Semiconductor Detectors

Radiation hardness

Radiation length X0

Scaling

Occupancy

Yesterday

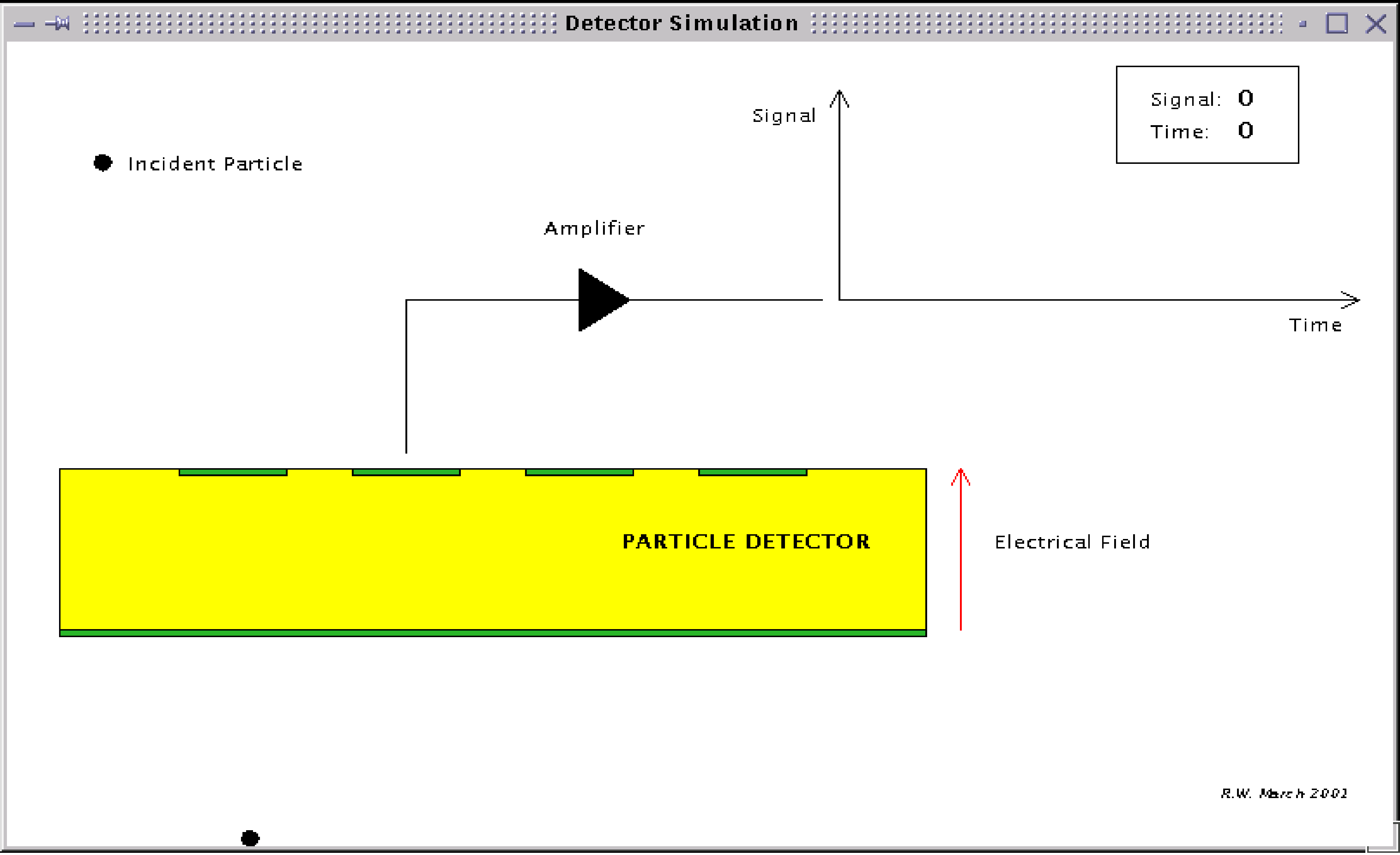
Today

Excursion: radiation hardness

Tomorrow?

Frank Hartmann, Karlsruhe, KIT

They Work Like This

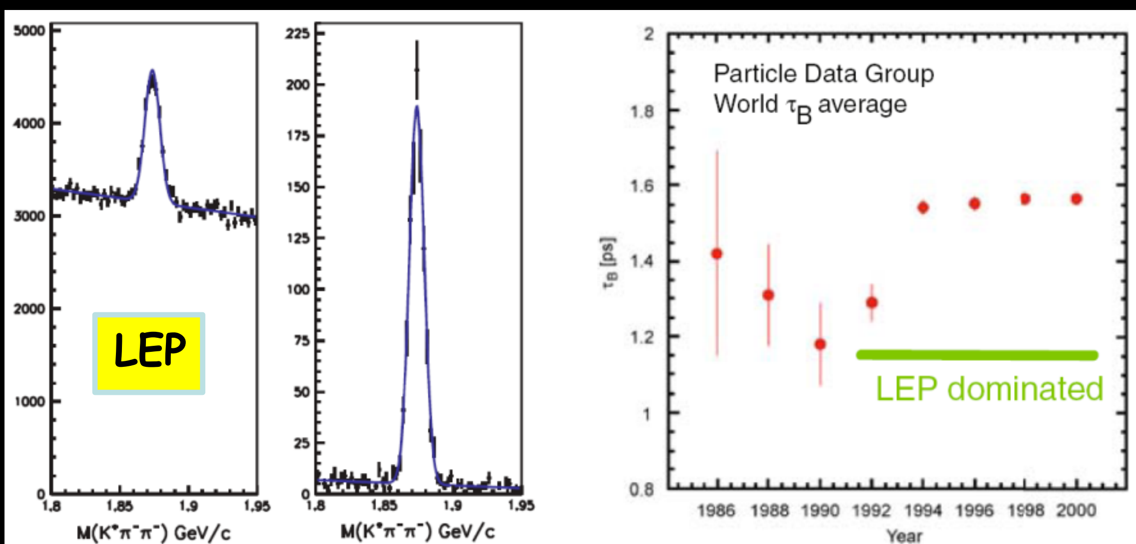


Historical aspects
Why use silicon? It's dictated by physics!

In the post era of the *Z and W discovery, after the observation of Jets at UA1 and* UA2 at CERN, John Ellis envisioned at a HEP conference at Lake Tahoe, California in 1983 "To proceed with high energy particle physics, one has to tag the flavour of the quarks!"

Silicon detectors give vertexing, which gives
- lifetimes
- top quark identification
- mixing background suppression
- B tagging

…… a lot of great physics!



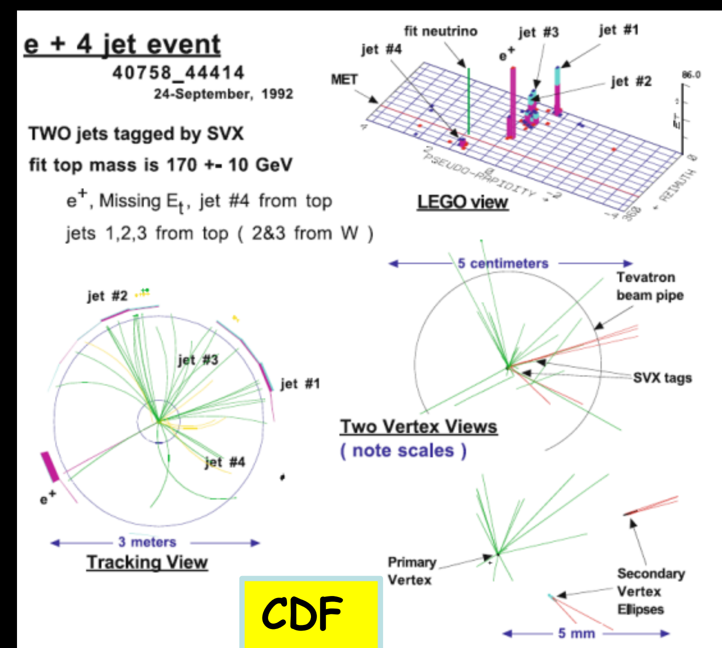
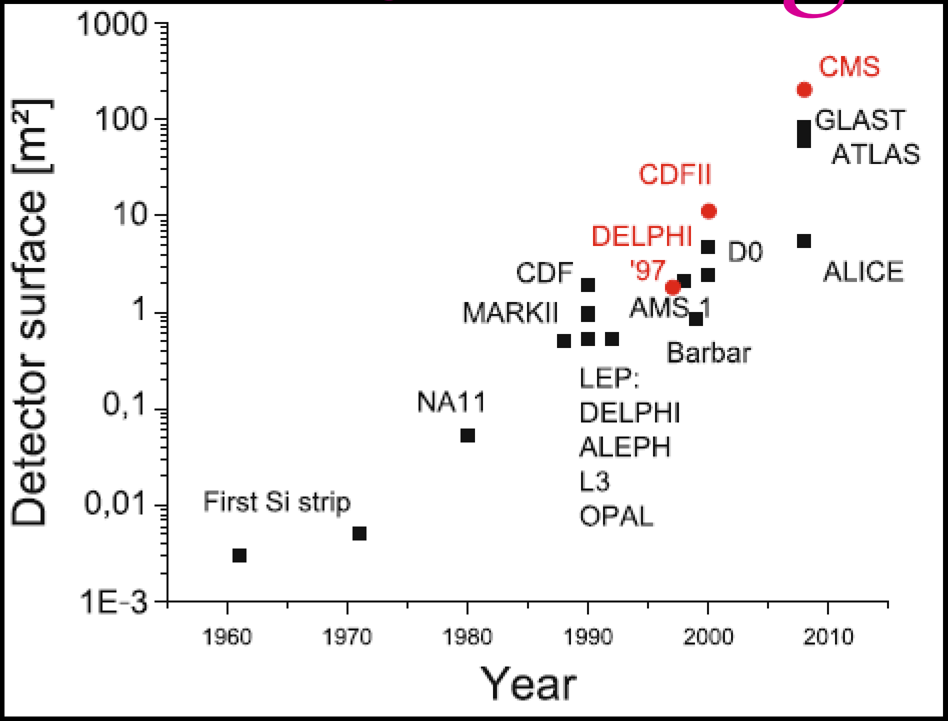


Fig. 4.23 A "Golden" t event. $t\bar{t}$ decaying into W^+b, $W^-\bar{b}$, where one W decays leptonically with the signature lepton ID plus missing energy, the second W decays into $q\bar{q}$ resulting in two jets together with the initial two tagged b jets. In total one lepton, four jets, two tagged b jets and missing energy were reconstructed [151]

scaling, scaling, **scaling**



50ties

Early strips

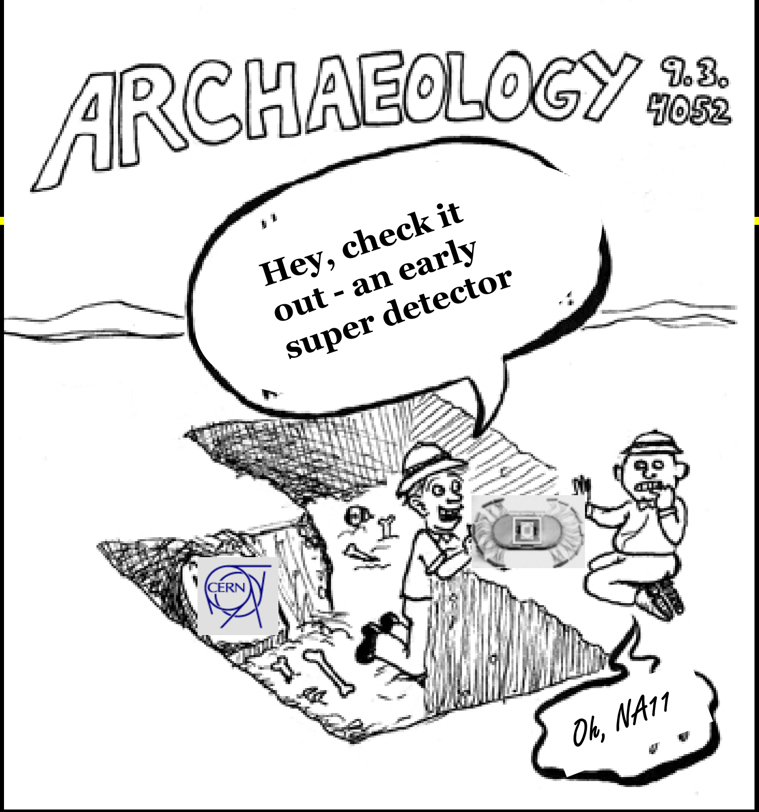
NA11

LEP & Tevatron

LHC

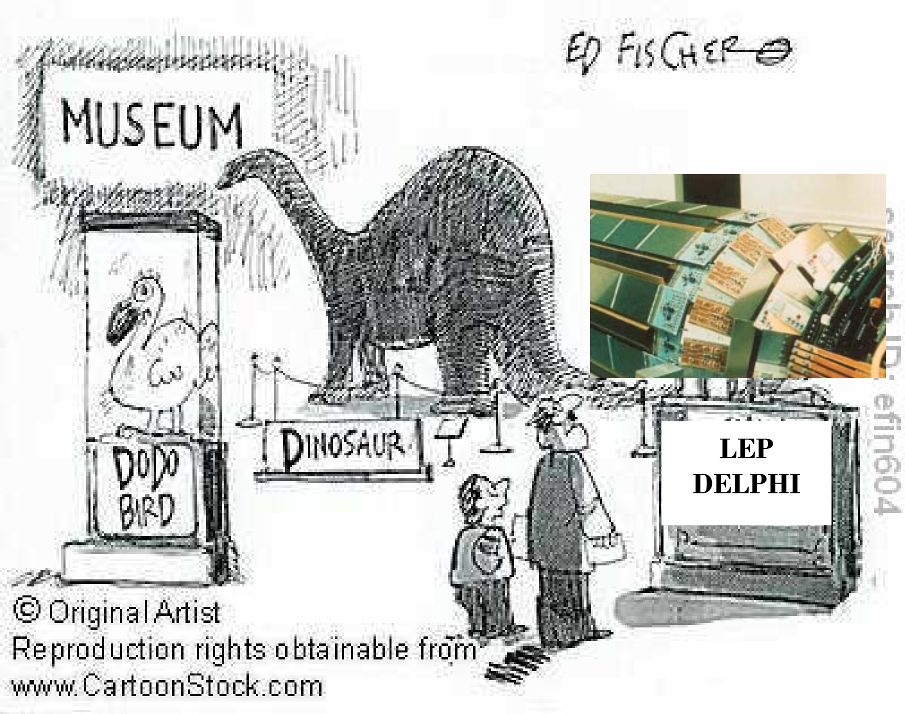
Beyond

EVOLUTION OF SEMICONDUCTOR DETECTORS



Beware: Examples only

YESTERDAY



Even a Bit Before Yesterday

PHYSICAL REVIEW VOLUME 84, NUMBER 4 NOVEMBER 15, 1951

Electron-Hole Production in Germanium by Alpha-Particles

KENNETH G. MCKAY
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received August 3, 1951)

The number of electron-hole pairs produced in germanium by alpha-particle bombardment has been determined by collecting the internally produced carriers across a reverse-biased $n-p$ junction. No evidence is found for trapping of carriers in the barrier region. Studies of individual pulses show that the carriers are swept across the barrier in a time of less than 2×10^{-8} sec. The counting efficiency is 100 percent. The energy lost by an alpha-particle per internally produced electron-hole pair is 3.0 ± 0.4 ev. The difference between this and the energy gap is attributed to losses to the lattice by the internal carriers. It is concluded that recombination due to columnar ionization is negligible in germanium.

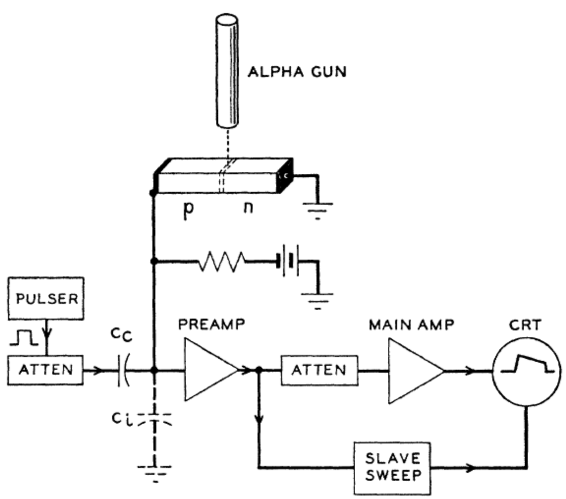


FIG. 2. Schematic of experimental equipment.

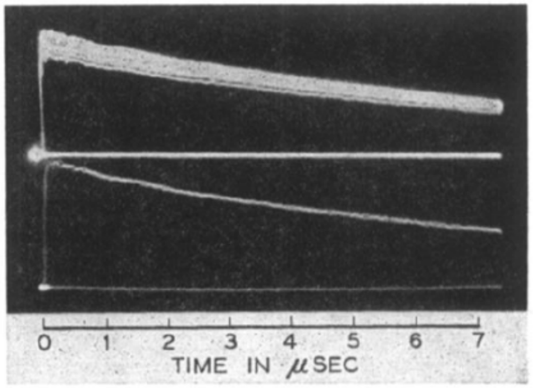


FIG. 3. Photograph of pulses from sixteen alpha-particles striking the $n-p$ barrier.

Yesterday

First Strip Sensor

NUCLEAR INSTRUMENTS AND METHODS 97 (1971) 465-469;

STRIPED SEMICONDUCTOR DETECTORS FOR DIGITAL POSITION ENCODING

E.L. HAASE, M.A. FAWZI*, D.P. SAYLOR and E. VELTEN

Institut für Experimentelle Kernphysik der Universität und des Kernforschungszentrums Karlsruhe, Germany

The counters are large area ion-implanted detectors with a common aluminium contact and a front contact consisting of five or twelve gold strips separated by 0.2 mm.

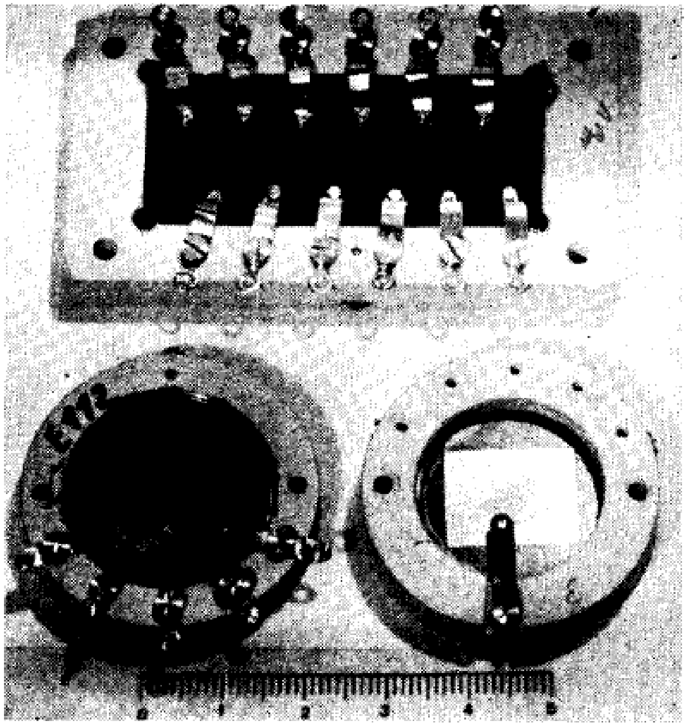


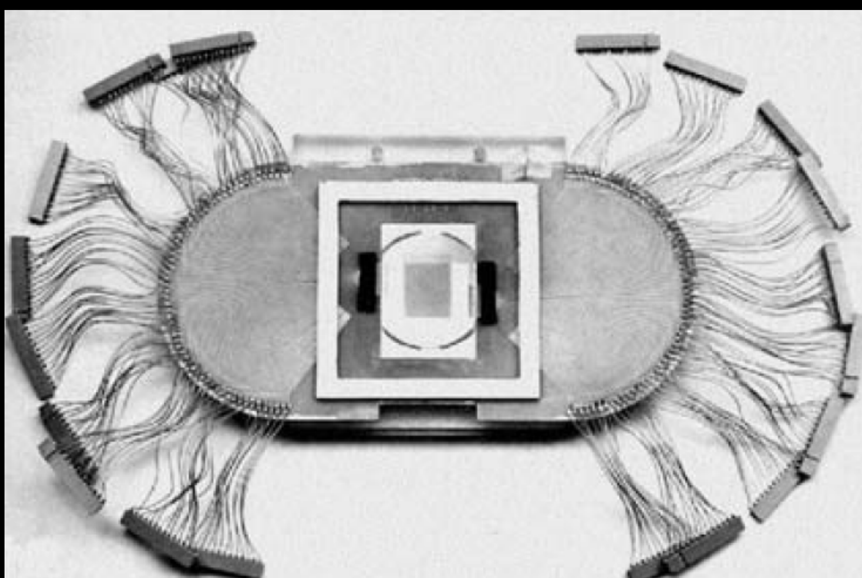
Fig. 1. Ion-implanted semiconductor detectors with subdivided front-contact and common back-contact.

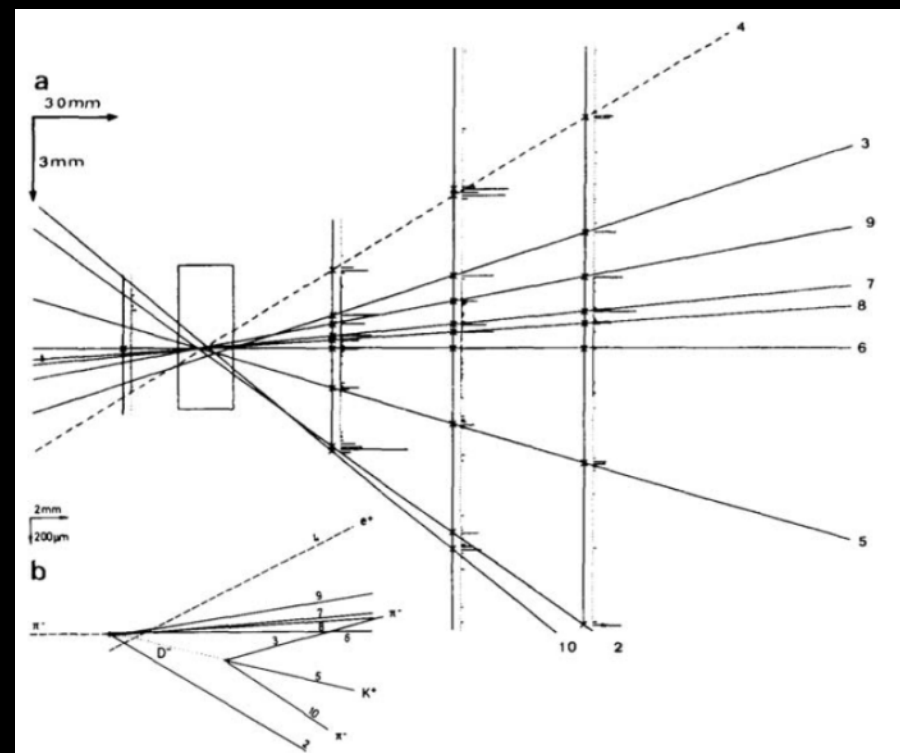
Today, I simply try to continue the good old tradition.

Yesterday

NA11

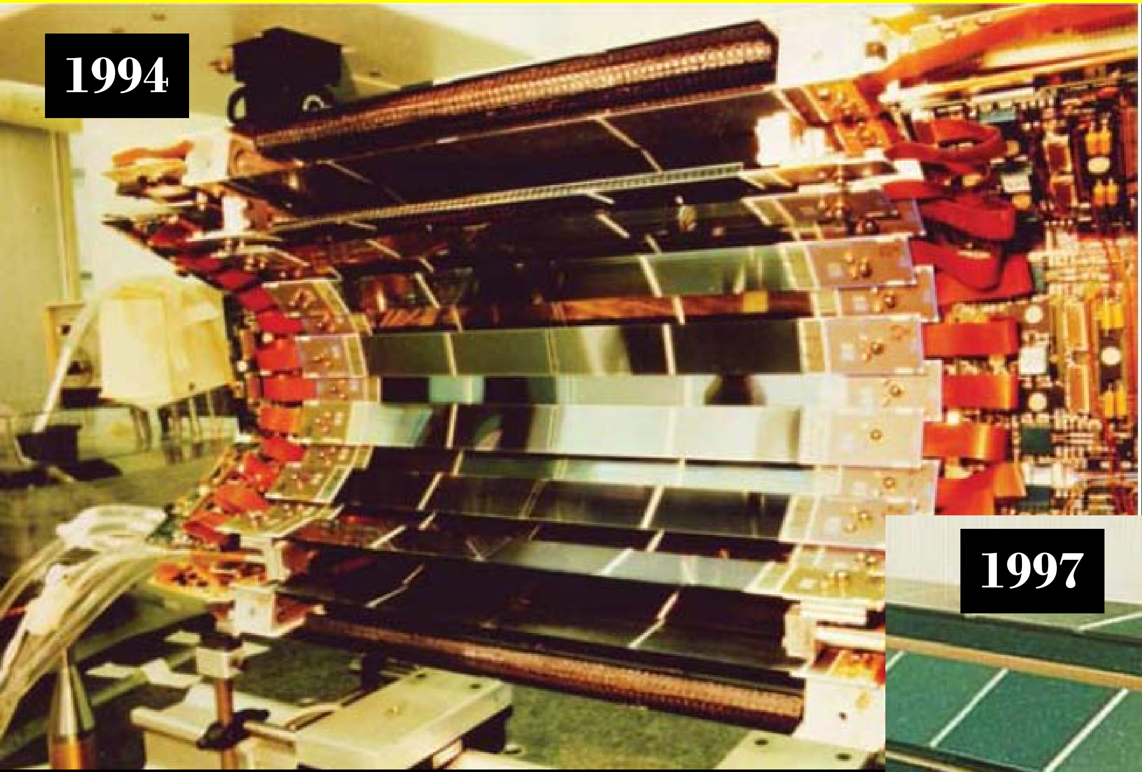
- C-quark identification via second vertex method
  - Proof of principle: Vertexing





Yesterday

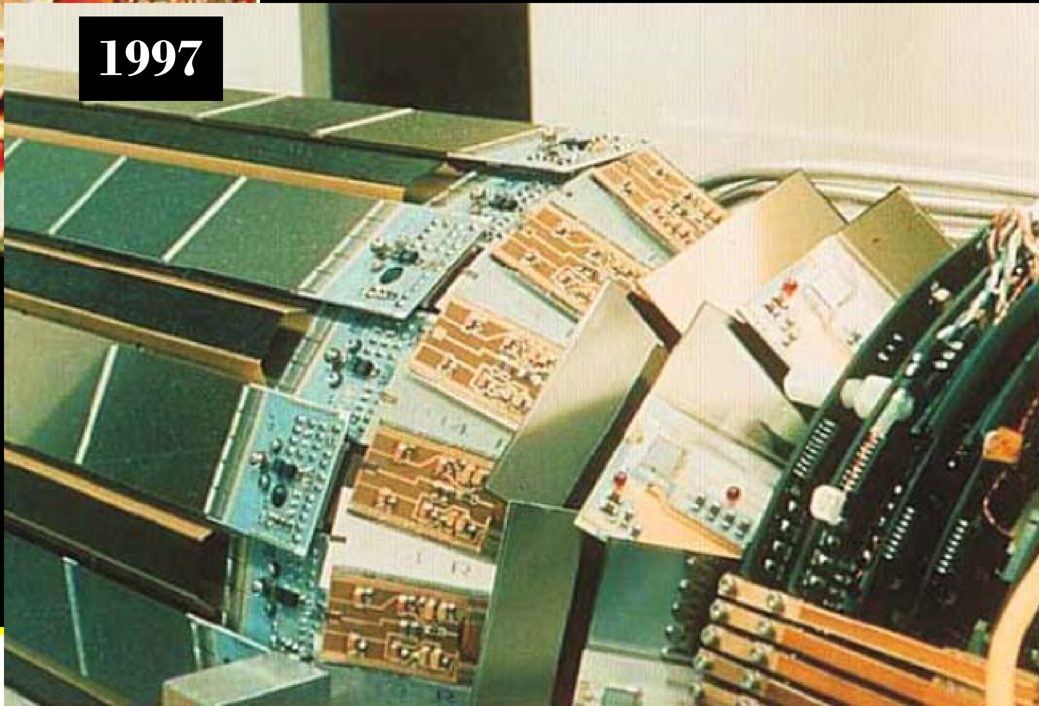
LEP: DELPHI as an example



Radiation length X0

Scaling

1997
3 double sided layers Rϕ, Rz
Extra forward strip sensors
Extra forward pixel



Even with the large size still clear bifurcation:
- Silicon gives Vertexing
- Gas gives Tracking

Yesterday

JINDARIANI, Sergo	Longevity Studies in the CDF Silicon Detectors
SITTA, Mario	The Silicon Drift Detector of the ALICE experiment
KUO, Chia-ming	First results on the performance of the CMS Preshower Detector
PARKES, Chris	Results from the first LHC beam reconstructed tracks in the LHCb Vertex Locator
Dr. WEBER, Martin	First Alignment of the Complete CMS Silicon Tracker
TRONCON, Clara	Commissioning of the ATLAS Pixel Detector with cosmic ray and beam data.
WILL, Johns	CMS Pixel Detector

TEVATRON

LHC time

TODAY

Scaling

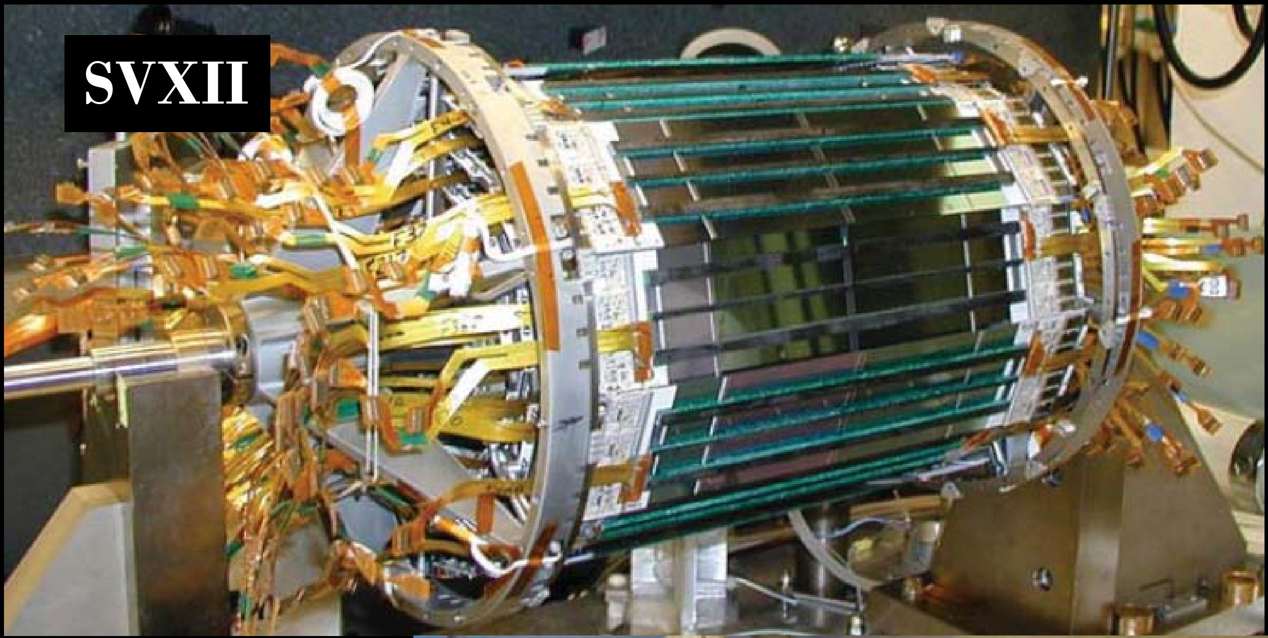
Radiation hardness

Tevatron: CDF as an example

Today

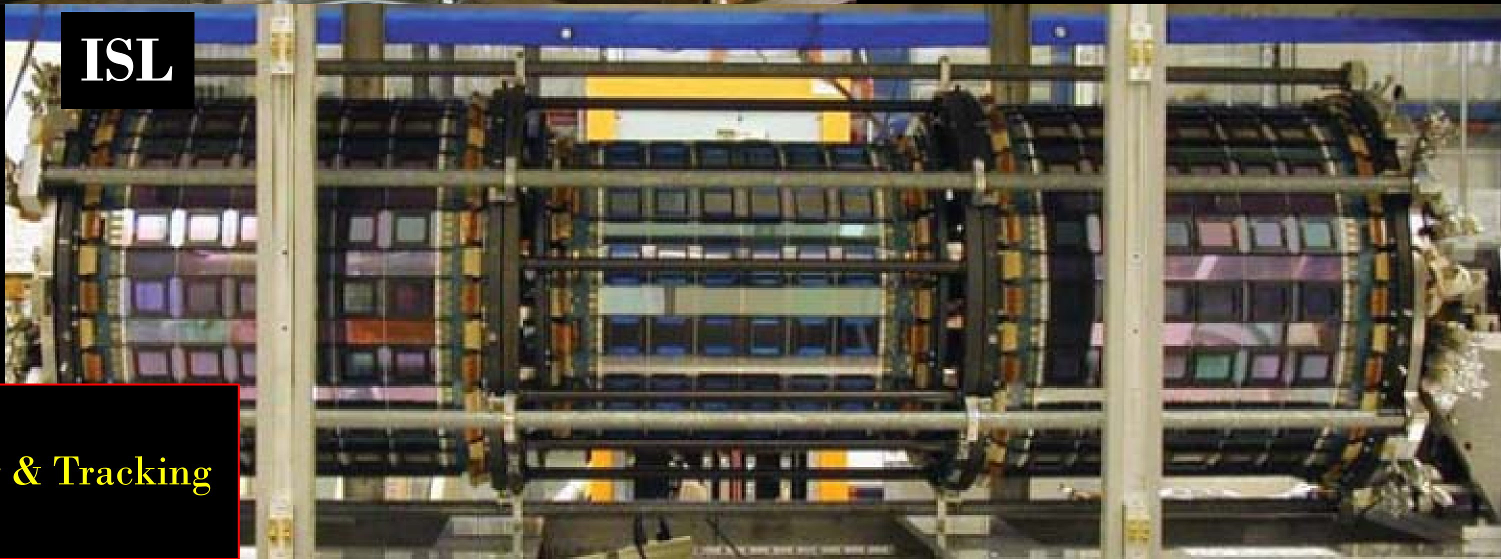
Scaling

Radiation hardness

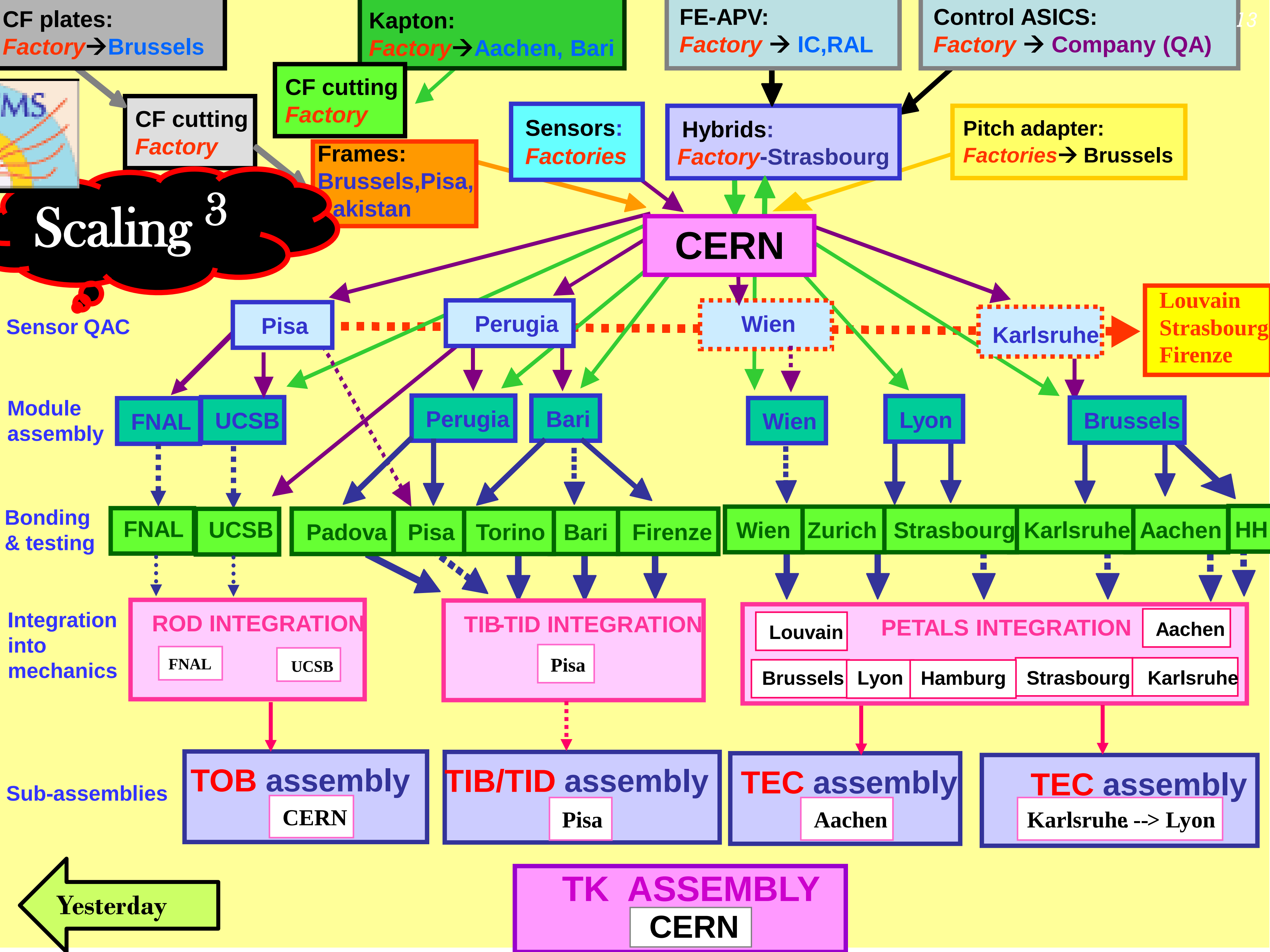


2000
7 double sided layers
1 innermost* single sided layer

*On beam pipe

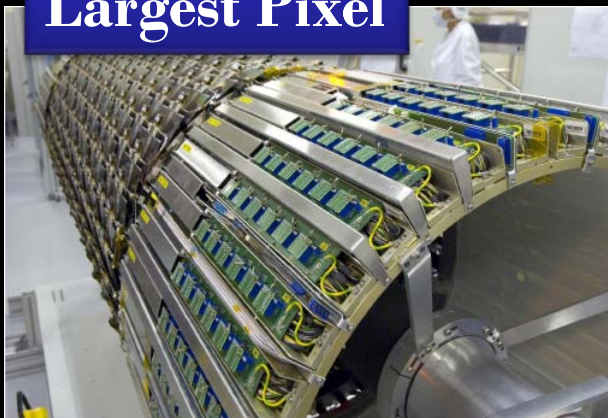


Bifurcation
Silicon gives Vertexing & Tracking
Gas gives Tracking


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,
akistan
Sensors:
Factories
Hybrids:
Factory-Strasbourg
Pitch adapter:
Factories→ Brussels
Scaling 3
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
Yesterday

