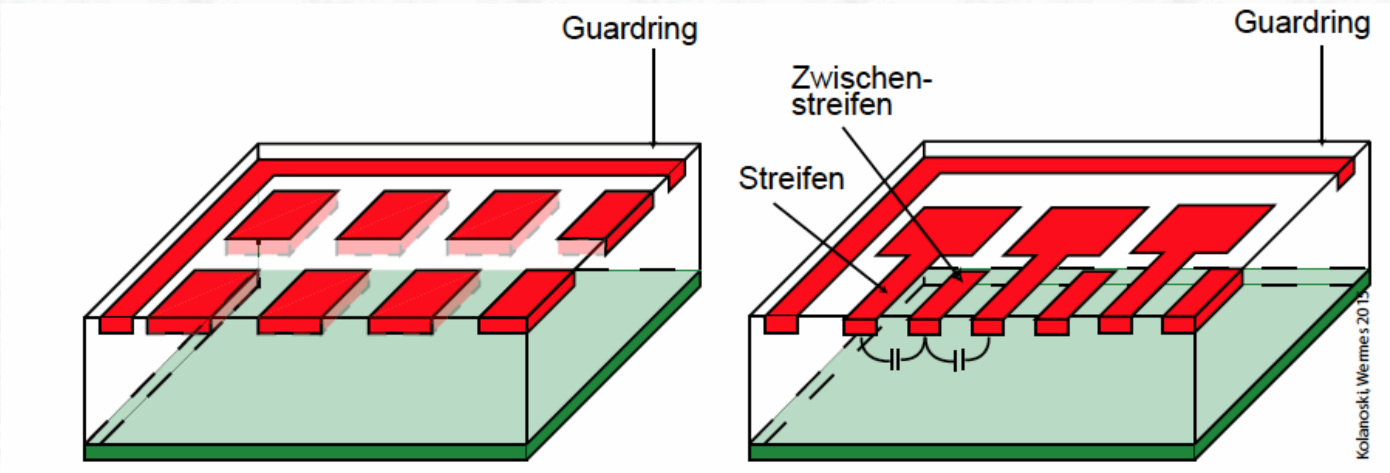
6.4 Silicon Pixel detectors



Basic concept: - segment a diode in two dimensions
- strips become pixels

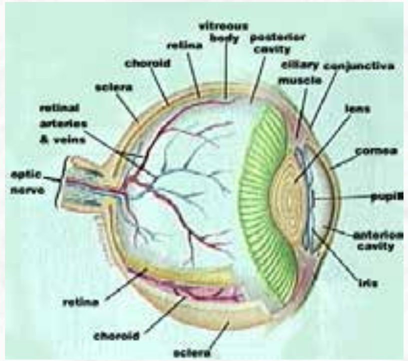
→ increased two-dimensional resolution → space points

Si-Pixel Detectors: CCD

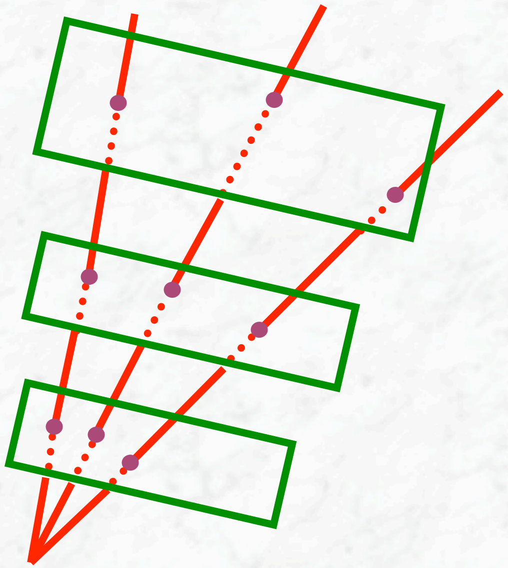
- Instead of strips measuring one dimension, have a matrix of points measuring two dimensions

as used in this

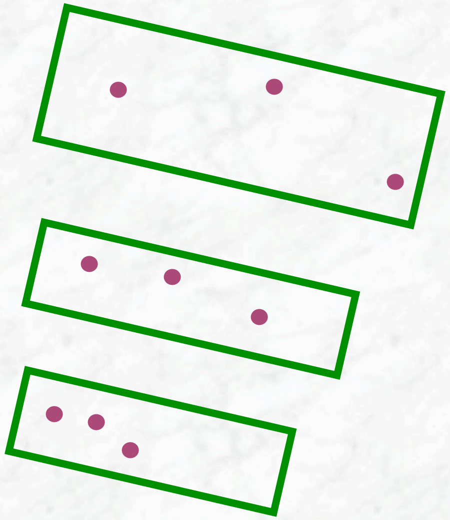
and in this



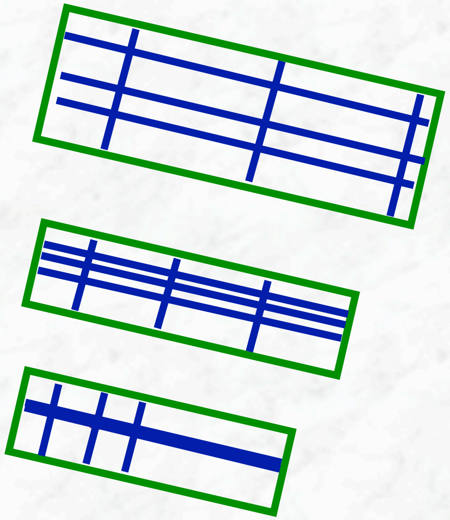
- Pattern recognition is much easier! Compare reconstructing



these tracks …



with this ….

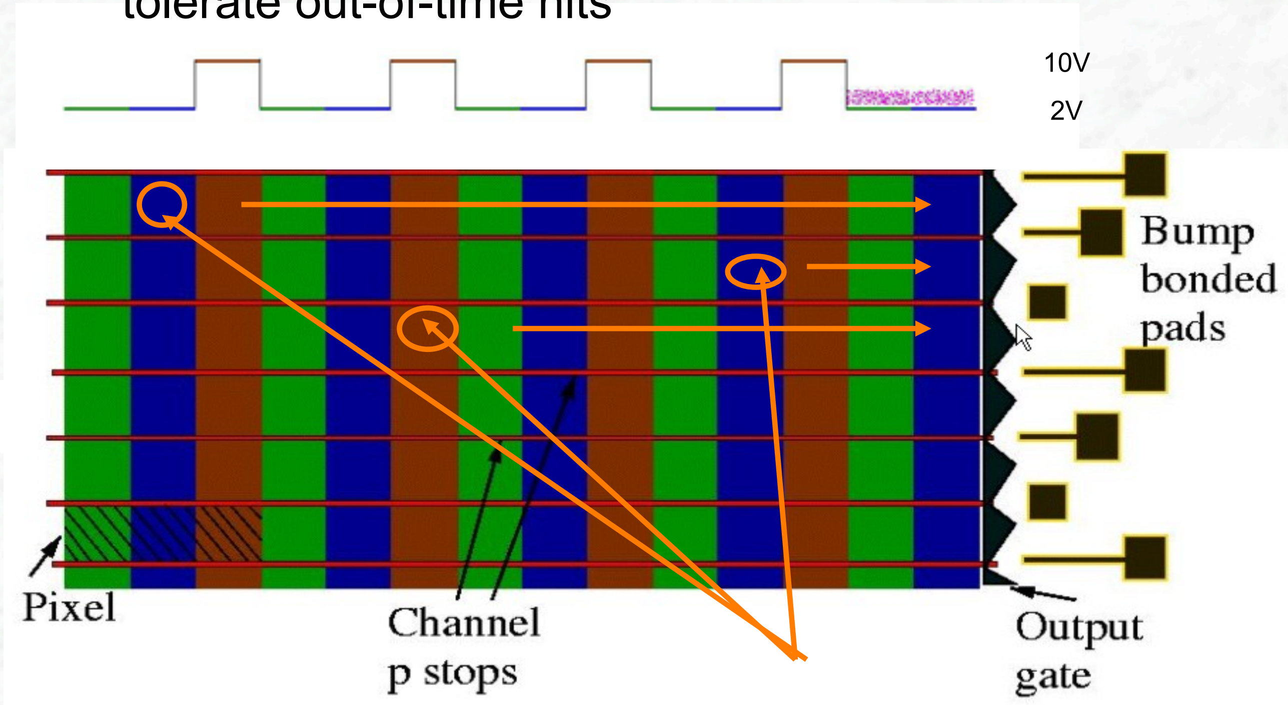


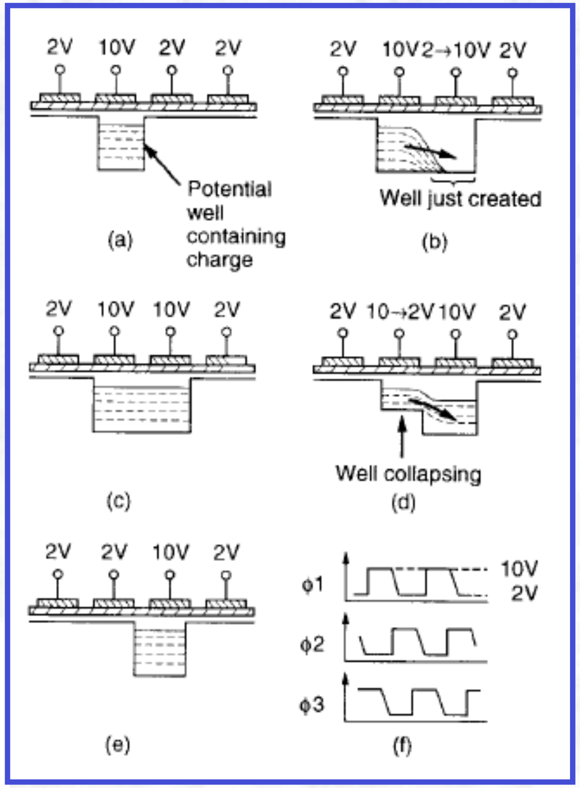
or with this!

