneous fields require small wire spacing
- large fields (high amplification) requires thin wires
- rigorous calculations available (see Sauli's paper)
- geometric tolerances cause gain variations

Geometry and problems

- sub milimeter precision required
- long chambers need strong wire tungsten/gold plated
- long chamber: large force to minimize sagging
- fixing wires becomes a difficult task

Choice of Gas System - Magic

Factors for gas system choice

- low working voltage
- high gain operation
- good proportionality
- high rate capability
- long lifetime
- fast recovery
- price
- *etc.*

The No-Brainers

Typical gas pressures for tracking detectors

- slightly over atmosphere:
  - higher then atmosphere to minimize incoming gas “polution”
  - remember a large tracker is not really air tight
  - not too high (difficult to maintain), but reasonable ionization

Typical temperatures

- most important: avoid large temperature differences
- slightly lower then room temperature
- affected by environment (silicon at T < -10°C at LHC)
- dew point is always dangerous....

Some Gas Properties

From Sauli's paper

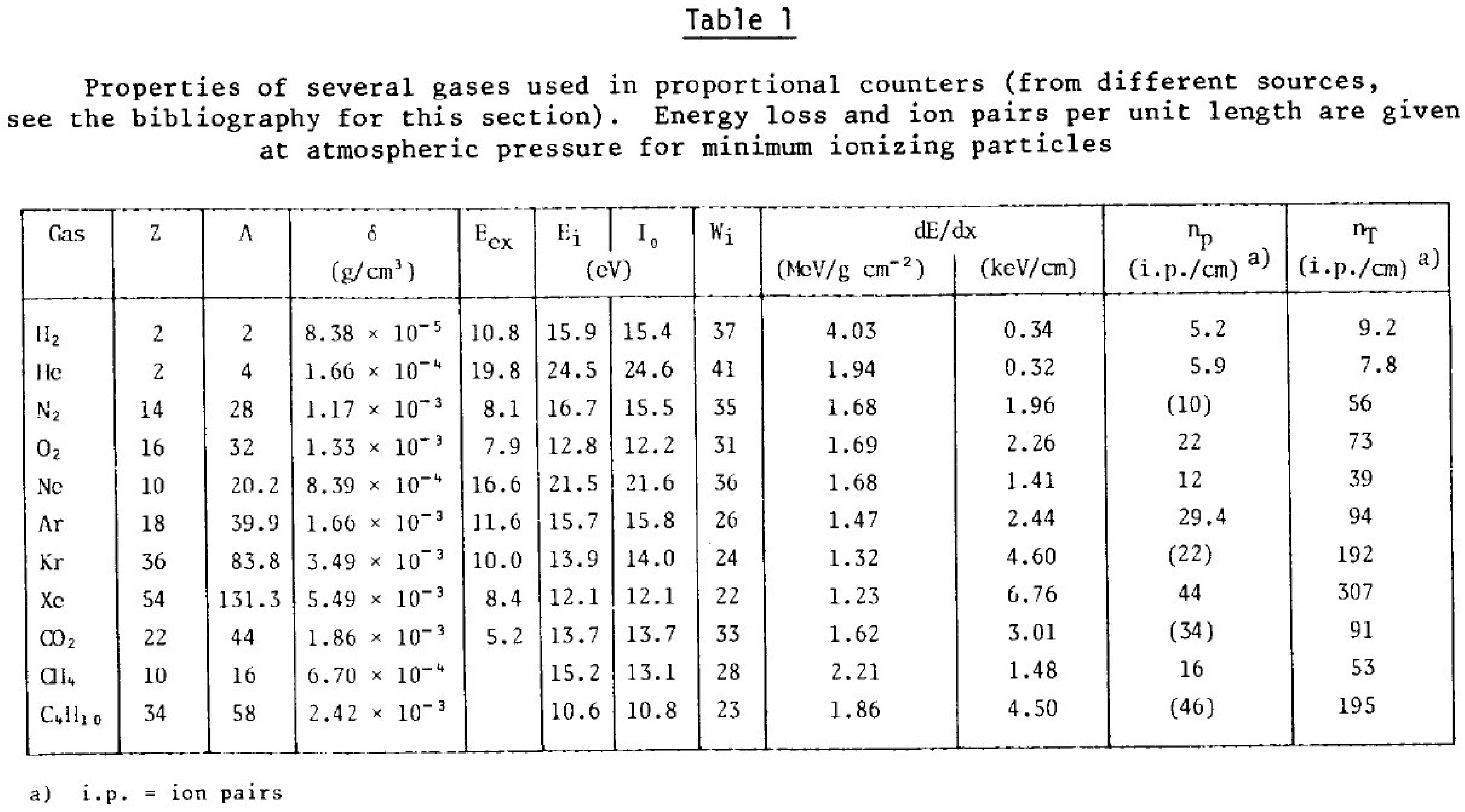


Table 1

Properties of several gases used in proportional counters (from different sources, see the bibliography for this section). Energy loss and ion pairs per unit length are given at atmospheric pressure for minimum ionizing particles