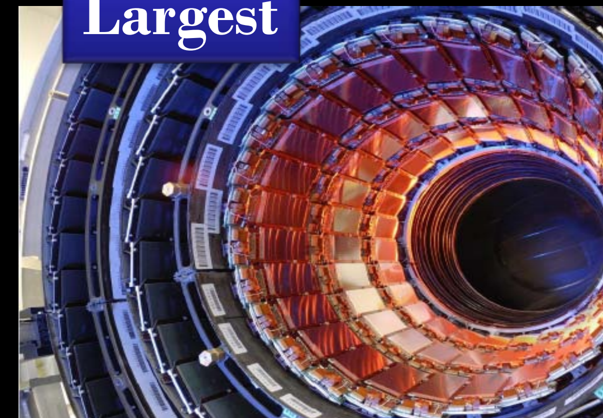
The LHC Puzzle: Who's Who?

Largest Pixel



Most modern

Largest



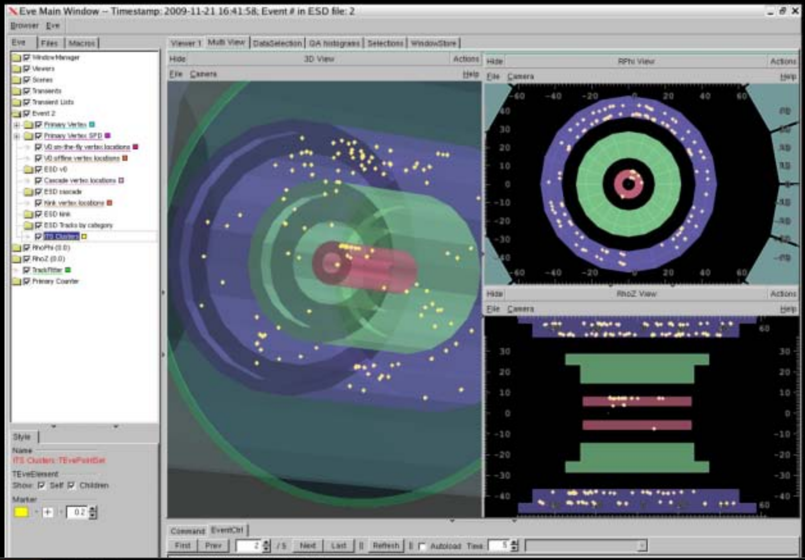
3 sensor technologies

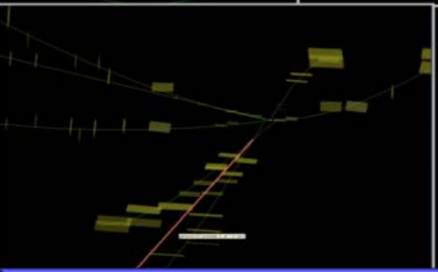
		ALICE	ATLAS	CMS	LHCB
Pixel	# channels	9.8M	80M	66M	
	# modules	240	1788	1440	
Strips	# channels	2.6M	3.2m	9.3M	86k
	# modules	1698	4088	15148	43

Bifurcation:
Silicon pixels give Vertexing
Silicon strips (& Si-Drift & TRT) give Tracking

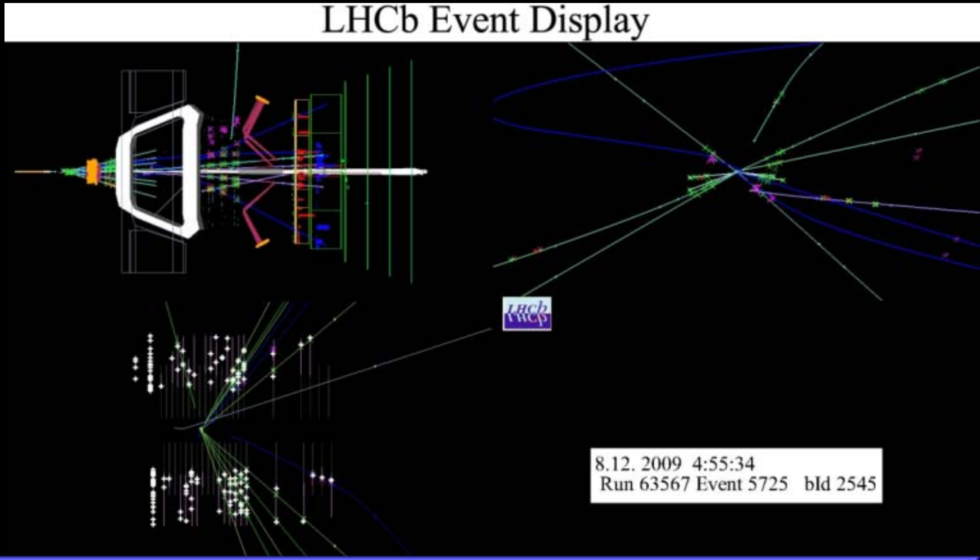
Today

LHC: Event Displays of ALICE & ATLAS & CMS & LHCB during collisions





Display of a candidate K-short reconstructed vertex. The V0 candidate is in red, the tracks in green, the hits associated to tracks in yellow, and the primary vertex in blue.



ALL LHC detectors have proven their magnificent performance with lots lots lots of cosmics and more important with the first collisions last year! Several particles and resonances already “re-discovered”

Do we understand the radiation damage mechanisms?

Yesterday?

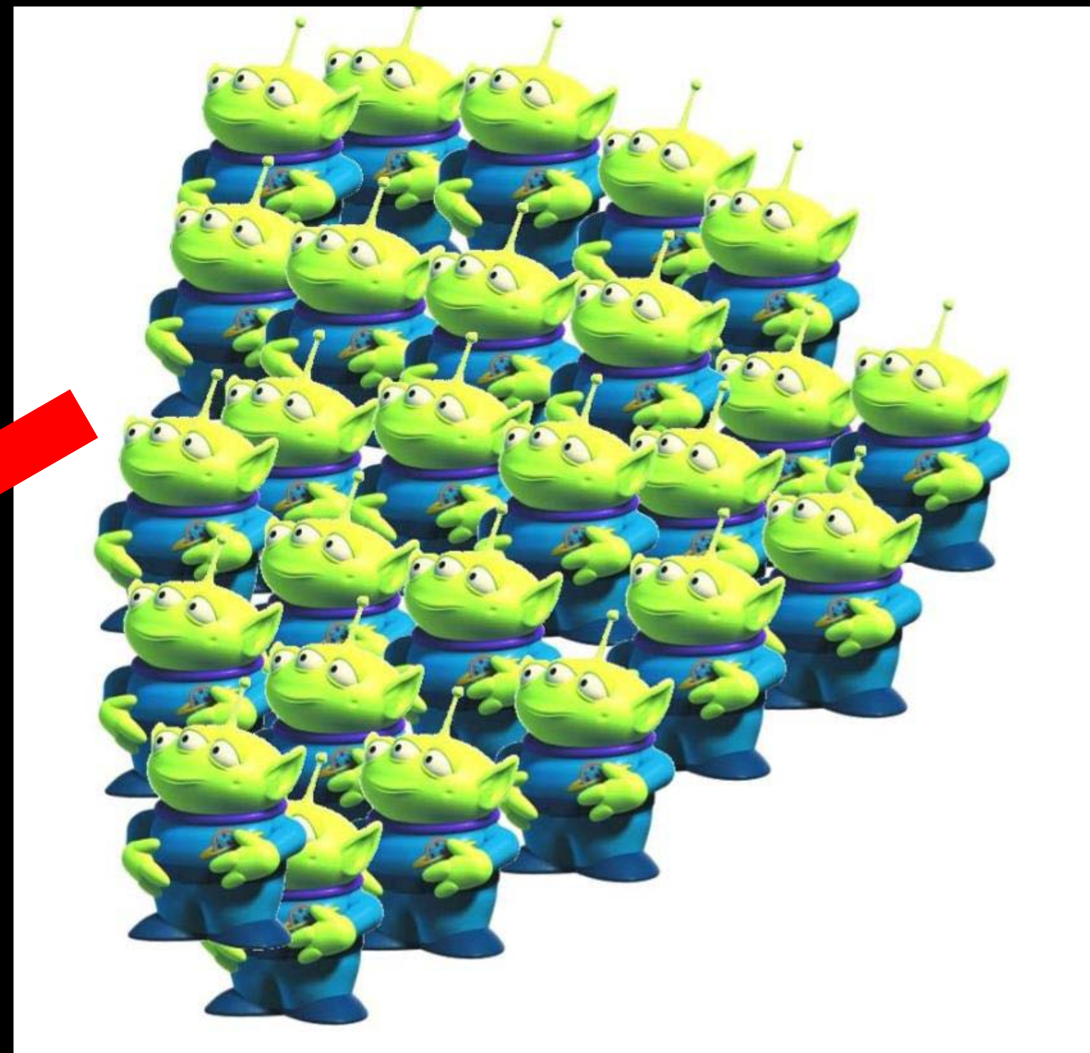
Today?

Tomorrow?

NECESSARY & LONG EXCURSION: RADIATION DAMAGE

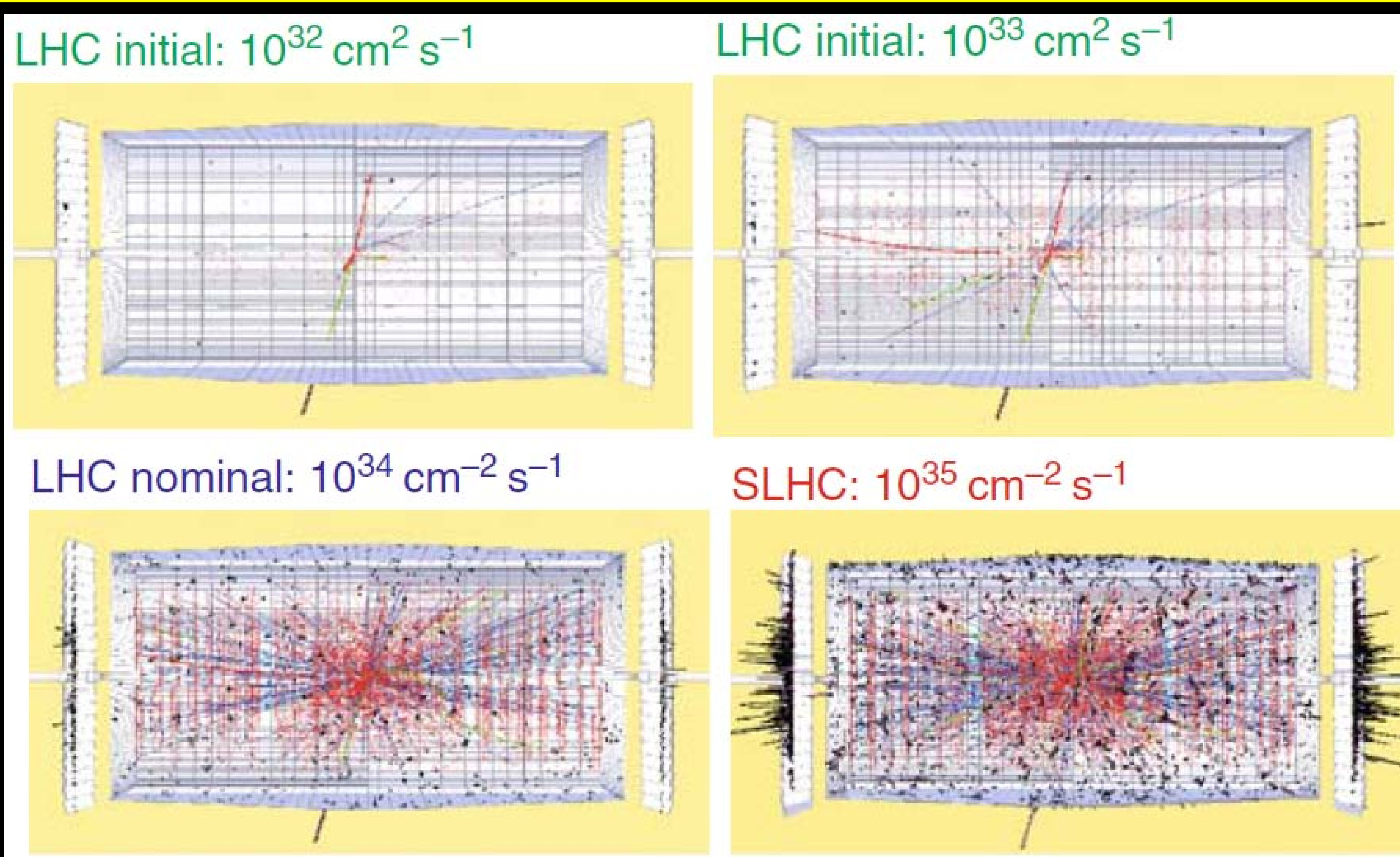
Let me quote the question Paula Collins asked at this podium 3 years ago

How do I cope with having 10 quadrillion particles thrown at me?*



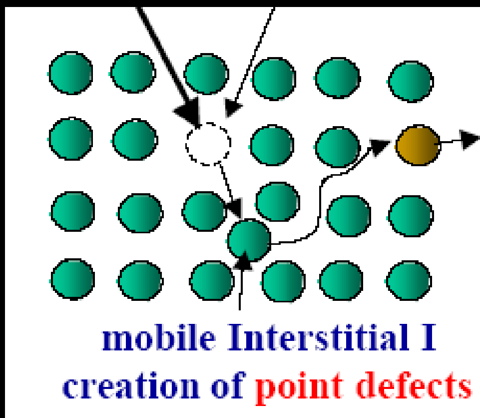
*10^{16} fluence / cm^2 at 4cm SLHC

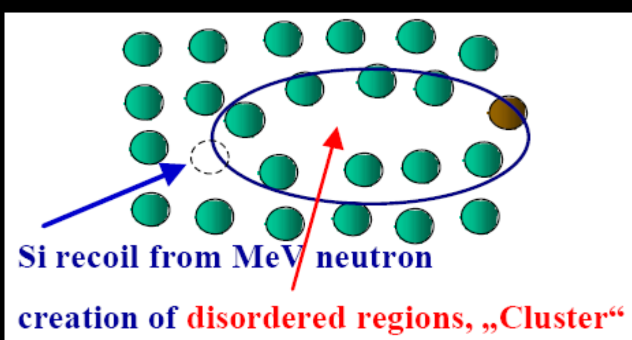
The Problem Piles Up ..

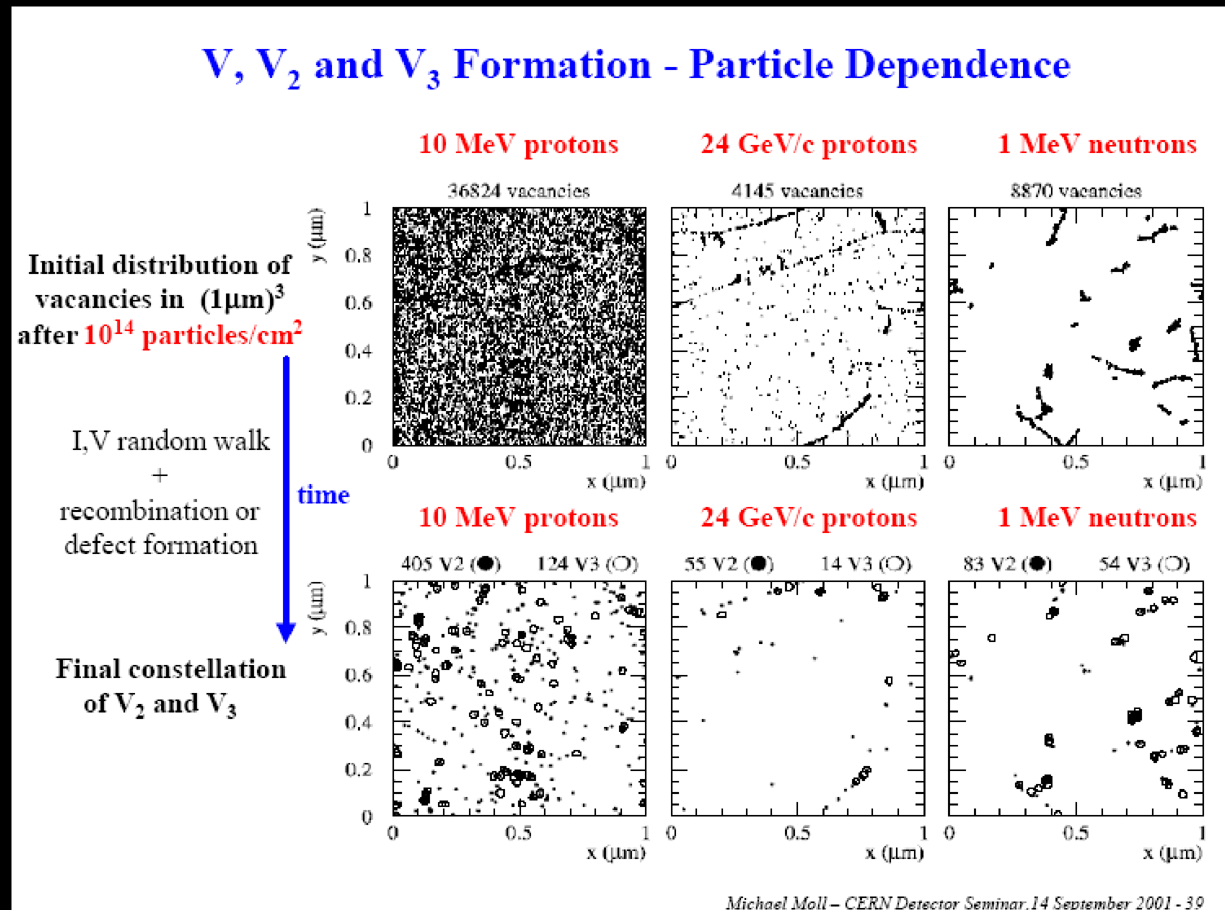


Radiation damage in silicon detectors
Bulk Damage (microscopic)

Yesterday – Today - Tomorrow







[Mika Huhtinen ROSE TN/2001-02]

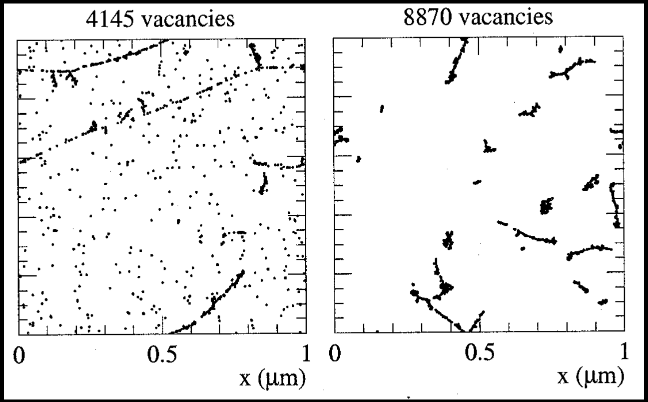
Today, we have a reasonable understanding, of microscopic defects corresponding to macroscopic electrical degradation

NIEL: The Mantra of Today

Today

Point defects + clusters

Dominated by clusters

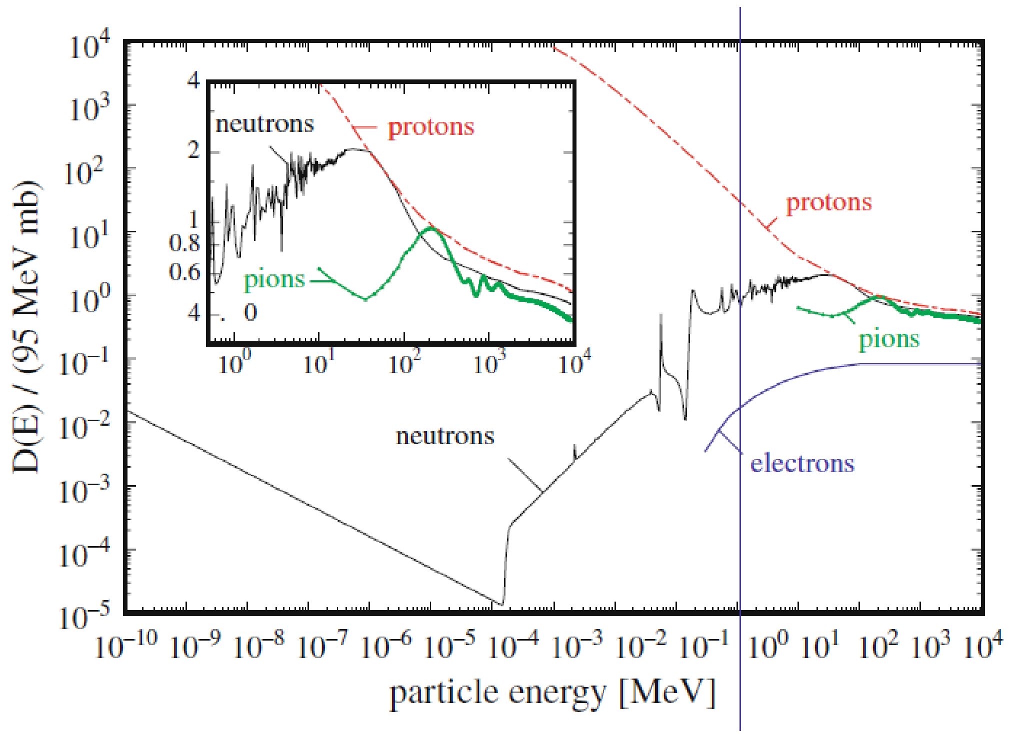


- Proton damage can be scaled to neutron damage
- Proton & neutron damage ADD UP
- "1 MeV neutron equivalent"

Mantra:

With κ you can scale to "1 MeV neutron equivalent"

$$\kappa = \frac{\int D(E)\phi(E)dE}{95MeV\,mb \cdot \Phi} = \frac{\Phi_{eq}}{\Phi}$$



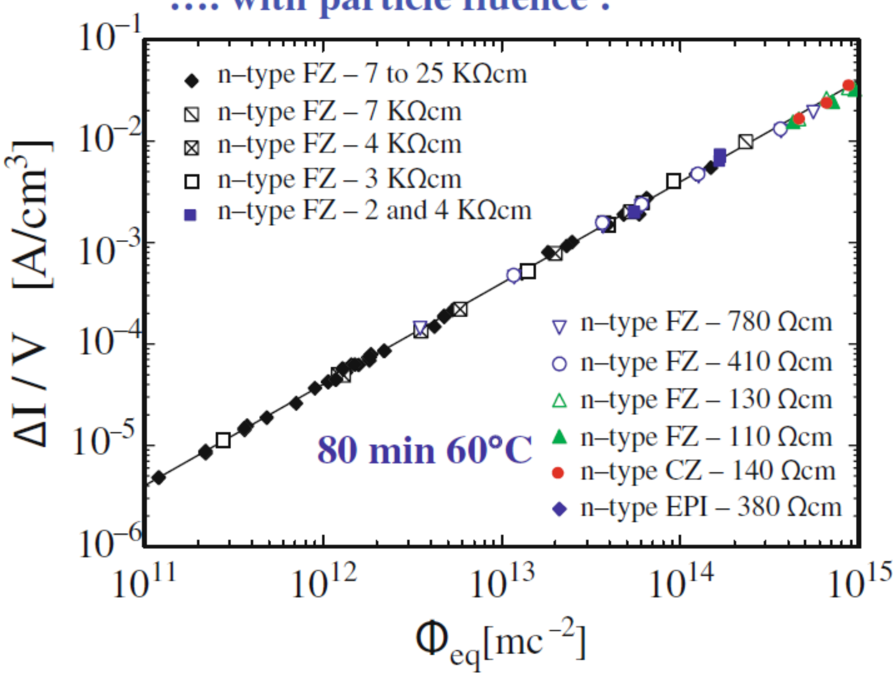
NIEL non ionizing energy loss

Radiation damage: Leakage Current

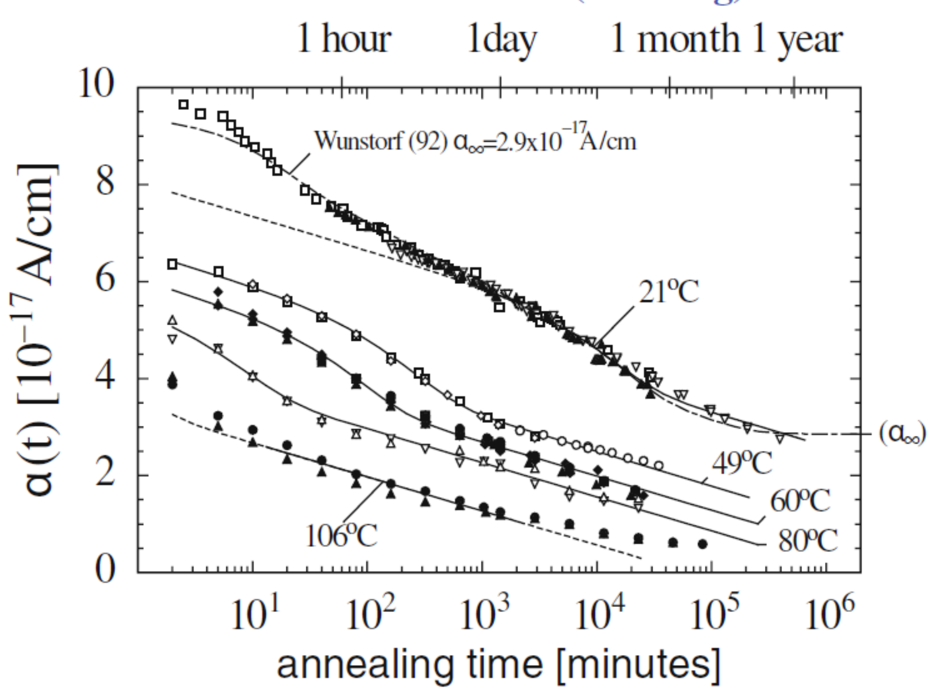
Yesterday – Today - Tomorrow

- $I \sim \alpha \Phi_{eq}$
- Still true for all silicon materials (n, p, FZ, MCz, oxygenated)
- Annealing always decreases current
- Rule of thumb: dominant damage item up to 10^{14} $1MeV_{eq}$

…. with particle fluence :



…. with time (anealing) :



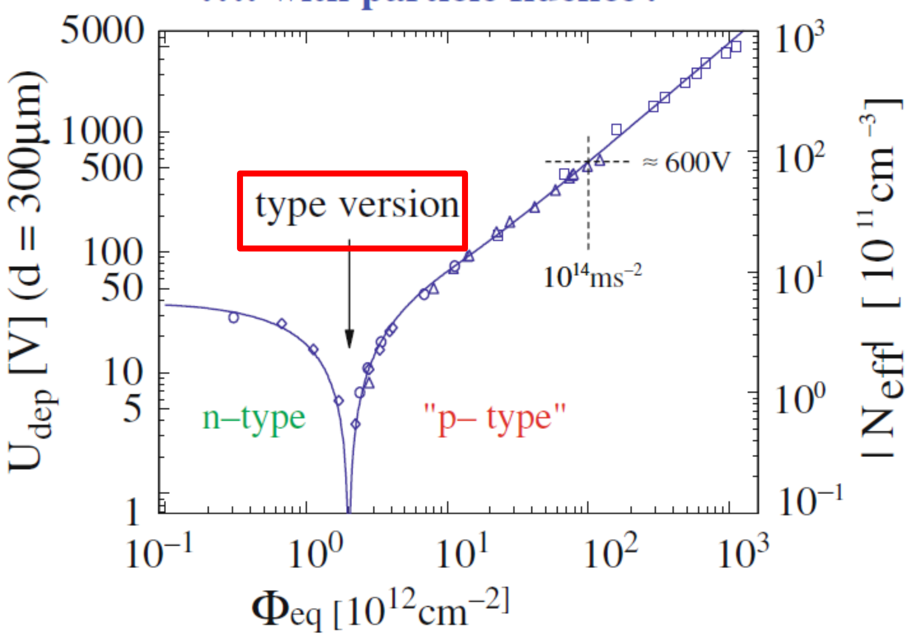
→ Noise, power

Radiation Damage: Neff – V_{dep}

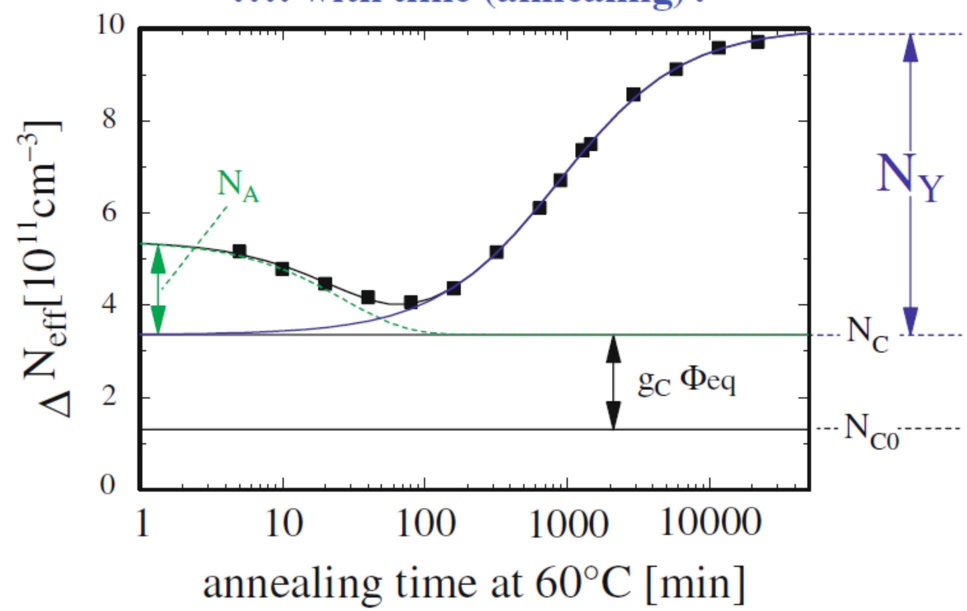
Today, but not "really" tomorrow!

