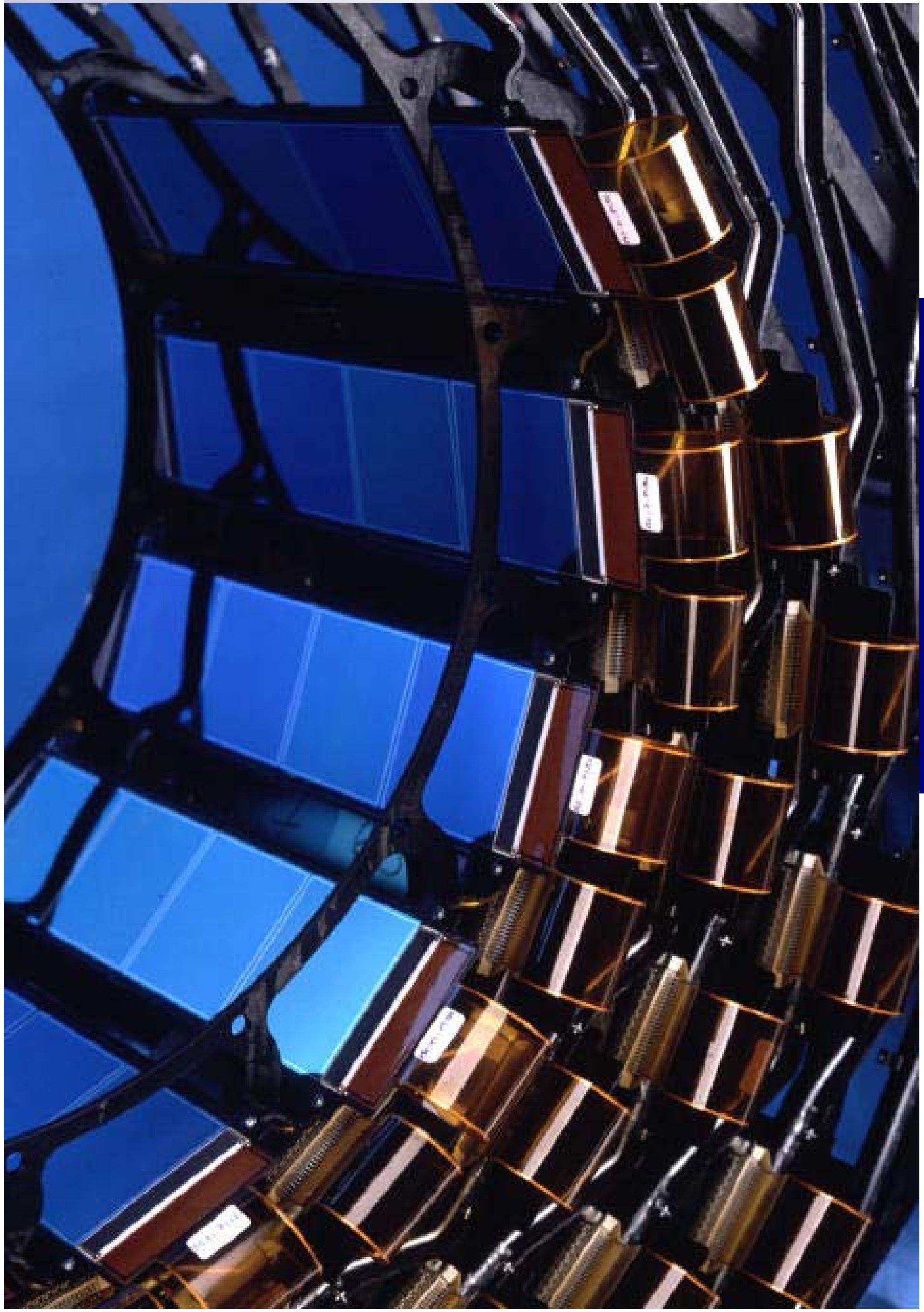


LHC luminosity upgrade: detector challenges

Lecture 2: Semiconductor detectors

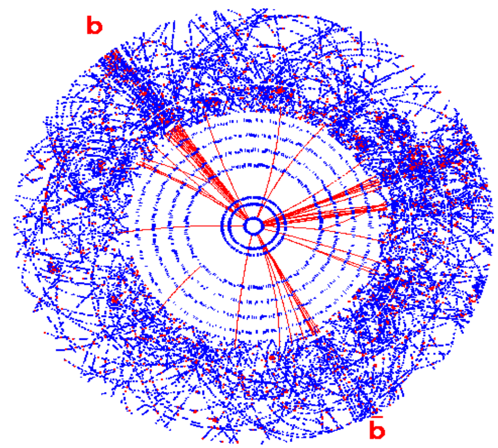
D. Bortoletto

Outline

- Tracking requirements for the LHC
- Principles of operation of semiconductor detectors (4 slides)
- Radiation damage (6 slides)
- What did learn from the LHC detectors for the SLHC challenges (lower power, less mass, higher radiation tolerance and higher speed performance)
- Strategies to improve semiconductor detectors:
  - New materials
  - Defect engineering
  - New structures
  - Optimization of operation conditions
- Electronics and integration issues
- Detector specific R&D and a snapshot to the future

Tracking requirements for the LHC

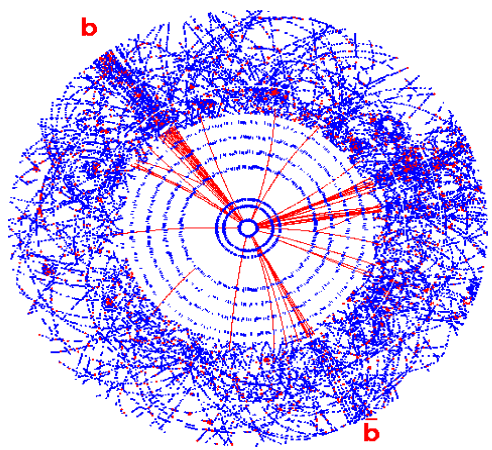
- Bunch spacing of 25ns $\Rightarrow$ fast detector response to resolve bunch crossings
- High luminosity: 10^{33}-10^{34} $cm^{-2}\ s^{-1}$ up to 20 minimum bias/bunch crossing
  - high detector granularity to keep occupancy low and resolve nearby tracks
- Excellent momentum resolution for low and high p_T tracks
- High track reconstruction efficiency
- Ability to tag b-jets and identify B-hadrons and τ's
  - Excellent impact parameter resolution
- Unprecedented irradiation level $\Rightarrow$ radiation hardness
  - Operating T $\approx$ -10º C to minimize radiation damage
  - Dose at 4 cm after 10 years: 500 fb^{-1}~3×10^{15} cm^{-2}
  - Dose at 22 cm after 10 years: 500 fb^{-1}~1.5×10^{14}
- Small amount of material in front of electromagnetic calorimeter
- Risk of failure (preference for known industrial technologies) and cost



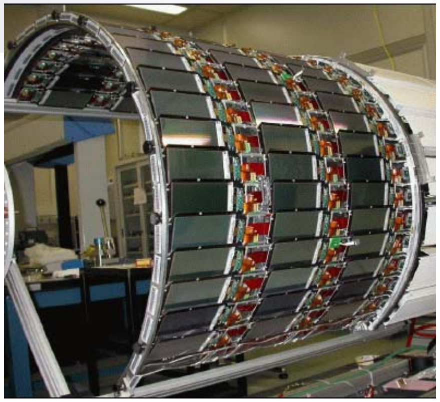
$H\rightarrow b\bar{b}$ LHC high lumi

Tracking requirements for the SLHC

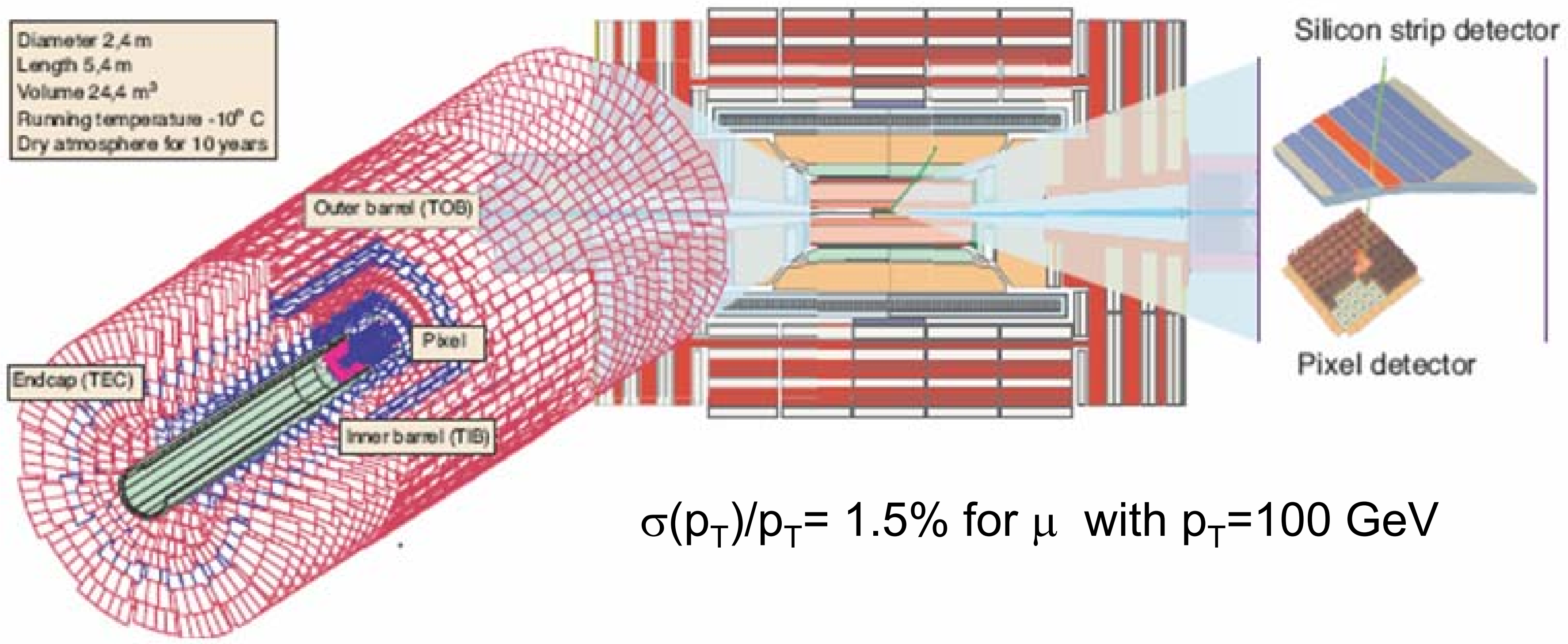
- Bunch spacing of 25ns (12.5 ns?) ⇒ fast detector response to resolve bunch crossings
- High luminosity: 10^{33}-10^{34} cm^{-2} s^{-1} (10^{35} cm^{-2} s^{-1}) up to 20 minimum bias/bunch crossing (100 minimum bias/bunch crossings)
  - high detector granularity to keep occupancy low and resolve nearby tracks
- Excellent momentum resolution for low and high p_T tracks
- High track reconstruction efficiency
- Ability to tag b-jets and identify B-hadrons and τ's
  - Excellent impact parameter resolution
- Unprecedented irradiation level ⇒ radiation hardness
  - Operating T ≈ -10º C to minimize radiation damage
  - Dose at 4 cm after 10 years: 500 fb^{-1}~3×10^{15} cm^{-2} (3000 fb^{-1}~1.8×10^{16} cm^{-2})
  - Dose at 22 cm after 10 years: 500 fb^{-1}~1.5×10^{14} cm^{-2}(3000 fb^{-1}~9×10^{15} cm^{-2})
- Small amount of material in front of electromagnetic calorimeter
- Risk of failure (preference for known industrial technologies), cost



CMS tracker

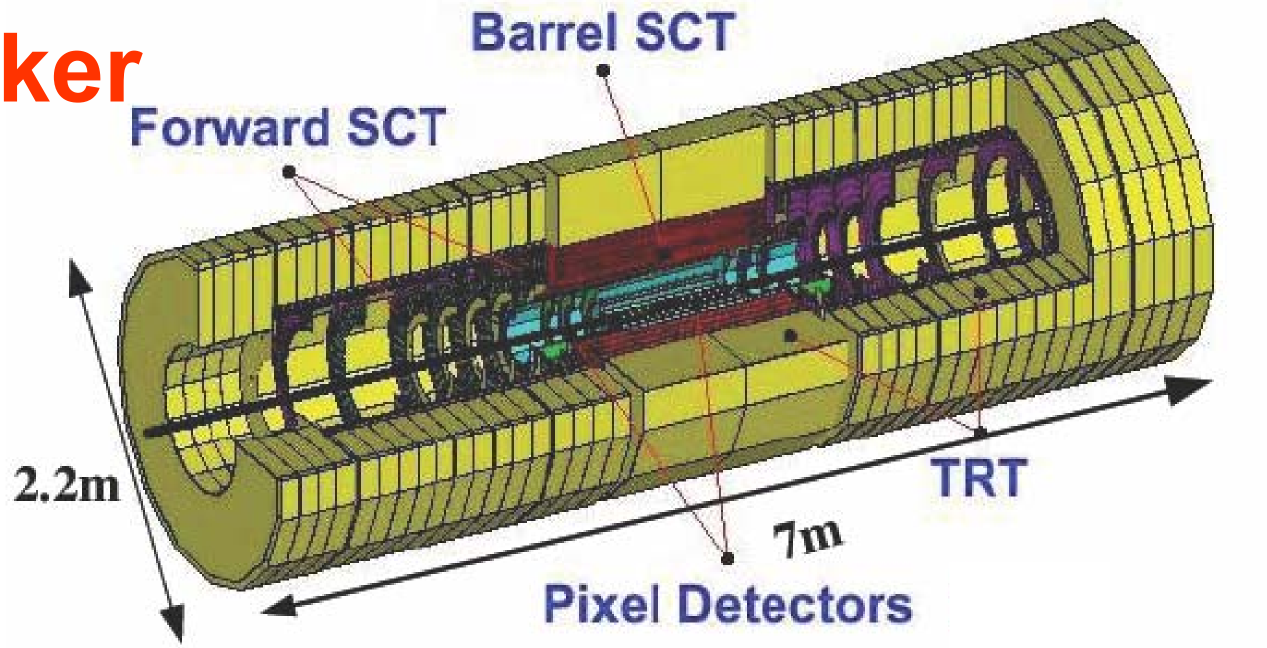


- About 200m^2 of active silicon area
- 1440 pixel modules with 66 million pixels
  - Pixel size: 100μm (r-ϕ) x 150μm (r-z),
  - Charge sharing due to large Lorentz angle (23°) + analog readout
  - spatial resolution ~10μm in r-ϕ, ~20μm in r-z
- 15148 silicon strip modules ~10 million strips



$\sigma(p_T)/p_T$= 1.5% for μ with p_T=100 GeV

ATLAS tracker

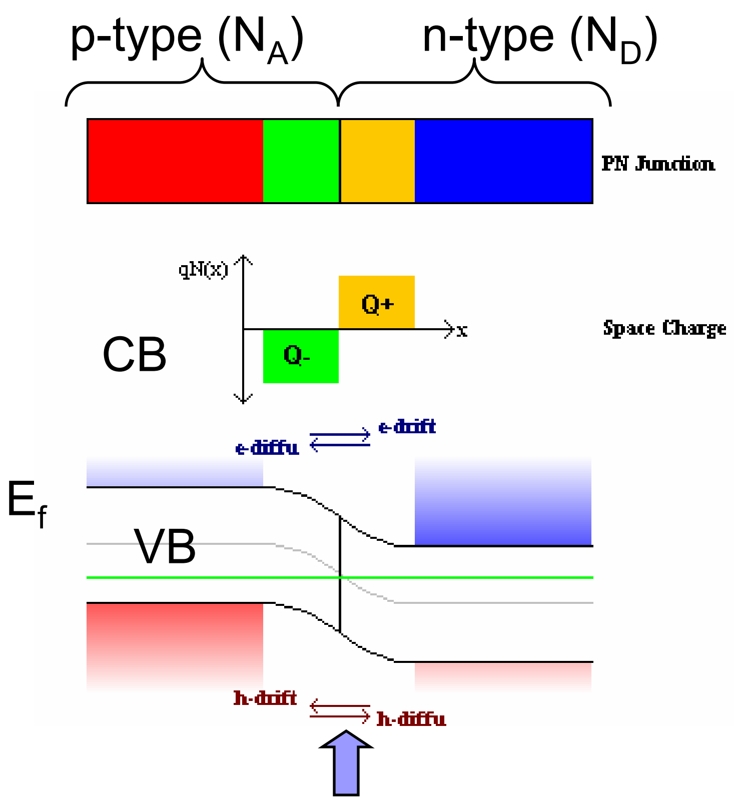


- Pixel:
  - 3 barrel layers, 2 x 3 disks ⇒ three 3d space points for 98% of tracks
  - Spatial resolution ~12μm in r-ϕ,~ 60μm in r-z
- Semiconductor tracker (SCT):
  - 4 barrel layers, 2 x 9 disks; 4088 modules, 61m^2
  - All modules are double sided (2.3˚)

B=2T
$\sigma(p_T)/p_T \sim 2\ [\sigma(p_T)/p_T]_{CMS}$

- Transition radiation tracker (TRT):
  - 370 000 drift tubes; spatial res. from drift time: 170μm per straw
  - Continuous tracking (> 30 hits per track), low cost, less material per point
  - Electron/pion separation
  - Concerns: occupancy, speed (maximal drift time: 40ns)

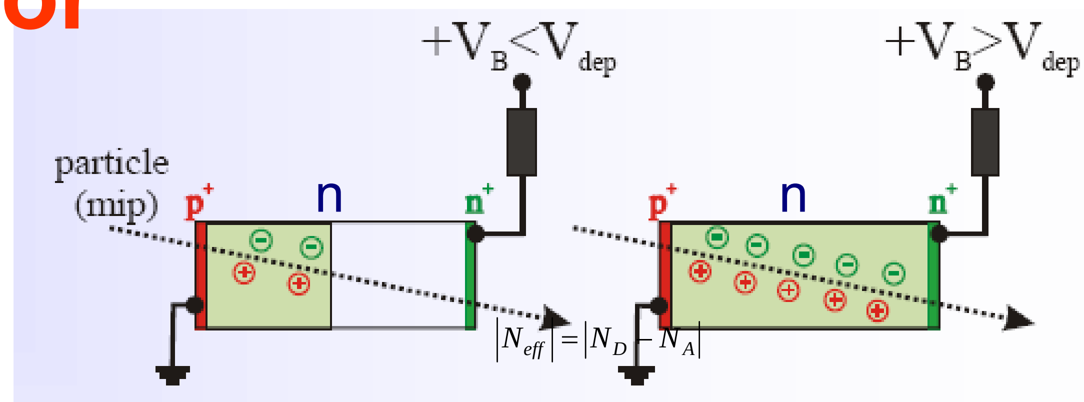
A silicon detector



Electron and holes combine

Solve Poisson eq.

$$-\frac{d^2}{dx^2}\phi(x) = \frac{q_0}{\varepsilon\varepsilon_0} N_{eff}$$



- Reversed biased p-n junction to establish region with no mobile carriers

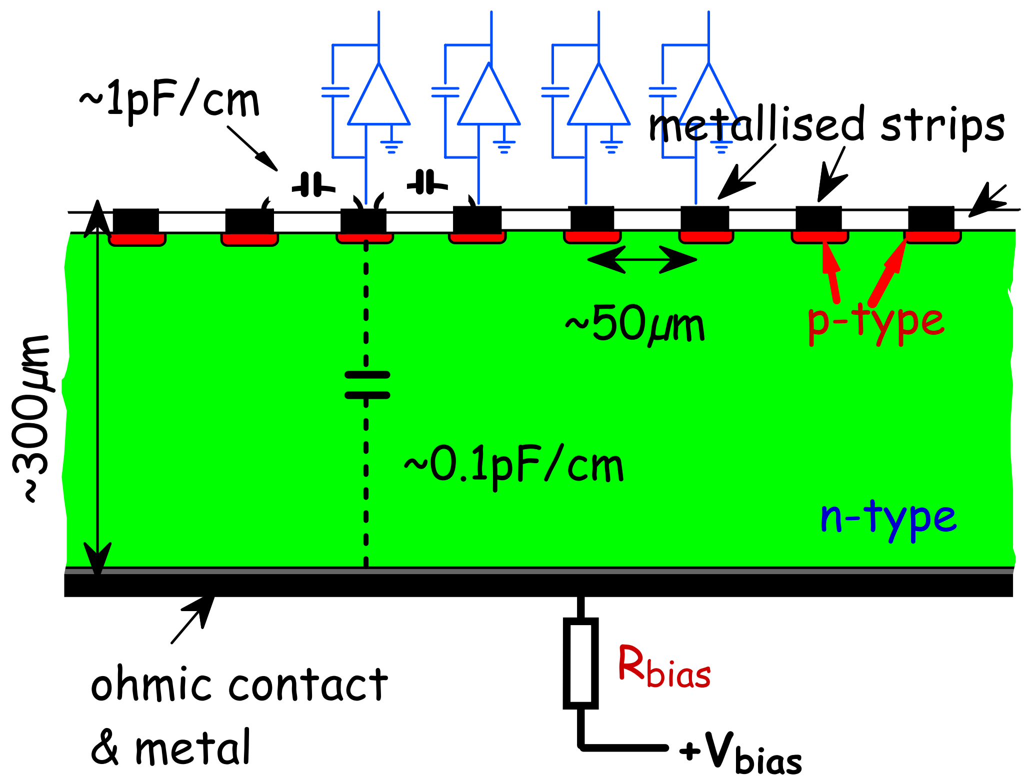
$$V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0}\left|N_{eff}\right| d^2$$

$$\left|N_{eff}\right| = \left|N_D - N_A\right|$$

- Increase external reverse bias
  - Increase E field ⇒ e^- and h drift to electrodes
  - Increase depletion region size
  - Reduce capacitance ≈ $\varepsilon\varepsilon_0 A/d$ (Measurement of C yields full depletion voltage)
  - Small current flow

Single sided detectors

- Make several p-n junctions by segmenting the p+ layer into strips
- Connect the strips to individual readout channels

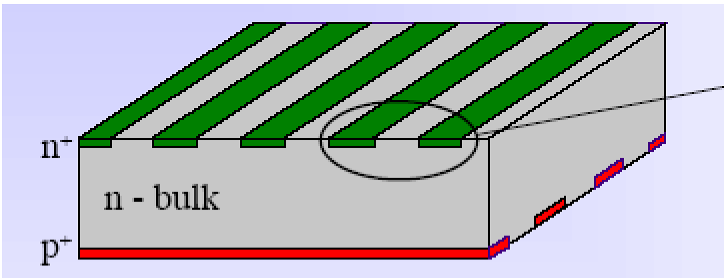


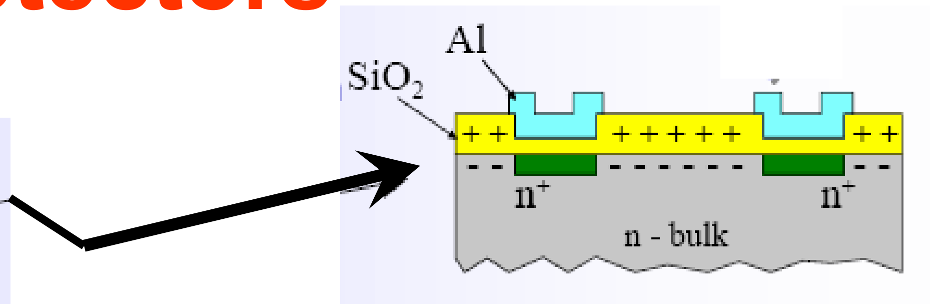
300 μm n-type silicon,
ρ=2Km.cm ($N_D \approx 2.2\times 10^{12}$ cm^{-2})$\Rightarrow V_d$=150V
p=50 μm ⇒ σ ~ 14.4 μm