C. Damerell, P.Collins

Si-Pixel Detectors: CCD

- First pixel detectors in HEP were CCDs derived from digital cameras
- CCD principle: MIP generates charge which is shifted out sideways to readout
- Very economic as $N_{readout} < N_{pixel}$
- CCDs work - but are slow and do not tolerate out-of-time hits





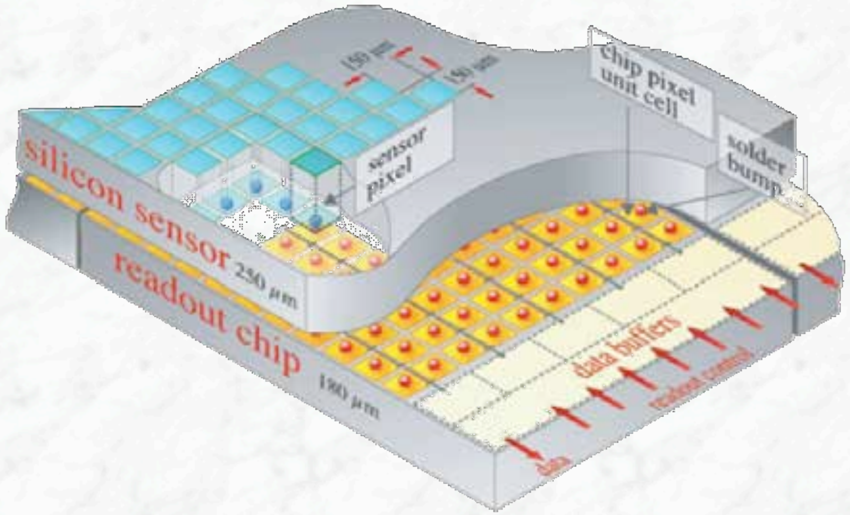
From Paula Collins

Pixel Detector Overview

- Different pixel detector types

- Hybrid Active Pixel Sensors (HAPS)
  - Detector and readout ASIC are sandwiched together ($N_{readout} = N_{pixel}$)
  - Limitation from readout:
    Pixel size > 120 x 120 µm with 130nm technology, 50 x 50 µm with 65nm
  - Used widely in collider experiments
    - ATLAS: 100M pixels (50x400 μm^2)
    - CMS: 23M pixels (150x150 μm^2)

HAPS design principle



- Monolithic Active Pixel Sensors (MAPS)
  - Preamplifier integrated into detector, ASIC nearby
  - Pixel size > 15 x 15 µm
  - Current research topic in many groups, (MIMOSA, IReS Strasbourg)

Pixel Detector Overview

Hybrid Pixels

	BX time	Particle Rate	Fluence	Ion. Dose
	ns	kHz/mm²	n_{eq}/cm^2 per lifetime*	Mrad per lifetime*
LHC (10^{34} $cm^{-2}s^{-1}$)	25	1000	2×10^{15}	79
HL-LHC (10^{35} $cm^{-2}s^{-1}$)	25	10000	2×10^{16}	> 500
LHC Heavy Ions (6×10^{27} cm^{-2} s^{-1})	20.000	10	$>10^{13}$	0.7
RHIC (8×10^{27} $cm^{-2}s^{-1}$)	110	3,8	few 10^{12}	0.2
SuperKEKB (10^{35} $cm^{-2}s^{-1}$)	2	400	~3 x 10^{12}	10
ILC (10^{34} $cm^{-2}s^{-1}$)	350	250	10^{12}	0.4

Monolithic Pixels

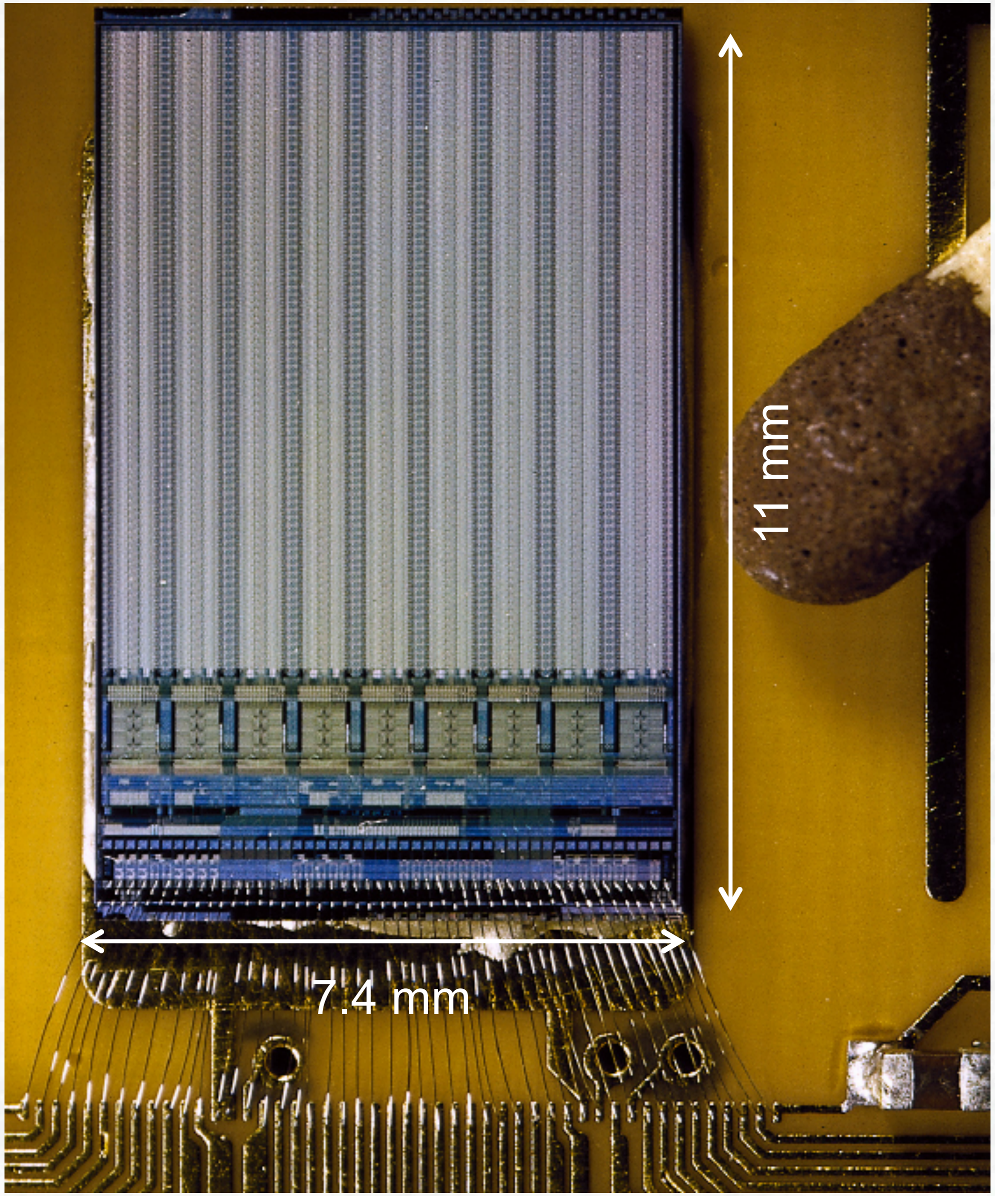
lower rates
lower radiation
smaller pixels
less material
better resolution

DEPFET: Belle II
MAPS: STAR@RHIC
and future
ALICE ITS

assumed lifetimes:
LHC, HL-LHC: 7 years
ILC: 10 years
others: 5 years

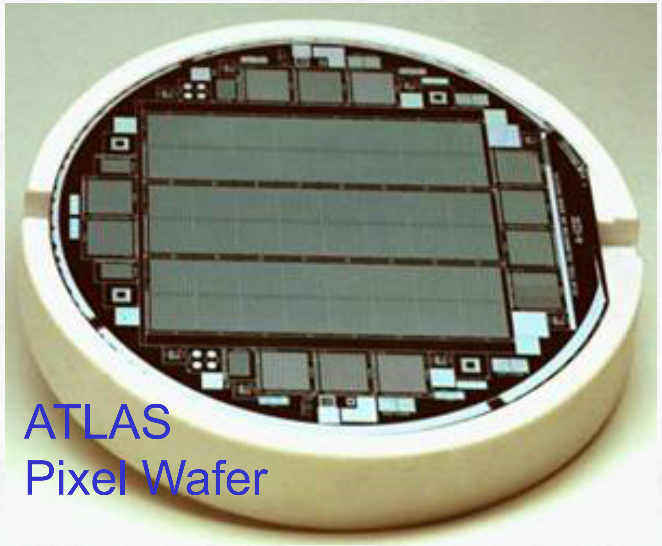
Hybrid Pixel - Example

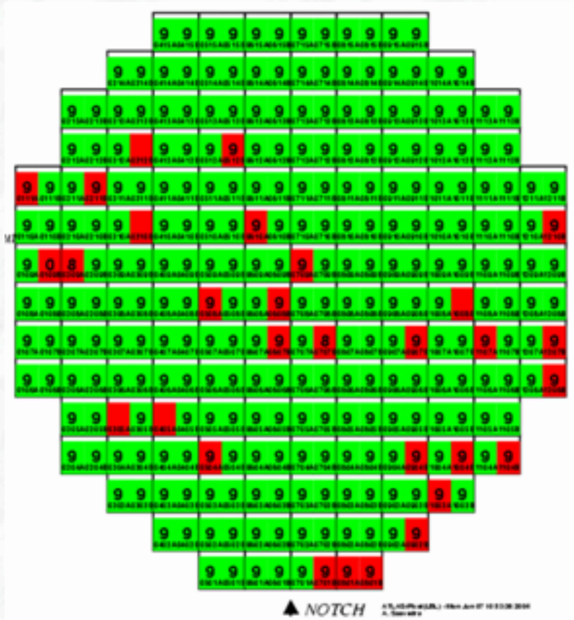
- ATLAS FE-I3
  - 0.25 µm CMOS technology
  - Pixel size 50x400 μm^2
  - 18 columns x 160 rows = 2880 cells
- End of column logic
  - Store hit information until readout
  - Hit selection on readout
- ATLAS Pixel Detector
  - Total area of 1.8 m^2

