R&D of silicon detectors for HEP experiments

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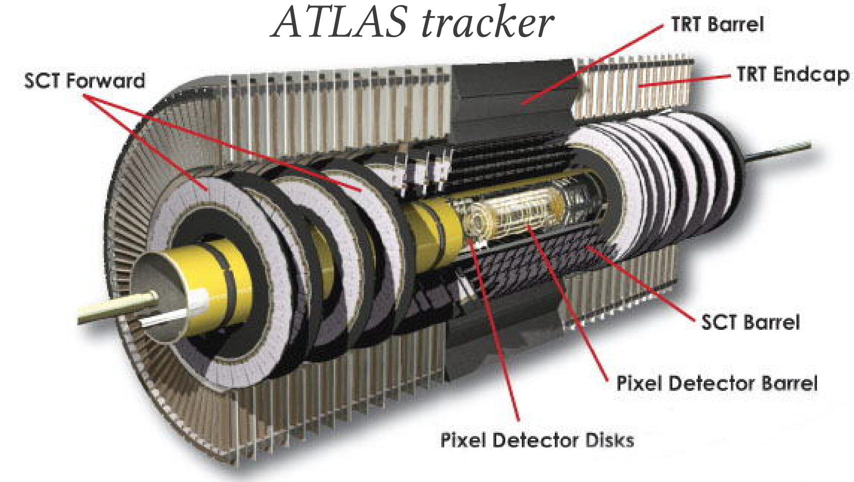
Introduction

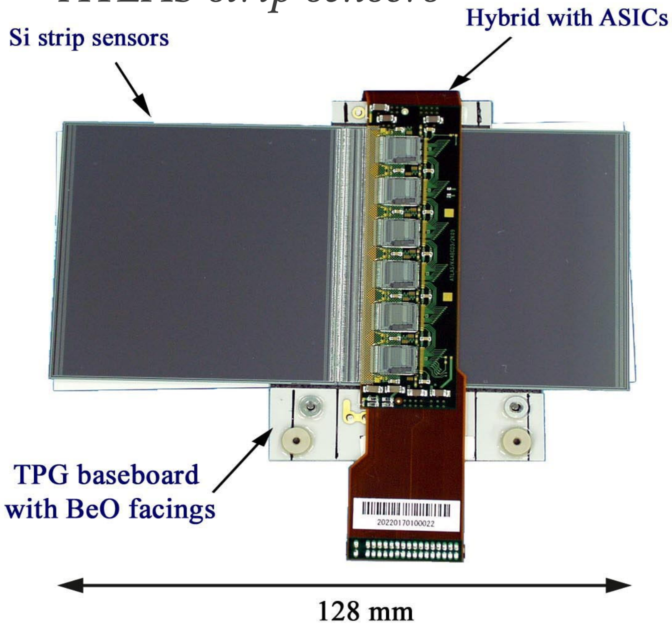
Segmented Si detectors in HEP:

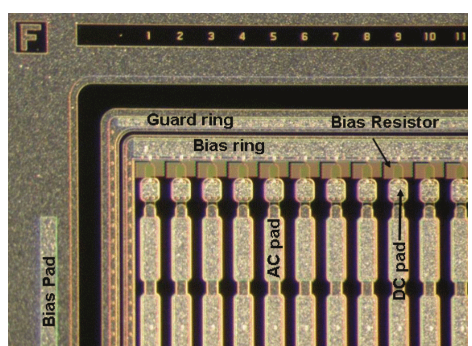
- Used for ~ 30 years
- Fundamental part of modern HEP experiments (ATLAS, CMS.. at LHC)
- Fast signal formation times, superior spatial resolution → accurate measurement of charged particle momentum in magnetic field
- Favorite choice for tracker (**Strip**) and vertex (**Pixel**) detectors → positioned close to interaction point → radiation damage (CERN RD50 collaboration)