- Detector size
  - limited by wafer size < 15cm diameter
- Signal speed
  - <E> ≈ 150V/300μm
  - p-type strips collect holes $v_{hole} \approx$ 15 μm/ns
- Connect amplifier to each strip
  - can also use inter-strip capacitance ⇒ reduce number of amplifiers to share charge over strips
- Spatial measurement precision
  - defined by strip dimensions and readout method $\sigma = p/\sqrt{12}$
  - ultimately limited by charge diffusion σ ~ 5-10μm

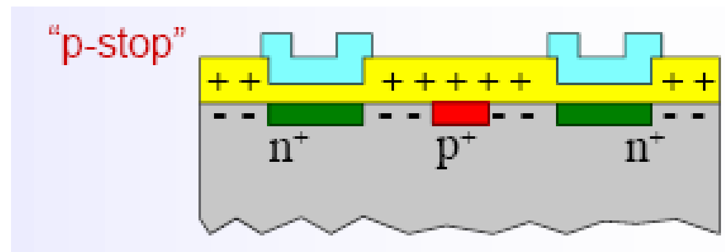
Double sided detectors

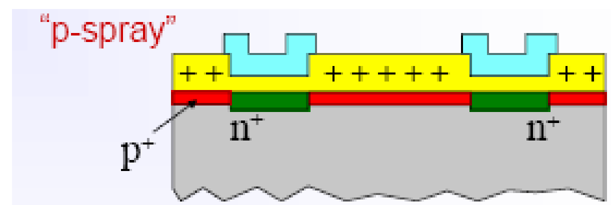
- Segment both n and p-side⇒ 2D

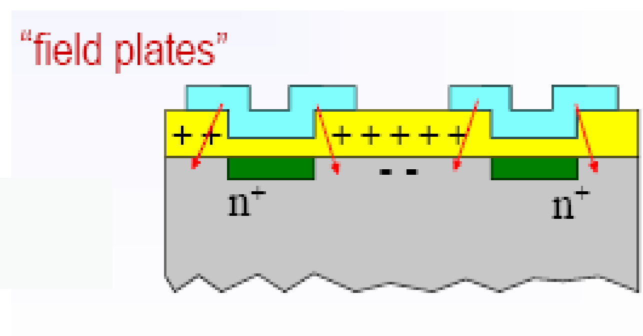




- Problem electron accumulation layer
  - n^+ strips are not isolated because of an accumulation layer at Si-SiO_2 interface due to positive charges in the SiO_2 layer
- Solution:
  - p-strips between n-strips (p-stops)
  - Moderate p-implantation over the all surface (p-spray)
  - Metal at negative potential over n^+ strips to repel electrons (field plates)
- These isolation techniques are also used in n+ on n detectors . Advantage v=μE:
  μ_e= 1350 cm² / V·s>> μ_h= 450 cm² / V·s





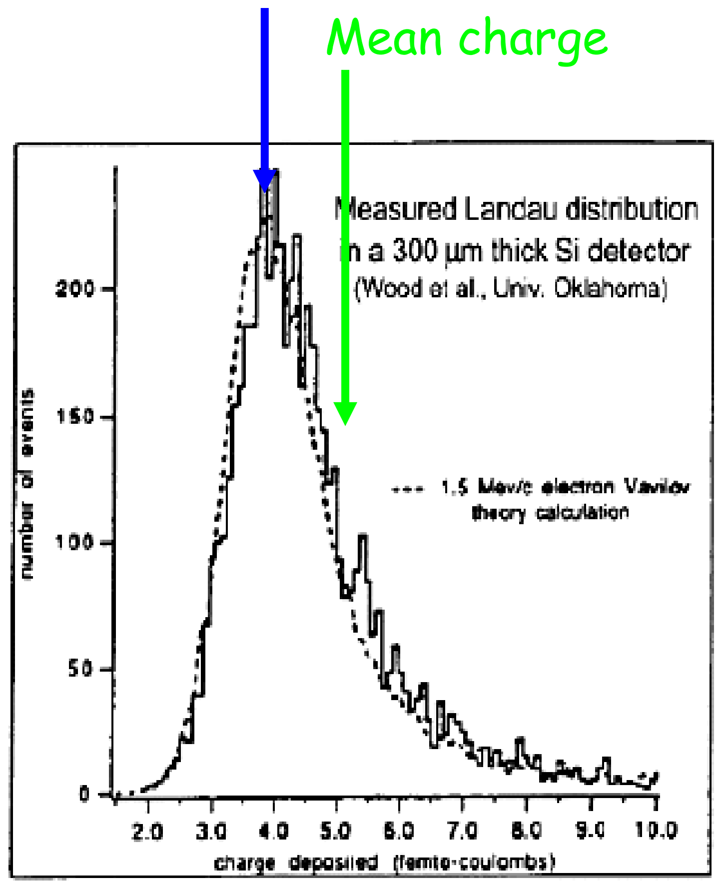


S/N before irradiation

- **Collected charge usually given for Minimum Ionizing Particle (MIP):**
  - Mean $dE/dx)_{Si}$ = 3.88 MeV/cm ⇒ 116 keV for 300 μm thick Si
  - Most probable loss = 81 keV for 300 μm Si
  - Since 3.6eV needed to make e-h pair ⇒ charge in 300 μm= 22500 e^- (=3.6 fC)
- **Landau distribution has a low energy tail which broadens because of noise.**
  - **Noise sources:**
    - **Capacitance ENC ∝ C_d**
    - **Leakage Current ENC ∝ √ I**
    - **Thermal Noise ENC ∝ √(kT/R)**
- **Typical Values S/N > 10-15**

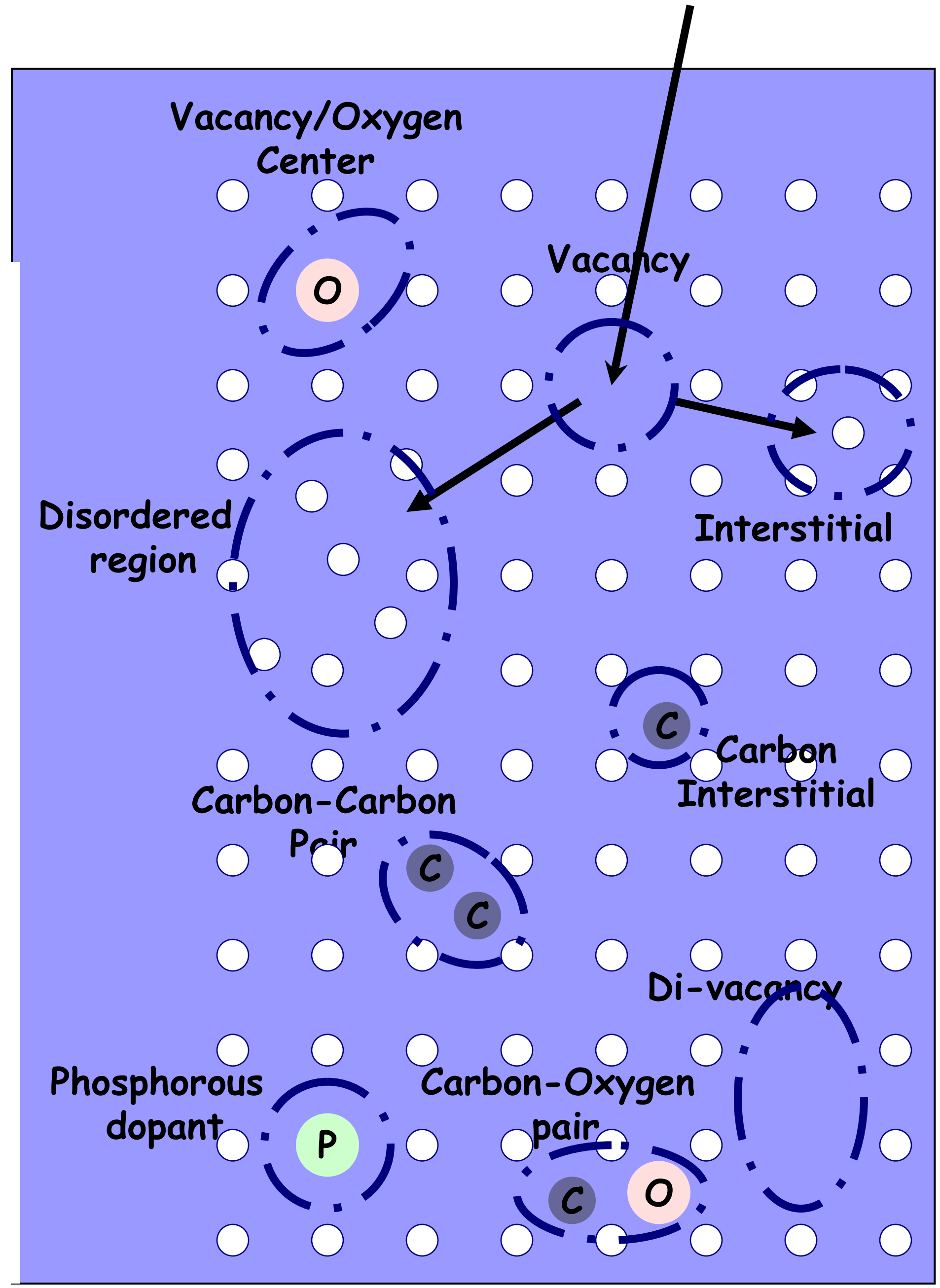
Most probable charge ≈ 0.7× mean

Mean charge



Bulk Damage- Microscopic view

- Bulk damage is mainly from hadrons displacing primary lattice atoms:
  - Vacancies, silicon interstitials, and large disordered regions
  - 1 MeV neutron transfers ≈60-70 keV to recoiling silicon atom, which in turn can displace clusters
- Defects can recombine or migrate through the lattice to form more complex and stable defects
  - Annealing can be beneficial
  - Defects can be stable or unstable
- Defects add levels in the band gap affecting macroscopic properties: N_{eff}, trapping and leakage current



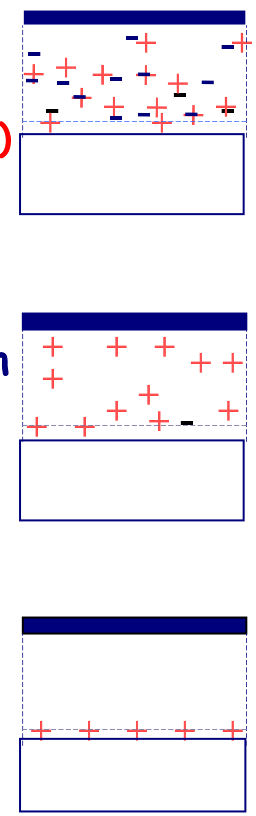
Surface Damage

- Surface damage generation:
  - Ionizing radiation creates e-h pairs in SiO_2
  - Many recombine, electrons migrate quickly, holes slowly migrate to Si/SiO_2 interface since $\mu_{hole} << \mu_{electron}$
  - Some holes 'stick' in the boundary layer
- Surface damage results in
  - Increased interface trapped charge
  - Increased fixed oxide charges
  - Surface generation centers
- Macroscopic effects
  - Increase in the sensors capacitance
  - Decrease in the interstrip resistance
  - Surface current
  - Risk to readout electronics
    - threshold shifts
    - noise and gain deterioration

Metal (Al)
Oxide (SiO_2)
Interface (SiO_x)
Semiconductor (Si)

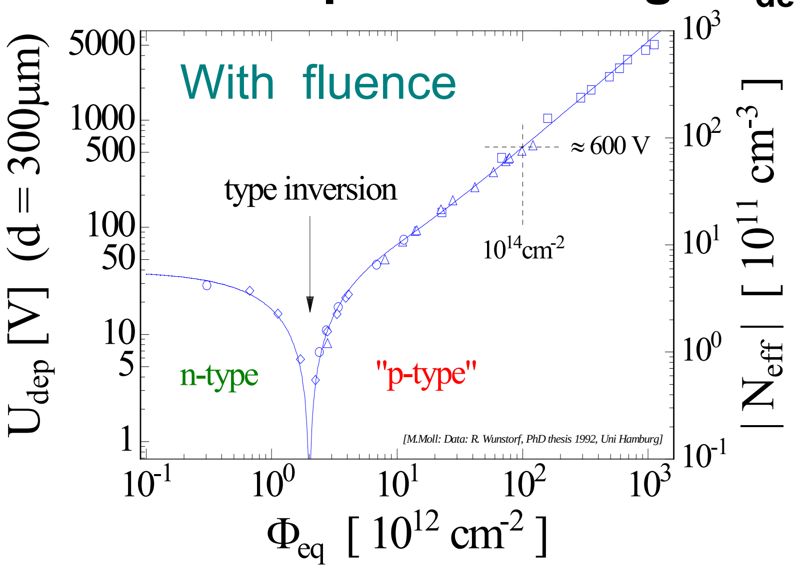
After electron transport:

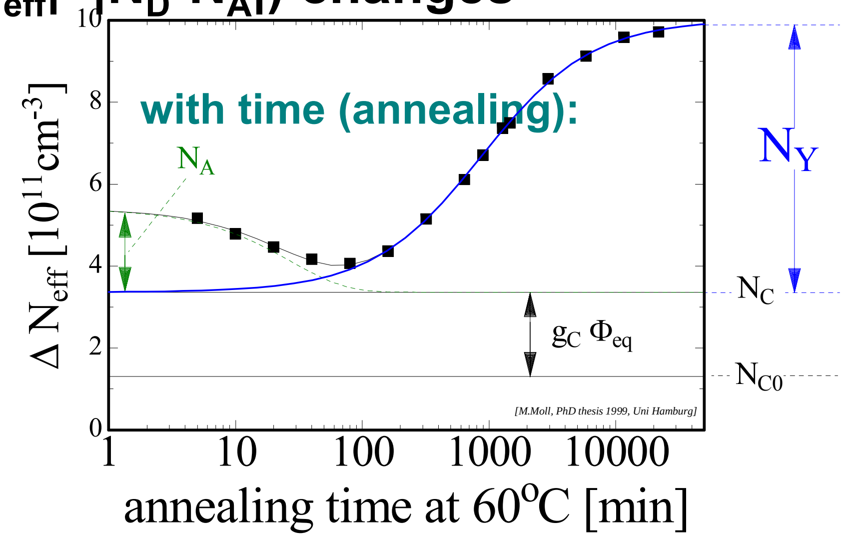
After transport of the holes:



Effective doping concentration

- The depletion Voltage V_{dep} ($|N_{eff}|=|N_D-N_A|$) changes





Most irradiation damages in the Si behave like acceptors ⇒ "Hamburg" model

$$|N_{eff}(\Phi_{eq},t,T)| = |N_D - N_A| =$$

$N_a(\Phi_{eq},t,T)$	Annealing
$+N_c(\Phi_{eq})$	Constant
$+N_y(\Phi_{eq},t,T)$	Anti-annealing

- **Short term: "Beneficial annealing"**
- **Long term: "Reverse annealing"**
  - time constant depends on temperature:

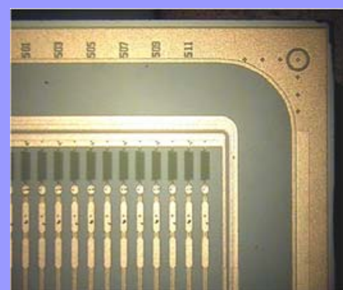
~ 500 years	(-10°C)
~ 500 days	(20°C)
~ 21 hours	(60°C)

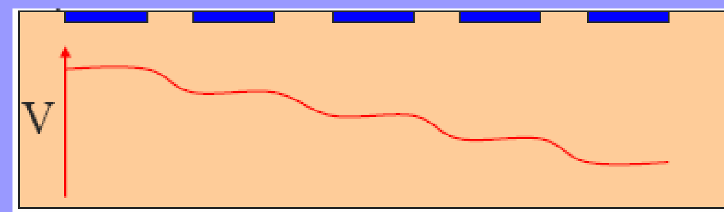
Detectors must be cooled even when the experiment is not running!

What did we learn for LHC?

Operation of devices at higher bias Voltages

- **Bias ring design**



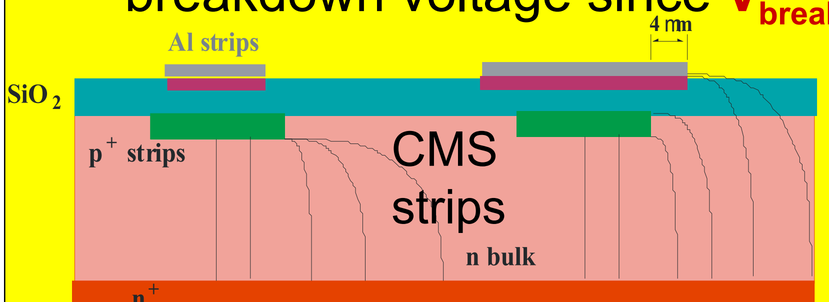


Multi-guard ring

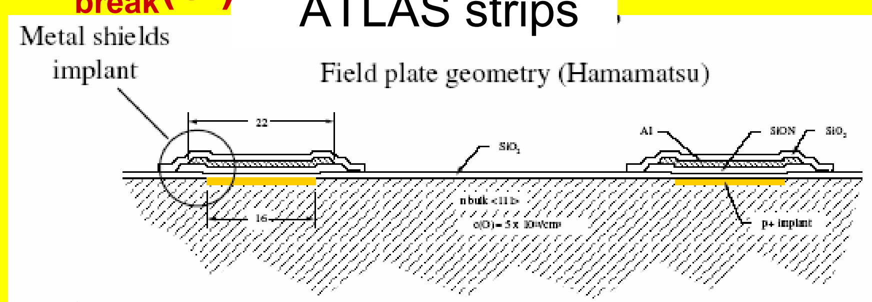
CMS and Atlas Pixels

CMS strips: one guard ring, the metal overhang as “continuous” multi-guard-structure.

- **CMS:** Metal overhang design Al strips overhang implants→ high breakdown voltage since $V_{break}(SiO_2) > V_{break}(Si)$



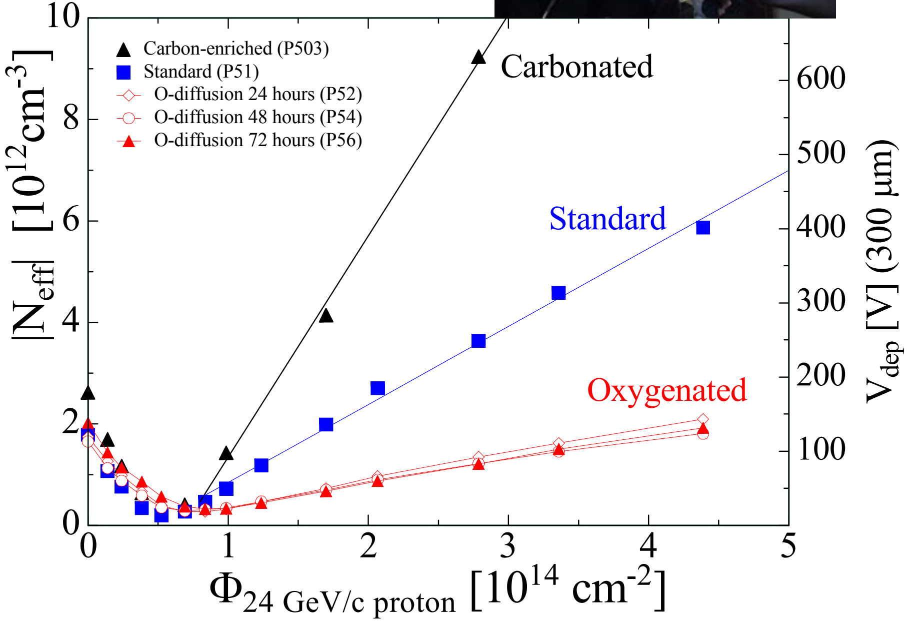
ATLAS strips

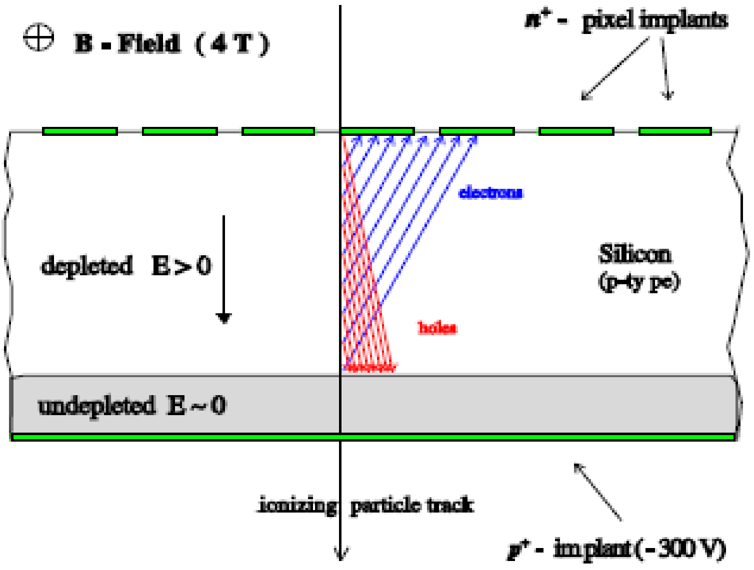


ATLAS: field plate geometry for the Hamamatsu detectors (86%), non field plate CiS (14%). CiS detectors show sensitivity to humidity

What did we learn for LHC

- **Oxygen is good!!! (RD48 was formed at CERN to develop radiation hard sensors for the LHC.)**
  - **DOFZ** silicon has less variation in V_{fd} with radiation compared to **FZ** ⇒ more *radiation hard*
    - **Atlas and CMS barrel pixel detectors use oxygenated silicon**

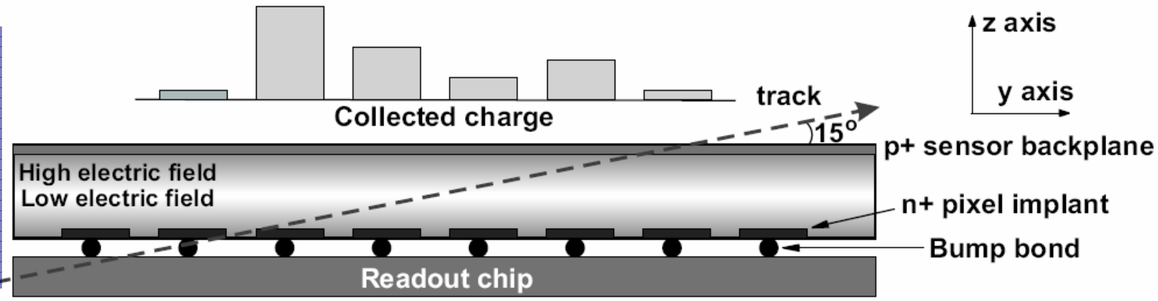




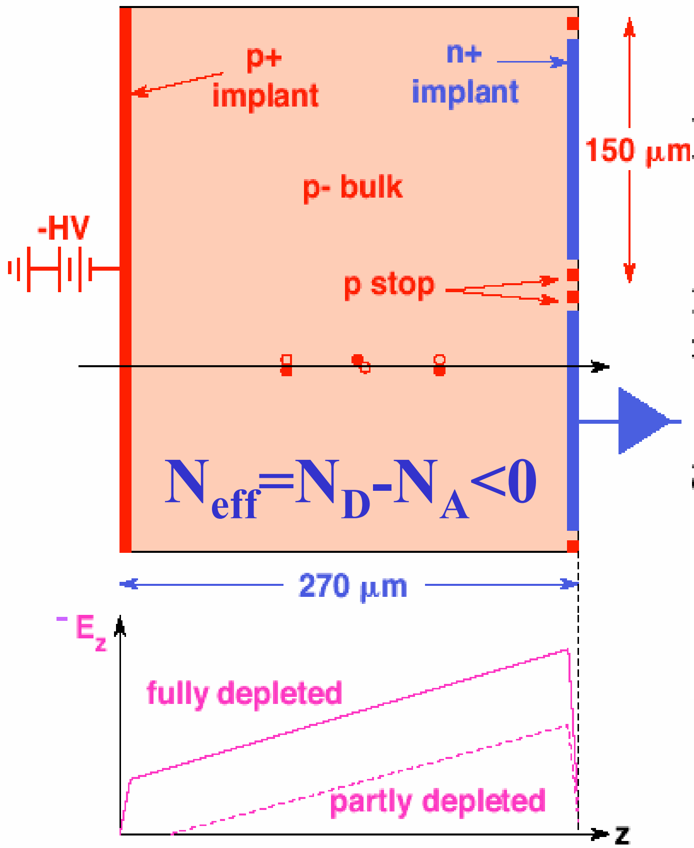
- **Space Charge Sign Inversion (SCSI)**
  - **n-on-n sensors allows operation with undepleted detectors.**
  - **Faster charge collection**
  - **Option chosen for Atlas and CMS pixels**

