Silicon Detectors
ICFA 03 School on Instrumentation in Elementary Particle Physics
Itacuruçá - BRAZIL

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(slides will be available at http://lhcb.web.cern.ch/
-> presentations)

Outline of Lectures

- **Lecture I**
  - Introduction
    - Why use silicon detectors?
    - The rise and rise of silicon in HEP
  - Basic Principles
    - Semiconductor Structures
    - Strip detectors
    - Signal, Noise, Resolution

Outline of Lectures

- Lecture II
  - Exotic structures
    - Double sided, Double metal
    - More and more pixels
    - Monolithic structures
    - CCD's
    - 3D detectors
    - Silicon Drift Detectors

Outline of Lectures

- Lecture III
  - RADIATION DAMAGE
    - LHC environment
    - Effects of the damage
    - Measuring the damage
    - Limiting the damage
  - Design your own silicon detector
    - Performance issues
    - Construction issues
    - Cost issues

About the lecturer

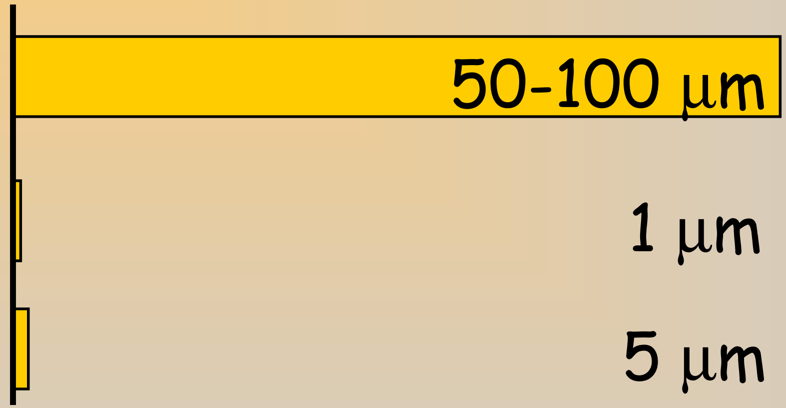
I come from Leeds in the North of England

In spite of this (or because of this?) I support Manchester United


The weather in the North of England usually looks like this
Looks just like Brazil! (so far..!)

Why Use Silicon?

- First and foremost: Spatial resolution



	Spatial resolution	high rates and triggering
Traditional Gas Detector	50-100 μm	Yes
Emulsion	1 μm	No
Silicon Strips	5 μm	Yes

- This gives vertexing, which gives

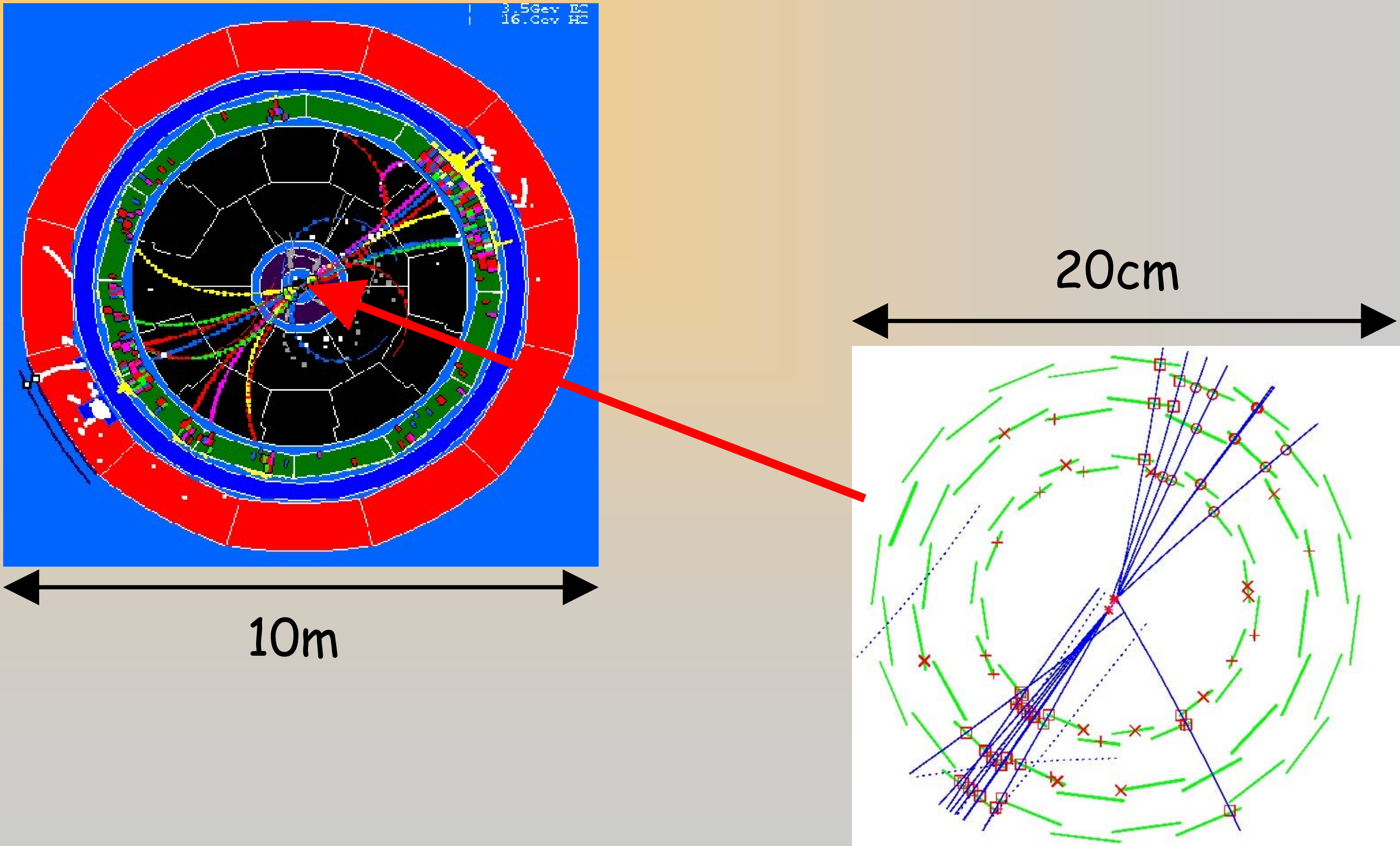
lifetimes	top quark identification
mixing	background suppression
B tagging	…… and a lot of great physics!

Why Use Silicon? (II)

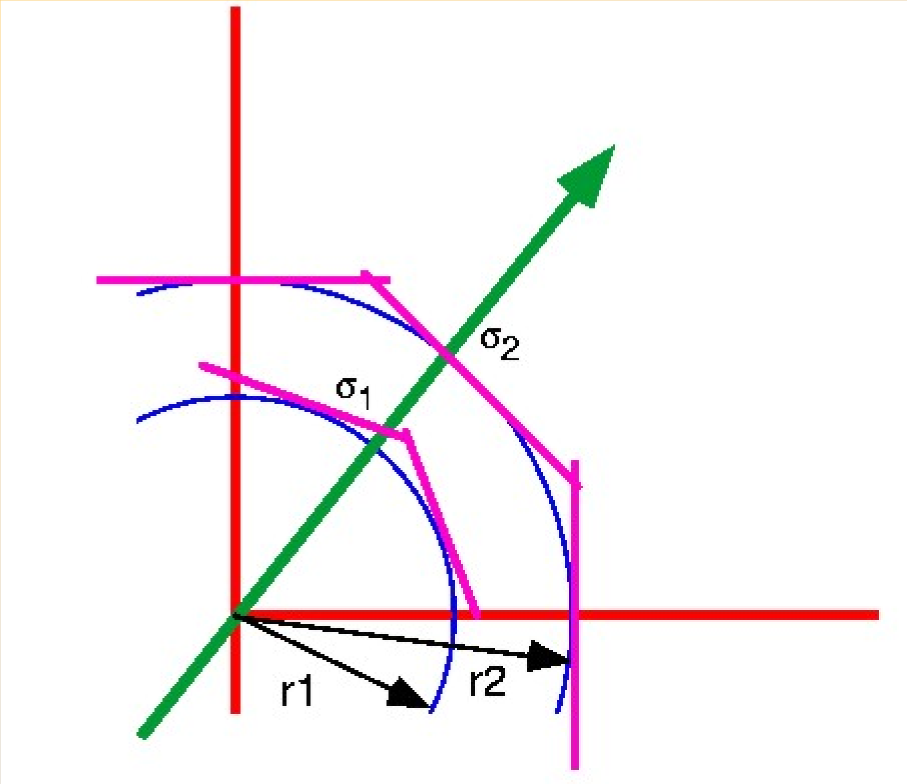
- We benefit from the huge technological advances in the IT industry

Even if the infrastructure is expensive, the basic ingredients are ridiculously cheap

A glimpse inside a typical particle detector



Single Track Resolution



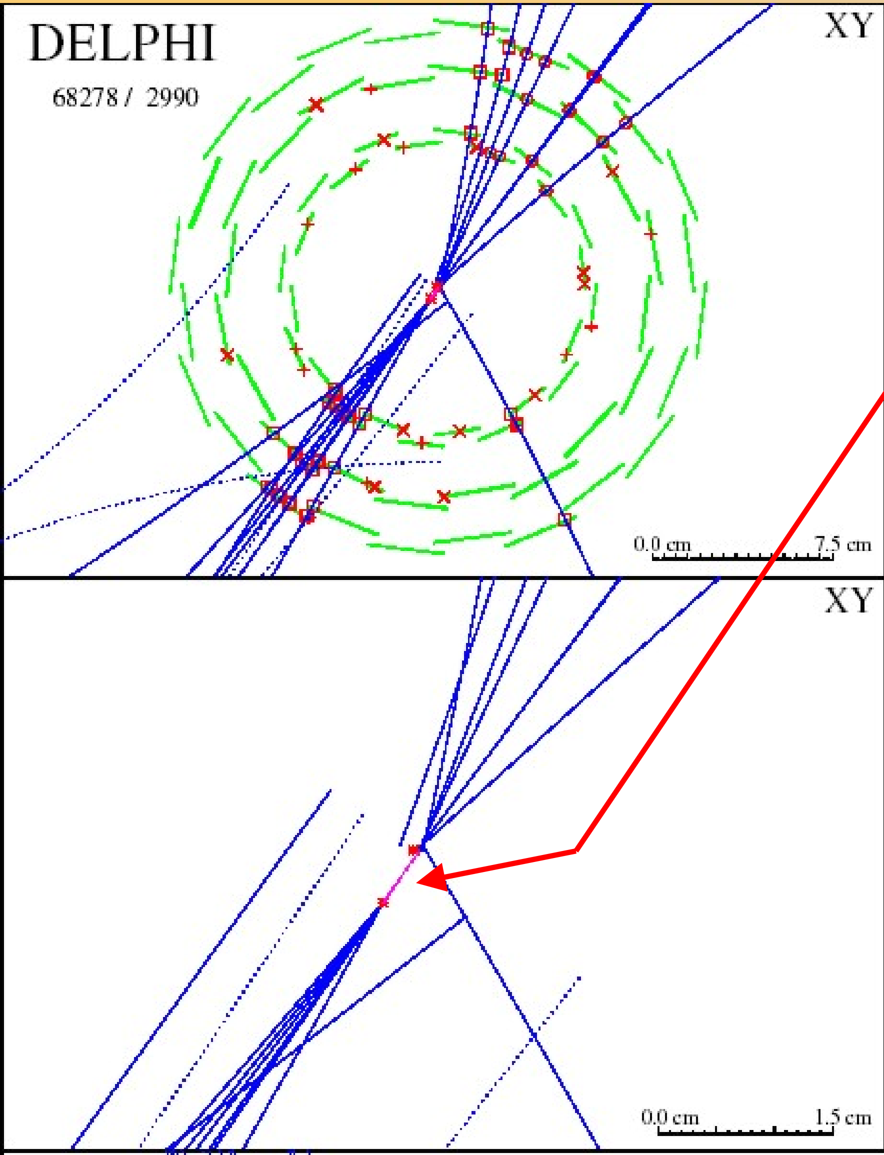
impact parameter resolution at the origin is given by

$$\sigma = \frac{r_2\sigma_1 + r_1\sigma_2}{(r_2 - r_1)^2}$$

So we want:

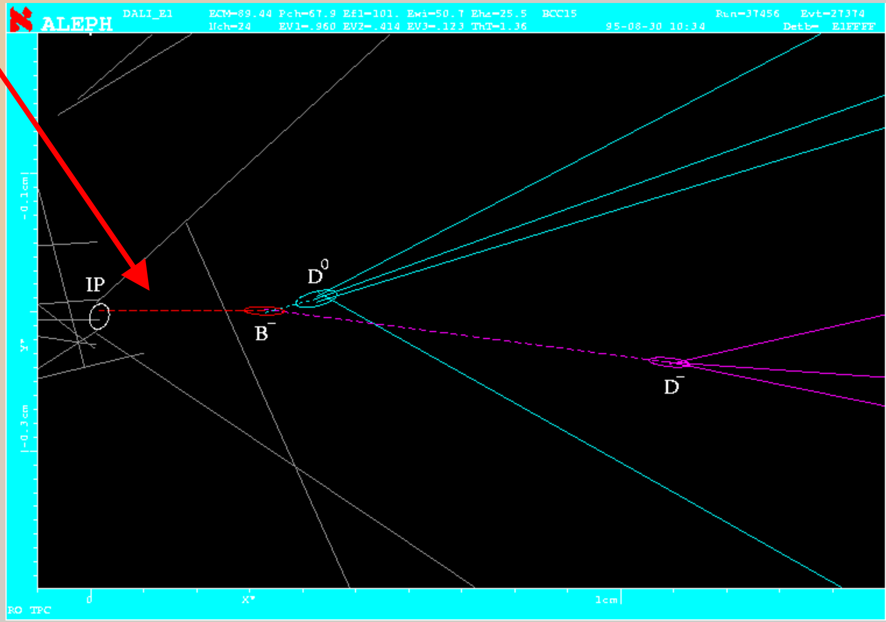
small	r_1
large	r_2
small	σ_1, σ_2

With this information we can look at the very centre of the interaction



And reconstruct the decay distance of long lived particles

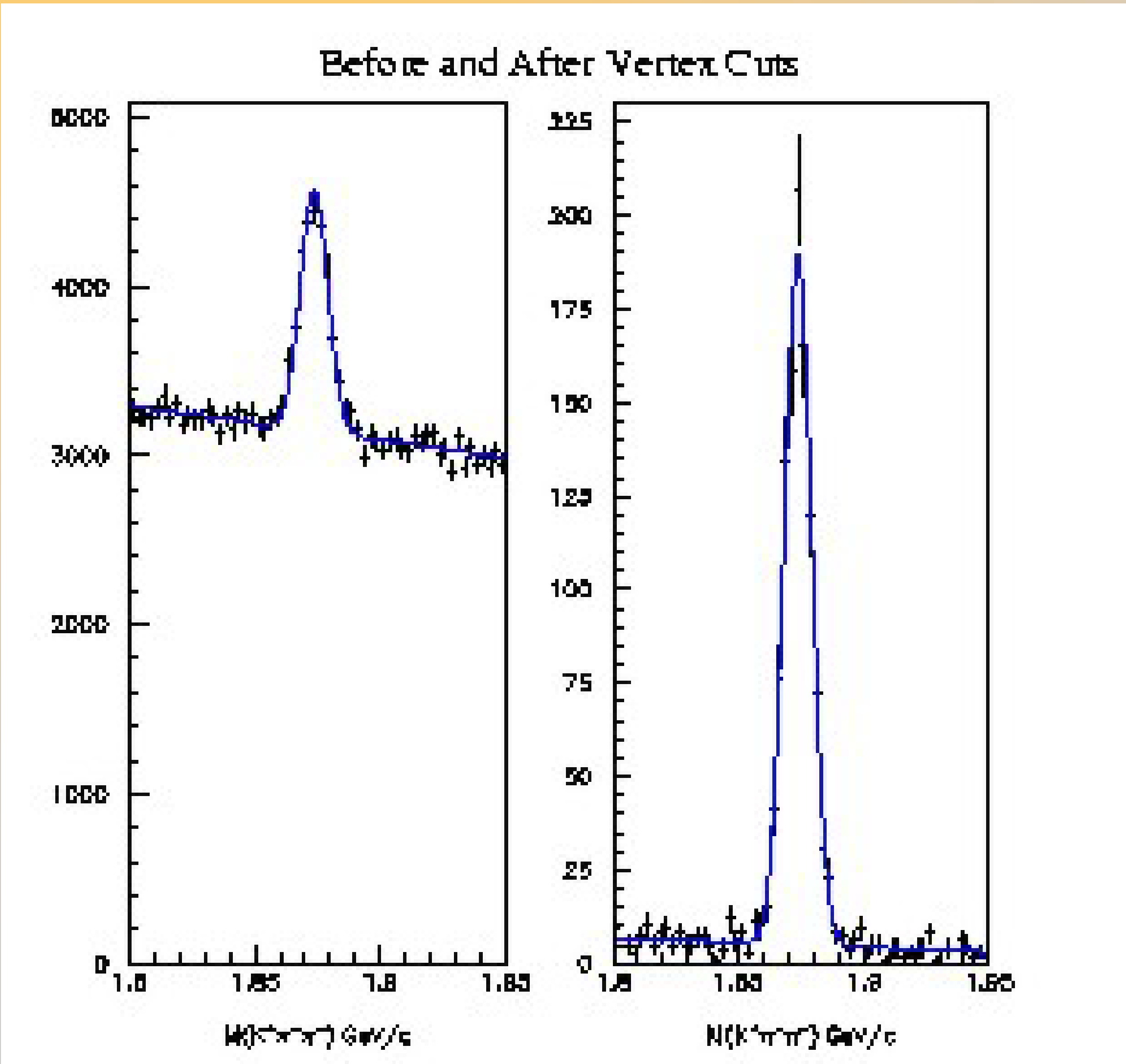
$$\tau_B \approx 1.6 \text{ ps} \quad l = c\tau\gamma \approx 500\ \mu\text{m}\cdot\gamma$$



$B \longrightarrow D^0\ D^*$

And even the decay products

By looking at the vertex one can also suppress the background



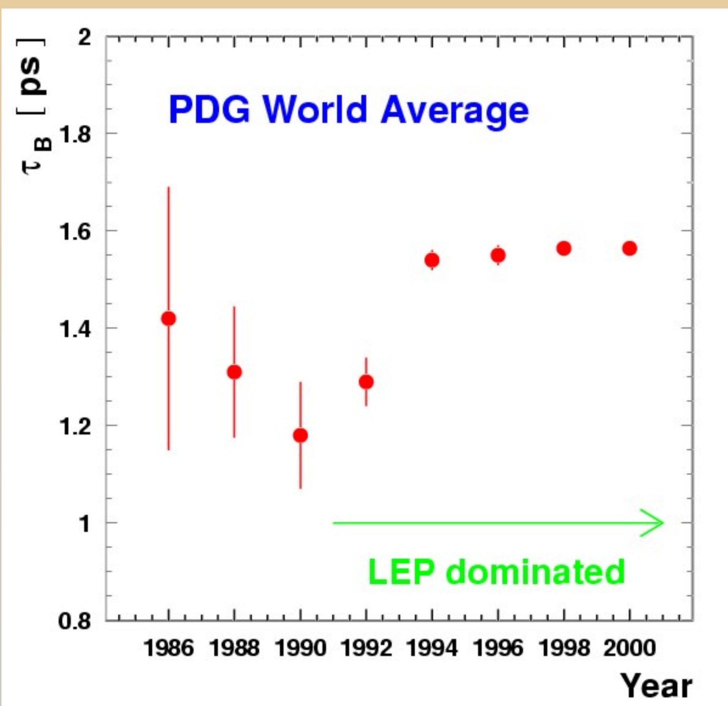
$D^+ \longrightarrow K\,\pi\,\pi$

mass peaks before and after 7σ vertex cut from primary beamspot

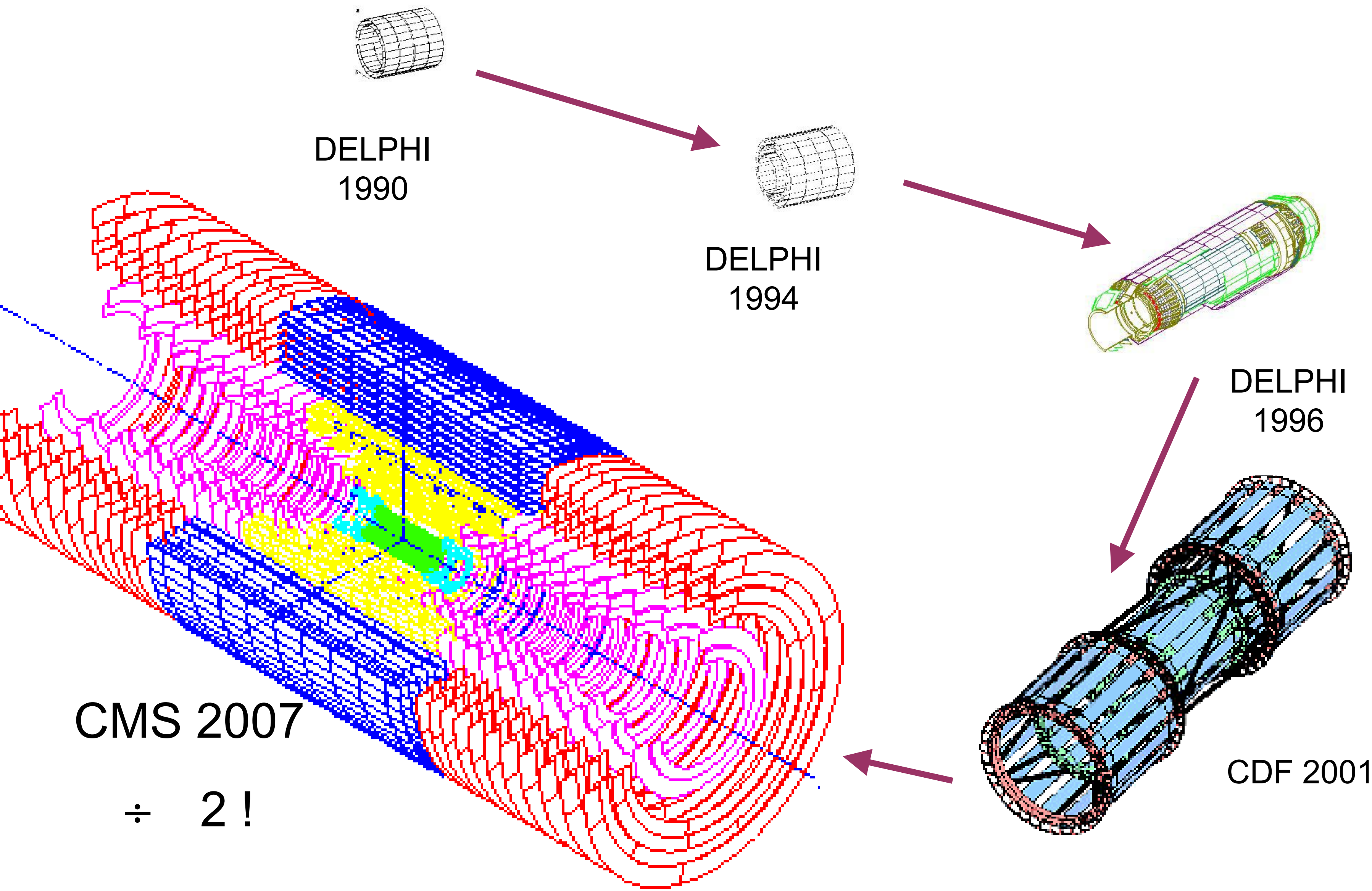
The New Technology came along Just In Time

- Proposals for LEP experiments did not contain silicon vertex detectors
  - Costly, bulky, small signal, miniaturization
- Late 80's MARK II (SLC) and early 90's all LEP experiments, with continuous upgrades
- Pixel detector at SLC in early 90's

These silicon vertex detectors have dramatically improved our b physics measurements!



Silicon for tracking: Large Systems

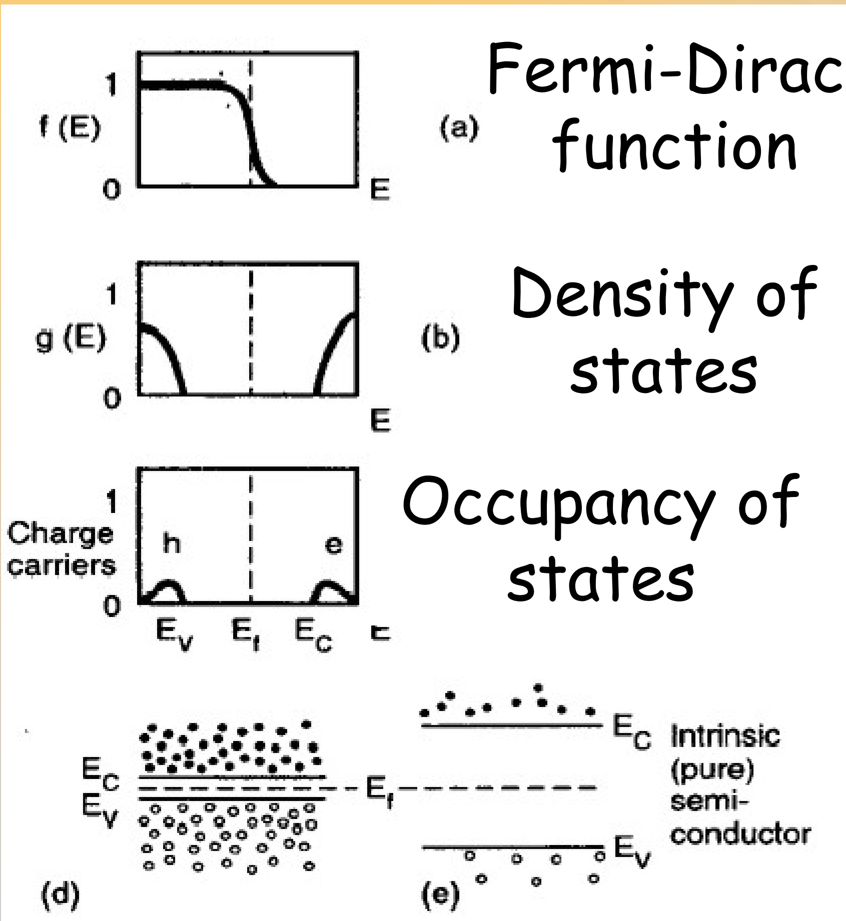


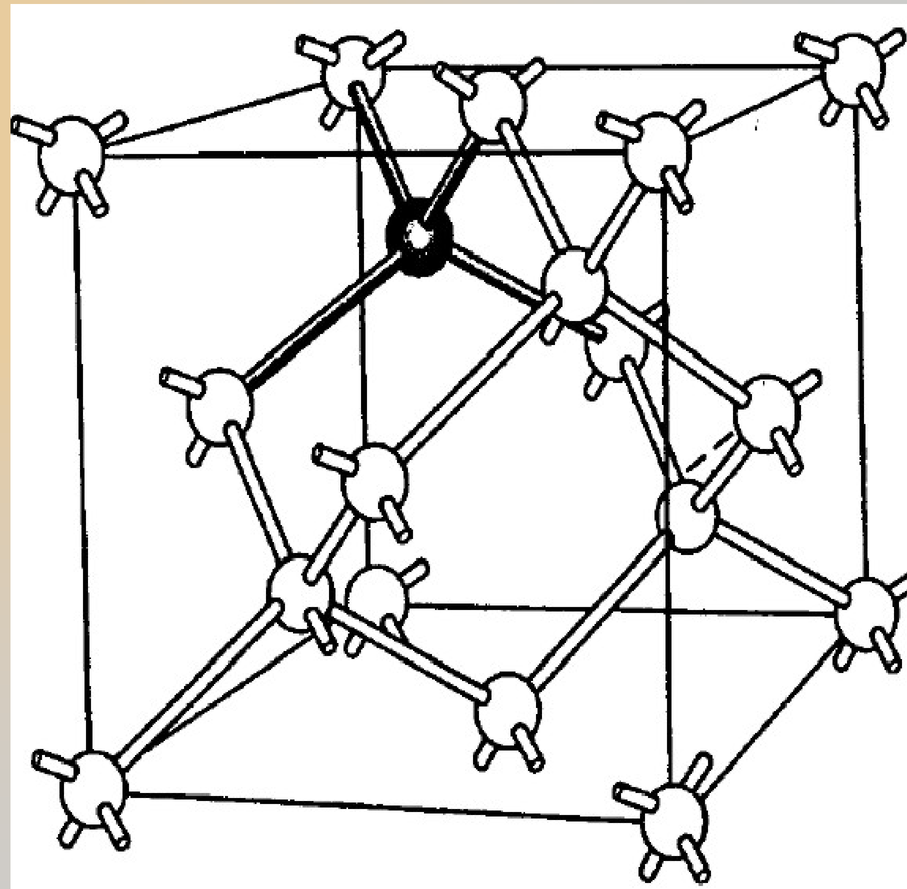
More and More Silicon

- All currently operating HEP collider experiments (FNAL, HERA, B-factories, HERA, RHIC, etc.) use silicon vertex detectors
- Most experiments in construction use silicon for vertexing and tracking, sometimes very large amounts
- At new facilities the radiation environment favours silicon over gaseous detectors
- Generally use strips for the large areas and pixels for the close, precise, measurements (more later)

Basic Principles (1)

How can we turn a piece of intrinsic silicon into something which will detect the passage of charged particles?