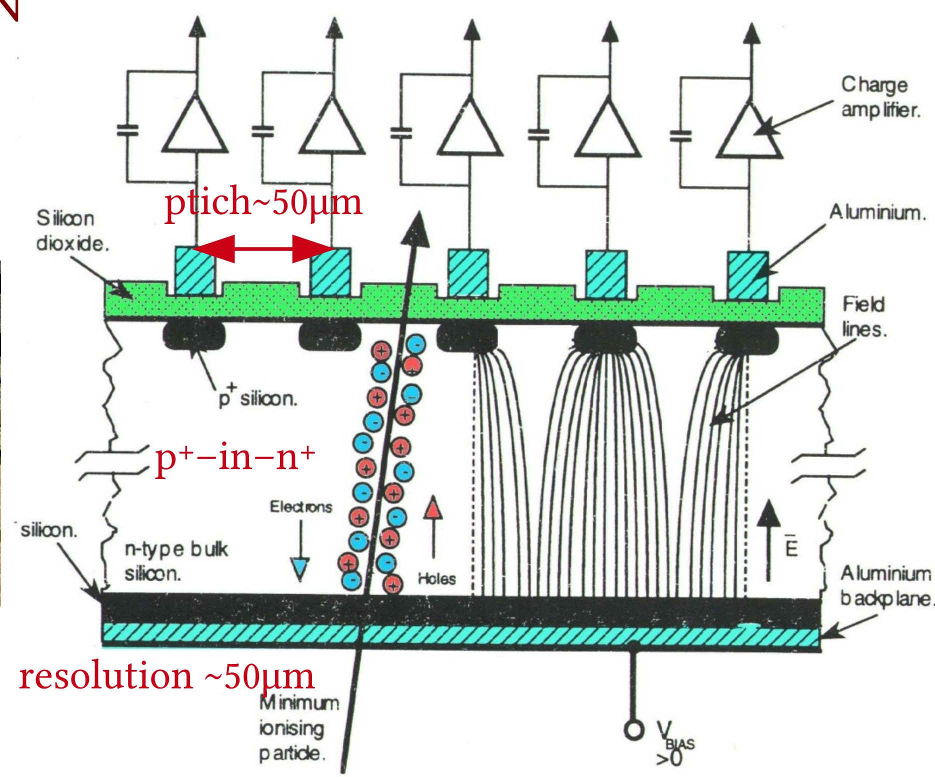
ATLAS tracker



ATLAS strip sensors

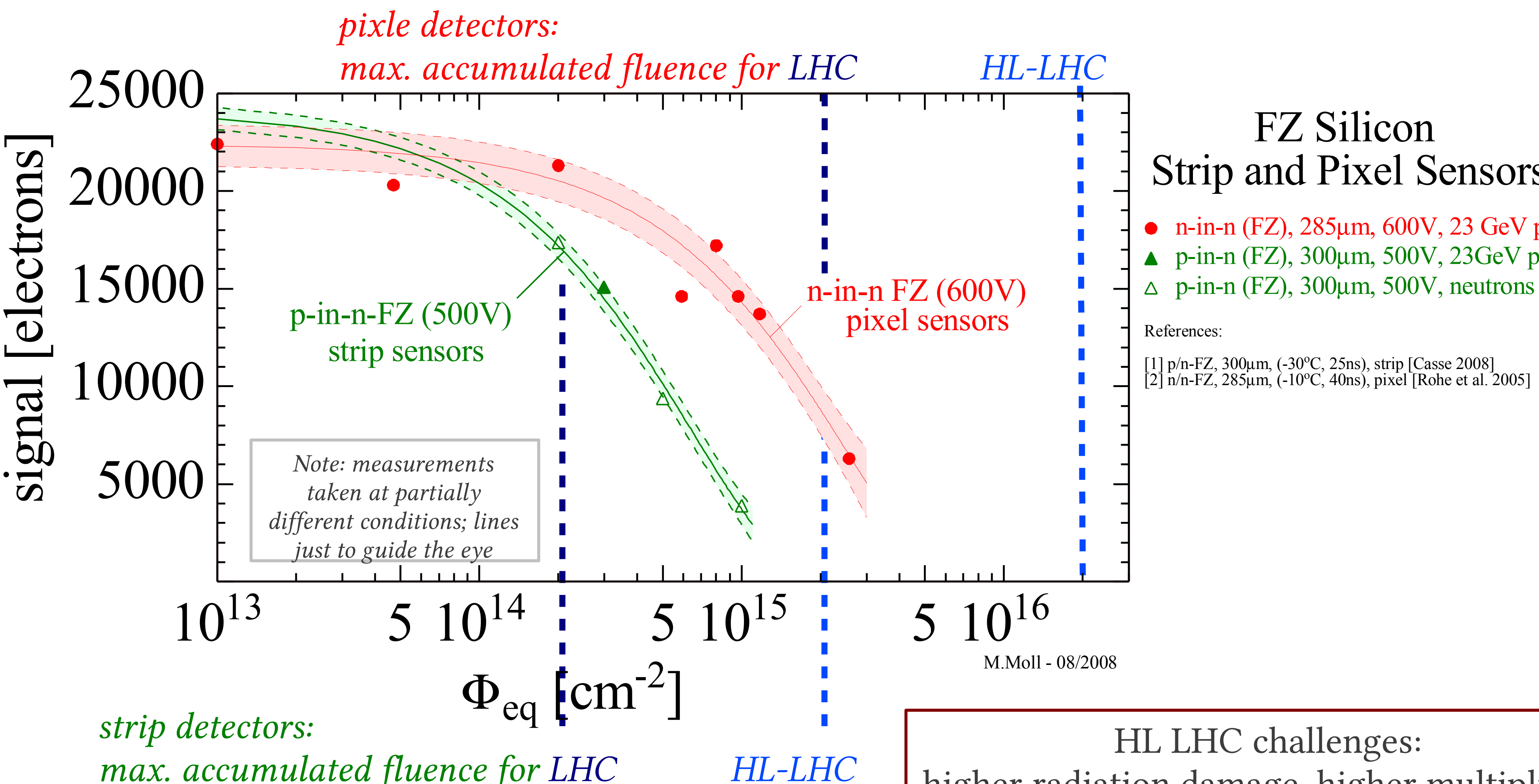






LHC: signal degradation

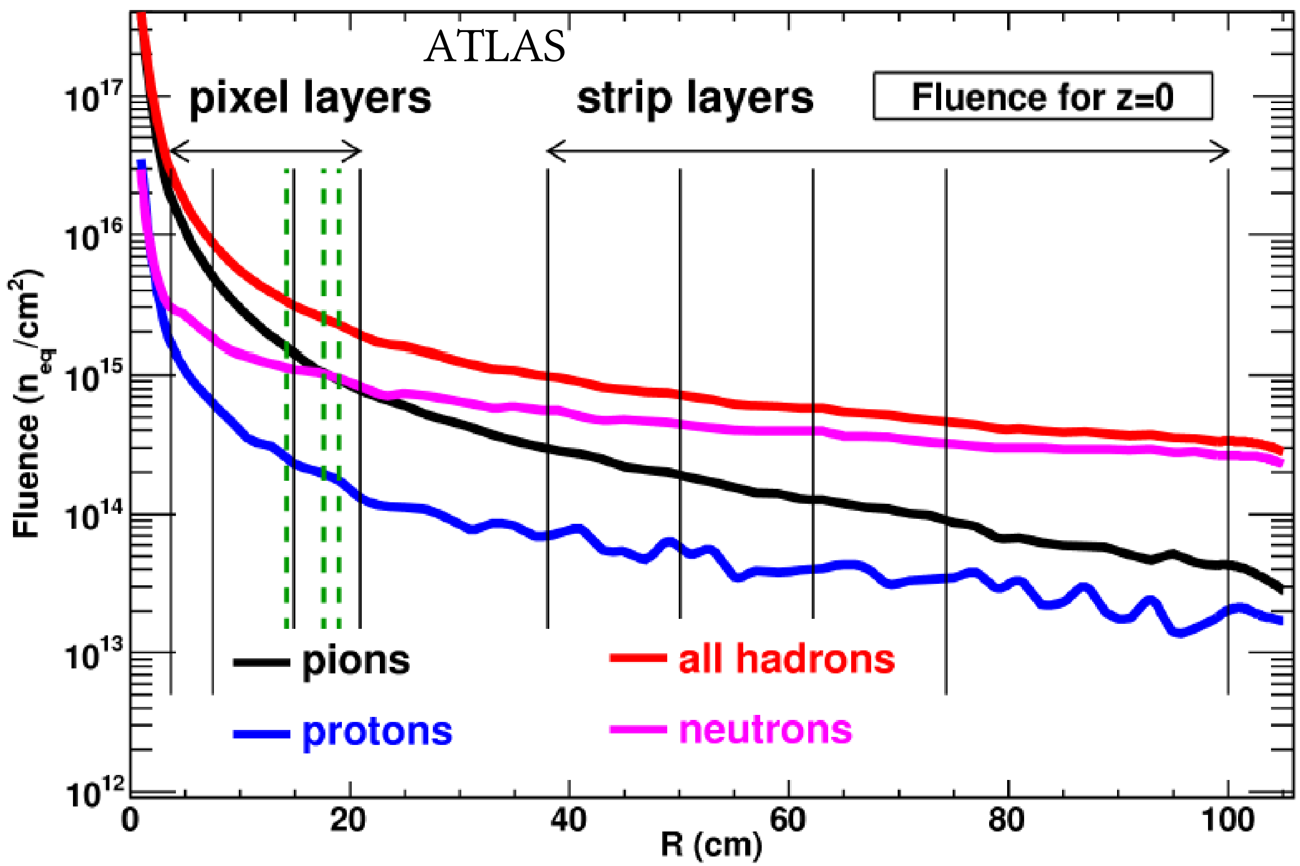
- LHC: L~10^{34}cm^{-2}s^{-1}, expected to accumulate ~350fb^{-1}
- High Luminosity (HL) LHC: L=5×10^{34}cm^{-2}s^{-1}, aiming to accumulate 3000fb^{-1} , planned for ~2022