- $V_{dep} \sim N_{eff}$; N_{eff} changes with Φ_{eq}
  - For n-FZ just acceptors are building up
- Different material behave differently (n, p, FZ, MCz, oxygenated)
- Annealing has two components with different time constants (a good and a bad one)
  - At least for n-type FZ material
- Rule of thumb: dominant damage item up to 10^{15} $1MeV_{eq}$

…. with particle fluence :



…. with time (annealing) :

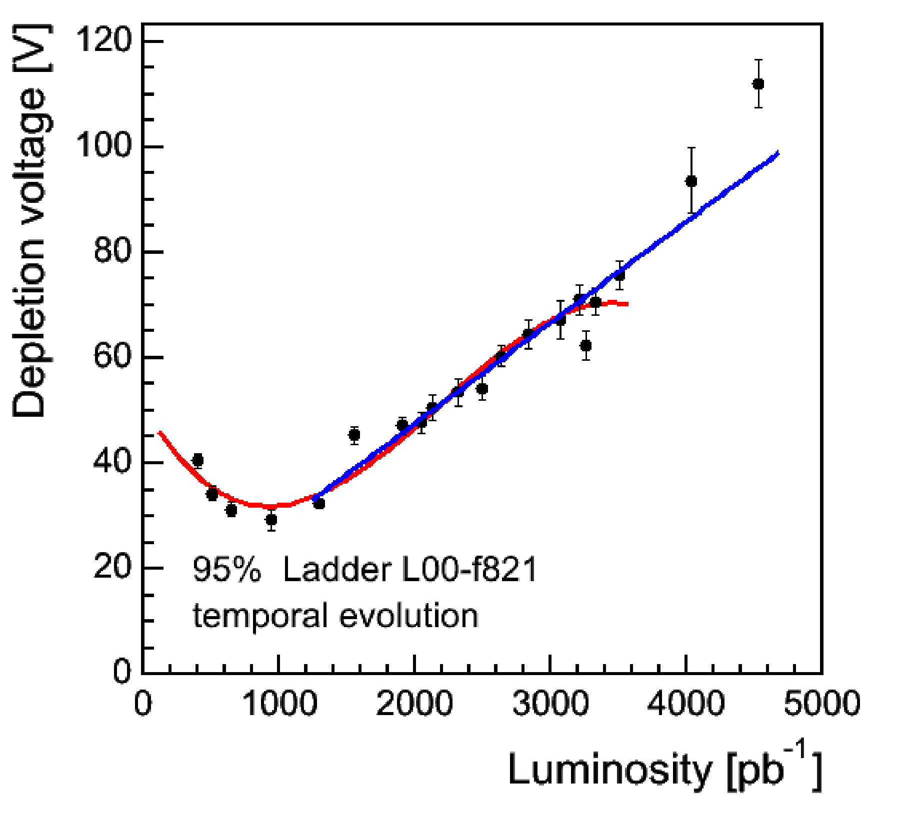


➔Operatibility, power

Tevatron: A Lively Example

Today

- CDF and D0 show us every year that the Hamburg Model is valid, although nature seems to be kind to us and radiation over a long period seems less damaging than fast “test” irradiation (10 LHC years in 10 minutes)



- Estimations for the future looks optimistic (loss in SVX-L0 will be compensated by Layer 00)
- Silicon Detectors will remain in good condition for physics (even if the run is extended to 2011 or 2012)

Encouraging results, that for the TEVATRON and LHC, the HH Model allows prediction!

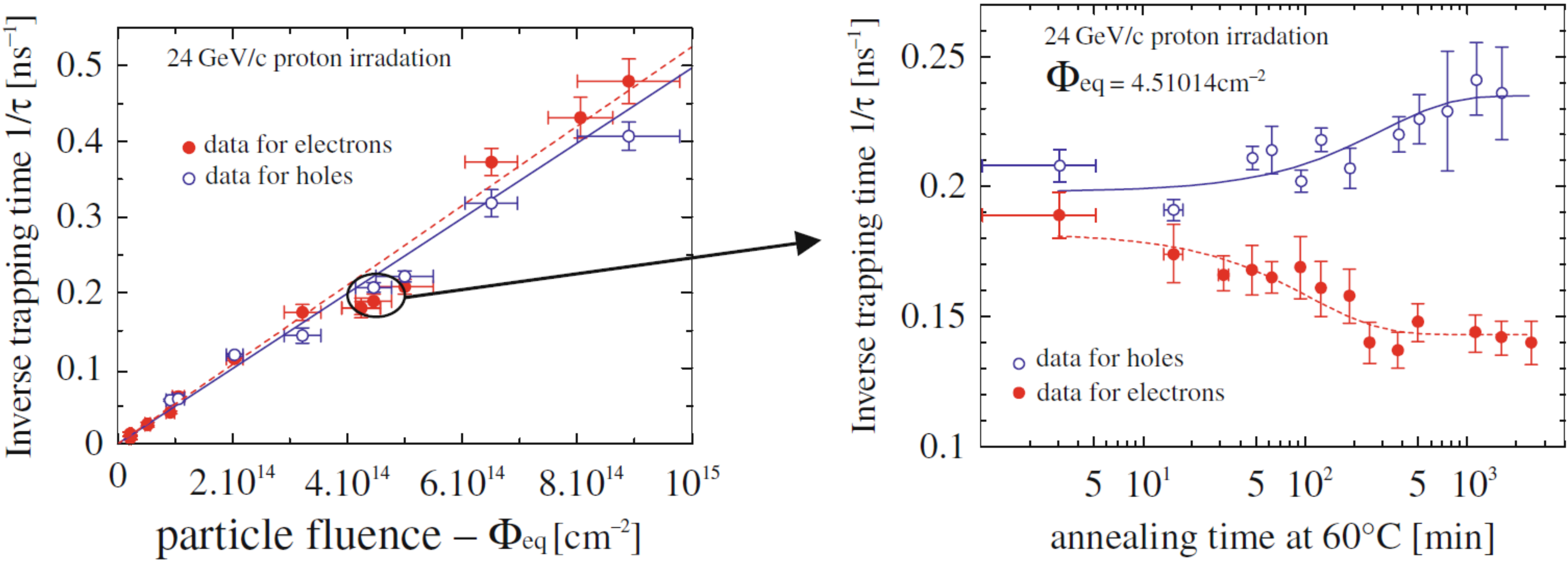
Radiation Damage: Trapping

Tomorrow

- Trapping τ_{eff} changes with Φ_{eq}
- Different materials behave differently (n, p, FZ, MCz, oxygenated)
- Rule of thumb: dominant damage item up to 10^{16} $1MeV_{eq}$
- τ_{eff} *(10^{15} n1 MeV/cm2) = 2 ns:* $x = (10^7\ cm/s) \cdot 2 \cdot ns = 200 \mu m$
- τ_{eff} *(10^{16} n1 MeV/cm2) = 0.2 ns:* $x = (10^7\ cm/s) \cdot 0.2 \cdot ns =$ <u>$20 \mu m$</u>

Annealing effect small

Increase of inverse trapping time ($1/\tau$) with fluence ..... and change with time (annealing):



→ signal

Now, what about type inversion???

What about introduction of acceptors ONLY?

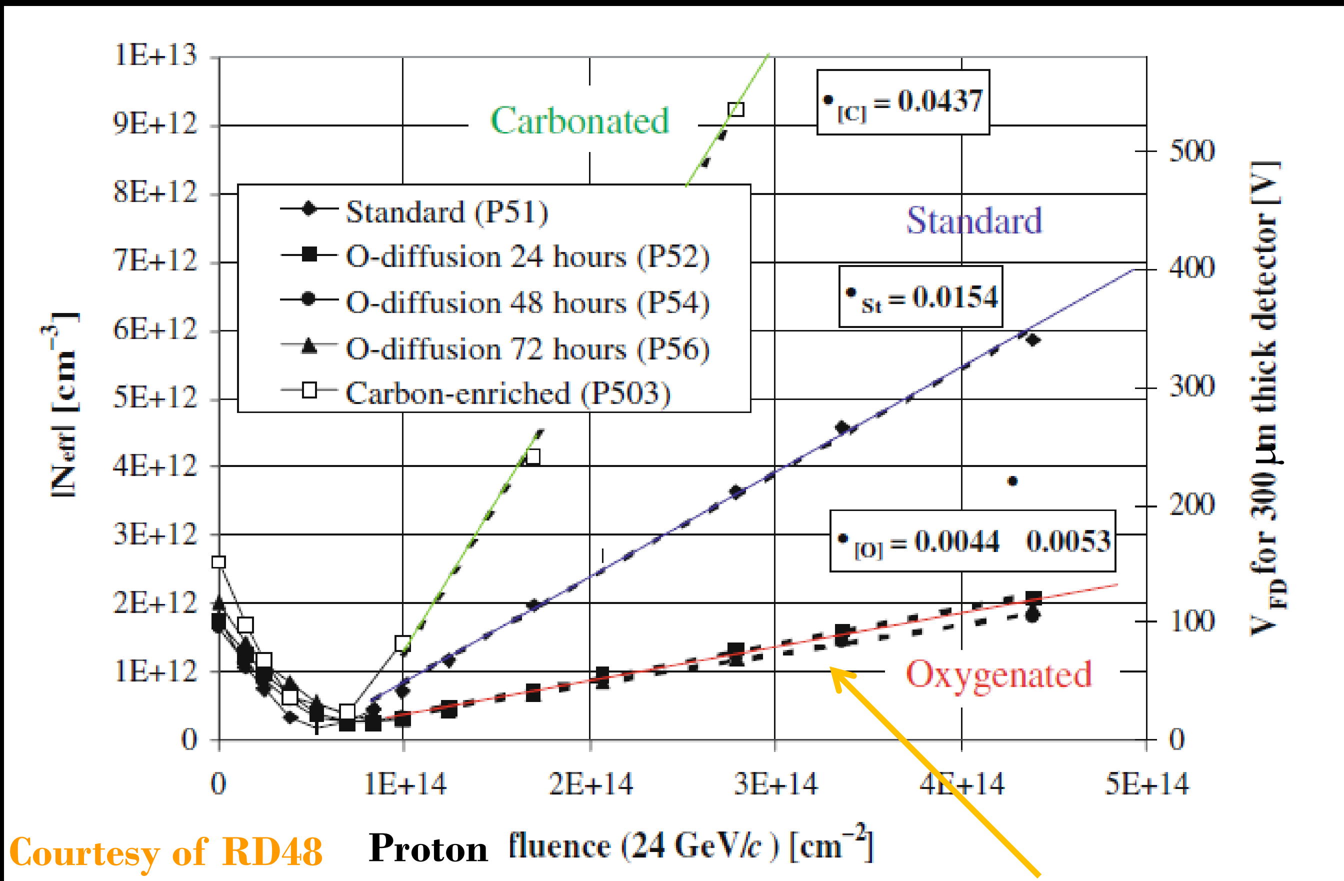
What about NIEL?

MATERIAL ENGINEERING
THE NEW MATERIALS
N-IN-P OR N-MCZ OR EPI

Oxygen is important! Material engineering

Today &Tomorrow

SPIEGEL, Leonard	A Program to Determine the Feasibility of MCz silicon as a Detector Material for Super-LHC Tracker Volumes



Oxygenating technique deployed in current LHC pixel detectors

Promising for the future

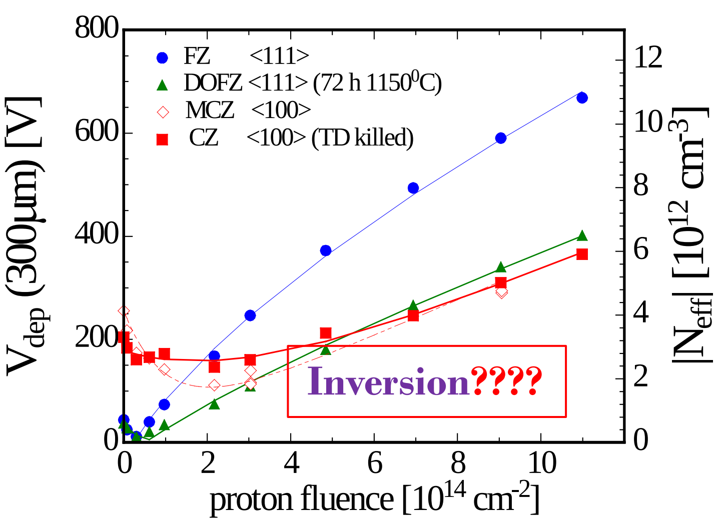
- E.g. Cz & MCz, oxygen enriched EPI material
  - Natural high oxygen content

That looks damn good!

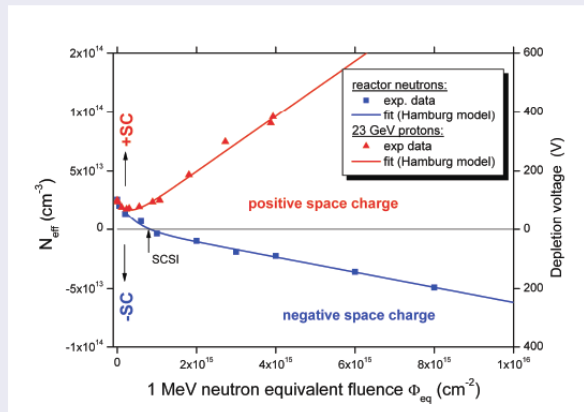
Inversion?????

Epitaxial silicon irradiated with 23 GeV protons vs reactor neutrons

24 GeV/c proton irradiation (n-type silicon)

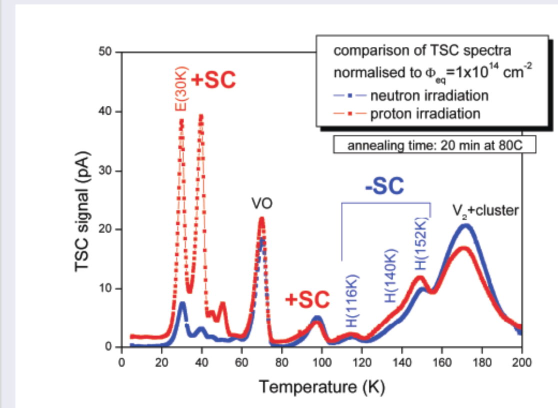


delopment of N_{eff} for EPI-DO after neutron and proton irradiation



I. Pintilie, et al., to be published.

TSC results after neutron and proton irradiation



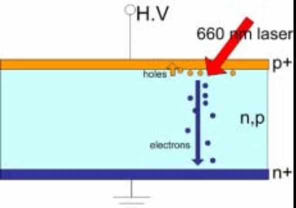
- SCSI after neutrons but not after protons
- donor generation enhanced after proton irradiation

This behaviour can be understood qualitatively as a build up of donors, which overcompensates the (classical) introduction of acceptors

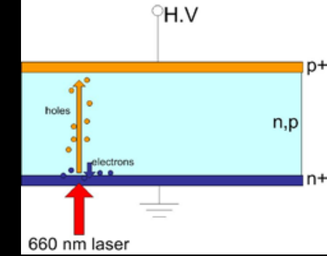
Mind, this effect affects N_{eff}~V_{dep} not trapping nor current

Obviously, the question of inversion or no-inversion has to be asked for individually per
- silicon type
- radiation source (p or n)

[A. Junkes, Hamburg University, RD50 Workshop June 2009]



TCT, E-Field, Depletion Zones

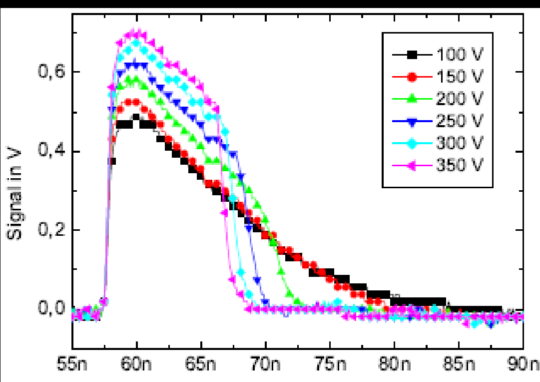


Long standing question: Does MCz, EPI, p-type invert or not?

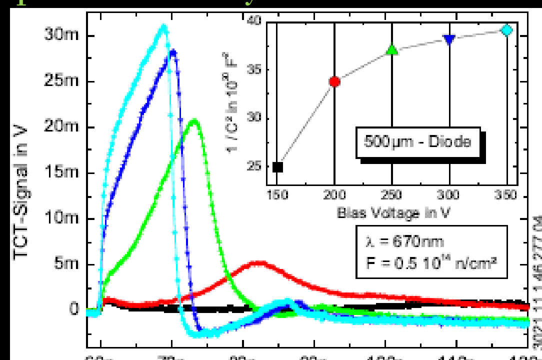
Different answers from different groups! <u>Answer Today: Neither!</u>

- The situation is more complex, we have a "double junction" structure!
  - CV scans are often ***not*** conclusive enough
  - TCT has to be interpreted correctly!

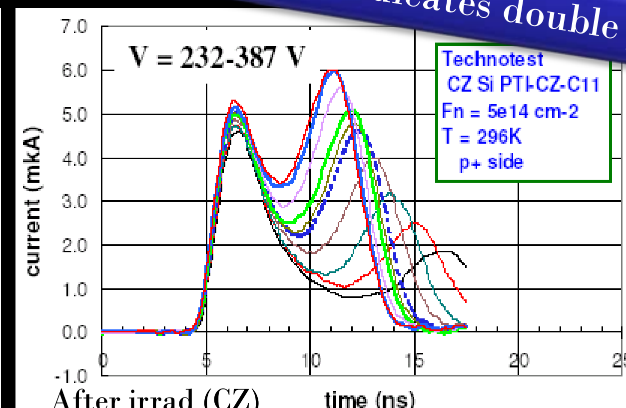
Double peak, indicates double junction



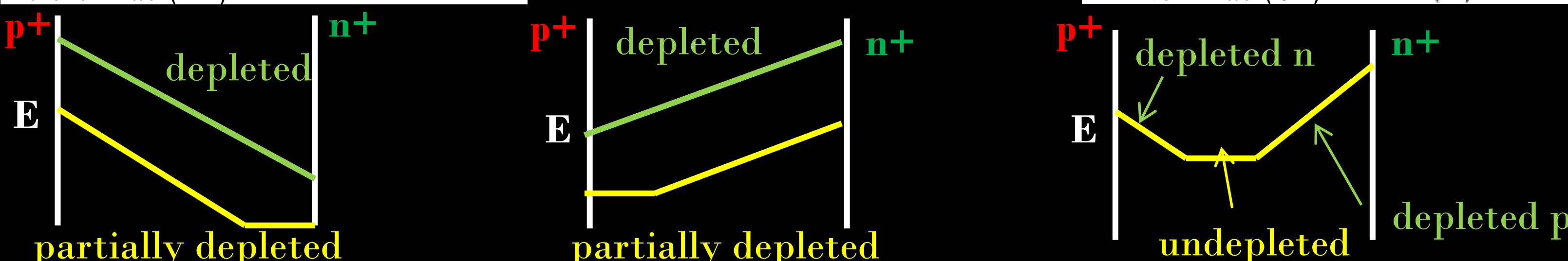
Before irrad (FZ)

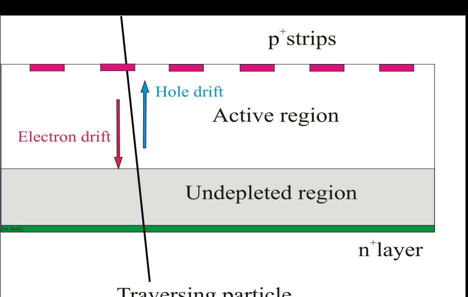


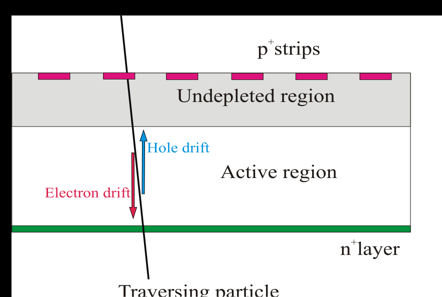
After irrad (FZ)

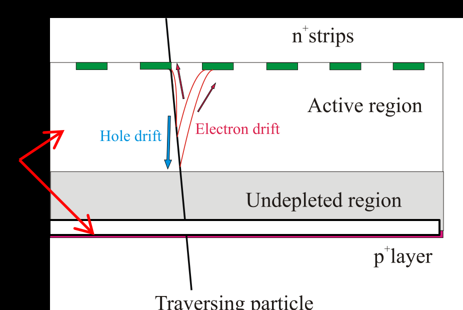


After irrad (CZ)









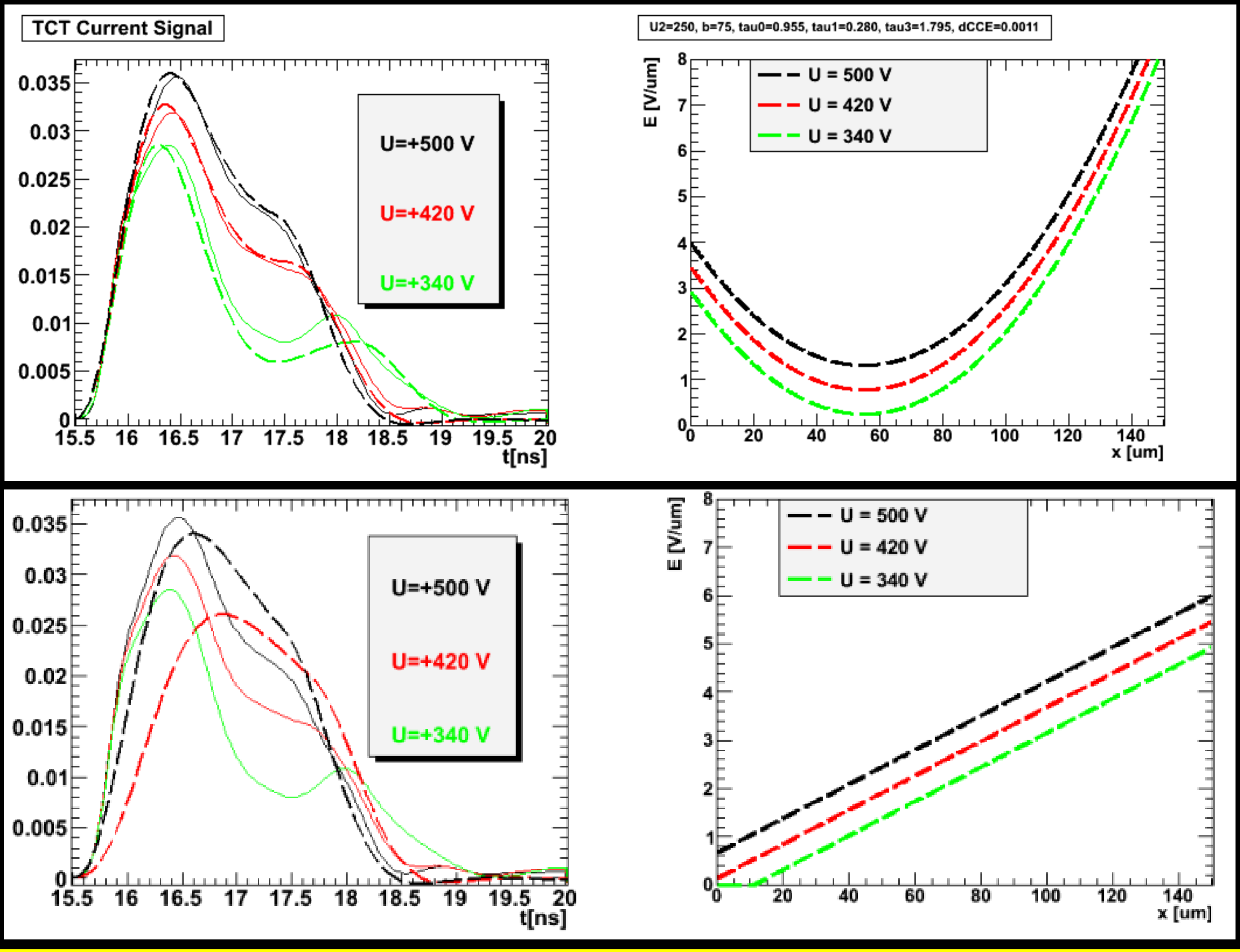
➔ V_{dep} is now an *abstract concept*

➔ CCE and S/N more meaningful

Is it a "simple" double junction? 2 linear E-fields?

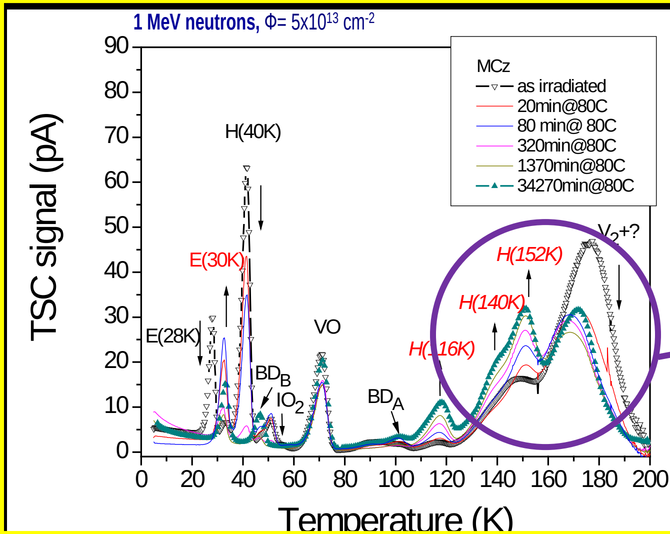
$\Phi_{eq}= 4\cdot 10^{15}$ cm^{-2} (EPI pad detector)

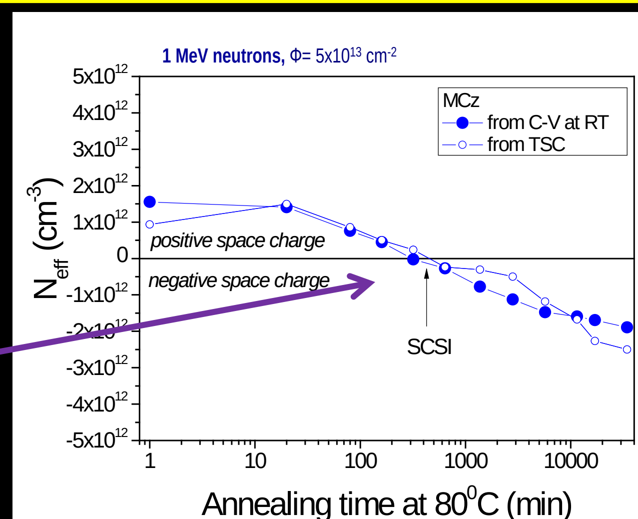
Comparing
Parabolic and Linear
Electric Field fits
the parabolic one wins!



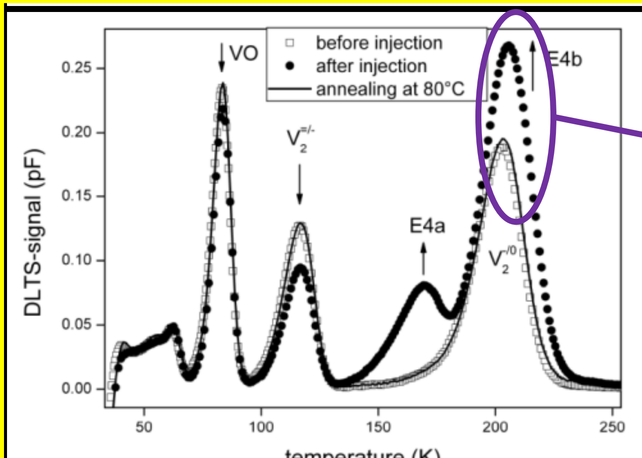
FROM Thomas Pöhlsen, Julian Becker, Eckhart Fretwurst, Robert Klanner, Jörn Lange (Hamburg University);15th RD50 Workshop, CERN, November 2009

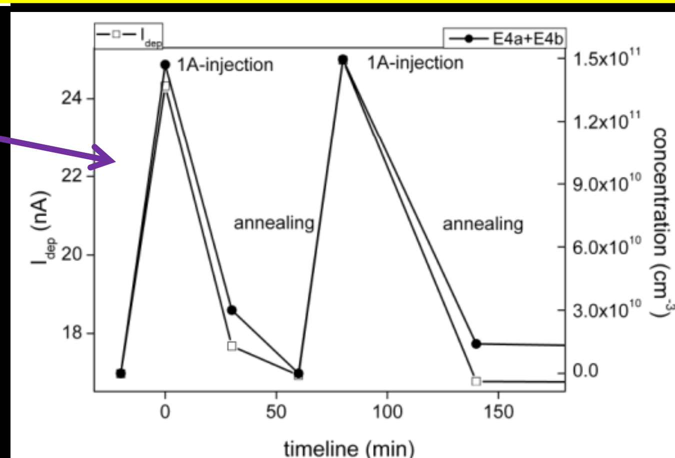
Our understanding between Microscopic defects and Macroscopic values grows monthly





- N_{eff} follows the concentration of acceptor levels (negative space charge) H116K, H140K, H152K which increase with annealing (see TSC plot)
- H116K, H140K, H152K do not form with γ radiation ➔ cluster defects





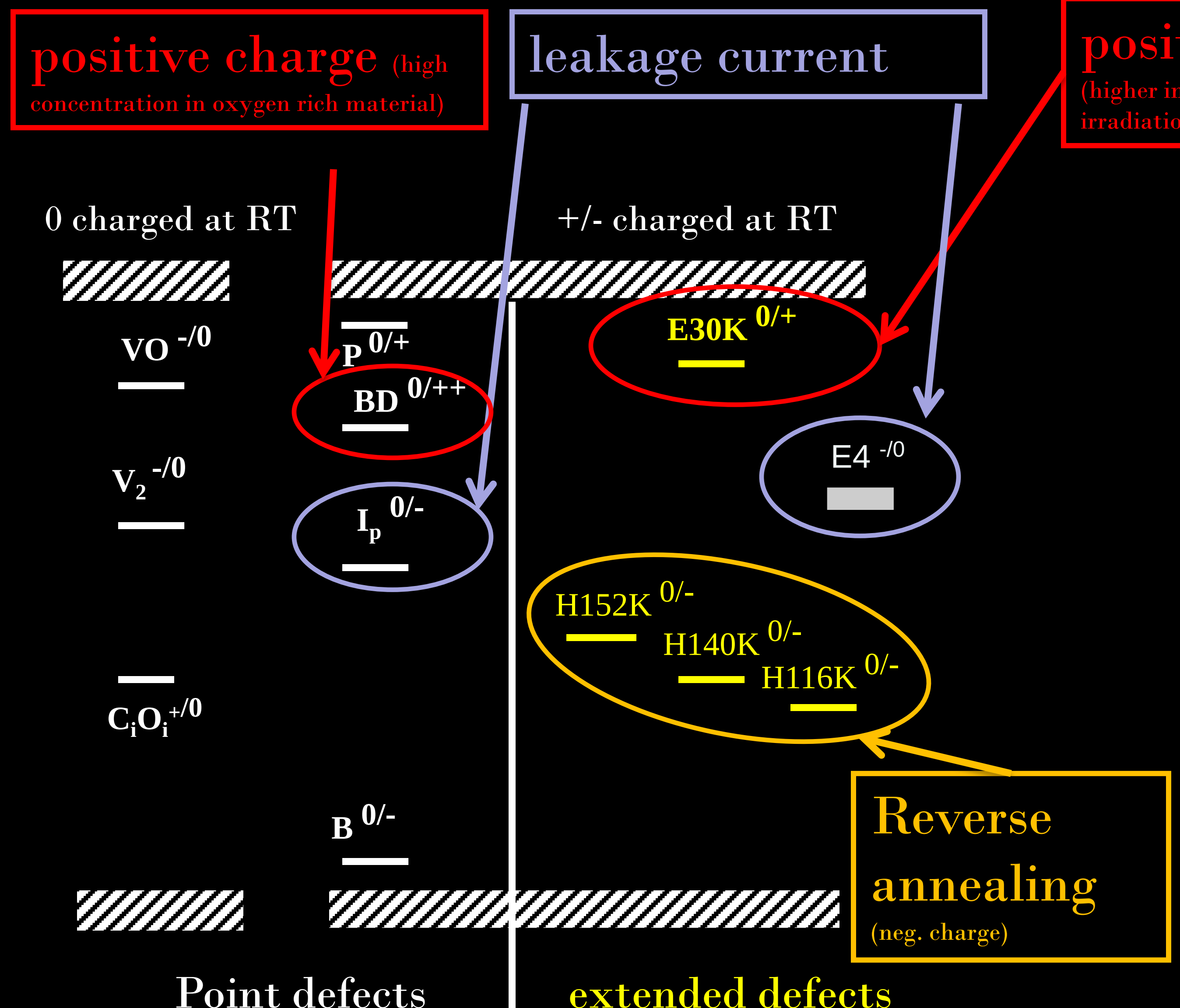
Current follows charge and discharge of E4 center

In a nutshell: we improve our understanding of the correlation between deep microscopic levels in the band and the macroscopic behaviour (current, Neff)

THX WODEAN

I. Pintilie, E. Fretwurst, G. Lindström, A. Junkes (e.g. *Appl. Phys. Lett. 92, 024101, 2008*)

Microcosmos meets Macrocosmos



<u>Point defects</u>

- $E_i^{BD} = E_c - 0.225$ eV
- $\sigma_n^{BD} = 2.3 \cdot 10^{-14}$ cm^2

- $E_i^{I} = E_c - 0.545$ eV
  - $\sigma_n^{I} = 2.3 \cdot 10^{-14}$ cm^2
  - $\sigma p^{I} = 2.3 \cdot 10^{-14}$ cm^2

<u>Cluster related centers</u>

- $E_i^{116K} = E_v + 0.33$eV
- $\sigma_p^{116K} = 4 \cdot 10^{-14}$ cm^2

- $E_i^{140K} = E_v + 0.36$eV
- $\sigma_p^{140K} = 2.5 \cdot 10^{-15}$ cm^2

- $E_i^{152K} = E_v + 0.42$eV
- $\sigma_p^{152K} = 2.3 \cdot 10^{-14}$ cm^2

- $E_i^{30K} = E_c - 0.1$eV
- $\sigma_n^{30K} = 2.3 \cdot 10^{-14}$ cm^2

MCz silicon in mixed fields

- Protons predominantly induce defects that are positively charged
- Neutrons predominantly induce defects that are negatively charged
- Mixed Fields: Compensation?