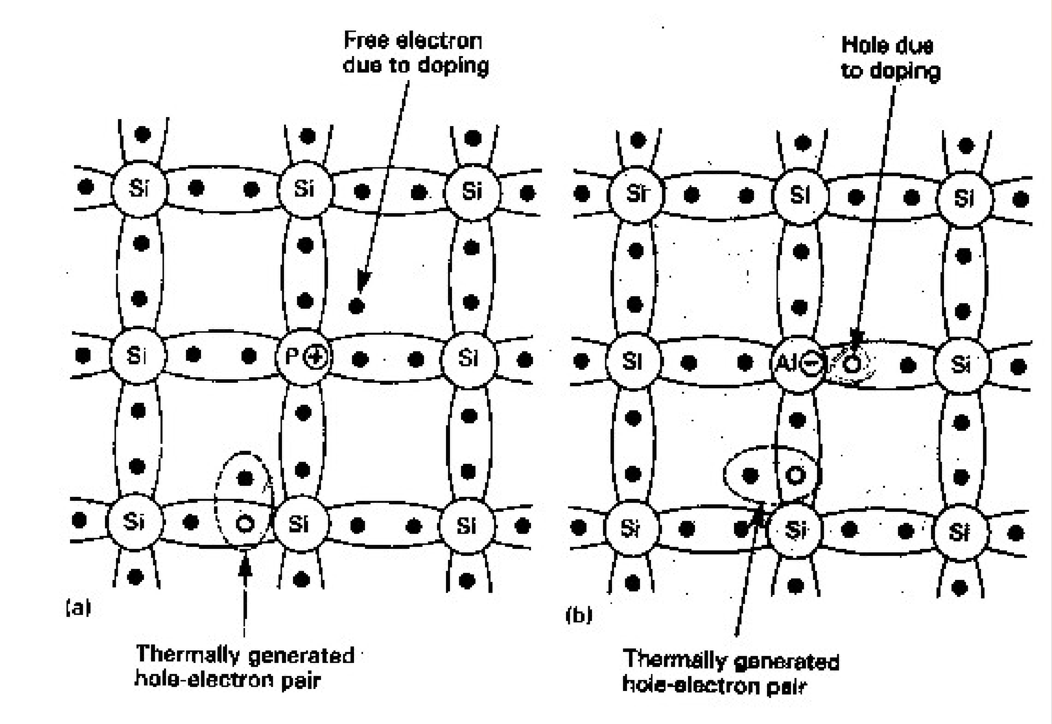


Crystal structure

Basic Principles (2)

The probability of an electron jumping from the valence band to the conduction band is proportional to $e^{\frac{-E_g}{kT}}$ where E_g, the band gap energy is about 1.1 eV and kT=1/40 eV at room temperature

- Next step is to dope the silicon with impurities



Phosphorus doping: electrons are majority carriers
Boron doping: holes are majority carriers

Some numbers:

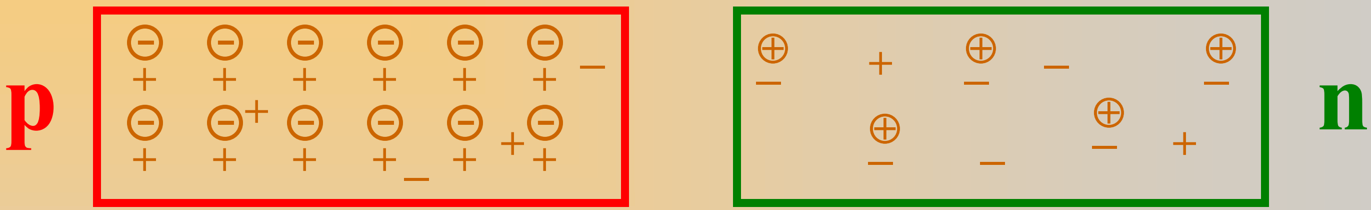
Intrinsic carriers: $10^{10}cm^{-3}$

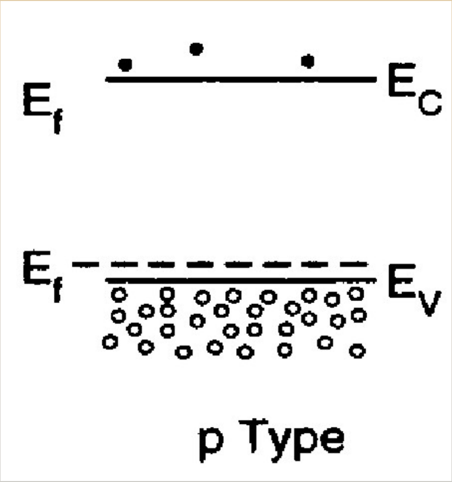
Doping concentration: $10^{12}cm^{-3}$

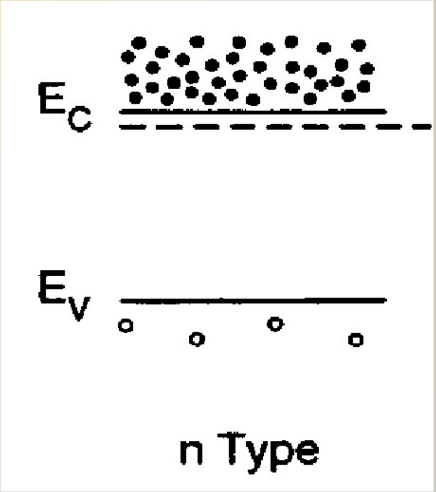
Silicon Density: $5 \times 10^{23}cm^{-3}$

Basic Principles (3)

Now we can construct a p-n junction

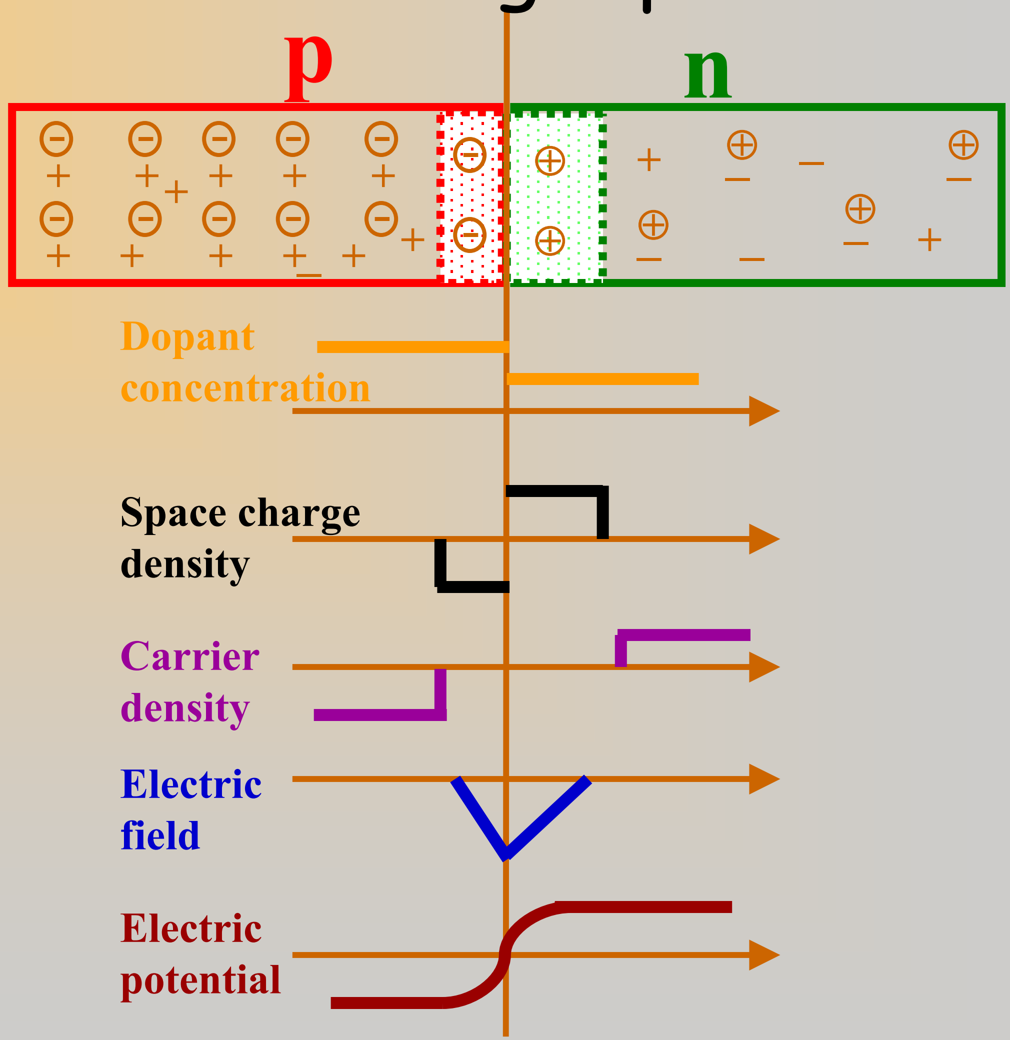






Basic Principles (4)

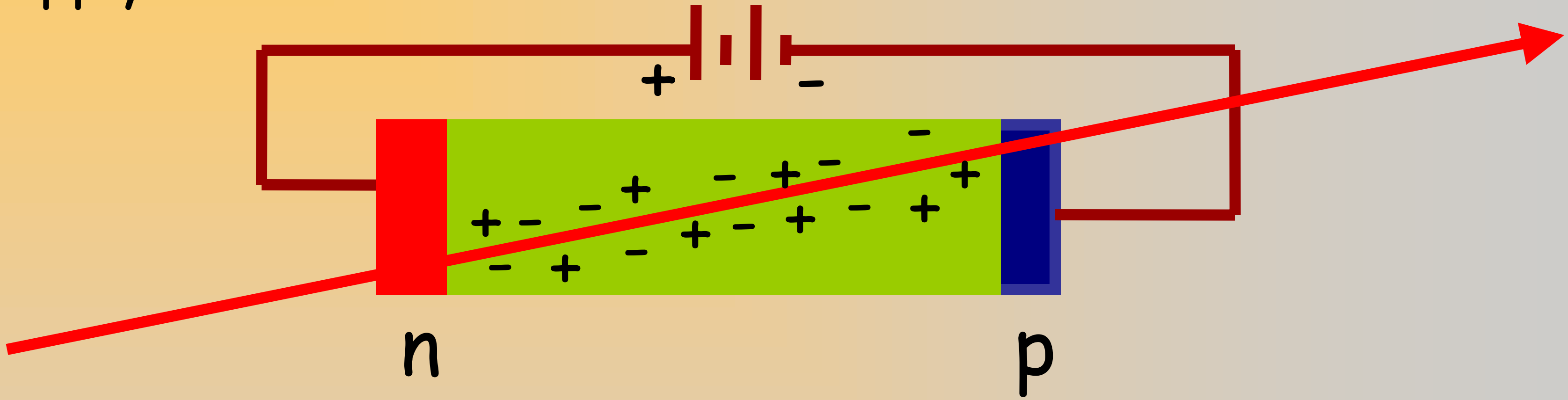
Now for the magic part!

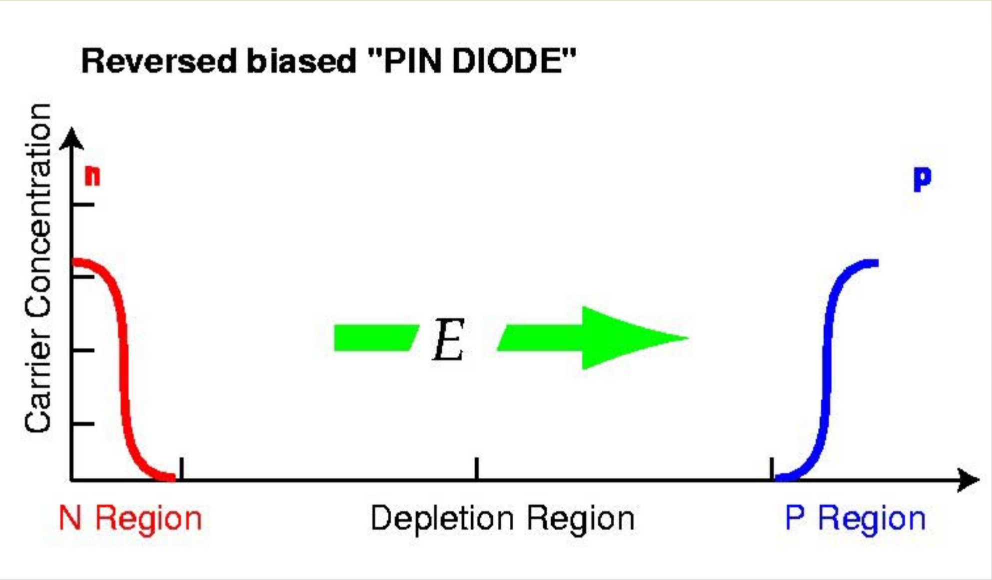


When brought together to form a junction, the majority diffuse carriers across the junction. The migration leaves a region of net charge of opposite sign on each side, called the space-charge region or depletion region. The electric field set up in the region prevents further migration of carriers.

Basic Principles (5)

The depleted part is very nice, but very small
Apply a reverse bias to extend it

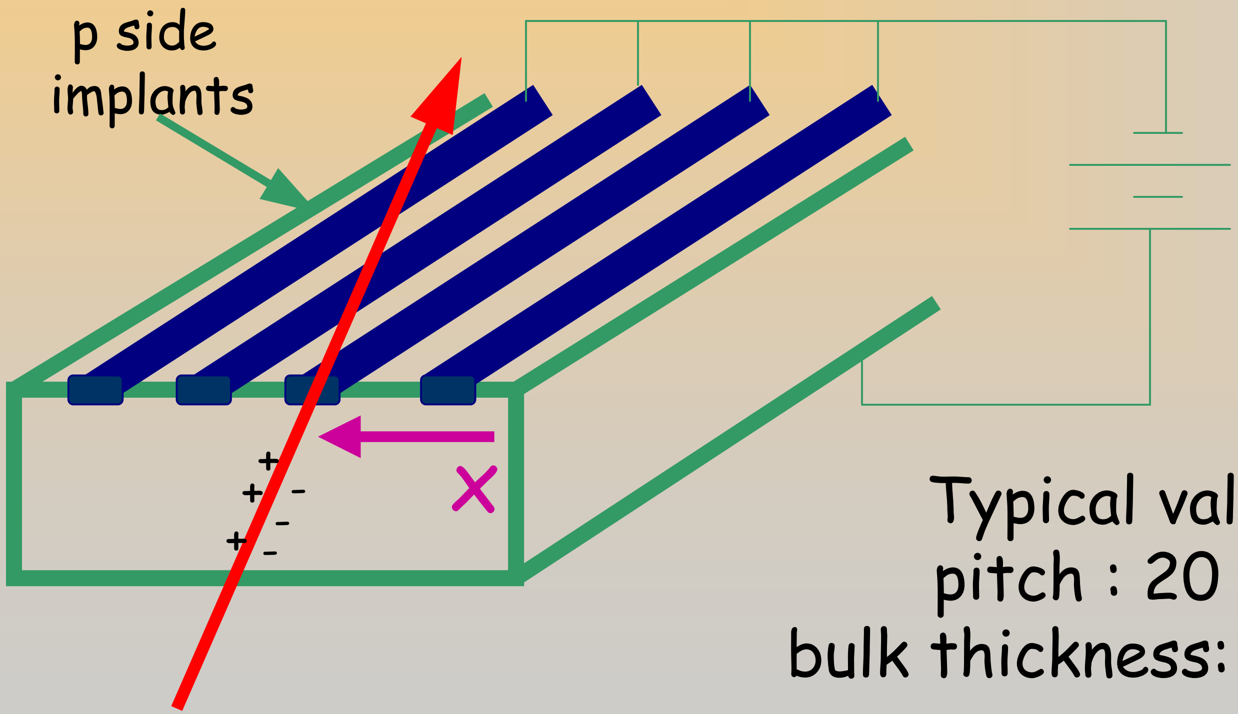




Electron-hole pairs created
By the traversing particle
drift in the electric field

Basic Principles (6)

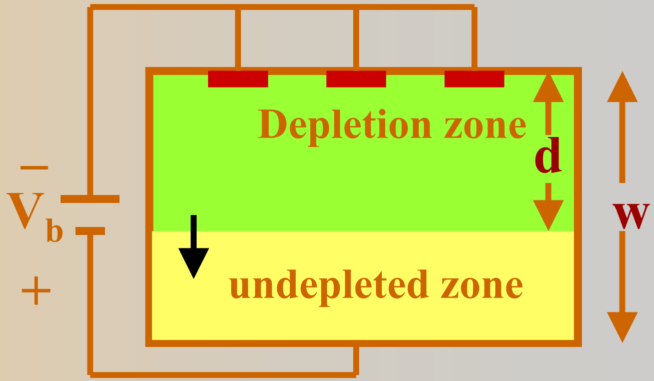
By segmenting the implant we can reconstruct the position of the traversing particle in one dimension



Typical values used are
pitch : 20 μm – 150 μm
bulk thickness: 150 μm – 500 μm

Properties of the depletion zone (1)

- Depletion width is a function of the bulk resistivity , charge carrier mobility μ and the magnitude of the reverse bias voltage V_b:



$$d = \sqrt{2\varepsilon\rho\mu V_b}$$

where ρ = 1/qμN for doped materiel and N is the doping concentration (q is always the charge of the electron)

- The voltage needed to completely deplete a device of thickness d is called the depletion voltage, V_d

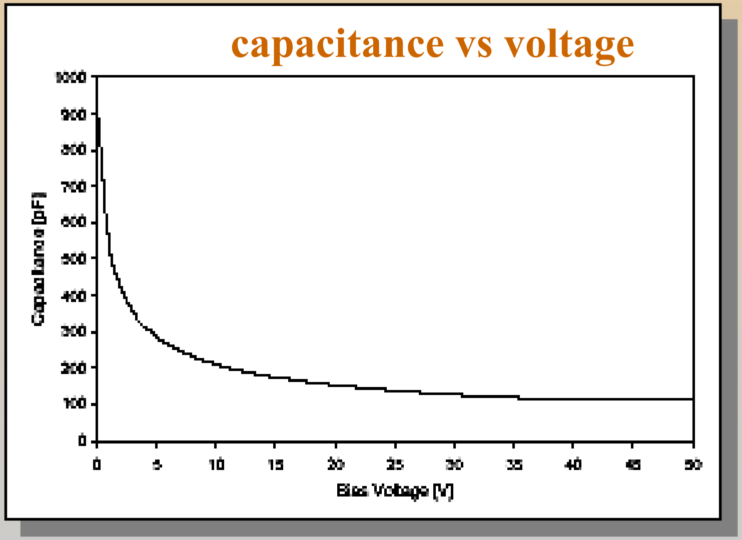
$$V_d = w^2 / (2\varepsilon\rho\mu)$$

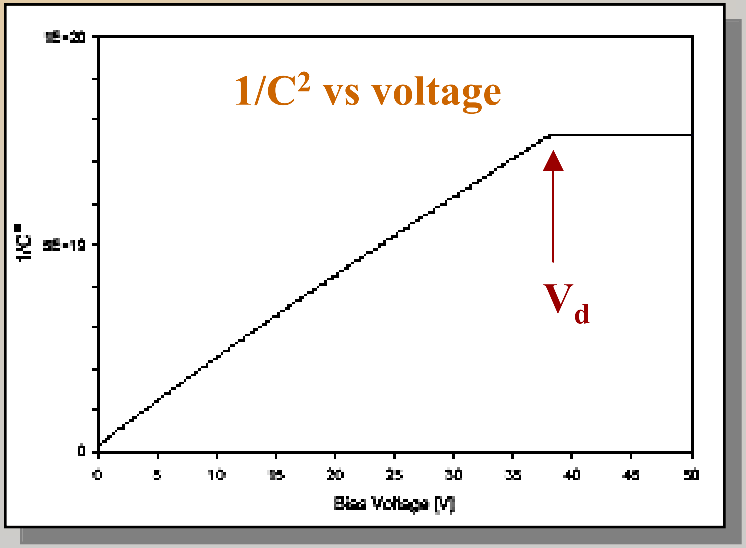
- Need a higher voltage to fully deplete a low resistivity material.
- One also sees that a higher voltage is needed for a p-type bulk since the carrier mobility of holes is lower than for electrons (450 vs 1350 $cm^2/V \cdot s$)

Properties of the depletion zone (2)

- The capacitance is simply the parallel plate capacity of the depletion zone. One normally measures the depletion behaviour (finds the depletion voltage) by measuring the capacitance versus reverse bias voltage.

$$C = A\sqrt{\varepsilon / 2\rho\mu V_b}$$





Signal size I

- Ionising energy loss is governed by the Bethe-Bloch equation

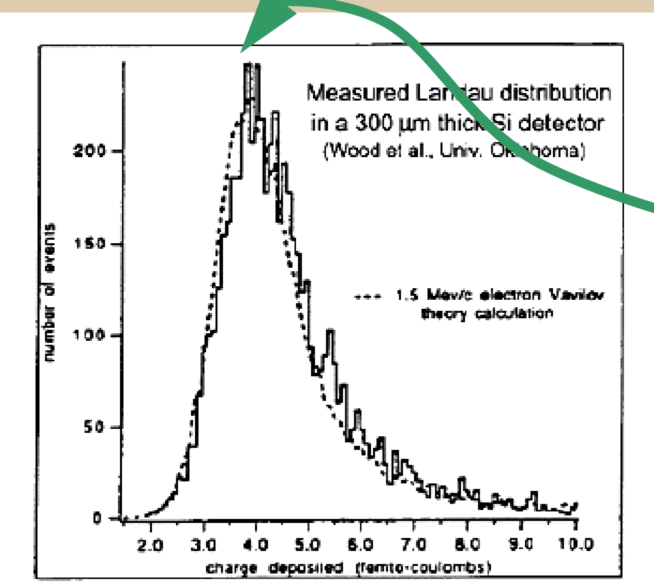
$$\frac{dE}{dx} = 4\pi N r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} [ln \frac{2m_e c^2 \gamma^2 \beta^2}{I(Z)} - \beta^2 - \frac{\delta}{2}]$$

- We care about high energy, minimum ionising particles, where

  dE/dx ~ 39 KeV/100 μm

An energy deposition of 3.6 eV will produce one e-h pair

So in 300 μm we should get a mean of 32k e-h pairs

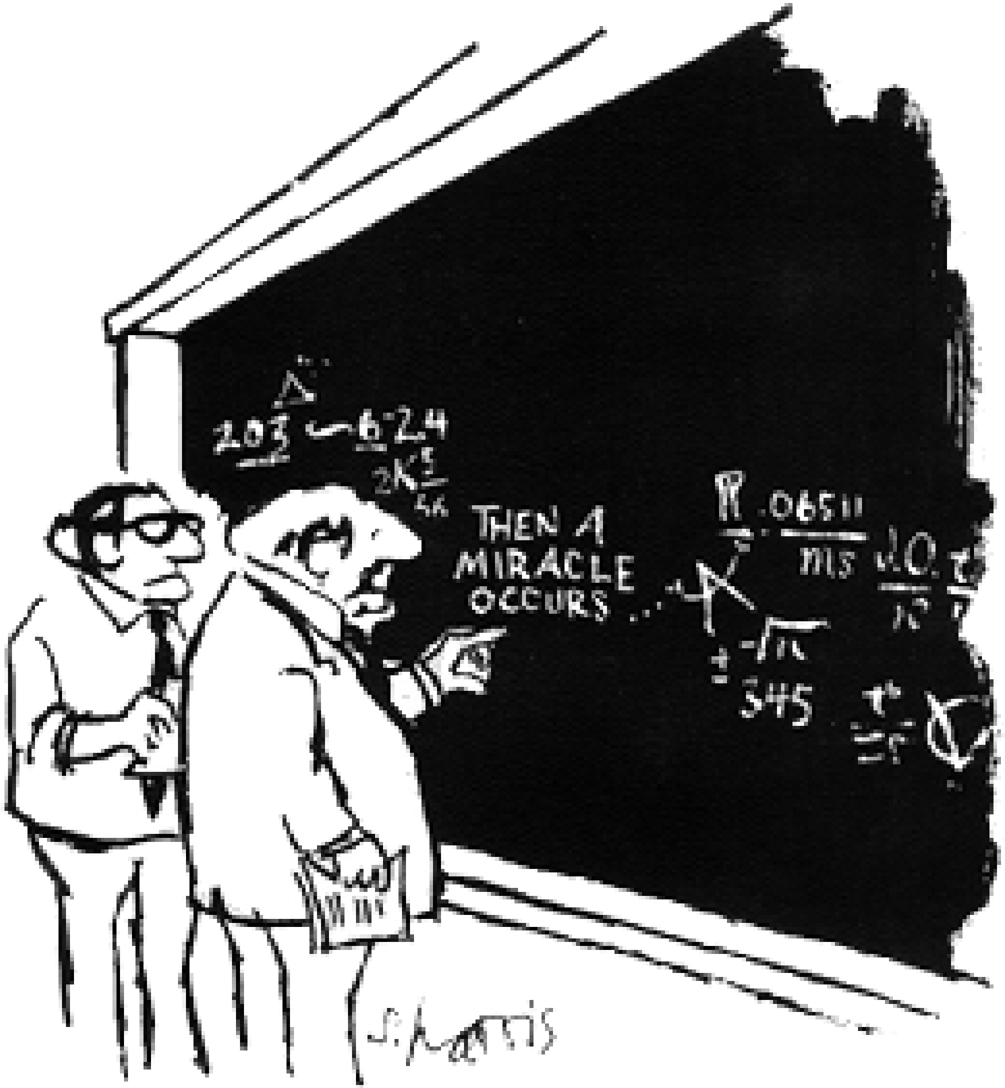


Fluctuations give the famous "Landau distribution"

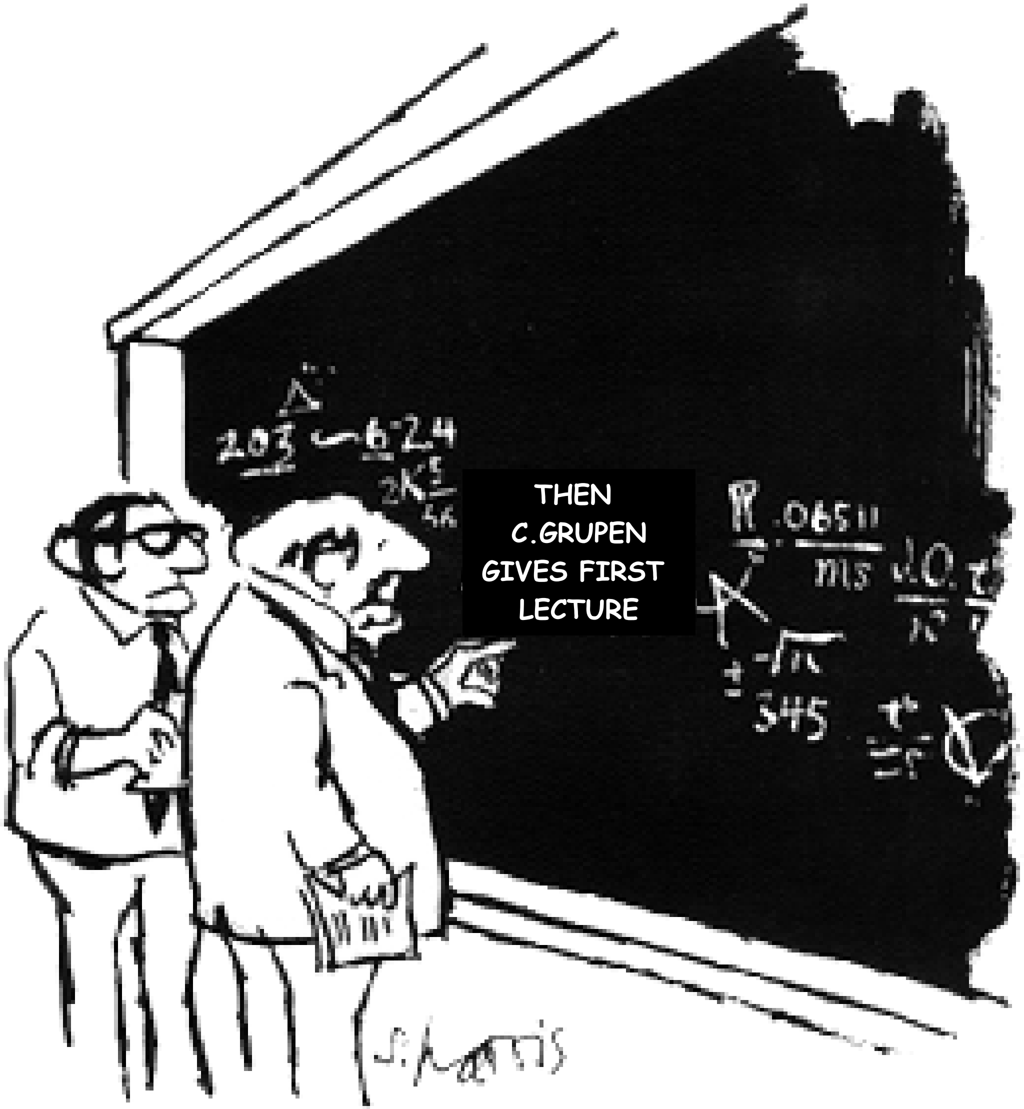
The "most probable value" is 0.7 of the peak

For 300 μm of silicon, most probable value is

22000 electron-hole pairs

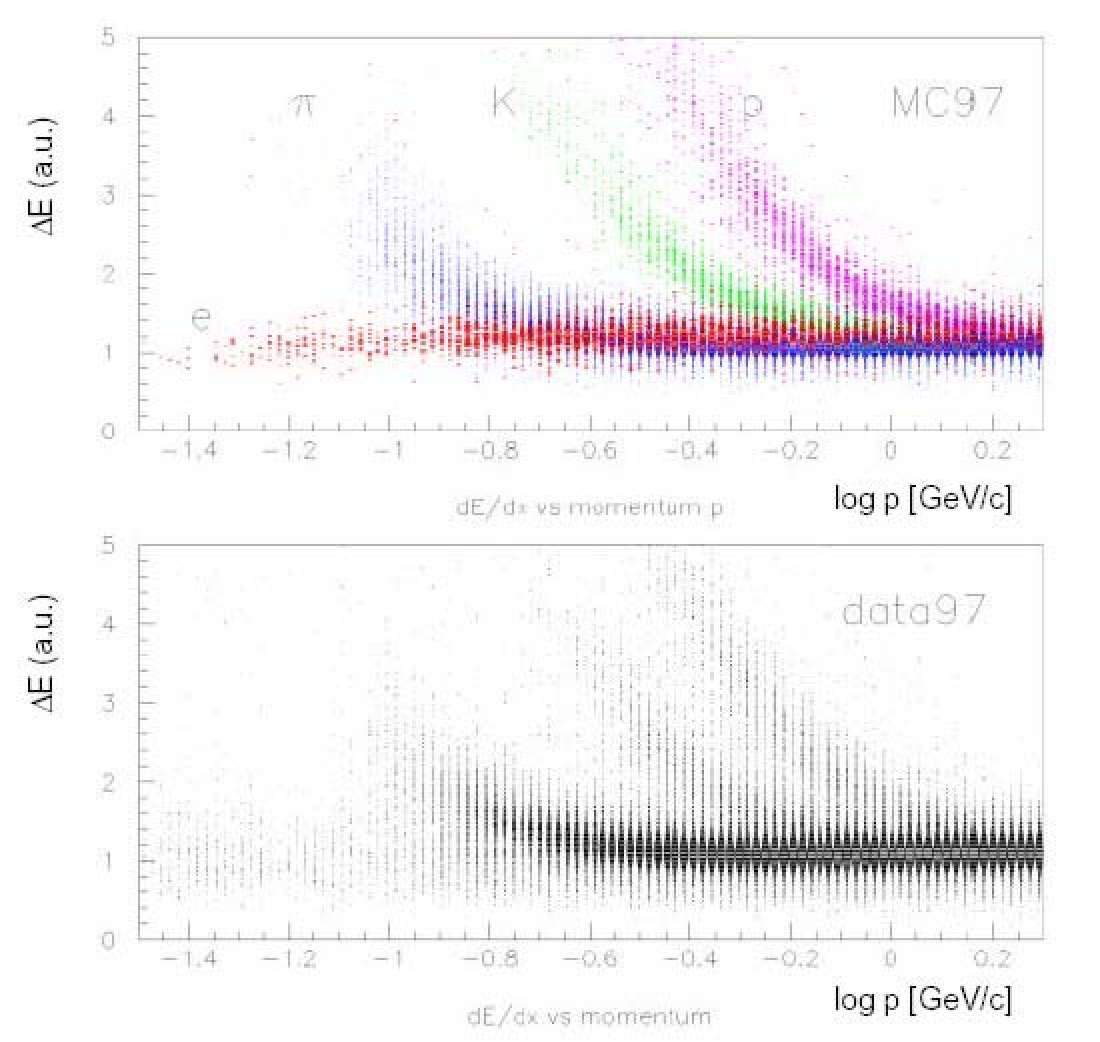


"I think you should be more explicit here in step two."



"I think you should be more explicit here in step two."

Signal size II



For very low momenta we can exploit the bethe bloch formula for particle identification

$$p = m_0 \beta\gamma$$

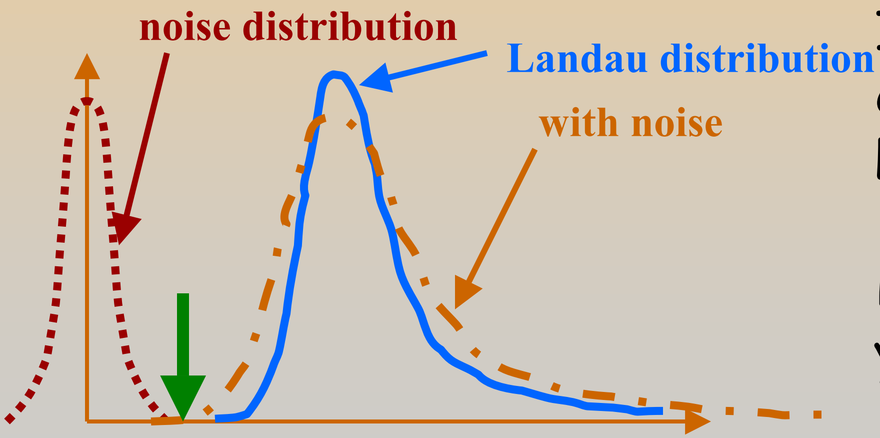
$$\frac{dE}{dx} \propto \frac{1}{\beta^2} \ln\left(\beta^2\gamma^2\right)$$

$\Rightarrow$ **Knowing p and β gives m**

NB Silicon is not the best type of detector for this application!

Noise I

Noise is a big issue for silicon detectors. At 22000e$^-$ for a 300 μm thick sensor the signal is relatively small. Signal losses can easily occur depending on electronics, stray capacitances, coupling capacitor, frequency etc.



If you place your cut too high you cut into the low energy tail of the Landau and you lose efficiency.

But if you place your cut too low you pick up fake noise hits

Noise II

- Usually expressed as equivalent noise charge (ENC) in units of electron charge e. Here we assume the use of a CR-RC amplifier shaper circuit is most commonly used.

- Main sources:
  - Capacitive load (C_d). Often the major source, the dependence is a function of amplifier design. Feedback mechanism of most amplifiers makes the amplifier internal noise dependent on input capacitive load. $ENC \propto C_d$
  - Sensor leakage current (shot noise). $ENC \propto \sqrt{I}$
  - Parallel resistance of bias resistor (thermal noise). $ENC \propto \sqrt{(kT/R)}$
  - Total noise generally expressed in the form (absorbing the last two sources into the constant term a): $ENC = a + b \cdot C_d$
  - Noise is also very frequency dependent, thus dependent on read-out method
- Implications on detector design:
  - Strip length, device quality, choice of bias method will affect noise.
  - Temperature is important for both leakage current noise (current doubles for $\Delta T \approx 7^{\circ}C$) and for bias resistor component

Noise III

One of the most important parameters of a silicon detector is the ratio between the

Signal

and the

Noise

This is often shown as S/N and has a big effect on the detector performance

Noise IV

- Example of noise
  - Some typical values for LEP silicon strip modules (OPAL):
    - ENC = 500 + 15 $\cdot C_d$
    - Typical strip capacitance is about 1.5pF/cm, strip length of 18cm so C_d=27pF

so ENC = 900e. Remember S=22500e

$\Rightarrow$ S/N $\approx$ 25/1

- Some typical values for LHC silicon strip modules
    - ENC = 425 + 64 $\cdot C_d$
  - Typical strip capacitance is about 1.2pF/cm, strip length of 12cm so C_d=14pF

so ENC = 1300e

$\Rightarrow$ S/N $\approx$ 17/1

Capacitive term is much worse for LHC in large part due to very fast shaping time needed (bunch crossing of 25ns vs 22μs for LEP)

Signal Diffusion (1)

- Charges drift in electric field E with velocity

$$v = E\mu$$

- $\mu =$ mobility cm^2/volt sec, depends on temp + impurities + E: typically 1350 for electrons, 450 for holes
- So drift times for: d=300 mm, E=2.5Kv/cm:

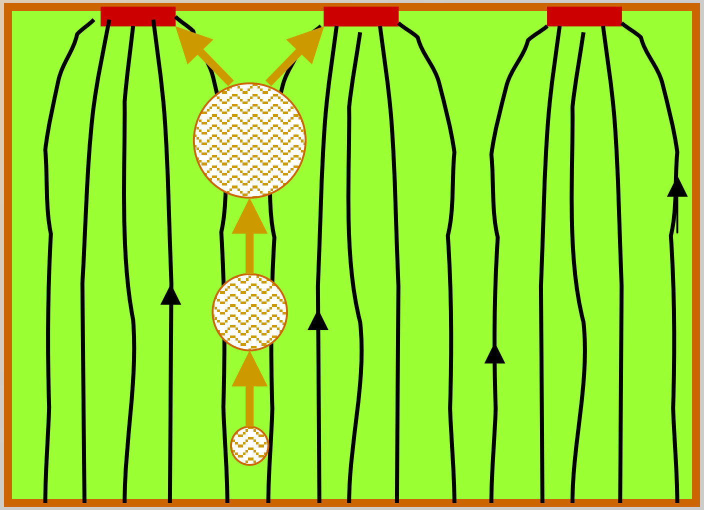
$t_d(e) = 9$ ns, $t_d(h)=27$ ns

Signal Diffusion (2)

- Diffusion is caused by random thermal motion
- Size of charge cloud after a time t_d given by

$\sigma = \sqrt{2Dt_d}$, where D is the diffusion constant, $D=\mu kT/q$

- For electrons and holes diffusion is roughly the same!