Gas	Z	A	δ (g/cm^3)	E_{ex}	E_i (eV)	I_0 (eV)	W_i	dE/dx (MeV/g cm^{-2})	dE/dx (keV/cm)	n_p (i.p./cm) a)	n_T (i.p./cm) a)
H_2	2	2	8.38×10^{-5}	10.8	15.9	15.4	37	4.03	0.34	5.2	9.2
He	2	4	1.66×10^{-4}	19.8	24.5	24.6	41	1.94	0.32	5.9	7.8
N_2	14	28	1.17×10^{-3}	8.1	16.7	15.5	35	1.68	1.96	(10)	56
O_2	16	32	1.33×10^{-3}	7.9	12.8	12.2	31	1.69	2.26	22	73
Ne	10	20.2	8.39×10^{-4}	16.6	21.5	21.6	36	1.68	1.41	12	39
Ar	18	39.9	1.66×10^{-3}	11.6	15.7	15.8	26	1.47	2.44	29.4	94
Kr	36	83.8	3.49×10^{-3}	10.0	13.9	14.0	24	1.32	4.60	(22)	192
Xe	54	131.3	5.49×10^{-3}	8.4	12.1	12.1	22	1.23	6.76	44	307
CO_2	22	44	1.86×10^{-3}	5.2	13.7	13.7	33	1.62	3.01	(34)	91
CH_4	10	16	6.70×10^{-4}		15.2	13.1	28	2.21	1.48	16	53
C_4H_{10}	34	58	2.42×10^{-3}		10.6	10.8	23	1.86	4.50	(46)	195

a) i.p. = ion pairs

Choice of Gas

Noble gas

- lowest electrical field necessary for multiplication
- suggests to be the main component
  - Krypton/Xenon are too expensive
  - Argon is fine and has highest specific ionization
- high gains do not work, consider energy balance:
  - excited noble gases radiate (Ar, 11.6 eV) to dissipate energy
  - radiation causes electron extraction from cathode
  - secondary current develops → discharge
  - gains up to 10^3-10^4 are possible

Need to catch photons and low energy electrons

Choice of Gas

Polyatomic molecules (ex. hydrocarbons, alcohols)

- more than 4 atoms per molecule preferred
- various non-radiative excited states (rotational, vibrational modes)
- thermal or chemical energy dissipation
  - thermal: through elastic collisions, heating environment
  - chemical: split molecules into radicals
- excitation modes cover spectrum of noble gas radiation
  - photons get captured → quenched
  - also low energy electrons get absorbed
- neutralization at the cathode does not create radiation
- gains higher than 10^6 are achieved

Choice of Gas

Polyatomic molecules, disadvantages

- radicals created in dissociation
- for high ionization gas characteristics changes rapidly
- requires sufficient gas exchange in the chamber
  - open system design
  - closed system design with cleaning, separate cleaning cycle
- worse, liquid and solid polymers can be created in neutralization – insulator layer on cathode/anode wires
- chamber performance suffers, Malter effect (1937):
  - charge builds up on insulator and potential difference causes ionization of the wire
  - ionization leads to a current, independent of the particles causing primary ionization → discharge

Limitations of Chambers

High occupancy no problem

- Alice uses huge chamber for tracking: 15k tracks/event
- uses Time Projection Chamber (TPC), 3m radius