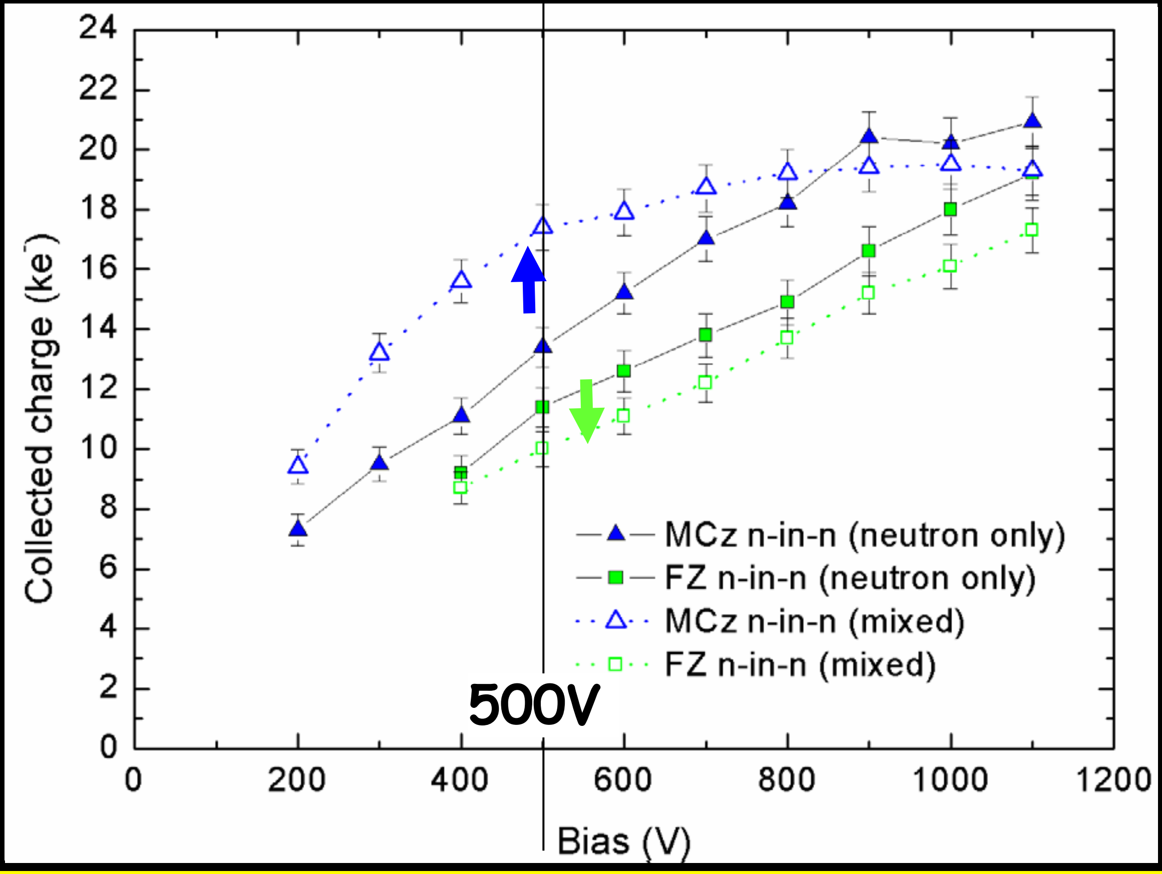
Mixed irradiations:

(a) $\Phi_{eq} = 5x10^{14}$ neutrons

(b) $\Phi_{eq} = 5x10^{14}$ protons

- FZ (n-in-n)
  - mixed irrad
  - Additive
    - $|N_{eff}|$ increases
- MCz (n-in-n)
  - mixed irrad
  - Compensating
    - $|N_{eff}|$ decreases

[T. Affolder et al. RD50 Workshop, Nov.2008]



Niel (non ionizing energy loss)

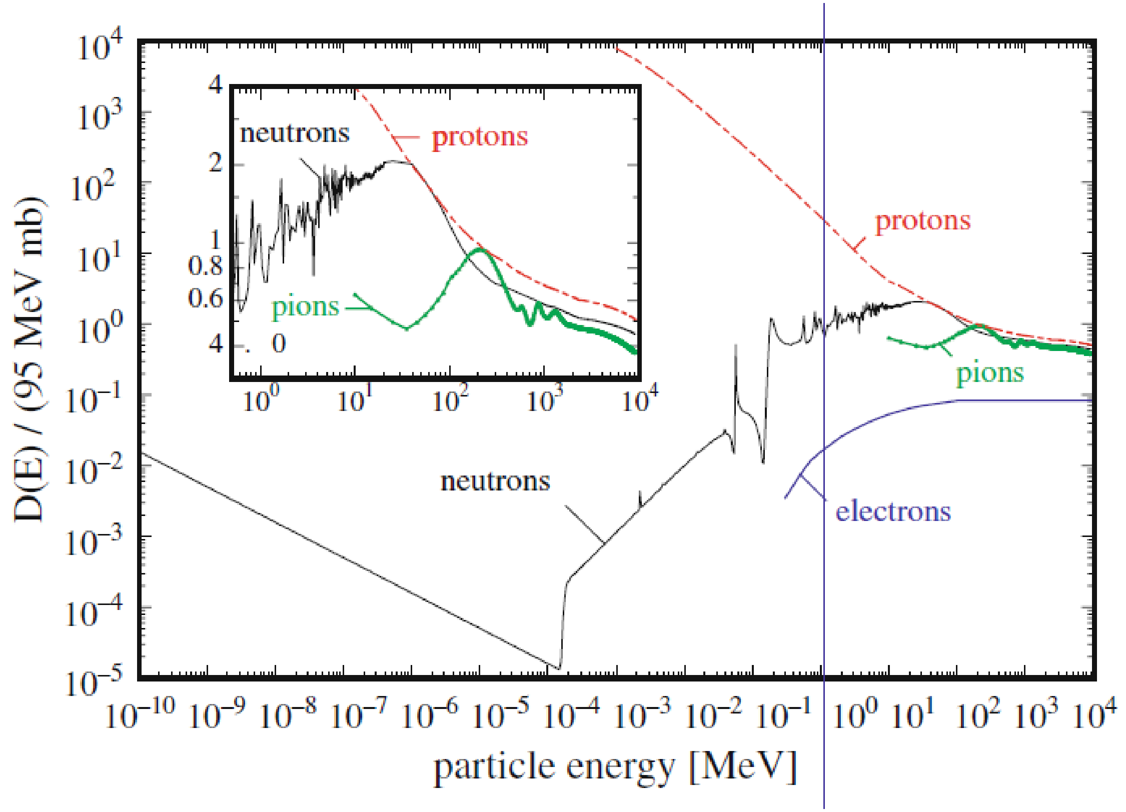
- Obviously, the "old" Mantra is not really true for new materials!
- Charged particles damage differently
- Neutrons may even compensate Proton damage
- It's still useful
  - E.g. for different proton energies
  - Leakage Current (Hadrons)
- ???????
  - There is still much surprise and fun in the game

~~**Mantra:**~~

~~With κ you can scale to~~

~~"1 MeV neutron equivalent"~~

$$\kappa = \frac{\int D(E)\phi(E)dE}{95MeV\,mb \cdot \Phi} = \frac{\Phi_{eq}}{\Phi}$$



➔ New materials are more radiation hard; but for each new sensor material, one always has to evaluate radiation hardness for neutrons and charged hadrons separately. Especially important for SLHC studies!

What is the SLHC challenge?

NOW, HOW DOES CCE EVOLVE WITH IRRADIATION & TIME

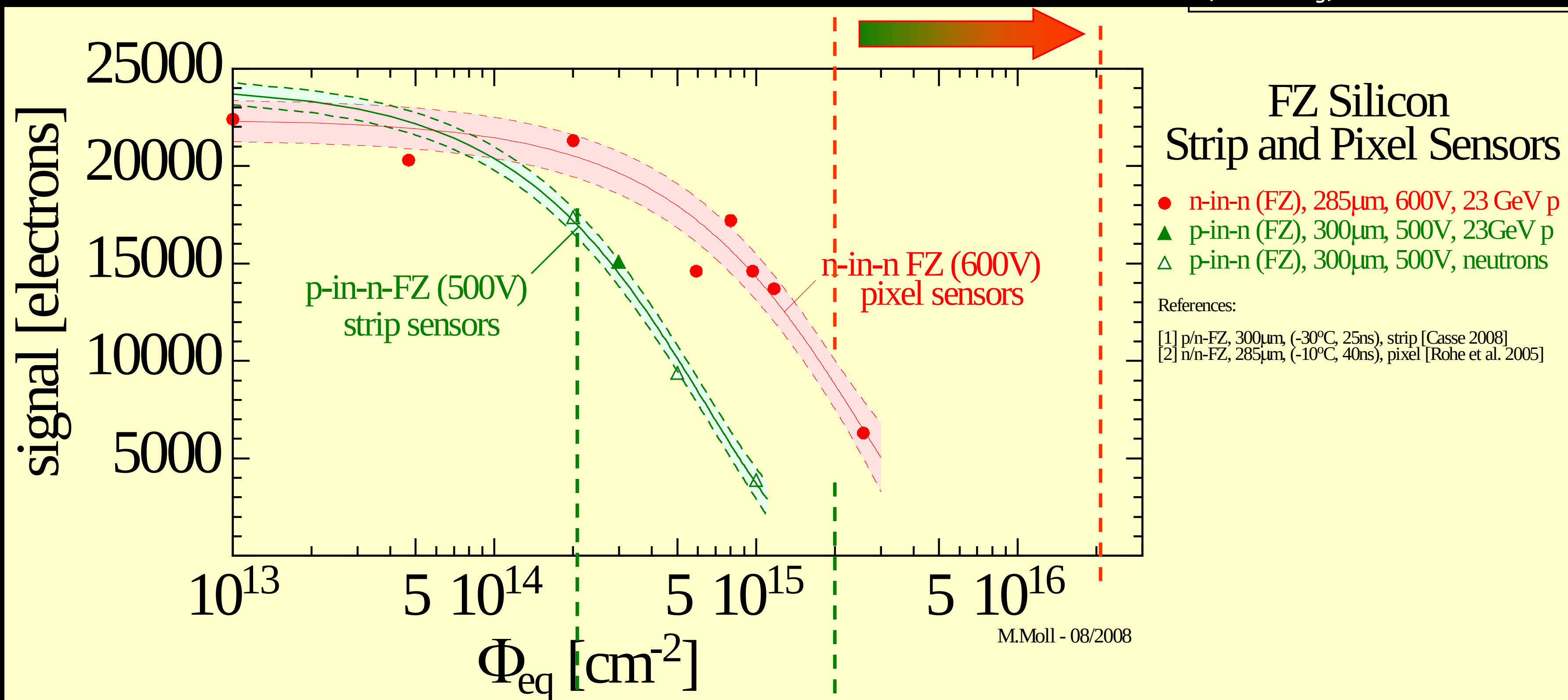
Signal degradation for LHC & SLHC Sensors

Today

Tomorrow

Pixel sensors:
max. cumulated fluence for LHC and SLHC

Note: Measured partly under different conditions! Lines to guide the eye (no modeling)!

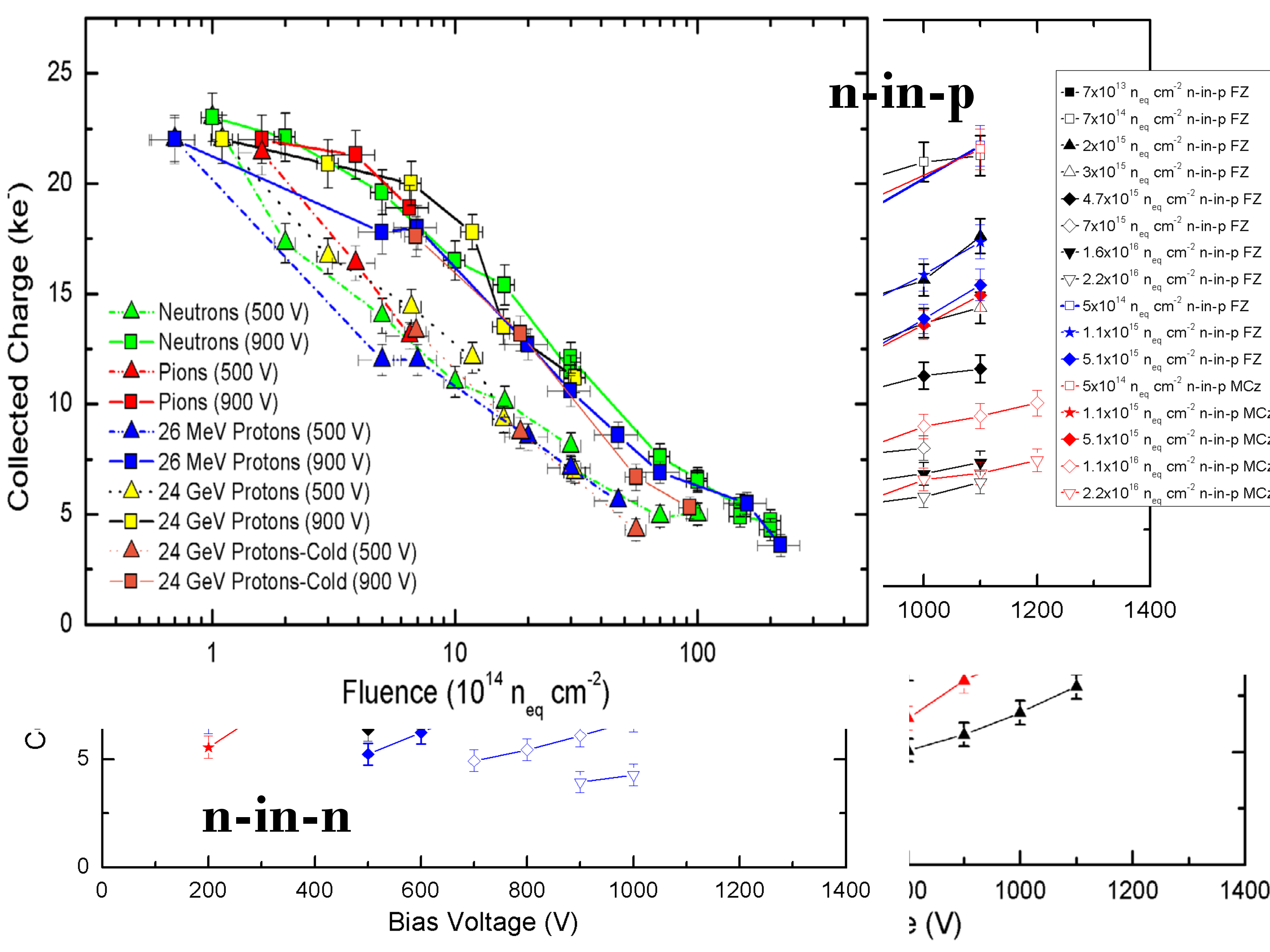


Strip sensors:
max. cumulated fluence for LHC and SLHC

SLHC will need more radiation tolerant tracking detector concepts!

Boundary conditions & other challenges: Granularity, Powering, Cooling, Connectivity, Triggering, Low mass, Low cost!

From RD50 (M. Moll)

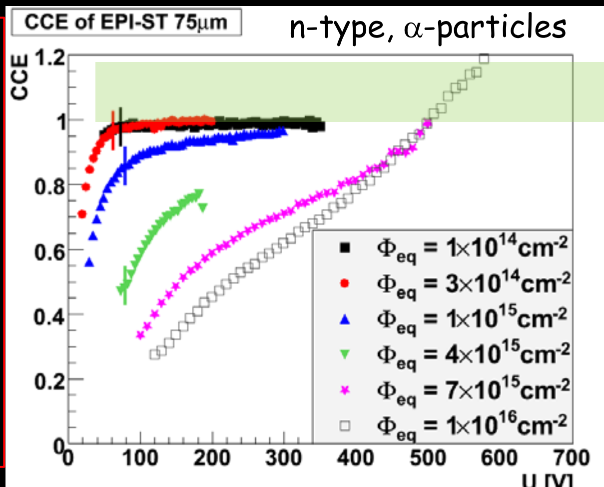


n-in-p
n-in-n
Collected Charge (ke⁻)
Fluence (10^14 n_eq cm^-2)
Bias Voltage (V)
Neutrons (500 V)
Neutrons (900 V)
Pions (500 V)
Pions (900 V)
26 MeV Protons (500 V)
26 MeV Protons (900 V)
24 GeV Protons (500 V)
24 GeV Protons (900 V)
24 GeV Protons-Cold (500 V)
24 GeV Protons-Cold (900 V)
7x10^13 n_eq cm^-2 n-in-p FZ
7x10^14 n_eq cm^-2 n-in-p FZ
2x10^15 n_eq cm^-2 n-in-p FZ
3x10^15 n_eq cm^-2 n-in-p FZ
4.7x10^15 n_eq cm^-2 n-in-p FZ
7x10^15 n_eq cm^-2 n-in-p FZ
1.6x10^16 n_eq cm^-2 n-in-p FZ
2.2x10^16 n_eq cm^-2 n-in-p FZ
5x10^14 n_eq cm^-2 n-in-p FZ
1.1x10^15 n_eq cm^-2 n-in-p FZ
5.1x10^15 n_eq cm^-2 n-in-p FZ
5x10^14 n_eq cm^-2 n-in-p MCz
1.1x10^15 n_eq cm^-2 n-in-p MCz
5.1x10^15 n_eq cm^-2 n-in-p MCz
1.1x10^16 n_eq cm^-2 n-in-p MCz
2.2x10^16 n_eq cm^-2 n-in-p MCz

Surprise:
SIGNAL AMPLIFICATION

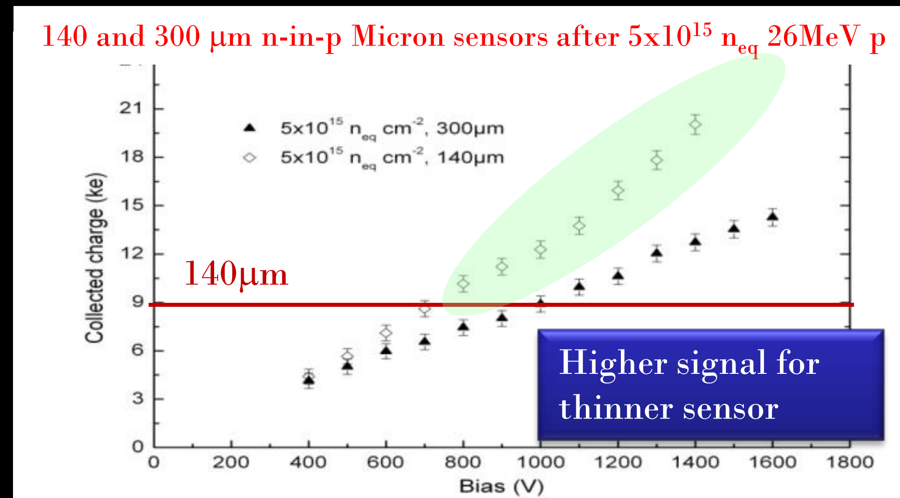
LANGE, Jörn	Charge multiplication in radiation-damaged epitaxial silicon detectors

Joern Lange, RD50 2009, EPI



Higher signal after irradiation

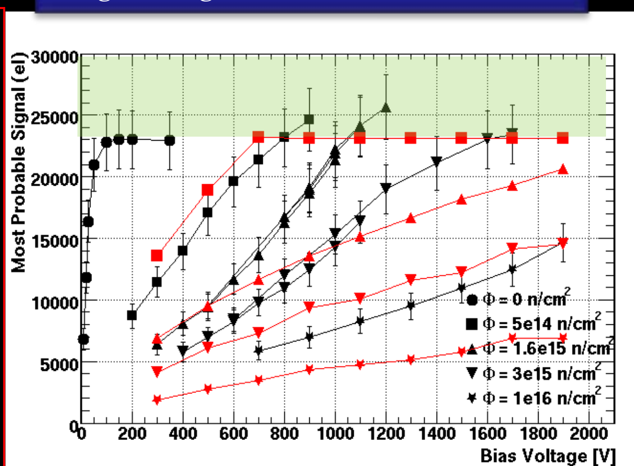
Not only the whole charge is recovered, but increased by $f = 1.75$



Higher signal for thinner sensor

G. Casse, Vertex 2009, n-in-p

I. Mandić et al., RESMDD 2008

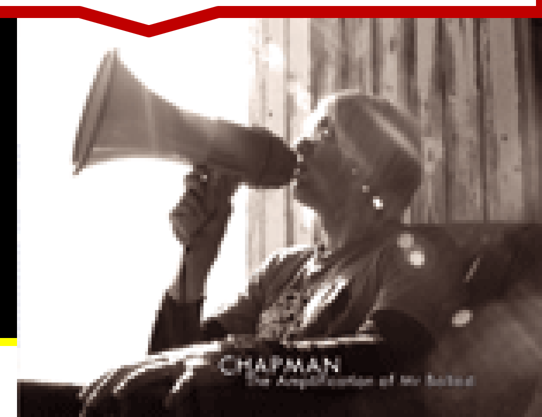


- More signal after irradiation
  - DOUBLING!!!!!
- Not compatible with trapping

- What about
  - Current?
  - Noise?

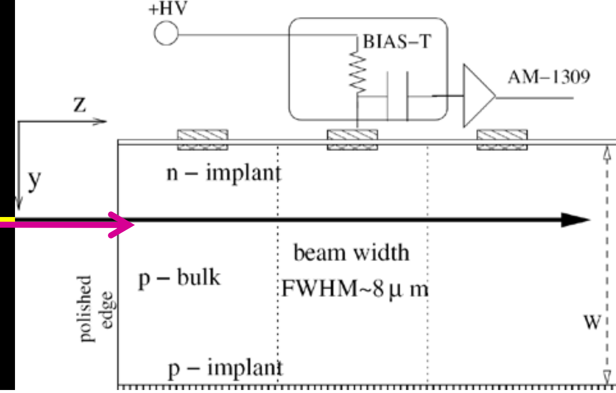
→ Further investigation

If you don't hear me!
I'll speak/signal **louder**

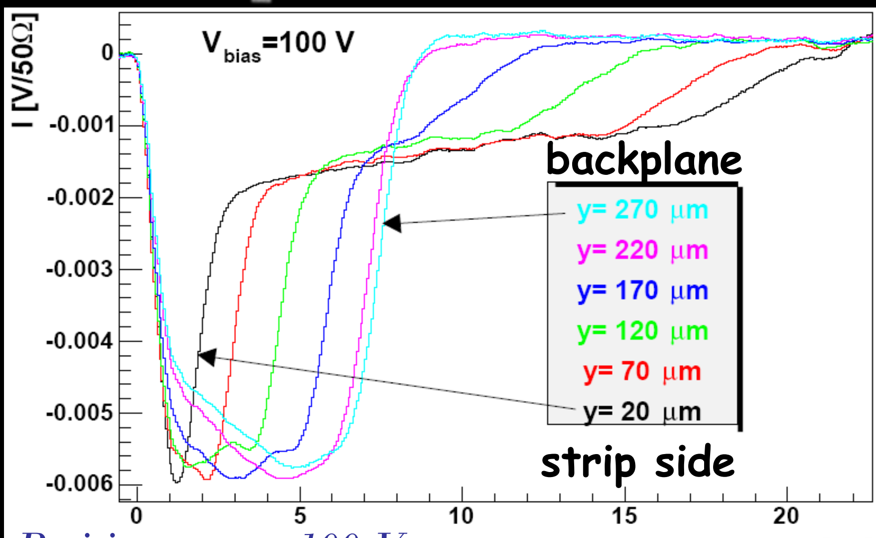


A new tool: EDGE TCT

IR Laser on edge

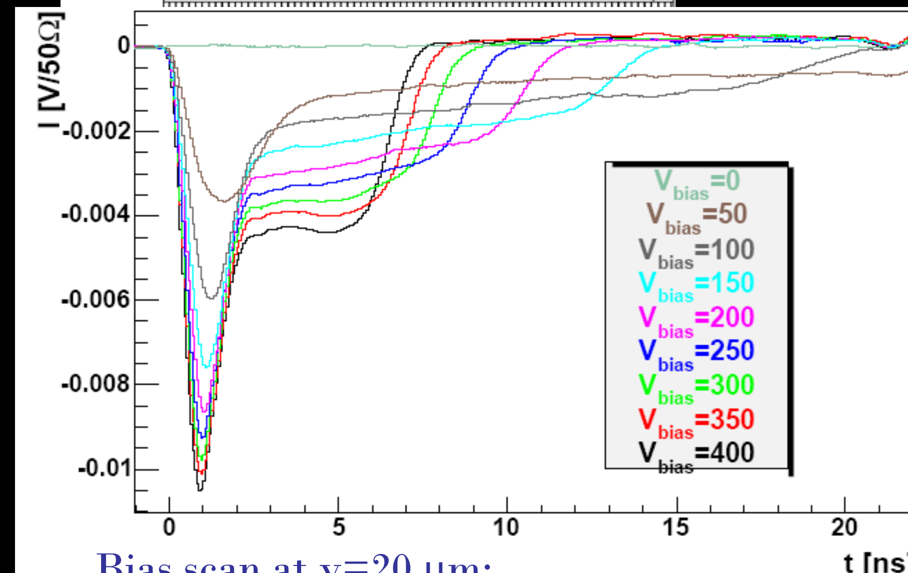


Current pulses – non-irradiated!



Position scan at 100 V:

- Long tail from drift of holes
- Current due to electron drift is superimposed!
- Shortest signal at y=220 μm (equal drift length of electrons and holes)

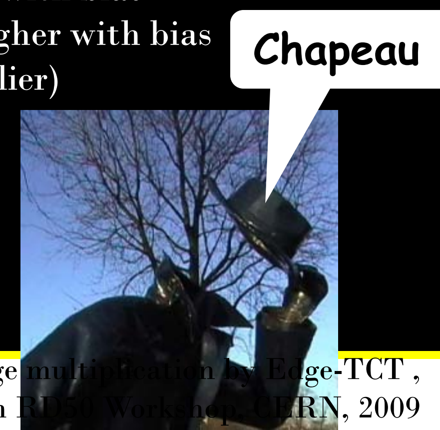


Bias scan at y=20 μm:

- Hole tail is getting shorter with bias
- Electron peak is getting higher with bias (the peak time is coming earlier)

Edge-TCT Method allows furthermore determination of

- Velocity profile
- Trapping time
- Electrical field
- Charge Collection Profile

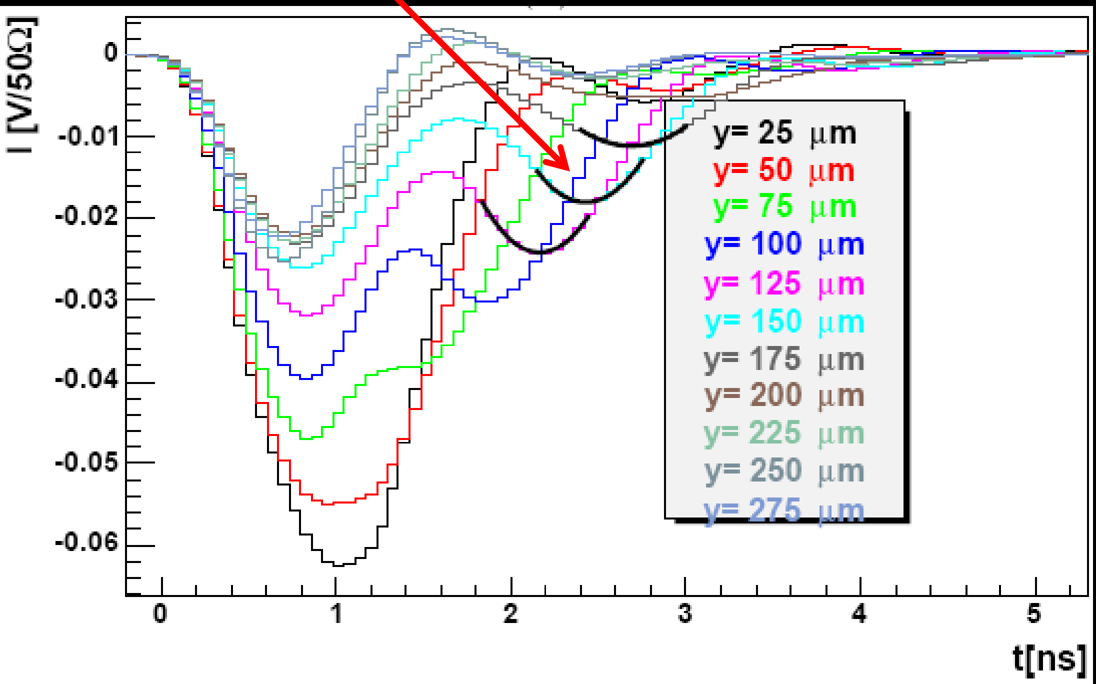


G. Kramberger, Investigation of electric field and evidence of charge multiplication by Edge-TCT, 15th RD50 Workshop, CERN, 2009

Edge TCT and amplification

n-in-p; $\Phi_{eq} = 5 \cdot 10^{15}\ cm^{-2}$

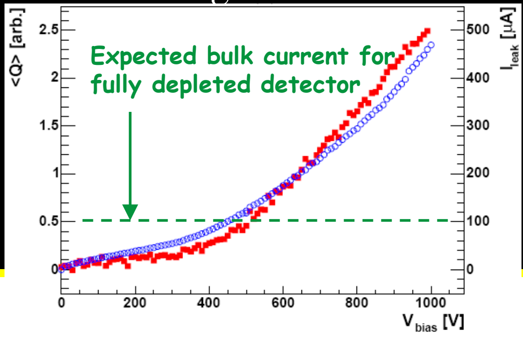
- 1st observation: A second peak emerges in the induced current signals which is related to electron drift (it shifts when moving away from the strip)!
  - It can only be explained by electrons entering very high field at the strips where they multiply. The second peak is a consequence of holes drifting away from the strips!



2nd observation: Velocity and electric field profiles do not give a consistent picture if number of drifting carriers does not increase in some parts of the detector. (derived value, not shown here)

3rd observation: The peak in the initial current is prolonged at higher voltages. Drift of multiplied holes prolongs the signal. (measured at y=30 μm) (derived value, not shown here)

4th observation: Charge collection and Q_{mip} correlation with leakage current (derived value)

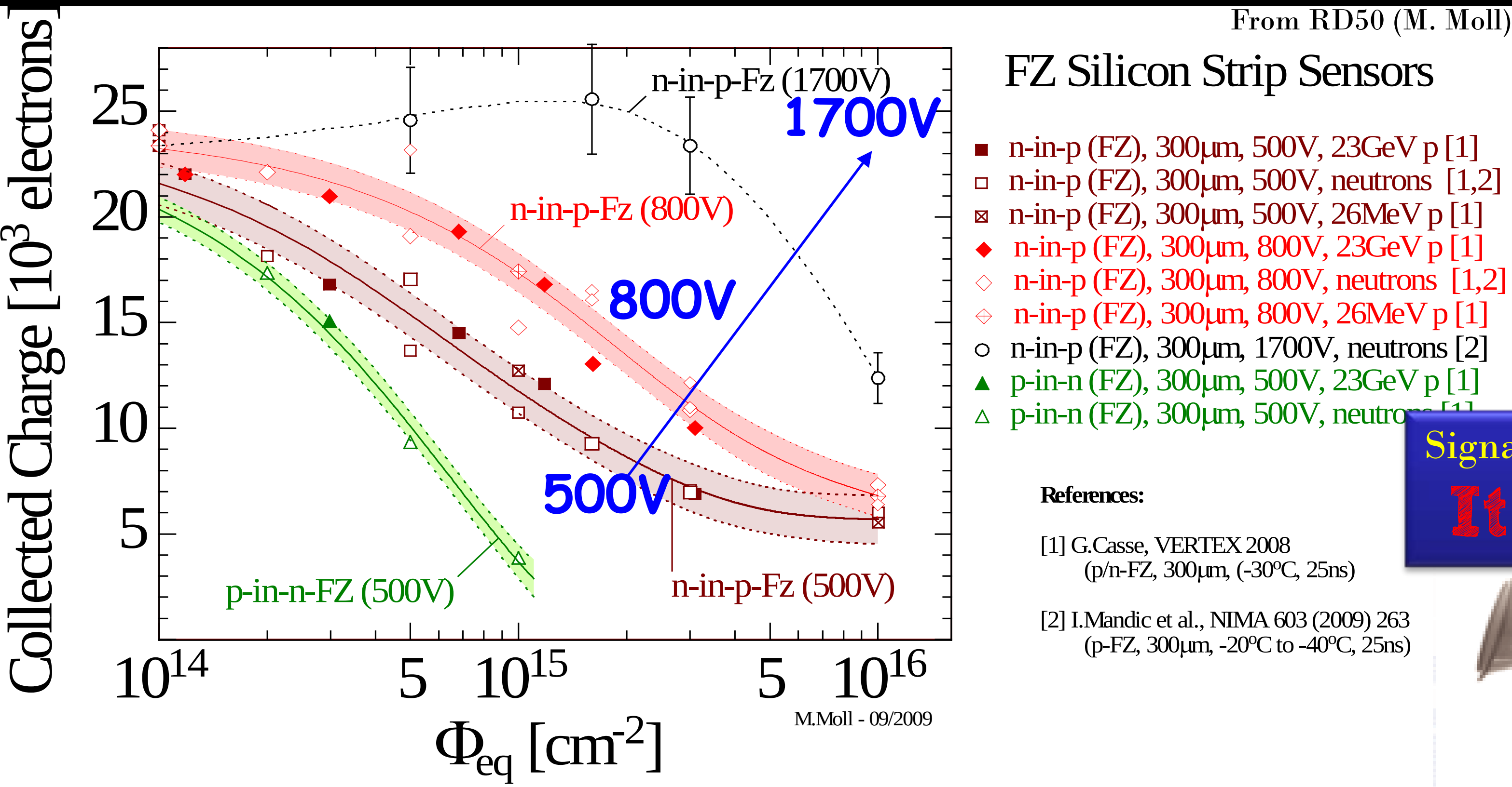


G. Kramberger, Investigation of electric field and evidence of charge multiplication by Edge-TCT , 15th RD50 Workshop, CERN, 2009

Good performance of planar sensors at high fluence

- Why do planar silicon sensors with n-strip readout give such high signals after high levels (>10^{15} cm^{-2} p/cm^2) of irradiation?
  - Extrapolation of charge trapping parameters obtained at lower fluences would predict much lower signal! Signal even higher than MIP deposit!
  - New Mantra: VOLTAGE, VOLTAGE, just increase VOLTAGE

From RD50 (M. Moll)



Signal amplification?!?!

It exists!!!!

Future will tell us, *if* amplification is really "a" correct operating mode!