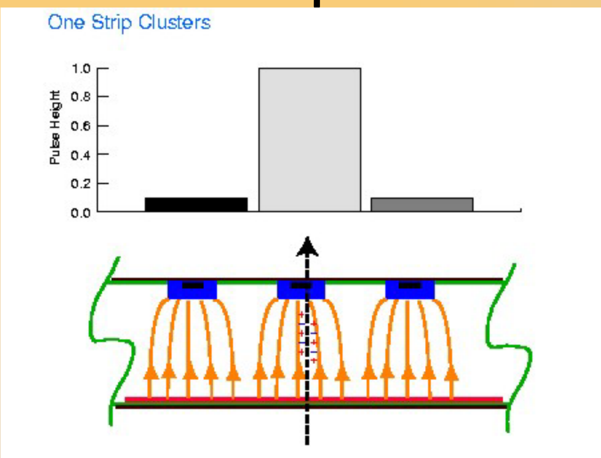
Typical value: 8 μm for 300 μm drift. Can be exploited to improve position resolution

Position Resolution I

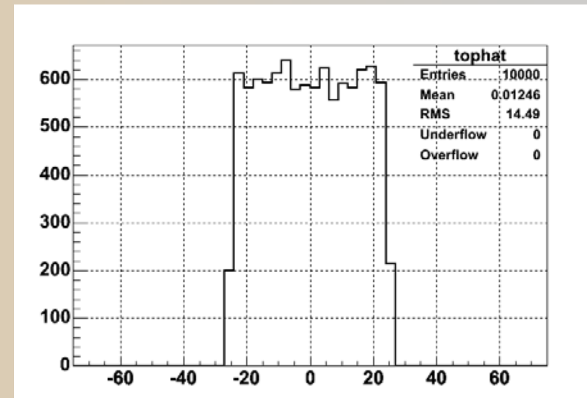
Resolution is the spread of the reconstructed position minus the true position

For one strip clusters

"top hat" residuals

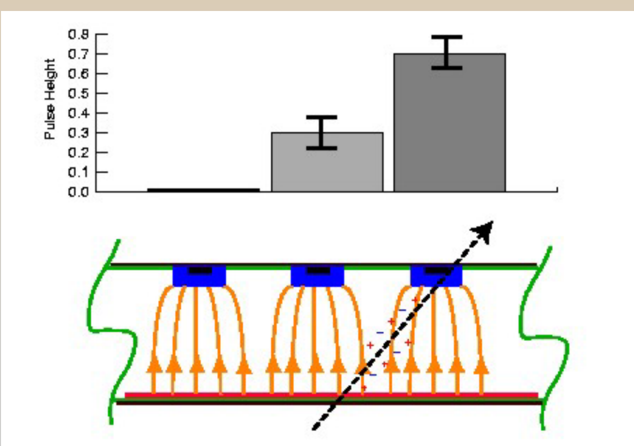


$$\sigma = \frac{\text{pitch}}{\sqrt{12}}$$

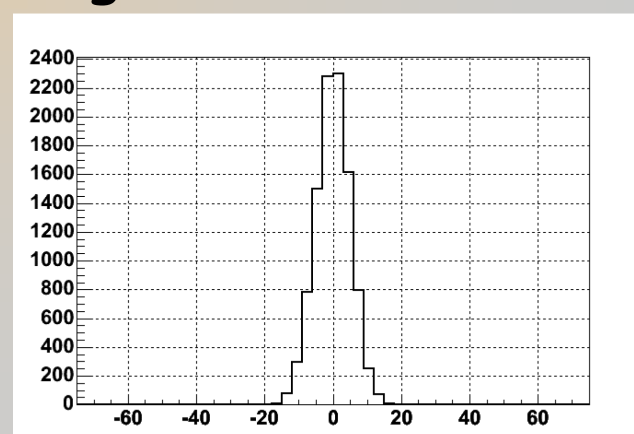


For two strip clusters

"gaussian" residuals



$$\sigma \approx \frac{\text{pitch}}{1.5 * (S/N)}$$

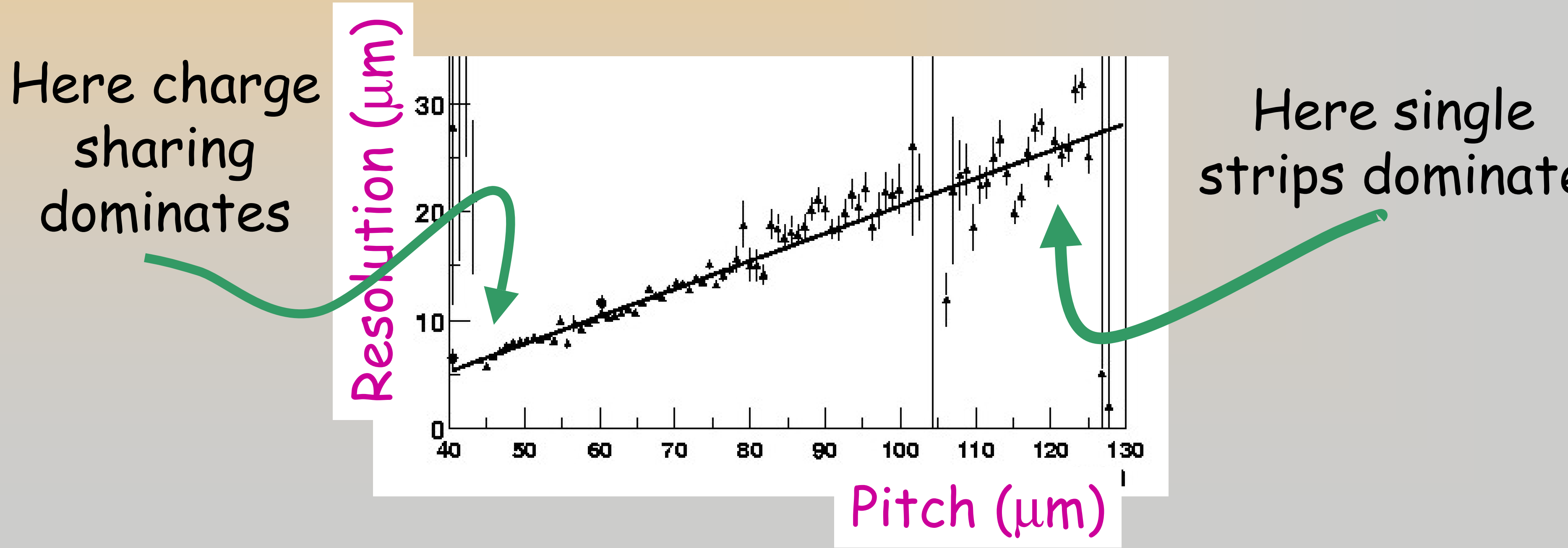


Position Resolution II

In real life, position resolution is degraded by many factors

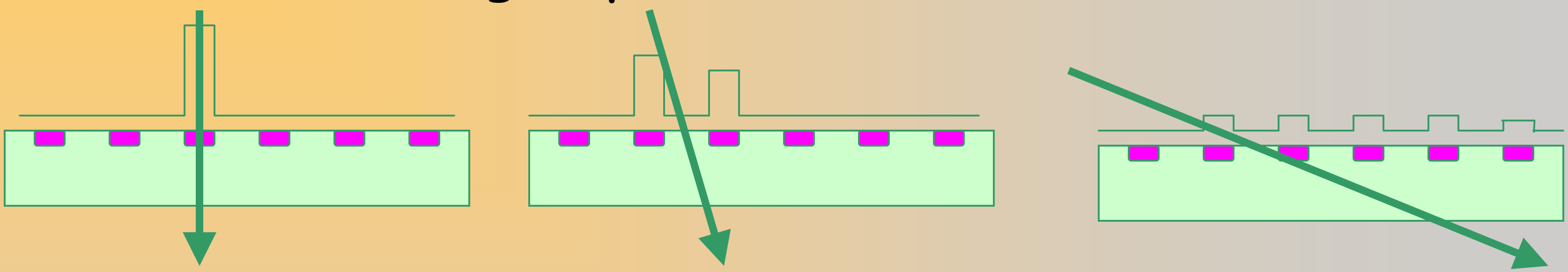
- ➢relationship of strip pitch and diffusion width (typically 25-150 μm and 5-10 μm)
- ➢Statistical fluctuations on the energy deposition

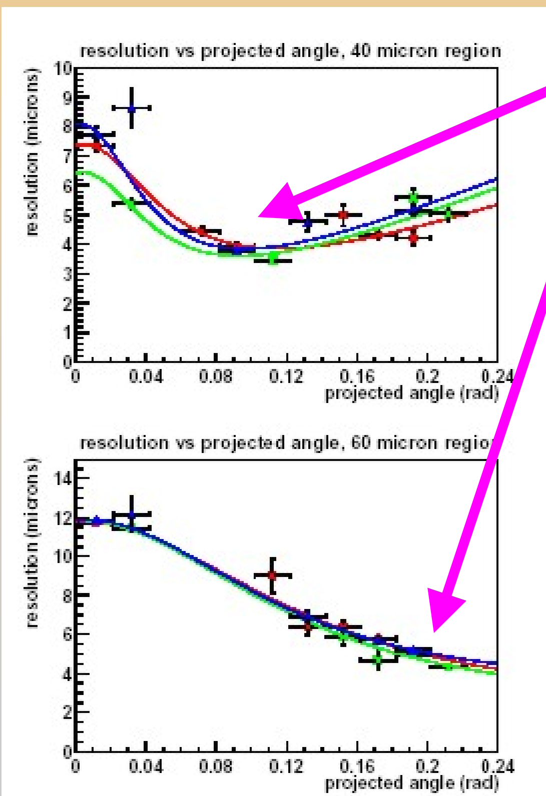
Typical real life values for a 300μm thick sensor with S/N=20



Position Resolution III

There is also a strong dependence on the track incidence angle



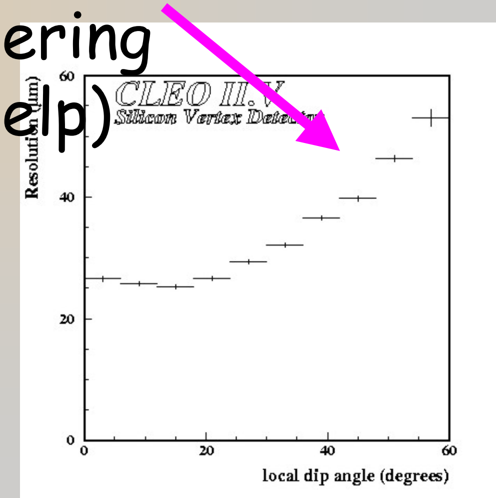


At small angles you win

At large angles you lose
(but a good clustering
algorithm can help)

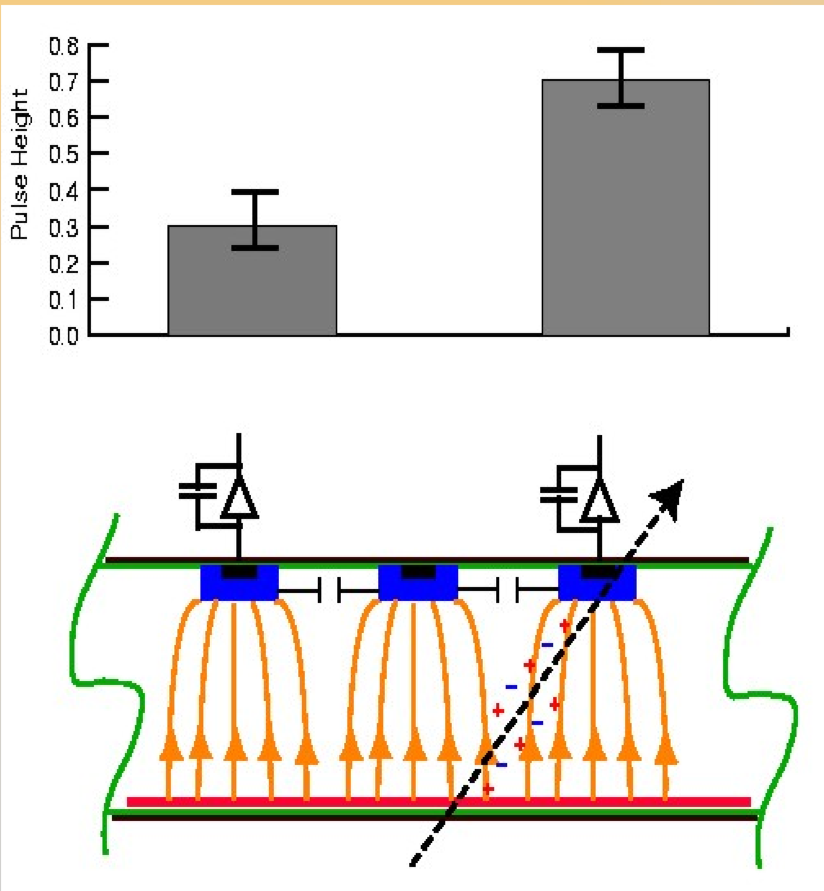
Optimum is at

$$\tan^{-1}\frac{\text{pitch}}{\text{width}}$$



Position Resolution IV

Fine pitch is good… but there is a price to pay! $$$$$
The floating strip solution can help



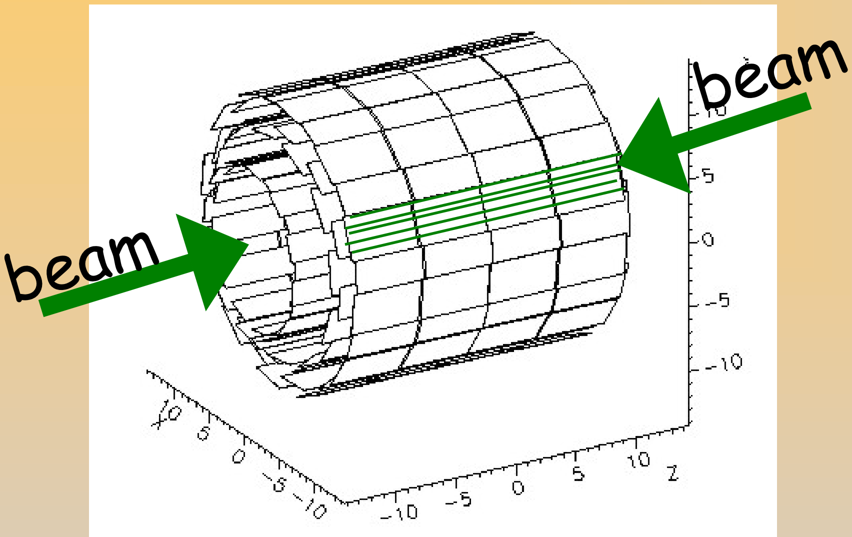
- The charge is shared to the neighboring strips via capacitative coupling. We don't have to read out every strip but we still get great resolution
- This is a very popular solution. ALEPH for instance obtain $\sigma \approx 12\ \mu m$ using a readout pitch of 100 μm and an implant pitch of 25 μm
- But you can't have everything for nothing! You can lose charge from the floating strips to the backplane, so you must start with a good signal to noise

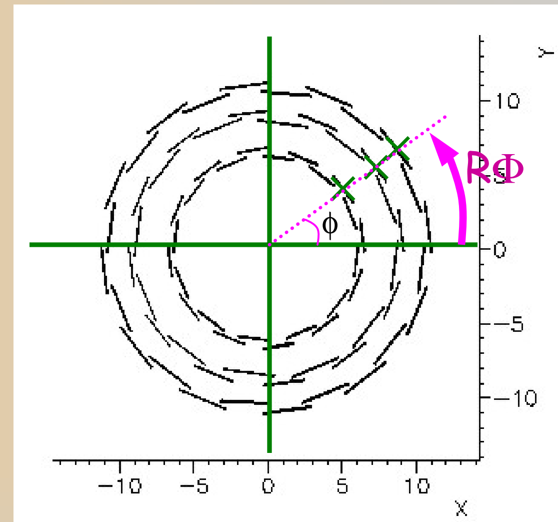
Summary so far of some silicon vital statistics

- Energy to create electron hole pair = 3.6 eV (≈ 30 eV for gas detectors)
- High specific density ⇒ m.i.p. gives an average of 108 e-h pair / μm
- High mobility so signal arrives quickly
- Silicon processing = heart of microelectronic industry so nice small devices are possible
- Silicon is rigid and self supporting
- But… no charge multiplication mechanism!

Silicon: More exotic structures

A bit of history: the first idea for precision silicon detectors in colliding beam experiments is to arrange overlapping ladders around the beam pipe





Side view:
Strips go in z ⟷ direction

Transverse view:
Measurement is of Rϕ coordinate

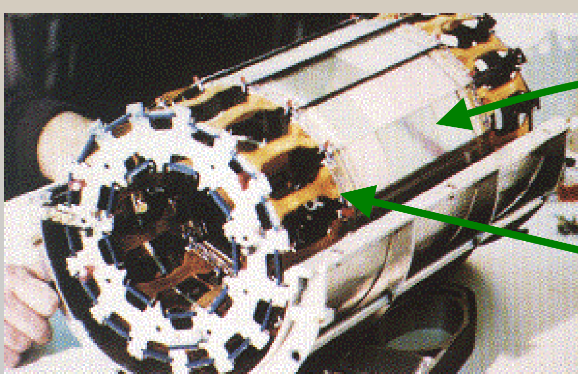
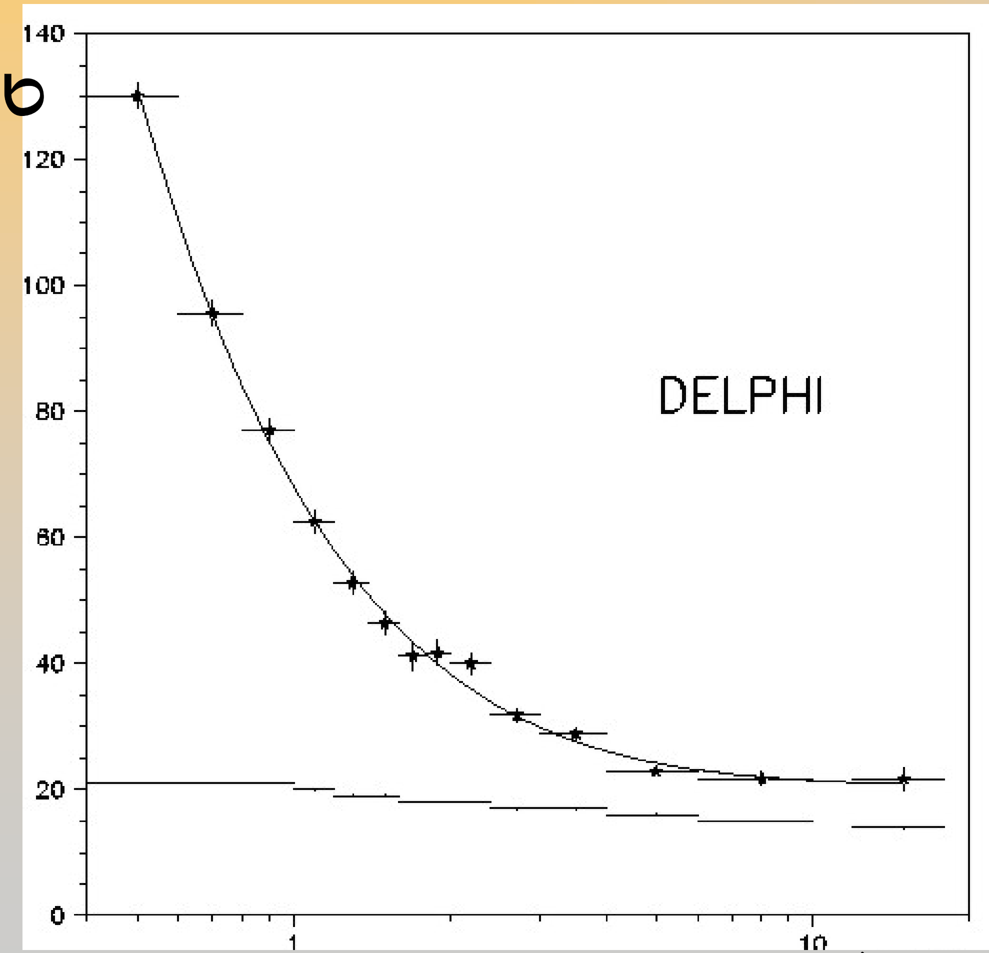


Photo of finished detector:
Note that
silicon is in the middle and
electronics on the outside

2D Impact Parameter precision

Measurement of the lifetime dominated by how well the impact parameter precision is known. This is momentum dependent

σ



$p \sin^{3/2}\theta$

$$\sigma^2 = A^2 + \left(\frac{B}{p \sin^{3/2}\theta}\right)^2$$

A comes from geometry
B comes from geometry and multiple scattering in the beampipe and in the silicon

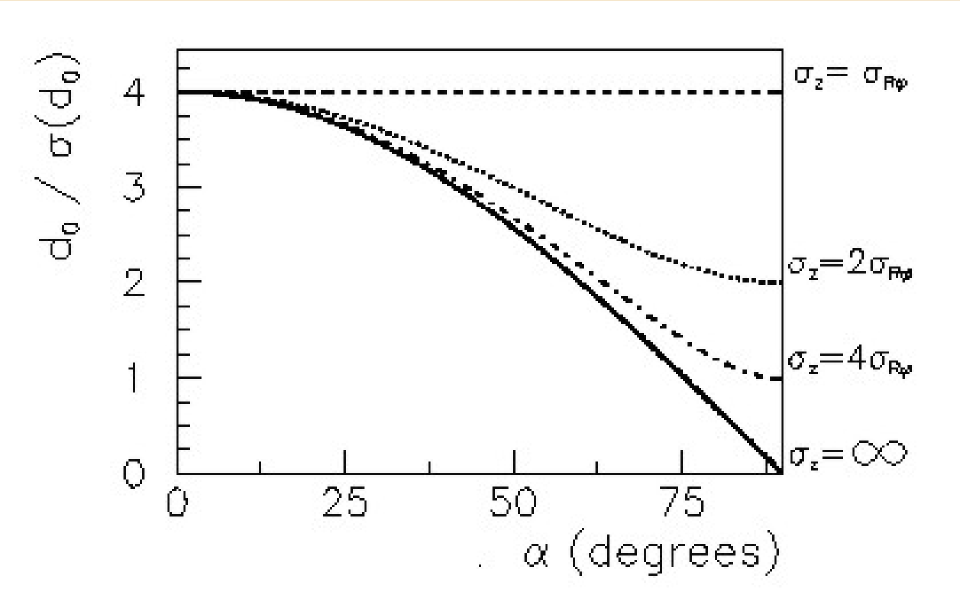
For DELPHI:

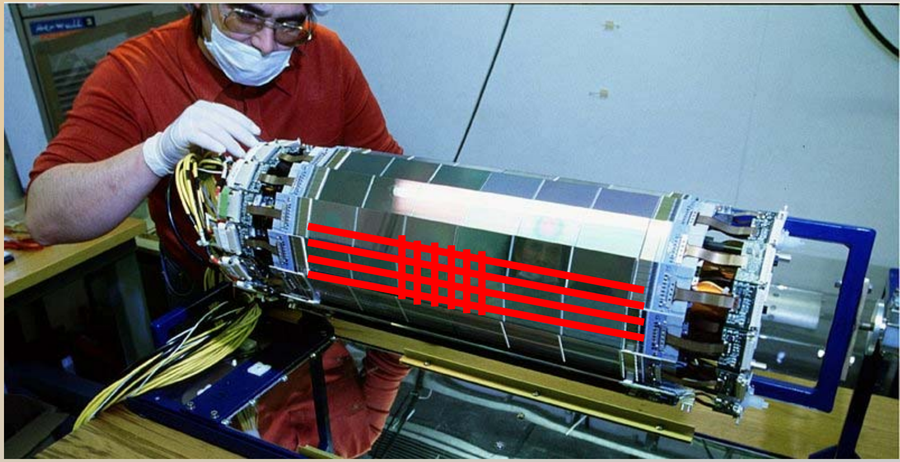
this is the tricky one!

A = 20 μm
B = 65 μm

3D Impact Parameter measurement

- We need to add measurement of orthogonal coordinate
- For this to be effective the precision must be comparable to the precision we had in Rϕ



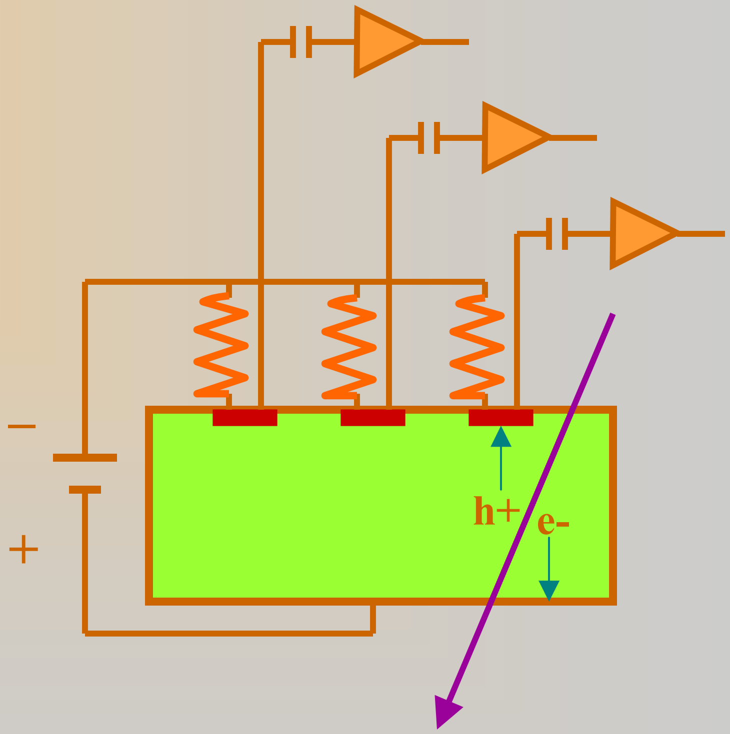


But this must be achieved by not adding material where we have been so careful to keep things thin

Can we do something extra on the silicon itself?

Solution I: Double sided sensors

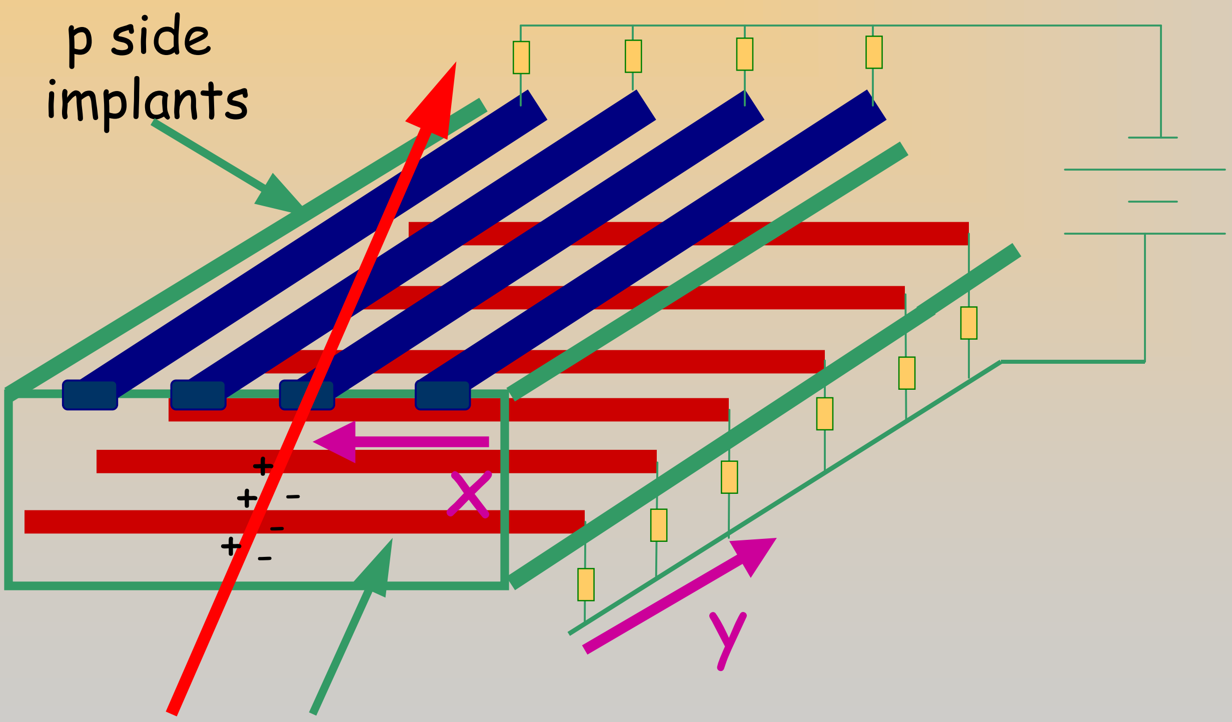
- A reminder of what the p strips look like
  - Strips are well isolated from each other in order to collect the charge on each individual strip
  - The bias is supplied via big resistors (often integrated onto the silicon wafer itself)
  - Readout is often AC coupled to avoid large currents into the amplifier



Why not apply the same technology to the other (n) side?

Double sided sensors II

The n+ implant on the back side of a single sided detector can be segmented into strips so that the orthogonal coordinate can be simultaneously measured. This gives true 3d hit information!

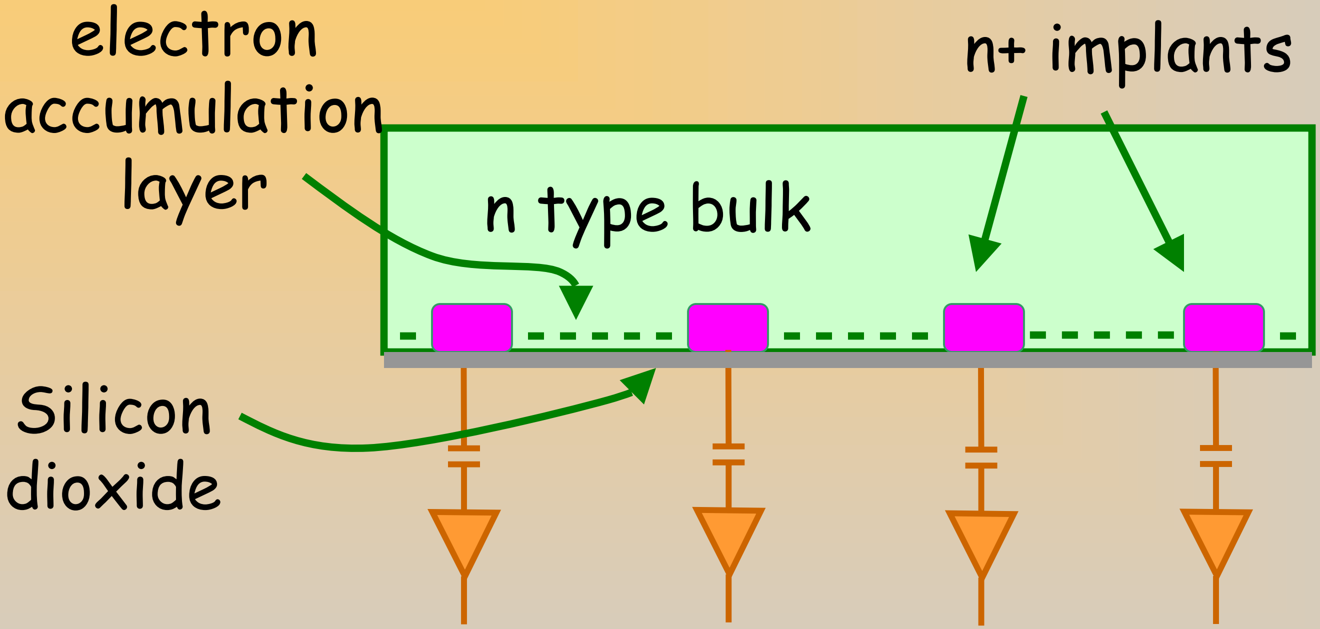


But!

- complex ($$$)
- strip isolation (see next slide)
- readout (see slide after)

Double Sided Sensors III

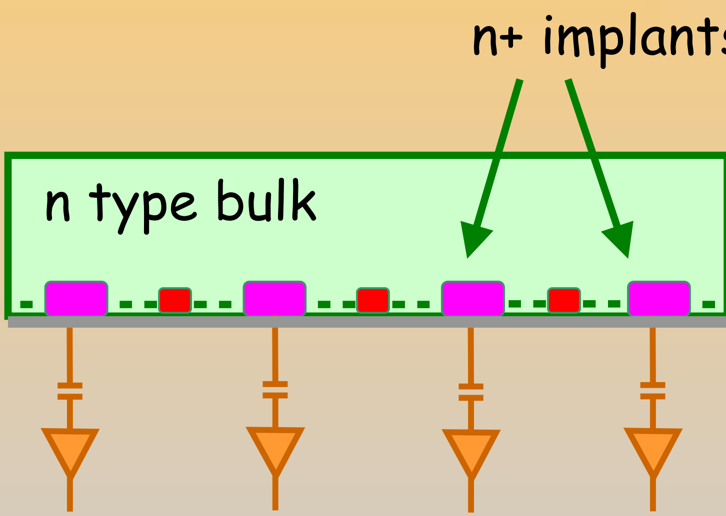
- Solving strip isolation problems



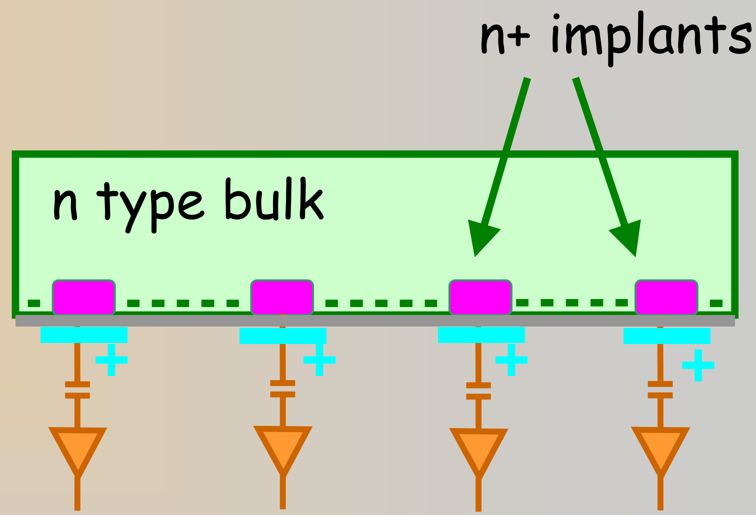
- At the Si-SiO_2 interface is a layer of fixed positive charge
- which attracts a layer of mobile electrons
- which shorts the n-strips together!