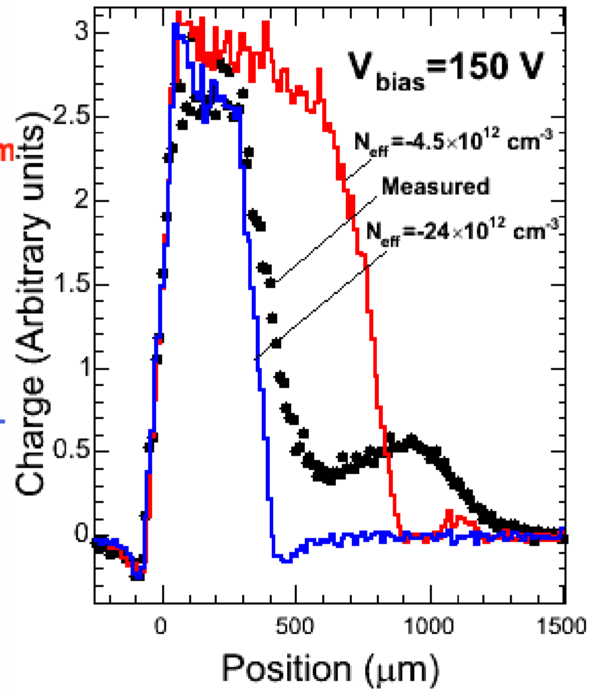
Models with constant N_{eff}

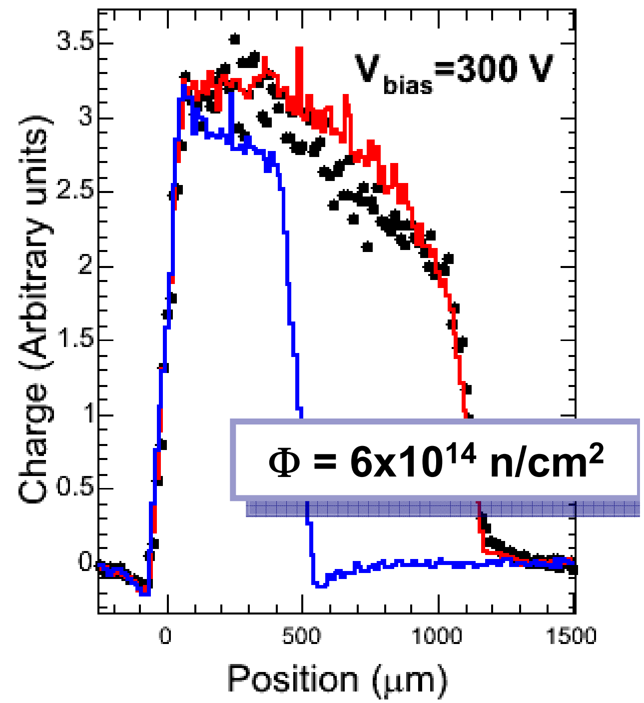
Charge collection measured using cluster profiles in a row of pixels illuminated by a 15º beam and no magnetic field



after type inversion

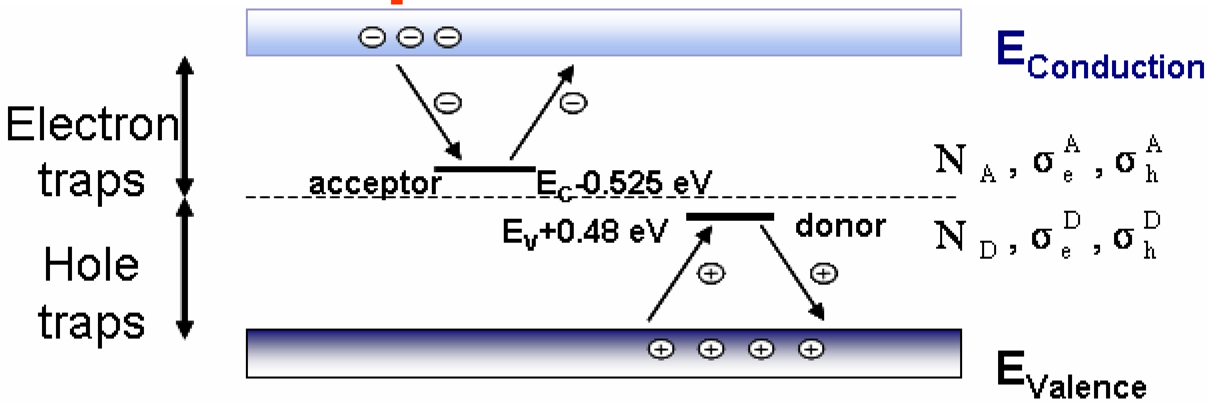




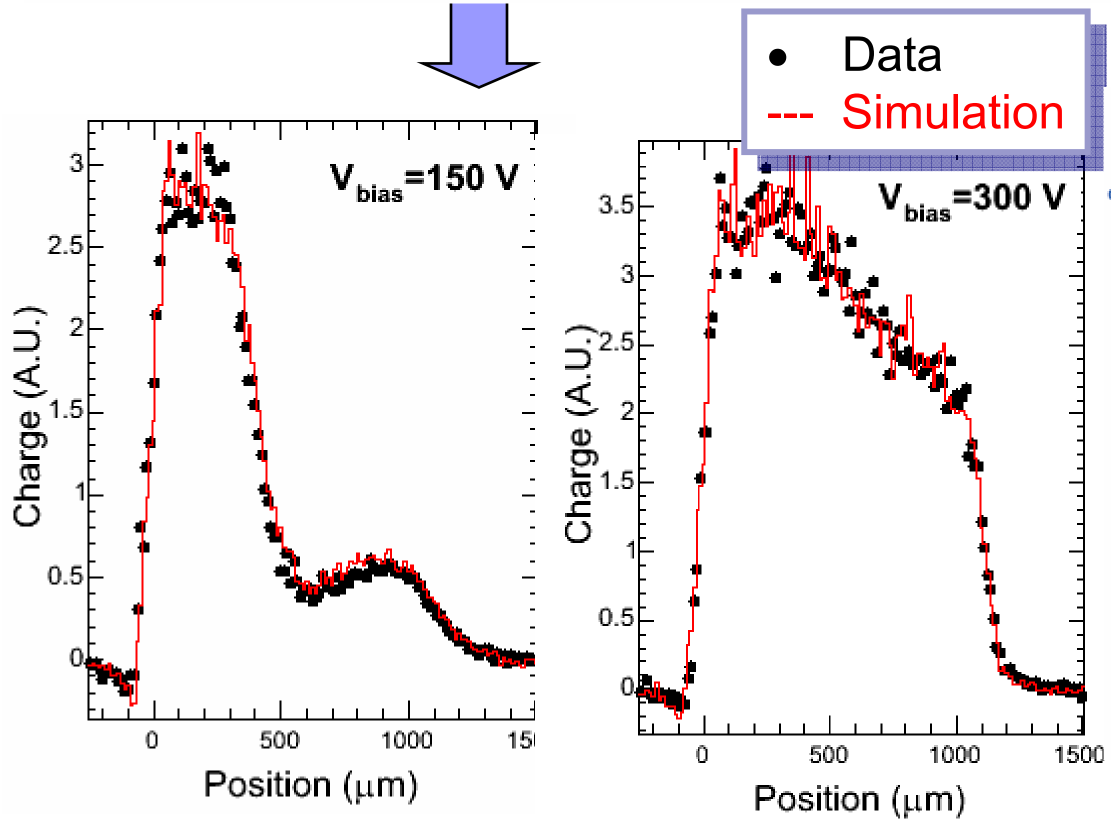


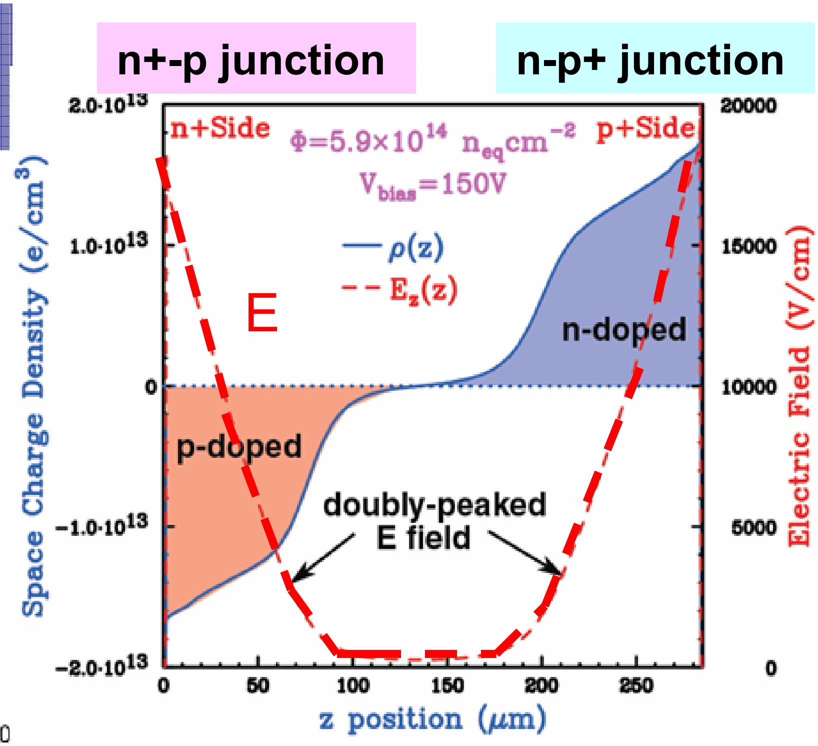
Model with constant space charge density does not describe the measured charge collection

Two trap model and double peak E field



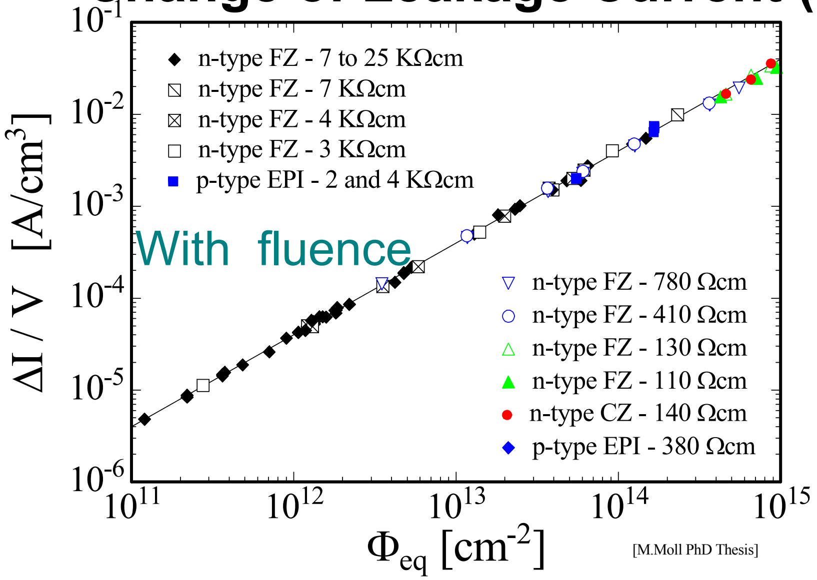
$E_{A/D}$ = trap energy level fixed
$N_{A/D}$ = trap densities from fit
$\sigma_{e/h}$ = trapping cross sections from fit
$\Phi_1 = 6\text{x}10^{14}$ n/cm^2,
$N_A/N_D = 0.40$, $\sigma_h/\sigma_e = 0.25$

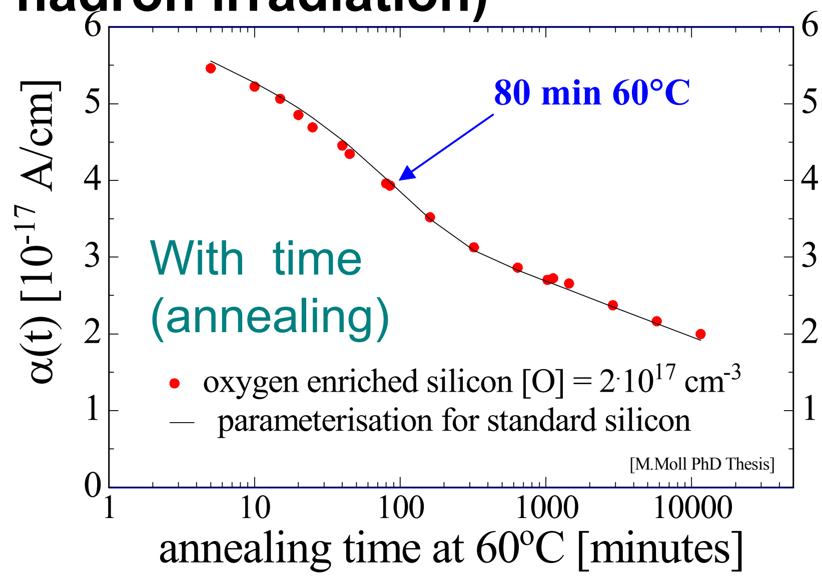




Leakage Current

- **Change of Leakage Current (after hadron irradiation)**





- Damage parameter α (slope in figure)

$$\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}$$

Leakage current per unit volume and particle fluence

- α is constant over several orders of fluence and independent of impurity concentration in Si ⇒ can be used for fluence measurement

- Leakage current decreasing in time (depending on temperature)
- Strong temperature dependence

$$I \propto \exp\left(-\frac{E_g}{2k_B T}\right)$$

⇒ Cool detectors during operation!
Ex: I(-10°C) ~1/16 I(20°C)

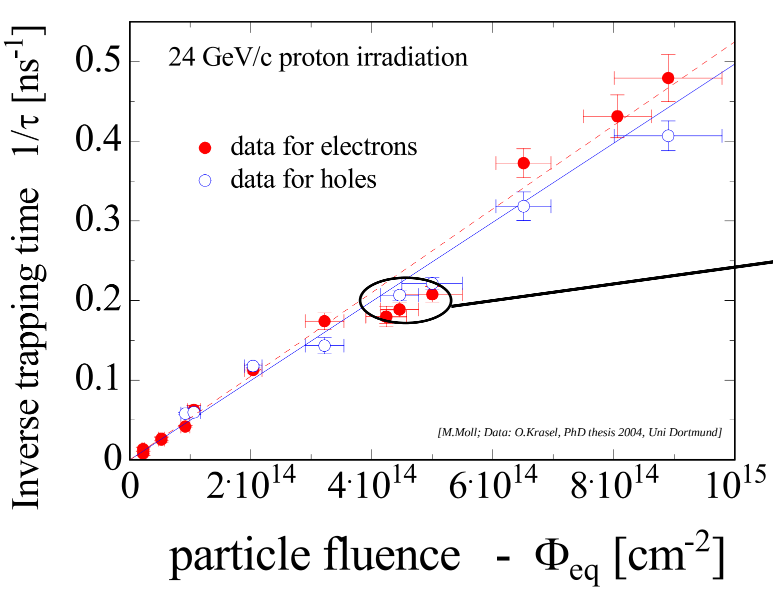
Trapping

- **Deterioration of Charge Collection Efficiency (CCE) by trapping**

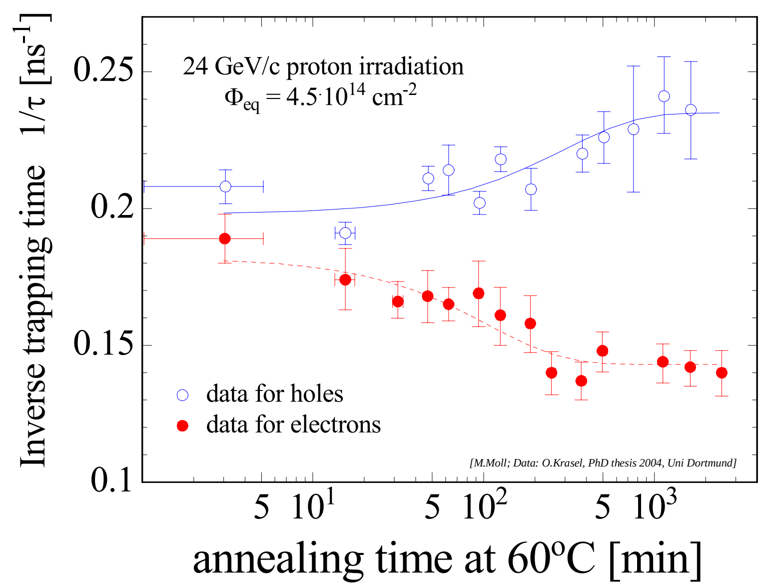
Trapping is characterized by an effective trapping time τ_{eff} for e^- and h:

$$Q_{e,h}(t) = Q_{0e,h} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t\right) \qquad \textbf{where} \qquad \frac{1}{\tau_{eff\ e,h}} \propto N_{defects} \propto fluence$$

Increase of 1/τ with fluence



1/τ changes with annealing

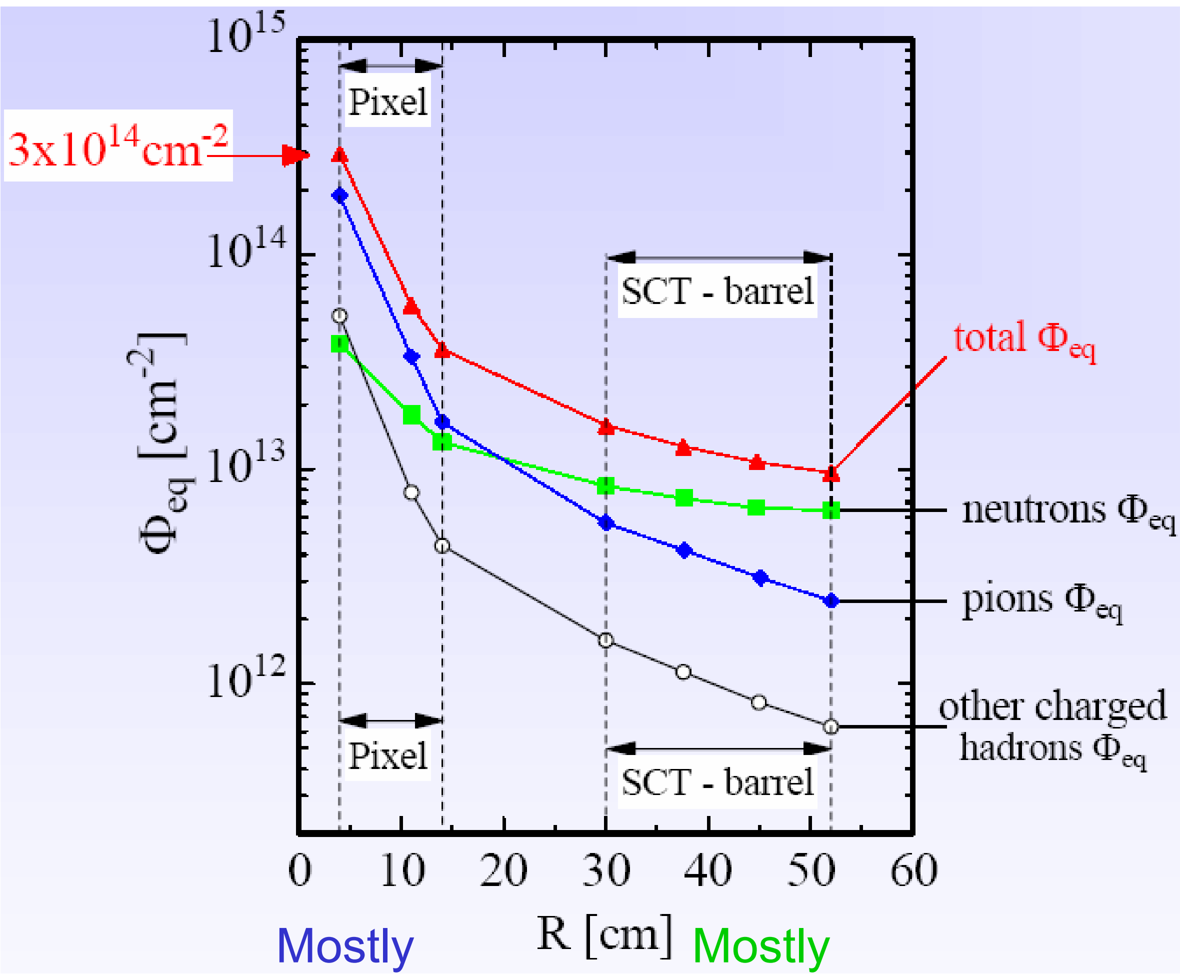


$$\tau_{eff}(10^{15}) = 2ns \qquad w = v_{sat}\tau_{eff} = \left(10^7\, cm/s\right) \times 2 \times 10^{-9} s = 200 \mu m$$

$$\tau_{eff}(10^{16}) = 0.2ns \qquad w = v_{sat}\tau_{eff} = \left(10^7\, cm/s\right) \times 2 \times 10^{-10} s = 20 \mu m$$

Huge Decrease in CCE?