Mantra for LHC: stay cold always except for very short periods — **Today**

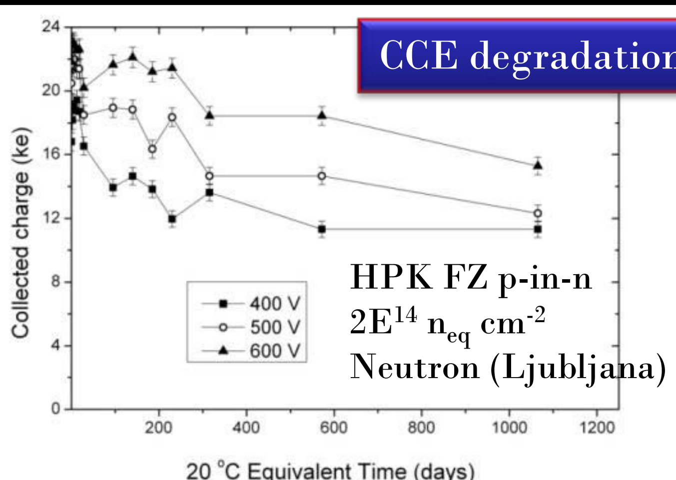
Mantra for SLHC: stay warm during maintenance periods????? — **Tomorrow**

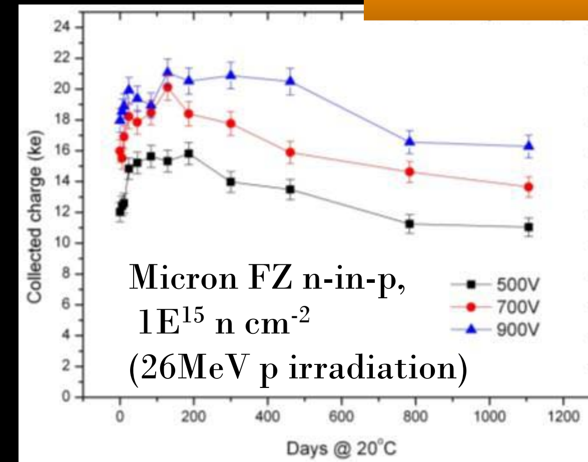
ANNEALING

Fine CCE annealing step study

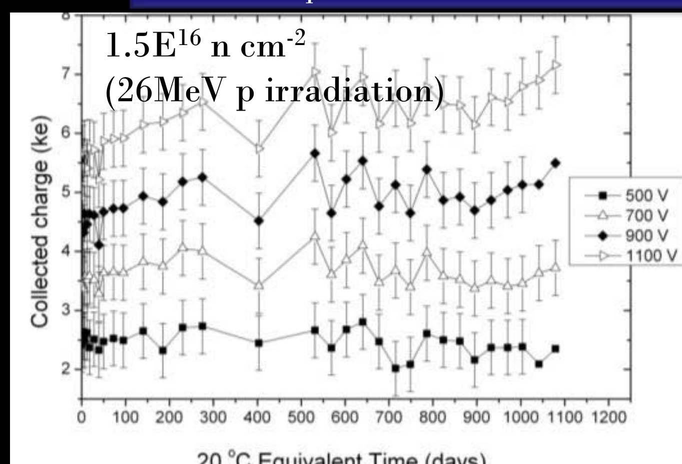
Tomorrow

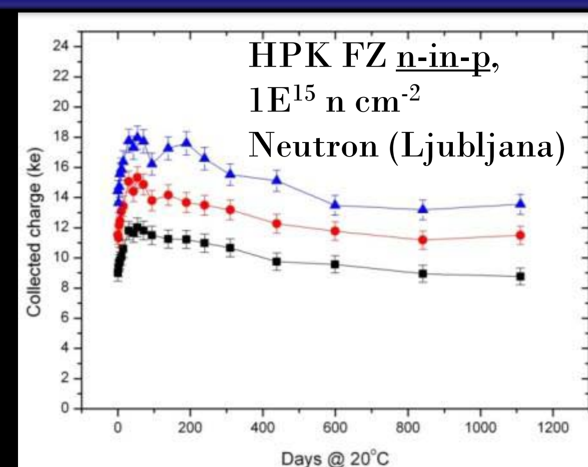
CCE degradation for p-in-n





NO CCE degradation for n-in-p (two vendors) (proton & neutron) up to Φ_{eq}= 1E15 & 1E16





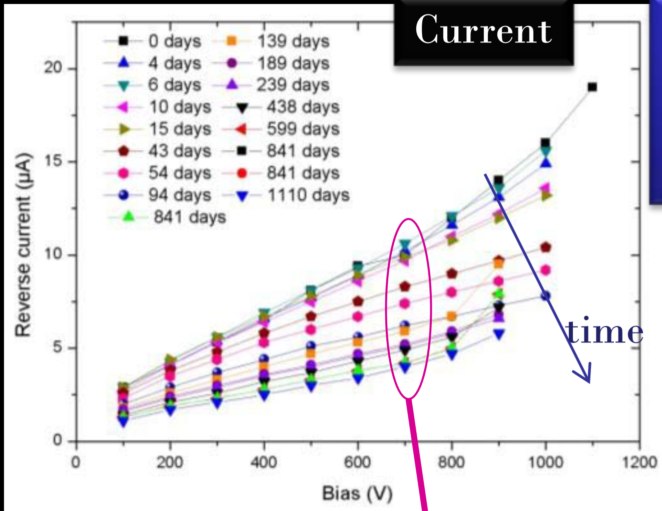
Be aware, voltages applied are way below depletion voltage

G. Casse; Vertex 2009

Fine step annealing study of current & shot noise & S/N

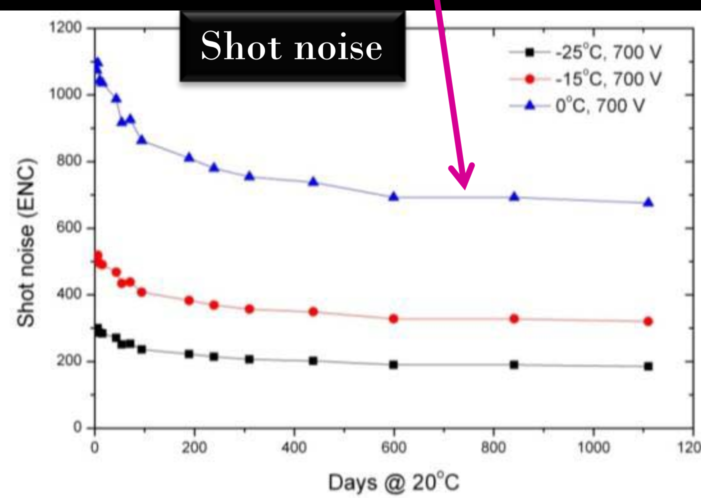
FZ n-in-p, $1E^{15}$ n cm^{-2}

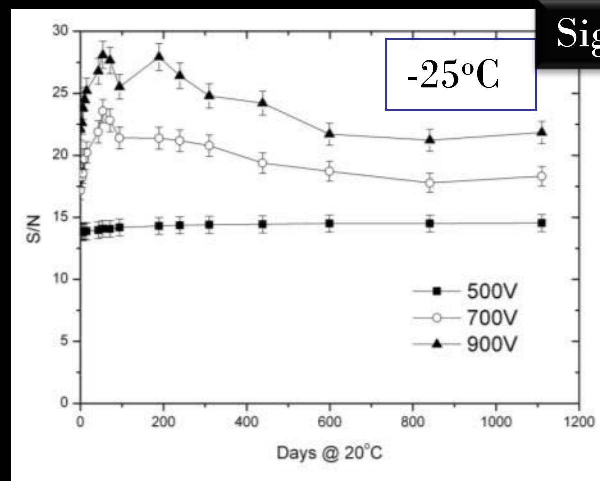
Tomorrow

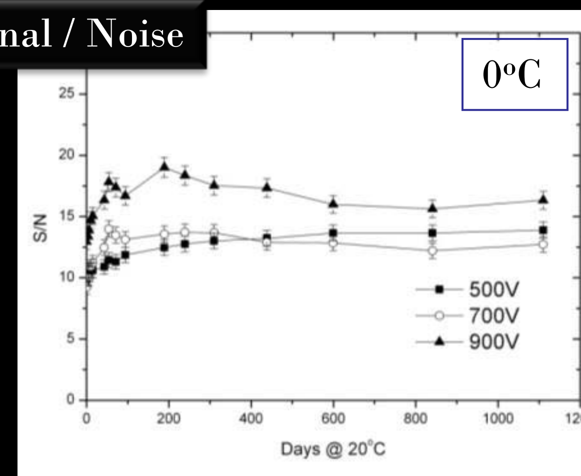


As usual, current decays

- ➔ power saving
- ➔ decrease of shot noise







Shot noise decreases with time (as does current)

S/N looks pretty stable to me

Can we claim

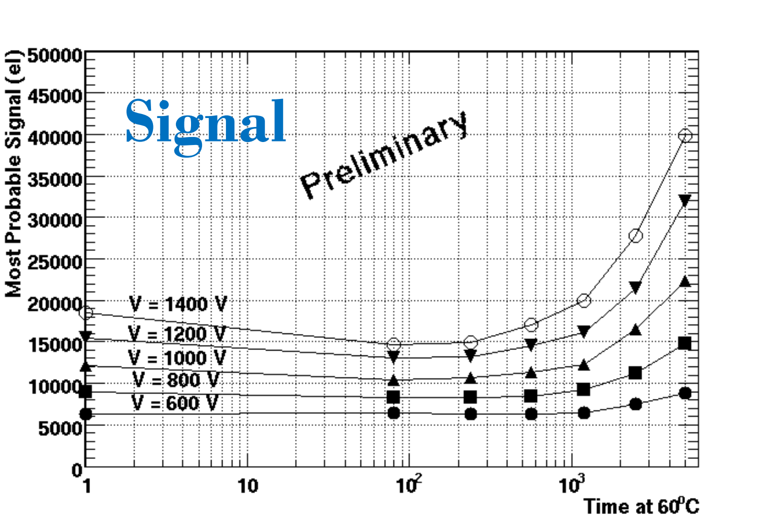
- (technically) to have no more need to deep frost sensors (during maintenance)?
- power reduction via warm up (annealing)?

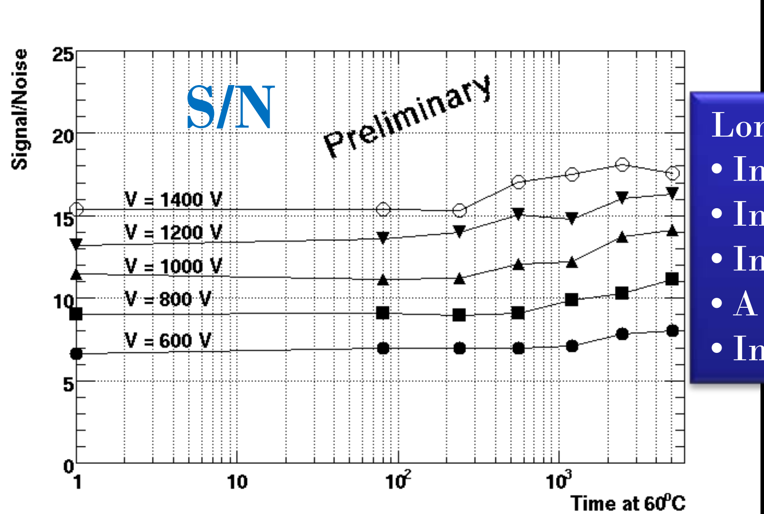
G. Casse; Vertex 2009

Another Annealing study

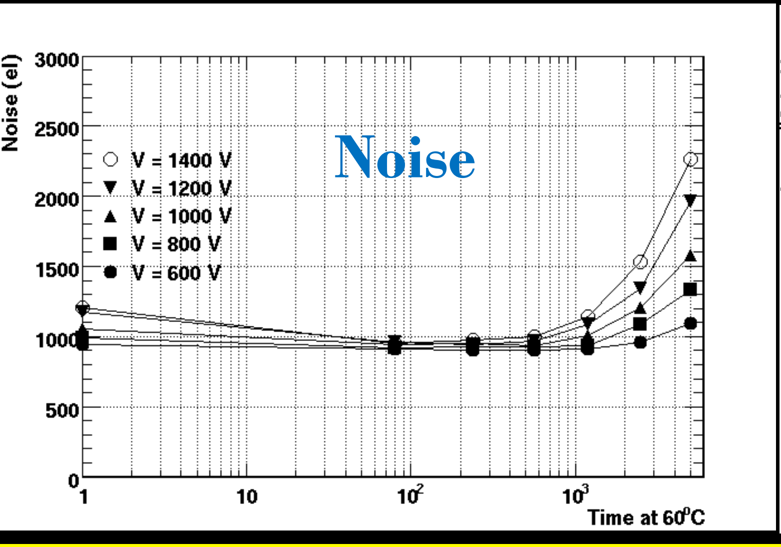
Tomorrow

HPK FZ n-in-p neutron Φ = $5 \cdot 10^{15}$ n/cm²

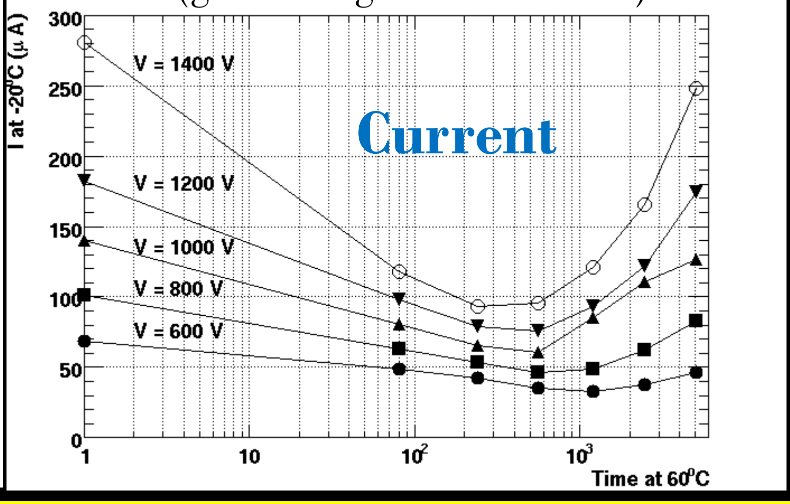




Long annealing ➔
- Increase of signal
- Increase of Noise
- Increase of current
- A bit increase of S/N
- Increase of Amplification?



Current (guard ring not connected) at -20°



Remember, the other annealing showed a decrease in current!

➔ Further study needed!

Summary "radiation excursion"

- Today:
  - Radiation damage for n-FZ understood on a detail level
    - See TEVATRON & LHC
    - Evolution of current and V_{dep} (trapping *no* issue yet)
    - Oxygen is beneficial!
    - NIEL Mantra: With κ you can scale to "1 MeV neutron equivalent"
      - Not to forget today's DOFZ pixel, where NIEL already does not work!
- Tomorrow
  - With new materials, we encountered new surprises
    - No SCSI
      - Double junction
    - NIEL is not really valid anymore: acceptor & donor creation
    - V_{dep} is a more and more *abstract* concept
      - S/N is the more important parameter
        - » In the end only Resolution, Efficiency & Power counts
    - Annealing is probably not so bad (for n-implant readout)
      - No change in CCE but decrease in current
    - Can we utilize the existing amplification feature?
    - Recipes for the future SLHC detectors exist

Today

Tomorrow

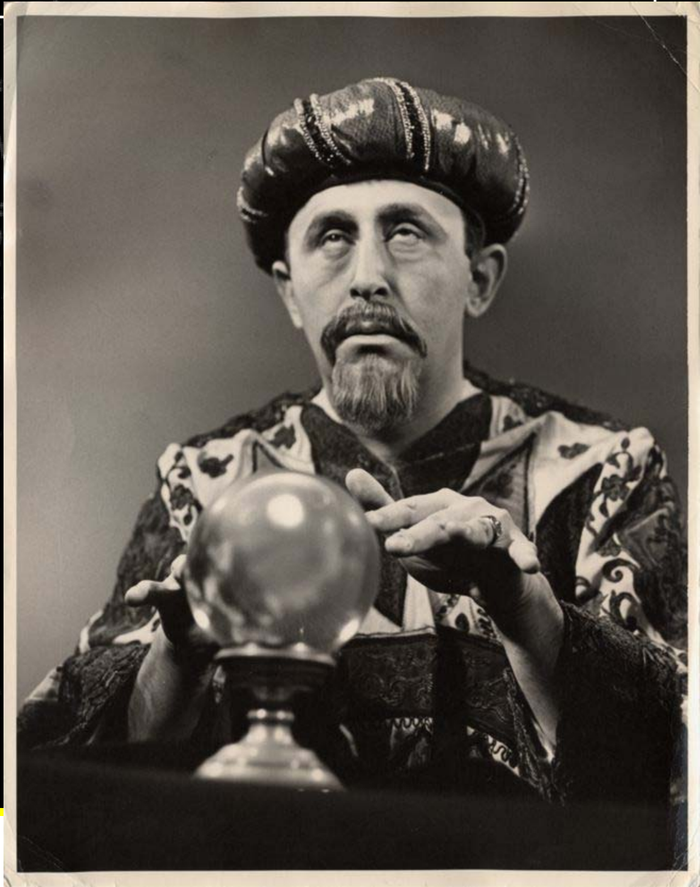
SEIDEL, Sally	Silicon Detectors for the sLHC
SPIEGEL, Leonard	A Program to Determine the Feasibility of MCz silicon as a Detector Material for Super-LHC Tracker Volumes
DOLEZAL, Zdenek	ATLAS Tracker Upgrade: Silicon Strip Detectors for the sLHC
Karl-Heinz Hoffmann	R&D on a novel sensor routing and test structure development
HAENSEL, Stephan	Tests of a Prototype of the Silicon Tracking System of the ILD Concept
FRIEDL, Markus	The Silicon Vertex Detector of the Belle-II Experiment

b-factories

SLHC

Linear Collider

TOMORROW??

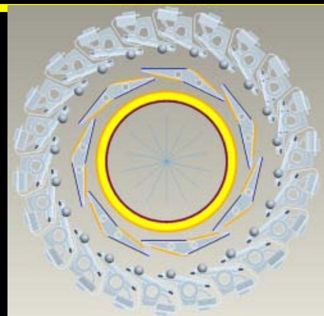


Next ATLAS, CMS & LHCB pixel (so called phase I)

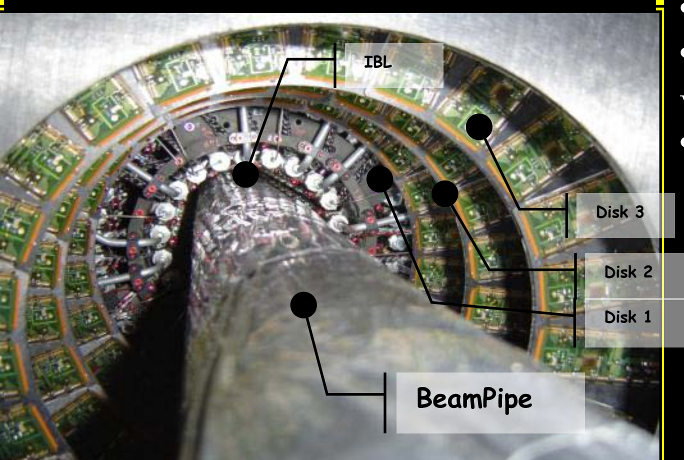
Tomorrow

ATLAS

ADD
Insertable B
Layer IBL



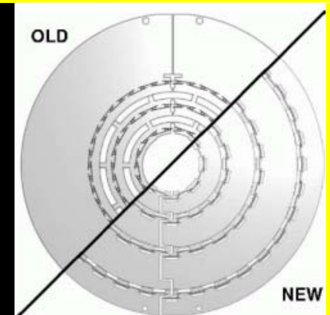
- Sensor surface ~ only 0.2 m^2
  - Planar; 3D; Diamond
- 1.5KW power cooled @ ~ -30→ - 40°C (evaporative cooling system)
- FE-14: Biggest chip in HEP to date (20.2mm x19mm)



CMS

EXCHANGE
full detector

3→ 4 layer
2 →3 disc

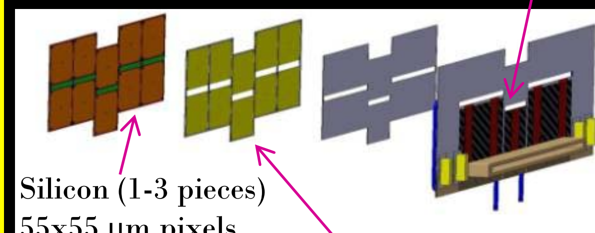


Phase I after ≈4? years operation:
- Same sensor as today (Planar n-in-n)
- 4-hits
- Ultra-light mechanics
  - 50% less material/layer
- CO_2 cooling
- One type of module
- Higher bandwidth readout over fine wires/optical links
- DC-DC

LHCB; VELO

EXCHANGE
full detector
- again very modern

Diamond as thermal plane



+ 800 µm pixels in areas under chip periphery

10 Timepix chips

Chip candidates:
- TIMEPIX or FPIX from Btev

Sensor candidates:
- n-in-n, n-in-p, 3D, diamond

Key aspect:
Readout of the full detector at 40 MHz → fully software-based trigger → flexibility.

and in the post-2010 Chamonix era, I cannot tell you *WHEN* phase I will be!

? ? SLHC Phase II

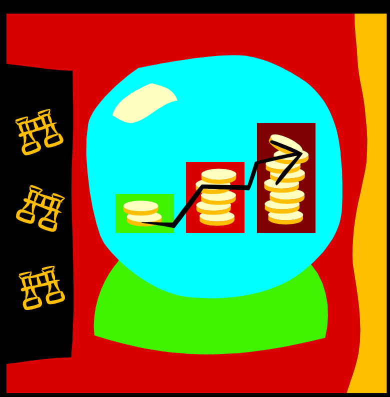
Radiation hardness

Radiation length X0

Occupancy

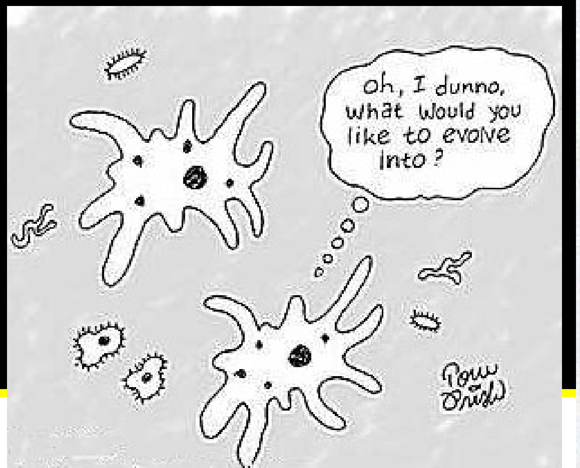
? ? ?

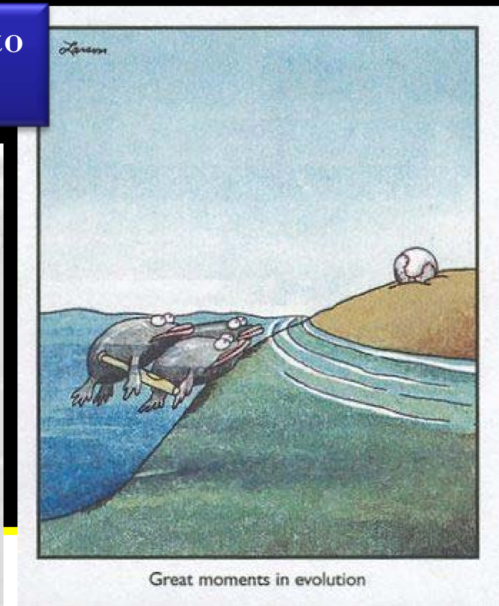
Every Crystal Ball tells something different



A single common view is:
It'll be expensive

In any case, we have to evolve into a sensor concept that survives



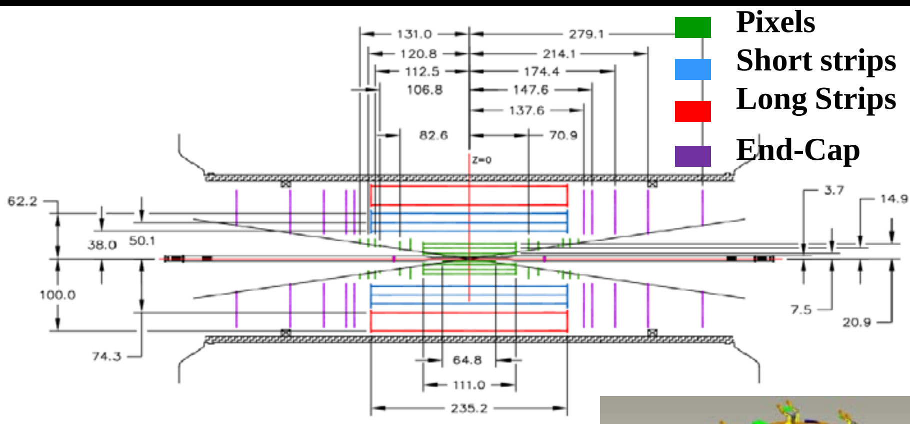


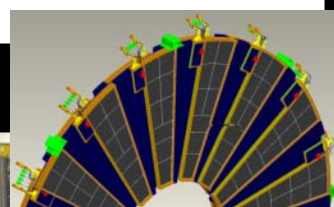
Radiation hardness

PHASE II
ATLAS & CMS

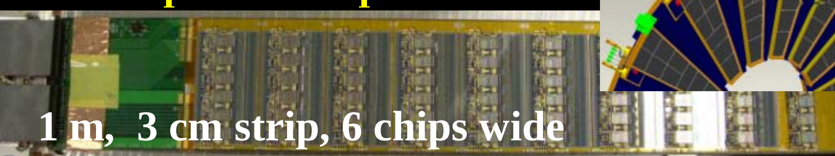
Tomorrow OR Later

All silicon tracker:
Design is very advanced! Lots of R&D already done!

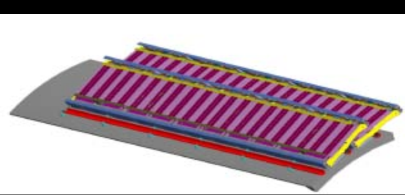




Stave & petal concept



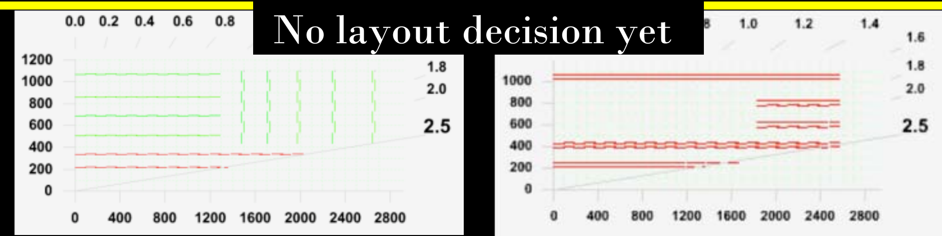
Supermodule concept



Short:

- p-FZ sensors
- 3D for inner pixel or ???
- Serial powering (or DC-DC)
- Improved cooling
  T_{Si}= -20°C (CO_2 or C_3F_8)

No layout decision yet

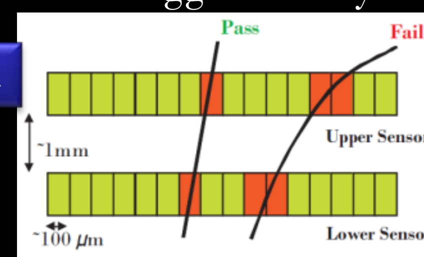


Short:

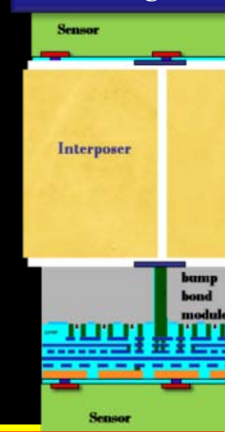
- no sensor decision yet: probably p-bulk → Investigate
  p-in-n-FZ(100µm, 200µm, 300µm), p-in-n-MCz(200µm),
  n-in-p-FZ(100µm, 200µm, 300µm), n-in-p-MCz(200µm),
  p-in-n EPI(75µm, 100µm), n-in-p EPI(75µm, 100µm)
- DC-DC powering!
- CO_2 cooling!
- Main challenge: First Level Silicon trigger
  - Reduce trigger rate by a factor 10 (p_T cut)

Integration

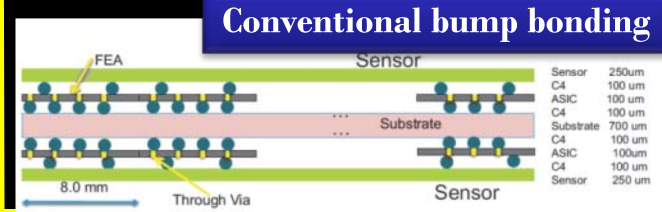
Method



3D integration



Conventional bump bonding



Bifurcation: Silicon pixels give Vertexing Silicon long pixels / short strips give Tracking

3D mature yet?

Introduced by: S.I. Parker et al., NIMA 395 (1997) 328

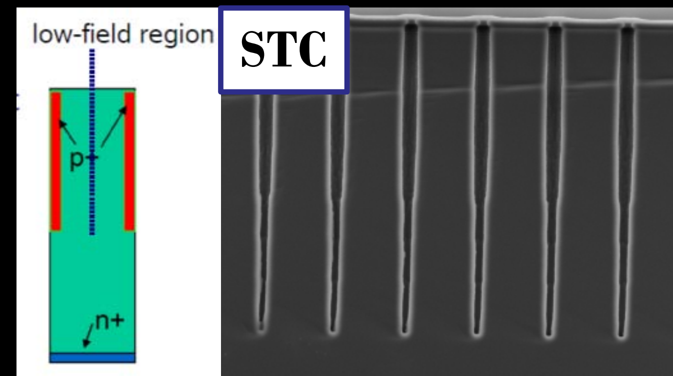
HANSSON, Per	Recent Test Beam Results of Radiation Hard 3D Silicon Pixel Sensors
PELLEGRINI, Guilio	Charge collection efficiencies of 3D detectors irradiated at SLHC fluences and testbeam operation results

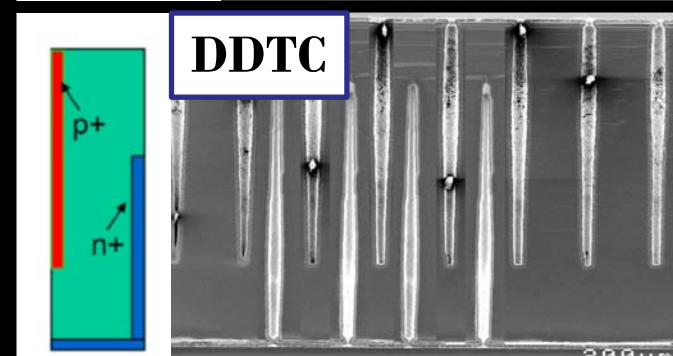
Short collection path/time = almost no trapping; charge of the complete volume is collected

"3D" electrodes: - narrow columns along detector thickness
- diameter: 10μm, distance: 50 - 100μm

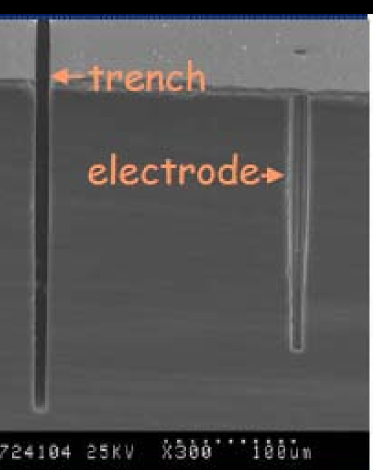
Lateral depletion:
☺ lower depletion voltage
☺ thicker detectors possible
☺ fast signal
☺ smaller trapping probability
radiation hard to several 10^{15}-10^{16}p/cm^2
☹ higher capacitances

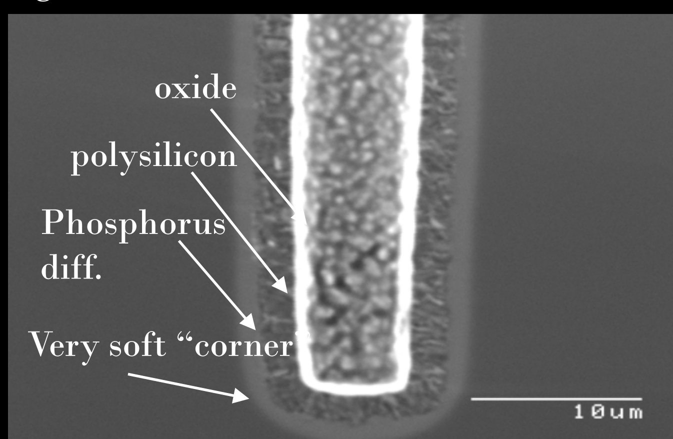
Edgeless: -Edge can be an active trench ☺





DRIE Deep Reactive Ion Etching





3D single column type (STC)
- suffer from a low field region between columns

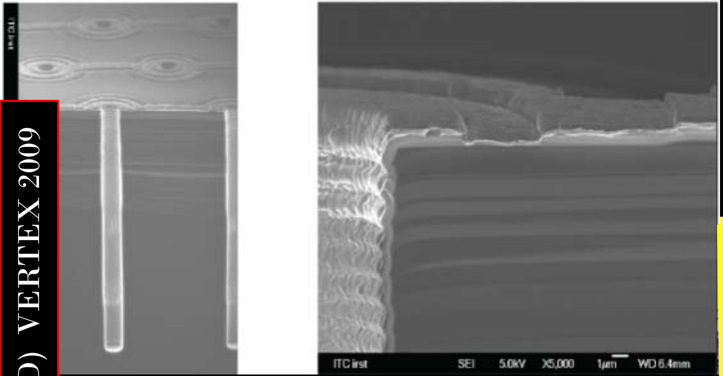
3D double-sided double type columns (DDTC)
- more complicated
- full field

Quintessence: excellent progress but still some miles to go!