HL LHC challenges:
higher radiation damage, higher multiplicity,
triggering, connectivity, cooling, powering

HL LHC: radiation field

- **Pixel detector:**
  pion radiation damage dominating (neutrons ~10%)
- **Strip detector:**
  damage mostly due to neutrons



ATLAS Radiation Taskforce
http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/RADIATION/RadiationTF_document.html

Radiation damage

- **Surface damage due to IEL** (Ionising Energy Loss)
  - accumulation of + charge in the oxide (SiO2) and at the Si/SiO2 interface
  - affects interstrip capacitance (noise), breakdown behavior
  - can be controlled by proper design and manufacturing process

- **Bulk damage due to NIEL** (Non Ionising Energy Loss):
  - Results in defects in crystal lattice $\longrightarrow$ new energy levels in the band gap
    - $E_{k,recoil}$>25eV: Si atom displaced out of its lattice site to form interstitial I and vacancy V (Frenkel pair), which can react with other defects to from new type of point defects (VO, V2,...)
    - $E_{k,recoil}$>5keV: cluster of displacements possible
    - nuclear reactions: resulting high energy fragments involved in the damage process
  - Comparing the damage:

    $\Phi_{\mathbf{eq}}$= equivalent fluence $\longrightarrow$ fluence of 1MeV neutrons needed to cause the same NIEL
  - NIEL scaling hypothesis: "Observed damage in Si bulk scales with energy deposited in the NIEL interactions" $\longrightarrow$ Does not hold in all cases (see later)!
  - Effects on detector performance:
    - Change of *effective dopant concentration* N_{eff} $\longrightarrow$ change in *full depletion voltage* V_{FD}
    - Increase of *leakage current* (increased noise, high power consumption)
    - Increase of *effective trapping time* (deterioration of *charge collection efficiency CCE*)

Rad-hard solid state detector development

Strategies

(1)Material engineering

(2)Detector engineering

(3)Change of detector operation

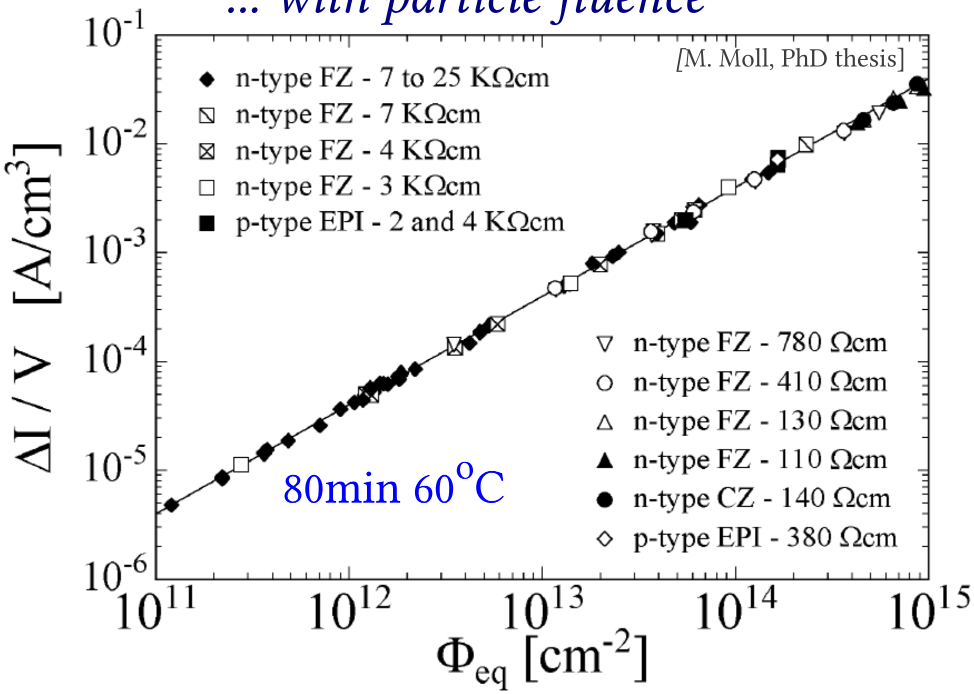
CERN RD39 collaboration
"Cryogenic Tracking Detectors"
operation at 100-200K
to reduce charge loss