Radiation hardness manageable

- can be managed though it is tough depending on design

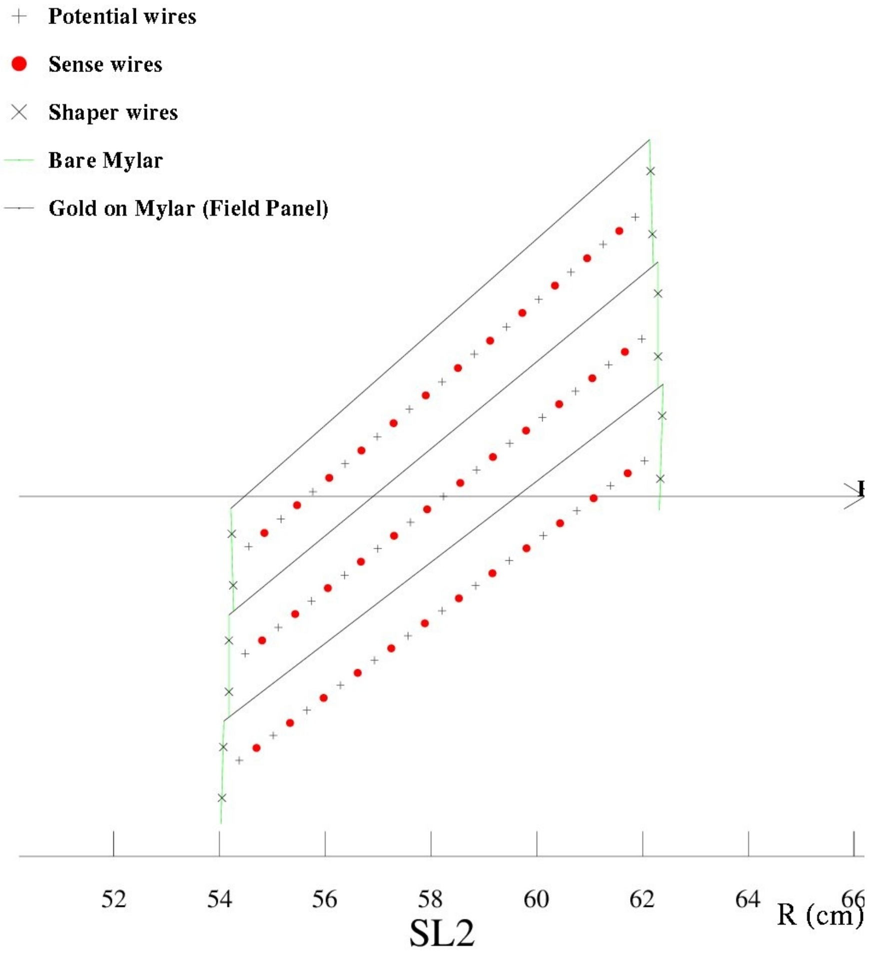
Drift speed is limiting factor

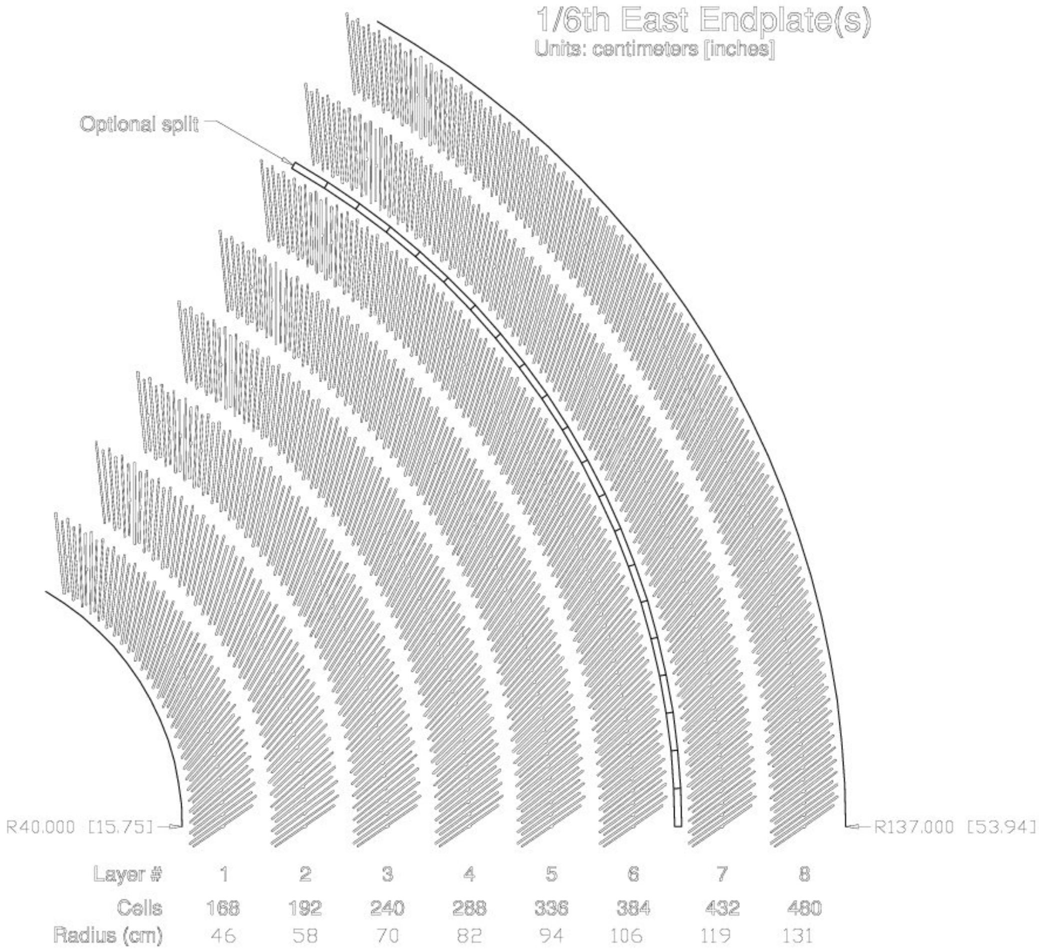
- high luminosity requirement at LHC (for *pp* operation)
- bunch crossing rate is 25 ns
- ion drift is to slow
- chamber would be “glowing”

Alternative: GEM (http://cerncourier.com/main/article/38/9/10) in Micro Strip Gas Chambers

CDF: Central Outer Tracker

Open Cell Design (at 396 ns bunch crossing)





check it out: http://fcdfwww.fnal.gov/~burkett/COT/newhome.html

Silicon Detectors

Main purpose

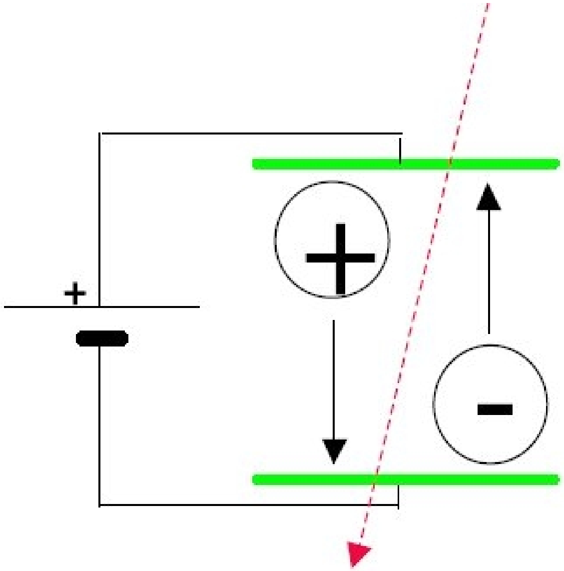
- determine 3 dimensional vertex of tracks precisely
- improve momentum resolution for large momenta