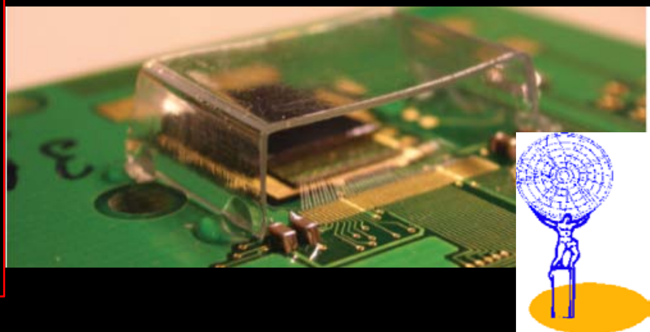
3D modules

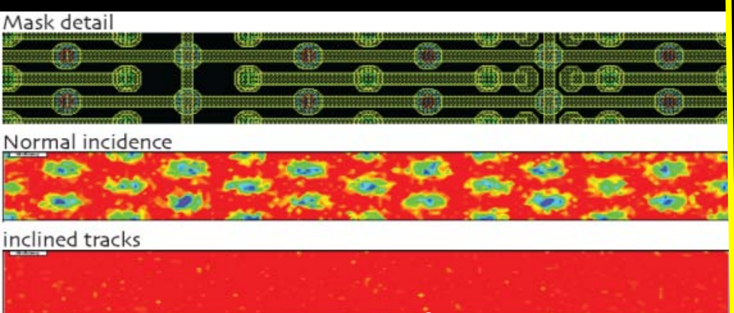
Today: Sensor producer: CNM, FBK/IRST, SINTEF, Stanford

O. Rohne et al. (ATLAS 3D) VERTEX 2009



Different cell sizes



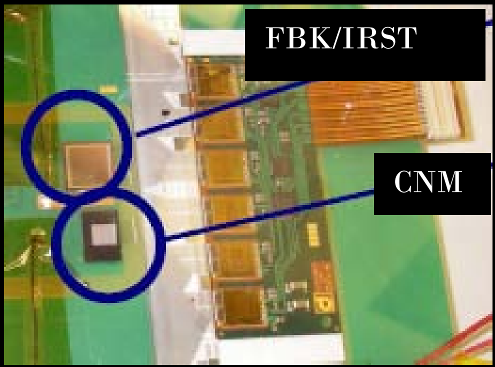


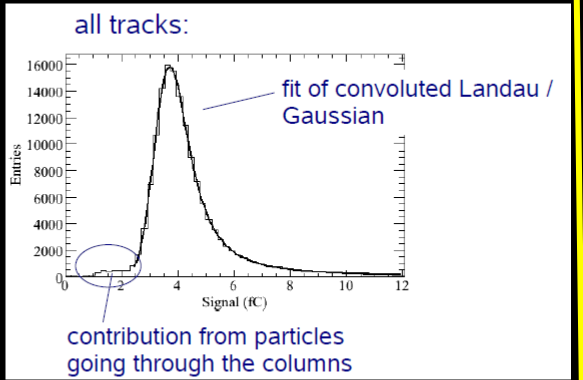
Fully efficient up to 99.8%
Resolution similar to planar

for inclined tracks

Michael Koehler 3D Test Beam Como 2009

Different produces



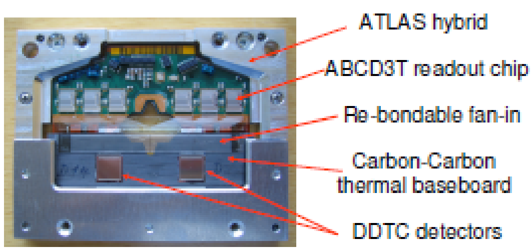


Maximum charge at 40 V: (3.5 ± 0.3) fC, (22 ± 2) ke⁻

- Signal to noise ratio: ~ 31
- Expected for 300 μm silicon: 3.7 fC, 23 ke⁻

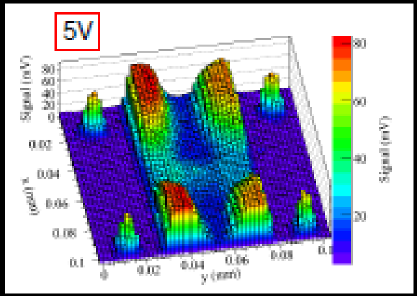
→ Measured signal in agreement with expected signal

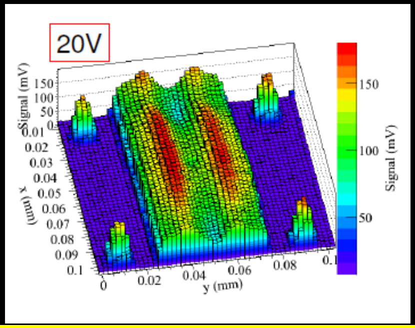
Test module



Fast binary readout, 20ns shaping time

Characterization with position resolved laser, λ=980nm; 2μm spot





Dalla Betta, Bad Wildbad Kreuth 2009

Today on the candidate menu of all detectors: to equip the innermost layers! **Bon Appétit**

RD42 Diamonds*

a semiconductor detector– ahem, I mean insulator

Dr. DOBOS, Daniel	Diamond Pixel Modules

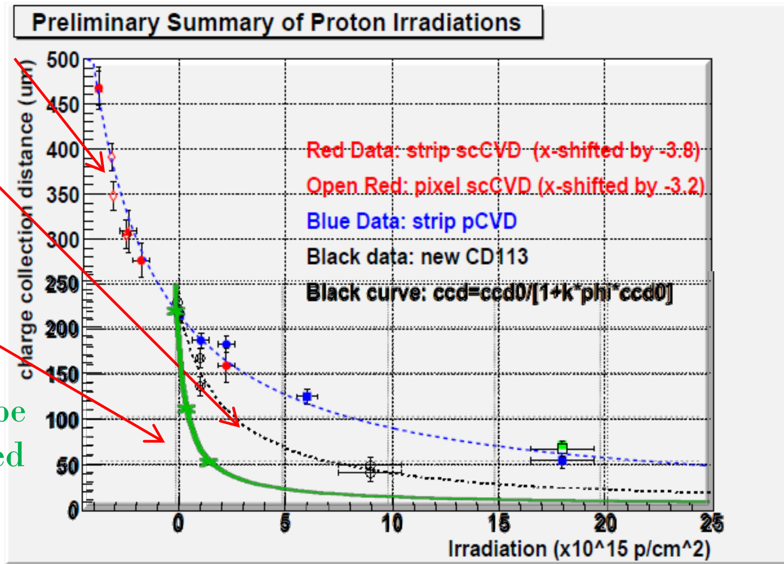
24GeV Proton Irradiation Summary 2009:

24GeV p

70MeV p

25 MeV p

25MeV To be crosschecked by RD42



pCVD and scCVD diamond follow the same damage curve: $1/ccd = 1/ccd_0 + k\,\phi$.

Diamonds are excellent and expensive detector material

- "Low" signal, but "no" current (noise)
  - Even at room temperature
- Low dielectric → low capacitance
- High Thermal Conductivity
- Very fast
- Radiation hard
  - Although most studies are done at high energy p
  - 70 MeV p damage 3 times more than 24GeV
  - 24 MeV p damage even more (de Boer et al.)

NIEL calculations done → less energetic protons do additional damage via elastic Coulomb scattering

W. de Boer et al. Phys.Status Solidi 204:3009,2007.

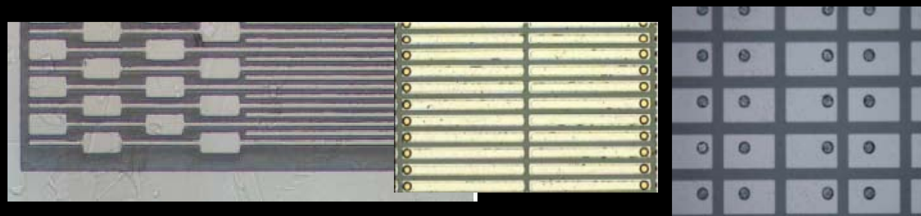
* are a girl's best friend

* are Harris' best friend

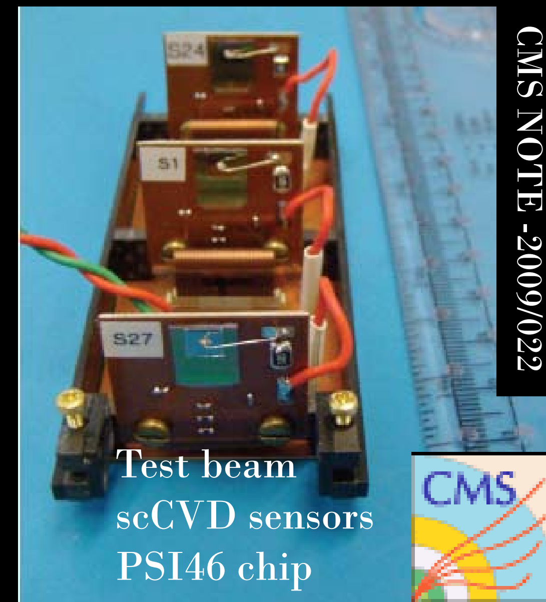
Harris Kagan; Joshua Moss Elba & Como 2009, & Kagan RD42 Collab Meeting 2009 & W. de Boer et al. "Radiation hardness of diamond and silicon sensors compared" 2007

Diamond II (modules)

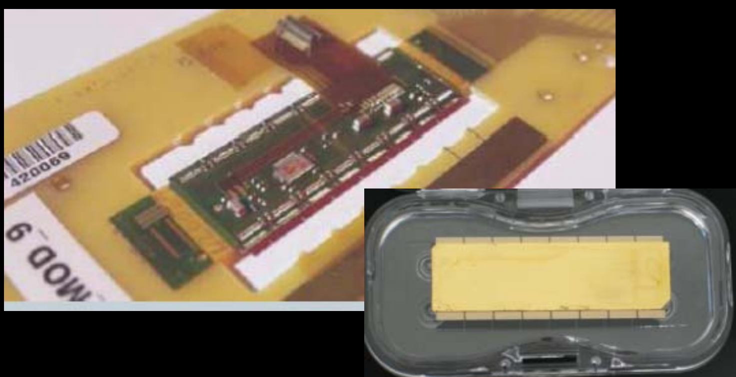
Segmentation :
Double sided strips
Pixels

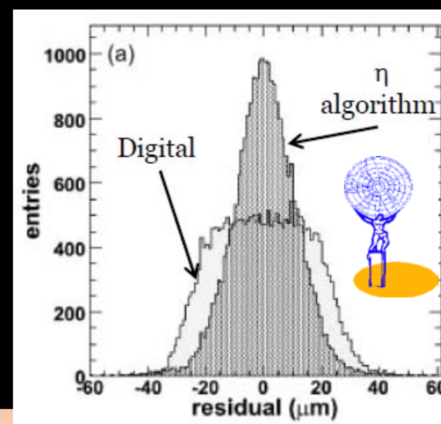


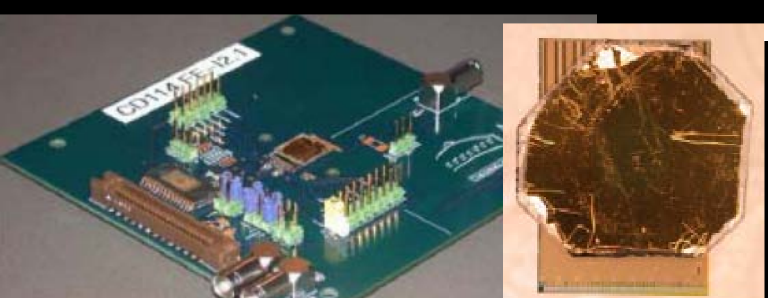
Pixel Luminosity Telescope (PLT)



ATLAS pCVD pixel module







ATLAS scCVD pixel module

- pCVD full ATLAS pixel module:
  - Resolution 14μm
  - Efficiency 97%
- sCVD ATLAS small module
  - Resolution 8.9 μm
  - Efficiency 99%
- sCVD CMS small module
  - Efficiency 99.3%, 99.6% 99.9%

On the basis of these results ATLAS officially approved Upgrade R&D on Diamond Pixel Detectors

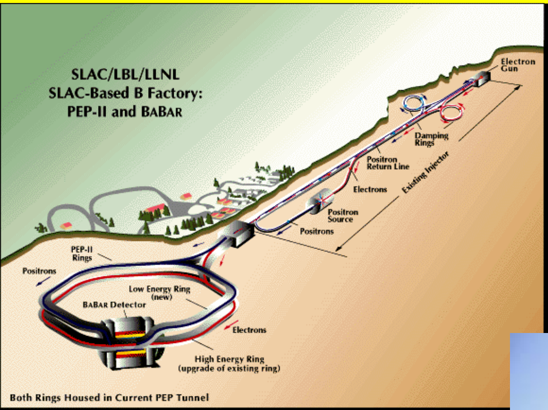
Harris Kagan, Elba & Como 2009, Joshua Moss, Elba 2009; A la Rosa 2008

Integration

~~Radiation hardness~~

Radiation length X0

Tomorrow



b-factories

linear collider

WHAT ABOUT DETECTORS FOR E+ E- COLLIDER?

Belle-II & SuperB

FRIEDL, Markus	The Silicon Vertex Detector of the Belle-II Experiment
MARINA PARDO, Carlos	The Belle-II Pixel Vertex Tracker at the SuperKEKB Flavor Factory
ANDRICEK, Ladislav	Ultra-Thin All-Silicon Module for High Precision Vertexing at Belle-II

Tomorrow

Occupancy

Radiation length X0

Integration

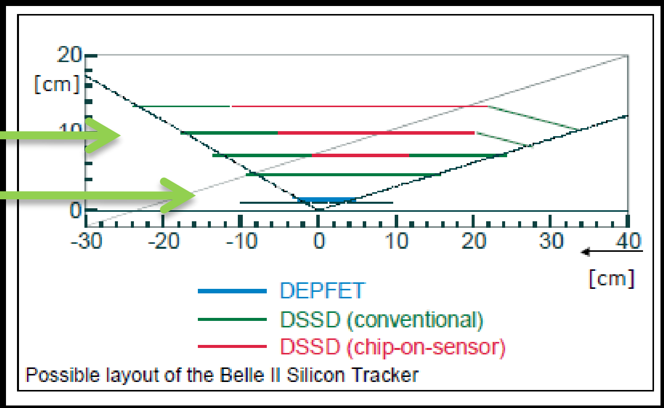
γ radiation

SuperKEKB accelerator upgrade with a target luminosity of $*10^{35}/cm^2/s$.

System size 3-4 of the present Belle

SVD

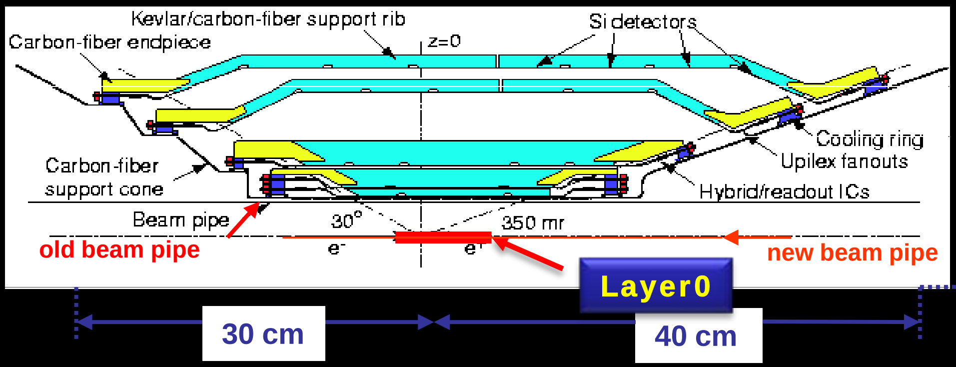
PXD



Possible layout of the Belle II Silicon Tracker

SuperBabar as old 5 layer SVT + Layer0 at R=1.5cm

Layer0: Backg. track rate 5MHz/cm2, TID 1MRad/yr



SVD Layout:

- DSSD sensors from 6" wafer
- Additional alternative "chip-on-sensor" sensor

PXD Sensor R&D Status - 3 variants pursued:

- DEPFET - Baseline
  - o Evolving from basic R&D to production
- KEK SOIPIX - SOI
  - o (promising concepts, at basic R&D stage)

Hybrid Pixels: Viable option - Baseline

CMOS MAPS: very promising

→ sensor & readout 50 μm thick!

Thin pixels with Vertical Integration:

- Reduction of material and improved performance
- First DNW MAPS (2 tiers) submitted (130 nm)

Striplets: thin double sided silicon sensor - short strips

- mature technology, less robust against bknd occupancy

Pixel Pixel Pixel: New Technology!?!? (see later)

The ILC Si-Sensor Candidates ZOO

Tomorrow & Later

- *Charge-Coupled Devices (CCDs), CPCCD (Column Parallel CCDs)*
- *Monolithic Active Pixels (MAPS) based on CMOS technology*
- *DEPFETs (DEpleted P channel Field Effect Transistor)*
- *SOI (Silicon on Insulator)*
- *ISIS (Image Sensor with In Situ Storage)*
- *Hybrid Active Pixel Sensors (HAPS) and 3D integration concepts*
- These basic technologies are coming in different flavours and specific technology combinations:
  - Standard CCDs as used in digital cameras are not fast enough, proposed *column parallel readout* CPCCD helps or *Short Column Charge-Coupled Device (SCCCD), where a CCD layer and a CMOS readout layer is bump* bonded together.
  - Chronopixels are CMOS sensors, with the capability to store the bunch ID (time).
  - ISIS sensors combine CCD and active pixel technology, a CCD like storage cell together with CMOS readout implemented.
  - Also *Flexible Active Pixels (FAPs) integrate storage cells in the traditional MAP cells.*
  - *Fine Pixel CCDs* (FPCCDs) are under discussion to decrease occupancy.

Tracking challenges at the ILC

Tomorrow OR Later

- Vertex detector:

  e.g. distinguish c- from b-quarks
  - goal impact parameter resolution

    $\sigma_{r\varphi} \approx \sigma_z \approx 5 \oplus 10/(p \sin\Theta^{3/2})$ µm **3 times better than SLD**
  - point resolution 1-5 mm
  - small, low mass pixel detectors, various technologies under study
  - transparency: ≈ 0.1% X_0 per layer = 100 µm of silicon

Radiation length X0

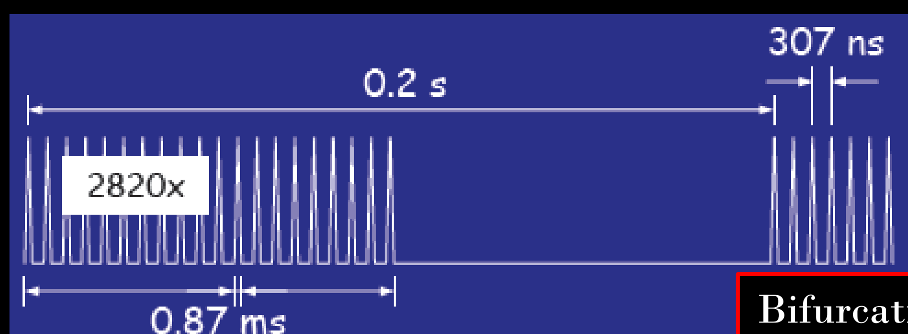
- Tracking:
  - superb momentum resolution

    → $\Delta(1/p_T) = 5\cdot10^{-5}$ /GeV

    3 times better than CMS

Tracking options considered:
- Large silicon trackers (à la ATLAS/CMS)
- Time Projection Chamber with ≈ 100 µm point resolution
  (complemented by silicon devices)

- Bunch timing:
  - 5 trains per second
  - 2820 bunches per train separated by 307 ns
    - no trigger
    - power pulsing
    - readout speed



Bifurcation:
Silicon pixels give Vertexing
Silicon strips OR gas give Tracking

J. Mnich, this conference 3 years ago

DEPFET

MAPS

ISIS

SOI

HAPS

CCD

PIXEL CANDIDATES (SELECTION)

DEPFET

DEPleted Field Effect Transistor

MARINA PARDO, Carlos	The Belle-II Pixel Vertex Tracker at the SuperKEKB Flavor Factory
FURLETOV, Sergey	A system for characterisation of DEPFET silicon pixel matrices and test beam results.
ANDRICEK, Ladislav	Ultra-Thin All-Silicon Module for High Precision Vertexing at Belle-II

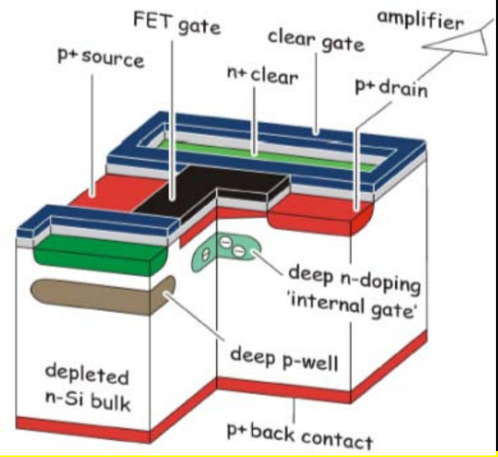
Key Figures

In pixel amplification

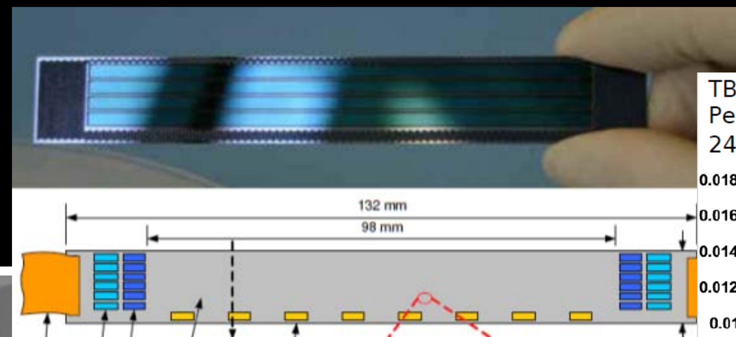
- Charge in deep n-well - internal gate modulates source drain current
- Clear (10V) needed
- Very low noise
- Low power consumption

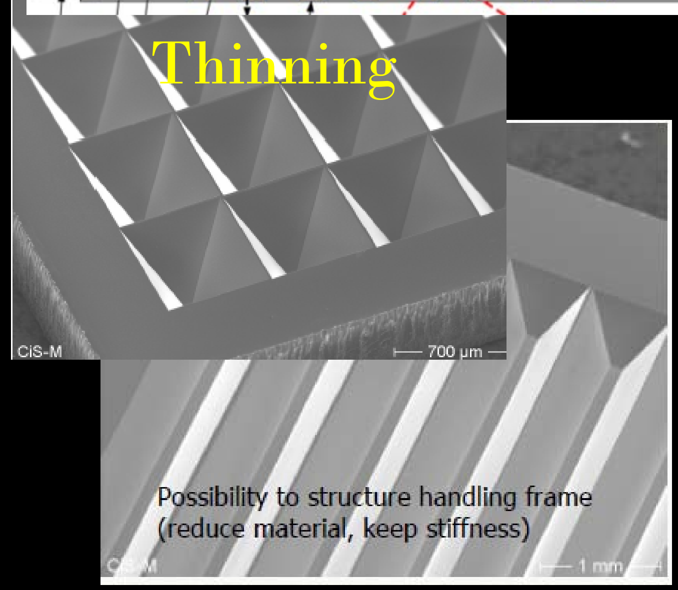
Fully depleted, high resistivity

- Fast and complete charge collection
- Lateral depletion

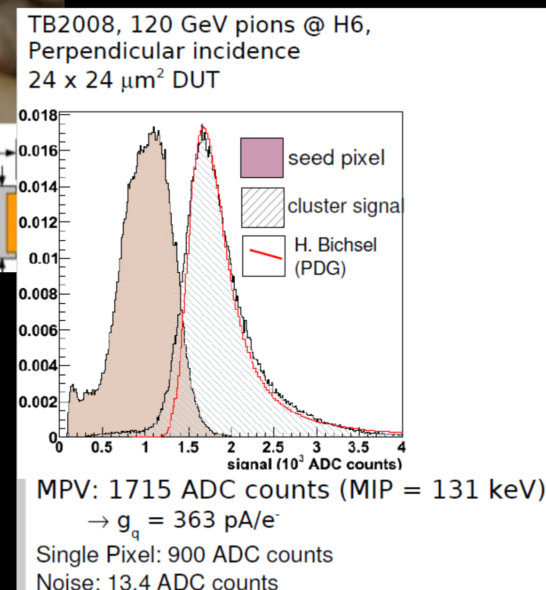


The all-silicon module





Superb test beam results



SNR 120
Res 2-3 μm
High efficiency

Candidates for ILC, SuperBELLE, MIXS, XEUS, XFEL and …

Carlos Lancaster@ Elba 2009; Marcel Vos@Vertex2009, Putten

MAPS (aka CMOS)

Monolithic Active Pixels

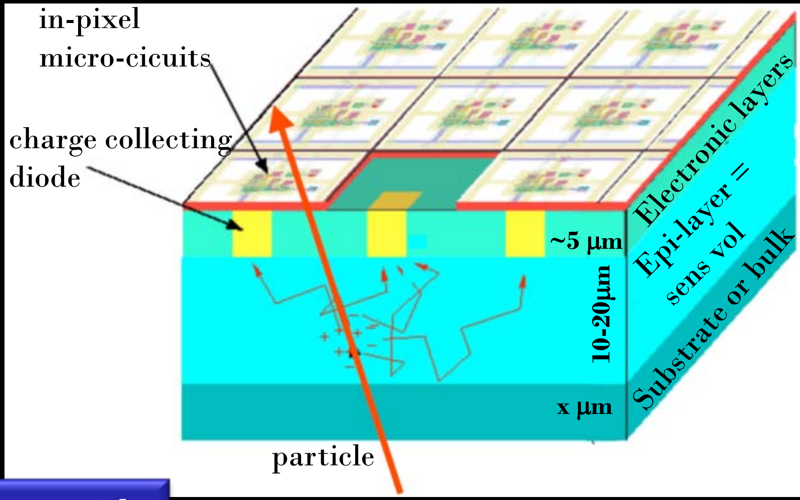
TRAVERSI, Gianluca	2D and 3D CMOS MAPS with high performance pixel-level signal processing
PAOLONI, Eugenio	Beam Test Results of Different Configurations of Deep N-well MAPS Matrices Featuring in Pixel Full Signal Processing.
PERIC, Ivan	The first beam test of a monolithic particle pixel detector in high-voltage CMOS technology
DE MASI, Rita	Towards a 10us, thin high resolution pixelated CMOS sensor system for future vertex detectors

Introduced 1999 as early R&D

- TODAY: Huge diversity of sensors - many groups
  - Today: e.g. Mimosa chip version **26** (0.35µm)

Sensor & electronic volume – same substrate

- Signal processing in-pixel (NMOS only)
  - e.g. Amplifier, sparsification
  - Column (N) parallel architecture; digitization at column level
- Charge generated in epitaxial layer → thermal propagation to electrode (~100 e-)
  - No depletion layer/voltage
- High granularity
  - Resolution ~2 µm
  - Very low noise
- Very thin (low X_0)
- Current generation rad hard up n*10^{13} n/cm^2



Lepix: monolithic detectors for particle tracking in standard very deep submicron CMOS technologies (90nm)

"High" voltage (~60V) CMOS technology, allows depletion of EPI-layer → 1000e-

Deployment:
Standard Digital cameras
EUDET telescope
STAR @ RHIC (commissioning 2010)
Candidates for:
ALICE, ILC, FAIR, SuperB

Fully Depleted MAPS based on vertical 3D Integration (TSV):

Thin, Fully Depleted Monolithic Active Pixel Sensor with Binary Readout based on 3D Integration of Heterogeneous CMOS Layers

Digital on top of Analog (for each pixel)

Many more new developments: Very promising – **The sky is open.**

A. RIVETTI (Como 2009); DULINSKI*, Wojciech, IEEE 09; *M.Koziel, ESSD 2009* ; *Rita De Masi*, Ivan Perić this conference (and many more)

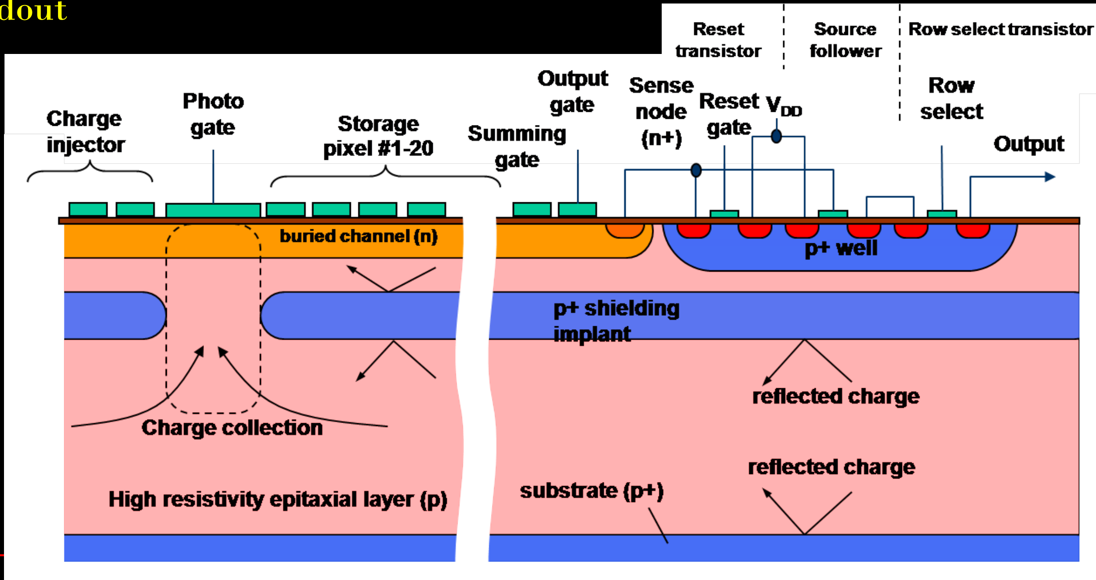
ISIS for ILC
In-situ Storage Image Sensor

- Signal charge (raw data) collected locally under an array of photogates into a buried channel (next to pixel)
- Charge is transferred to an 'in-pixel' register, 20 times during the 1 ms-long train
- Leisurely readout in the 200 ms-long quiet period after the train; excellent noise performance, and immunity to RF pickup during the bunch train
- 1 MHz column-parallel readout at end of ladder is sufficient, with on-chip edge logic for
  - cluster finding, centroid determination and data sparsification
- Important additional ISIS feature: easy to drive because of the low clock frequencies:
  - 20 kHz during capture, 1 MHz during readout

ISIS combines

- CCDs
- active pixel transistors and
- CMOS edge electronics

in one device: specialised process



- Proof of principle ISIS by e2v
- ISIS2 – 180nm process by Jazz Semiconductor

Also for ILC Tera-Pixel Active Calorimeter
High speed cameras

Chris Damerell@ESSD Wildbad Kreuth 2009 & Z Zhang@Vertex 2009 Putten

SOI Silicon on Insulator

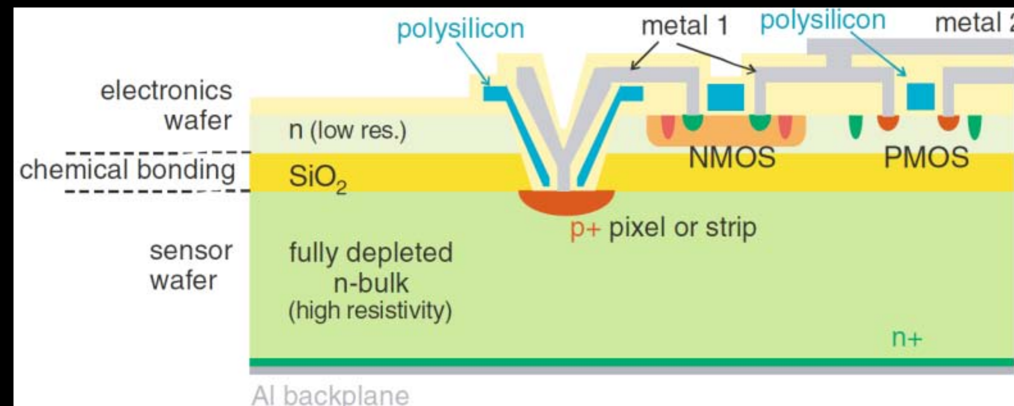
ARAI, Yasuo	Development of SOI Pixel Detectors
SOUNG YEE, Lawrence	TRAPPISTe-1 Monolithic Pixel Detector in SOI Technology

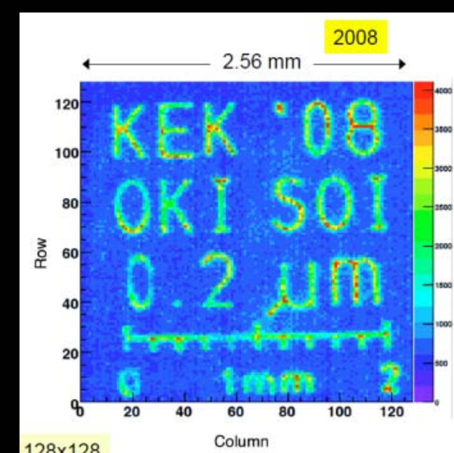
Introduced: SUCIMA 2003 by ITE Warsaw

Chemical bonding of *low* resistivity electronics wafer with *high* resistivity sensor wafer – FULL INTEGRATION

- Full CMOS capability: NMOS & PMOS
  - In-pixel processing
  - Low power, high speed
  - Back gating effect – V_{dep} effects analog transistor functionality ☹
- Full depletion
- Radiation hardness ~ feature size
- High granularity possible
  - Single point resolution of 1µm achievable for a S/N of 20

Feature size today: 0.15-0.2µm





Candidates for:
SuperBelle, ILC, SLHC, etc.