- Defect engineering
  - introduction of defects, impurities in silicon bulk to improve radiation hardness
  - Example: **<u>oxygen rich silicon</u>** (MCz, Cz, EPI, DOFZ)
- New materials
  - Silicon Carbide (SiC), Gallium Nitride (GaN), Gallium Arsenide: strong rad. damage observed, no potential for HL-LHC
  - **<u>Diamond</u>** (CERN RD42 Collaboration)
- Detector engineering
  - **<u>p-type silicon detectors</u>**
  - thin detectors, epitaxial detectors
  - **<u>3D detectors</u>**
  - Monolithic devices

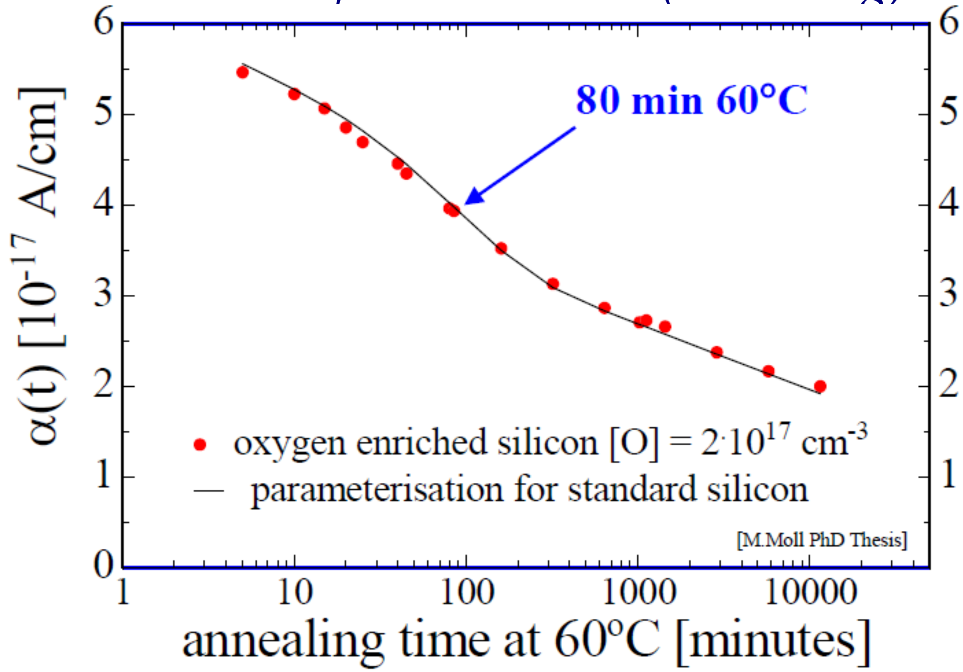
Leakage current

Change of leakage current

... with particle fluence



...with time after irradiation (annealing)



Damage parameter α:

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

- constant over several orders of fluence
- independent of Si impurity
- independent of particle type (except γ)
  ⇒ can be used for fluence measurement
- Note: NIEL scaling holds