Double Sided Sensors IV

- Two methods have been shown to be successful in isolating the strips



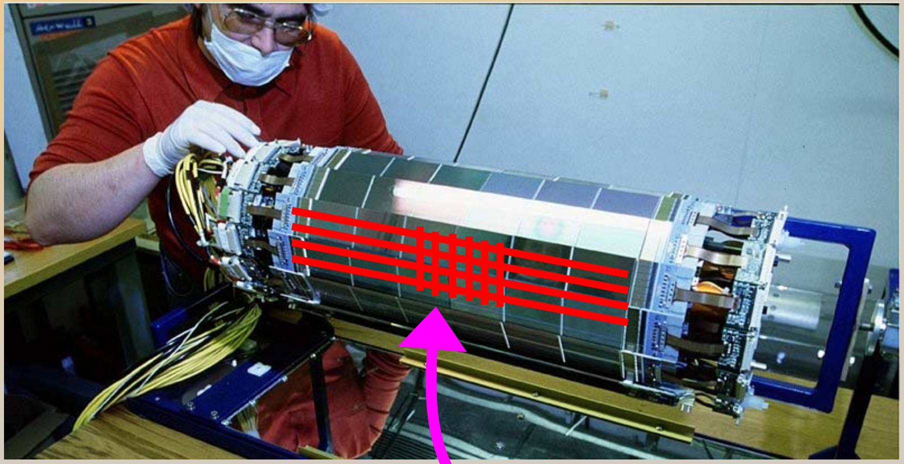
or



Put p+ "blocking electrodes" between the n+ strips (no need to bias them)

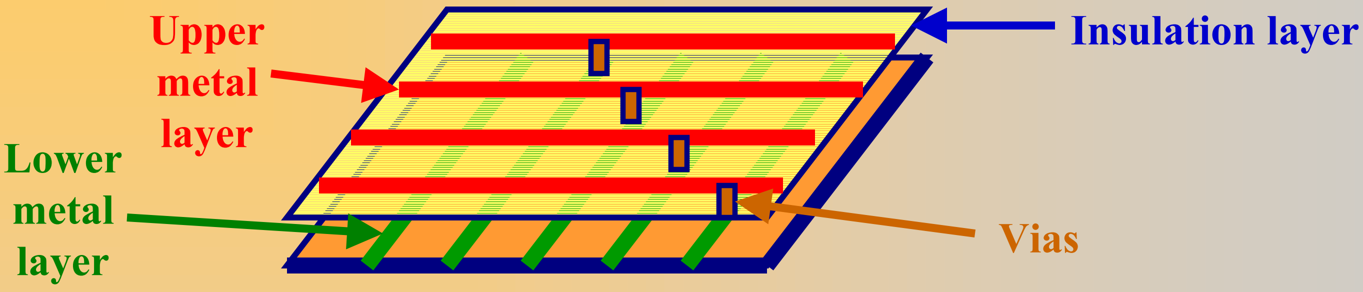
Put "field plates" (metal over oxide) over the n-strips and apply a potential on the plates to repel the electrons

So now.. we have two measurements for the price of one sensor? Not quite yet....



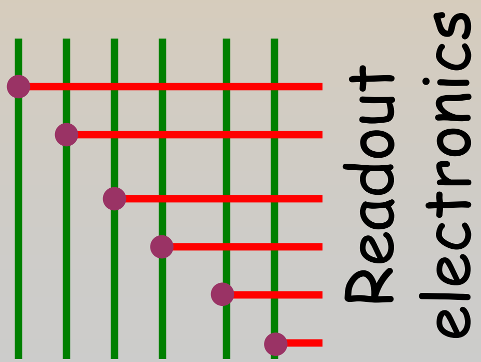
How do we read out these orthogonal strips??

Double Metal Technology

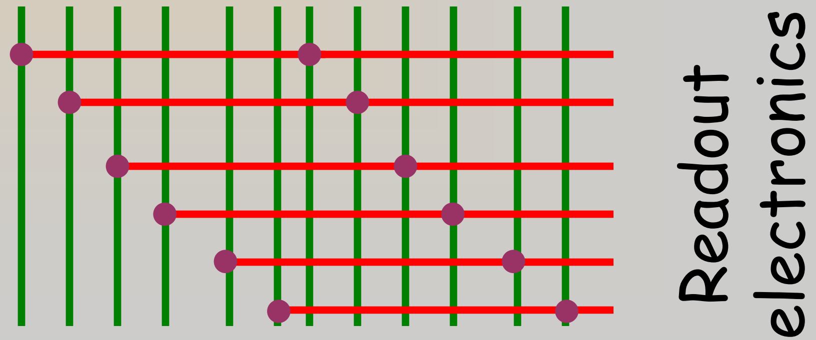


Add an insulation layer, and above that add another layer of strips which are going in the right direction – the direction of the readout electronics. This might be orthogonal to the strips and might not – many weird and wonderful patterns are possible

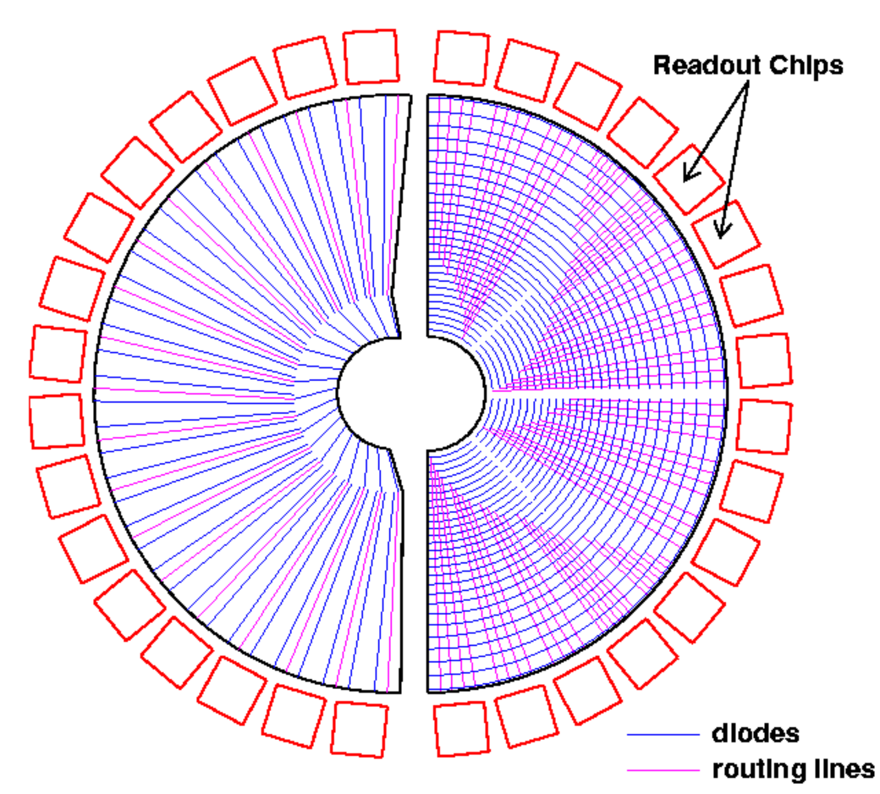
a simple solution..



.... a solution with multiplexing



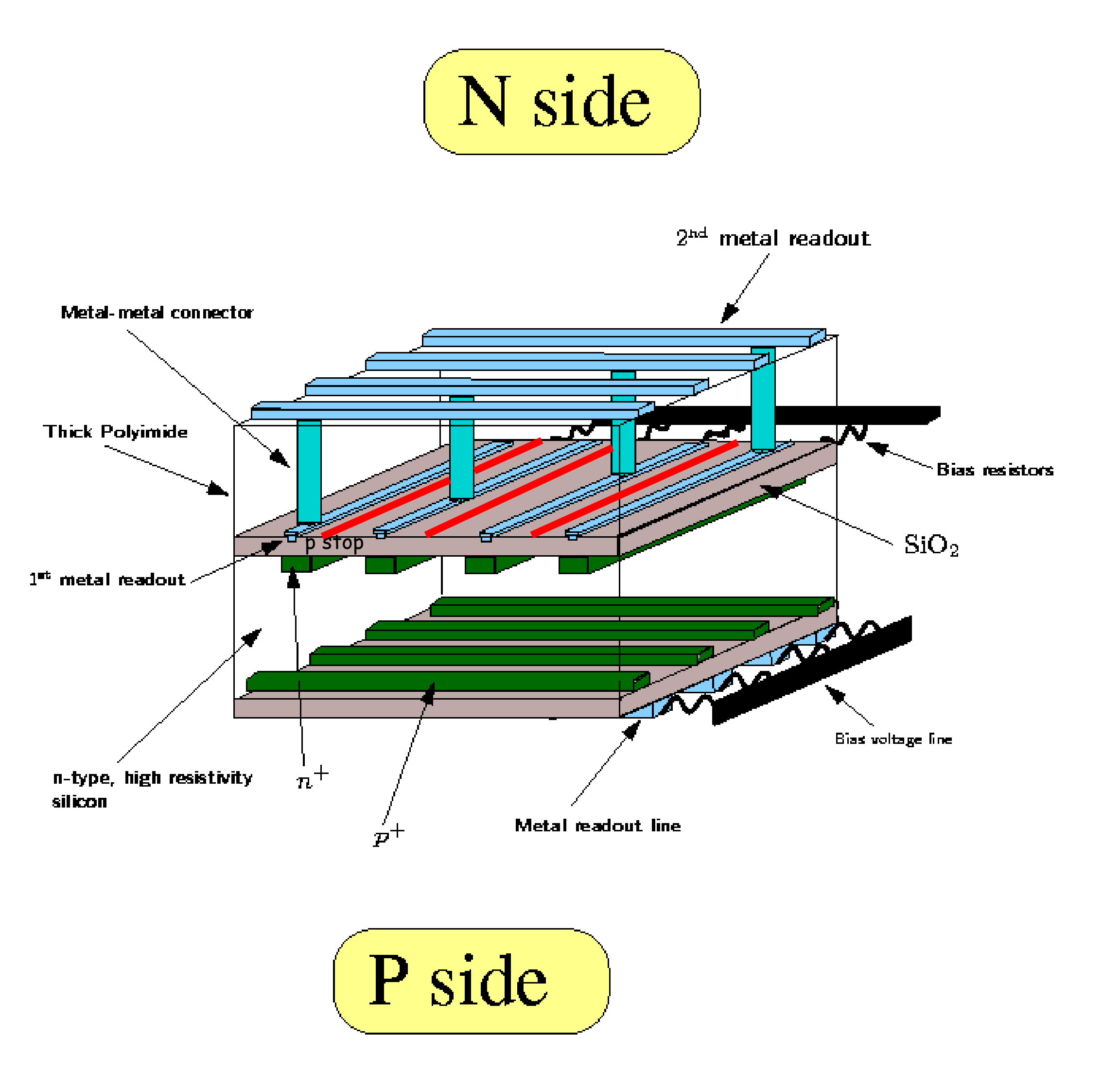
A real life example



The LHCb sensors must measure R and Phi and must keep the electronics on the outside – an obvious application for double metal technology!

These detectors are single sided and n-on-n

The DELPHI sensors had strips on the p side and strips on the n side and p stops and field plates and double metal and and and…



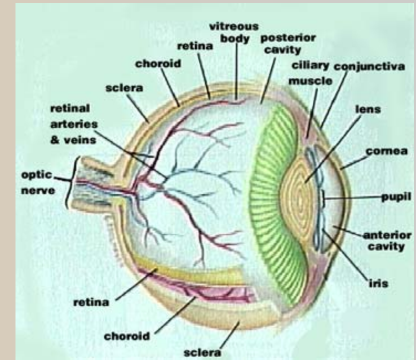
the ultimate in strip detector technology

Pixel sensors

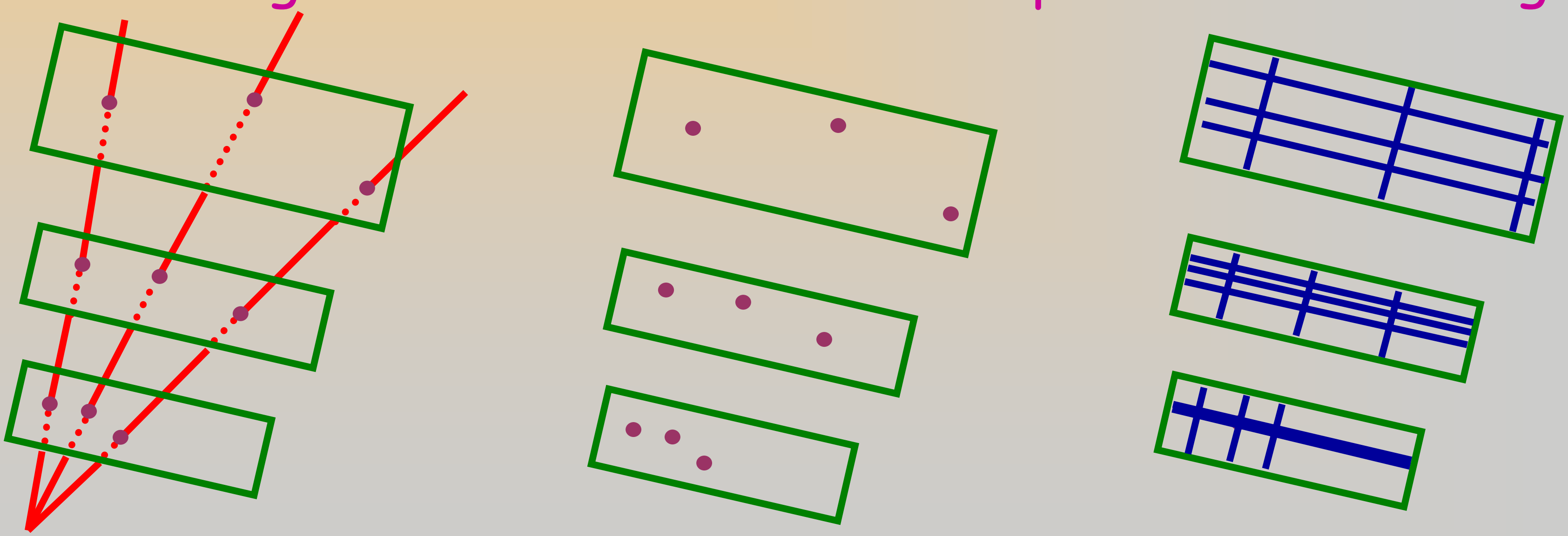
- Instead of strips measuring one dimension, have a matrix of points measuring two dimensions

as used in this

and in this



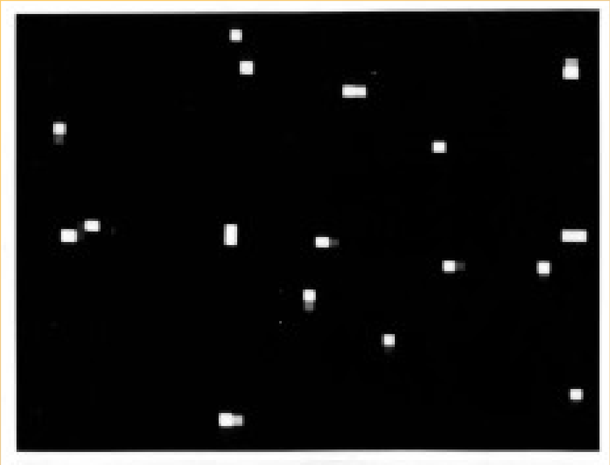
- Pattern recognition is much easier! Compare reconstruting



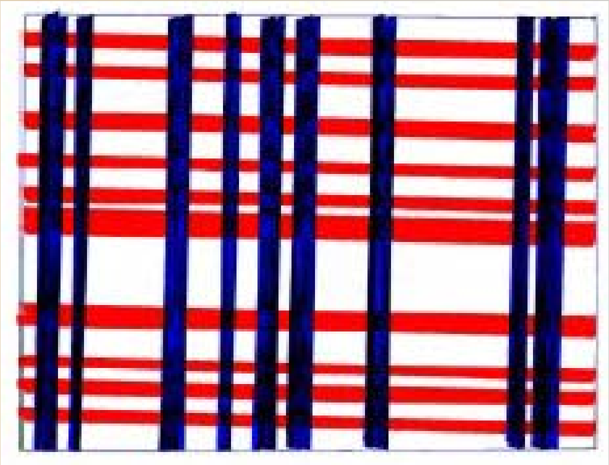
these tracks … with this …. or with this!

These wonderful
matrix based detectors
will enable us to save
the world!

a real life example



1 mm^2 of CCD in CERN testbeam in 1980

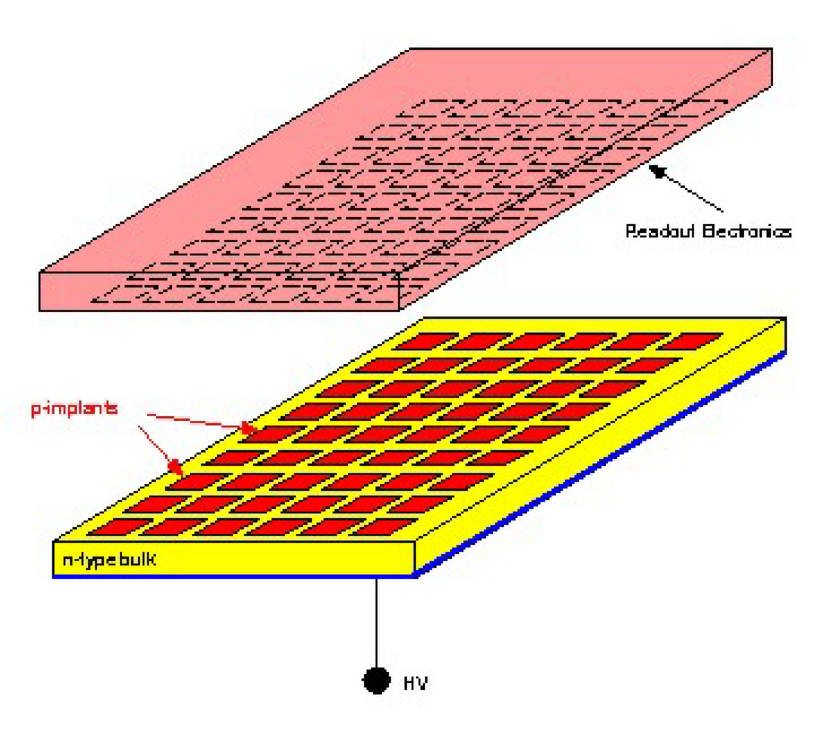


hypothetical performance of 20 μm pitch microstrip

- 17 hits should give $17^2 = 289$ candidates in microstrip (but we only see 90)

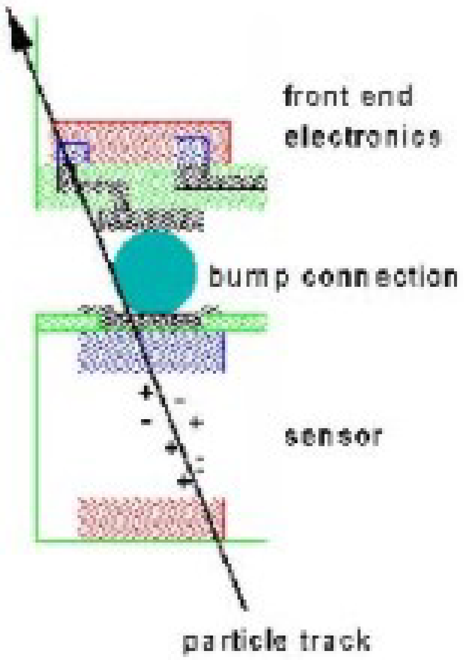
In the future we want to get closer and closer to the interaction point, so the tracks become more and more dense – it is all about "occupancy"!

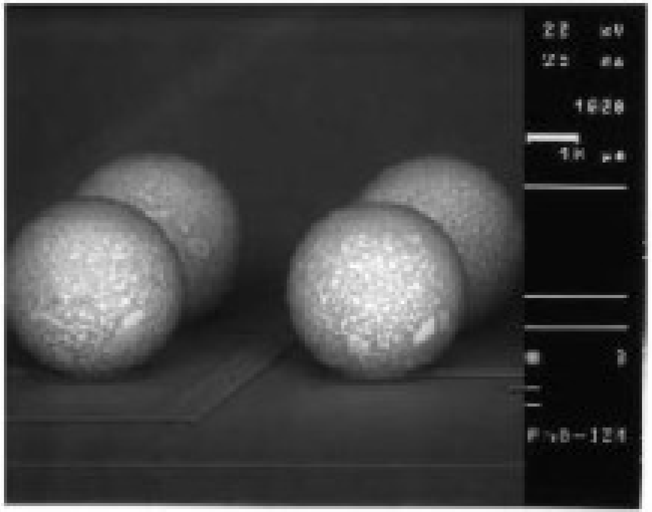
challenge: interconnect to electronics



- Sensor is just like a strip sensor but with the p+ implants further subdivided into tiny squares
- Many similarities:
  - biasing, depletion works in the same way
  - charge sharing between pixels improves resolution
  - capacitance, leakage current of each pixel << strip
- each electronic channel mounted directly on its pixel -> electronics is in the tracking volume
  - radiation
  - material
  - pixel size > 100 μm

electronics interconnect

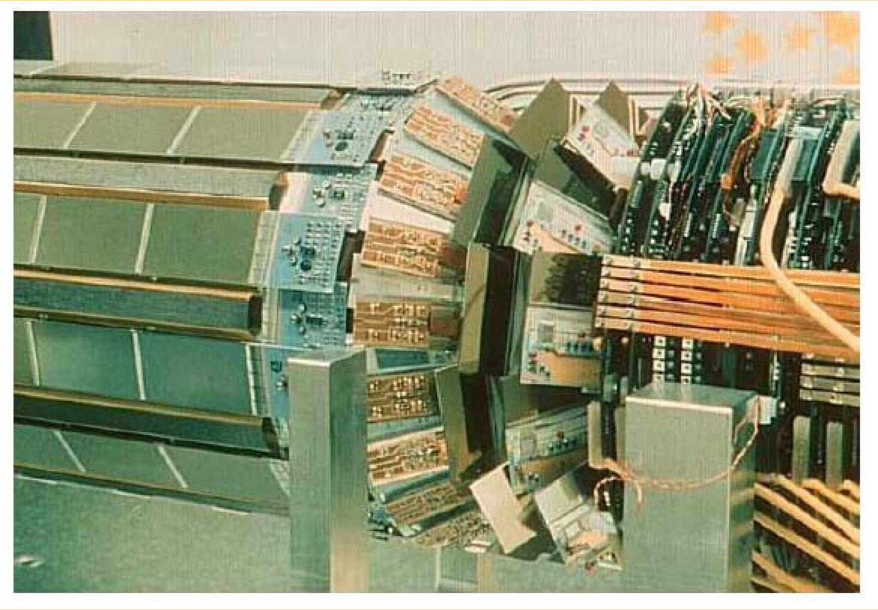




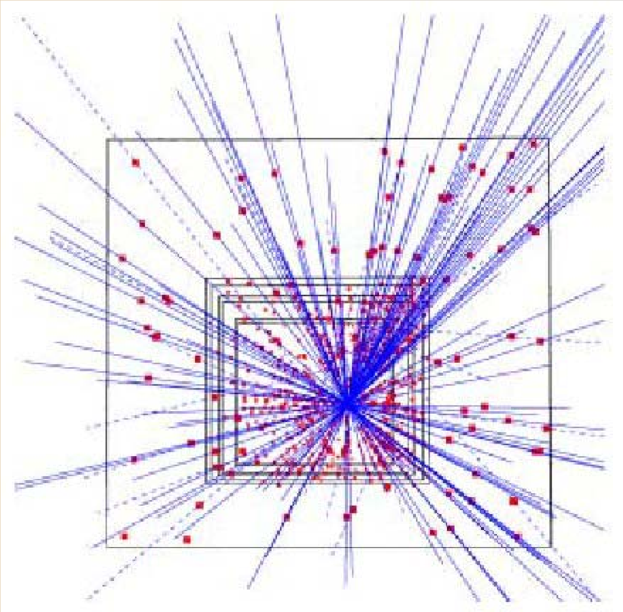
sensor and FE-chip connected
using bump and flip chip technology
(failure rate ~ 10^{-4})

bumps: 50 µm pitch
PbSn or In
6-20 µm high
~3000 / chip, 48000 / module

Pixels have been successfully used



e.g. in DELPHI



and in WA97

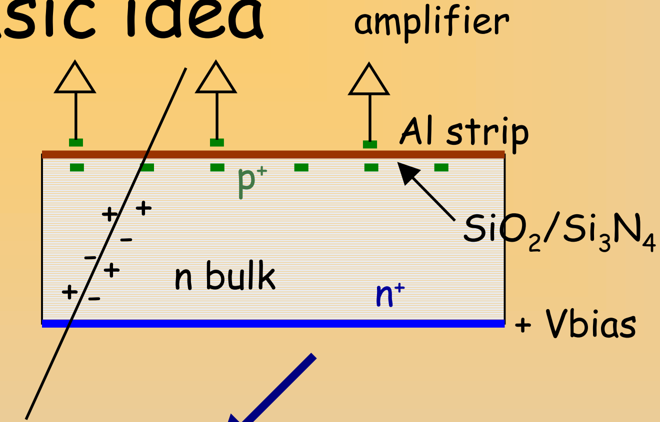
and will be very important for b tagging and multijet processes at the LHC and the future LC, e.g.

$$e^+e^- \rightarrow H^+H^- \rightarrow t\bar{t} \rightarrow b\bar{q}q\bar{b}\bar{q}q$$

$$e^+e^- \rightarrow AH \rightarrow t\bar{t}t\bar{t}$$ (12 jets!)

Summary (so far) and outlook

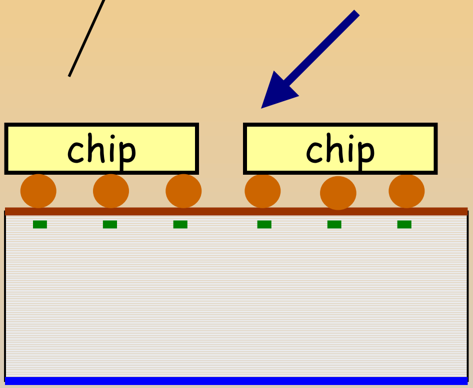
Basic idea



Start with high resistivity silicon

More elaborate ideas:

- n+ side strips – 2d readout
- Integrate routing lines on detector
- Floating strips for precision

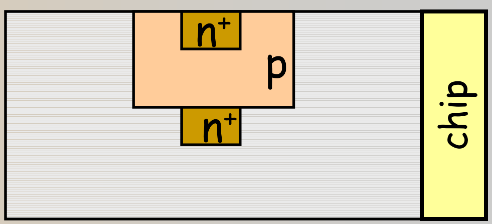


Hybrid Pixel sensors

Chip (low resistivity silicon)

bump bonded to sensor

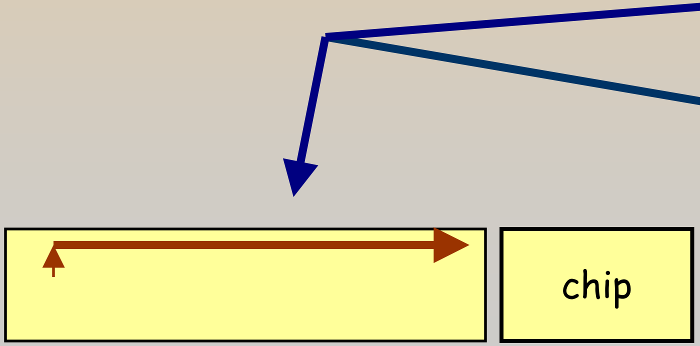
Floating pixels for precision



DEPFET:

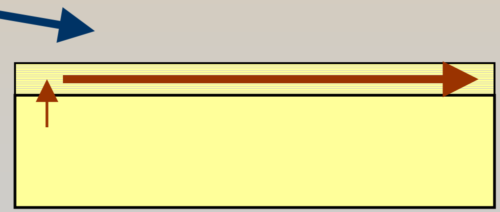
Fully depleted sensor

with integrated preamp



CCD: charge collected in thin layer

and transferred through silicon

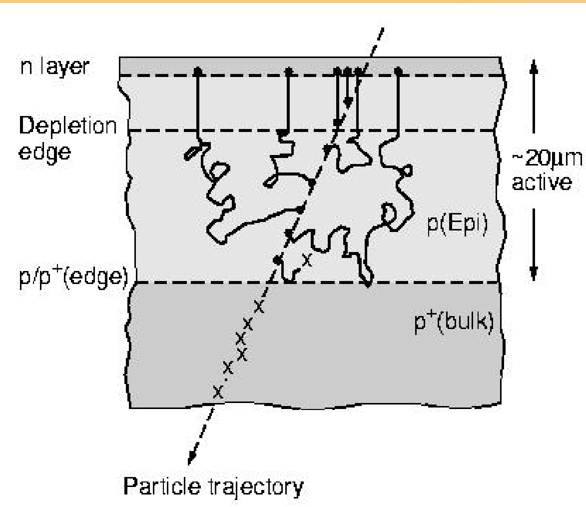


MAPS: standard CMOS wafer

Integrates all functions

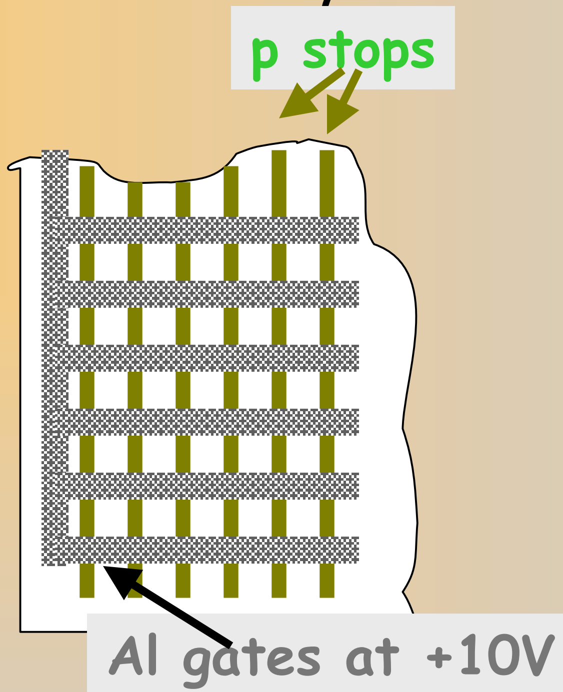
CCD pixel detectors I

CCDs invented in 1970 – widely used in cameras, telescopes etc.