D. Contarato ESSD2009 & PSD2008;

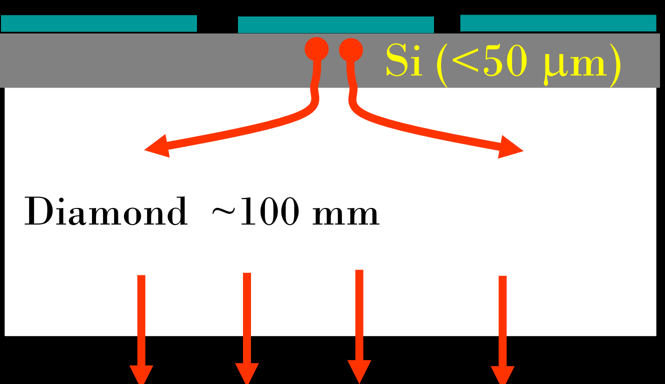
Silicon on Diamond

Uniform, continuous wafer bonding on a μm scale demonstrated

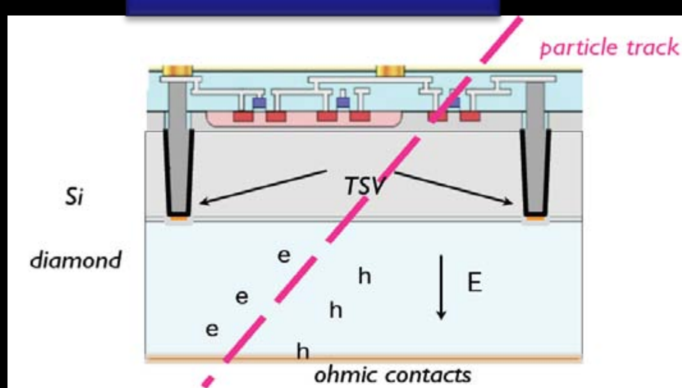
Diamond is
- radiation hard,
- solar-blind,
- nearly tissue equivalent,

has
- a low dielectric constant
- a very low leakage current
- a perfect thermal conductivity

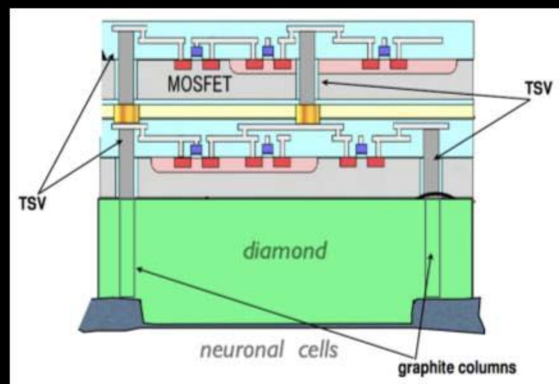
Use case 0
Heat sink



Use case I
Active pixel sensor
SoD



Use case II
3D Bio integration
Bio-SoD

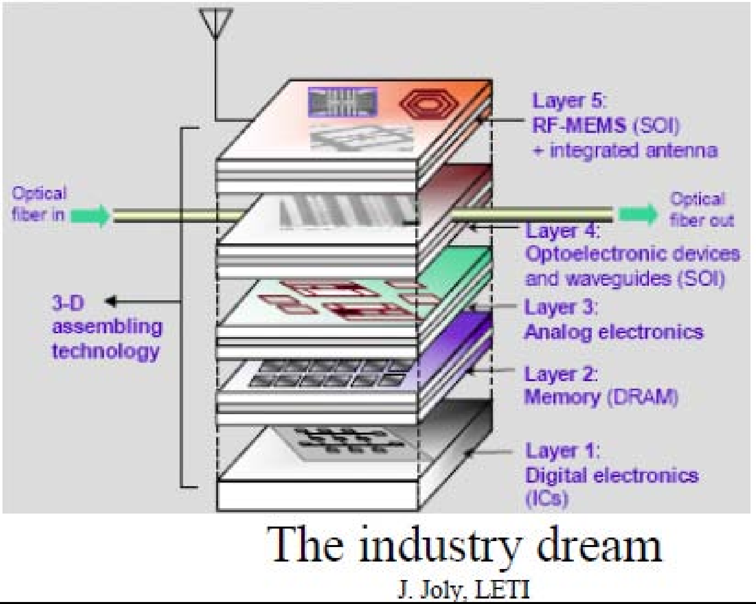


Research under the framework of the national INFN experiment RAPSODIA (2007-2009)

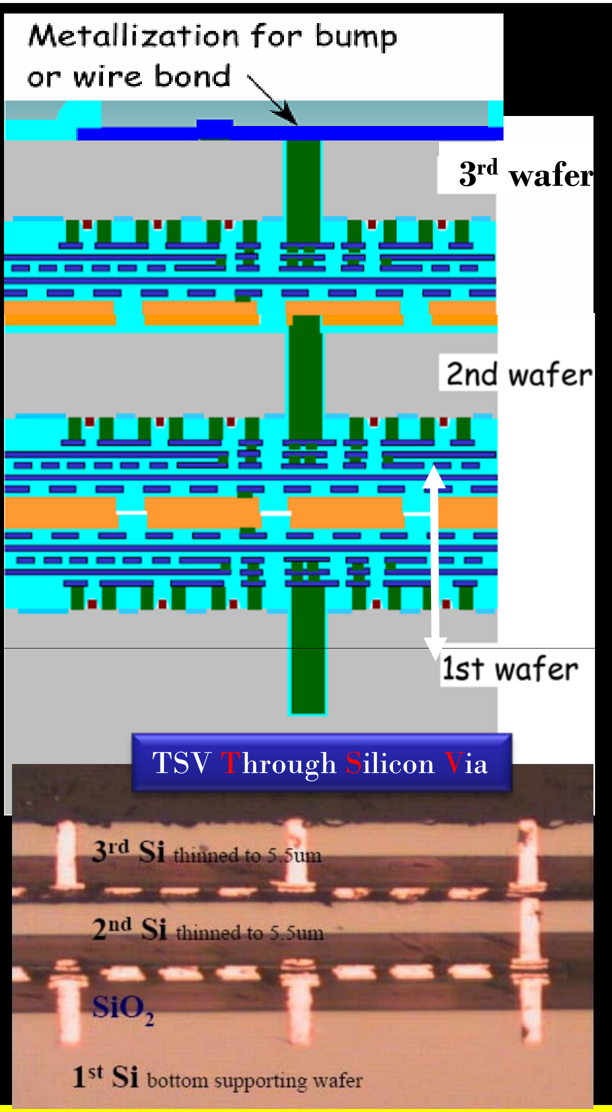
3D integration – Vertical Integration Technologies

Integration

What is a 3D chip?
– A 3D chip is comprised of 2 or more layers (N) of semiconductor devices which have been thinned, bonded, and interconnected
➔ monolithic circuit.
– Frequently the layers are comprised of devices made in different technologies.
Reasons for 3D in industry
– Reduce interconnect length
- Improve speed
- Reduce interconnect power
- Reduce crosstalk
– Reduce chip footprint size
- Can HEP take advantage of this technology?



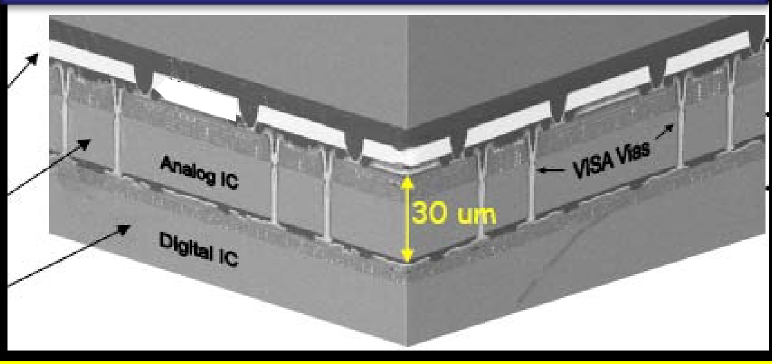
The industry dream
J. Joly, LETI



We are trying!

Si pixel sensor
BiCMOS analogue
CMOS digital

Possible HEP dream (schematic)



Option for ILC, SuperB & CMS Phase II: Trigger layers

Ray Yarema; Vertex, 2005, Nikko, Japan & ILC Vertex 2008, Mennagio, Italy / R. Lipton CMS meetings

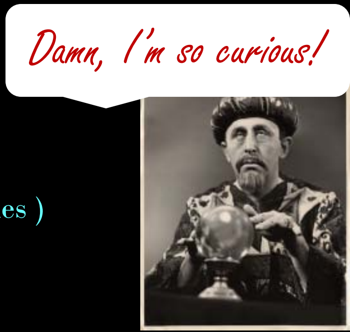
Summary

Yesterday – Today → Tomorrow??

- Semiconductor sensors have been operated since the 50ties very successfully, matured during the LEP era and are instrumented in every current HEP detector and new most ambitious developments are candidates for **ALL** future detectors

As for the high radiation tolerance

- Today we solved the problems of increasing leakage current and designed detectors to cope with increasing depletion voltage, tomorrow we have to solve trapping, where the newly found charge amplification is possibly a viable solution
- There are recipes for radiation tolerant technologies (SLHC)
  - Planar n-strip readout is a viable option for all outer layers
    - The Oxygen Mantra is still valid (Oxygenated FZ or MCz are more tolerant vs. charged particles)
    - Higher voltage always helps
    - Diamond and 3D helps (first modules sighted)



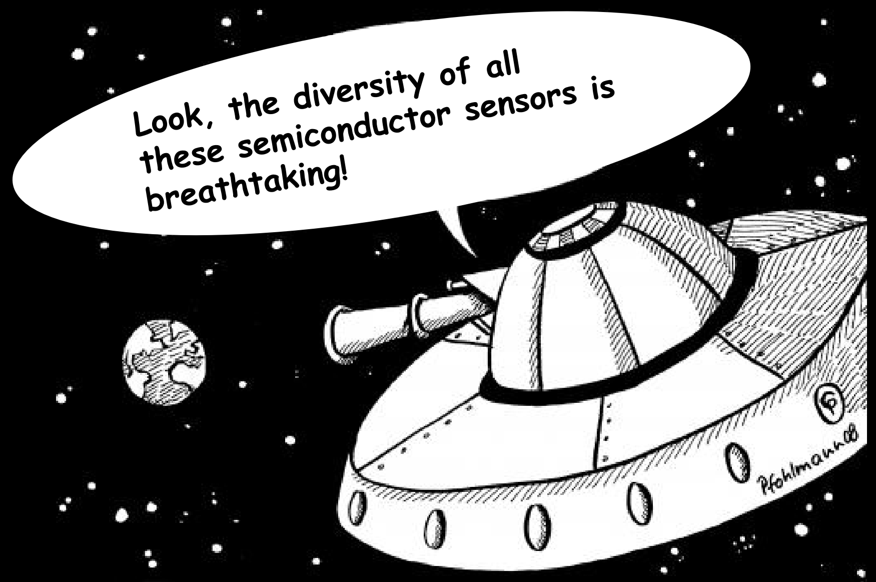
INTEGRATION of sensor and electronics is becoming more and more interesting for SLHC but even more for a linear collider

- HAPS, FAPS, MAPS, CCDs, DEPFET, SOI, ISIS the number of acronyms is already too large for me to keep in mind
- 3D: Stack "sensor – analogue circuits – digital circuits" on top of each other → TSV

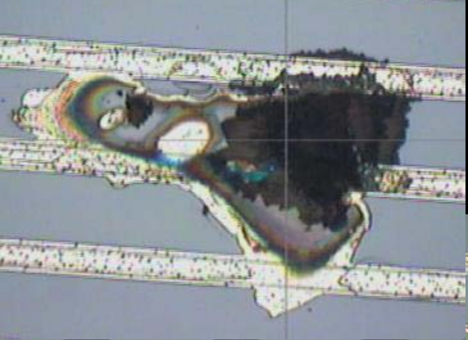
→ New developments on all frontiers

I'm lucky to participate in such a lively environment of history, operation and R&D!

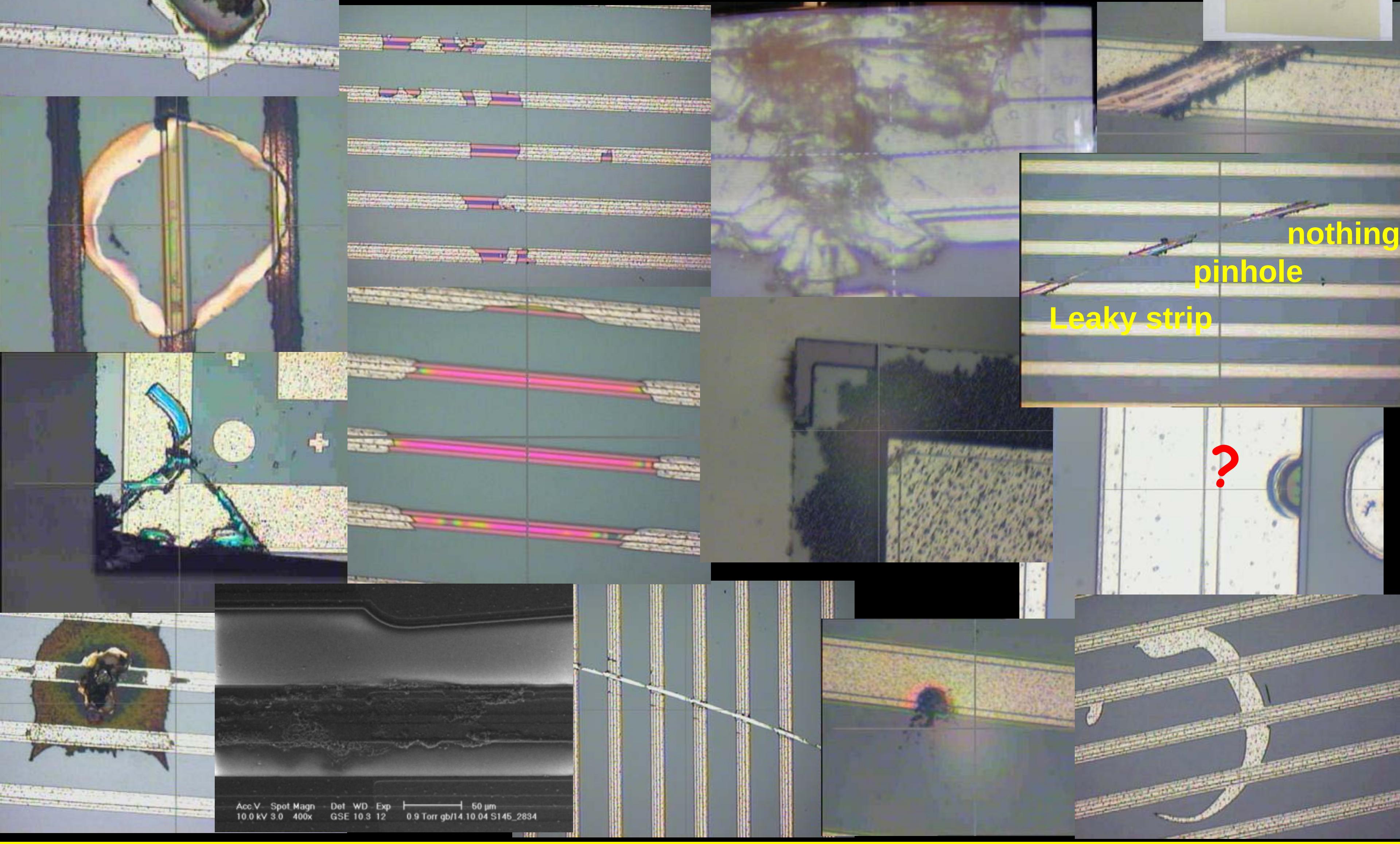
THE END



Thank you very much for your attention



The ART of sensor defects



THX to all sources

- 12th, 14th, 15th RD 50 Workshop 2009
- Frontier Detectors for Frontier Physics (ELBA May 2009)
- Vertex 2009 (VELUWE, the Netherlands September 2009)
- RD09 - 9th International Conference on Large Scale Applications and Radiation Hardness of Semiconductor Detectors (Florence, Italy 2009)
- Astroparticle, Particle, Space Physics, Detectors and Medical Physics Applications (Como, Villa Olmo 2009)
- 11th European Symposium on Semiconductor Detectors, 7-11th June 2009; Bad Wildbad Kreuth
- RD42 Collaboration Meeting
- PLUS MANY MANY MANY VERY FRIENDLY SOURCES
- Frank Hartmann „Evolution of Silicon Sensor Technology in Particle Physics“

Electronics – radiation hardness deep sub micron

Very brief

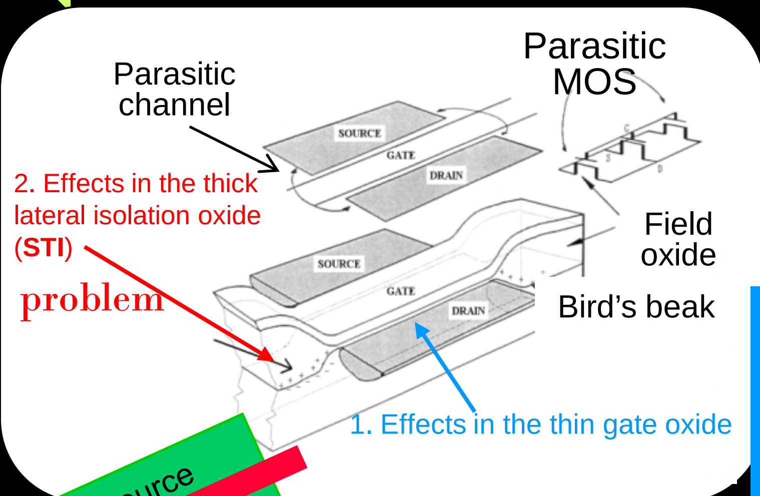
¼ µm CMOS introduced by CERN-MIC after qualification in 1999 as an alternative to expensive “military grade” technology
➔ New rad-hard digital library

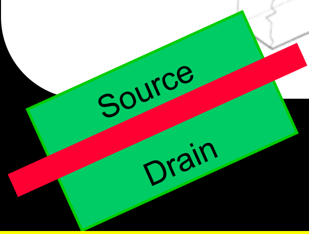
What do we have to think about?

1. Cumulative effects: Total Ionizing Dose (TID)
2. Single Event Effects (SEE)

Yesterday

Baseline: # trapped charge decreases as oxide thickness decreases



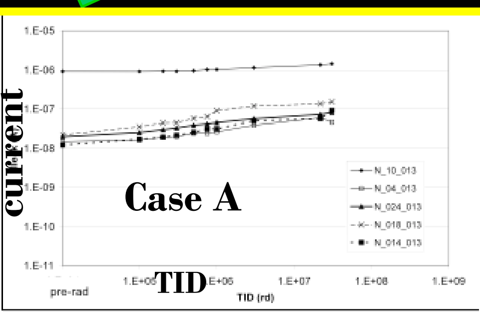


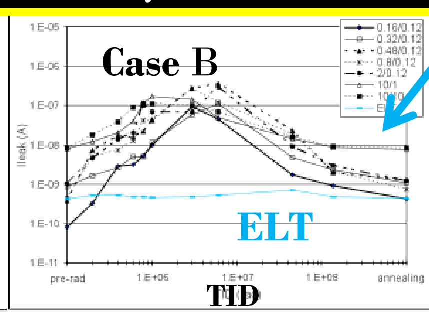
➔ ELT
enclosed layout transistor

Tomorrow

Hardness by Design (HBD)

- Oxide decreases with feature size
  - 90, 130nm more radiation hard than 250nm?
- A vast, but not complete, set of data on the radiation effects in 130nm CMOS is available
  - Transistor leakage current & Vthr change with TID visible
    - Magnitude of change vendor dependent
  - Still: TID effects measured at the transistor level indicate the possibility to work without a dedicated HBD library
    - Test of complex circuitry needed!
  - Still” ELT & guard rings avoid current degradation
    - Possible to work with HBD library (encouraged)
    - BUT higher cost! Otherwise regular monitoring of the “natural” oxide radiation tolerance needed
  - SEU & SEL probability higher with lower Vdd and lower capacitance
    - Anyhow, the problem is not new and need to be addressed during design (as for LHC)
- Measurements on 90nm technologies are ongoing, and indicate TID tolerance generally better than for the 130nm
  - Very small Vthr change even for high doses
  - Leakage current increases with dose though



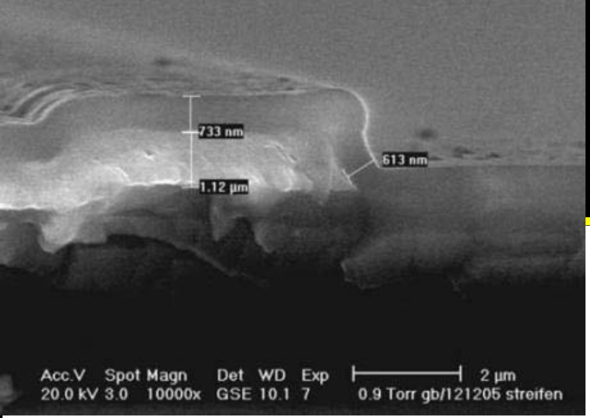


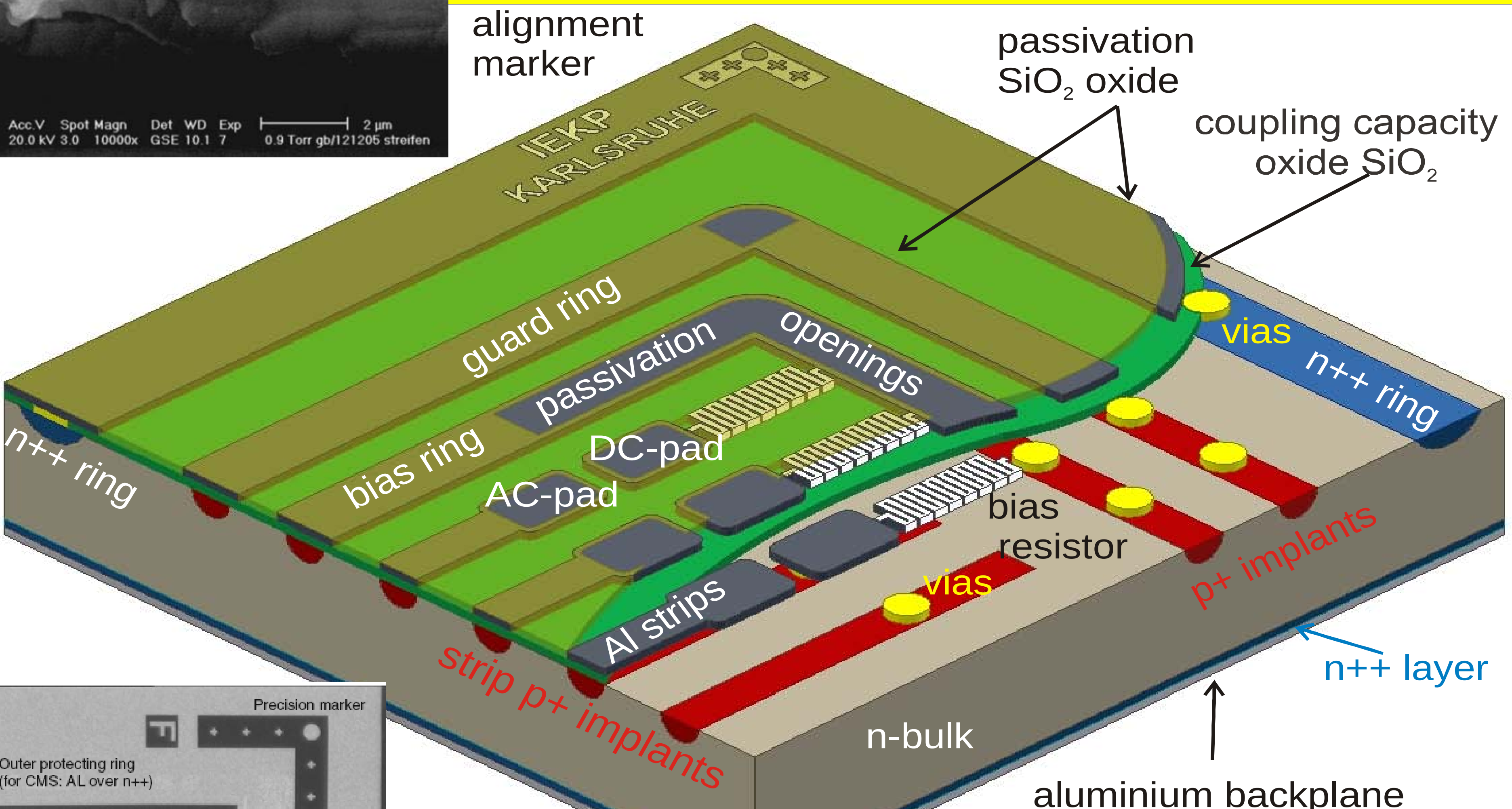
Radiation effects in deep submicron CMOS technologies by Federico Faccio
CERN, ESE seminar, Jan2010 (~80 slides)

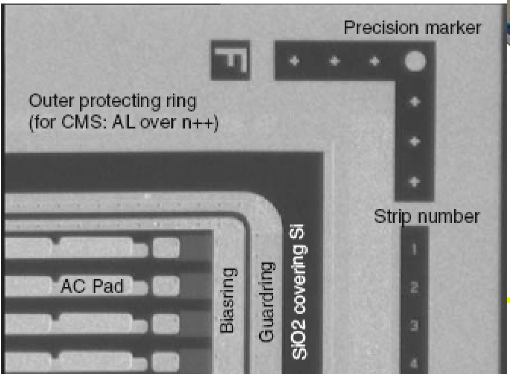
Glossary

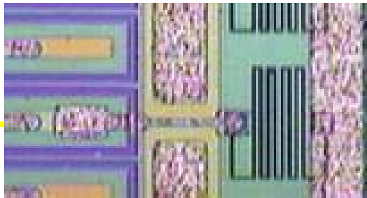
- TCT: Transient Charge Technique
- TSC: Thermal Stimulated Current
- DLTS: Deep Level Transient Spectroscopy (current or capacitance)
- CCE: Charge Collection Efficiency
- CCD: Charge Collection Distance
- V_{dep}: depletion voltage
- FZ: float zone; silicon ingot grown by float zone method
- Cz: Czochralski or MCz: magnetic Czochralski
- SCSI: Space Charge Sign Inversion
- TID: Todal Ionizing Dose

Ingredients of a modern strip sensor

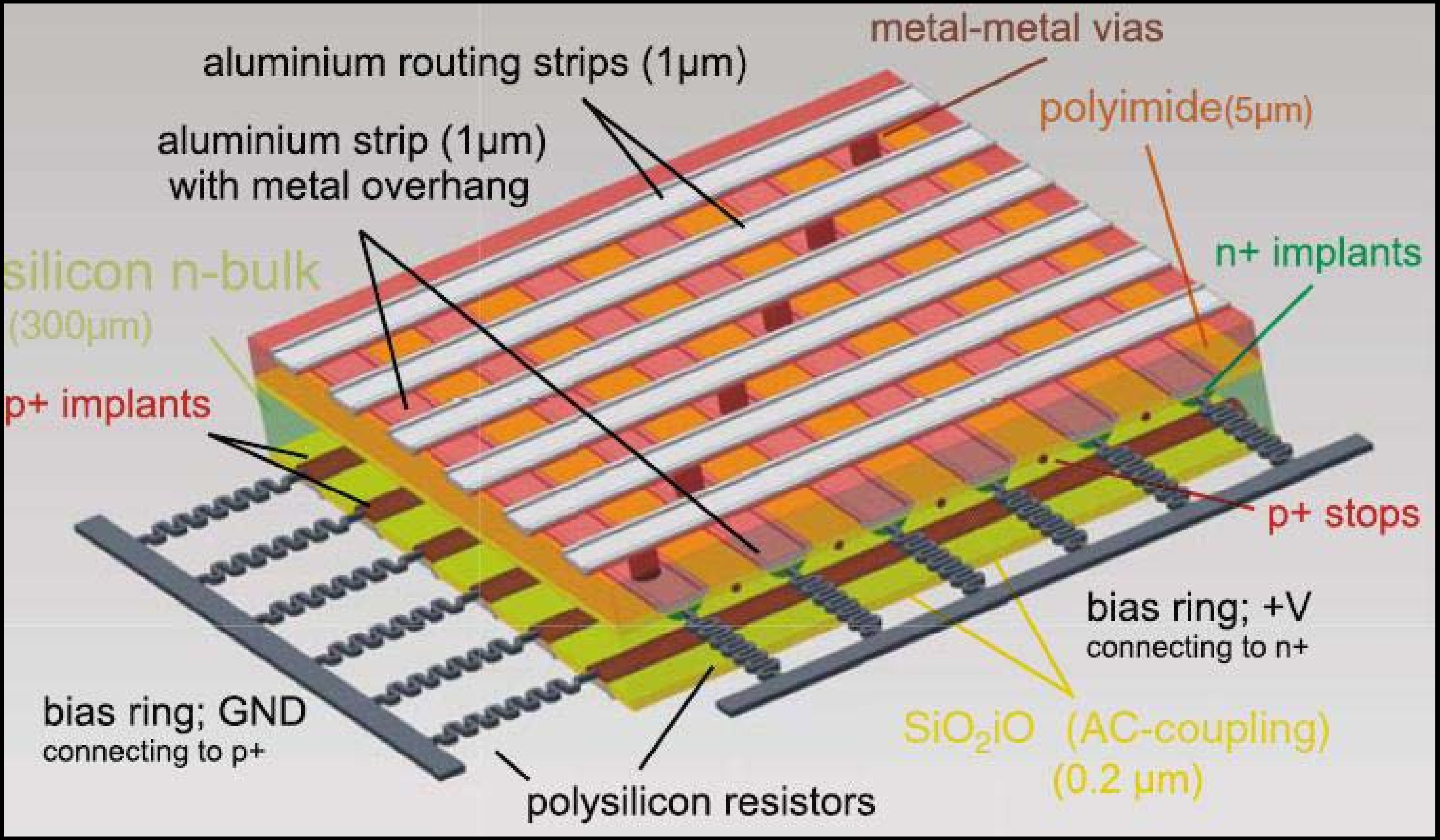




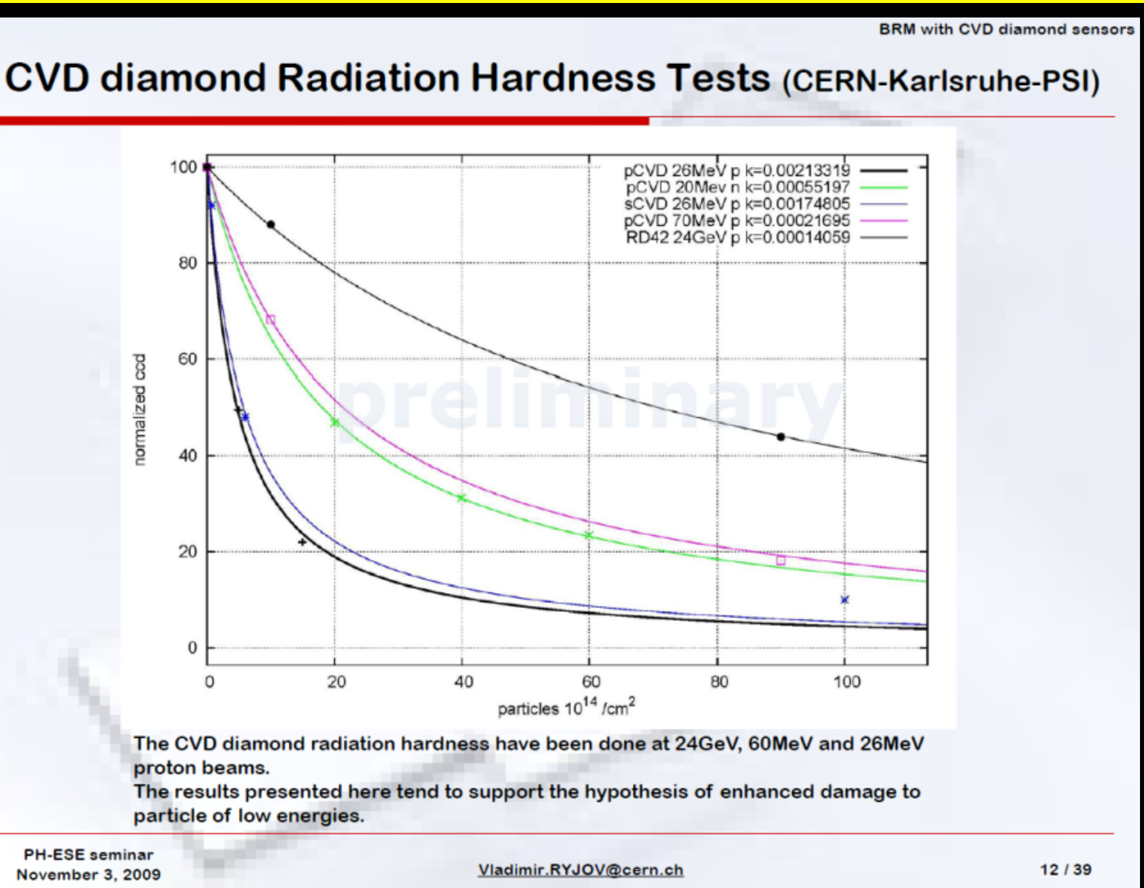




DELPHI, sensor most complicated



Radiation Hardness of CVD Diamond



Intrinsically, diamond gives a smaller induced charge than silicon for a given particle energy loss, but detectable signals are still found after heavy irradiation.
The radiation hardness of CVD sensors has been evaluated in Karlsruhe, PSI-Villigen and at CERN and the test results are presented here.
The plot shows normalized charge collection distance as a function of irradiation. The conversion factor for CCD to charge is ~36 e/μm.
The results presented here tend to support the hypothesis of enhanced damage to particle of low energies.

The smaller inelastic nucleon-Carbon cross section and the light nuclear fragments imply that at high energies diamond is an order of magnitude more radiation hard than silicon, while at energies below 0.1 GeV the difference becomes significantly smaller.

http://indico.cern.ch/conferenceDisplay.py?confId=69661

Comparison Diamond & Silicon NIEL

W. de Boer et al. Radiation hardness of diamond and silicon sensors compared 2007; Phys.Status Solidi 204:3009,2007

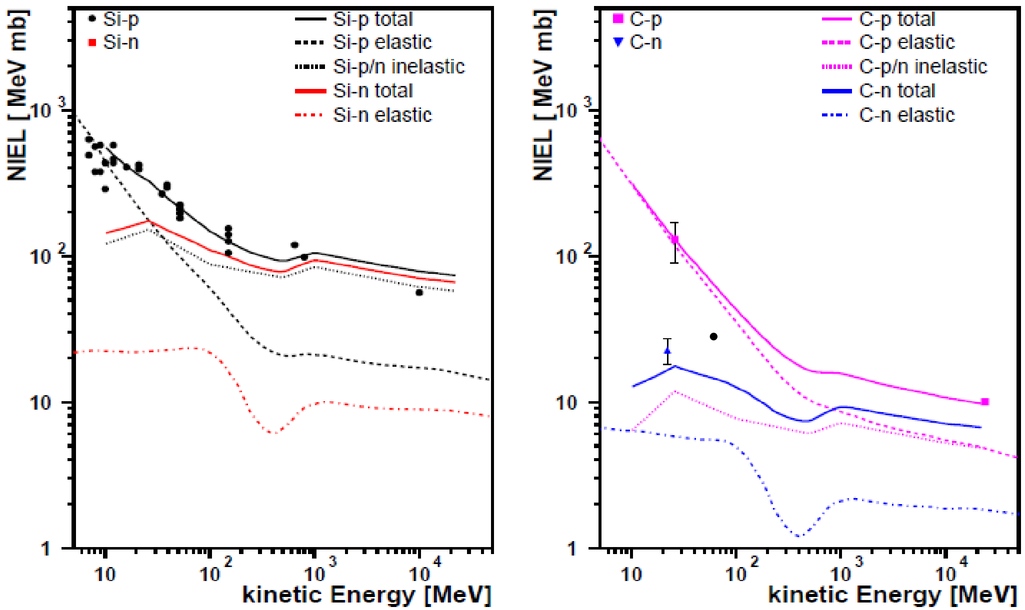


Fig. 4 *NIEL damage cross section of Si (left) and Diamond (right) for protons and neutrons (solid lines: upper one for p, lower one for n) as function of the incident energy. The different cross section contributions from elastic and inelastic scattering have been indicated as well.*

Signal decrease factor 2 after

10E14 25MeV p

10E15 24GeV p

Still better than silicon but not much!