Also

- improve momentum resolution in general

Basic operation principle same as gas detectors except *E* field now in a solid

	GAS	Liquid	Solid
Density	low	Moderate	High
Atomic number Z	low	Moderate	Moderate
Ionization energy ε_i	Moderate	Moderate	Low
Signal speed	Moderate	Moderate	Fast



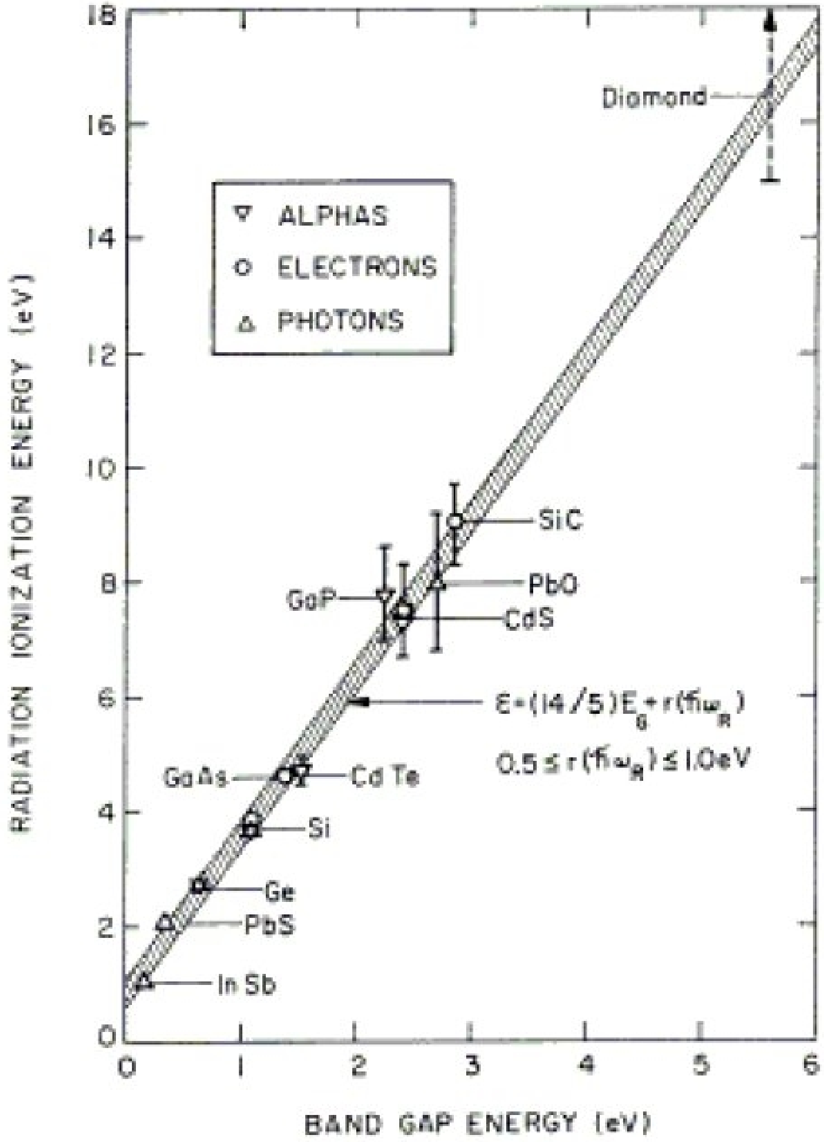
Why (Semi) Conductors?

Why go to solids?