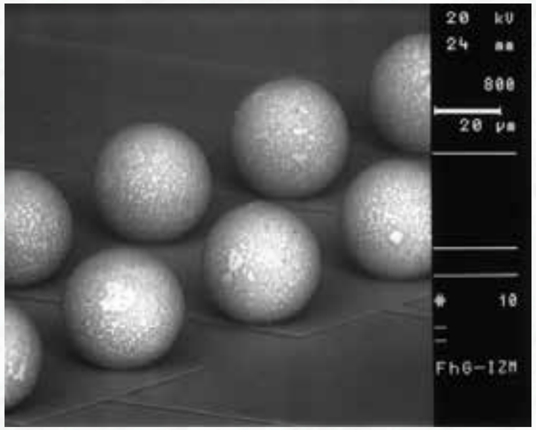


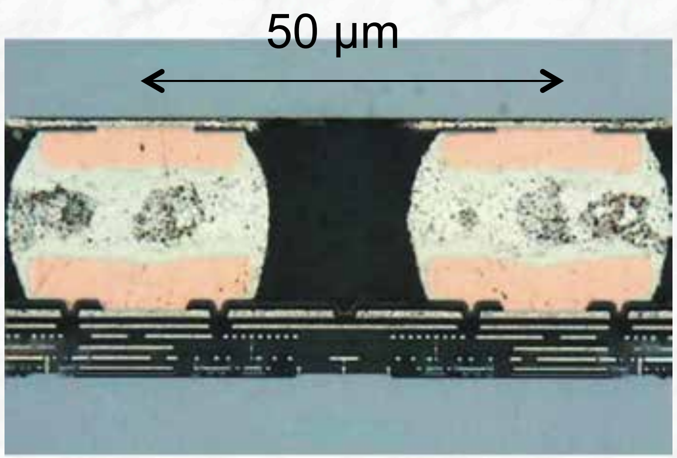
Hybrid Pixel - Assembly

- Sensors
  - Oxygenated Si
  - Wafer size: ~10 cm across, ~250 μm thick
- Electronics
  - Chip size limited by yield
  - Wafer size ~20 cm
- Hybridization
  - PbSn or Indium bumps
  - ‘flip-chip’ to mate the parts
  - ~3000 bumps per chip, ~50000 per module



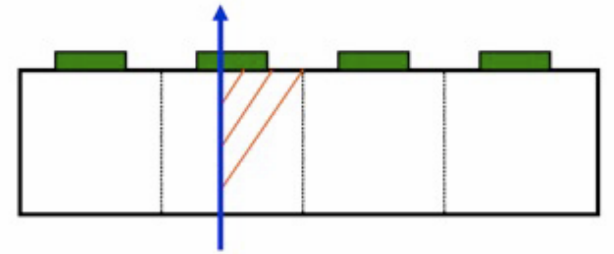


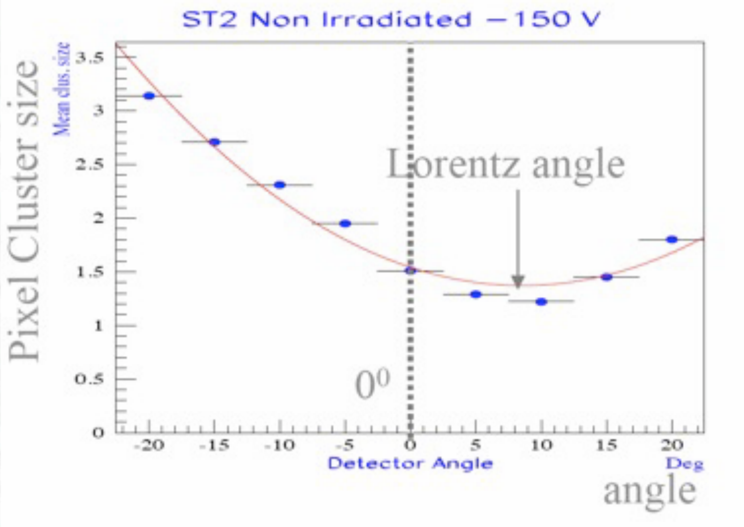


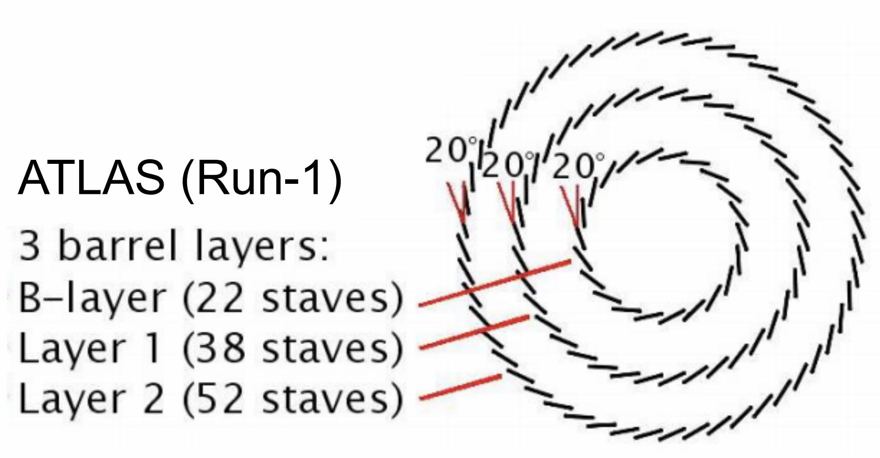


Signal generation in a magnetic field

- Lorentz angle α_L, analogous to chapter 4.3.3
- Measurement approach
  - Number of pixel hits is minimal when particle incident angle equal to Lorentz angle
- Tracking detectors are often built at a tilt angle to compensate Lorentz angle
  - e.g. 20° for ATLAS Pixel Barrel



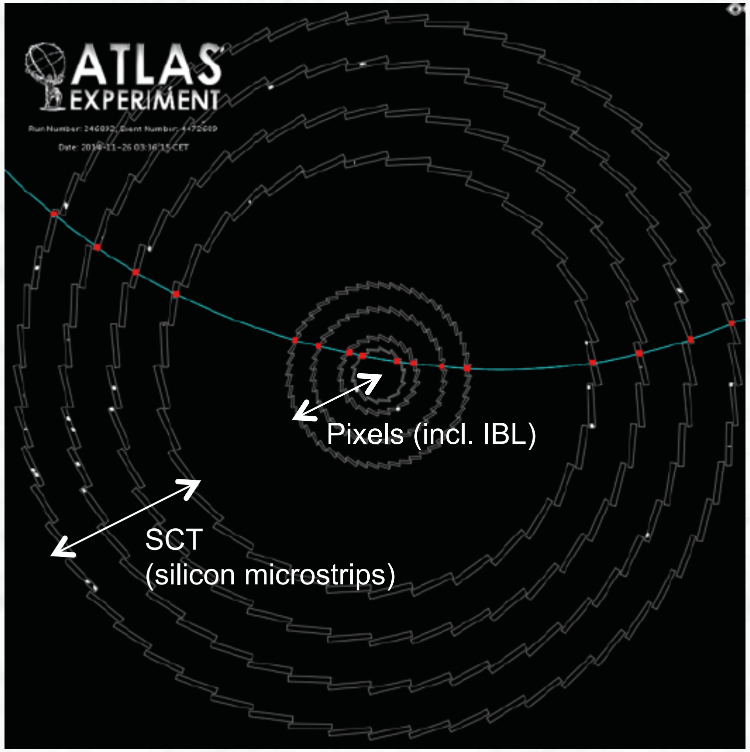


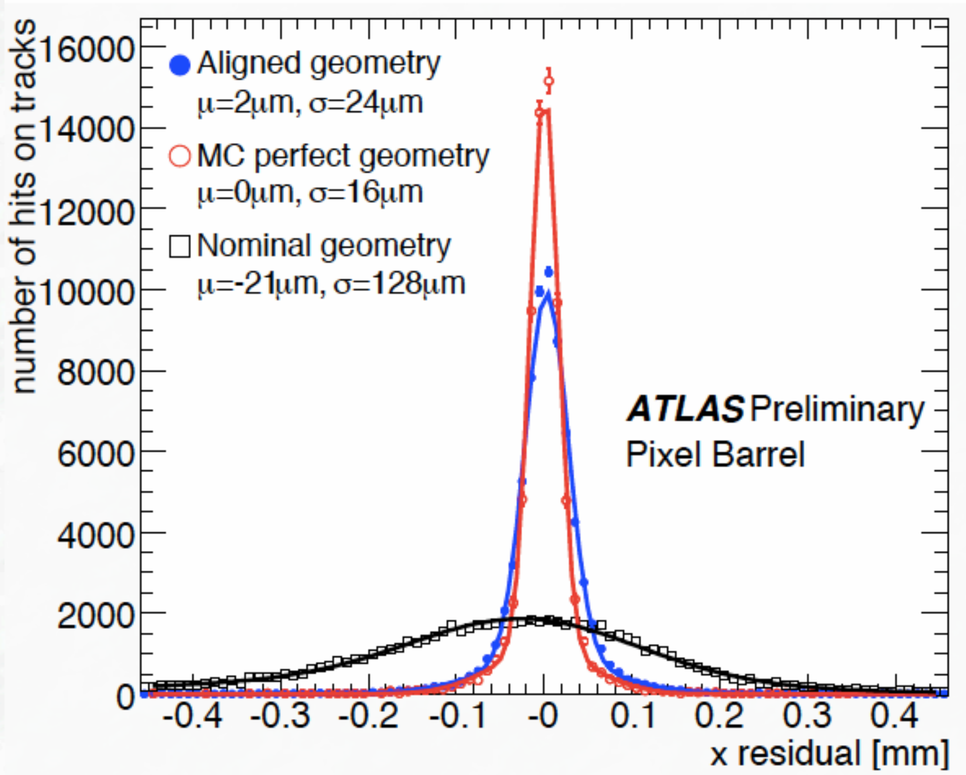


$$\boxed{\tan \alpha_L = \mu_{Hall} B_\perp}$$

Pixel alignment

- Pixels = very good resolution of individual hits (ATLAS and CMS ~20μm)
- precision for track measurement requires very precise (~μm) alignment of Pixel layers
- Residual defined as difference of extrapolated hit position and measured hit position, e.g. for cosmic muons
  - Integrated over all hits on a track