Current LHC trackers



Mostly pions

Mostly neutrons

LHC Fluence per year at full luminosity

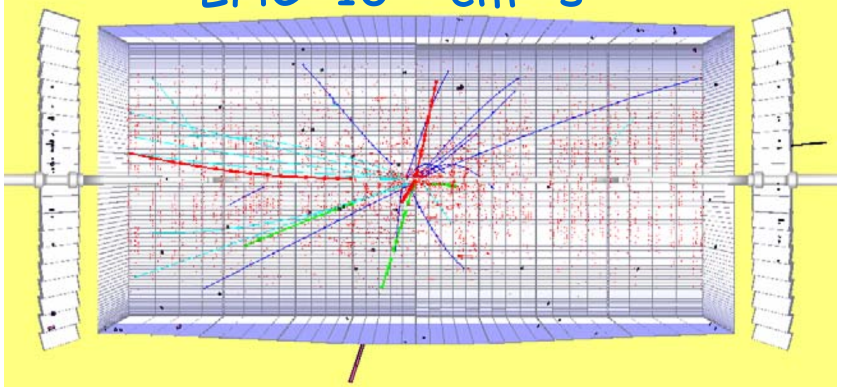
CMS

- Three regions to match radiation damage and occupancy
  - n-on-n pixels (r<20 cm)
    - $\Phi=3.0 \times 10^{14}$ cm^{-2}/year, 270 μm thick sensors Low resistivity (1.5-2 KΩ·cm) oxygenated for the barrel.
  - p-on-n strips
    - Inner region (20cm <r<50cm)
      - $\Phi=1.6 \times 10^{14}$ cm^{-2}, 320 μm thick, Low resistivity (1.5-2 KΩ·cm), pitch ~80 μm
    - Outer region (r>50cm)
      - $\Phi=3.5 \times 10^{13}$ cm^{-2}, 500 μm thick, High resistivity (3.5-7.5 KΩ·cm), pitch ~ 200 μm

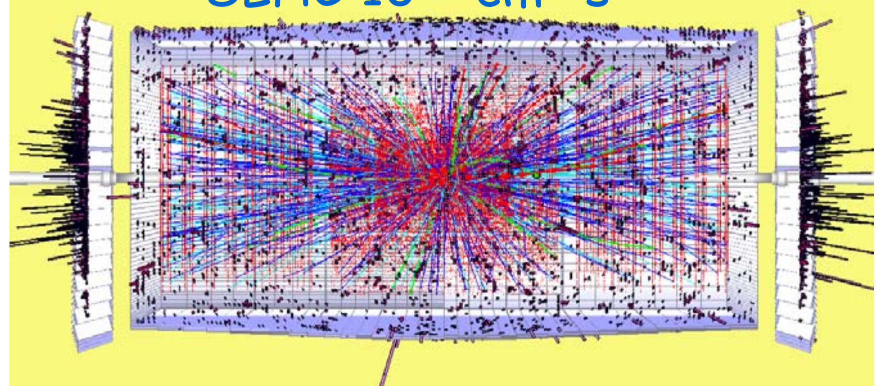
SLHC and tracking

H→ZZ→eeμμ m(higgs)=300 GeV all tracks with p_T<1 GeV removed

LHC 10^{33} $cm^{-2}s^{-1}$



SLHC 10^{35} $cm^{-2}s^{-1}$



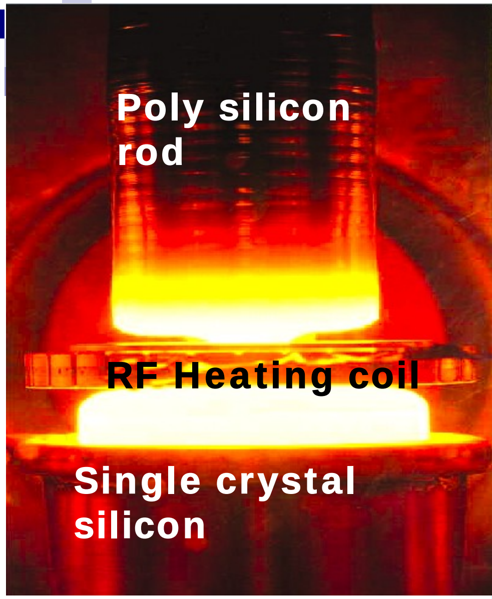
- **Integrated Luminosity (radiation damage) dictates the detector technology**
- **Instantaneous rate (particle flux) dictates the detector granularity**
  - **more granularity if we aim at same performance we expect from the LHC trackers**

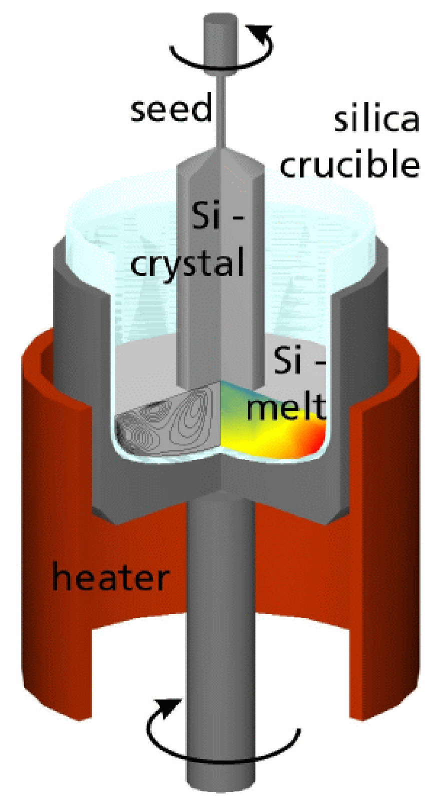
R (cm)	Φ (p/cm²)	Technology	S
>50	10^{14}	Present p-in-n (or n-in-p) Limitation I_{leak}	~20Ke⁻
20-50	10^{15}	Present n-in-n (or n-in-p) Limitation V_{dep}	~10Ke⁻
<20	10^{16}	RD needed Limitation trapping	~5Ke⁻

Radiation hard devices for the SLHC (RD50 et al)

- **Silicon Defect Engineering**
  - Understanding radiation damage
    - Macroscopic effects and Microscopic defects
    - Simulation of defect properties & kinetics
    - Irradiation with different particles & energies
  - Oxygen rich Silicon
    - DOFZ, Cz, MCZ, EPI
  - Oxy. dimer & hydrogen enriched Si
  - Pre-irradiated Si
  - Influence of processing technology
- **New Materials**
  - Silicon Carbide (SiC), Gallium Nitride (GaN)
  - Diamond: CERN RD42 Collaboration
  - Amorphous silicon (TFA)

- **Device Engineering**
  - p-type silicon detectors (n-in-p)
  - thin detectors
  - 3D
  - Semi 3D detectors Stripixels
  - Cost effective detectors
  - Simulation of highly irradiated detectors
  - Monolithic devices
- **Change operational conditions**
  - CERN-RD39 “Cryogenic Tracking Detectors”





Float Zone

- Using a single Si crystal seed, melt the vertically oriented rod onto the seed using RF power and "pull" the monocrystalline ingot
- Can be oxygenated by diffusion at high T

Czochralski silicon

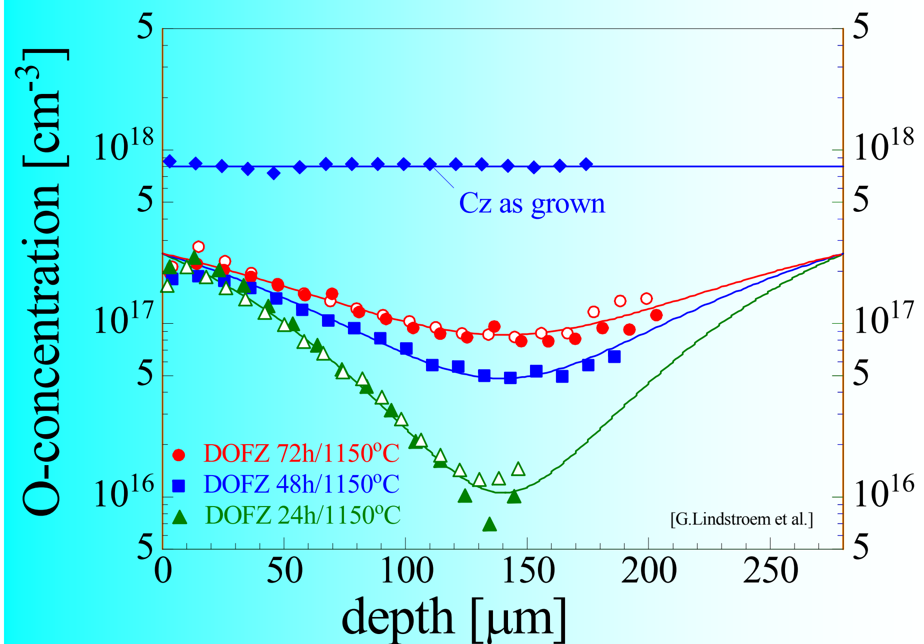
- Pull Si-crystal from a Si-melt contained in a silica crucible while rotating.
- Silica crucible is dissolving oxygen into the melt ⇨ high concentration of O in CZ
- Material used by IC industry (cheap), now available in high purity for use as particle detector (MCz)

Epitaxial silicon

- Chemical-Vapor Deposition (CVD) of Silicon
- CZ silicon substrate used ⇨ diffusion of oxygen
- Growth rate about 1μm/min
- Excellent homogeneity of resistivity
- 150 μm thick layers produced (thicker is possible)
- price depending on thickness of epi-layer but not extending ~ 3 x price of FZ wafer

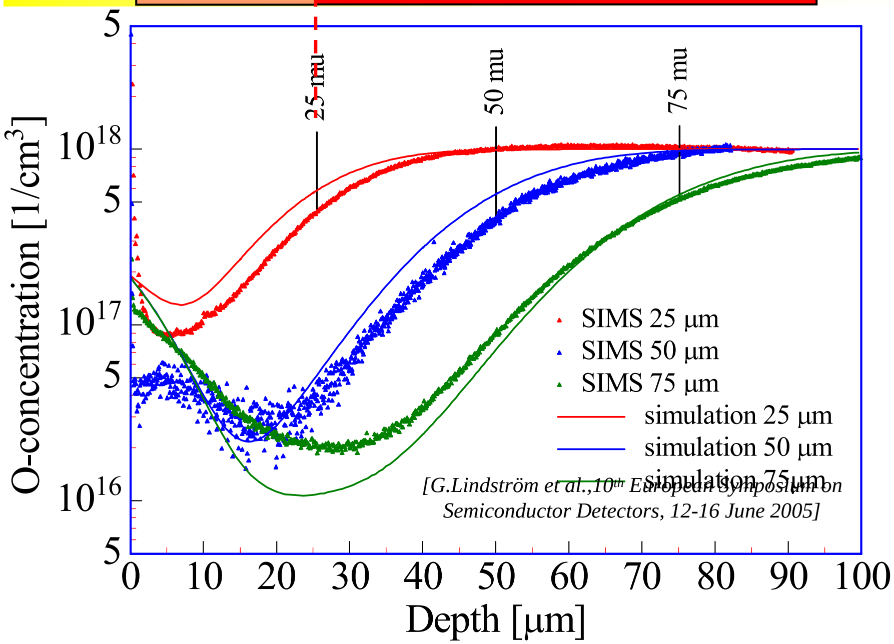
Oxygen concentration in FZ, CZ and EPI

- Cz: high homogeneous concentration and formation of Thermal Donors (reducing acceptors due to radiation)



- DOFZ: inhomogeneous oxygen distribution, increasing with time at high temperature

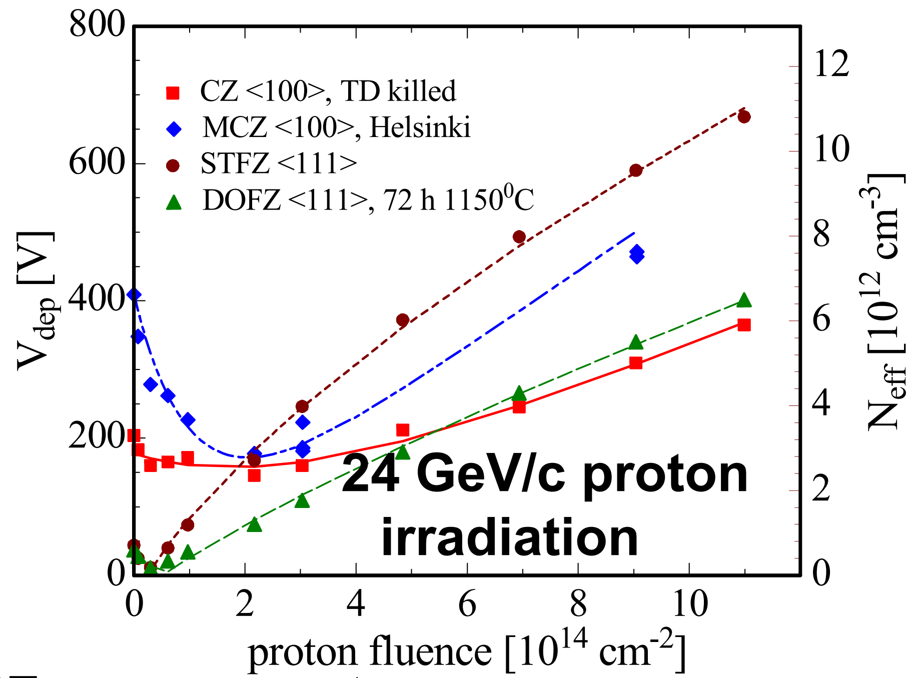
- Epitaxial silicon



- EPI: inhomogeneous O concentration due to diffusion from substrate into epi-layer during production

Standard FZ, DOFZ, Cz and MCz Silicon

- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm^2
  - strong N_{eff} increase at high fluence
- **Oxygenated FZ (DOFZ)**
  - type inversion at ~ 2×10^{13} p/cm^2
  - reduced N_{eff} increase at high ϕ



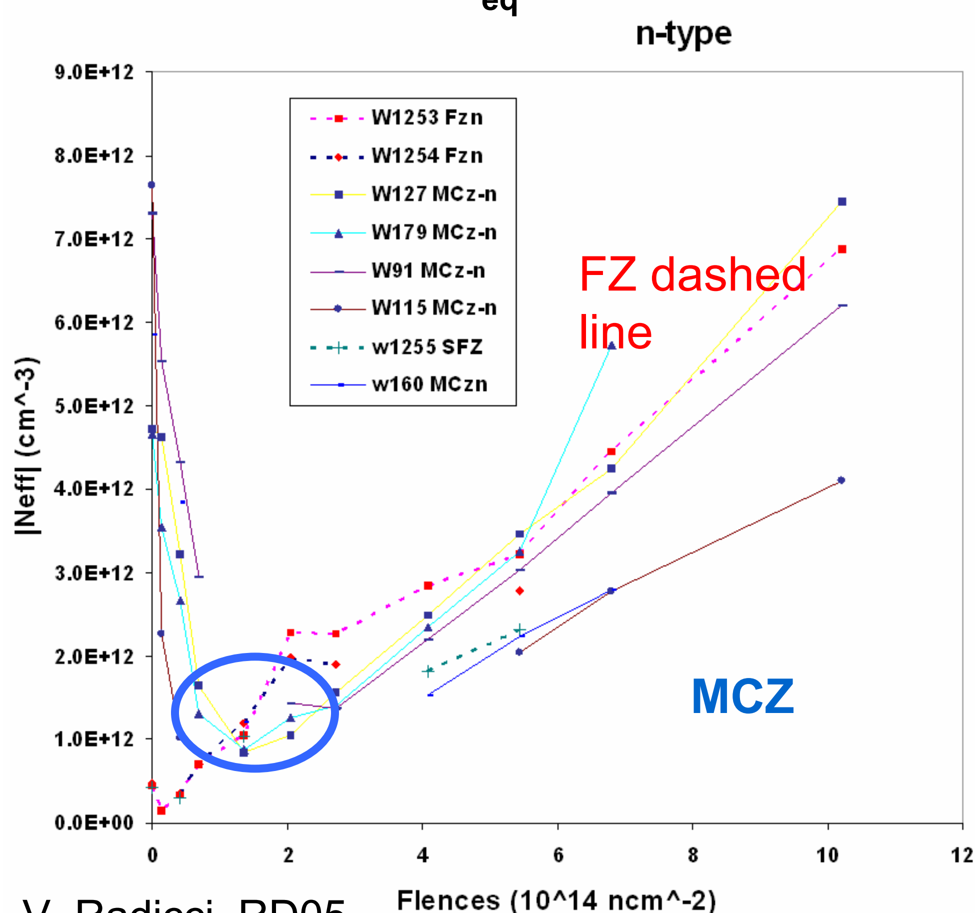
- **CZ silicon and MCZ silicon**
  - no type inversion in fluence range
  - **Verified for CZ and MCz silicon by TCT measurements** ⇒ donor generation overcompensates acceptor generation
- **Common to all materials (after hadron irradiation):**
  - **reverse current increase**
  - **increase of trapping (electrons and holes) within ~ 20%**

Many groups are studying MCz: INFN, Glasgow, BNL, Helsinki Institute of Physics HIP, Purdue, Liverpool, Rochester etc.…

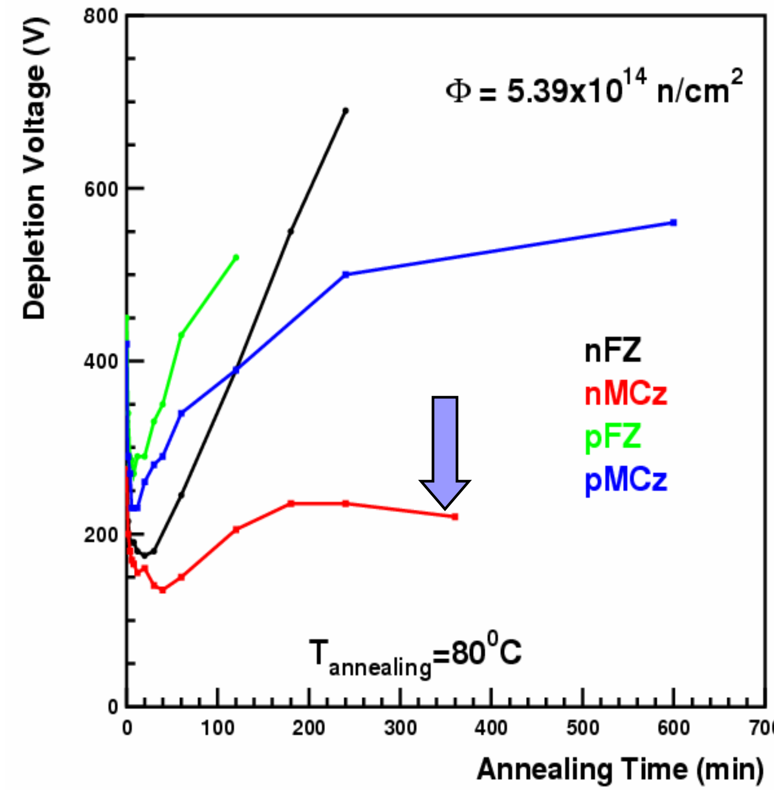
Irradiation studies

SMART

- Irradiation with 24 Gev/c protons at CERN SPS to 6.0×10^{13}, 3.0×10^{14}, 3.4×10^{15} n_{eq}/cm^2; Irradiation with 26 MeV protons Karlsruhe in the range: 1.4×10^{13}-2.0×10^{15} n_{eq} $/cm^2$



V. Radicci, RD05

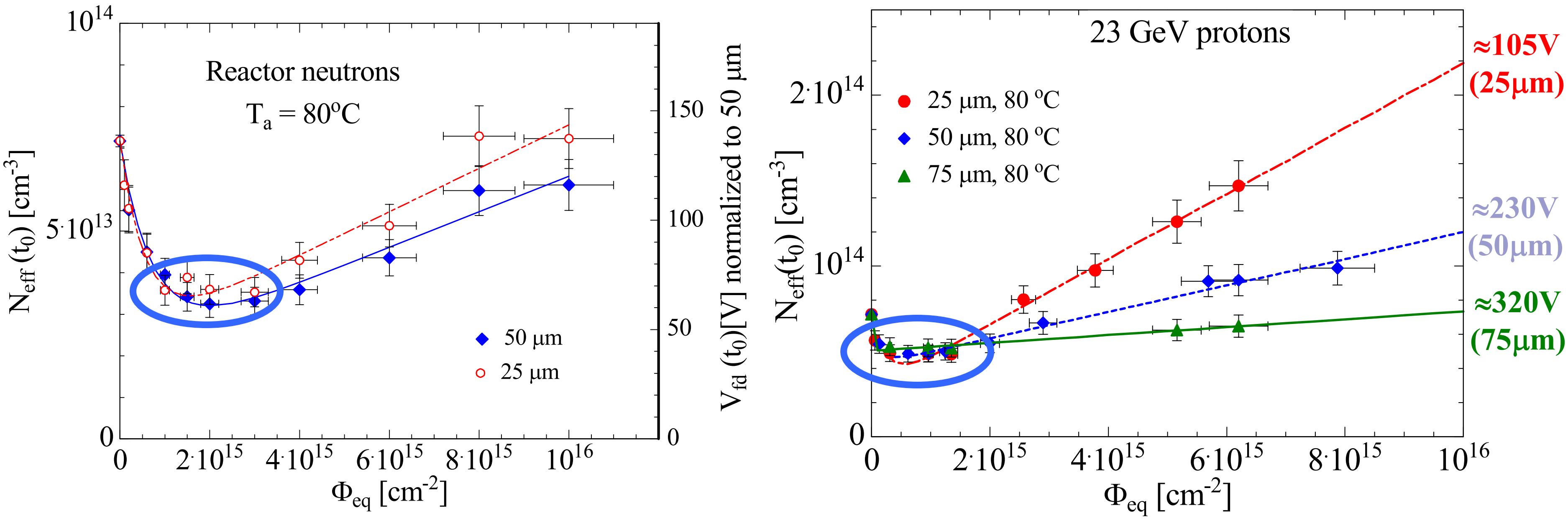


MCz: improved reverse annealing **could simplify operational conditions**

EPI Irradiation

G.Lindström et al.,10th European Symposium on Semiconductor Detectors, 12-16 June 2005

- Epitaxial silicon grown by ITME
  - Layer thickness: 25, 50, 75 μm; resistivity: ~ 50 Ωcm
  - Oxygen: [O] ≈ $9\times10^{16}cm^{-3}$; Oxygen dimers

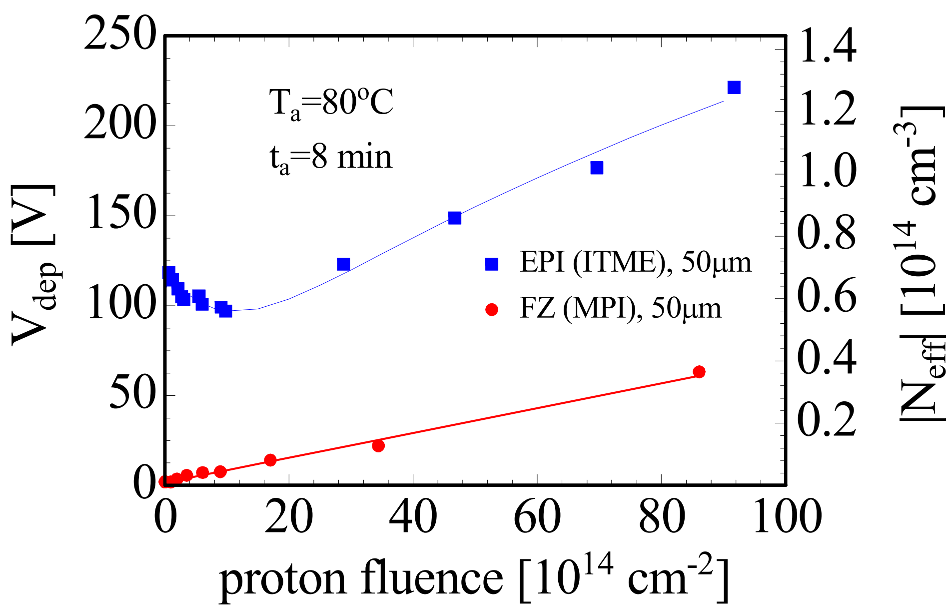


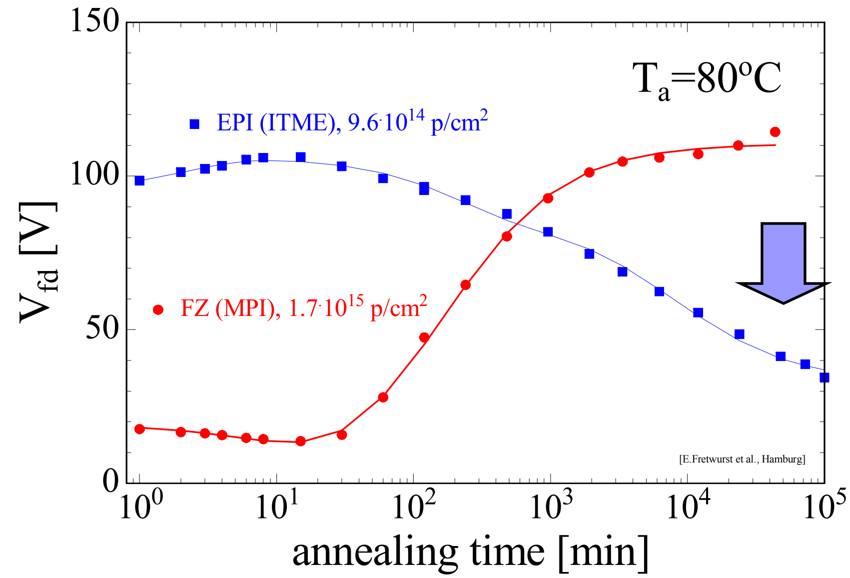
  - No type inversion in the full range up to ~ 10^{16} p/cm^2 and ~ 10^{16} n/cm^2 (type inversion only observed during long term annealing)
  - Proposed explanation: introduction of shallow donors bigger than generation of deep acceptors

EPI Annealing

[E.Fretwurst et al.,RESMDD - October 2004]

- 50 μm thick silicon detectors:
  - Epitaxial silicon (50Ωcm on CZ substrate, ITME & CiS)
  - Thin FZ silicon (4KΩcm, MPI Munich, wafer bonding technique)



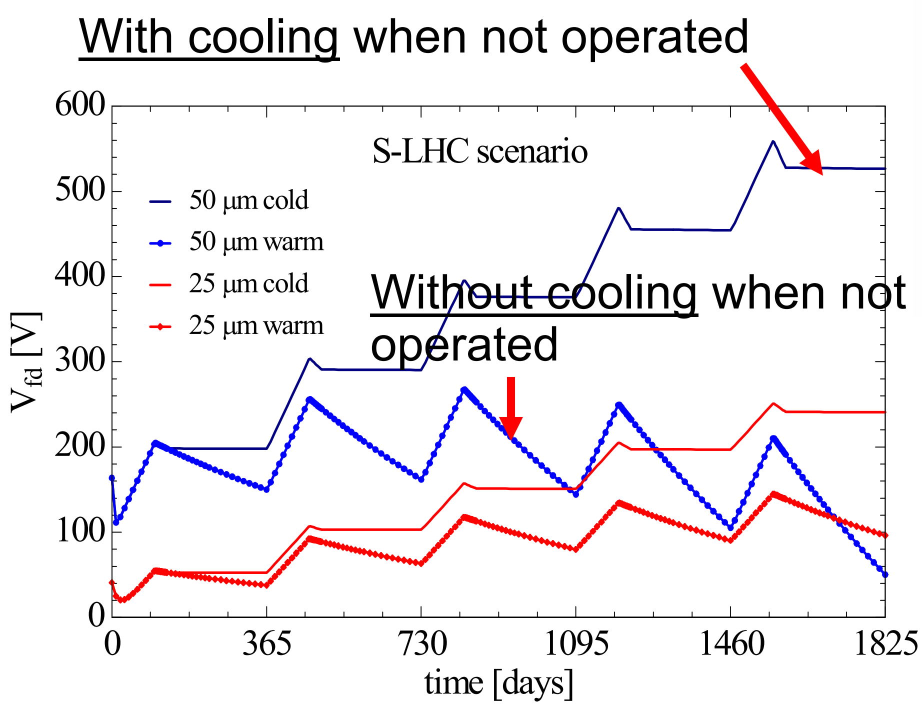


- **Thin FZ silicon:** Type inverted, increase of depletion voltage with time
- **Epitaxial silicon:** No type inversion, decrease of depletion voltage with time ⇒ No need for low temperature during maintenance of SLHC detectors!