- increase *dq/dE*
- fast response

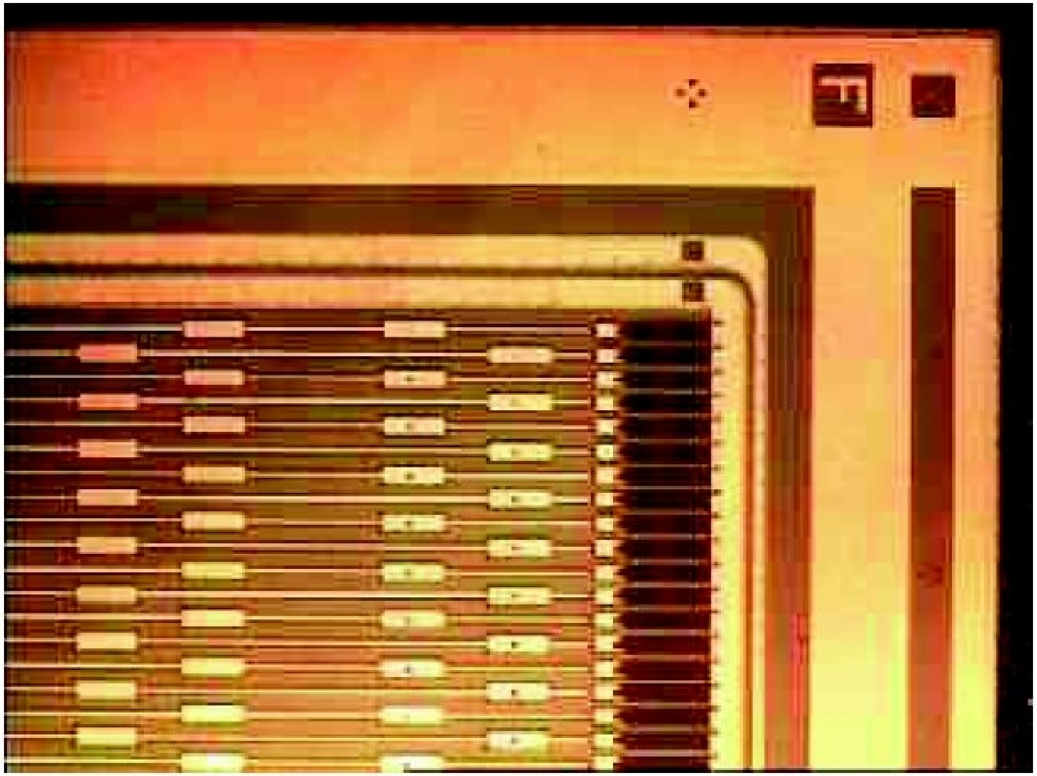
Semi conductors?

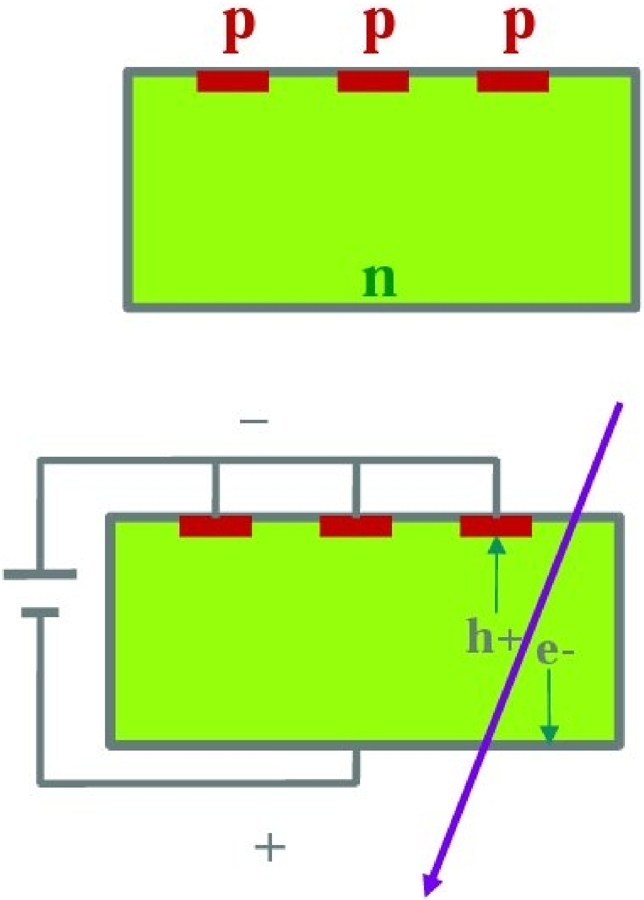
- high electric field (drift)
- large signal charge
- small DC current (depletion)



Silicon Strips

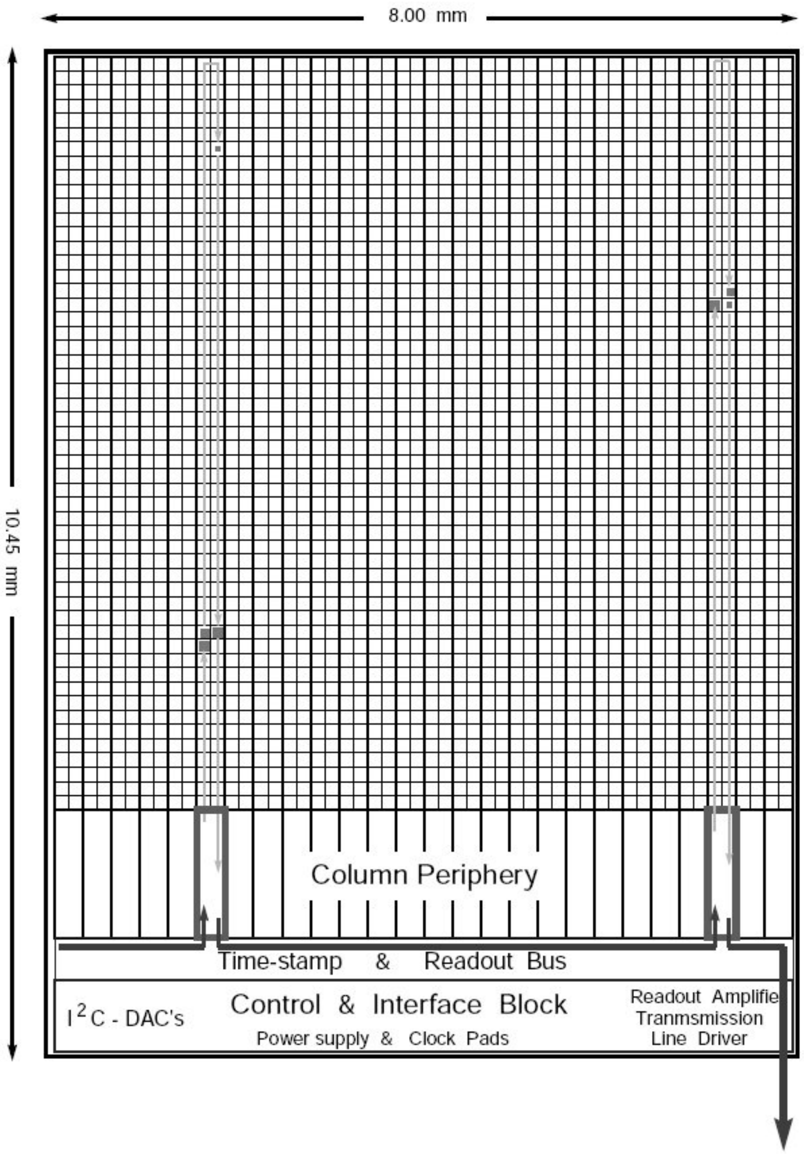
1 dimensional ambiguity (resolve with stereo, 90deg)