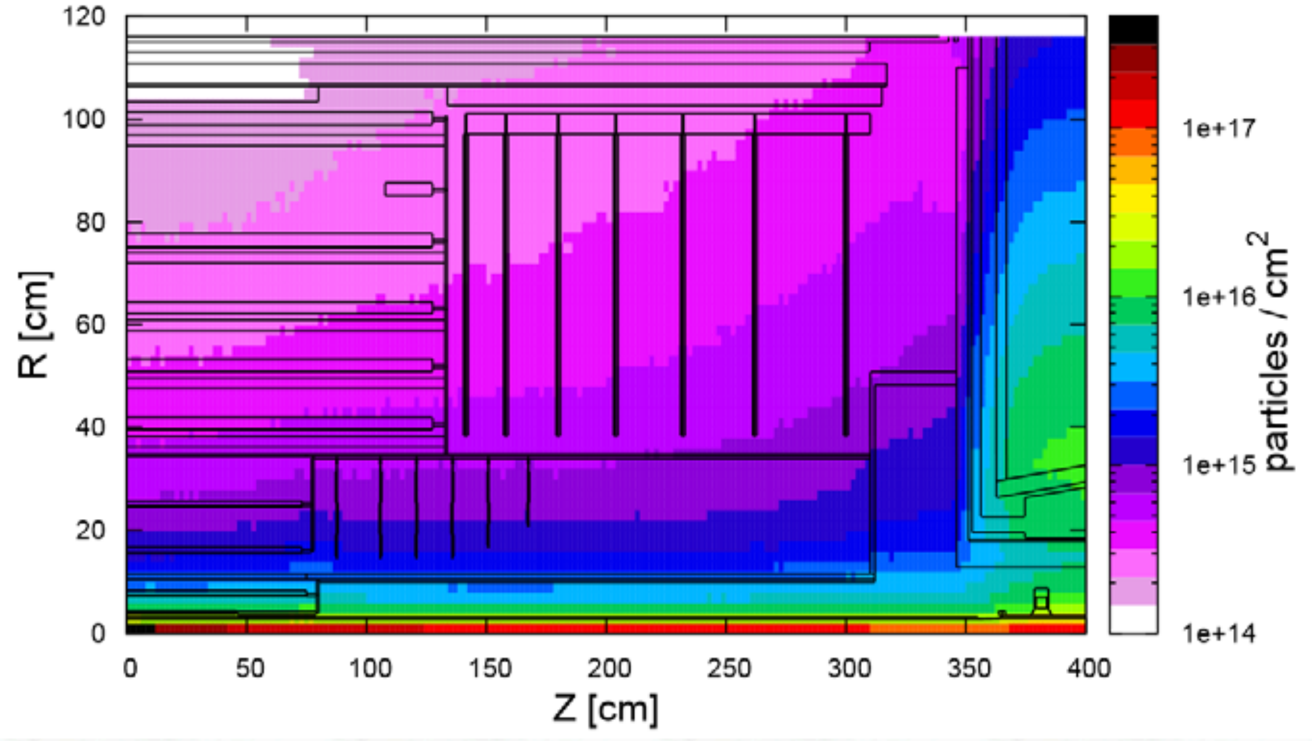
Pixel Detector Summary

- Compared to silicon strip detectors
  - Advantages
    - 2-dimensional information like double sided-micro strip, but more simultaneous hits allowed
    - Low capacity -> low noise
  - Disadvantages
    - Large number of readout-channels -> expensive, large data volume, contacts can be complicated (for hybrids “bump bonding”, “flip chip”, …)
- Hit resolution $\Delta x/\sqrt{12}$ $\Delta y/\sqrt{12}$
- Pixel Detector tasks
  - Precision 3D tracking points
    - Huge advantages in high density tracking environments
  - Vertexing (see section 6.6)