- Leakage current decreasing with annealing
- strong temperature dependence

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

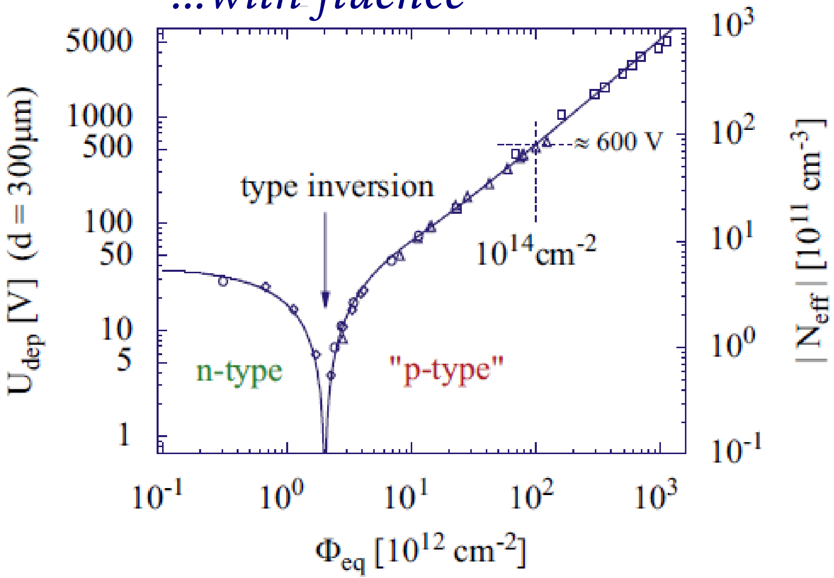
⇒ cooling during operation needed!

- Example: $I(-10°C) \sim 1/16\ I(20°C)$

Full depletion voltage

Change of V_{FD} (N_{eff}) in standard n-type FZ detectors

...with fluence



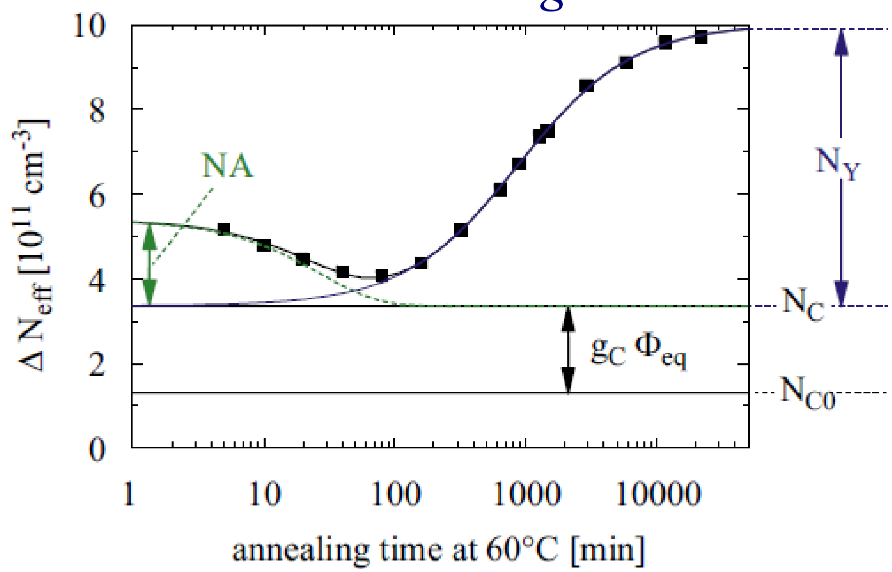
- "Type inversion": Neff changes from positive to negative (Space Charge Sign Inversion – SCSI)
- acceptor generation

$$V_{FD} = \frac{e_0 D \mid N_{eff} \mid}{2\epsilon_0 \epsilon_{Si}}$$

full depletion voltage

effective dopant concentration (space charge density)

...with annealing time



- 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)

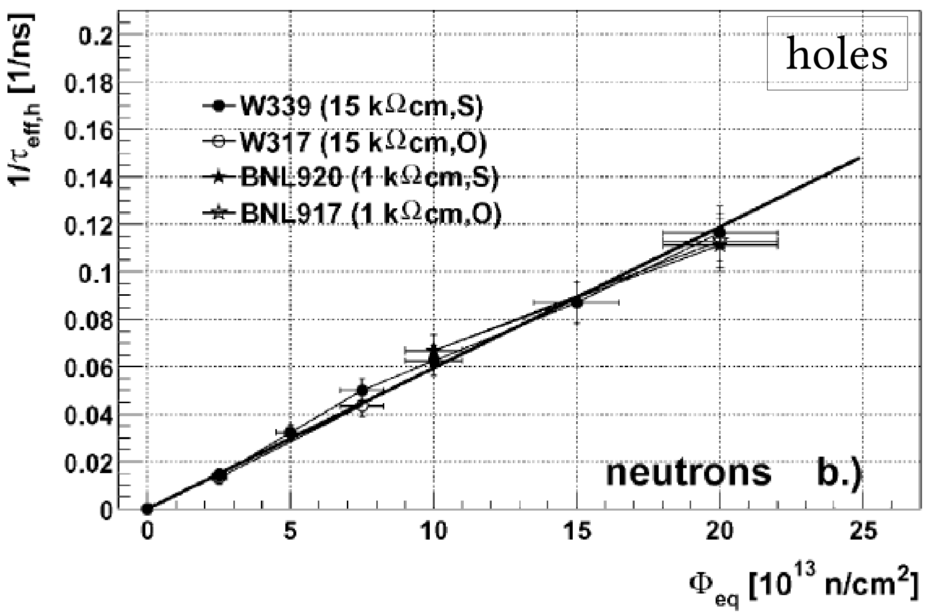
$\Rightarrow$ **Detectors must be cooled even when the experiment is not running!**