Silicon Pixels

Full 3 dimensional point

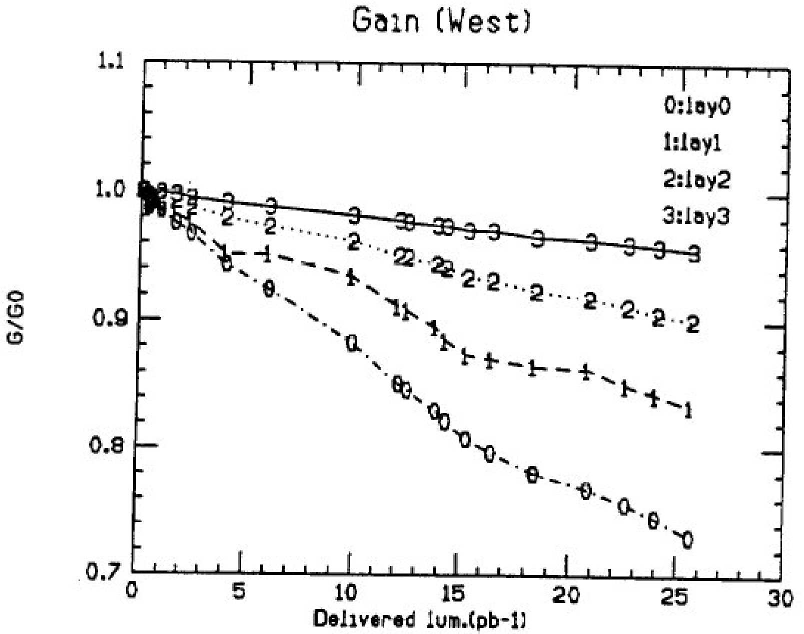


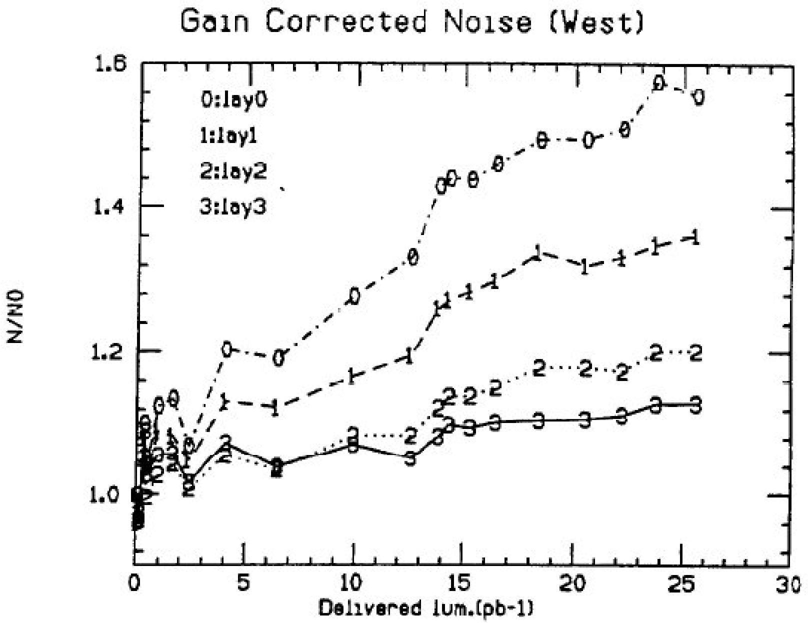
Features

- very small, many channels
- close to beam
- radiation hardness crucial
- readout tricky, “bonding”
- established technology:
  - camera, night vision devices