6.5 Radiation damage of silicon detectors

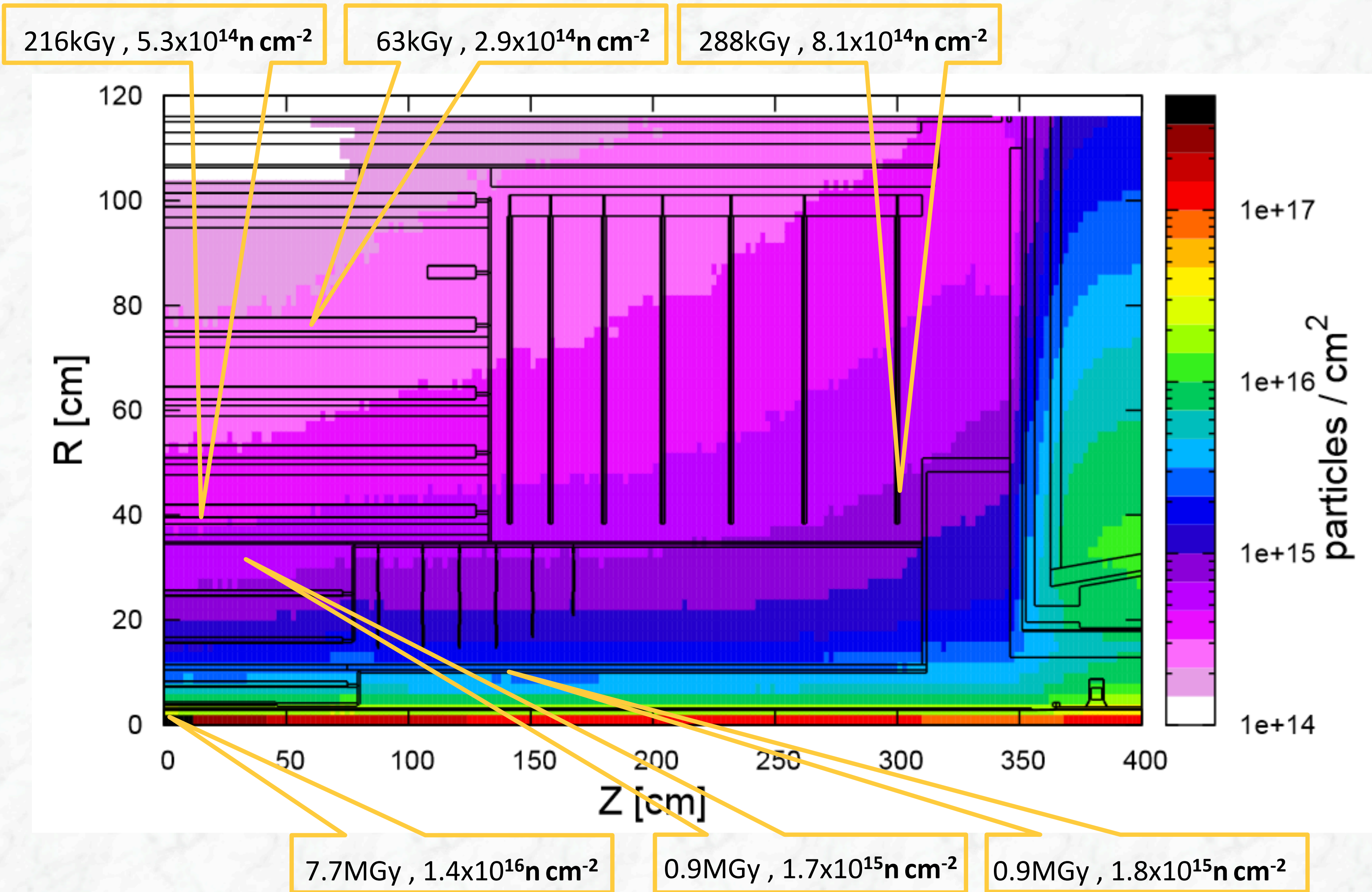
- Radiation damage in the silicon bulk

- Radiation tolerant silicon detectors

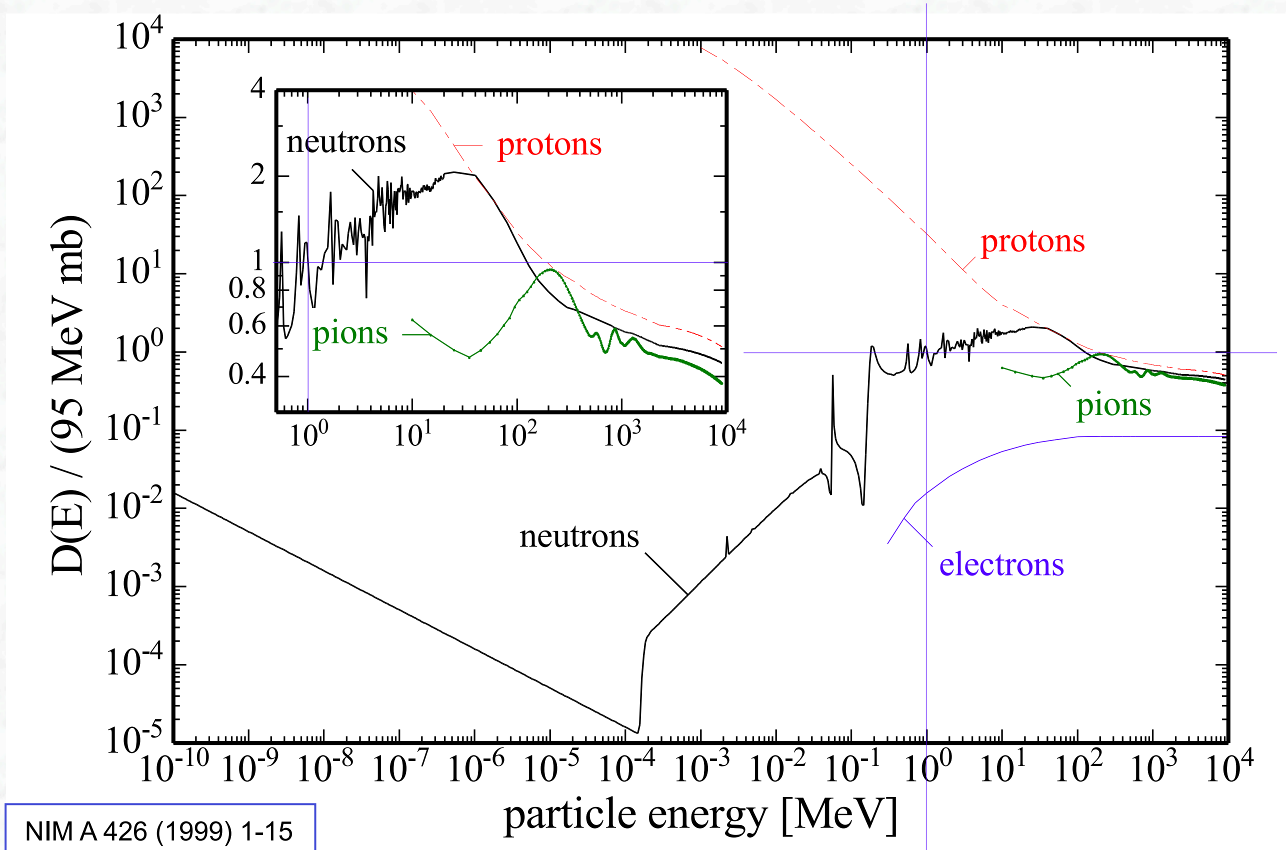


Expected particle fluences at the HL-LHC after 10 years of operation (3000 fb^{-1}) of 1 MeV n_{eq}

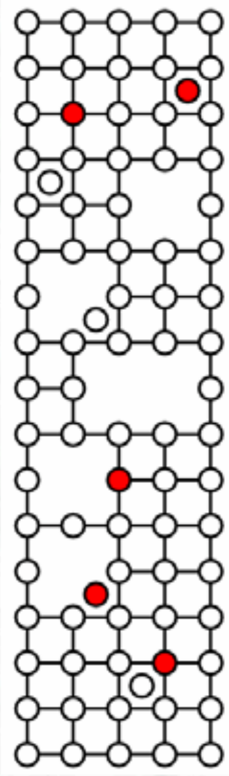
Radiation Levels (Details)



Non Ionizing Energy Loss — NIEL



NIM A 426 (1999) 1-15



NIEL scaling allows to estimate long-term radiation effects (caused by operation of a detector over many years) by an accelerated exposure to the corresponding equivalent dose of one particle type

(typically available at radiation facilities, pion beams, proton beams, neutrons at reactors)

Radiation damage can be normalized in units of

"1 MeV neutron equivalent"

→ independent of particle type and energy

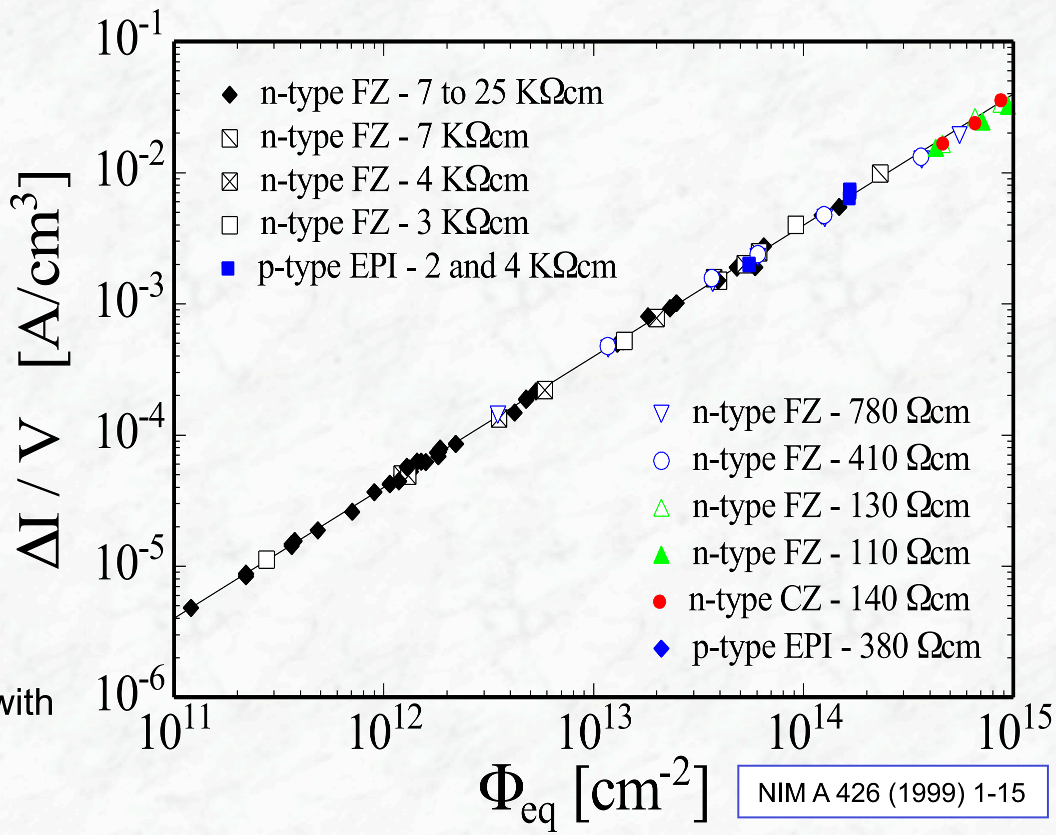
[NIEL scale factors]

Radiation damage

- Non-Ionizing Energy Loss (NIEL) is a volume (bulk) effects
  - Net effect: development of acceptors
  - Increased leakage currents and bias voltage
  - Increase in current ΔI is proportional to the equivalent particle fluence Φ_{eq}

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

  - Annealing: ΔI decreases again with time
  - The annealing time constant decreases with temperature
    → faster recovery at low temperatures
  - Also ΔI itself depends strongly on the temperature (doubling every 8°)