~1000 signal electrons are collected by a combination of drift and diffusion over a ~20μm region just below surface

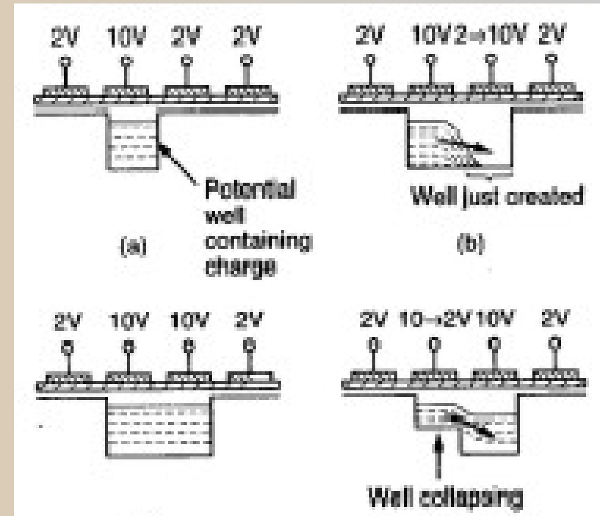
(Note, very thin detectors possible)



•Next, must define a matrix on the surface to constrain the electrons with p stops

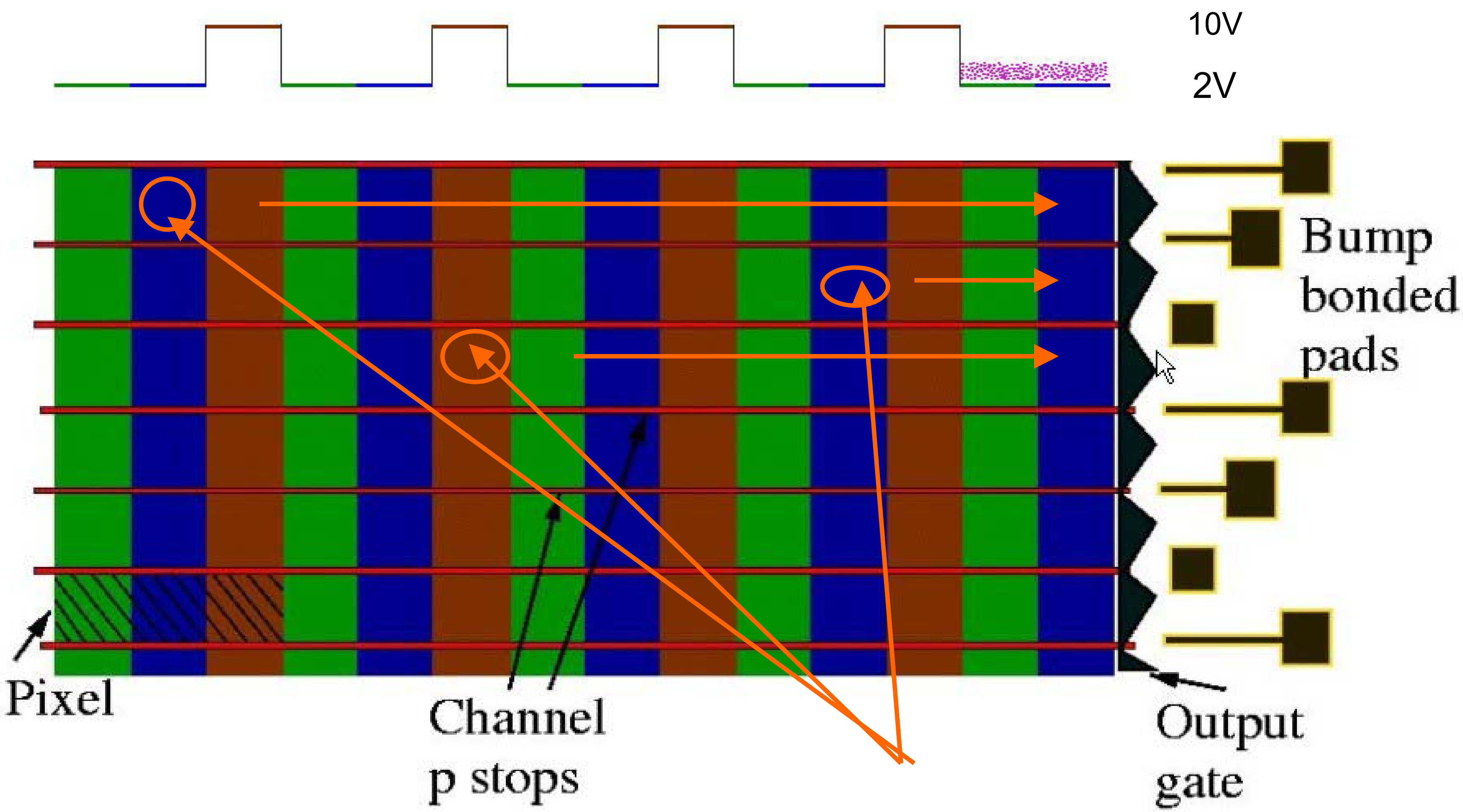
•and with + voltage "gates"

(Note, very tiny pixels possible ~20 μm x 20 μm



Finally, we need a way to move these charges around (by manipulating gate voltages)

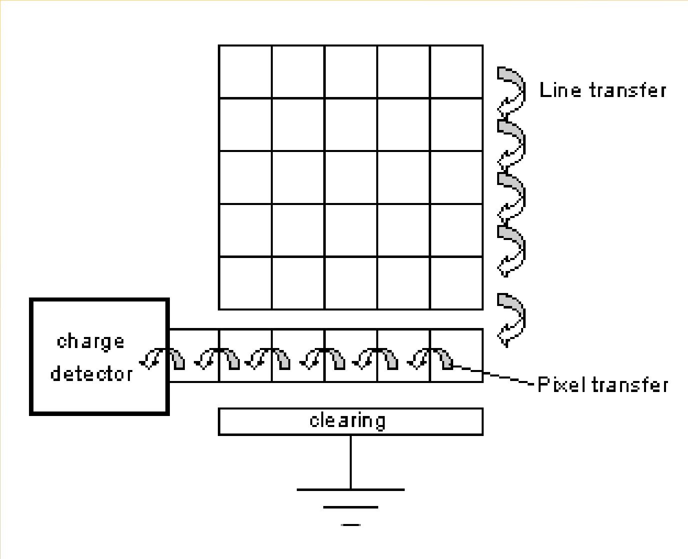
CCD pixel detectors II



The speed to get the charge to the edge of the detector depends on the frequency at which you can operate the gates

CCD pixel detectors III

Traditionally, it takes a long time to read out all the charge, but the detector is sensitive all the time



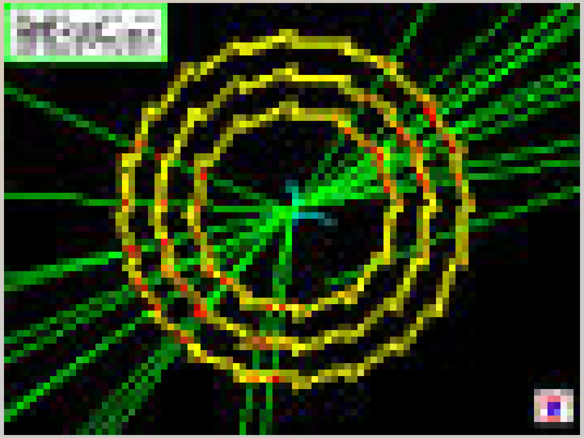
Some solutions for this:

-use the bottom half of the matrix just for storing information and read it out later (good for cameras)

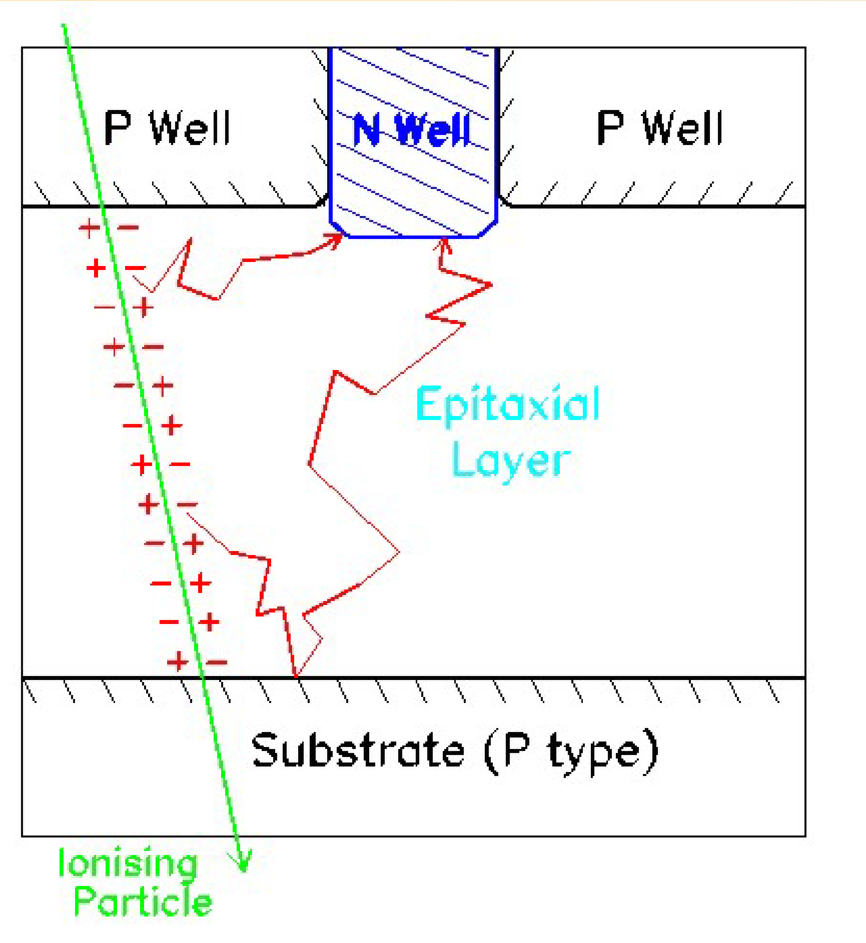
- readout each channel individually (latest, most high tech R&D)

CCD's successfully used for HEP:

1980-1985	NA32	120 kpixels
1992-1995	SLD	120 Mpixels
1996-1998	SLD upgrade	307 Mpixels
	TESLA	799 Mpixels



Monolithic Active Pixel Sensors (MAPS) The ultimate solution?



Like the CCD, the charge is collected from an epitaxial layer, but it is collected into a matrix of n wells and then processed directly on the silicon surface (no charge shifting)

This is a new technology but shows very promising performances:

-excellent resolution

-ease of design and manufacture

-radiation hard

-fast

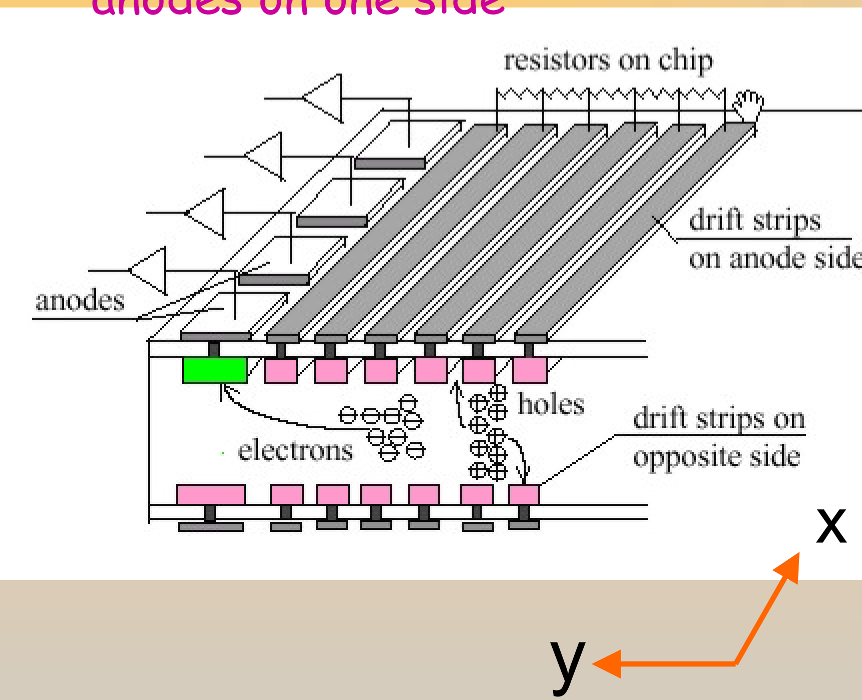
Watch this space!

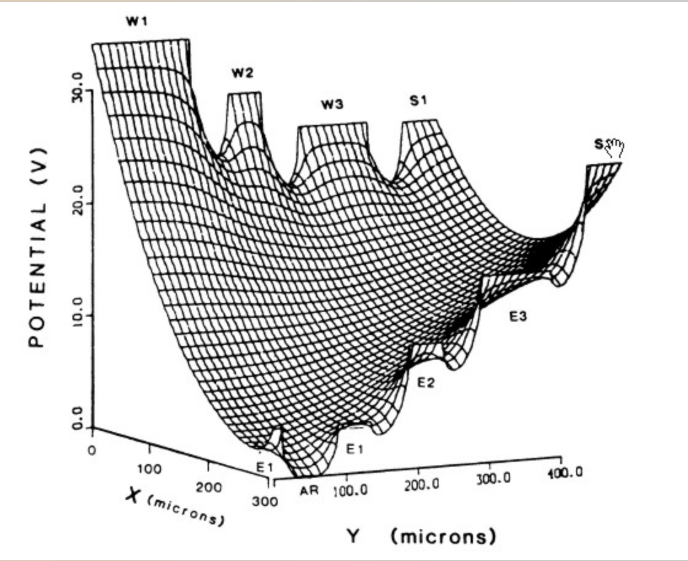
What about using the fourth dimension?

By using time information we can also find out the position – Silicon Drift Detectors

Silicon Drift Detectors

- p$^+$ segmentation on both sides of silicon
- Complete depletion of wafer from segmented n$^+$ anodes on one side

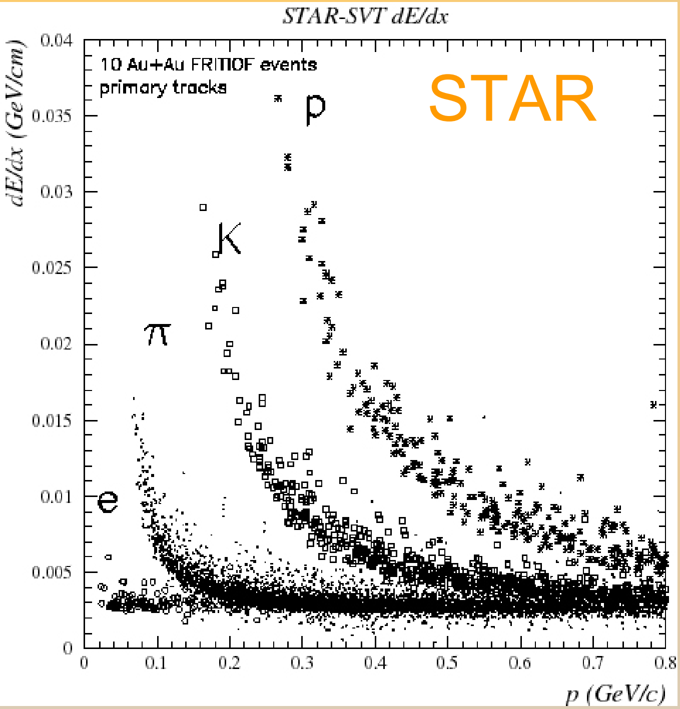




- Electrons drift along potential trough in detector mid plane skewed towards anodes at the end
- X coordinate measured with drift time (~8 μm/ns)
- Y coordinate measured from anode c.o.g.
  - Drift velocity must be predictable
    - Temperature control
    - resistivity control
    - Calibration techniques

- Reduction of channels vs pixel detectors
- Multi track capability
- dE/dx capability
- Small anode capacitance

Silicon Drift Detectors



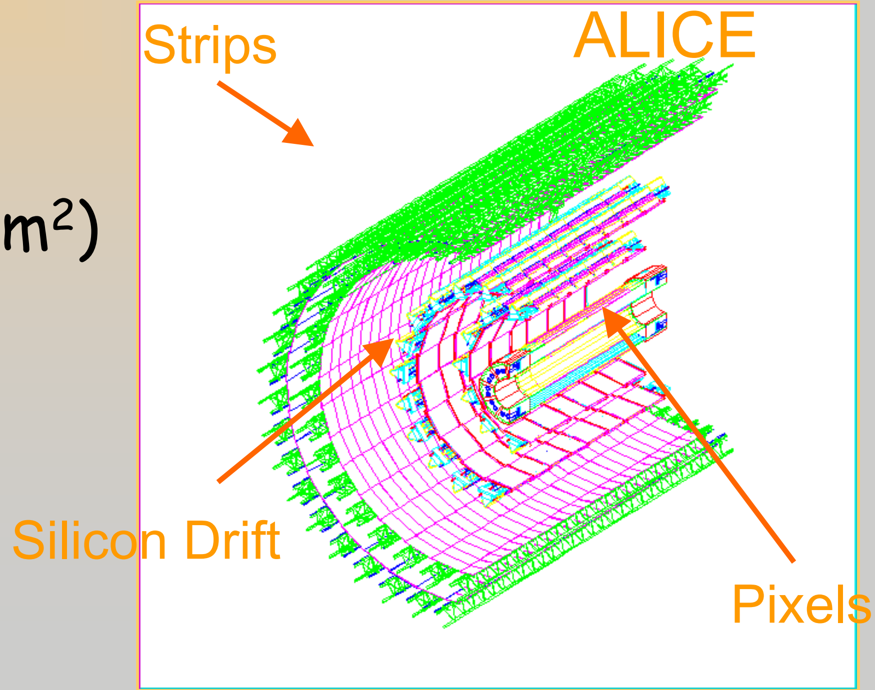
- SDD fully functioning in STAR SVT since 2001
- 216 wafers, 0.7 m^2
- 10 mm in anode direction
- 20 mm in drift direction
- Particle ID

SDD also chosen by ALICE (1.3 m^2)

Similar requirements:

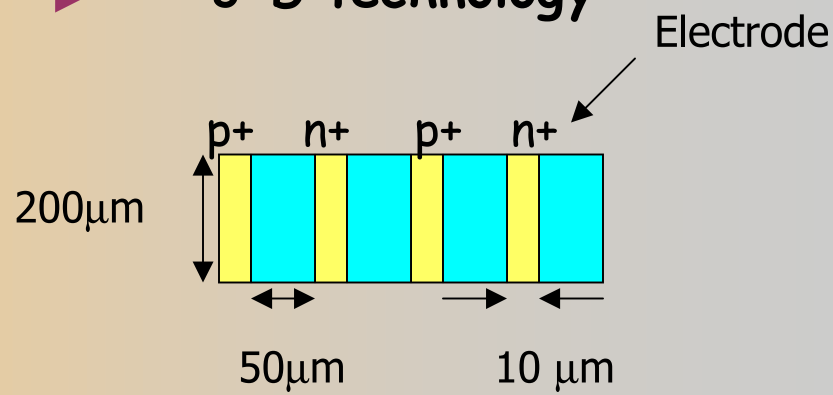
-high multiplicity

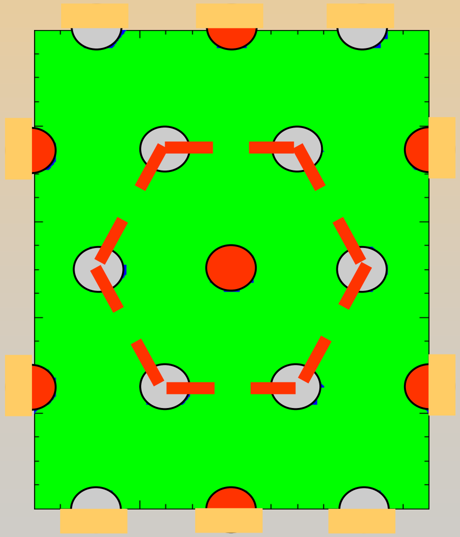
-dE/dx



And now for something completely crazy: "3d detectors"

Planar technology → **3-D technology**

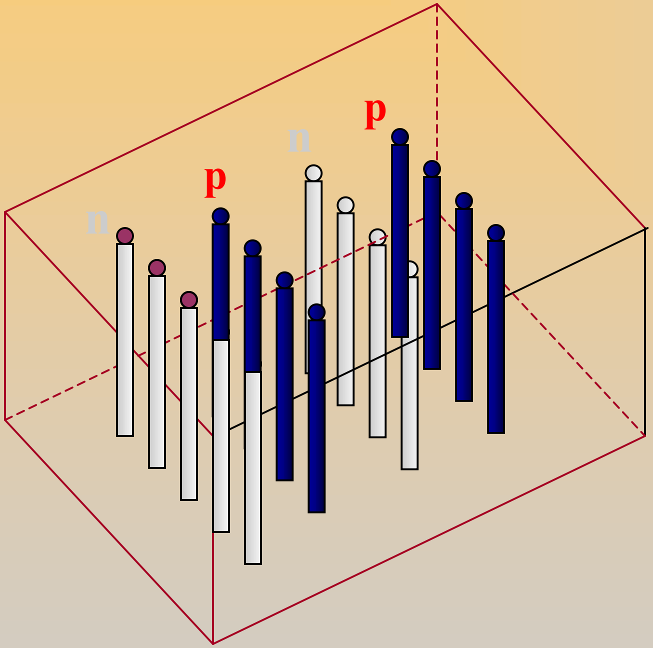




Unit cell defined by hexagonal array of electrodes

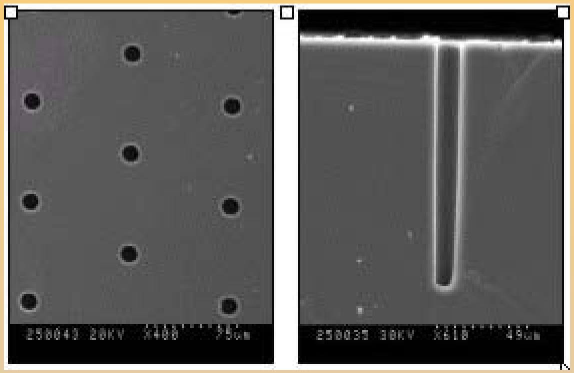
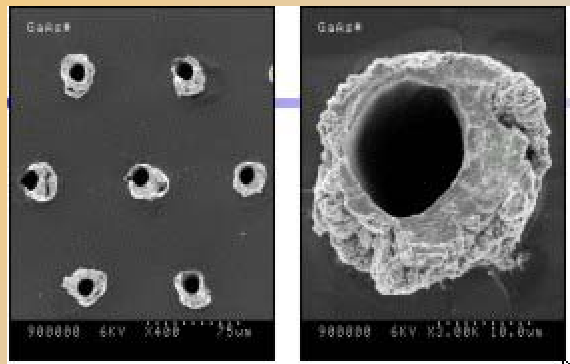
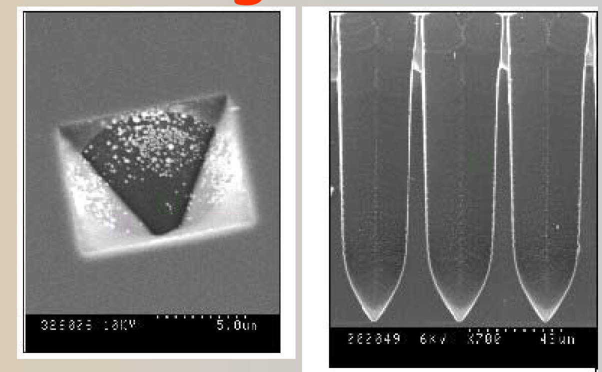
- Maximum drift and depletion distance governed by electrode spacing
  - Lower depletion voltages
  - Radiation hardness
  - Fast response
  - At the price of more complex processing
  - Narrow dead regions on edges

How do we make the holes?



(not like this)

3D detectors: Excavating the holes

Dry Etching	Laser Drilling	Electrochemical etching
		
➢Standard photolithography process	➢ Any material ➢ No photolithography	➢No sidewall damage
➢Sidewall damage ➢Si and GaAs only	➢Slow process for big arrays ➢Sidewall damage ➢Tapering ➢Repeatability	➢Si only (GaAs and SiC?) ➢Complex photolithography
1µm / min.	1 hole / 3-5sec.	0.6µm / min.
Hole depth/diameter ~ 26	Hole depth/diameter: ~ 40 (but..)	Hole depth/diameter: ~ 25

What does "CCD" stand for?

C hris

C

D amerell

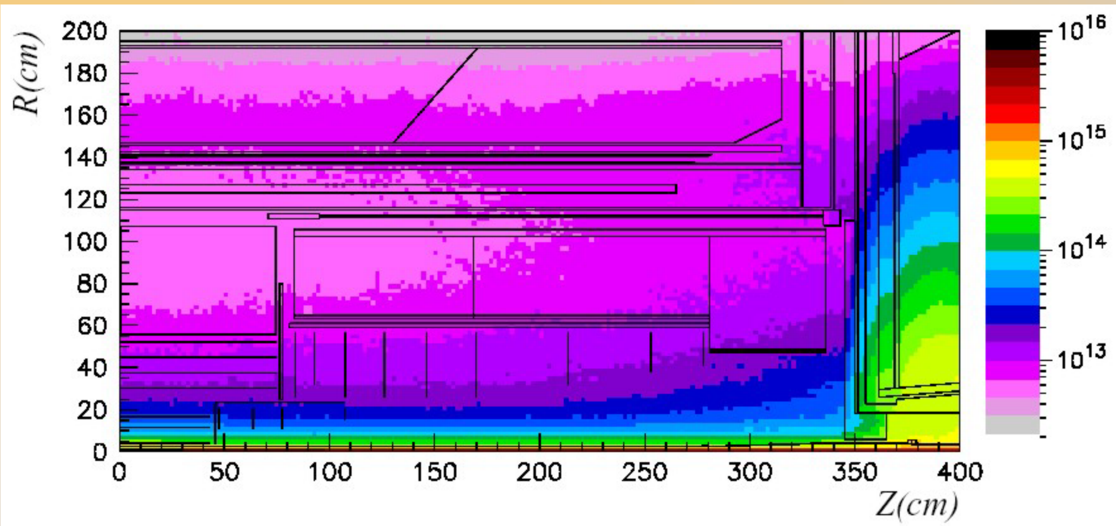
is a reasonable suggestion!

In fact, Charge Coupled Device

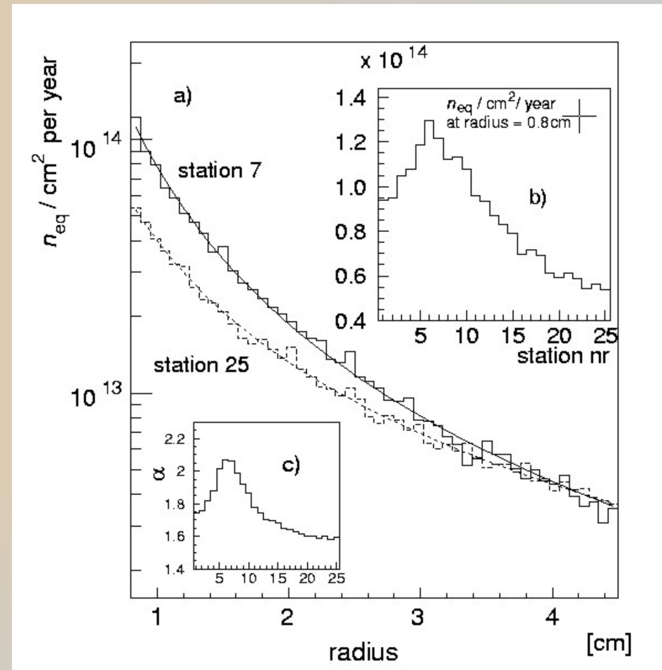
Radiation

The LHC environment will be FIERCE

- $L = 10^{34}\ cm^{-2}\ s^{-1}$
- 8×10^{8} pp collisions / second
- Hadron fluences up to $10^{15}\ cm^{-2}$



ATLAS flux (per year)



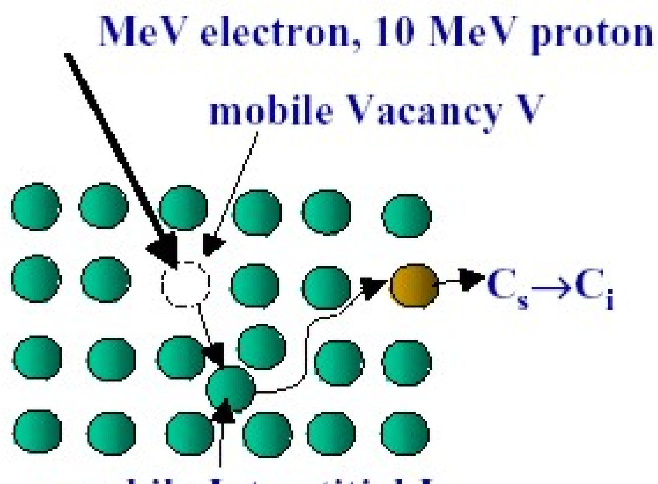
LHCb vertex detector dose

"VLHC" will be MUCH WORSE

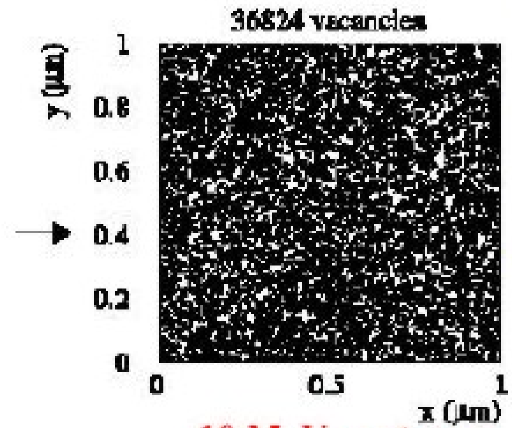
- $L = 10^{35}\ cm^{-2}\ s^{-1}$
- Hadron fluences up to $10^{16}\ cm^{-2}$

Radiation Effects (from E. Fretwurst)

Basic Damage Effects: Creation of Primary Defects



creation of point defects



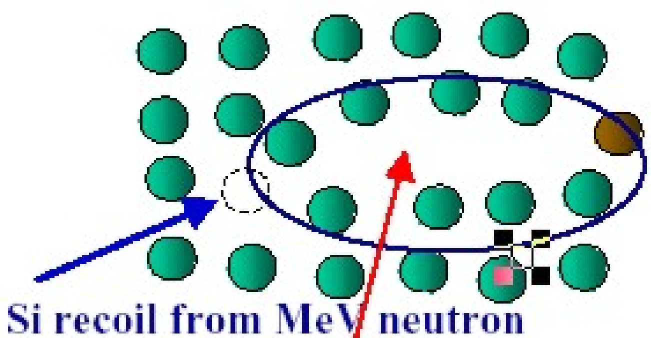
10 MeV protons

Simulation
(M. Huhtinen)

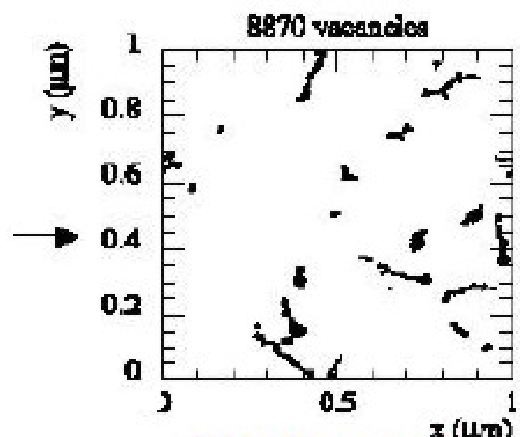
Initial distribution of vacancies in $(1\mu m)^3$ after 10^{14} particles/cm^2

Gammas
electrons
low energy protons

Point Defects



creation of disordered regions, „Cluster“



1 MeV neutrons

1 MeV Neutrons

Cluster Damage

High energy particles

Point Defects

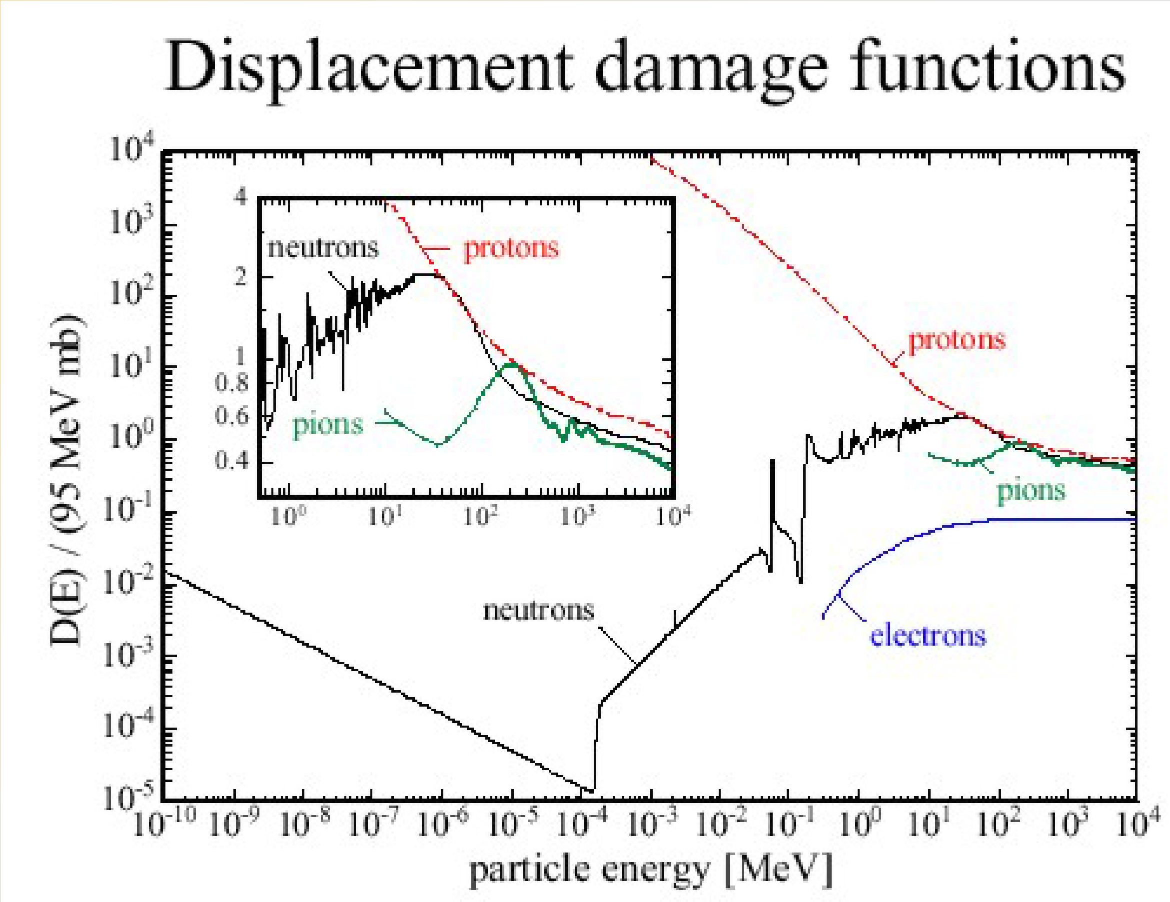
+ Cluster Damage

NIEL - Non Ionizing Energy Loss

A common language:

"1 MeV neutron equivalent"

Use the NIEL scaling factors



- NIEL allows first level comparison between different experiments/beam tests
- Has been known to fail for neutrons/charged hadrons in some cases