Radiation Hardness

CDF Run I



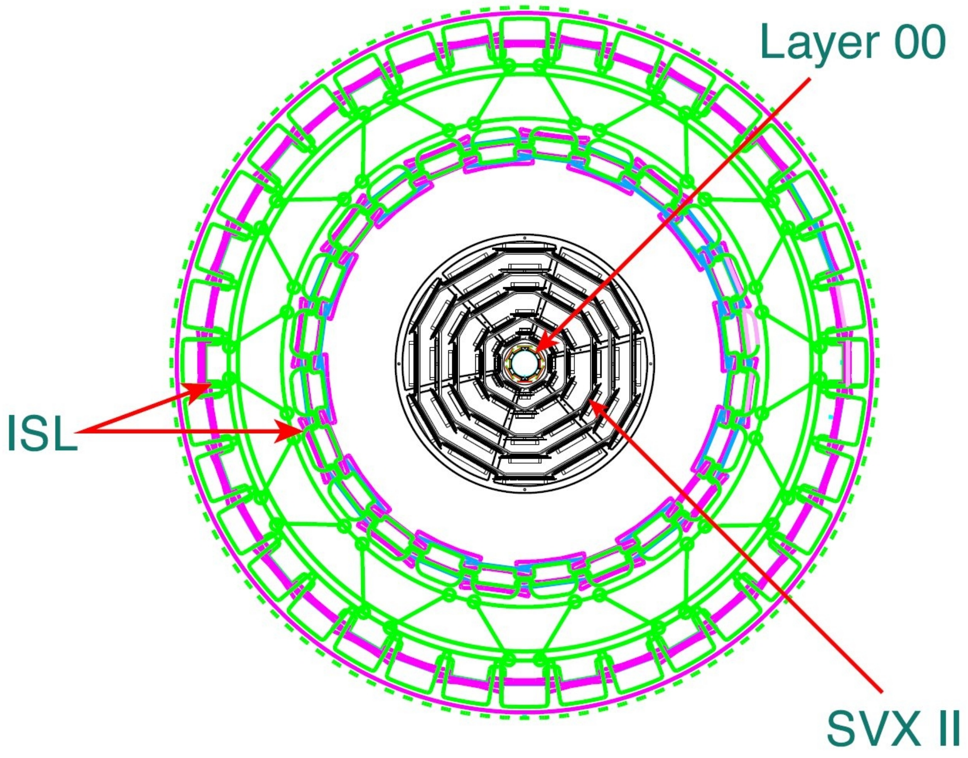


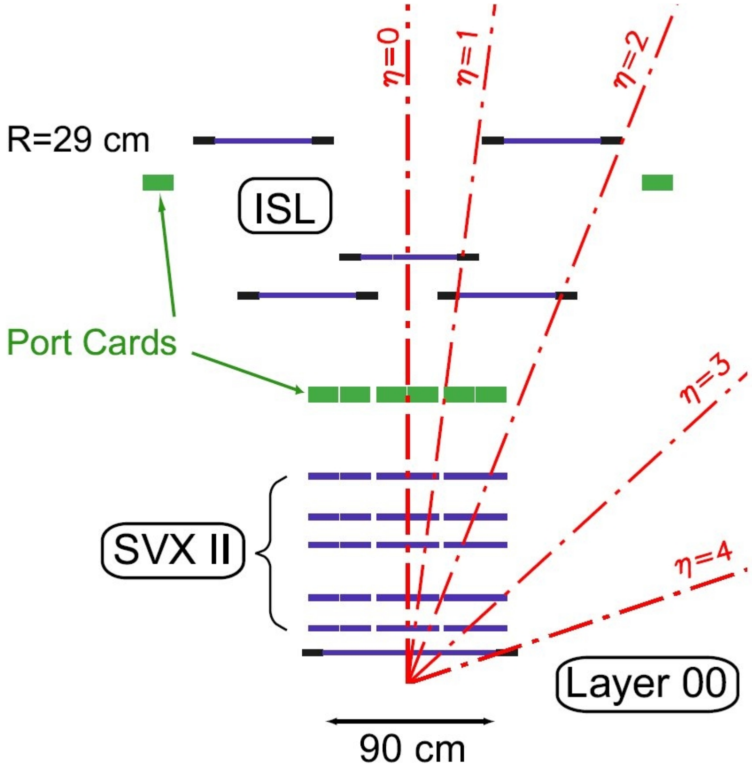
What does it mean?

- particle damages silicon structure
- band gap changes
- leakage currents increase
- gain drops
- detector looses efficiency and precision
- detector needs exchanging
- already well planned for CMS
- diamond detector extremely radiation hard, but difficult

CDF Silicon Detector

Design (0.75M channels, ≈3 m^2)