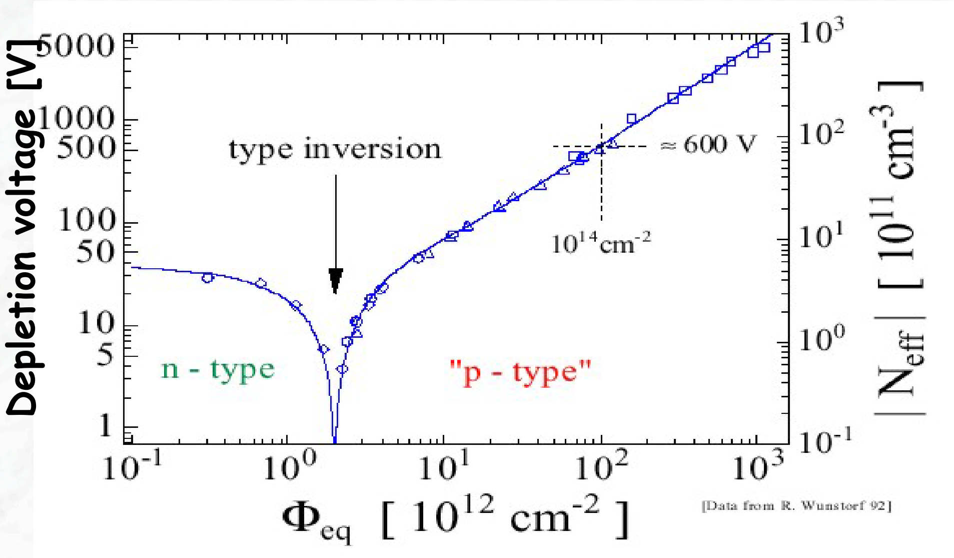


NIM A 426 (1999) 1-15

- In addition there are surface effects, however, they are less dramatic

Radiation damage

- Development of acceptor centres leads to **type inversion**: **n-Si → p-Si**



- p-n junction moves from the p-strip side to the n-backplane

  → Depletion (as function of bias voltage) develops from the „wrong“ side

  → Standard p-in-n Si-detectors cannot any longer be completely depleted

After type inversion: depletion of p-in-p

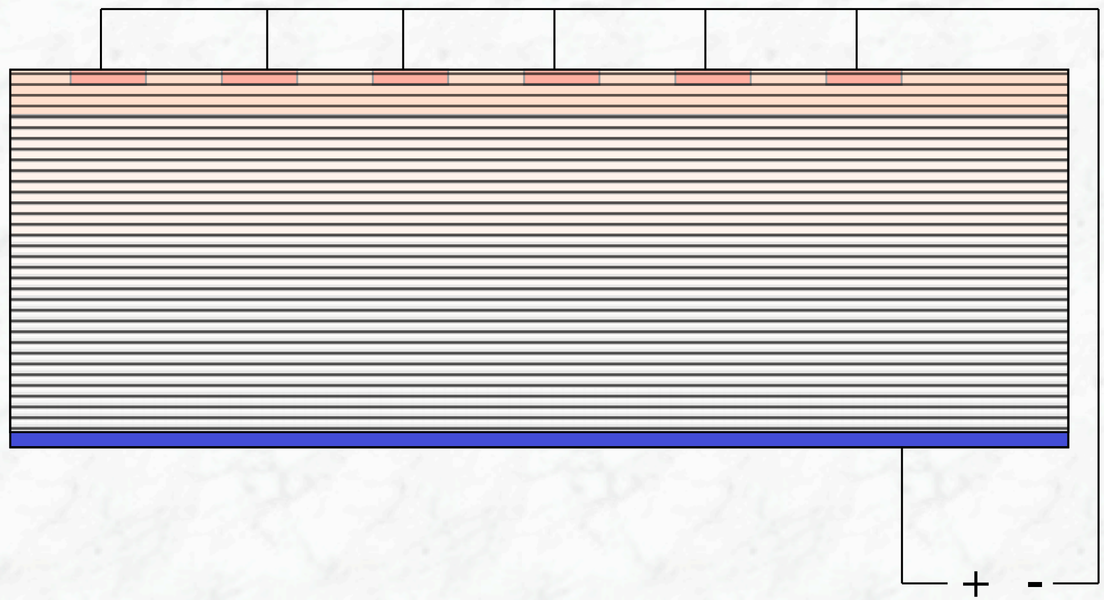
- Type inversion due to radiation damage

- Silicon bulk is effectively p-doped

- The p-in-n detector has developed into a “p-in-p” detector, for which only the back plane is still n-doped

- The depletion zone now grows from the n^+-back side to the p-strips

- Strips are only isolated from each other by total depletion
  → very high voltages required



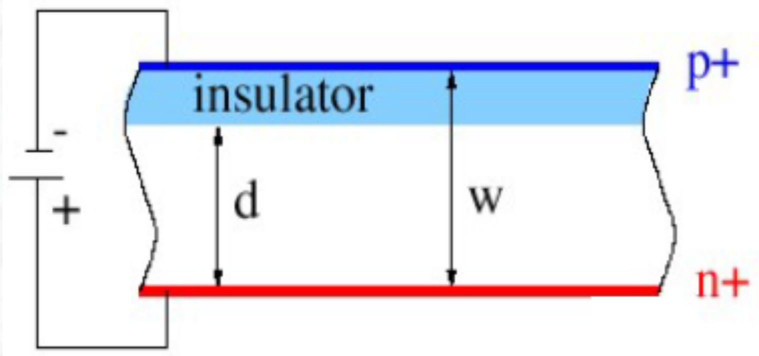
Partial depletion after type inversion

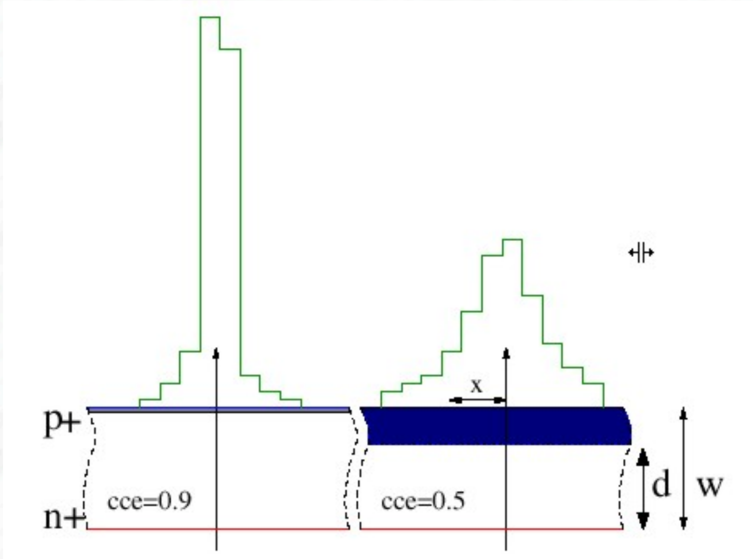
- After type inversion and increasing radiation damage, higher and higher
  bias voltages are required to achieve
  full depletion

- Areas around strips can at some point not any longer be depleted,
  - Strips in a non-depleted layer
  - Strips are not electrically isolated any longer
  - Charged particles (mip) produce larger clusters (some of which can be below threshold (S:N)-threshold)

    → loss of efficiency

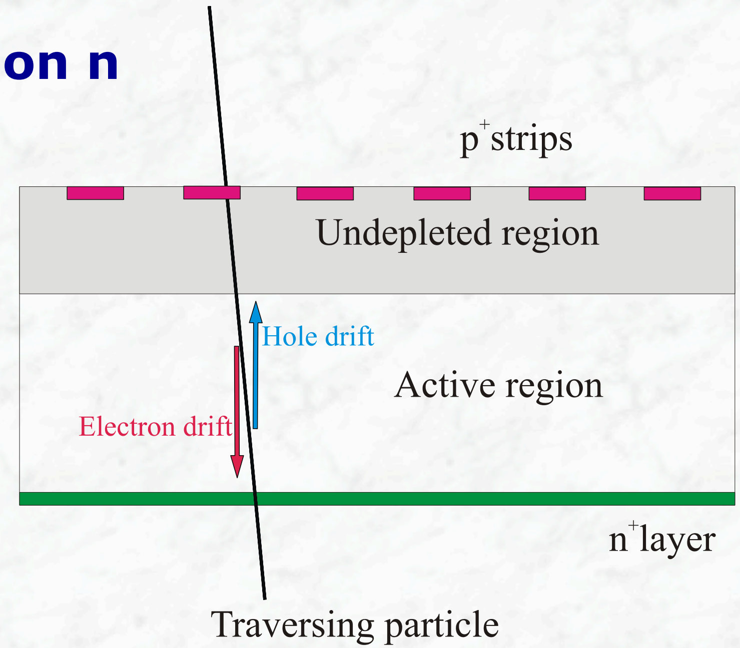
    (in particular a problem for binary readout schemes with small pitches)



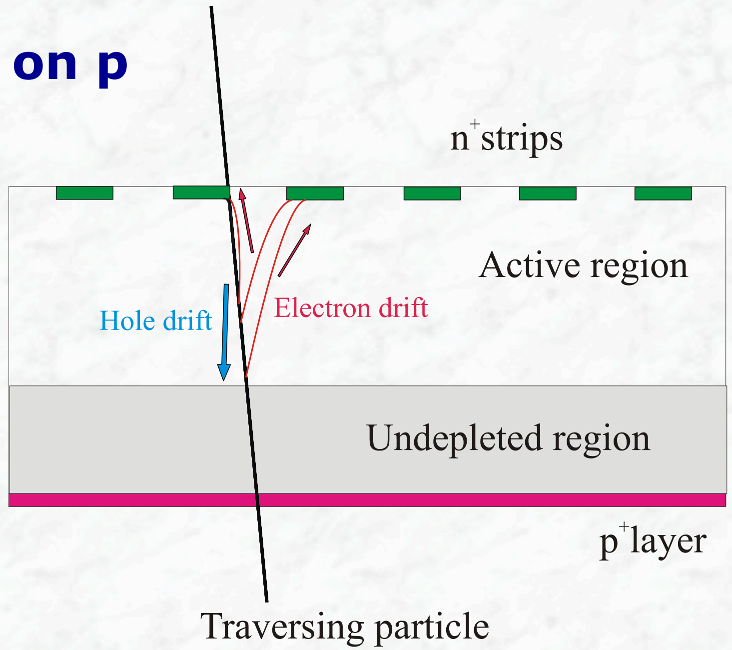


Signals in under-depleted n- and p-type Si detectors

p^+ on n



n^+ on p



p-on-n silicon, under-depleted:

- Charge spread – degraded resolution
- Charge loss – reduced charge collection efficiency (CCE)

n-on-p silicon, under-depleted:

- Less degradation with under-depletion
- Limited loss in CCE
- Collection of electrons (fast)

Trapping of charges

- Trapping of charges (attachment) due to radiation-induced defects in the bulk constitutes an additional degradation

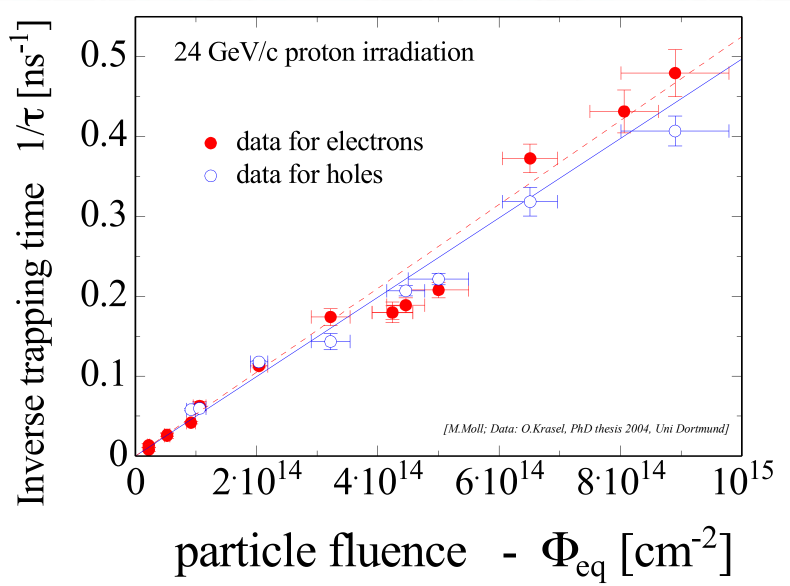
- Trapping can be quantified via effective trapping times τ_{trap} for e^- and h^+