Radiation Induced Changes in detector properties

- Change of depletion voltage
  - Due to defect levels that are charged in the depleted region ⇒ time and temperature dependent, and very problematic!
- Increase of leakage current
  - Bulk current due to generation/recombination levels
- Damage induced trapping centers

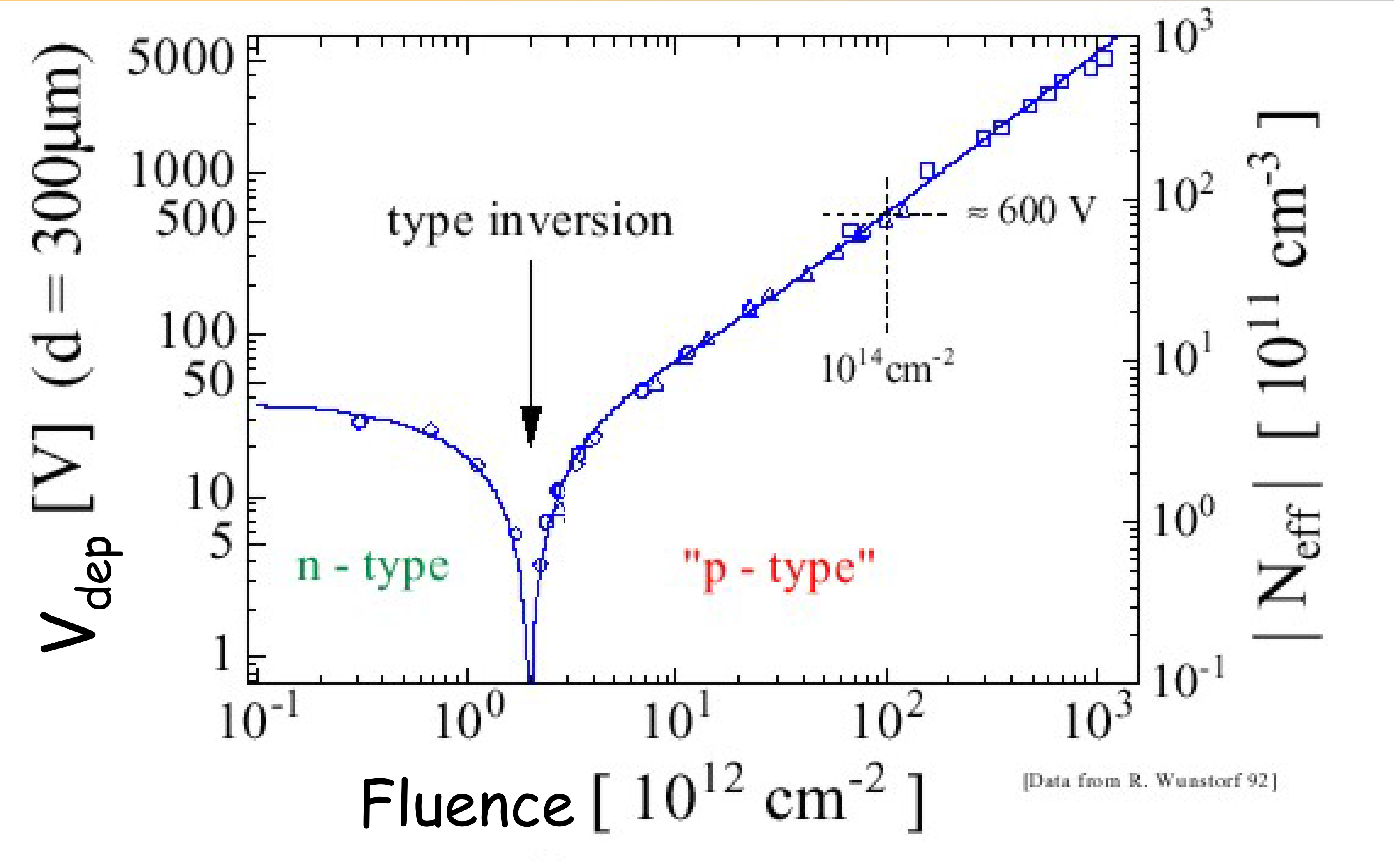
  ⇒ decrease in collected signal charge

Changes in depletion voltage

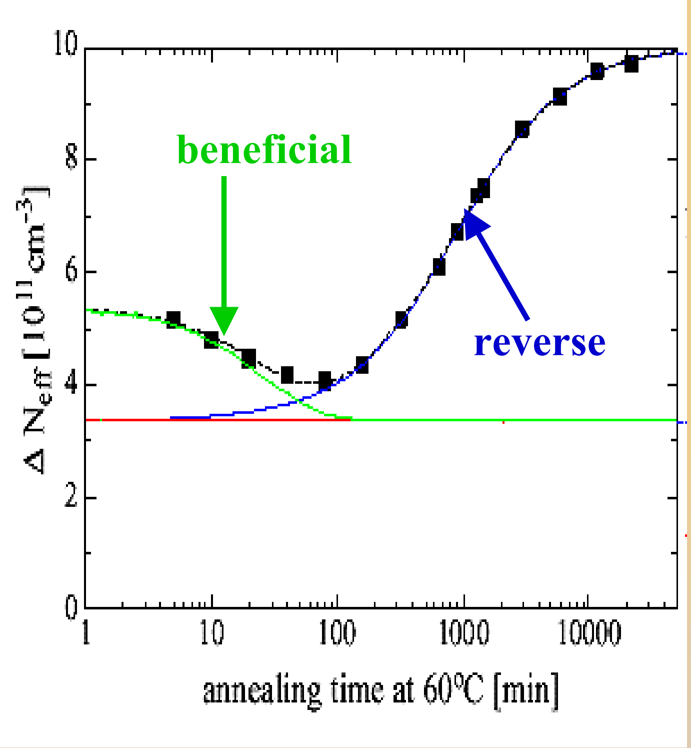
Reminder:

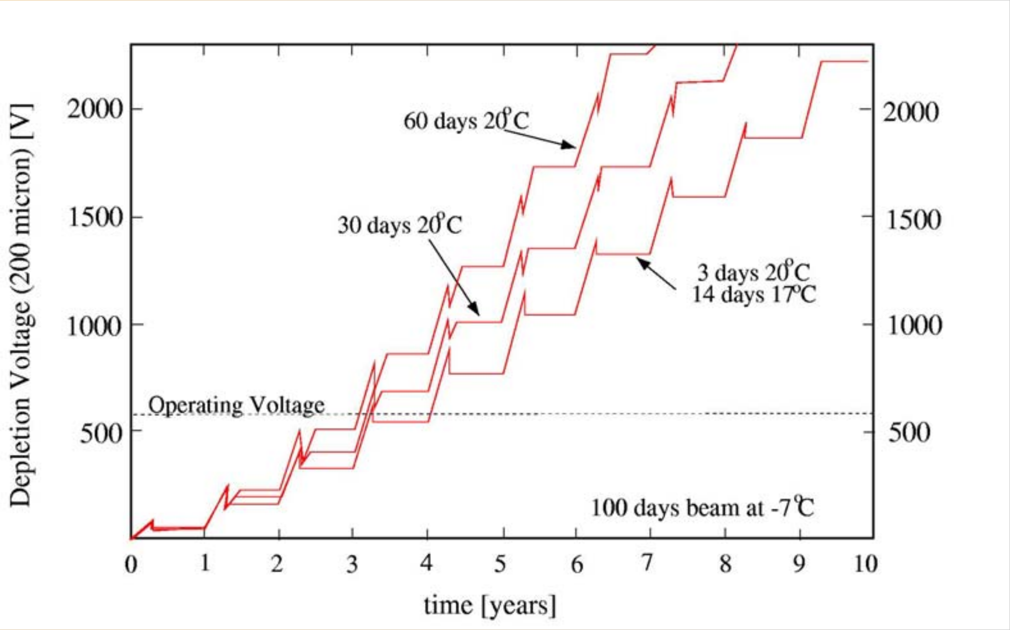
$$V_{dep} \propto |N_{eff}| \, d^2$$

N_{eff} +ve -> n type silicon (e.g. Phosphorus doped – Donor)
N_{eff} -ve -> p type silicon (e.g. Boron doped – Acceptor)



Time dependence of N_{eff} after irradiation





Just after irradiation, the damage "heals" and the depletion voltage improves. This "beneficial annealing" is temperature dependent

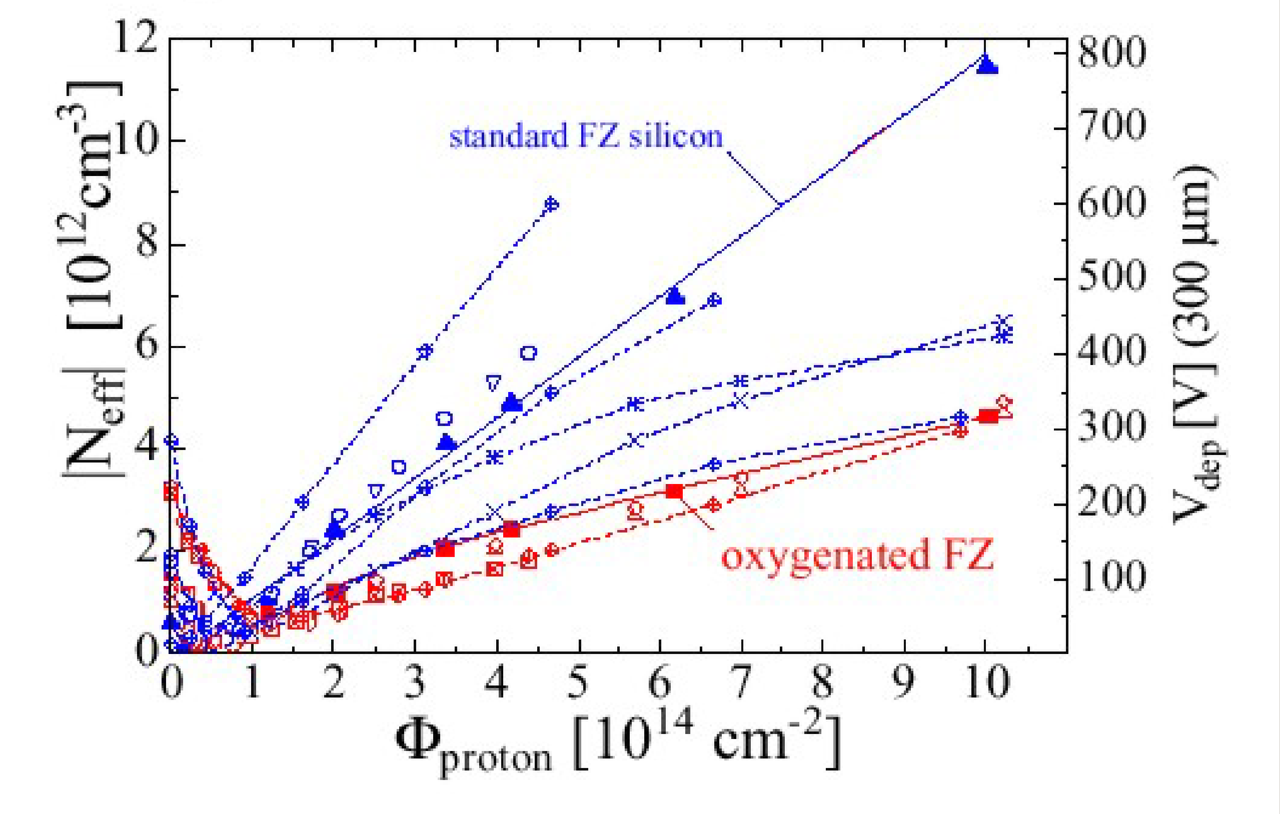
Over a longer period of time the build up of negative space charge increases again, this is known as "reverse annealing", also very temperature dependent

Annealing effects lead to the following situation for a running

silicon detector at the LHC:

- **Must keep the detector cold (-10˚C or less) most of the time to avoid reverse annealing.**
- **Can allow a short period at 20˚C after each years run for beneficial annealing.**

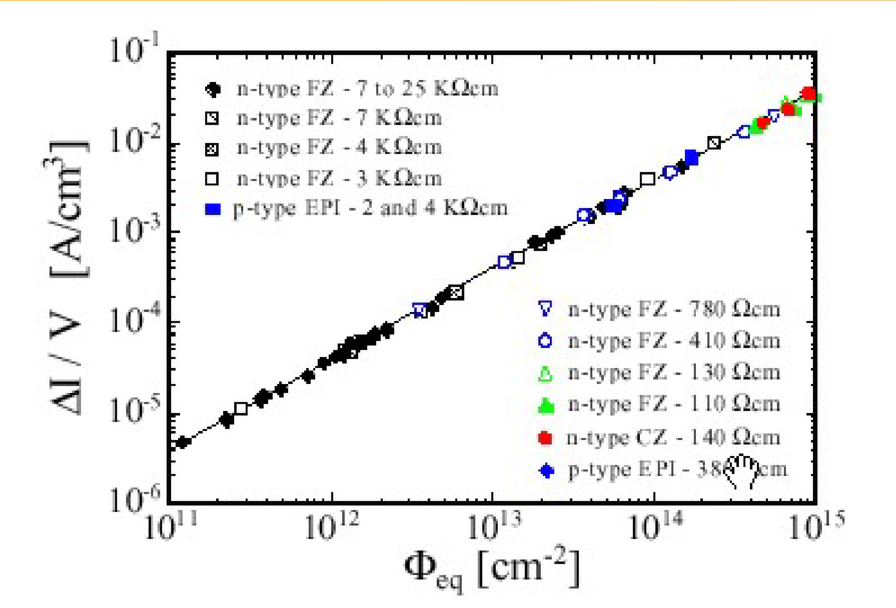
N_{eff}: a word of caution



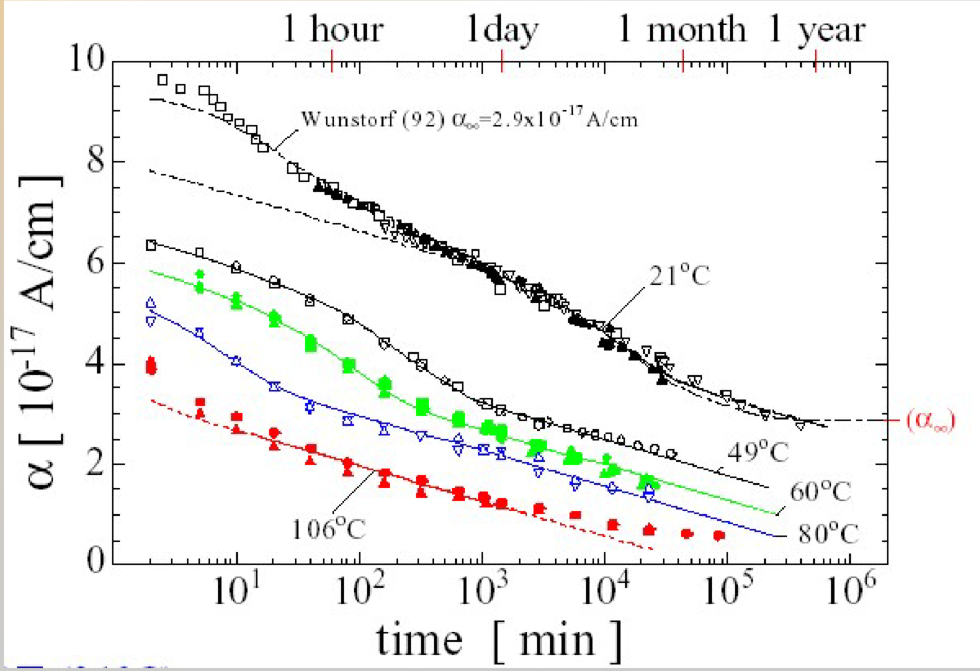
In real life, the overall principles are the same, but there can be a wide range of variation

even for standard materials

Leakage current



- Current increases linearly with fluence
- $\alpha = \Delta I/(\phi \times Vol) = 4 \times 10^{-17}$ A/cm
- Note, results are identical for inverted/not inverted, n type, p type, all the same!



- High currents are bad because
  - they introduce noise
  - they make it hard to deliver bias voltage to the detector
  - risk of thermal runaway
- current is highly temperature dependent
- Over time the current anneals

A Closer Look at Charge Collection: Mr Ramo

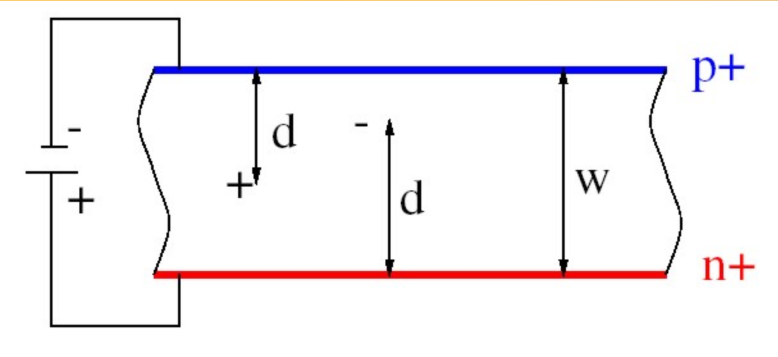
I co-invented the electron microscope

I pioneered microwave technology

I founded TRW

I had a theorem

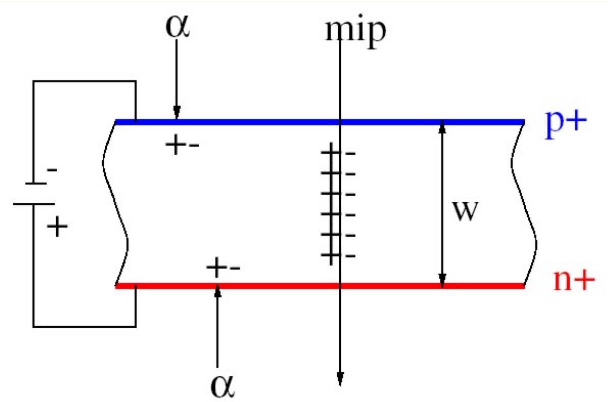
Charge Collection Efficiency I



Induced charge in two parallel electrodes given by

$$q = e\frac{d}{w}$$

- The charge only drifts in the depleted width of the silicon, so d is proportional to $\sqrt{V_{bias}}$
- The amount of charge depends on the signal, for instance for a m.i.p. $e \propto \mathbf{d} \propto \sqrt{V_{bias}}$
- w depends on the detector characteristics (see next slides)



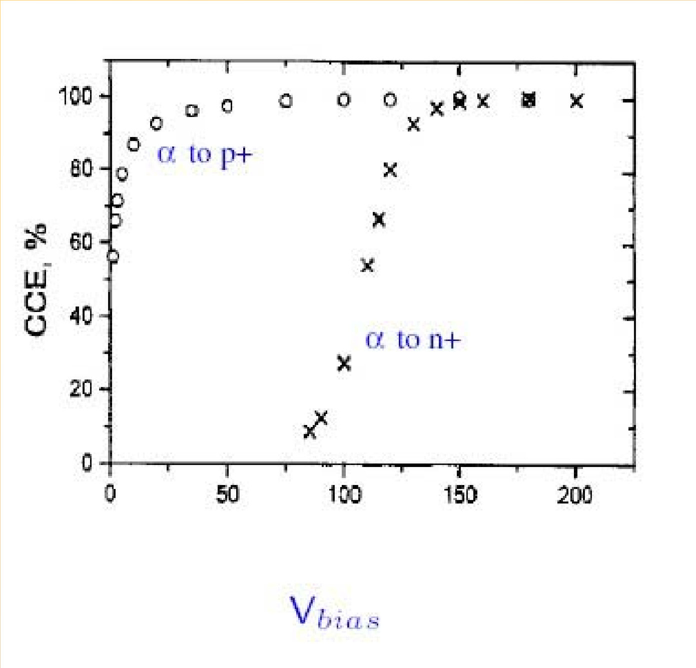
Can investigate with:

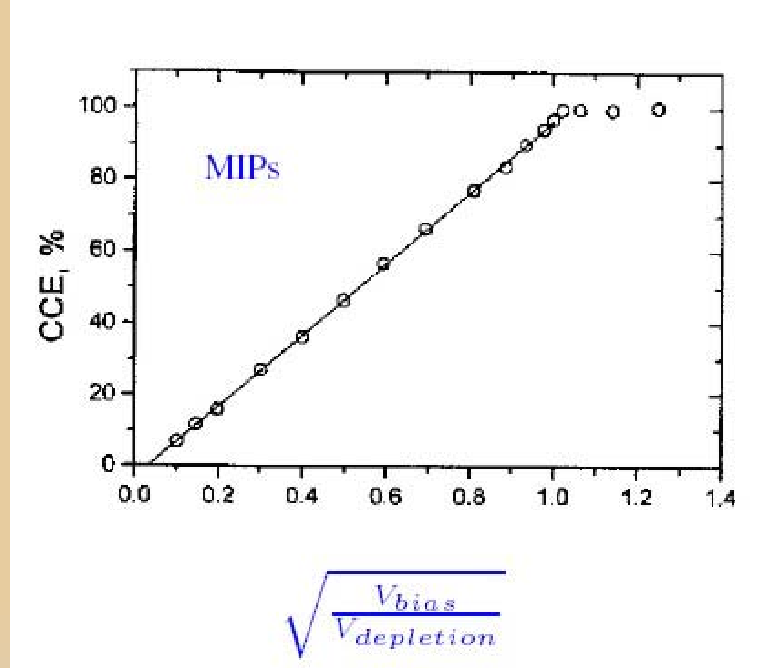
–α particles shone on p+ side (electrons move)

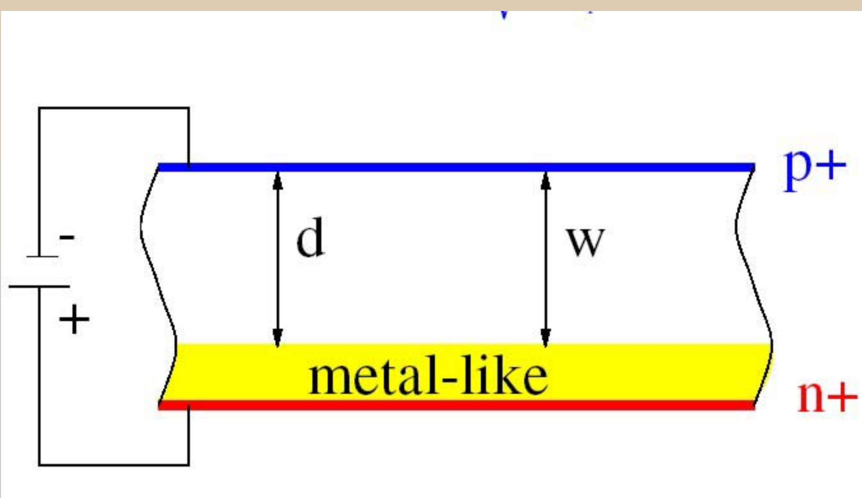
–α particles shone on n+ side (holes move)

-mips give uniform production along track

Charge Collection Efficiency: non-irradiated sensors



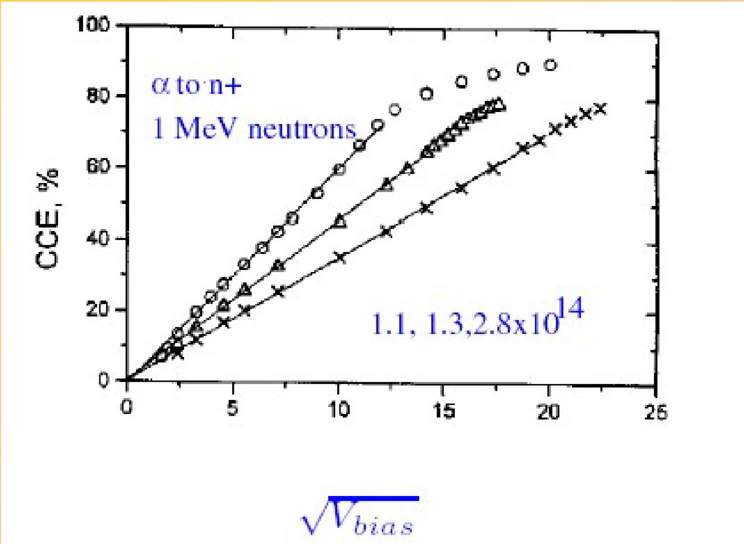


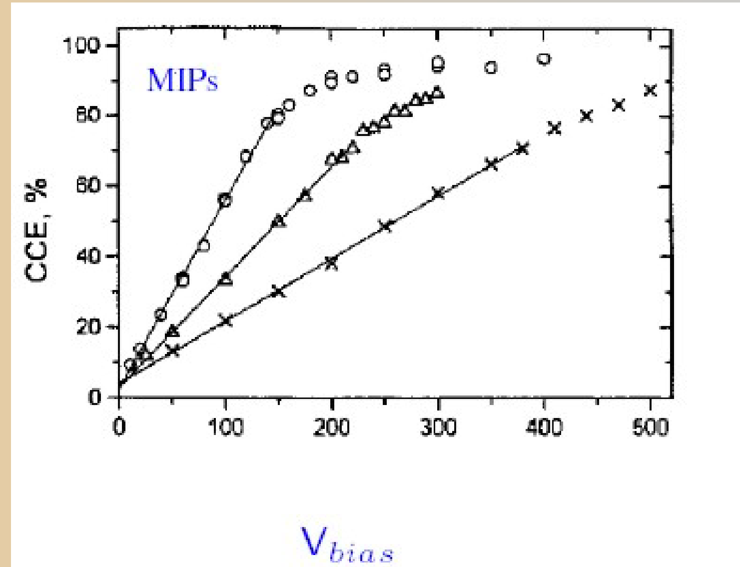


- a → n+: diode depletes around 115 V
- a → p+: 100% after a few volts, hence d/w = 1
- m.i.p. deposited ionisation ∝ d ∝ $\sqrt{V_{bias}}$

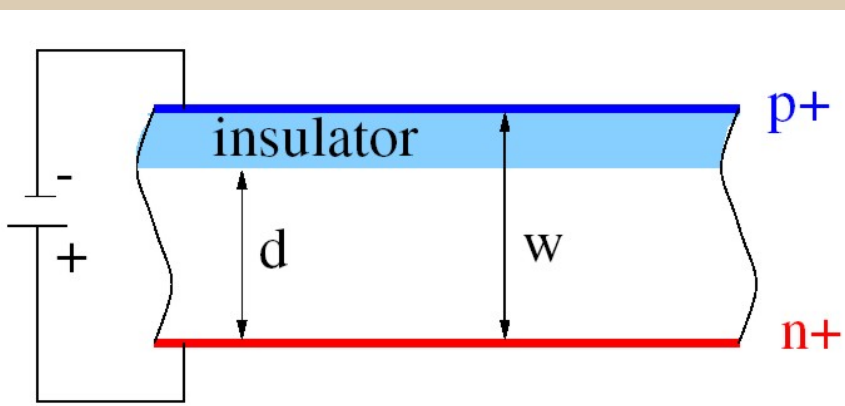
These results agree well with this picture

Charge Collection Efficiency: Irradiated Sensors



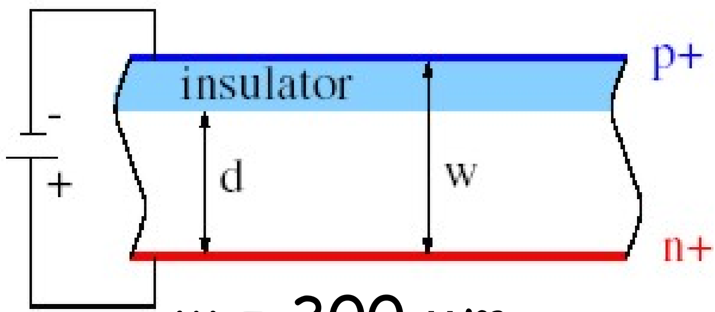


$$q = e\frac{d}{w}$$



	$\alpha \rightarrow n+$	MIP
e	constant	$\propto d \propto \sqrt{V_{bias}}$
d	$\propto \sqrt{V_{bias}}$	$\propto \sqrt{V_{bias}}$
q	$\propto \sqrt{V_{bias}}$	$\propto V_{bias}$

Charge Collection Efficiency in under-depleted detectors

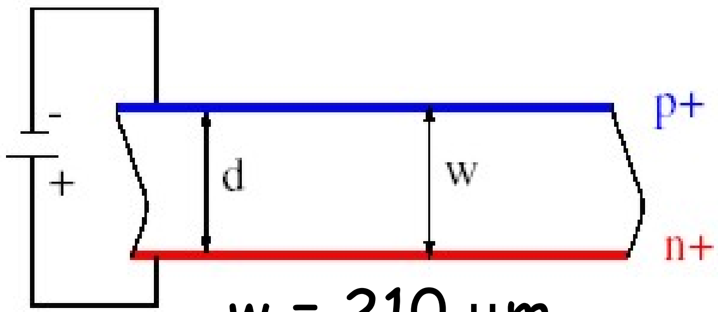


w = 300 μm

$$q = e\frac{d}{w}$$

Thinner sensors can be an advantage!

w	300μm thick	210μm thick
$V_{depletion}$	800 V	400 V
V_{bias}	400 V	400 V
d	210μm	210μm
e/h	19000	19000
Δq	13300	19000



w = 210 μm

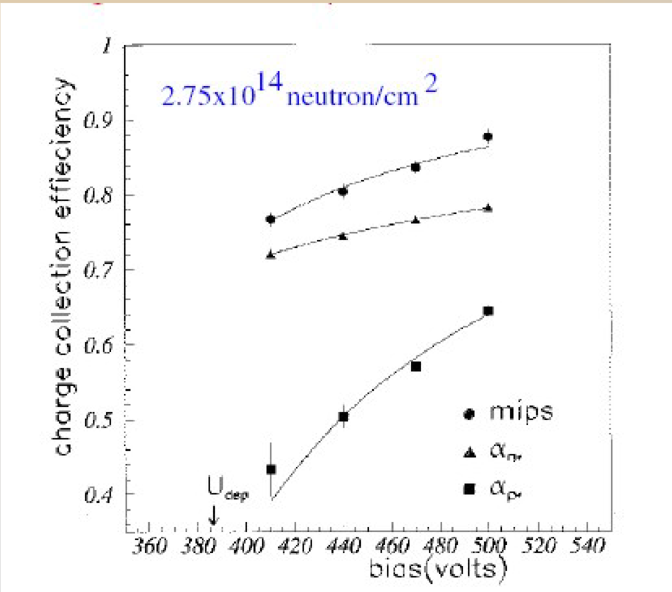
Thin sensors also have less current, less power, less risk of thermal run-away

Charge Trapping

This effect dominates above fluences of $10^{15}\ n_{eq}\ /\ cm^2$

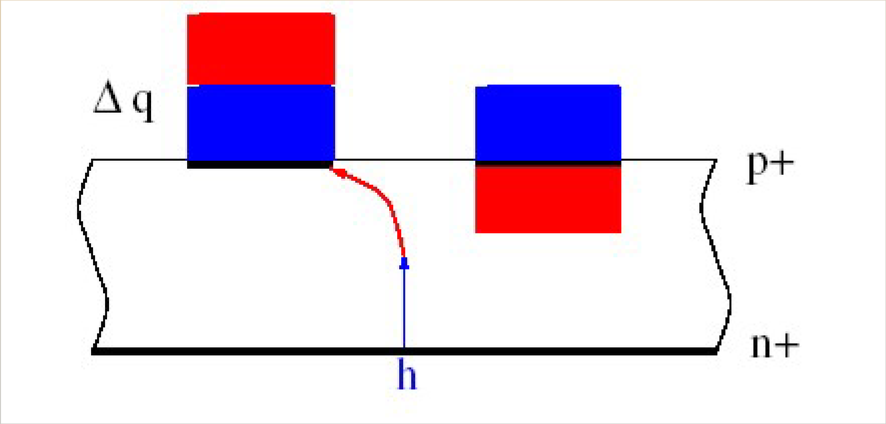
In Ramo's formula, it modifies d, the distance charge travels

- d depends on drift time vs carrier lifetime
  - collection time is d/v_{drift}
  - $v_{drift} \propto$ drift-field, roughly V_{bias}/d
  - for $V_{bias} < V_{depletion}$ collection time = d^2/V_{bias}, while $d^2 \propto V_{bias}$
  - for $V_{bias} > V_{depletion}$ collection time decreases until saturation



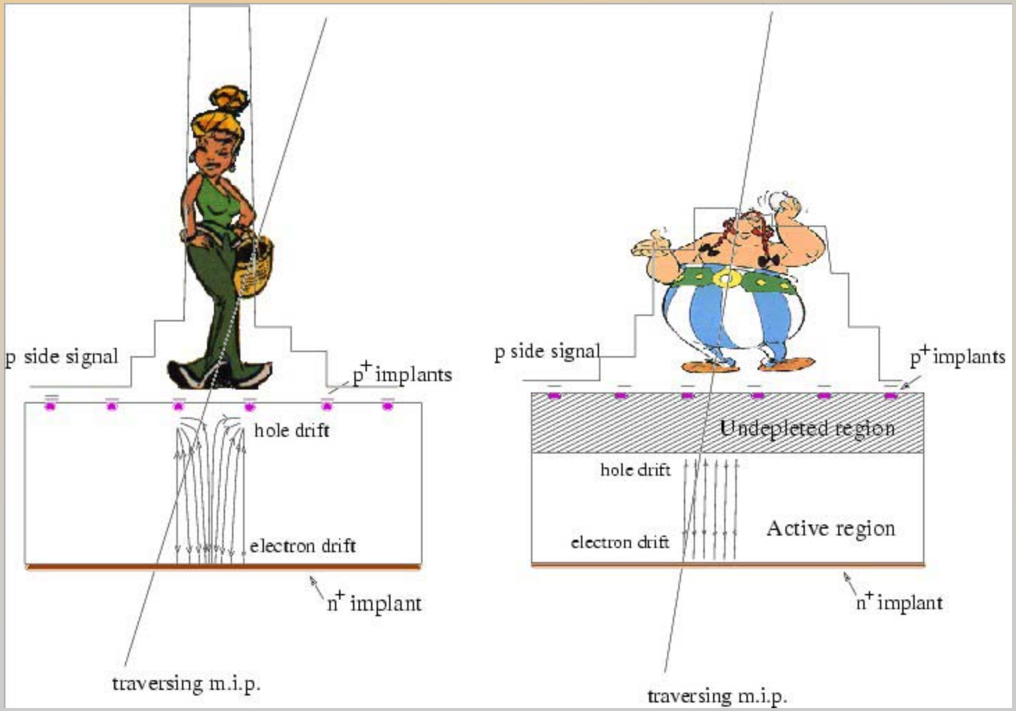
Cluster Shapes I

- So far we have considered diodes
- when we segment into strips, we have to consider each element of the charge drift
- Example, release one hole from the n+ side



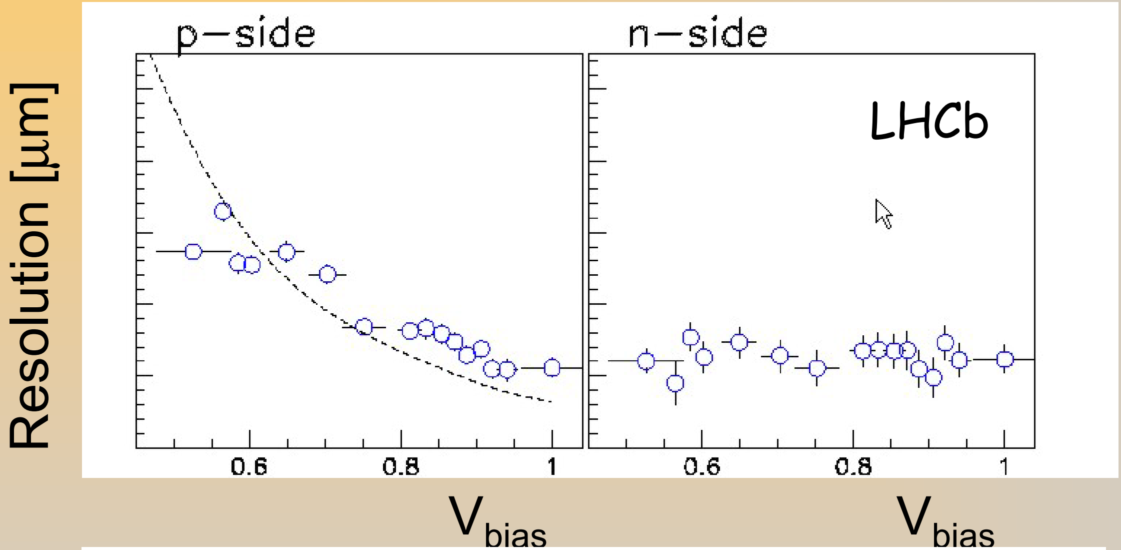
Cluster Shapes II

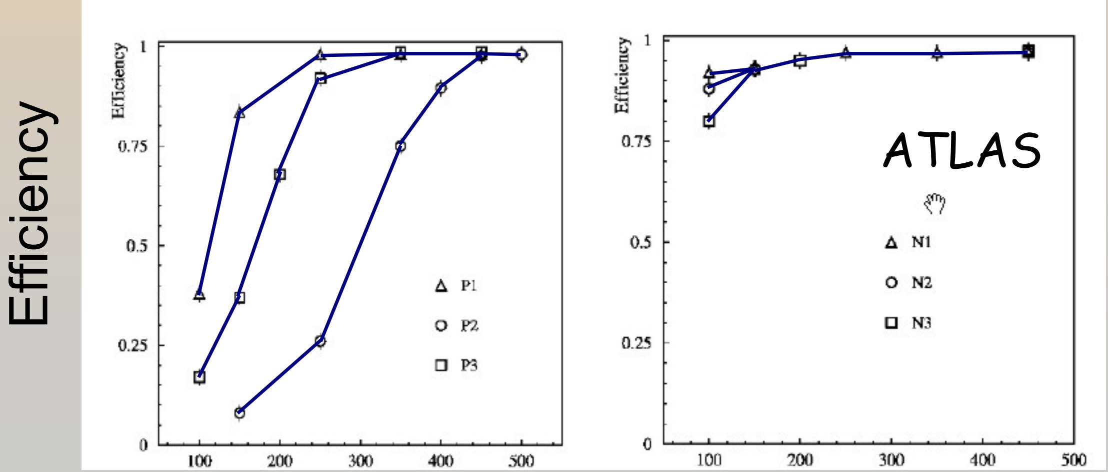
- In non-irradiated detectors charge sharing comes from diffusion
- In irradiated detectors there is extra charge sharing if the charge stops drifting due to under-depletion or to trapping. Sometimes this is not desirable!