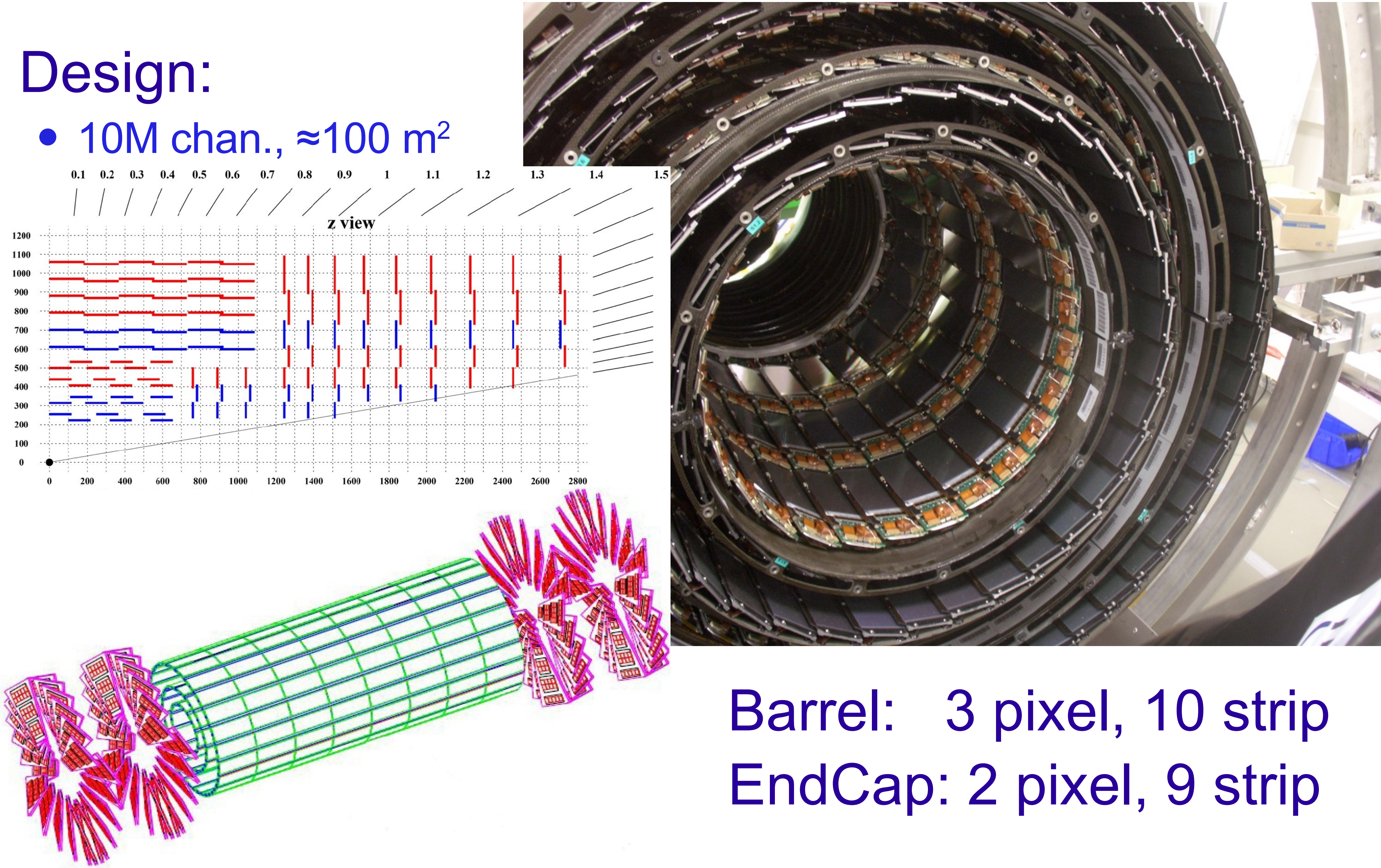
Features (all strips):

- up to 8 layers, innermost 1.2 cm, outermost 29 cm
- resolution at PV per track ≈30 μm (x,y) ≈40 μm (z)

CMS (Silicon) Tracker

Design:

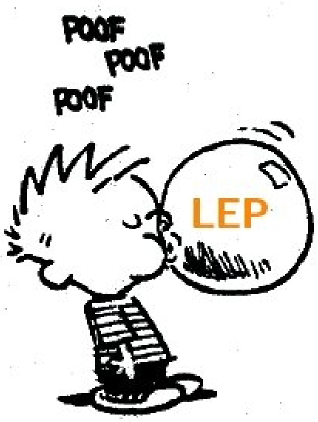
- 10M chan., ≈100 m^2

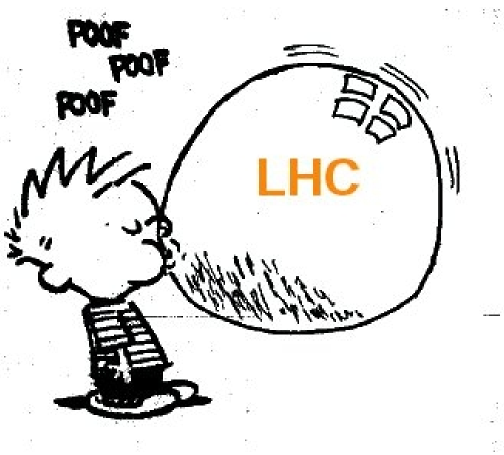


Barrel: 3 pixel, 10 strip

EndCap: 2 pixel, 9 strip

Large Silicon Detectors





Whoops...

P.Collins, ICHEP 2002

Conclusions

Tracking detectors

- detect charged particles only
- measures: arrival time and charge deposition
- derives: 3 dimensional location and energy

Sensitivities

- innermost measures vertex (best hit resolution, needed)
- overall radius measures momentum

Design

- inside, always silicon (best pixels), highest track density
  resolution: tens of µm
- outside, if possible gas detector (low material budget)
  resolution: hundreds of µm

Next Lecture

Track reconstruction and fitting

- general idea of track reconstruction
- particle hypothesis
- multiple scattering
- energy loss
- magnetic field
- calibration of the tracking