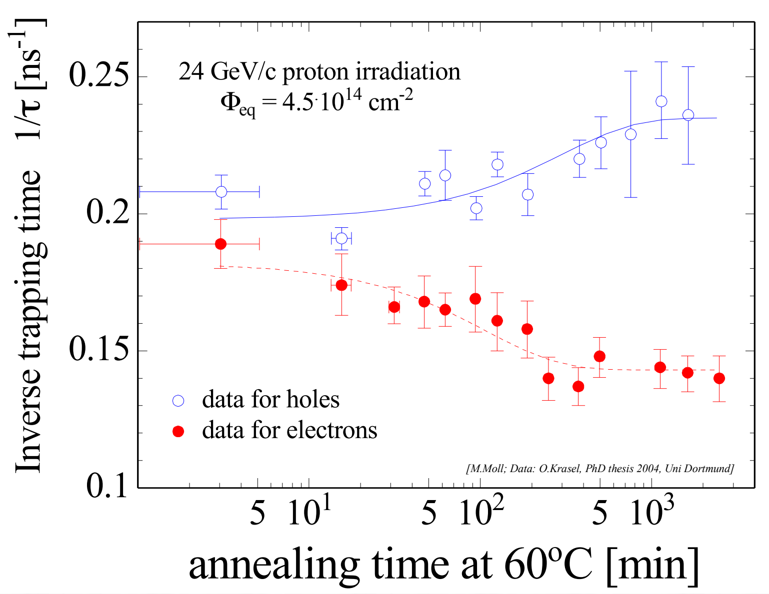
- Trapping times decrease with increasing radiation

$$Q_{e,h} = Q_{0\,e,h} \exp\left(-\frac{\tau_{coll}}{\tau_{trap\ e,h}} \right)$$

with

$$\frac{1}{\tau_{trap\ e,h}} \propto N_{Defects} \propto radiation\,dose$$





IEEE TNS 51 (2004) 3055-3062

Trapping of charges

$$\tau_{coll} = \frac{d}{v} = \frac{d}{\mu \cdot E}$$

- After irradiation τ_{trap} is identical for e^- and h^+
- After annealing trapping rate is higher for h^+
- Mobility of electrons is found to be ~3x higher than of holes
  - $\mu_e = 1350\ cm^2\ V^{-1}\ s^{-1}$
  - $\mu_h = 480\ cm^2\ V^{-1}\ s^{-1}$
  - Collection time (100 V, 300 μm) for e =7 ns, for h = 19 ns

$$\tau_{eff}(10^{15} n_{eq}) = 2ns \qquad w = v_{sat}\tau_{eff} = 200\mu m$$

$$\tau_{eff}(10^{16} n_{eq}) = 0.2ns \qquad w = v_{sat}\tau_{eff} = 20\mu m$$

Annealing: time dependence

- N_{eff} has three components with different time dependence

- Stable Damage:

  Donor removal, stable acceptors

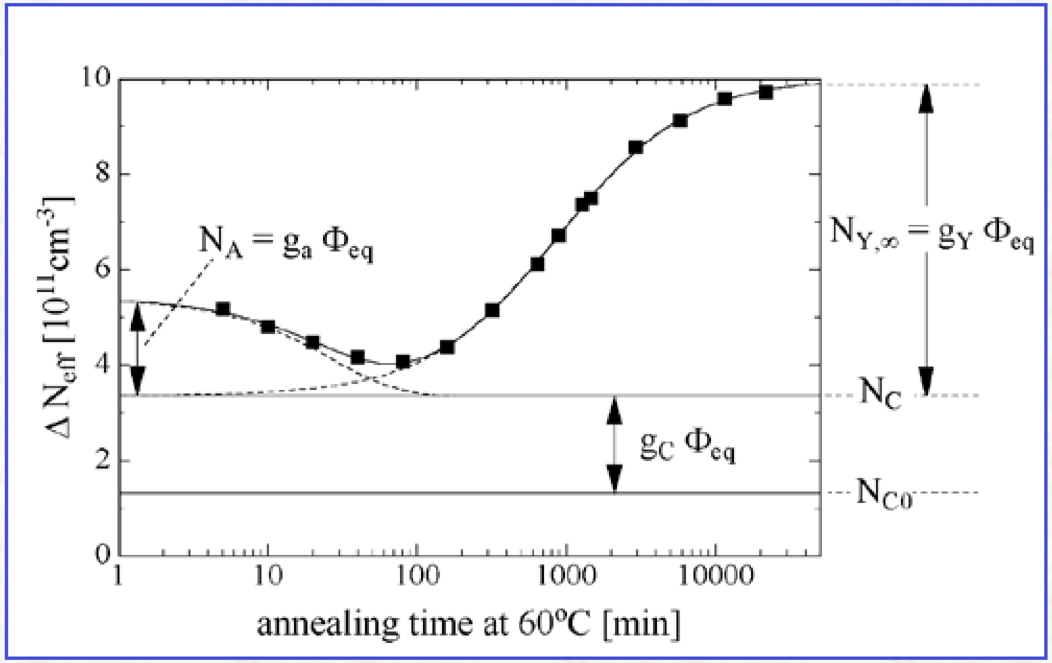
  $N_c = N_{C,0}(1-\exp(-c\Phi)) + g_c\Phi$

- Short Term Annealing

  $N_a = \Phi\, g_a \exp[-t/\tau_a(T)]$

- Reverse Annealing

  $NY = \Phi\, g_Y \exp[1-(1+t/\tau_Y(T)^{-1}]$



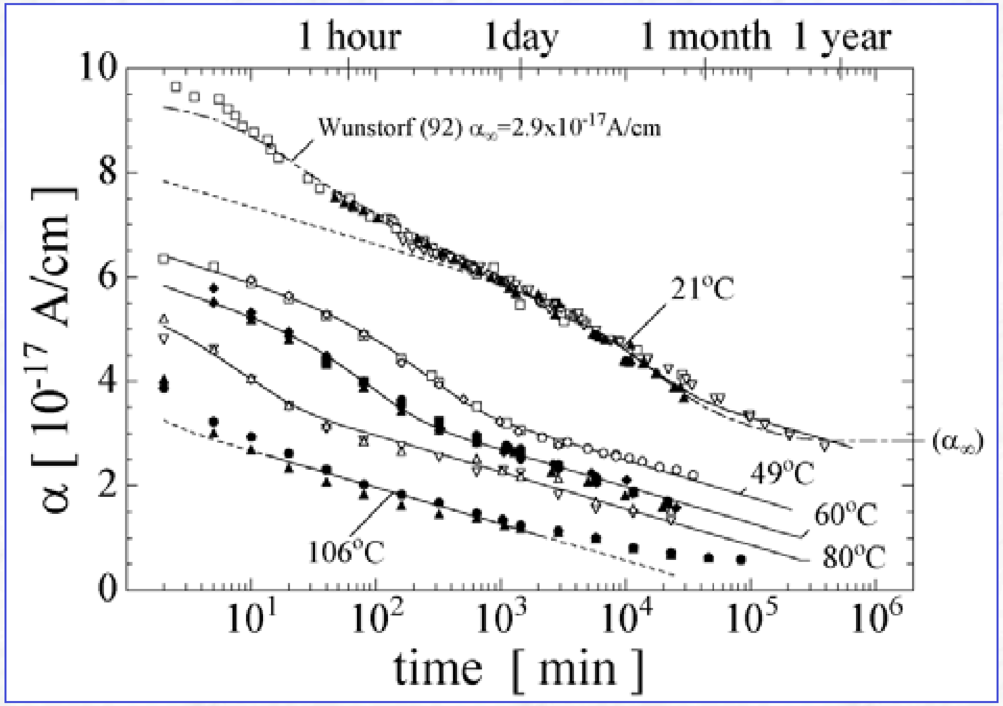
NIM A 466 (2001) 308 - 326

Annealing: temperature dependence

- „Current-related damage constant“ α shows a strong temperature dependence

- Faster annealing at higher temperature

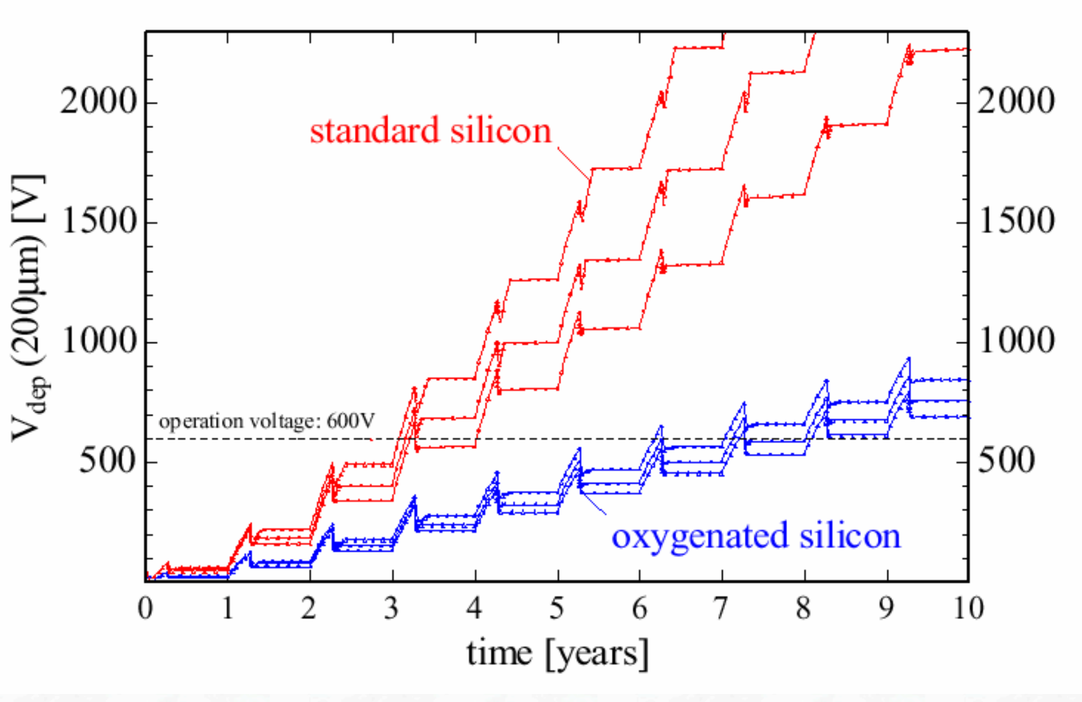
- Cause is the temperature dependent mobility of defects