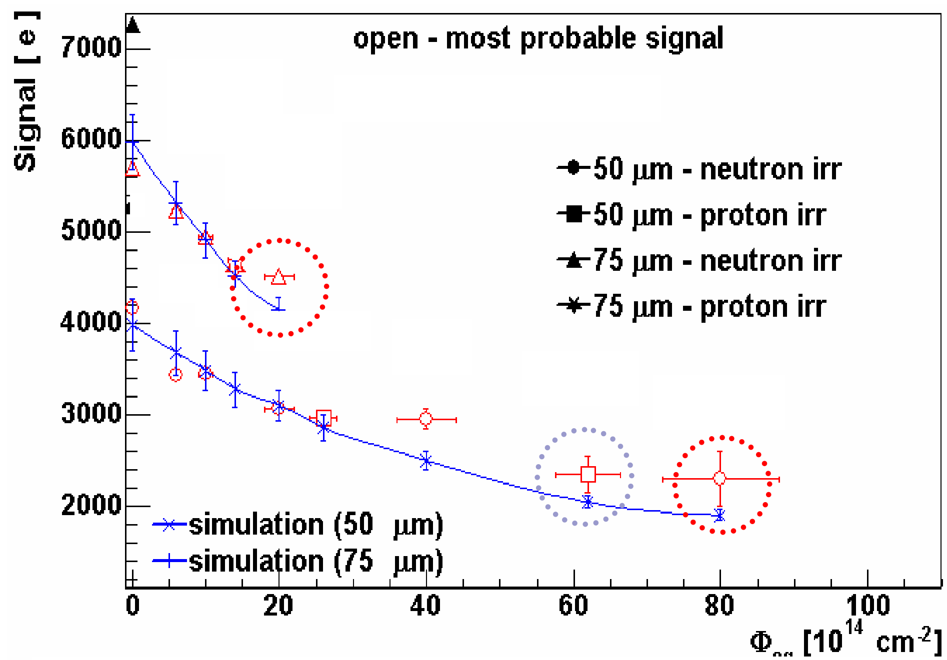
EPI SLHC

G.Lindström et al.,10th European Symposium on Semiconductor Detectors, 12-16 June 2005 (Damage projection: M.Moll)

- Radiation @ 4cm: Φ_{eq}**(year) = 3.5 × 10^{15} cm^{-2}**
- SLHC-scenario:
  - **1 year = 100 days beam (-7°C)**
  - **30 days maintenance (20°C)**
  - **235 days no beam (-7°C or 20°C)**



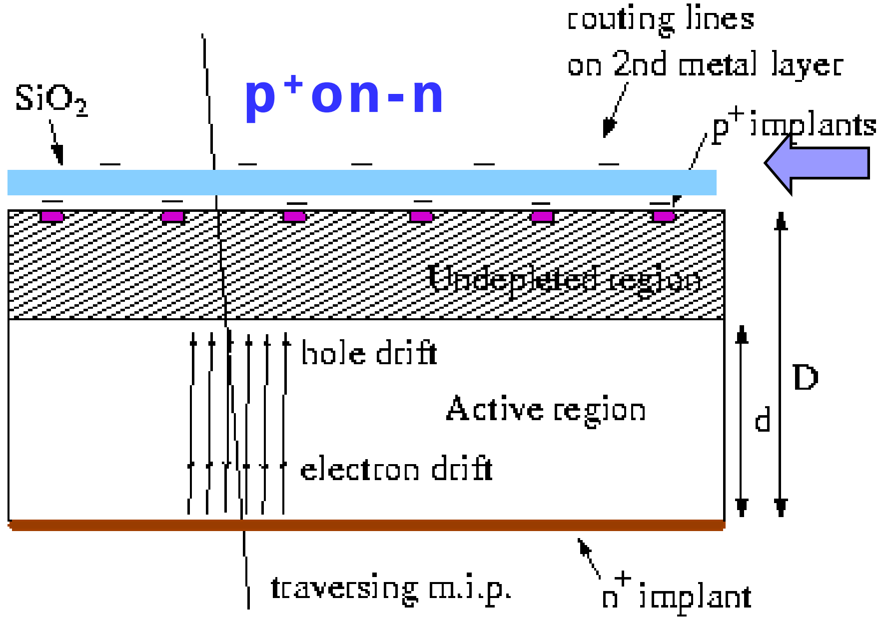
50 µm EPI silicon: a solution for pixels detectors at SLHC?



- CCE measured with β from ^{90}Sr
  - 25ns shaping time
  - proton and neutron irradiations of 50 µm and 75 µm epi layers

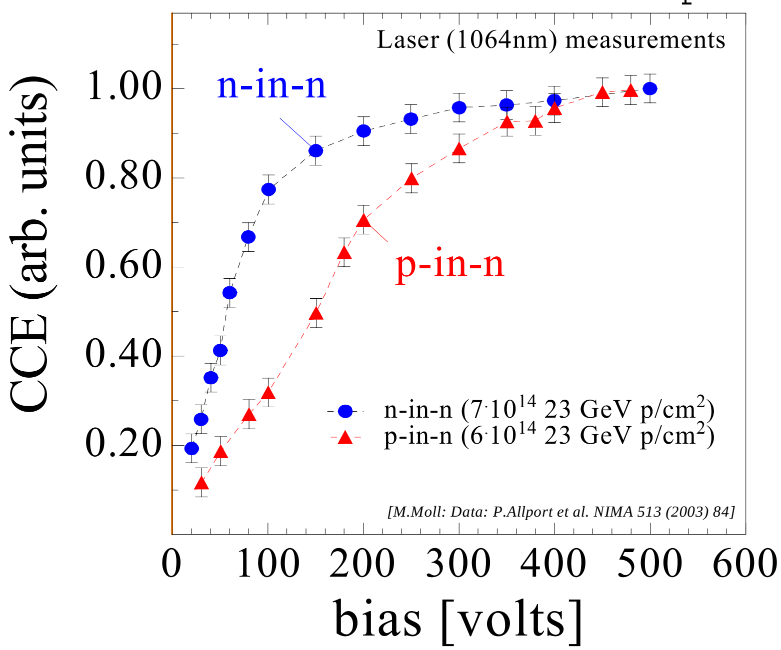
- CCE (50 µm) Φ_{eq}= 8x10^{15} n/cm^{-2},<u>2300 e</u>
- CCE (75 µm) Φ= 2x10^{15} n/cm^{-2}, <u>4500 e</u>
- CCE (50 µm): Φ= 1x10^{16}p/cm^{-2} <u>2400 e</u>

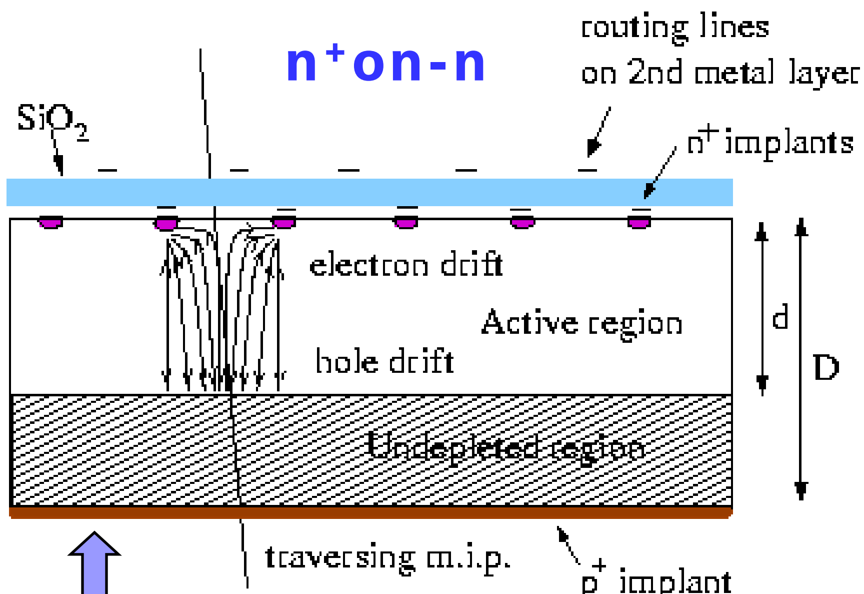
p-in-n versus n-in-n detectors



p-on-n silicon, under-depleted:

- **Charge spread ⇒ degraded resolution**
- **Charge loss ⇒reduced CCE**



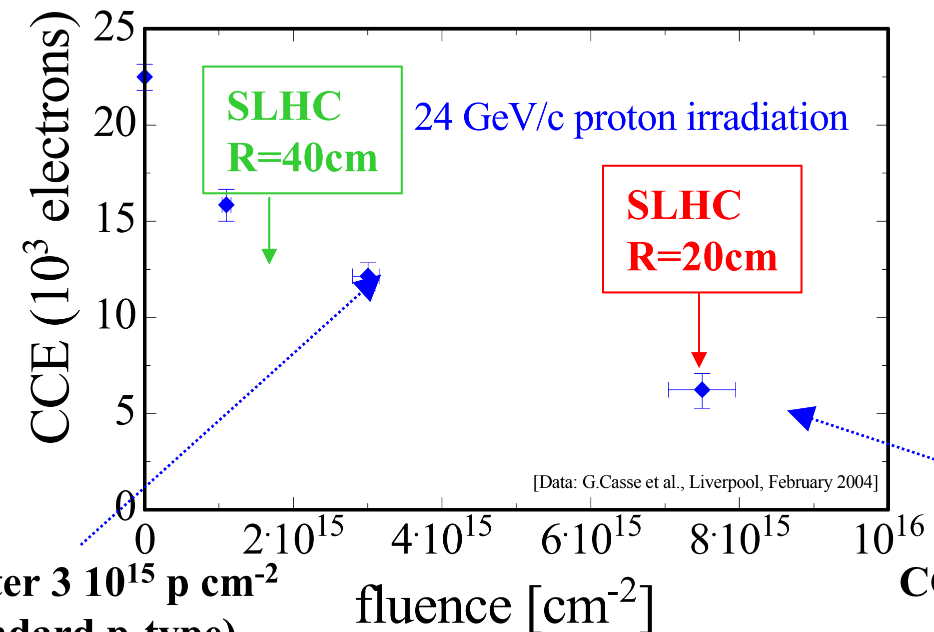


n-on-n silicon, under-depleted:

- **Limited loss in CCE**
- **Less degradation if under-depleted**
- **Collect electrons (fast)**

n-in-p microstrip detectors

- Miniature n-in-p microstrip detectors (280μm)
- Detectors read-out with LHC speed (40MHz) chip (SCT128A)
- Material: standard p-type and oxygenated (DOFZ) p-type



G. Casse et al., NIMA535(2004) 362

At the highest fluence Q~6500e at V_{bias}=900V

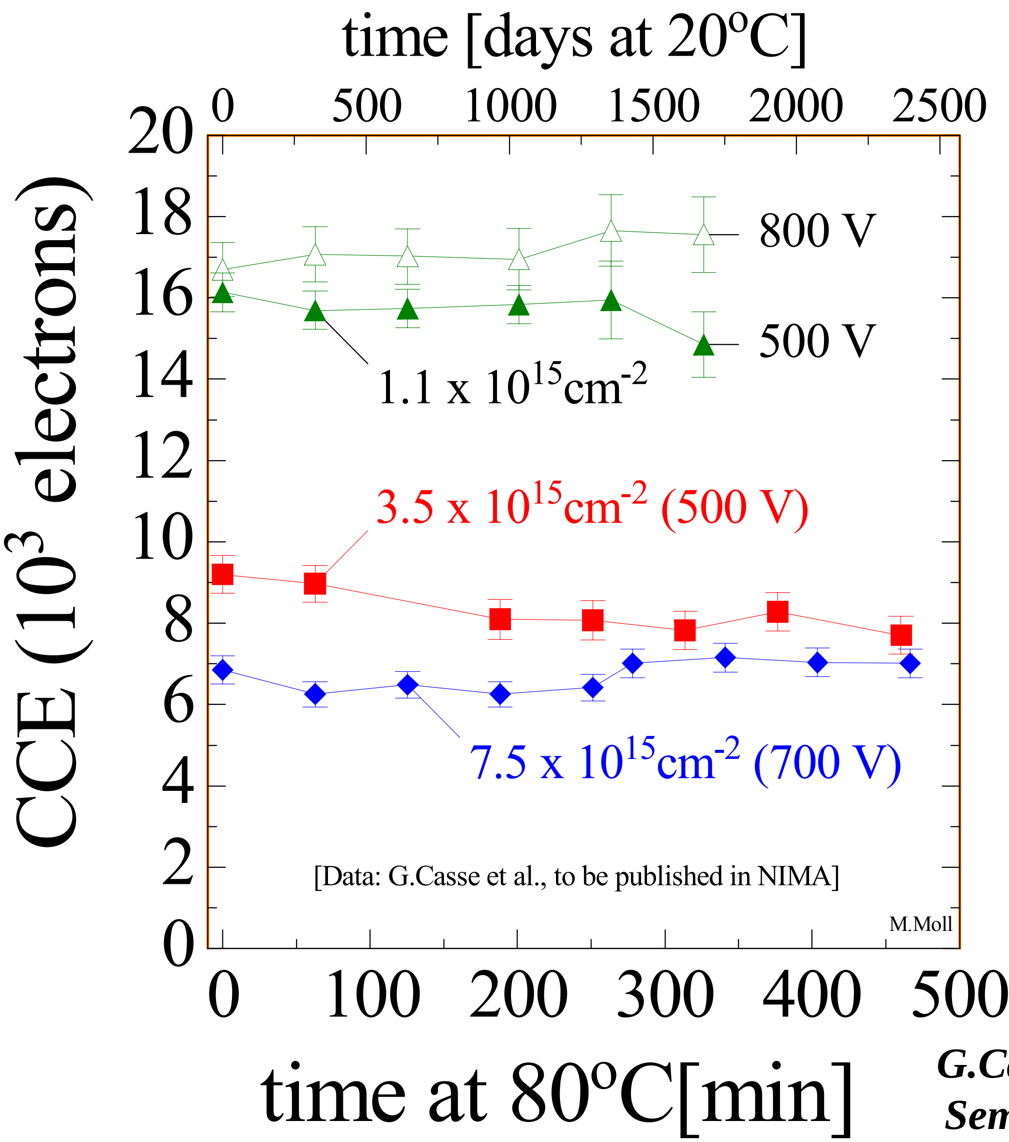
CCE ~ 60% after 3 10^{15} p cm^{-2} at 900V(standard p-type)

CCE ~ 30% after 7.5 10^{15} p cm^{-2} 900V (oxygenated p-type)

Charge collection in planar silicon detectors might be sufficient for all but inner-most Pixel layer!

Benefit: Single sided processing ~50% cheaper than n-in-n

Annealing of p-type sensors



- p-type strip detector (280μm) irradiated with 23 GeV p (7.5×10^{15} p/cm^2)
- expected from previous CV measurement of V_{dep}:
  - before reverse annealing: V_{dep}~ 2800V
  - after reverse annealing V_{dep} > 12000V
- no reverse annealing visible in the CCE measurement !

G.Casse et al.,10th European Symposium on Semiconductor Detectors, 12-16 June 2005

Novel Materials

Property	Diamond	GaN	4H SiC	Si
E_g [eV]	**5.5**	**3.39**	**3.26**	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4\cdot10^6$	$2.2\cdot10^6$	$3\cdot10^5$
μ_e [cm^2/Vs]	1800	1000	800	1450
μ_h [cm^2/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2\cdot10^7$	-	$2\cdot10^7$	$0.8\cdot10^7$
Z	6	31/7	14/6	14
ε_r	5.7	9.6	9.7	11.9
e-h energy [eV]	**13**	**8.9**	**7.6-8.4**	**3.6**
Density [g/cm^3]	3.515	6.15	3.22	2.33
Displacem. [eV]	**43**	**19.2±2**	**25**	**13-20**

- **Wide bandgap**
  diamond=5.5
  SiC=3.3eV

< leakage current than silicon

- **Signal:**

Diamond 36 e/μm
SiC 51 e/μm
Si 89 e/μm

> charge than diamond

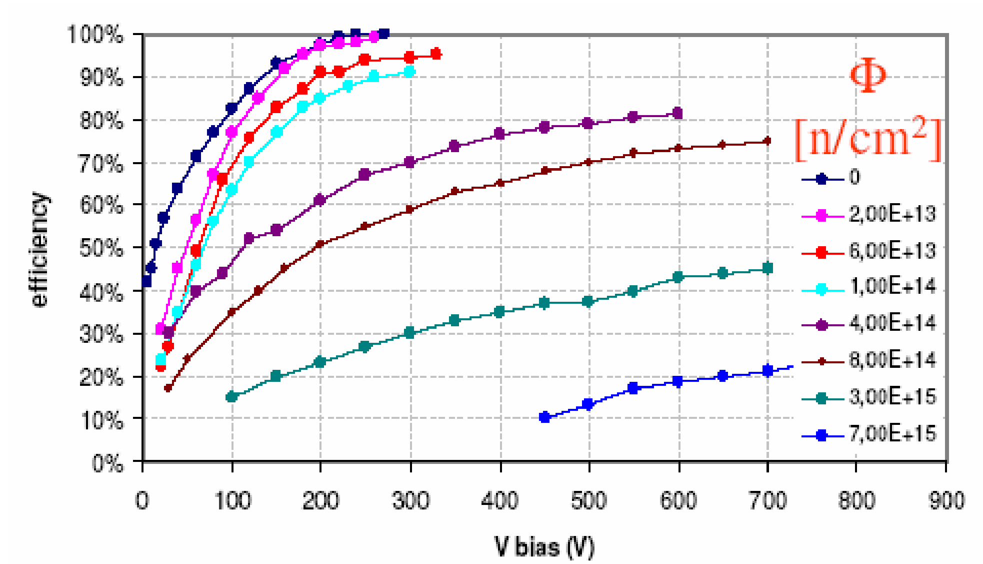
- **> displacement threshold than silicon**

⇒radiation harder than silicon (?)

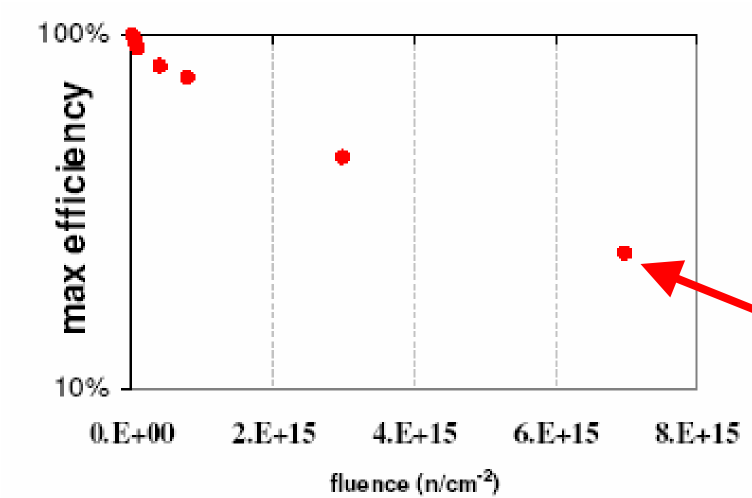
- Diamond:
  - Dielectric constant (2.1 × lower than SI) → low capacitance
  - Higher Electron and hole mobility →fast collection times

SiC: CCE after irradiation

- Material: epitaxial layers by CREE Res. Inc. and IKZ (Institüt fur Kristallzüchtung, Berlin)
- Devices: Schottky diodes, Alenia Marconi Systems (Rome)
- Depletion depth: 20-40 μm
- Effective doping: 5.3×10^{14} cm^{-2}
- Irradiated with protons at CERN PS to 1.6×10^{16}/cm^2 and neutrons al Ljubjana to 7×10^{15}/cm^2



S.Sciortino et al., presented on the RESMDD 04 conference, in press with NIMA



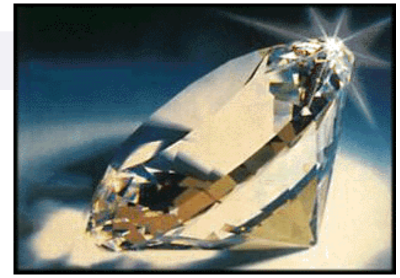
CCE before irradiation

- 1100 e$^-$ @400 V with α particles
- 1400 e$^-$ @200 V with MIPS (100% CCE)

CCE after irradiation

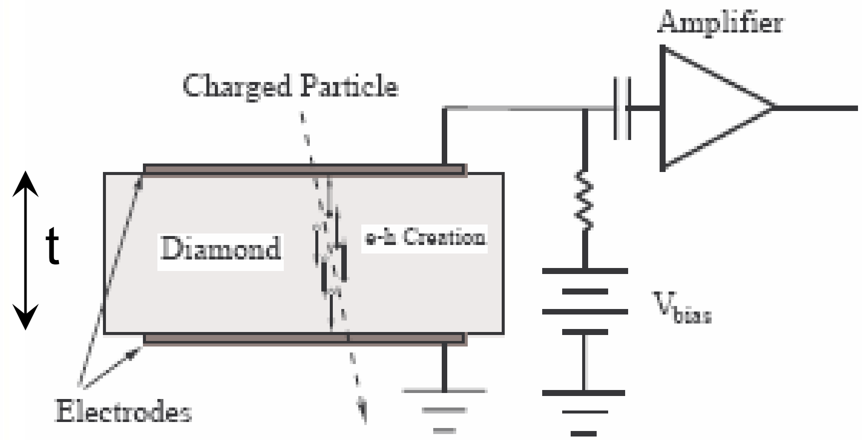
- 20% CCE (α) after 7×10^{15} n/cm^2!
- 35% CCE (β) (~ 300 e$^-$) after 1.4×10^{16} p/cm^2 much less than in silicon

Diamond

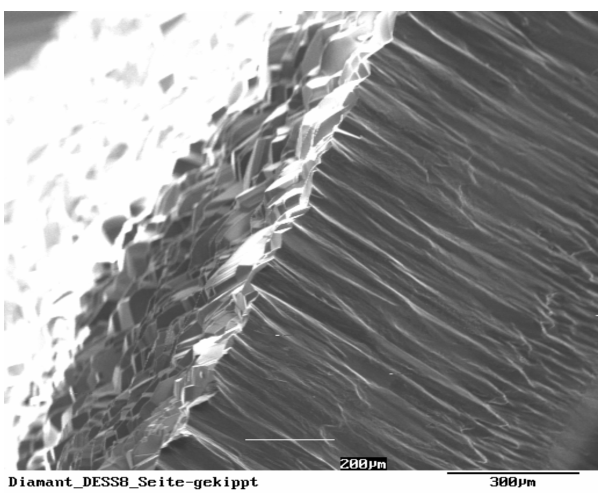


- Ionization energy is high: MIP≈ 2x less signal for same X_0 (w.r.t. SI)
  - Diamond: ~13.9ke⁻ in 361 μm
  - SI: ~26.800 ke⁻ in 282 μm
- In Polycrystalline Diamond grain-boundaries, dislocations, and defects:
  - limits carrier lifetime, mobility and charge collection distance and position resolution