Cluster Shapes III

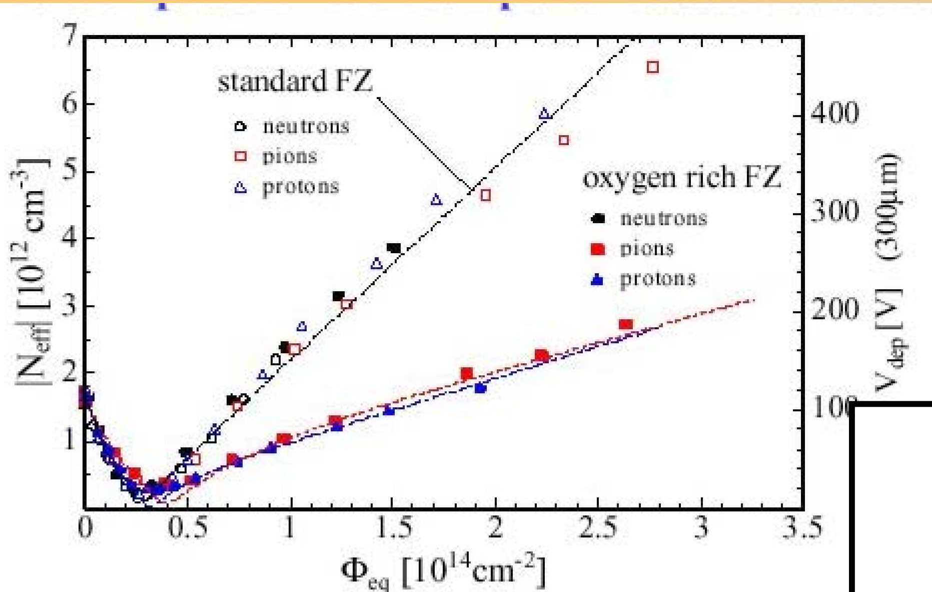
- The charge spreading can have two bad effects:
  - loss of resolution
  - loss of efficiency because the S/N of individual strips is smaller





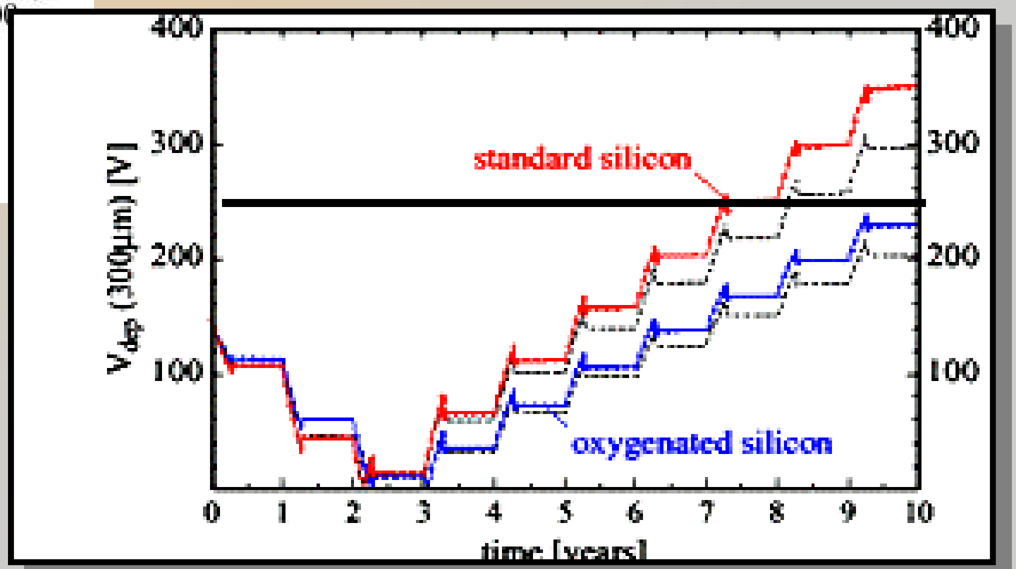
Exotic solutions

A lot of work has gone into studying the microscopic mechanisms which lie behind radiation damage. A recent breakthrough has been oxygenated silicon



Oxygenated silicon shows an improvement in depletion voltage behaviour

Which can increase the lifetime of LHC experiments



What about the structures we considered so far?

Strip detectors should be made thin and n-on-n for the ultimate radiation hard performance, if you care about resolution. The leakage current and bias voltage rise can eventually kill you

- HAPS Pixel sensors:
  - small leakage currents ☺
- CCD sensors
  - many charge transfers – susceptible to trapping ☹
  - not high rate capability ☹
- MAPS
  - in principle as radiation hard as pixels ☺
- 3d detectors
  - small leakage currents ☺
  - very small depletion distances ☺
  - very small drift distances ☺

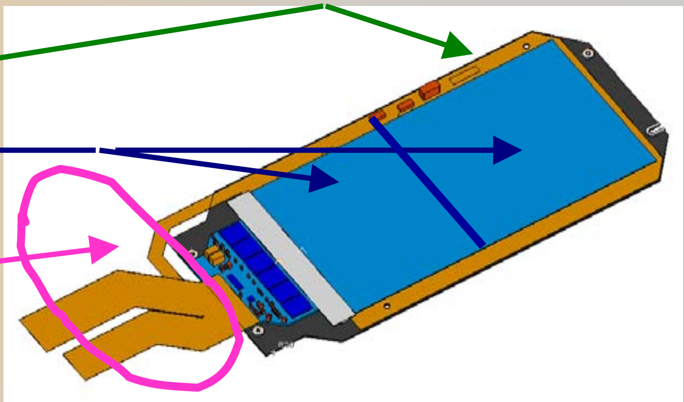
Build your own silicon detector I

We consider here the "module", the basic building block of a silicon tracking detector.

Module concept

– Modular design: try to make identical sub-units. Units consist of:

- mechanical support structure
- sensors
- front-end electronics and signal routing (connectivity)



- Constraints
  - Low mass (multiple scattering)
  - Rigid, strong
  - Low coefficient of thermal expansion (CTE)
  - Good thermal conduction
  - Restricted space
  - Low cost (!)
  - Radiation hard
  - Works at low temperatures

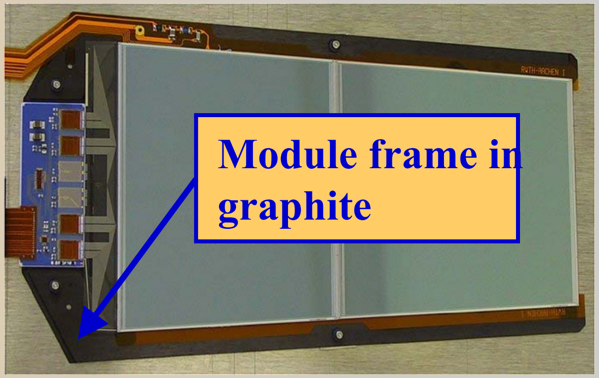
source: Alan Honma

Build your own silicon detector II

- Mechanical support structure (frame)

  Exotic materials often needed to meet the conflicting requirements:

  - Carbon-fibre, graphite composite materials: low mass, high strength, high thermal conductivity, low CTE, often used in aircraft industry (cost factor).
    - Hexcel, foams used for rigidity



- For applications where the support infrastructure is in the active detection volume (all collider experiments and some fixed target) $\Rightarrow$ minimize material. Use low Z metals (beryllium, aluminium) for beam pipe, support fixtures, thermal contacts and cooling system when possible.
- Components are usually glued together.
- Difficulties come from need for radiation hardness, for operation at large temperature extremes and for efficient cooling of electronics.

source: Alan Honma

Build your own silicon detector III

- Sensor design choices

  Sensor design must first follow physics requirements, still many choices:

  - Geometrical shape
  - Thickness
  - Read-out and implant pitch
  - p or n bulk silicon, resistivity
  - Double-sided or single-sided
  - Type of biasing structure
  - AC or DC coupling
  - Double-metal read-out?

In many cases there are conflicting design trade-offs between these choices. One finds that economics (limited project budget) often forces decision direction. Examples of trade-offs:

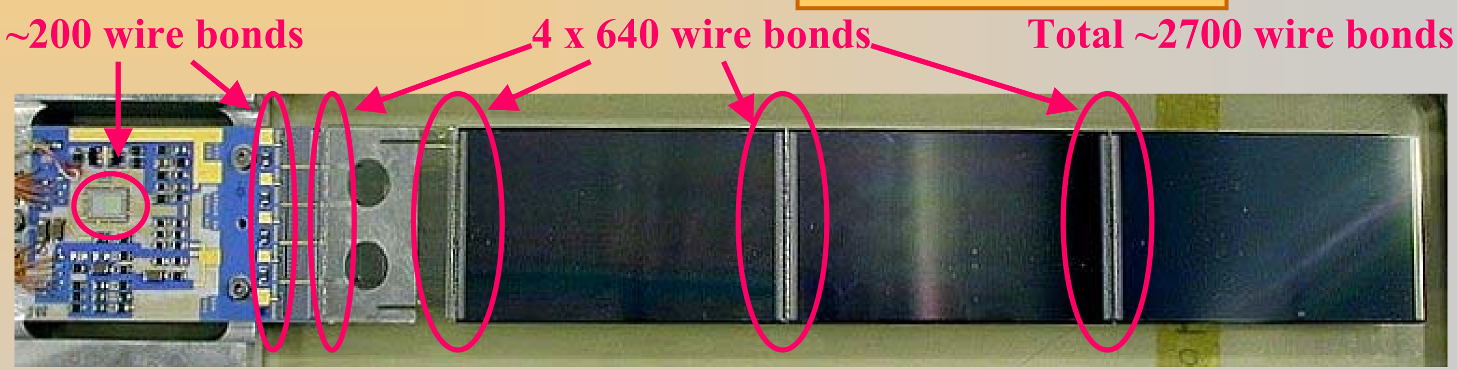
Choice	Pro	Con
Double-sided sensor	Less material for two read-out coordinates	Processing cost about 3x that for single-sided
500µm thickness	More signal	Higher bias voltage required, more material

source: Alan Honma

Build your own silicon detector IV

- Front-end electronics and connectivity (1)
  - Often several sensors have their strips connected together in series (saves on electronics channels, OK when occupancy is low) to make multi-sensor modules. These connections are done by wire bonding.

OPAL (LEP) module



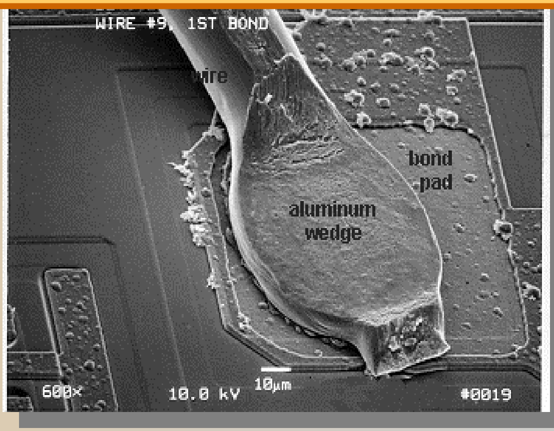
  - Wire bonding: the standard method for connecting sensors to each other and to the front-end chips. Usually employed for all connections of the front-end chips and bare die ASICs. A “mature” technology (has been around for about 40 years).
  - Soldering, High Density Interconnects, tab bonding etc. all extra possibilities

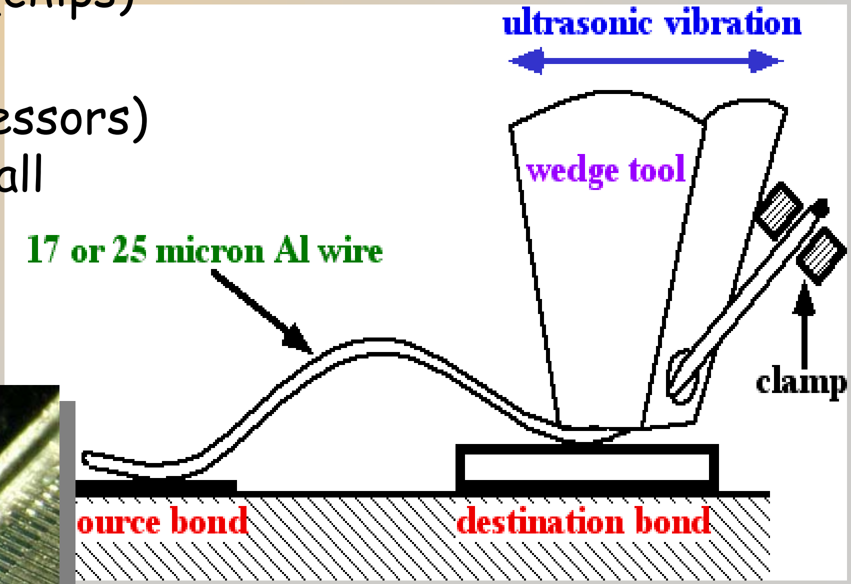
source: Alan Honma

Build your own silicon detector V

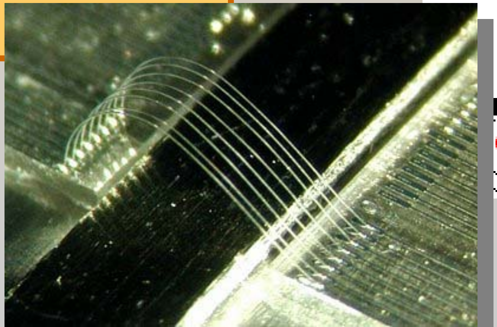
- Wire bonding (cont)
  - Uses ultrasonic power to vibrate needle-like tool on top of wire. Friction welds wire to metallized substrate underneath.
  - Can easily handle 80μm pitch in a single row and 40μm in two staggered rows (typical FE chip input pitch is 44μm).
  - Generally use 25μm diameter aluminium wire and bond to aluminium pads (chips) or gold pads (hybrid substrates).
  - Heavily used in industry (PC processors) but not with such thin wire or small pitch.

Electron micrograph of bond "foot"





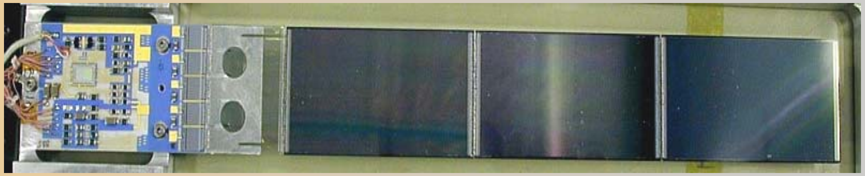
View through microscope of wire bonds connecting sensor to fan-out circuit

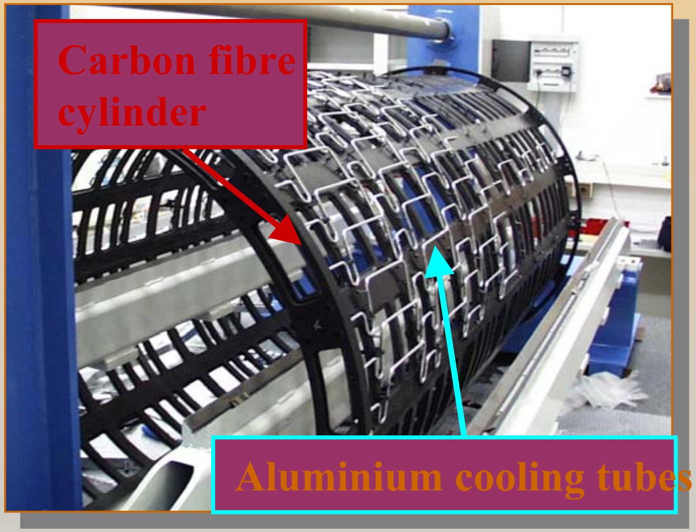


source: Alan Honma

Construction of detector modules (7)

- Assembly of modules into a detector
  - Modules are mounted onto a low-mass structure. Good thermal contact with cooling system required. Finally, cabling of services.





CMS prototype structure

ALEPH 1998

source: Alan Honma

Build your own silicon detector VI

- Other "downstream" data acquisition electronics
  - Data transmission (optical or electrical $\Rightarrow$ grounding, material budget issues)
  - ADC conversion (if not already done)
  - Multiplexing, triggering, buffering, ...

  These electronics are often similar or identical to those for other detector systems in an experiment.
- Other vital electronic systems needed for silicon detector
  - Control system
  - Monitoring system
  - Power supply system
  - Radiation protection system (sometimes must be very fast: $<1\mu s$)
  - Safety system (interacting with all the above): usually considered part of "slow controls", this system must have a very fast reaction time. Example: fast reaction to cooling failure in LHC (thermal runaway).

source: Alan Honma

top ten references (and references therin)

- VERTEX DETECTORS: The state of the art and future prospects: CJS Damerell
- Silicon Pixel and CCD Tracking Detectors: CJS Damerell, SNOWMASS 2001
- Silicon Detectors for Particle Physics: Pablo Hopman, 1997 IEE NSS Short Course on Detectors for High Energy Physics
- Semiconductor Pixel Detectors: K.M.Smith
- Applications of Silicon Detectors: Hartmut F.-W. Sadrozinski
- Silicon Detectors: Alan Honma, NATO Advanced Study Institute on Techniques and Concepts of High Energy Physics
- Study of Radiation Damage in Silicon Detectors for High Luminosity Experiments at the LHC: Doctoral Thesis, Dejan Zontar
- Radiation Damage in Silicon Detectors: Michael Moll, CERN EP-TA1-SD Seminar 14 Feb 2001
- Overview of Silicon Detectors: Hans Dijkstra, VCI 2001
- Radiation Damage and Defect Engineering in Silicon: E. Fretwurst, Seminar Bonn July 03

Summary I

* silicon detectors based on the simple principle of the p-n junction; now a "mature" technology
* Thanks to microelectronics industry widespread use and drop in price
* Taking over from wire chambers for high background environments
* Many fun design options possible
* Pixels; hybrids, CCDs, MAPs, etc. give great advantages, use when possible/suitable

HAVE FUN IN THE LAB!

Summary II

Summary III

Thank you very much to the organisers of the school for the invitation to this beautiful place

I wish you all the best for the development of football in this country!

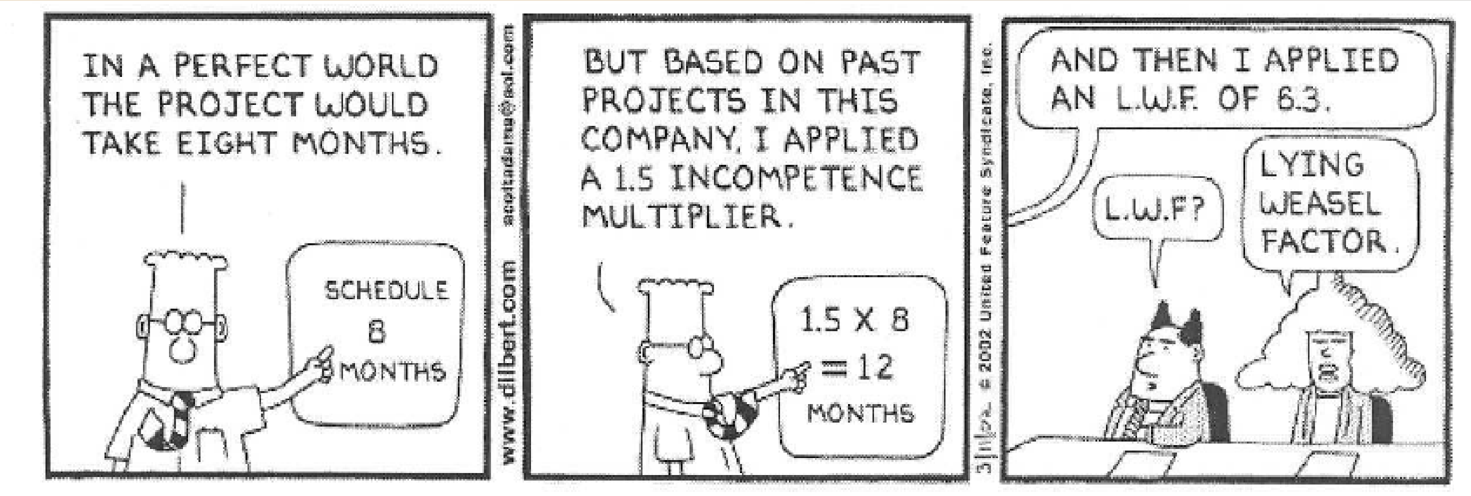
FROM NOW ON BACKUP SLIDES

Construction: Tales of the unexpected

Range from the glamarous

- resonating wire bonds
- Endoscopic operations on cooling tubes
- super long kapton problems
- Chemically active packing materials

Through to the less glamarous



(Vendors lie)

Cautionary tales I

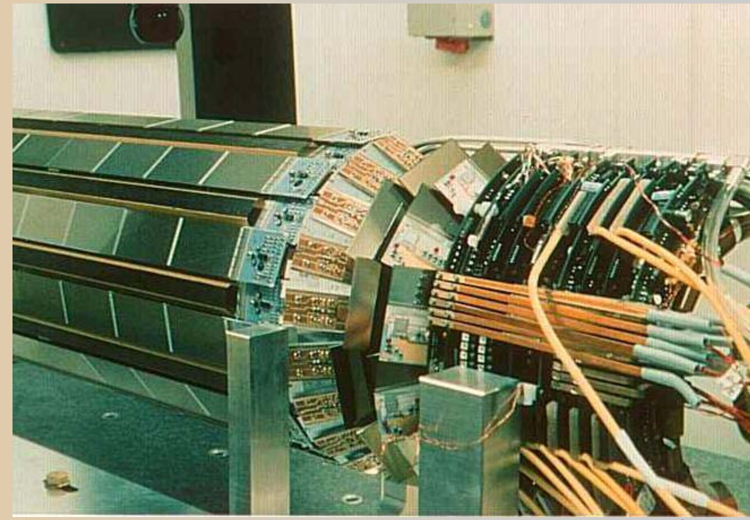
DELPHI "sticky plastic saga"

Received sensors from vendor, tested and distributed to assembly labs. All = OK

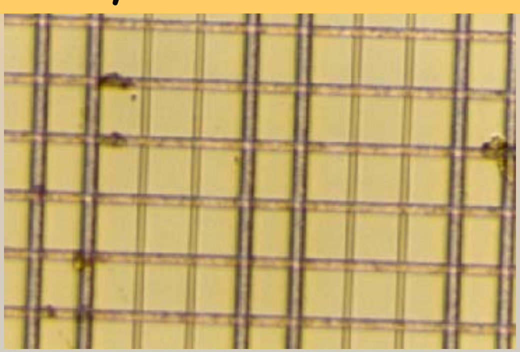
Assembly labs got worse results – confirmed at CERN

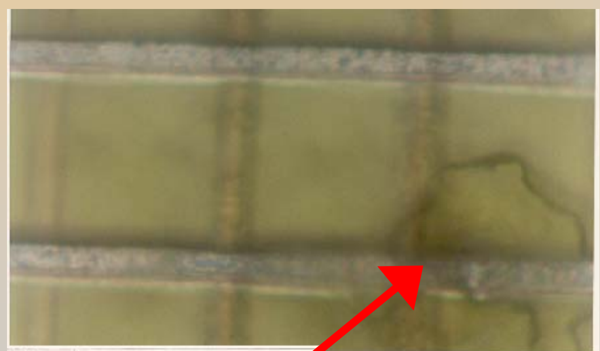
US TO VENDOR: YOUR SENSORS AGE!

VENDOR: YOU ARE RUINING THEM!



Finally found "flakes"





Zoom on flake thru packing

Zoom on packing

A story repeated with variations elsewhere

Vendor had changed anti static packing plastic – 60 sensors affected, big delay

Cautionary tales II

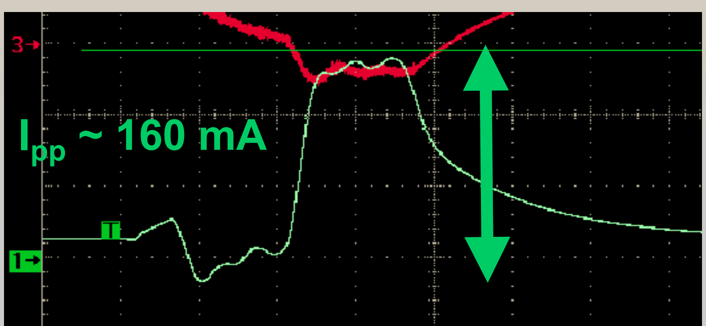
CDF "resonating bond saga"

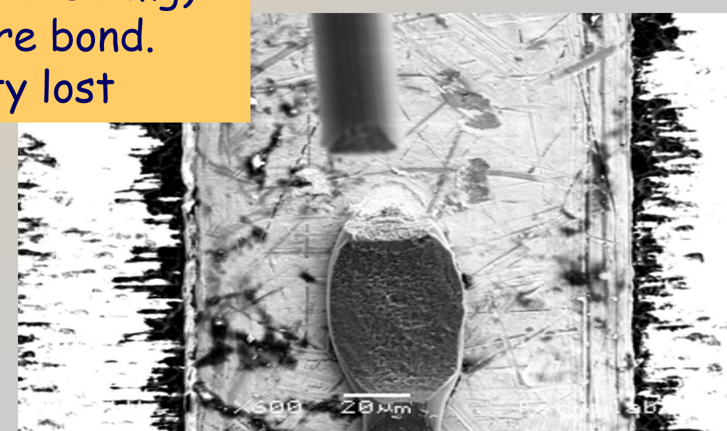
Jumper bond wires route signal from Rϕ to Rz side of module

Under a very particular set of conditions:

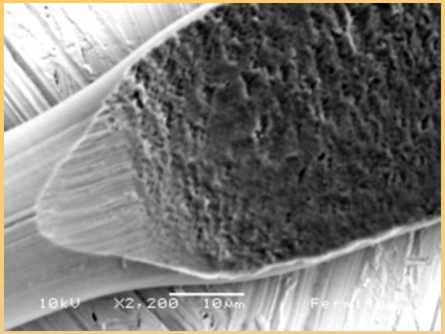
- L2 "torture test" or SVT trigger
- Bonds orthogonal to 1.4T field
- Large current swing (100 mA – only on one bond)

If pulsed at the right frequency the tiny Lorentz force (10-50 mg) can excite resonances which fatigue the heel of the wire bond. Eventually cracks are induced and electrical continuity lost

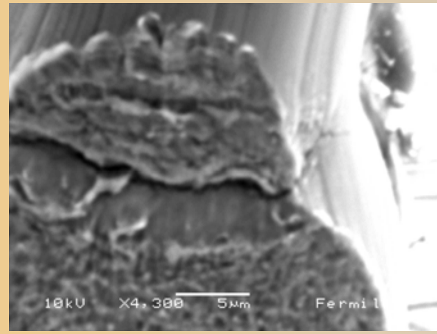




What happens at the heel



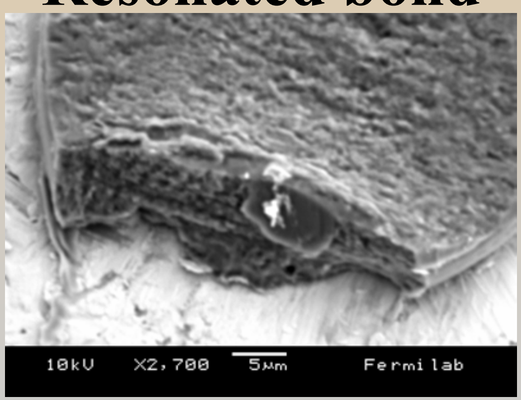
QuickTime™ and a decompressor are needed to see this picture.



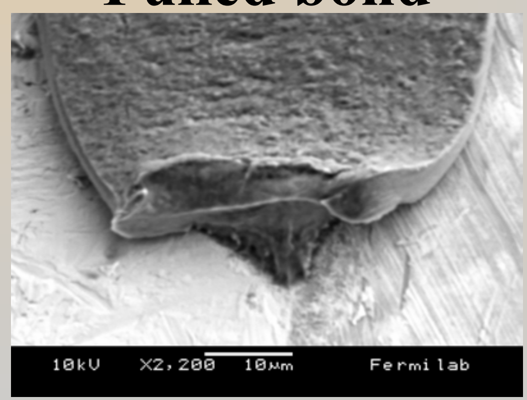
QuickTime™ and a decompressor are needed to see this picture.

Wire-bonds break due to fatigue stress on their heel induced by resonant vibration. These resonant vibrations are a direct consequence of the oscillating Lorentz forces induced by the magnetic field on wire-bonds with non-DC current.