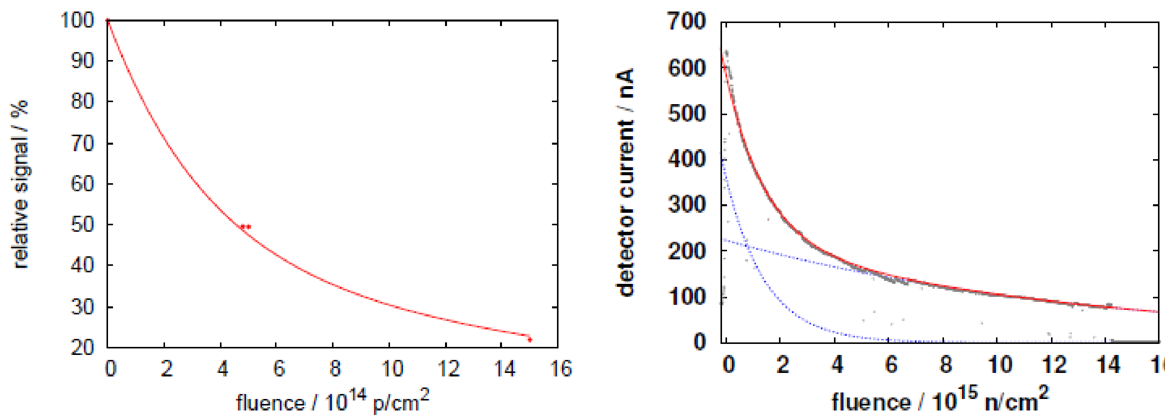
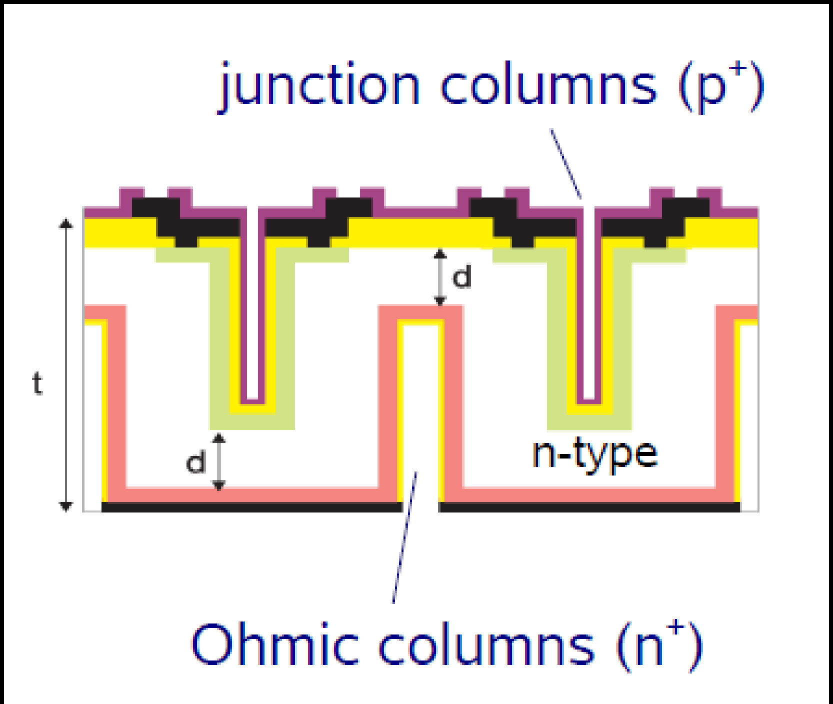
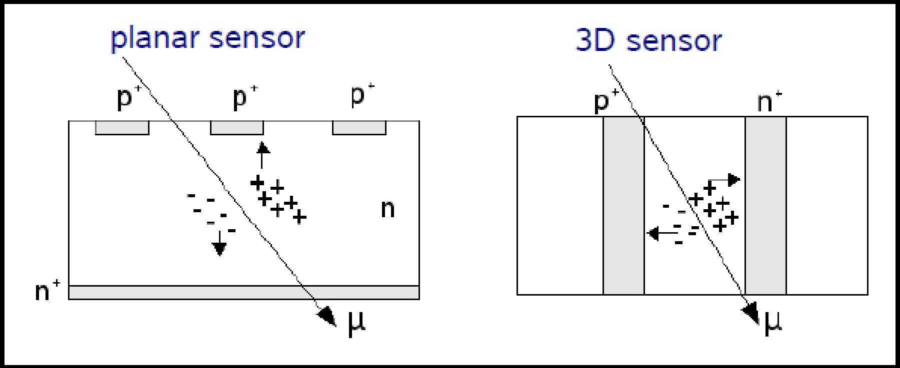


Fig. 3 *The decrease of the ionization signal in a pCVD diamond sensor after irradiation with 26 MeV protons (left) and 20 MeV neutrons (right).*

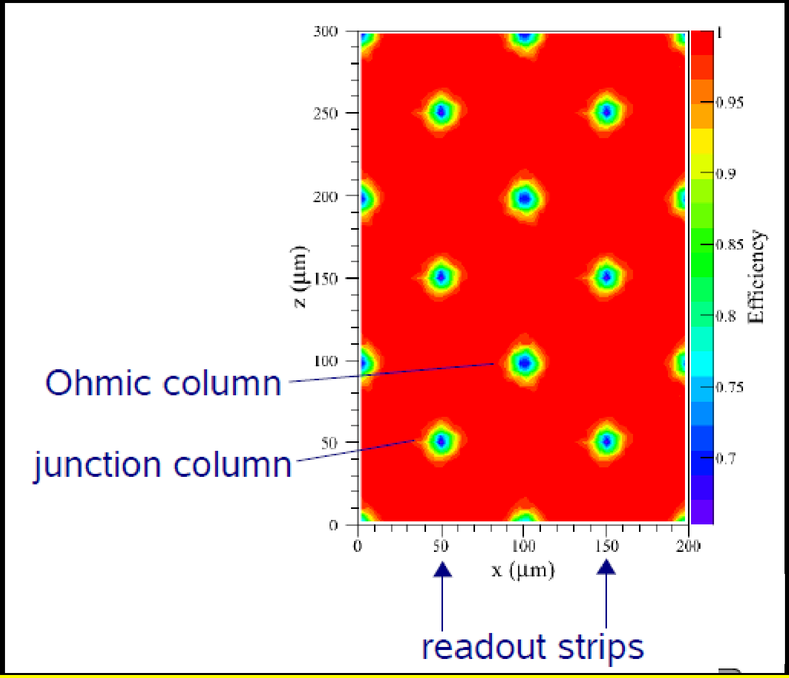
More 3D



junction columns (p^+)
d
t
d
n-type
Ohmic columns (n^+)

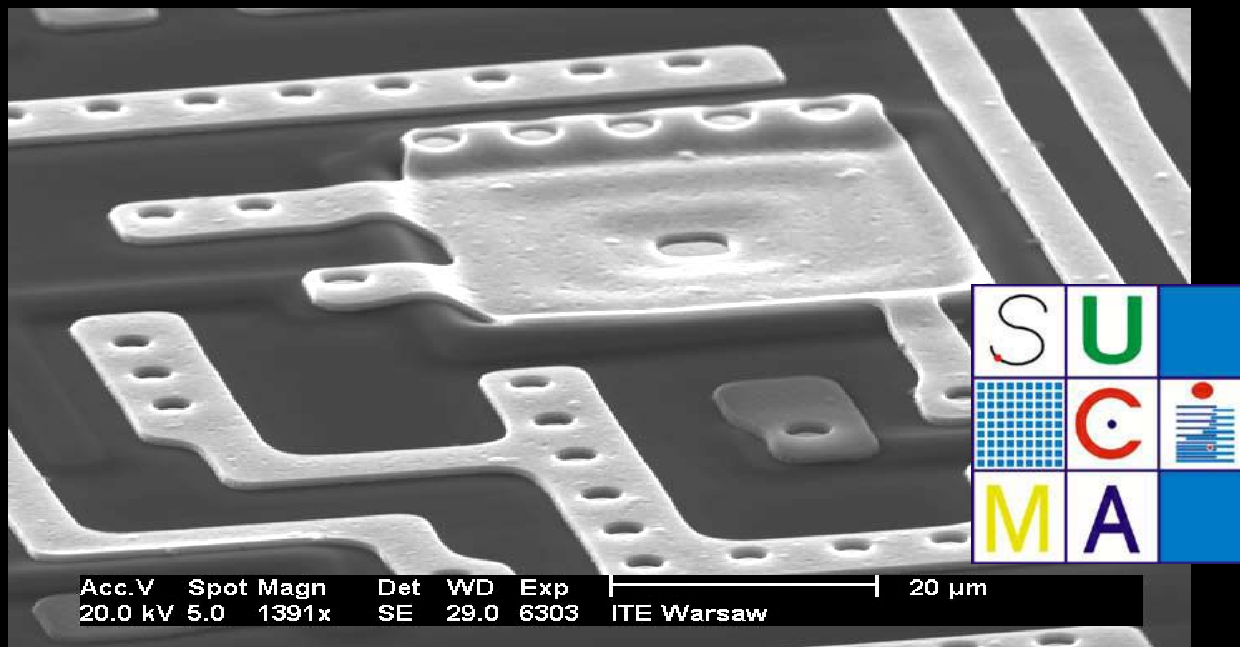


planar sensor
p^+
p^+
p^+
n
n^+
μ
3D sensor
p^+
n^+
μ



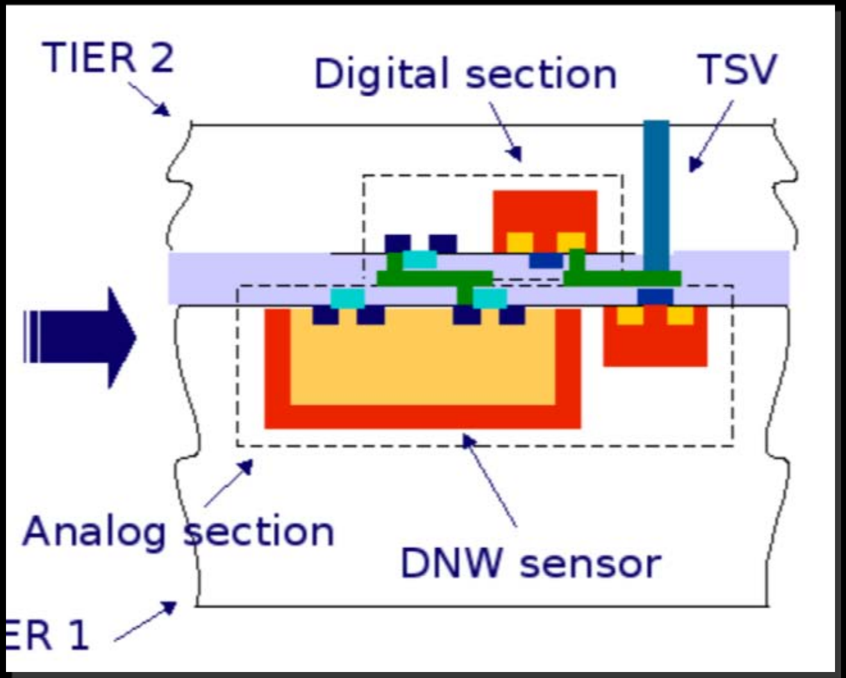
Ohmic column
junction column
z (μm)
x (μm)
Efficiency
readout strips

Sucima, SOI from IET

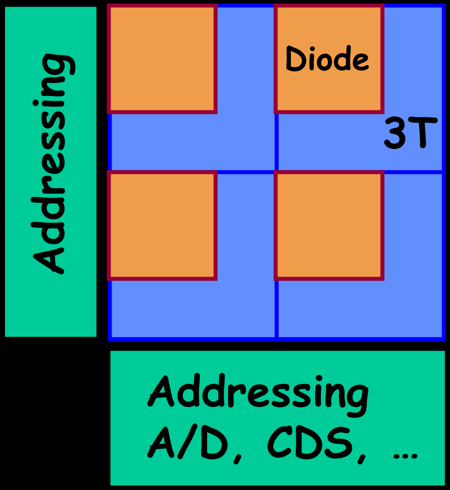


Silicon Ultra fast Cameras for electron and gamma sources in Medical Applications

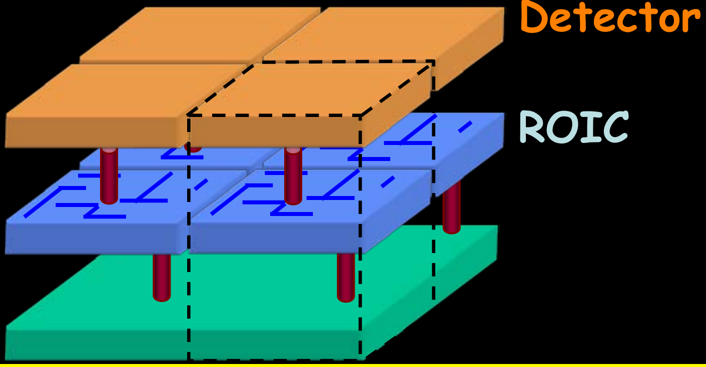
3D electronics interation



Conventional MAPS

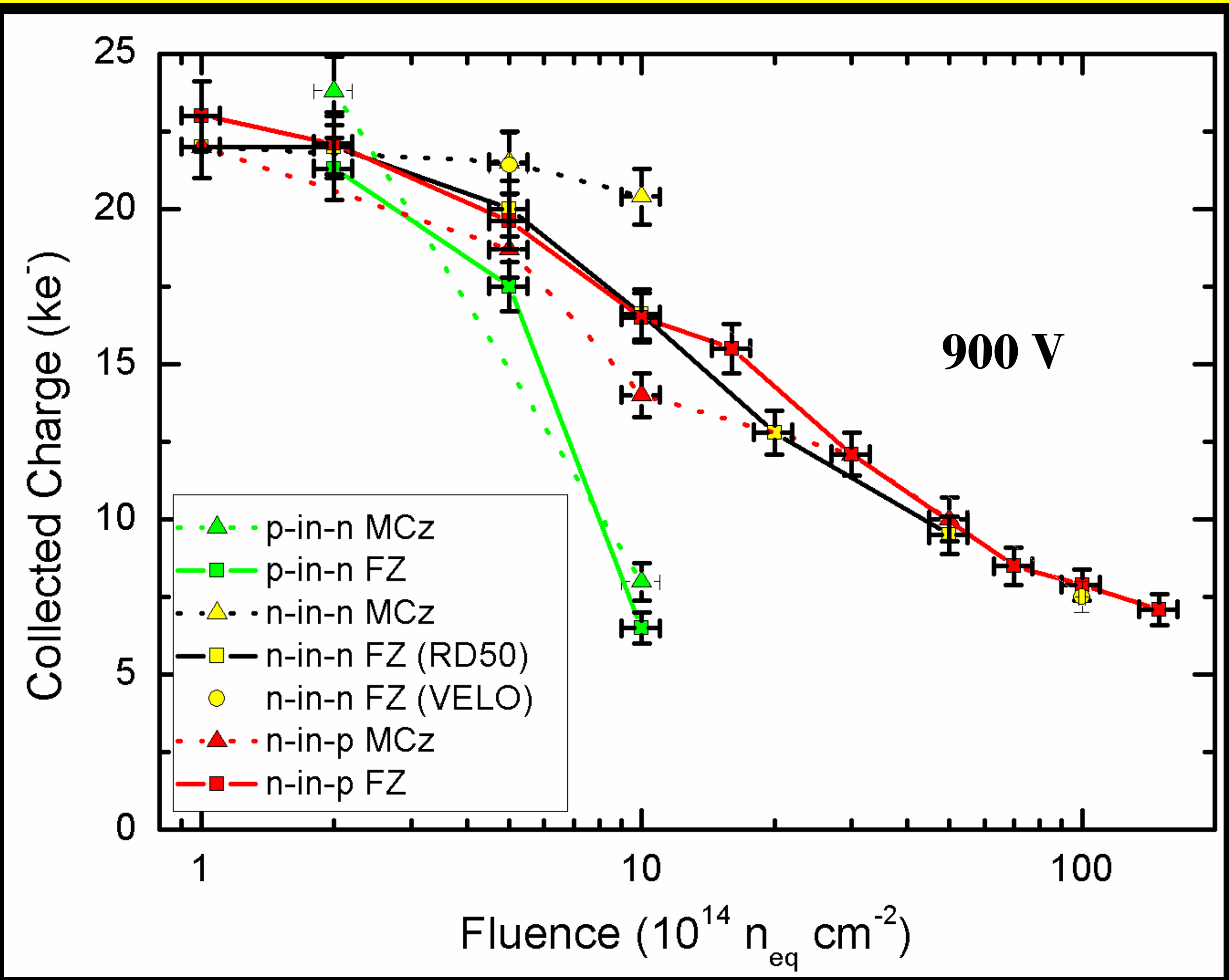


3-D Pixel



Neutron Comparison

- After ~5×10^14 n cm^-2, n-in-n FZ, n-in-p FZ, n-in-p MCz very similar
- At higher voltage n-in-n MCz superior up to maximum fluence (10^15 n cm^-2)
  - Need higher fluence data to determine if this continues
- p-in-n shows inferior performance as expected



Appears once trapping dominates, all n-strip readout choices studied are the same after neutron irradiation

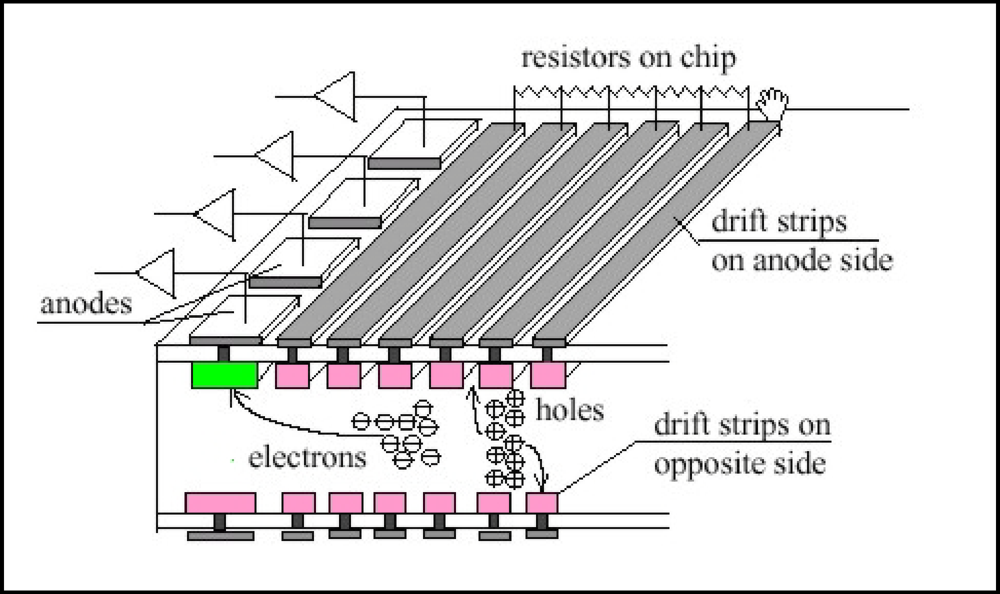
Thx to G. Casse & A. Affolder (Liverpool) (RD50 June 2009 & Vertex2009)

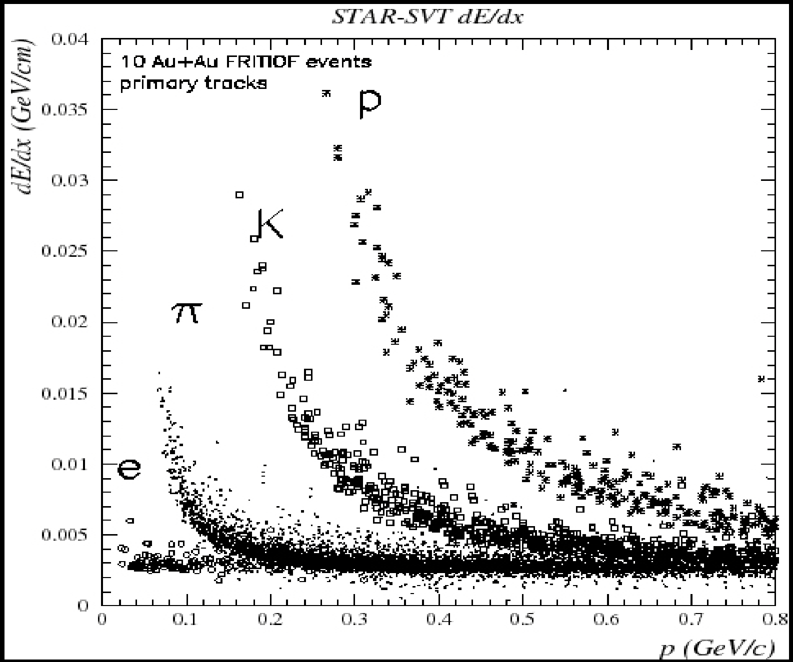
MIND: What are the important parameters?

- In principle ONLY:
  - Efficiency & Resolution & Power Consumption
- But we also interested in:
  - Current
  - Depletion voltage
  - Trapping
  - Charge Collection Efficiency
  - Signal to Noise
  - Strip parameters
- We need to understand the relation to
  - Fluence dependence
    - By particle type
  - Time & Temperature dependence
    - Defining operation and maintenance periods

Si Drift

Unfortunately, I have not enough time to cover Si-Drift
Successfully deployed in the heavy ion collider detectors (STAR, ALICE)





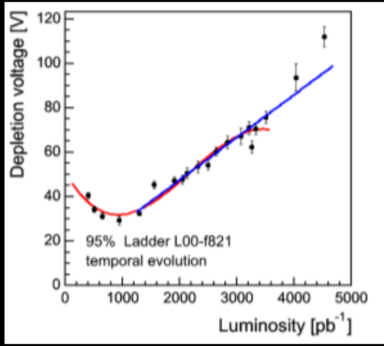
Older more detailed slide versions

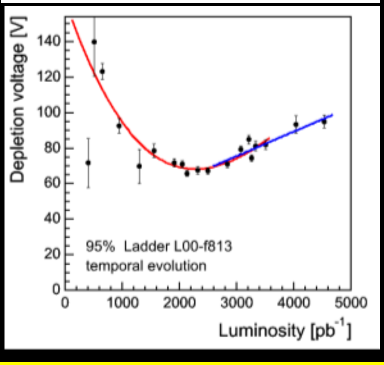
Tevatron: A Lively Example

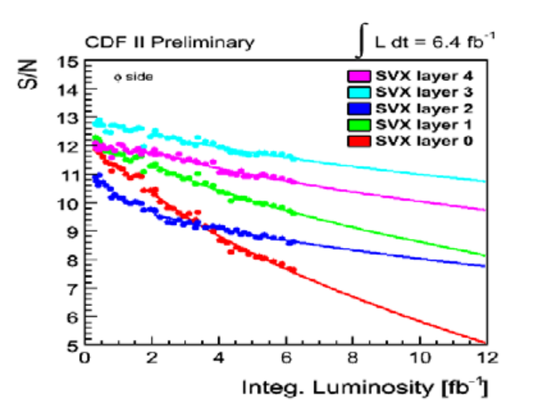
Today

JINDARIANI, Sergo	Longevity Studies in the CDF Silicon Detectors

- CDF and D0 show us every year that the Hamburg Model is valid, although nature seems to be kind to us and radiation over a long period seems less damaging than fast "test" irradiation (10 LHC years in 10 minutes)
- V_{dep} determined by noise vs. voltage scans for double sided sensors (L0 to L5) and with S/N vs. voltage for single sided sensors (L00)







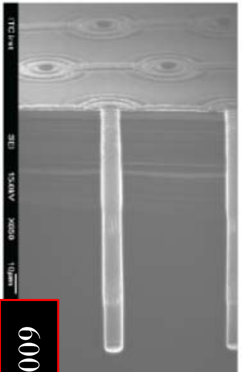
- Estimations for the future looks optimistic (loss in SVX-L0 will be compensated by Layer 00)
- Silicon Detectors will remain in good condition for physics (even if the run is extended to 2011 or 2012)

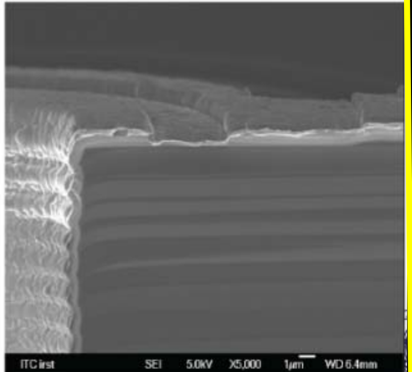
Encouraging results, that for the TEVATRON and LHC, the HH Model allows prediction!

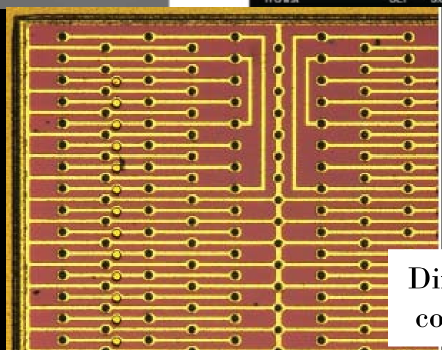
3D modules, examples

Today: Sensor producer: CNM, FBK/IRST, SINTEF, Stanford

O. Rohne et al. (ATLAS 3D) VERTEX 2009

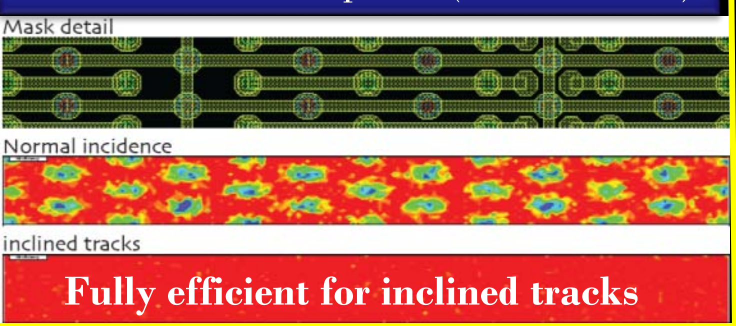






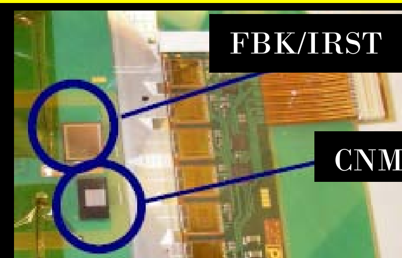
Different pixel configurations

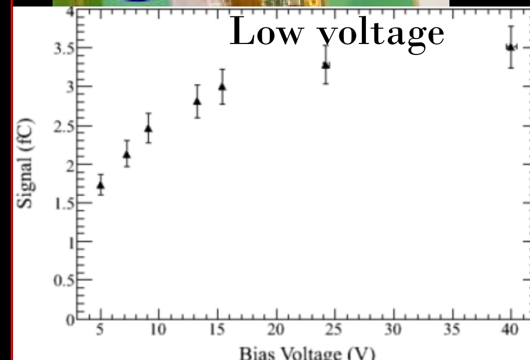
Efficiency up to 99.8%
Resolution similar to planar (inclined tracks)

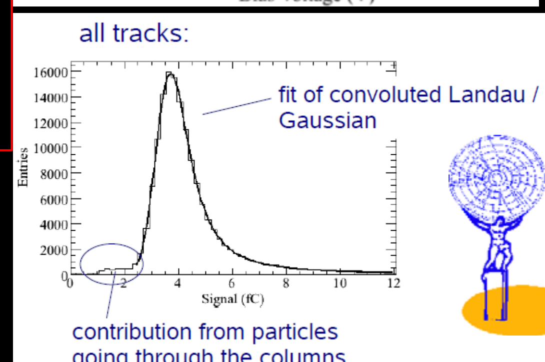


Fully efficient for inclined tracks

Michael Koehler 3D Test Beam Como 7 October 2009





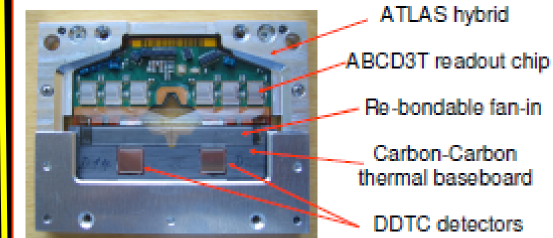


Maximum charge at 40 V: (3.5 ± 0.3) fC, (22 ± 2) ke⁻

- Signal to noise ratio: ~ 31
- Expected for 300 µm silicon: 3.7 fC, 23 ke⁻

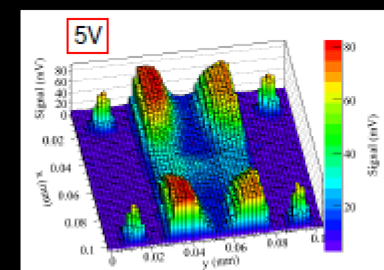
→ Measured signal in agreement with expected signal

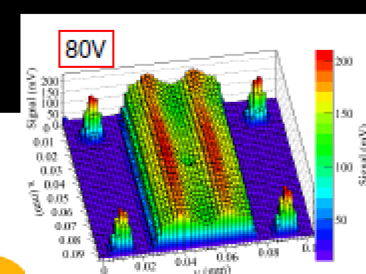
Test module



Fast binary readout, 20ns shaping time

Characterization with position resolved laser, λ=980nm; 2µm spot





Dalla Betta, Bad Wildbad Kreuth 2009

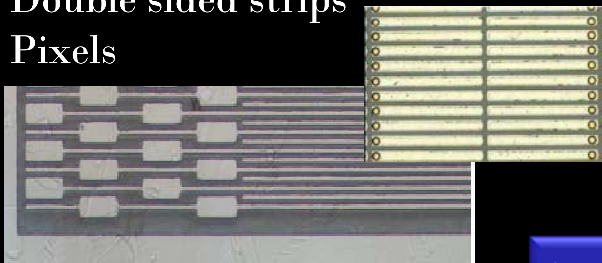
Today on the candidate menu of all detectors to equip the innermost layers! **Bon Appétit**

Diamond II (modules)

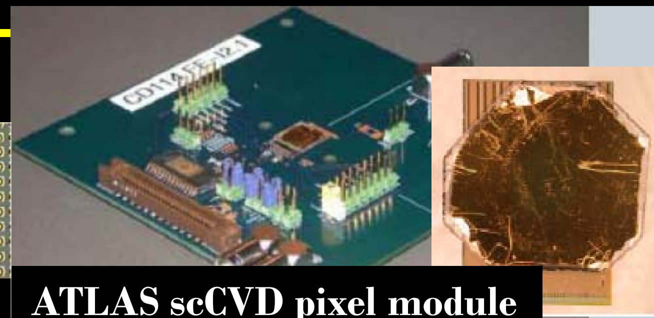
Successfully done:

Double sided strips

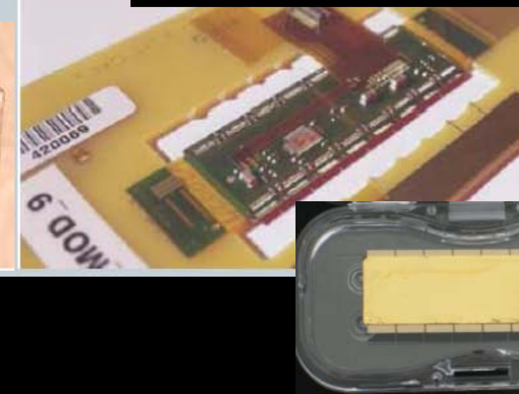
Pixels

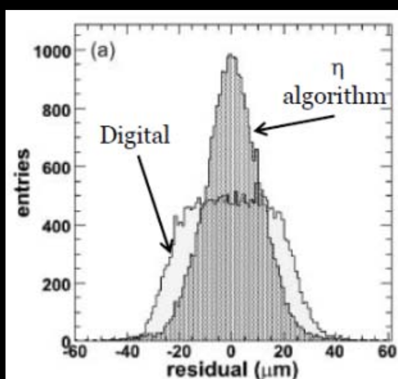


ATLAS scCVD pixel module

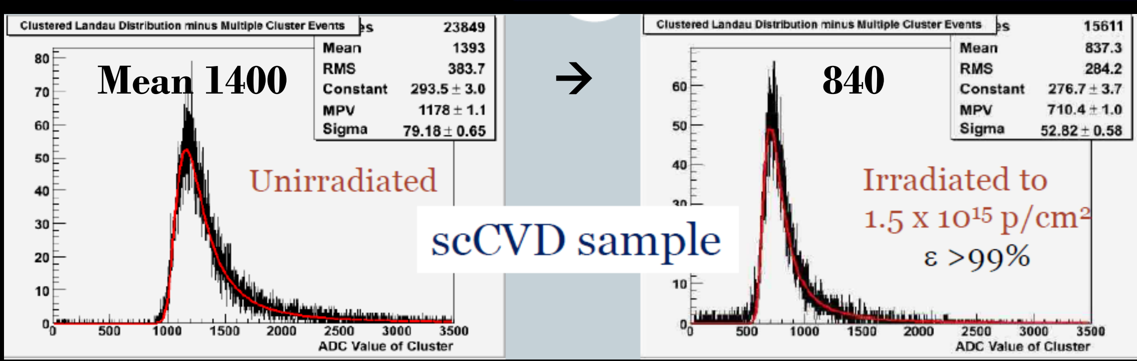


ATLAS pCVD pixel module

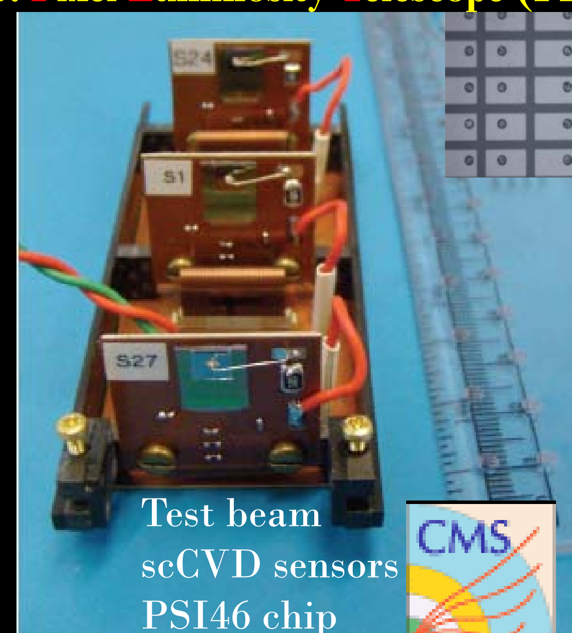




- pCVD full ATLAS pixel module:
  - Resolution 14mm
  - Efficiency 97%
- sCVD ATLAS small module
  - Resolution 8.9 mm
  - Efficiency 99%
- SCVD CMS small module
  - Efficiency 99.3%, 99.6% 99.9%



CMS: Pixel Luminosity Telescope (PLT)



CMS NOTE -2009/022

On the basis of these results ATLAS officially approved Upgrade R&D on Diamond Pixel Detectors

Harris Kagan, Elba & Como 2009, Joshua Moss, Elba 2009; A la Rosa 2008