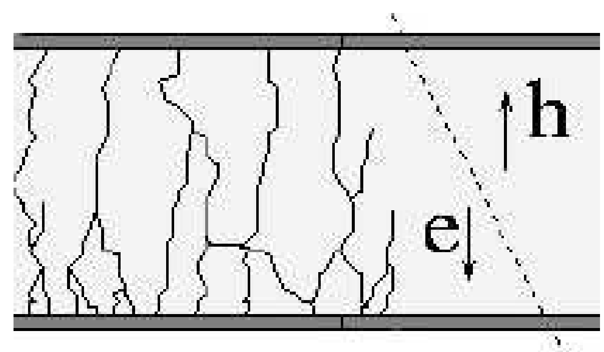
Signal formation



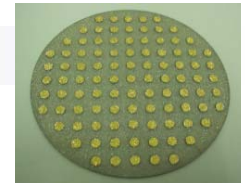
$Q=Q_0\ d/\ t$ where d= collection distance=distance e-h pair move apart



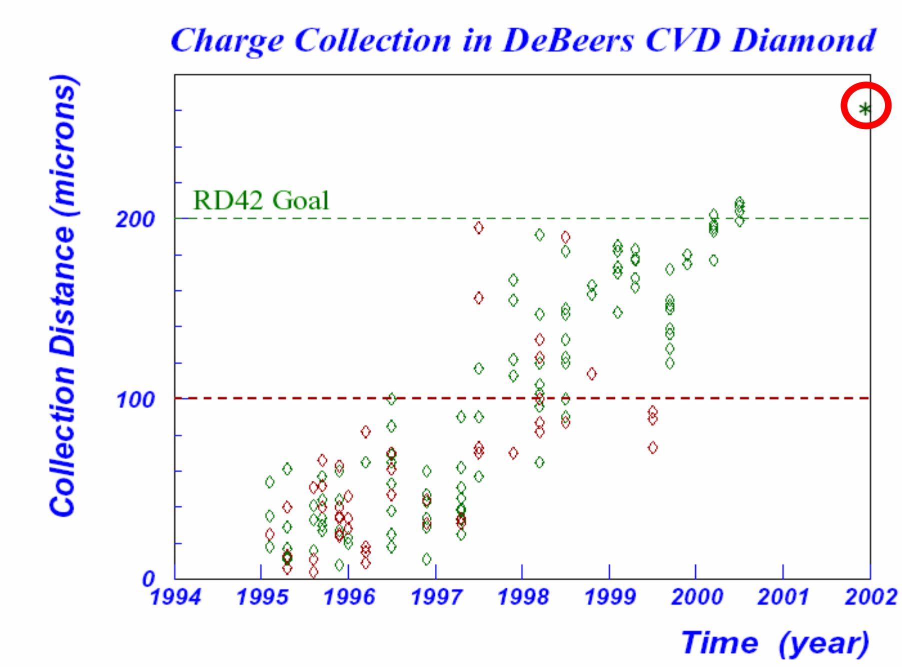
Polycrystalline Diamonds traditionally grown by CVD

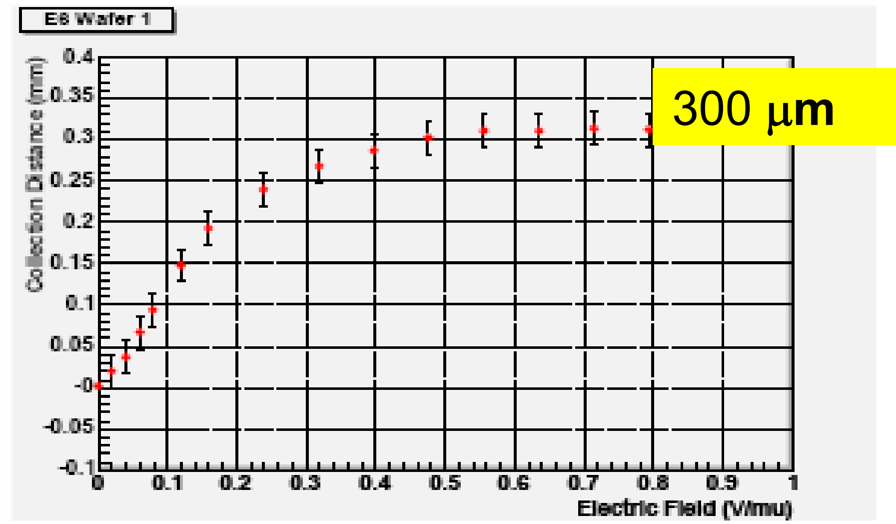


Polycrystalline Diamonds



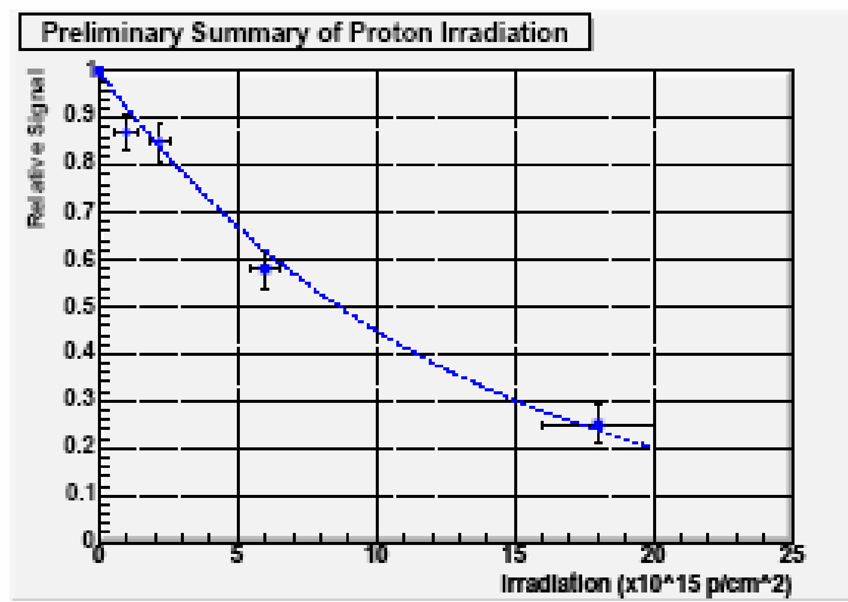
– RD42 in collaboration with vendors have achieved collection distance > 300 μm





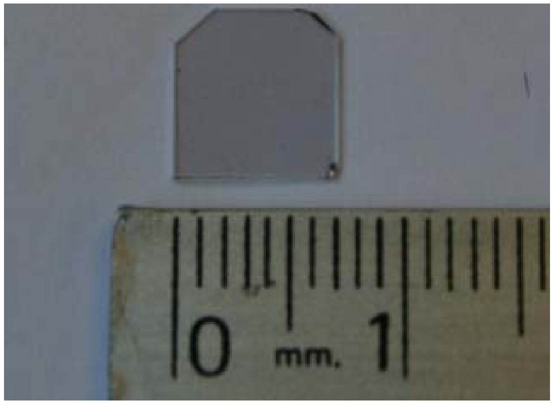
–Wafers diameter >12 cm

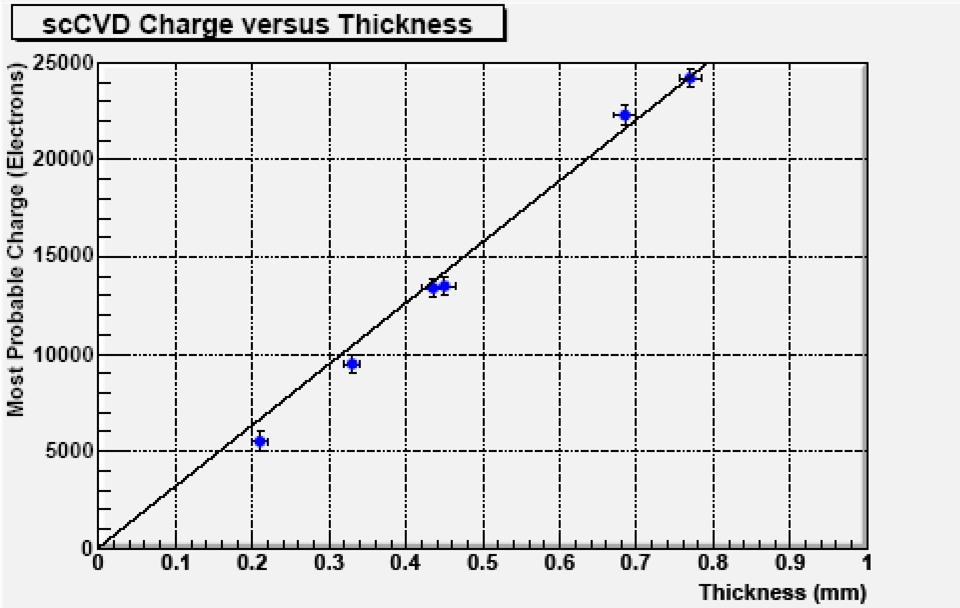
- Excellent radiation hardness
  - 60% CCE at 2.9 10^{15} π/cm^2
  - 23% improvement in resolution
  - 25% CCE at 1.8×10^{16} p/cm^2
- Used in successfully for radiation monitoring for BaBar, Belle, CDF, CMS



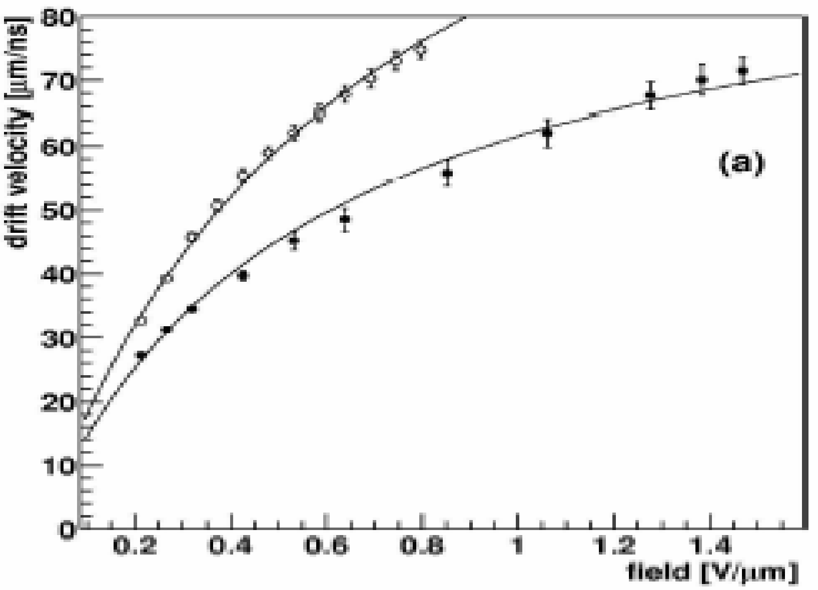
Single Crystal Diamond

- Single crystal diamond has been fabricated with Element six ≈ 10 mm × 10mm, >1 mm thickness.
- Largest scCVD diamond ≈ 14 mm × 14 mm.





- High quality scCVD diamond can collect full charge
- Width of Landau distribution is ≈ 1/2 that of silicon, ≈ 1/3 that of pCVD diamond

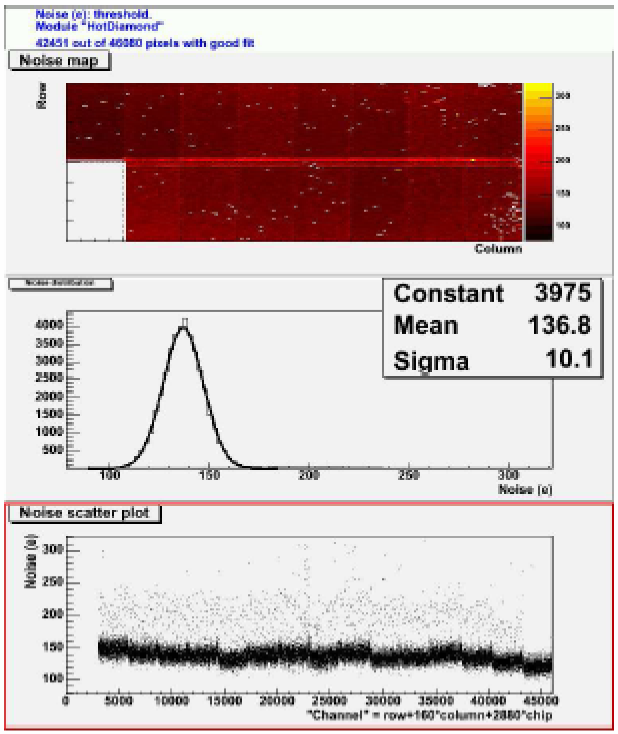


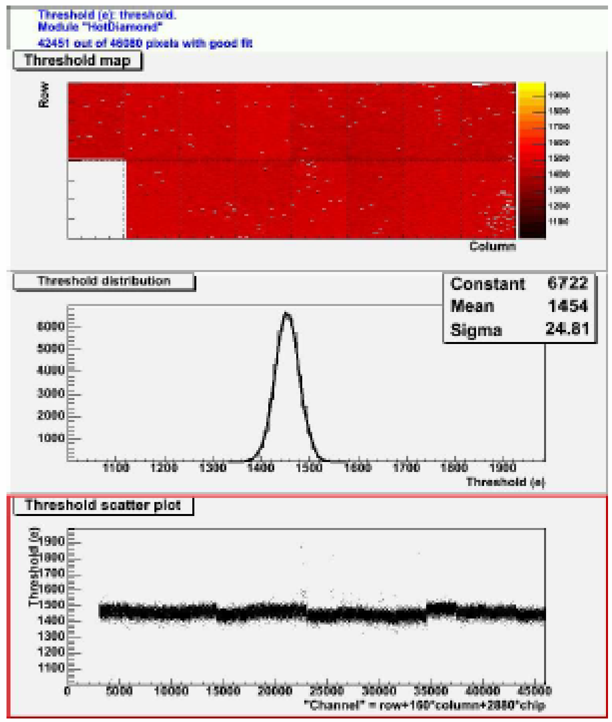
- Excellent mobility. For this sample:
  - μ_{0h} = 1714 cm²/Vs, μ_{0e} = 2064 cm²/Vs

  High drift velocity ⇒ better lifetimes ⇒ charge trapping might not be an issue

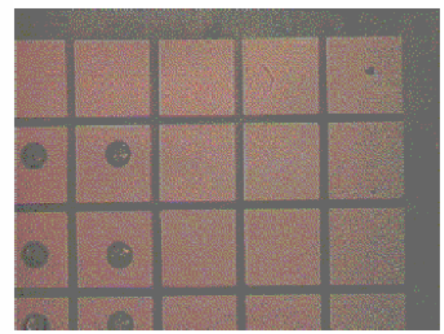
Diamond Atlas module

- Beam test at DESY with 4-6 GeV electrons
- Results: Noise ~ 137e, Mean Threshold 1454e, Threshold Spread ~ 25e.





Harris Kagan
Vertex 2005
Nikko, Japan



CMS diamond pixel

- Preliminary efficiency >97.5%
  - still need to correct for dead or missing channels.

Device Engineering: 3D detectors

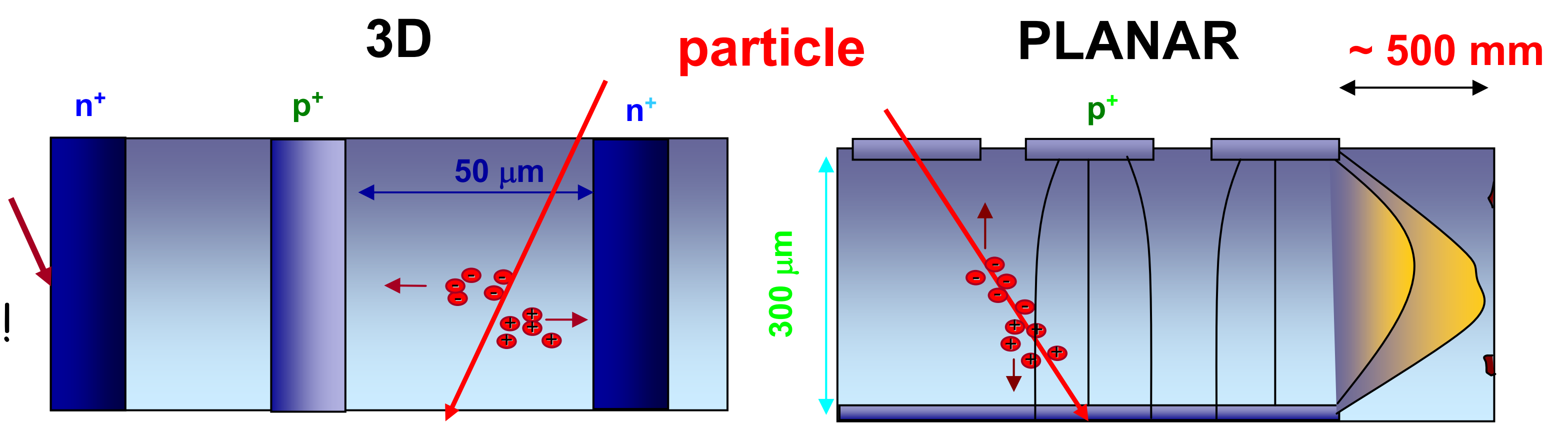
(Introduced by S.I. Parker et al., NIMA 395 (1997) 328

- Combine **VLSI** and **MEMS** (Micro Electro Mechanical Systems)

Electrodes:
- Narrow columns processed inside the bulk instead then implanted on surface: 3D
- Diameter: 10μm; Distance: 50-100μm

Lateral depletion:
- Lower depletion voltage
- Short collection distance ⇒ fast signal
- More rad hard

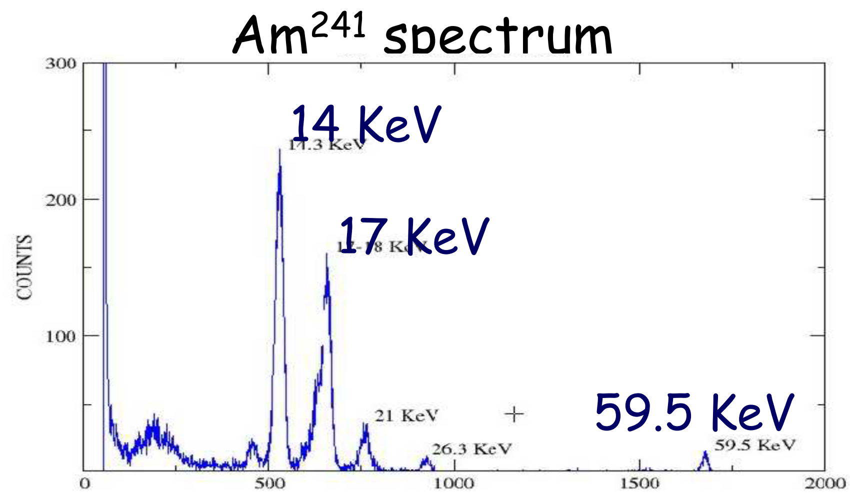
- **The edge** could become electrode!!



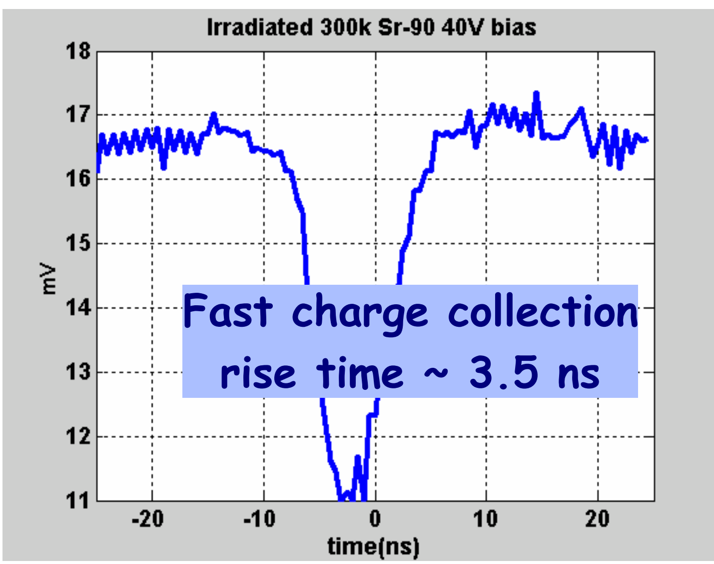
	3D	PLANAR
Q collection path	50μm	300 μm
$V_{depletion}$	<10V	70 V
Q Collection time	1-2 ns	10-20 ns

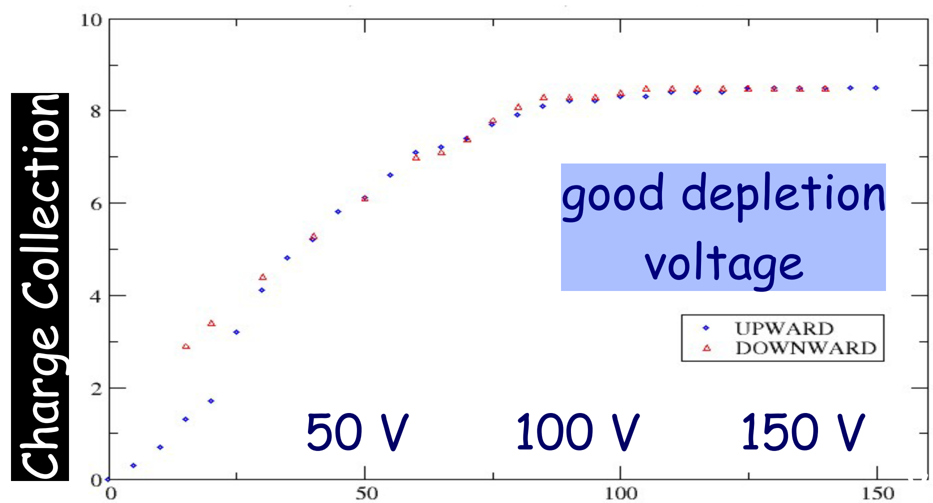
3D detectors: characteristics

- Low leakage currents
- Low depletion voltages
- Gaussian X ray lines
- Fast charge collection



Performance after irradiation~10^{15} p/cm^2

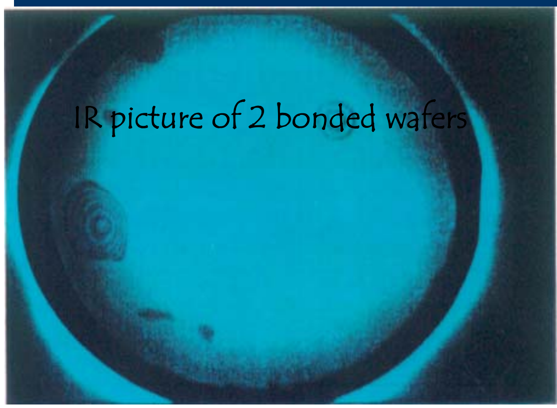




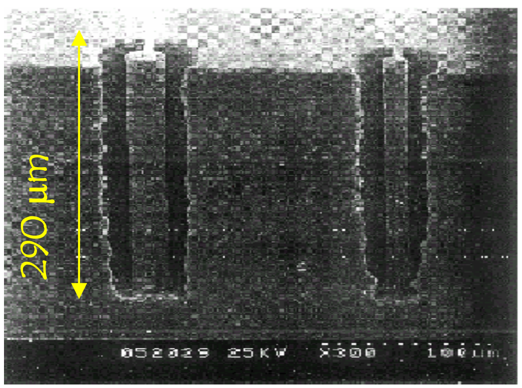
3D DETECTOR FABRICATION

Non Standard Processing: Wafer bonding, Deep reactive ion etching , Low pressure chemical vapor deposition, Metal deposition ⇒ Mass production expensive