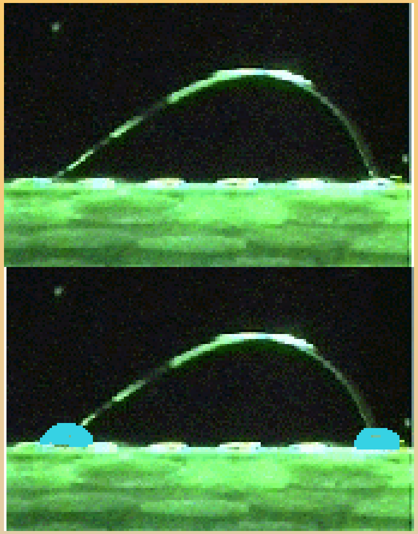
Resonated bond



Pulled bond



Possible solution (obvious)



Small drops of encapsulant

(Sylgard 186 Silicone Elastomer from Dowcorning)

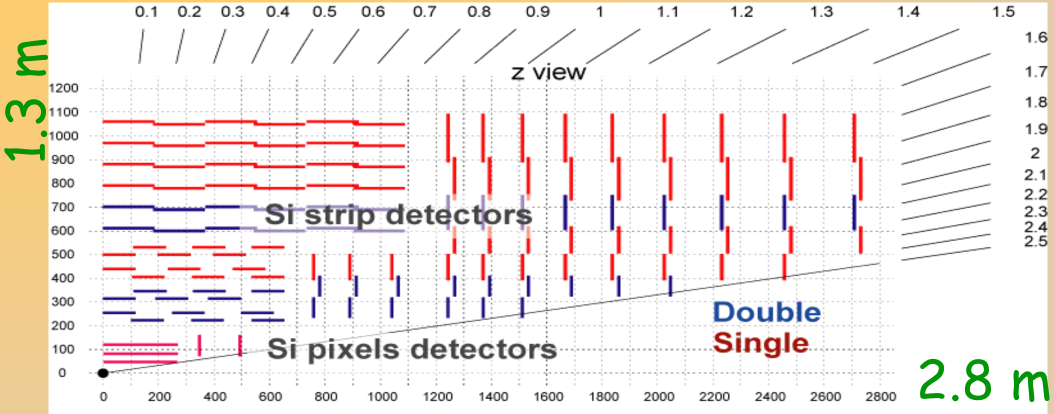
limit the oscillation amplitude by more than a factor of 30 by covering just the first

50-100 μm of the wire.

We were not able to break these wire-bonds!

- **The small amount of encapsulant was placed by hand**
  - **By placing the encapsulant only at the foot the problematic associated with not perfectly matched CTEs should be minimized**
- **No effort on our side toward any large scale technique**

Cautionary Tales III



CMS are confronting the enormous challenge of tracker construction with a sophisticated QA scheme

Type	IB1	IB2	W1	W1'	W2	W3	W4	W5A	W5B	W6A	W6B	W7A	W7B	OB1	OB
thickness	320	320	320	320	320	320	320	500	500	500	500	500	500	500	500
Number	1536	1188	288	288	864	880	1008	1440	1440	1008	1008	1440	1440	3360	705

15 different designs

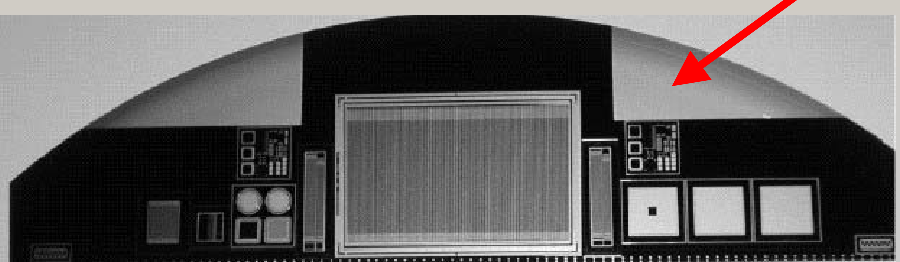
24244 different sensors!

To be completed within 2 years!

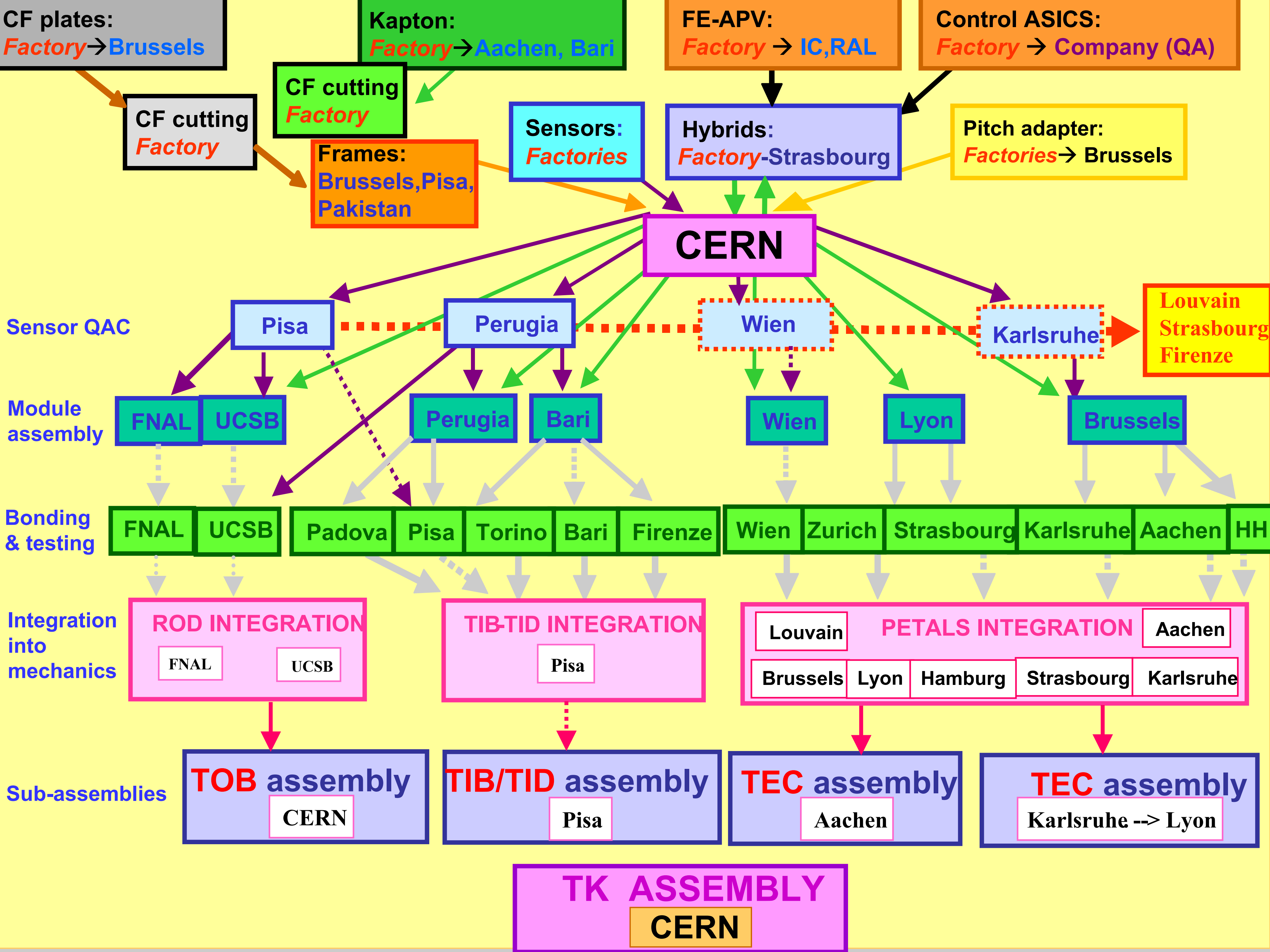
Full testing on pre-series (5% of sensors): IV, CV, strips, optical, irrad

Irradiation of 5% of test structures and 1% of strips

CMS process control on test structures: (12 measurements)



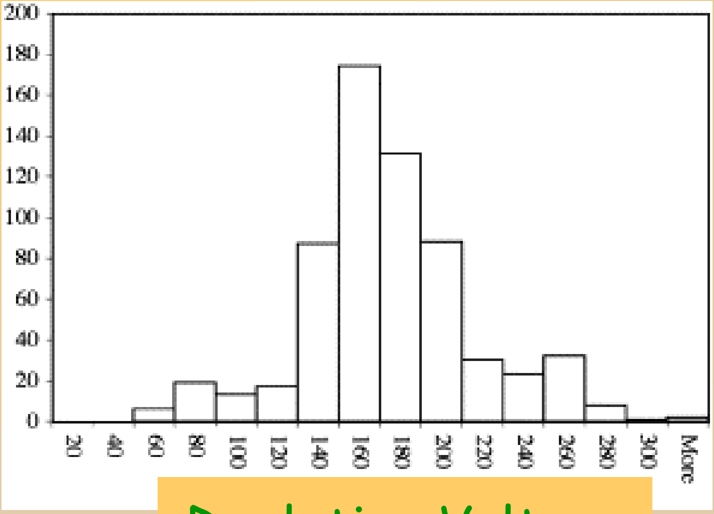
Scheme has weeded out many problems at an early stage and gives confidence in sensor performance



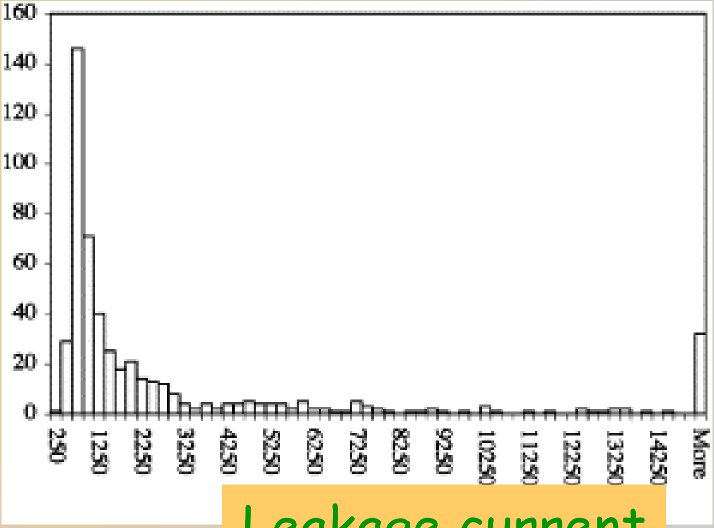
CF plates: Factory→Brussels
Kapton: Factory→Aachen, Bari
FE-APV: Factory → IC,RAL
Control ASICS: Factory → Company (QA)
CF cutting Factory
CF cutting Factory
Frames: Brussels,Pisa, Pakistan
Sensors: Factories
Hybrids: Factory-Strasbourg
Pitch adapter: Factories→ Brussels
CERN
Sensor QAC
Pisa
Perugia
Wien
Karlsruhe
Louvain Strasbourg Firenze
Module assembly
FNAL
UCSB
Perugia
Bari
Wien
Lyon
Brussels
Bonding & testing
FNAL
UCSB
Padova
Pisa
Torino
Bari
Firenze
Wien
Zurich
Strasbourg
Karlsruhe
Aachen
HH
Integration into mechanics
ROD INTEGRATION
FNAL
UCSB
TIB-TID INTEGRATION
Pisa
PETALS INTEGRATION
Louvain
Aachen
Brussels
Lyon
Hamburg
Strasbourg
Karlsruhe
Sub-assemblies
TOB assembly
CERN
TIB/TID assembly
Pisa
TEC assembly
Aachen
TEC assembly
Karlsruhe --> Lyon
TK ASSEMBLY
CERN

Cautionary Tales III

Sample measurements:



Depletion Voltage



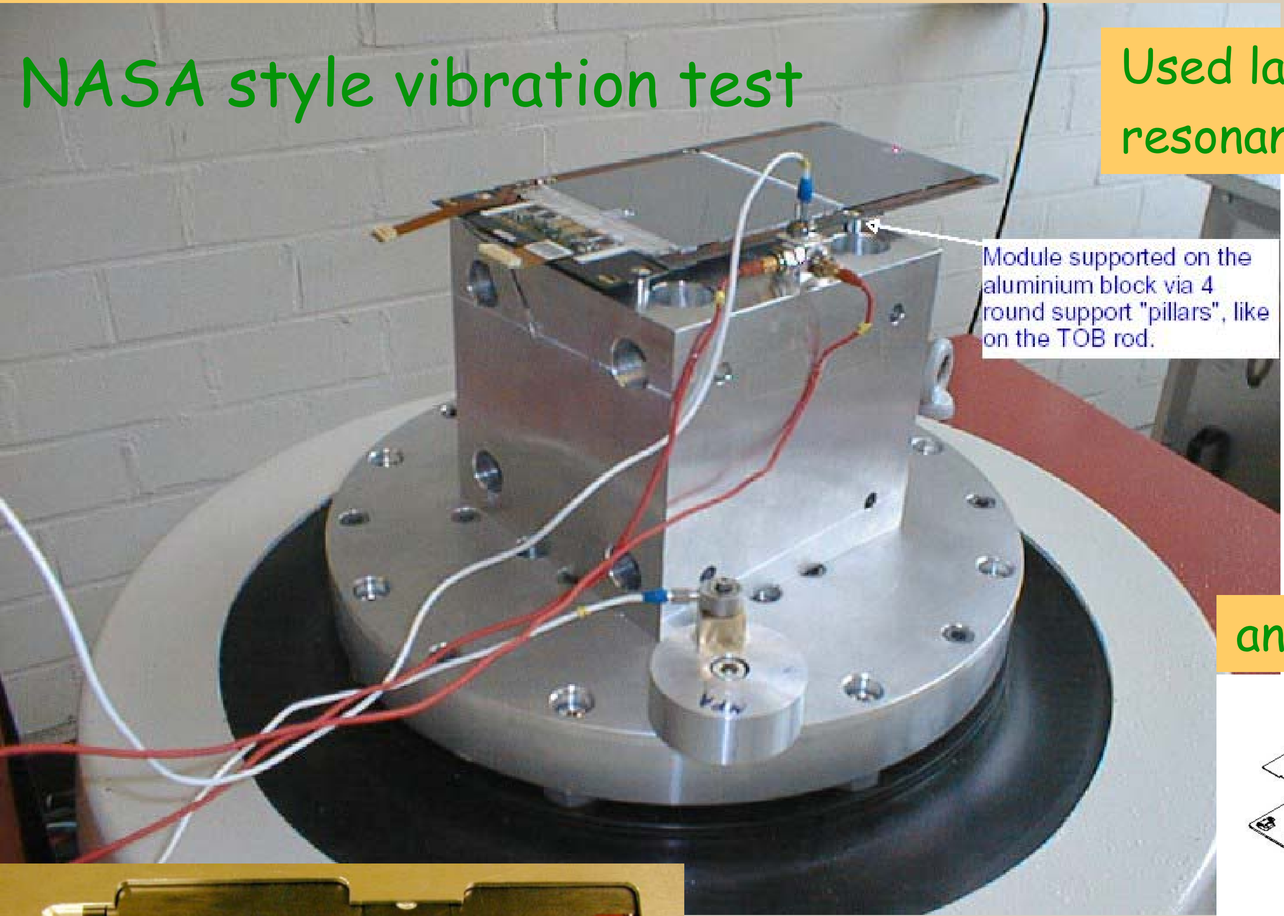
Leakage current

Note however that even CMS are not totally immune to the occassional broken bond! Commercial transportation of some modules caused 20% of bonds to break (these modules were fixed in ~1 day)

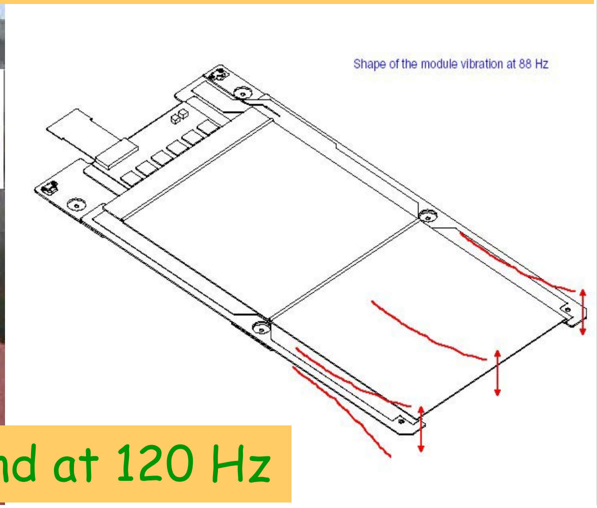
Vibration tests show that transportation can give > 3.4 g force

Cautionary Tales III

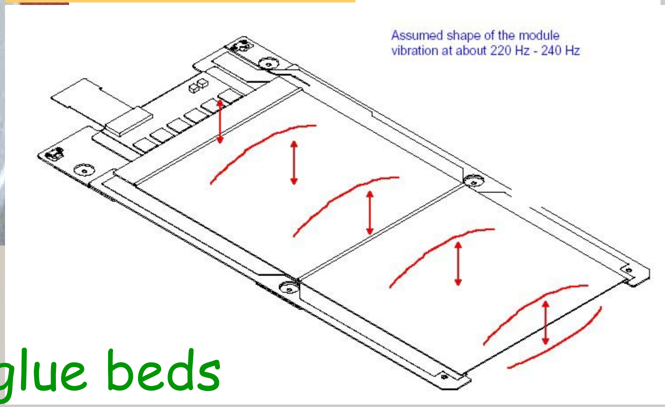
NASA style vibration test

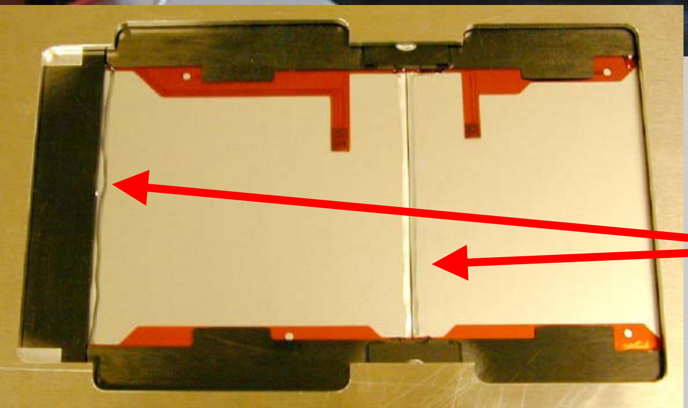


Used laser to identify cantilever resonances at 88 Hz



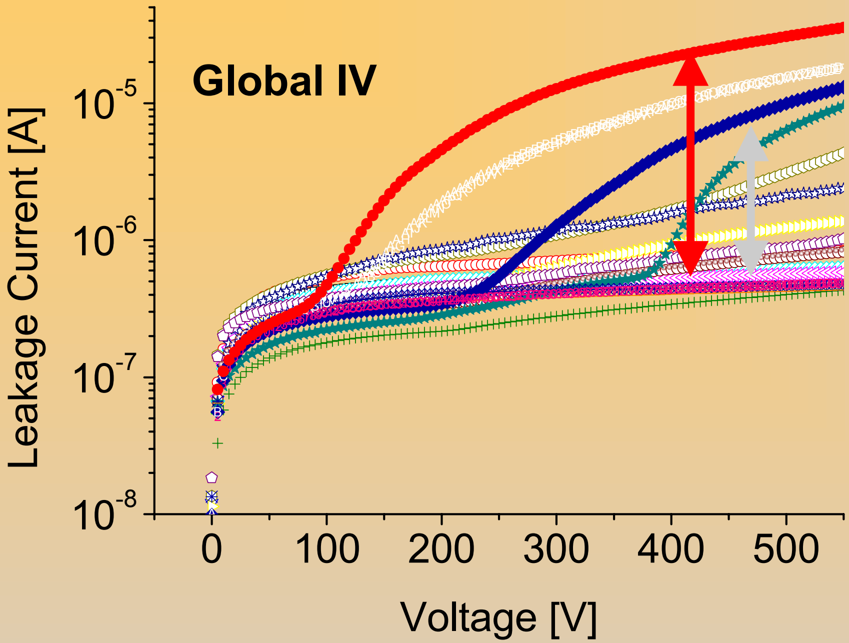
and at 120 Hz

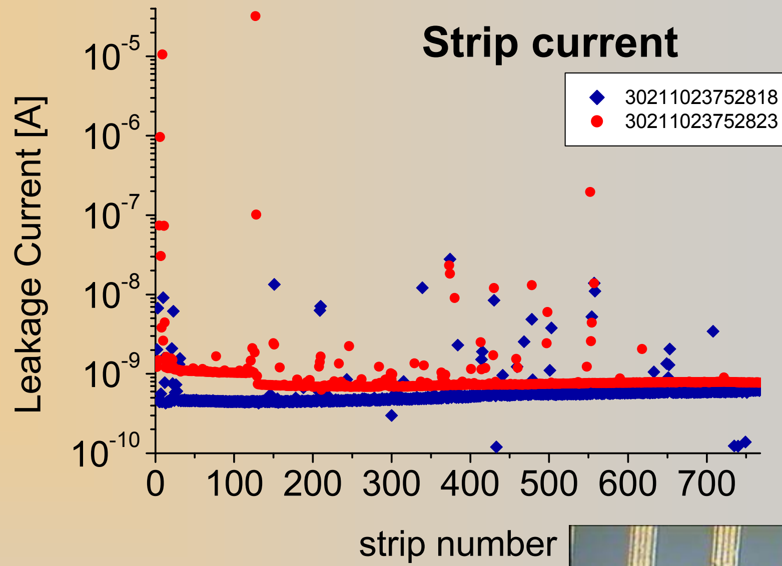


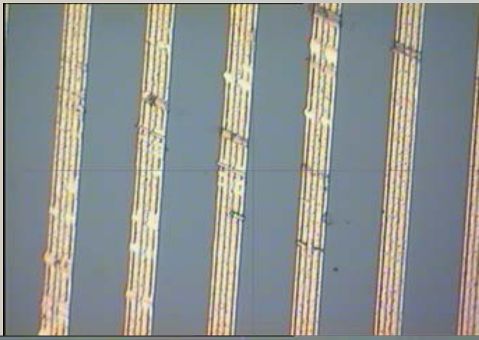


Reinforcement glue beds totally solved the problem

Cautionary Tales IV



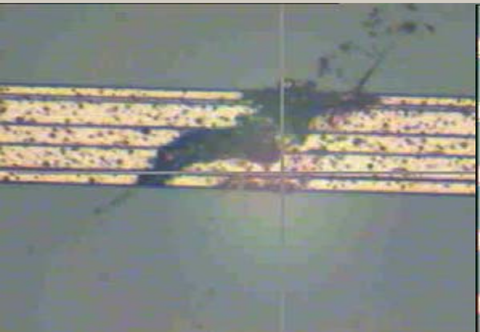


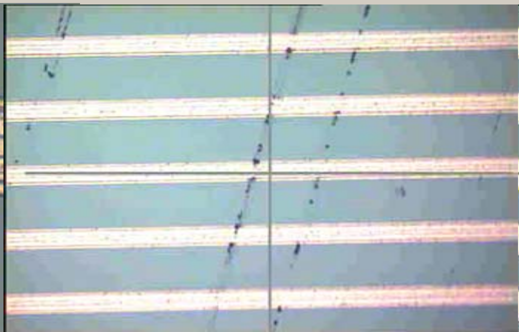


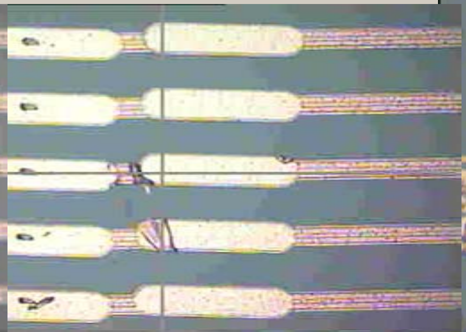
Individual strips are driving the global current;
2nd increase match with sum of a handful strips!

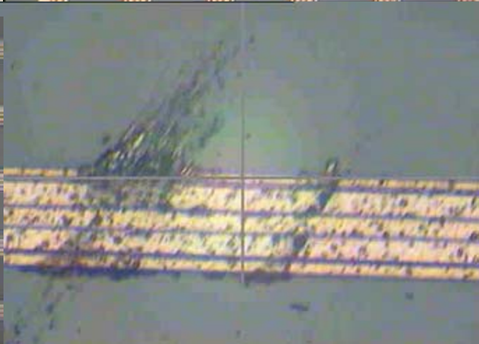
Hm???? Scratches on the metal affect currents???

But NO pinholes – only leaky strips ➔ NO P+ defect!

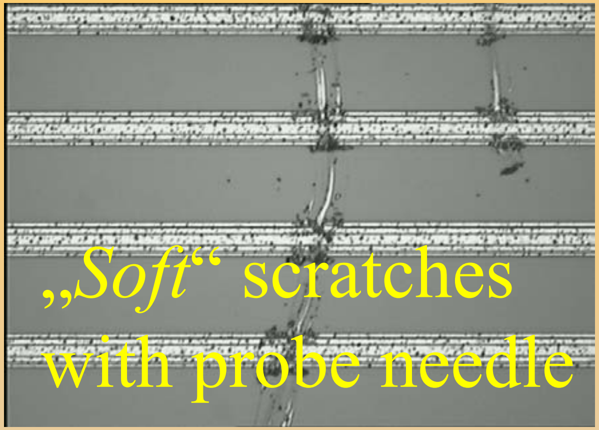


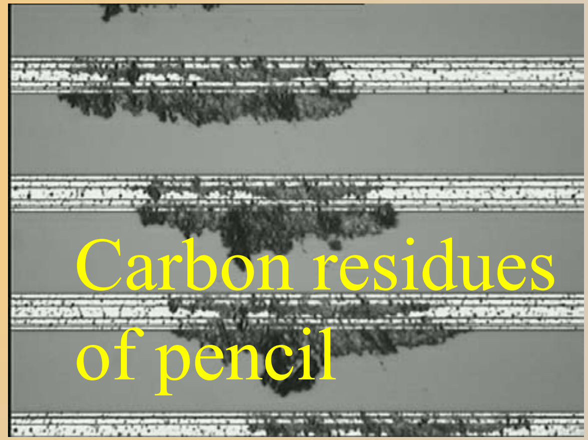


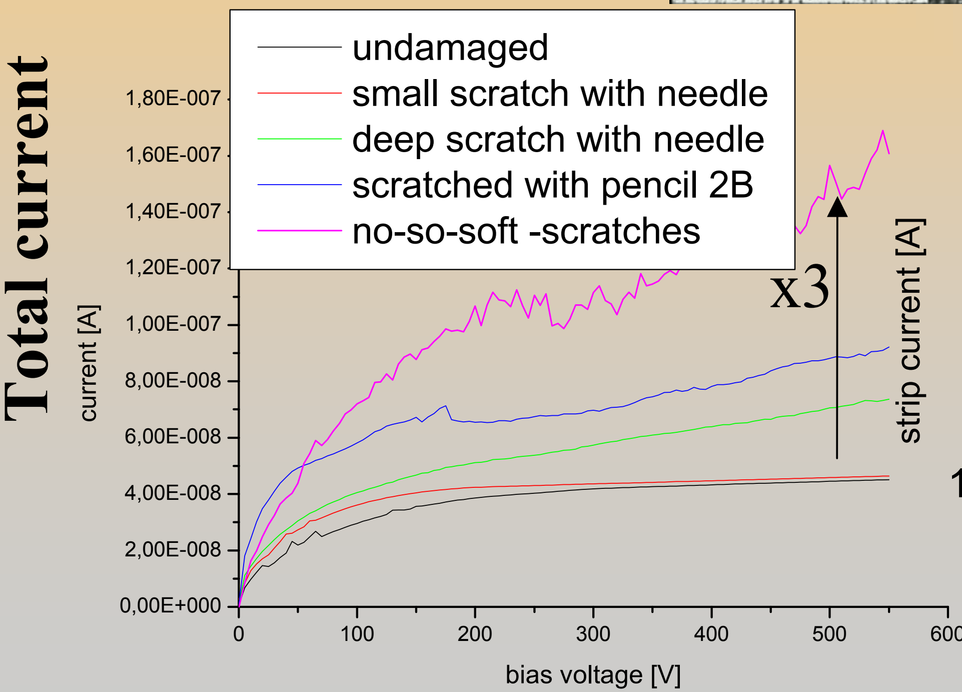


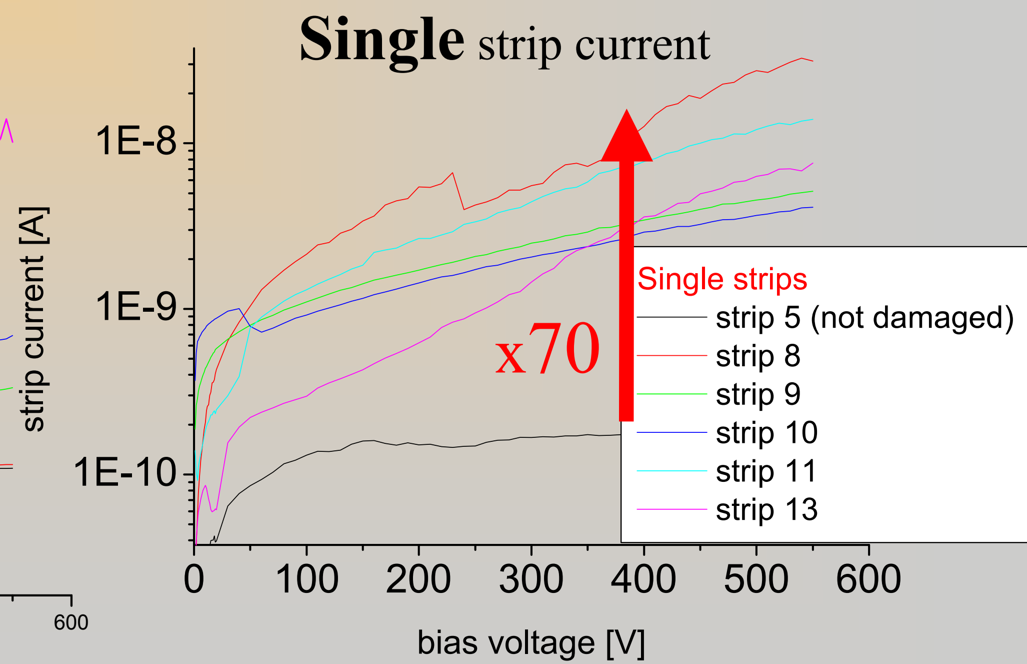


Cautionary Tales IV



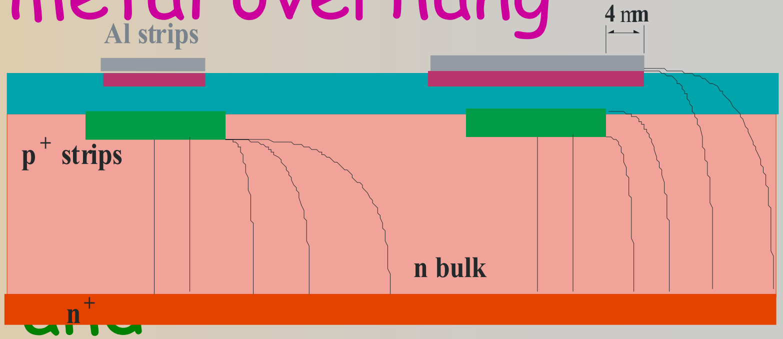


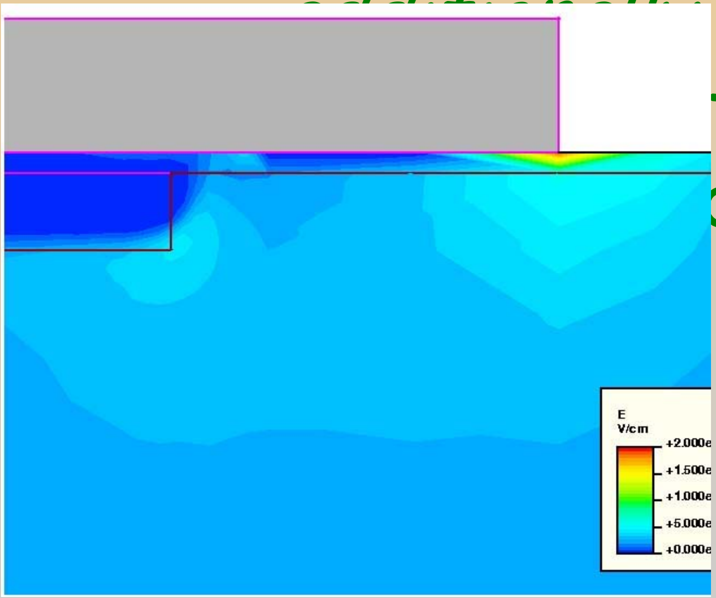


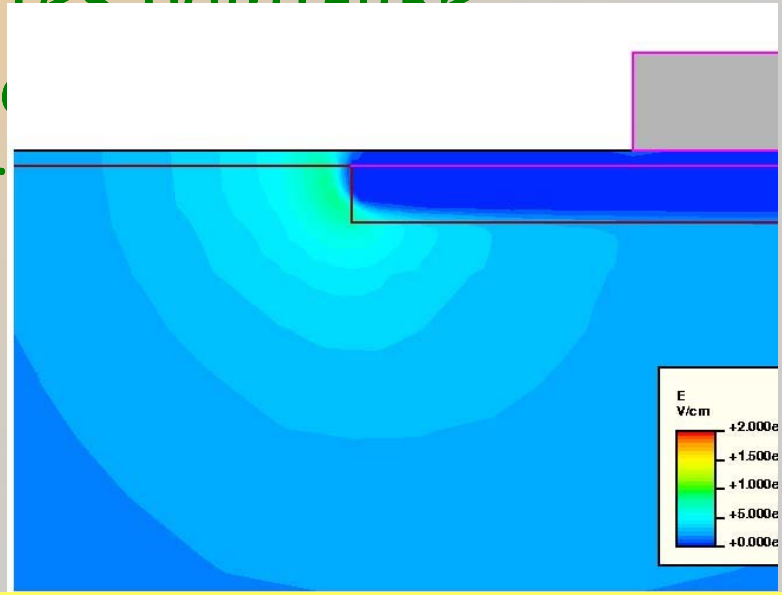


Cautionary Tales IV

- High voltage stability due to metal overhang (Design!)
- High field in Si_2O instead of
- Scratches removes overhang and
  additionally creates point-like
  ting
  d wit







Scratches were actually the main source of sensor problems (reflected in no. of sensor rejects)