Trapping

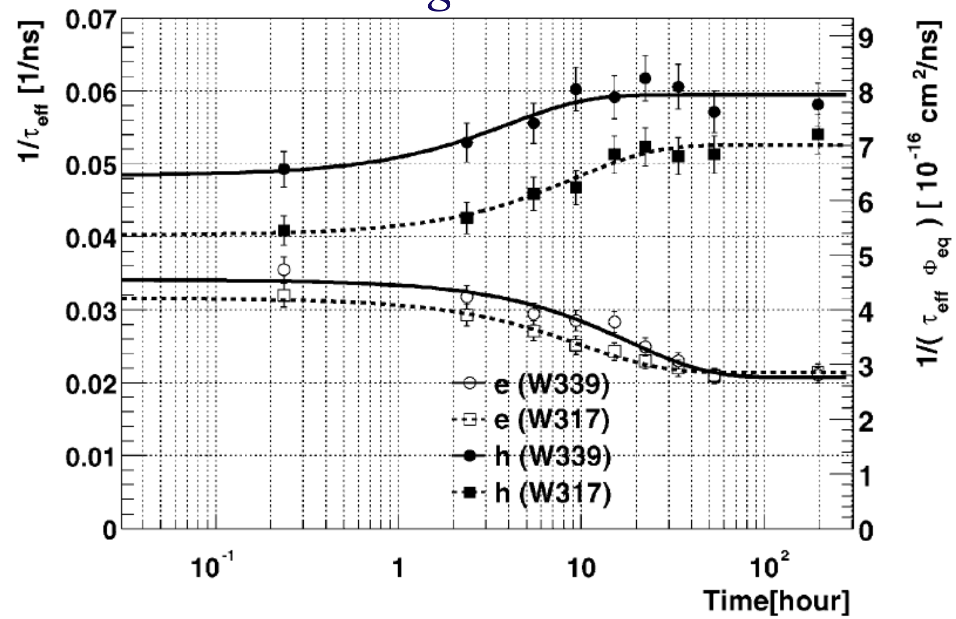
- CCE degradation due to partial depletion (**underdepletion**) and **trapping**
- Trapping is described by effective trapping probability for holes and electrons $1/\tau_{\text{eff } e,h}$