1) ETCHING THE ELECTRODES



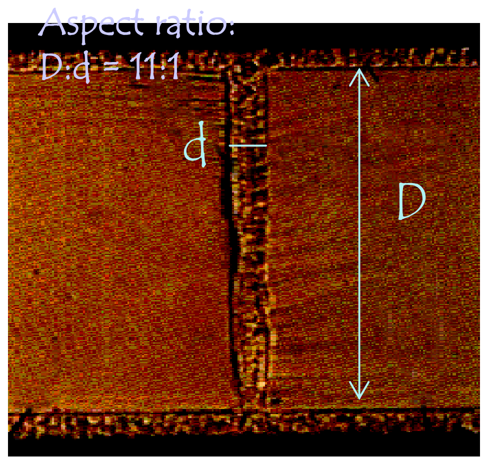
WAFER BONDING
(mechanical stability)
$Si\text{-}OH + HO\text{-}Si \rightarrow Si\text{-}O\text{-}Si + H_2O$



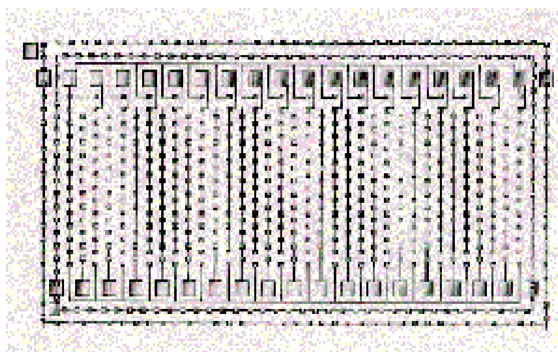
DEEP REACTIVE ION ETCHING
(electrodes definition)
Bosh process
SiF_4 (gas) $+C_4F_8$ (teflon)

C shaped test structure
~1 µm difference between top and bottom

2) FILLING THE ELECTRODES



LOW PRESSURE CHEMICAL VAPOR DEPOSITION
(Electrodes filling with conformal doped polysilicon)
$2P_2O_5 + 5\,Si \rightarrow 4P + 5\,SiO_2$
$2B_2O_3 + 3Si \rightarrow 4\,B + 3\,SiO_2$

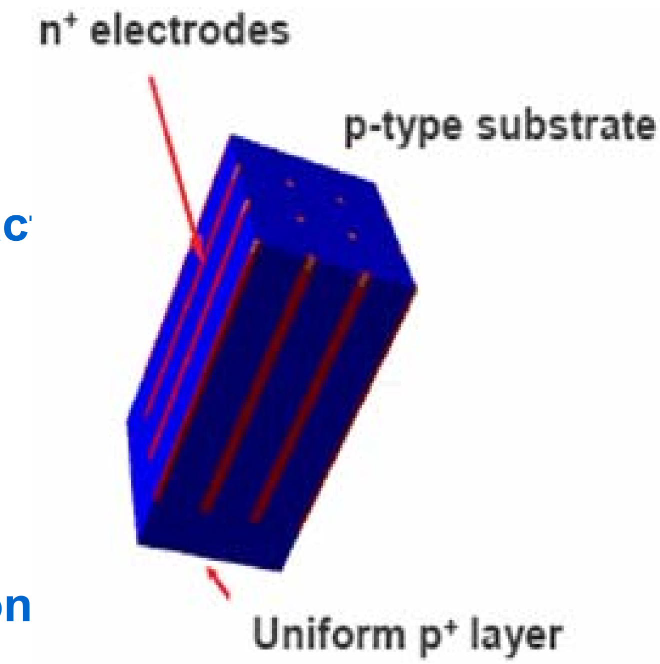


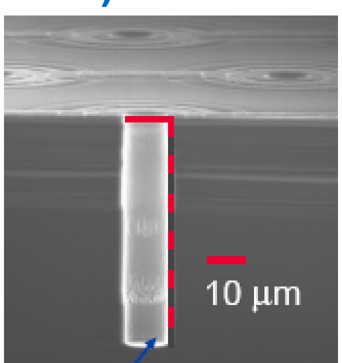
METAL DEPOSITION
Shorting electrodes of the same type with Al for strip electronics readout or deposit metal for bump-bonding

3D detectors

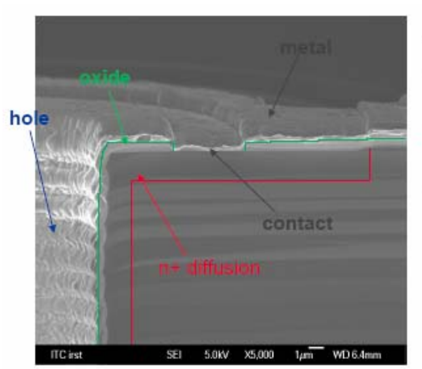
Claudio Piemonte (*ITC-irst*)

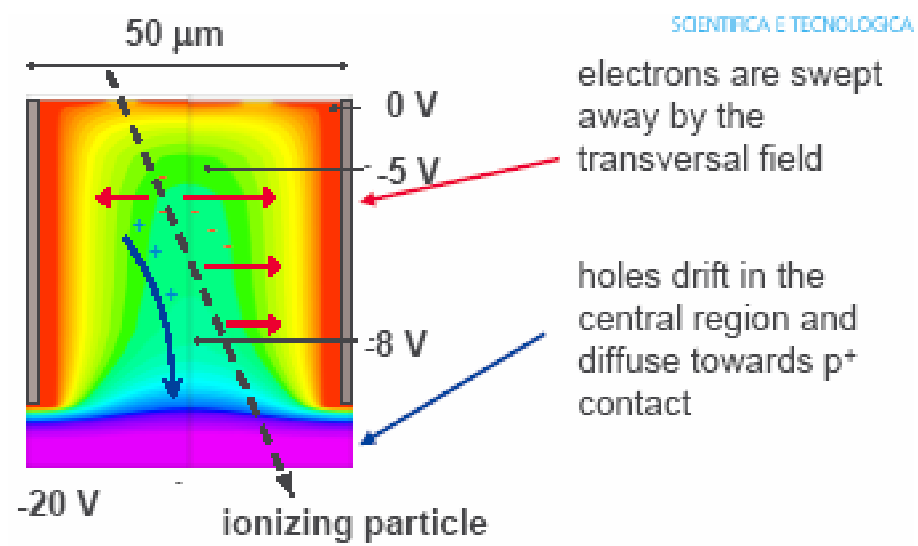
- **3D Single Type Column (3D-STC) aiming at process simplification**
  - **n+ columns in p-type substrate**
  - **Bulk contact provided by a uniform p+ contact on backside**
  - **Holes not etched through the wafer**
  - **No hole filling (holes are doped but not filled with polysilicon)**
  - **CNM: Hole etching (DRIE); IRST: other processing (contacts or polysilicon deposition etc.)**





Hole depth: 120µm

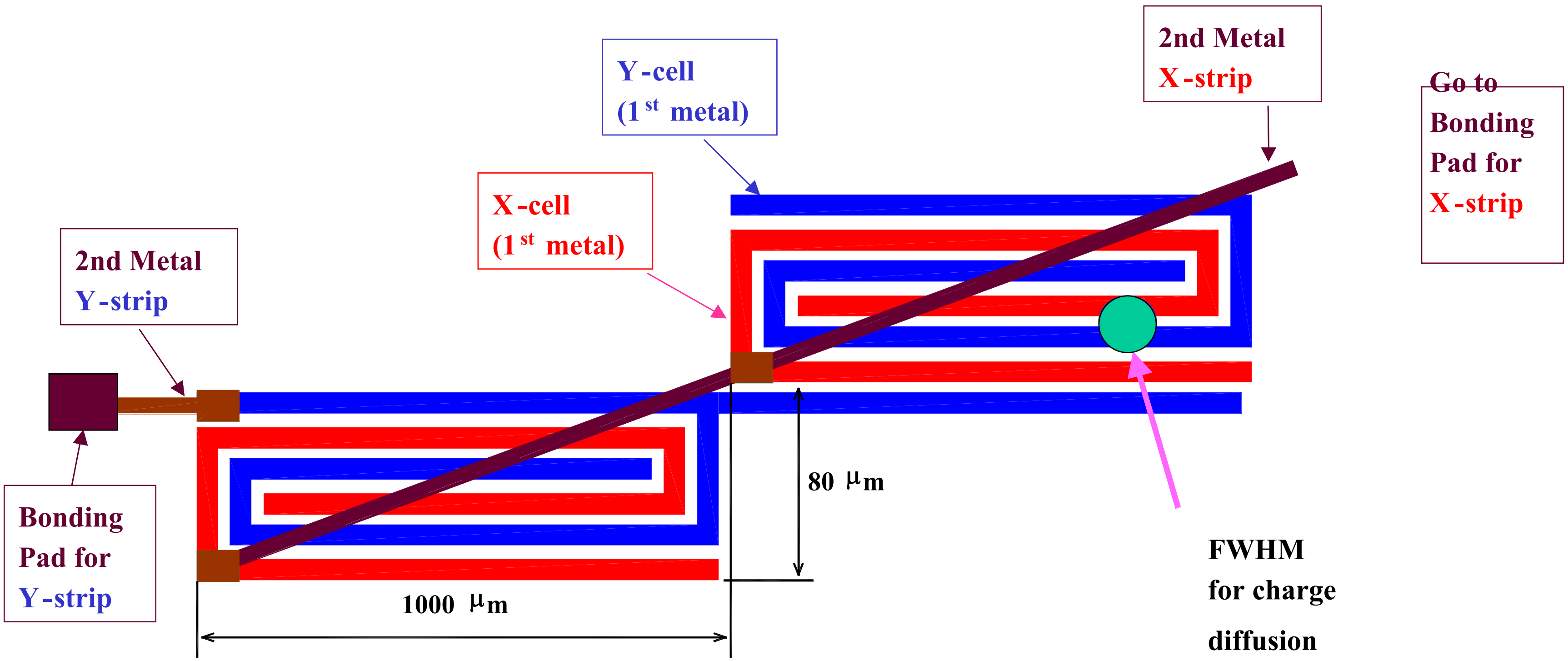




IRST-Trento and CNM Barcelona

Other new structures: Stripixel

- Several concepts for new **(planar and mixed planar & 3D)** detector structures aiming for improved radiation tolerance or less costly detectors **(see e.g. Li - 6th RD50 workshop, or Bortoletto- 5th RD50 Workshop)**
- Example: Stripixel concept or semi 3D:



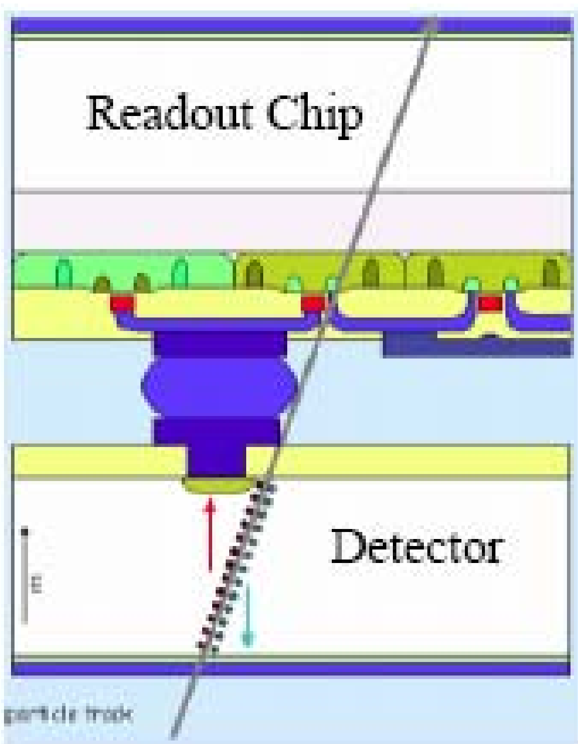
Z. Li, D. Lissauer, D. Lynn, P. O'Connor, V. Radeka

Monolithic Active Pixel Sensors (MAPS)

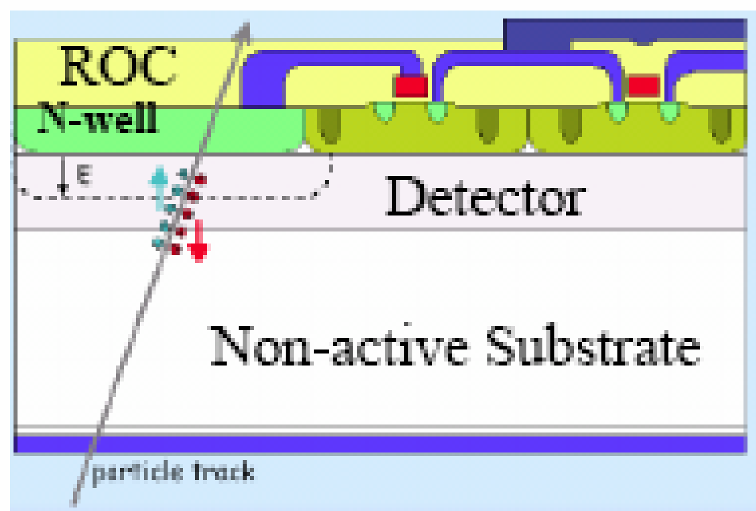
- Hybrid Pixel sensors have achieved a level of maturity in HEP. Future problems are cost, mass, and cooling of detectors under high radiation.

- Much work is being done on MAPS to reduce mass (ILC)
- A MAPS is a silicon structure where the detector and the primary readout electronics are processed on the same substrate.
  - Only the top few microns of an IC contain active circuitry.
  - The rest is merely a support structure.

Bum
bonc



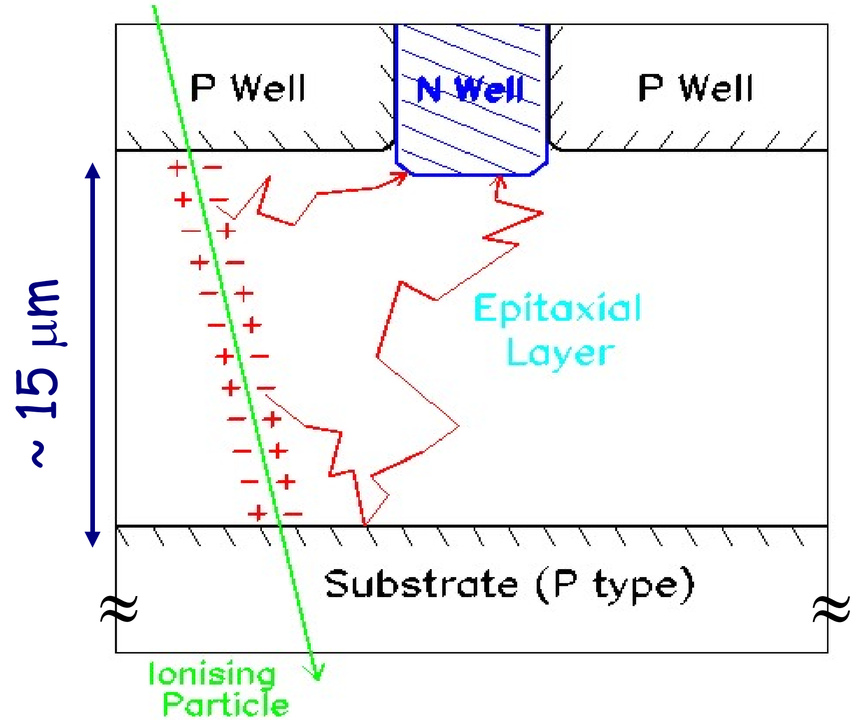
Hybrid Pixel Principle



MAPS Principle

Kucewicz, Krakow

MAPS with Standard CMOS processes



- Many groups studying this concept: RAL, IReS, Hawaii, INFN SLIM etc.
- Principle of operation:
  - Signal charge created in the epitaxial layer Q=80e-h/μm
  - The charge is ≈1000 e- and it can be measured because of the small capacitance of the electrode
  - Used in CMOS cameras

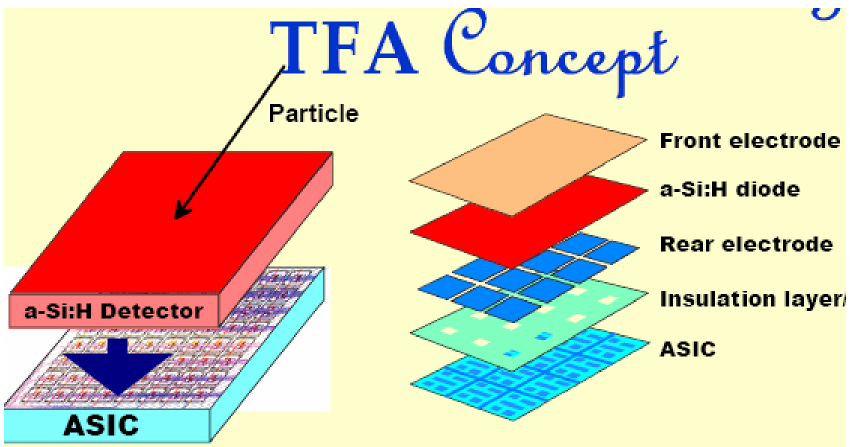
- **Advantages**
  - signal processing integrated on sensor substrate
  - Sensors may be thinned down to <20 μm
  - Standard processing ⇒ chip and fast turn around

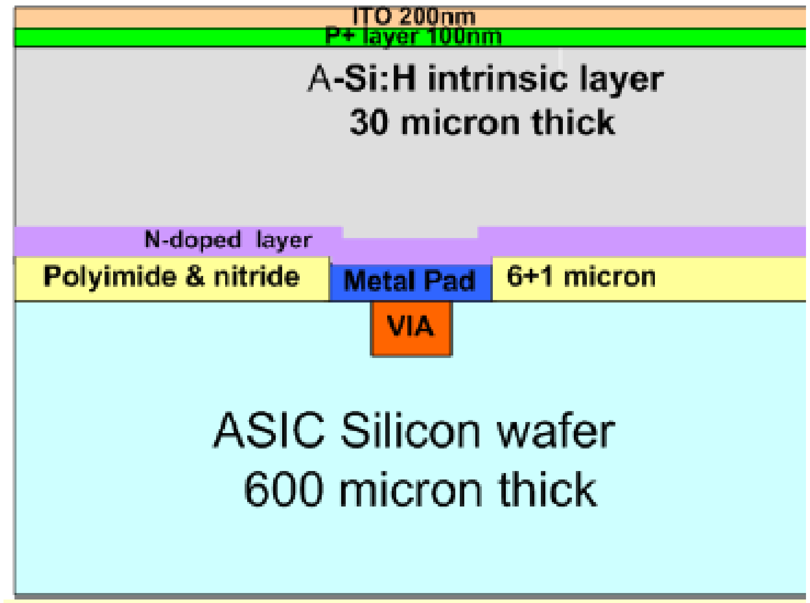
- Challenges:
  - Transistors options are limited
  - Newer processes have thinner or no-epi ⇒ vary small signals
  - Sparsification difficult to implement
  - Limited readout speed
  - Triple well processes in 0.13 μm are promising

Thin Film on Asic (TFA)

Development centered at CERN, Pierre Jarron's talk at Vertex 04

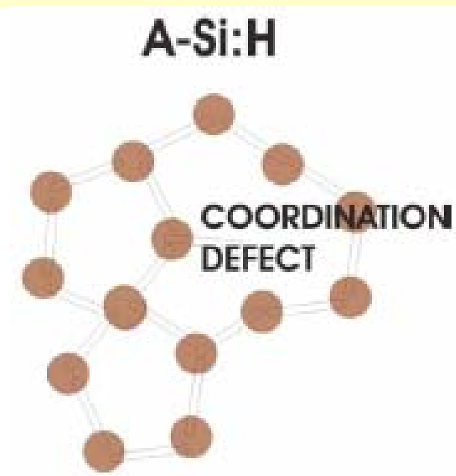
- TFA is an emerging pixel sensor technology
- Deposition of a-Si:H layer above readout ASICs





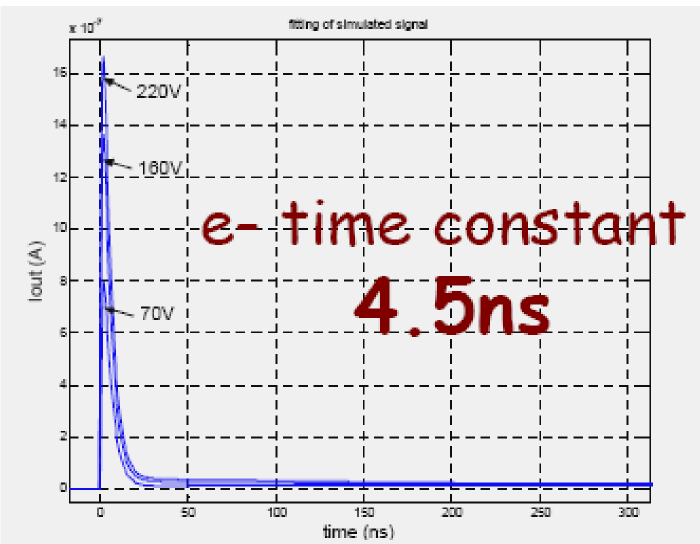
Amorphous structure

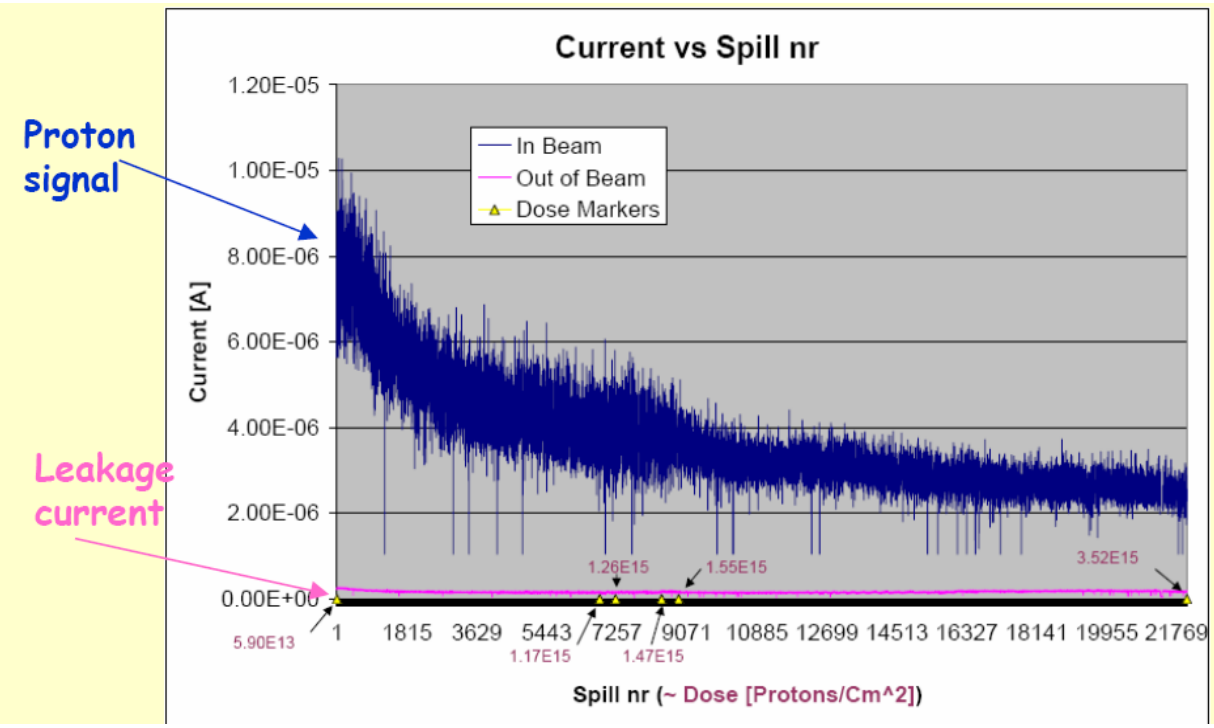
- Dangling bonds compensated by H
- H compensates impurities or radiation-induced defects
- Short time annealing
- Band tail formation due to bonding disorder



A:Si-H properties and rad hardness

- a-Si:H film ultra rad hard:
  - No I_{leak} increase after a fluence of 1.8×10^{16}p/cm^2.
  - Slight degradation of CCE and Photo-Conductivity after 3.5×10^{15}p/cm^2 CCE. It can be recovered after 1 hour annealing at 150°C