NIM A 466 (2001) 308 - 326

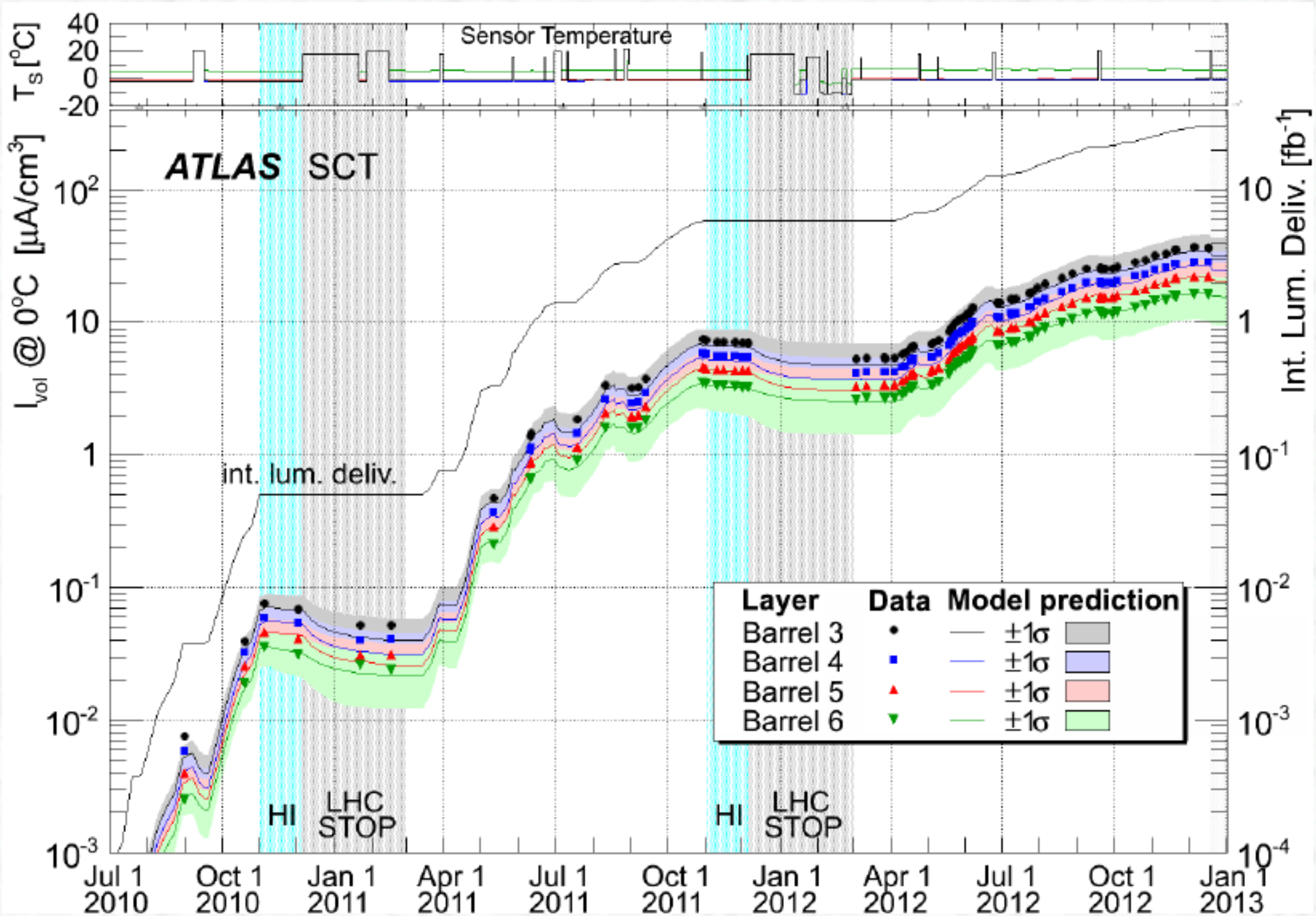
Operation of Si detectors at the LHC

- Simulation of the operation of Si-Pixel detectors at the LHC
  - Detectors will be cooled, temperature during operation at -7°C
  - For maintenance, detectors have to be warmed up to 20°C
  - 3 Scenarios, assuming different time duration of maintenance
- The cumulative annealing depends strongly on the duration of the various phases



RD50, G. Lindström et al.
NIM-A 465 (2001) 60-69

Evolution of Current in ATLAS Si Strip Detector

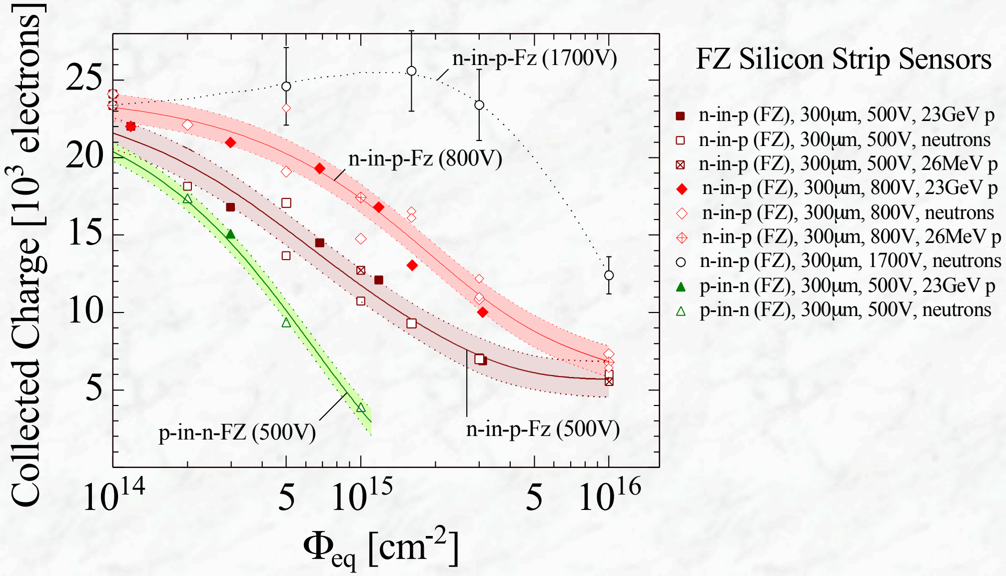


Example: ATLAS Strip Detector

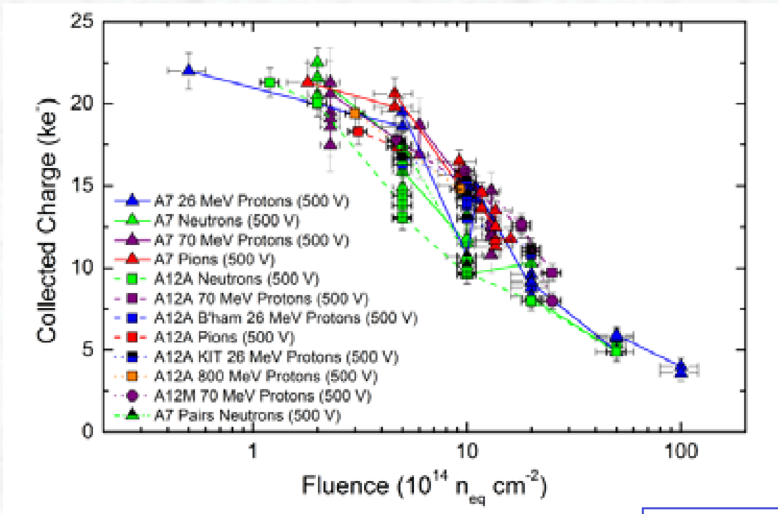
CERN-PH-EP-2014-049

Cumulated Radiation Effects

- RD50 test results for irradiated silicon strip detectors
- Signal comparison of p-in-n and n-in-p
- Signal plotted for increasing radiation dose (three bias voltage)
- P-in-n dies below 10^{15} N_{eq}
- High bias voltages give more signal for same fluence (depletion)



- ATLAS test results for irradiated P-type silicon strip detectors
- Signal plotted for increasing radiation dose (bias voltage fixed)
- Different sensors and particle types
- Signal drops globally CERN-LHCC-2015-020
- 5ke- signal still at 10^{16} N_{eq}



CERN LHCC-2015-020

Summary Radiation Damage

- Radiation damage at LHC and HL-LHC unavoidable
- **Doping** changes
  - Net effect: acceptor-production proportional to radiation dose
  - Voltage for full depletion increases with N_{eff}
  - Type inversion n -> p, depletion on the „wrong“ side
    - for HL-LHC silicon with p-doping
- **Leakage current** increases strongly (HL-LHC: factor~10^3). Problems:
  - Higher noise (with $\sqrt{I}$)
  - Heat produced increases with I_{bias} and U_{bias} (has to mitigated by cooling)
- **Trapping**
  - Charge carriers are trapped -> lower signal. Holes are affected more strongly than electrons.