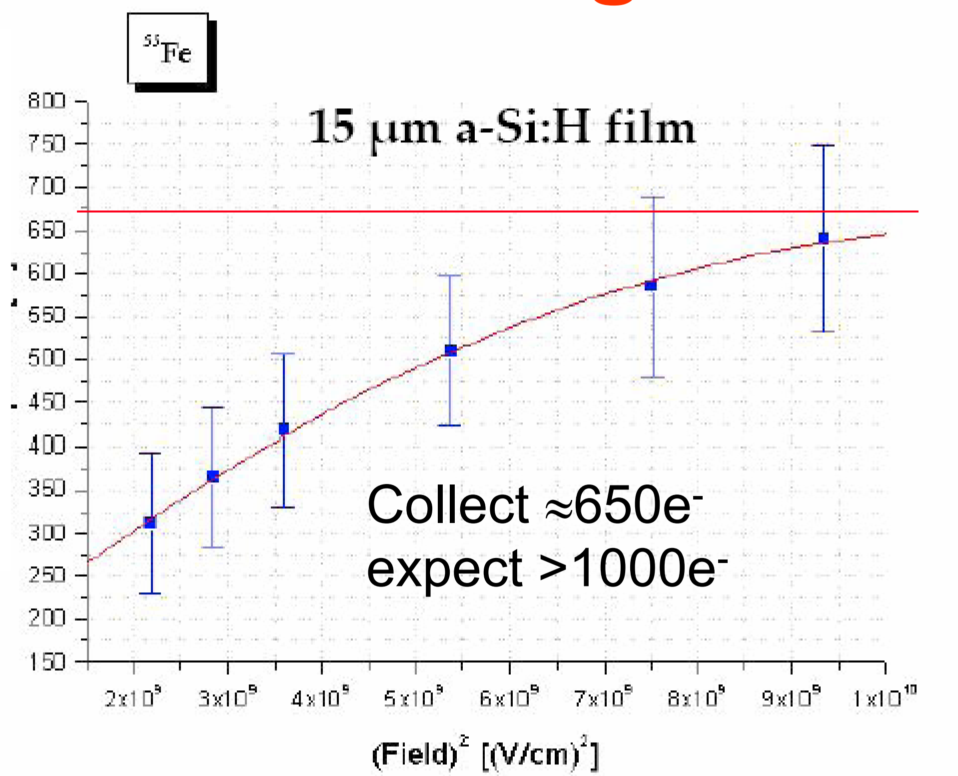




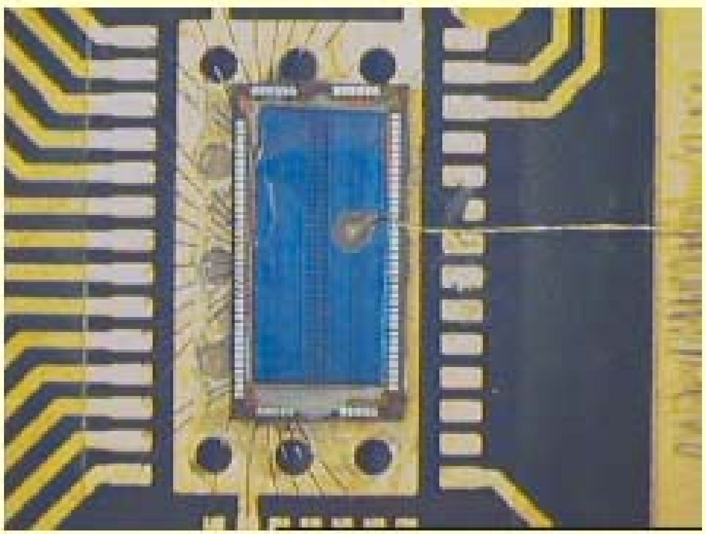
a-Si:H detector film signal
- fast component from e- drift

Advantages/Technical challenges

- CCE Not yet understood:
  - e-h creation energy 3.6-5 eV
- Develop thicker film
- Low noise readout to handle small signal
- Non-commercial process, Deposition with plasma reactor at IMT, Neuchatel



Collect ≈650e$^-$
expect >1000e$^-$



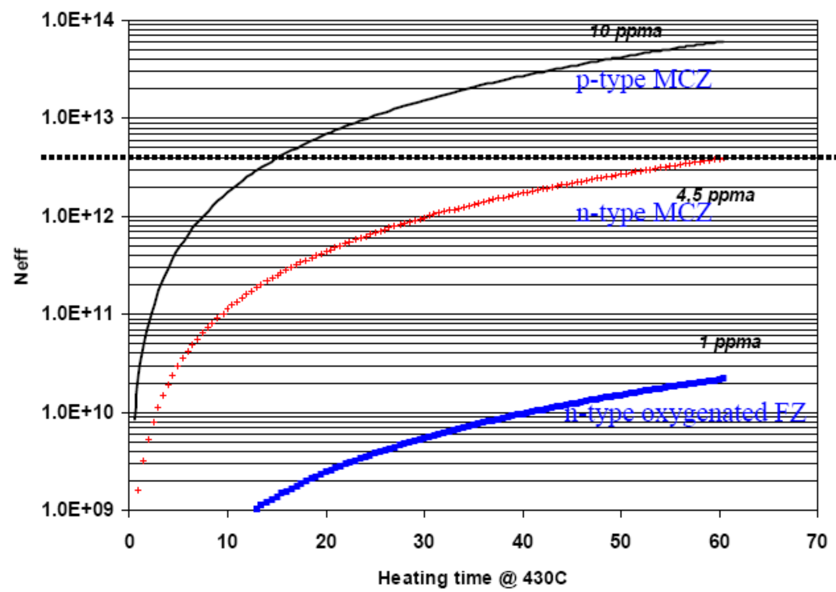
30 μm thick sample

Planarity ⇒edge effects

- Ultra-rad hard sensors
- Low cost pixel detector technology
  - Film deposition cost estimated ≈ 30% of deep sub-micron wafer.
  - For 8", about \$2000 + \$600 for 100cm^2 (yield 75%)

Change of operation conditions

- Device Recovery/Improvement Via Elevated temperature annealing (DRIVE)
- Thermal annealing of radiation damage in FZ or DOFZ:
  - If T>450 °C will destroy the detector and/or electronics
  - If T< 450 °C, reverse annealing (generation of more negative space charges) makes detectors worse



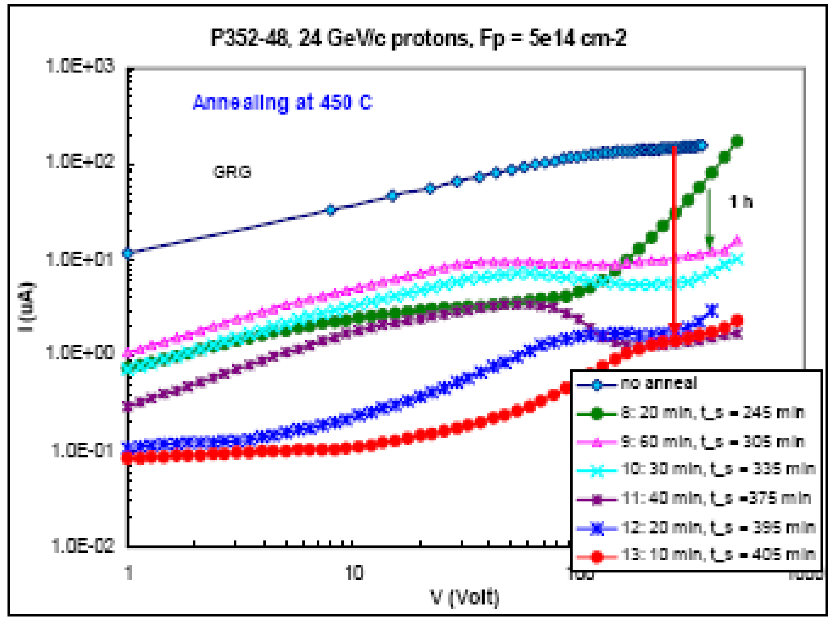
- For high resistivity MC_Z Si thermal annealing with T= 200 °C - 450 °C will generate thermal donor (TD, positive space charge) due to high oxygen concentration [O]
- IDEA: Adjust annealing T and time, and [O] so that TD creation rate cancels compensates the original negative space charges due to irradiation⇒ manageable V_{dep}

Extra slide

DRIVE first results

Z. Lee BNL

- Detectors:
  - p^+-n-n^+pad structures with multi-GRs n-type MCz Si ρ=1 kOhm·cm,
  - p^+-p-n^+ pad structures with multi-GRs p-type MCZ Si ρ=3 kOhm·cm
- Irradiation 24 Gev and 20 GeV protons
- Measurements:
  - After each annealing step (at BNL):
    - I-V and C-V dependences
    - acurrent pulse response using TCT with a laser pulse generation of non-equilibrium carriers
  - After final annealing (at Ioffe Inst.):
    - Spectra of deep levels (C-DLTS)

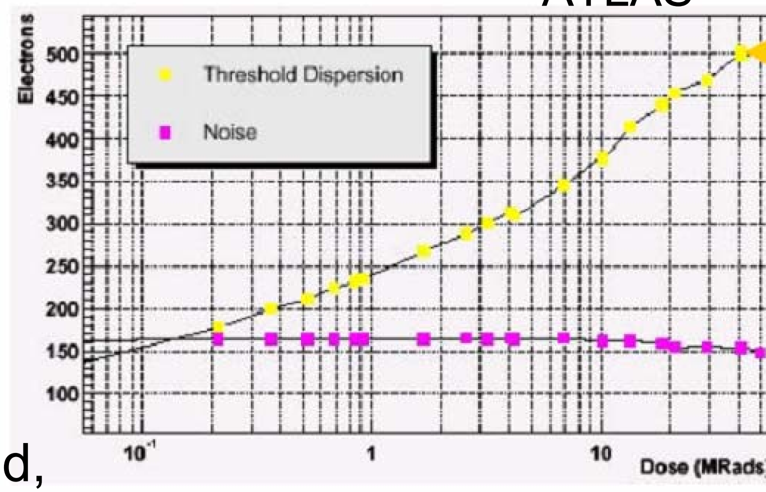


- Interesting results. For ex. :
  - I_{leak} decreases after 1st anneal, but increases at high biases
  - After t_{ann}= 305 min: I_{leak} becomes saturated
  - After final anneal, I_{leak} decreased by more than 2 orders of magnitude

Sub-micron technology

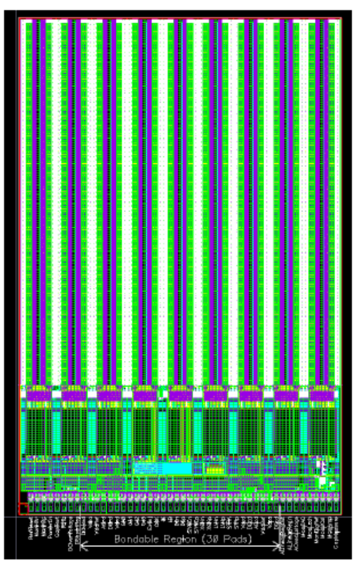
- LHC pixel development:
  - 5K channels per cm^2 ⇒unprecedented level of integration
  - 40 MHz operation at power density below $0.5W/cm^2$
  - radiation hardness of 50MRad, and high SEU-tolerance.

ATLAS

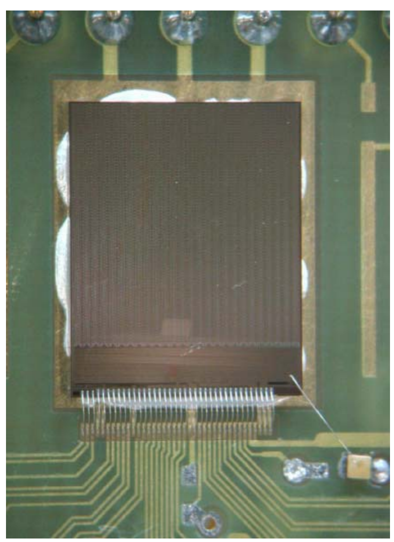


Increase in threshold dispersion (re-tuning necessary

No noise change



Atlas Chip

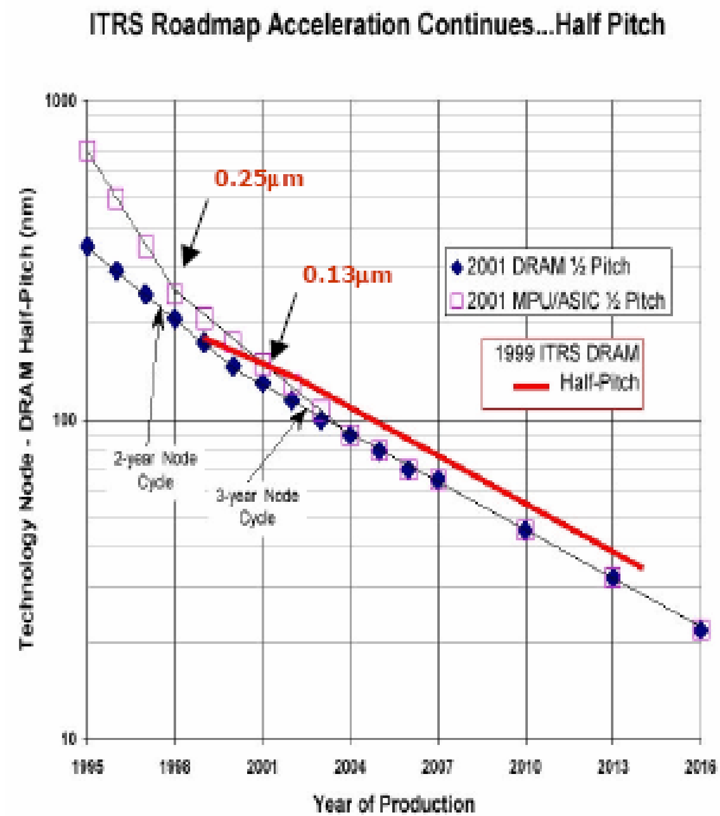


CMS Chip

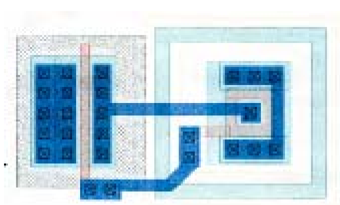
- Technology was initially unavailable. Adequate performance achieved in rad-soft 0.8μ CMOS, but transfer to rad-hard failed to meet requirements.
- The arrival of 0.25μm CMOS with rad-tolerant layout rules was key to development of the current ROCS.
- Working with mainstream commercial vendor (IBM) ⇒ average yield of ~80%.

Sub-micron technology

- Both ATLAS and CMS are investigating IBM 0.13µ CMOS8RF electronics:
  - First measurements show that 0.13µm CMOS appears to be more radiation hard than 0.25µm CMOS.
  - VT shifts at about 70MRad are reduced by factors of 5 or more (X-ray studies).
  - Cost of runs is high: 0.25µm engineering run is ≈150K$, 0.13µm is ≈600K$
- CMS/ATLAS common chip development??

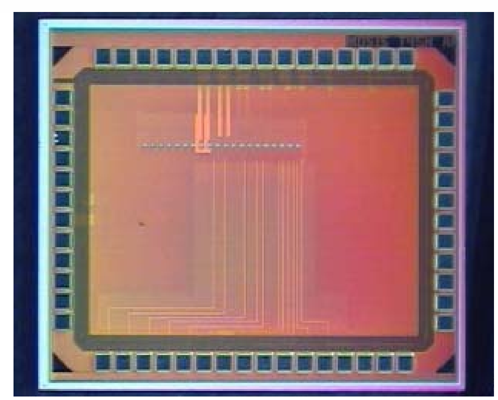


Standard



ELT

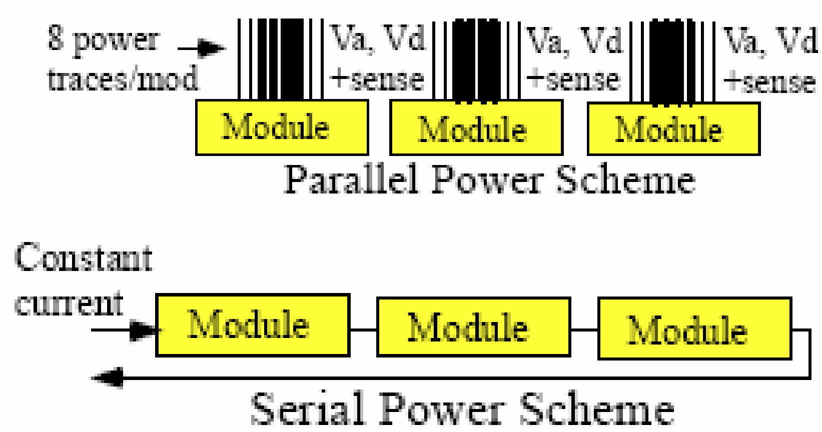
- Can we fully use gain of 0.13 µm? Can we waive some of the special design rules ?
- In 0.25 µm DSM size penalty due to Enclosed Layout Transistor (ELT). Size penalty, reduces sensitivity to SEU.
- ATLAS Designed test chip in IBM 0.13µ CMOS technology to addresses performance of SEU-tolerant storage schemes.



Other major issues

- Uncertainty in the crossing frequency: (25ns, 15 ns, 10 ns, and 12.5ns) ⇒ Critical for ROC
  - CMOS logic power is ∝ to CV^2f
    - The power supply voltage decreases from 2.5 to 1.5 V going from 0.25 µm to 0.13 µm ⇒power reduction of 2.77 at fixed f
    - The gate capacitance/unit area goes up, the gate area goes down ⇒ decrease in C ≈1.73 for a given complexity
    - The frequency might increase limiting the power savings.
  - Power in analog section is $\propto I_{rms} \times V$
    - Decrease in V reduces the power by 1.66 at constant I
    - The current in the analog section may actually be increased to compensate for lower dynamic range limiting power saving

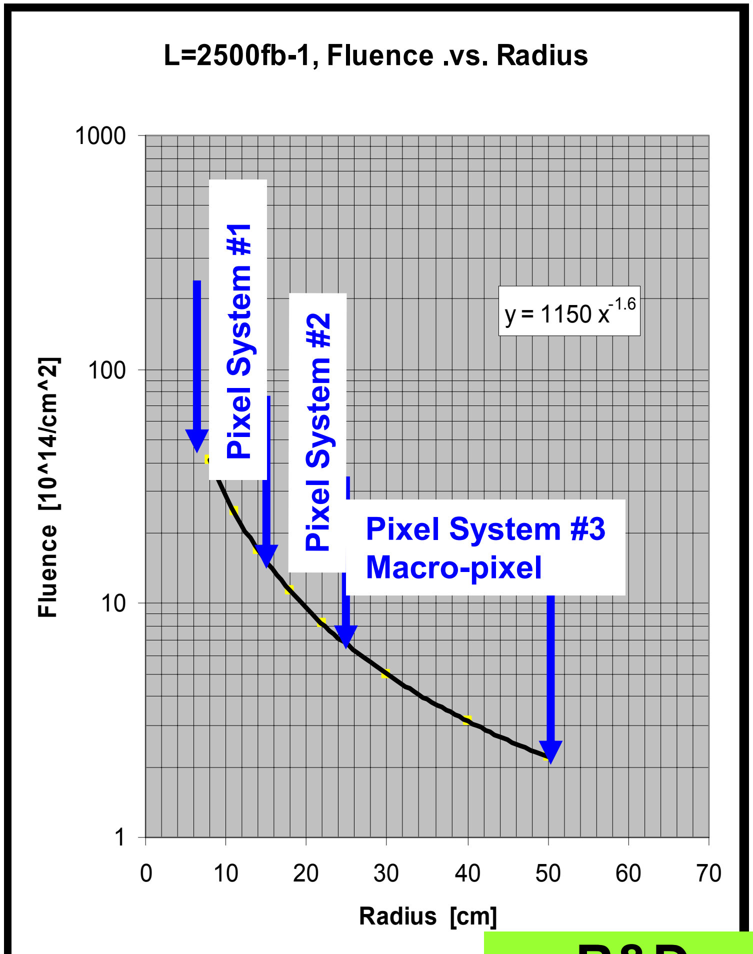
- The requirement of more granularity ⇒ increase in channel counts ⇒ cooling ⇒ more mass
- Serial powering of high density detectors can offer: reduced number of power cables, reduce mass, reduced power dissipation



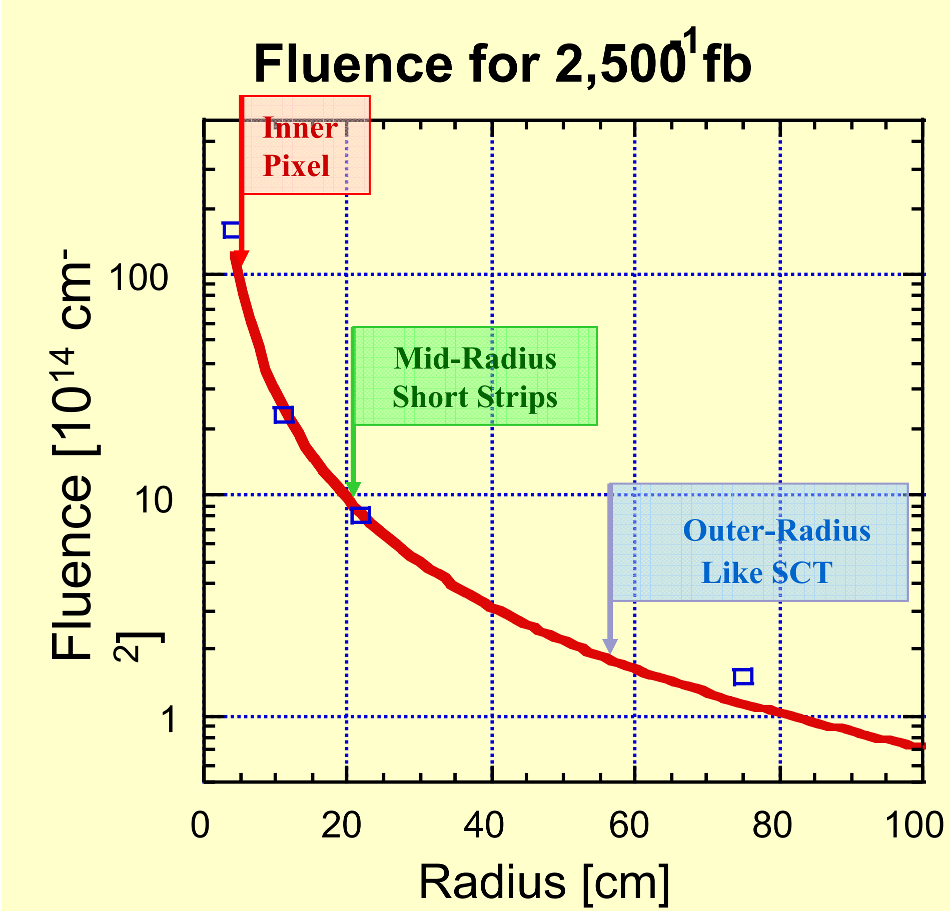
- Large systems are hard to build
  - Qualification must be taken seriously
  - Many complex system issues

Detector specific developments

- **CMS and Atlas are starting look at detector configurations:**



CMS-Horisberger



- **R&D needed below <20 cm**
- **Cost issues everywhere**

Summary

- At fluences up to $10^{15}cm^{-2}$ (Outer layers of a SLHC detector) the change of depletion voltage and the large area is the major problem:
  - CZ silicon detectors could be a cost-effective radiation hard solution (no type inversion, use p-in-n technology)
  - p-type silicon microstrip detectors show very encouraging results: CCE ≈ 6500 e; Φ_{eq}= 4×10^{15} cm^{-2}, 300μm, collection of electrons no reverse annealing observed in CCE measurement!
- At the fluence of $10^{16}cm^{-2}$ (Innermost layer of a SLHC detector) the active thickness is significantly reduced due to trapping. Options are:
  - Thin/EPI detectors
  - 3D detectors, TFA
  - Diamond

→ Radiation hard electronics for low signals

- Performance of 0.13 DSM electronics is promising
- Integration issue (power, cooling and mass) are complex. LHC experience will be very useful to avoid mistakes

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