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

$1/\tau_{\text{eff } e,h}$ dependence on fluence



.... and annealing time

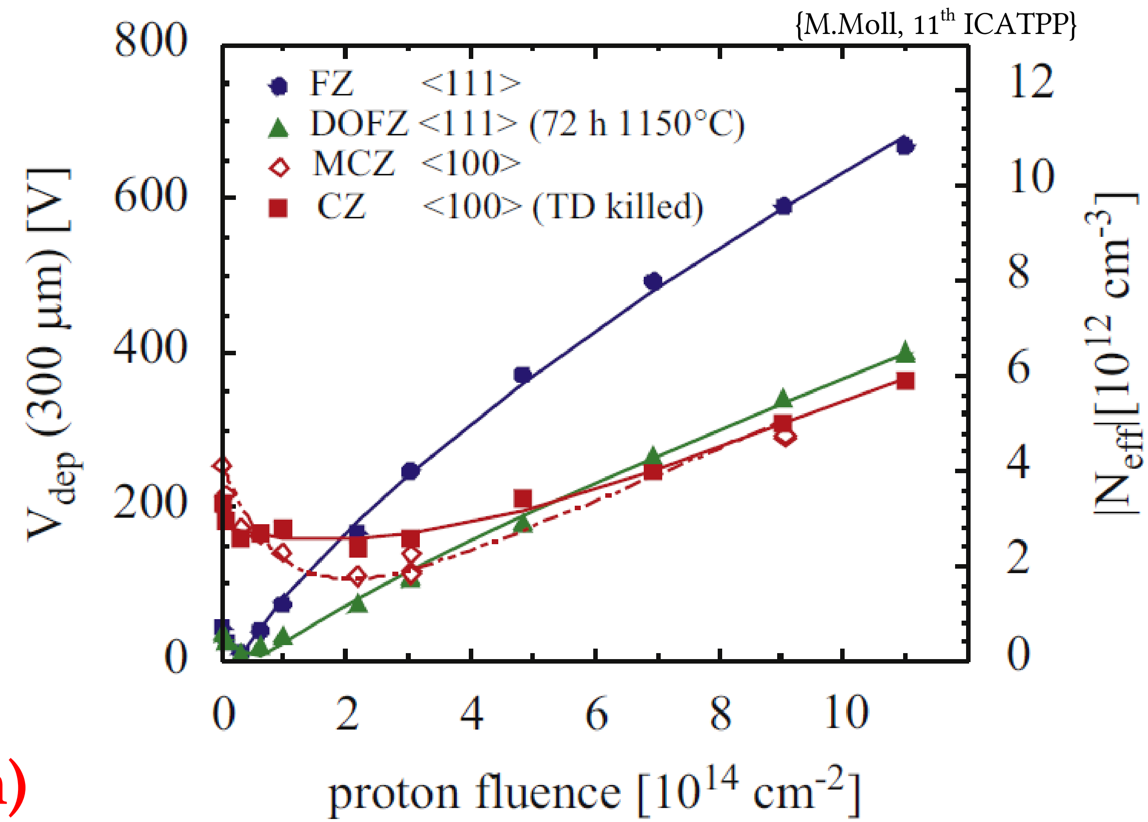


- After irradiation: trapping stronger for holes than electrons; charged hadrons induce more trapping compared to neutrons (NIEL violation)
- Common to all materials after irradiation (apart from γ): same increase of trapping (electrons and holes) within ~20%
- Annealing: increases trapping for holes, decreased for electrons

Oxygen rich Si: proton irradiation

Irradiation with 24GeV/c protons

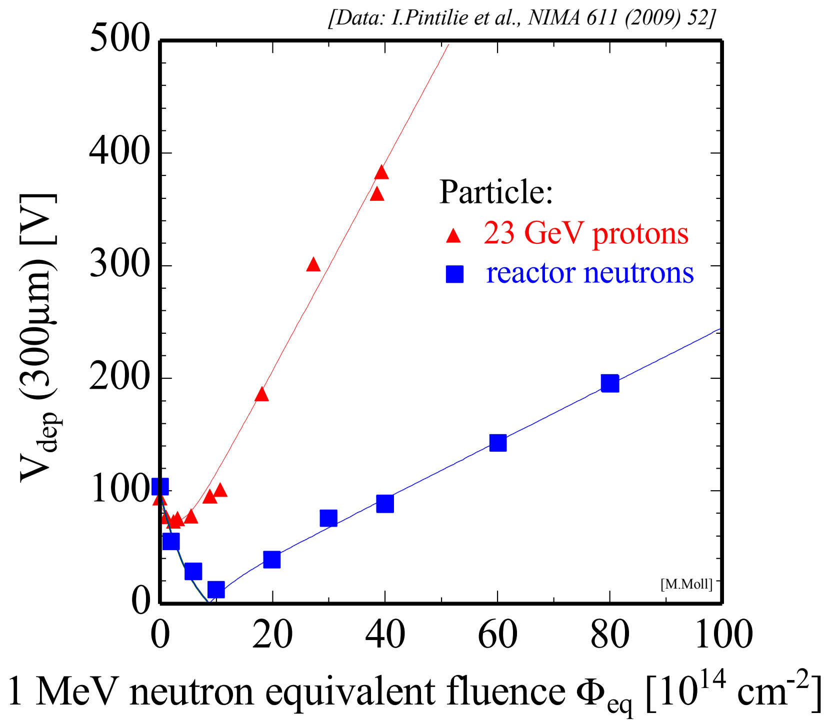
- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm2
  - strong N_{eff} increase at high fluence
- **DOFZ silicon (is oxygen rich)**
  - type inversion at ~ 2×10^{13} p/cm
  - smaller Neff increase at high fluence

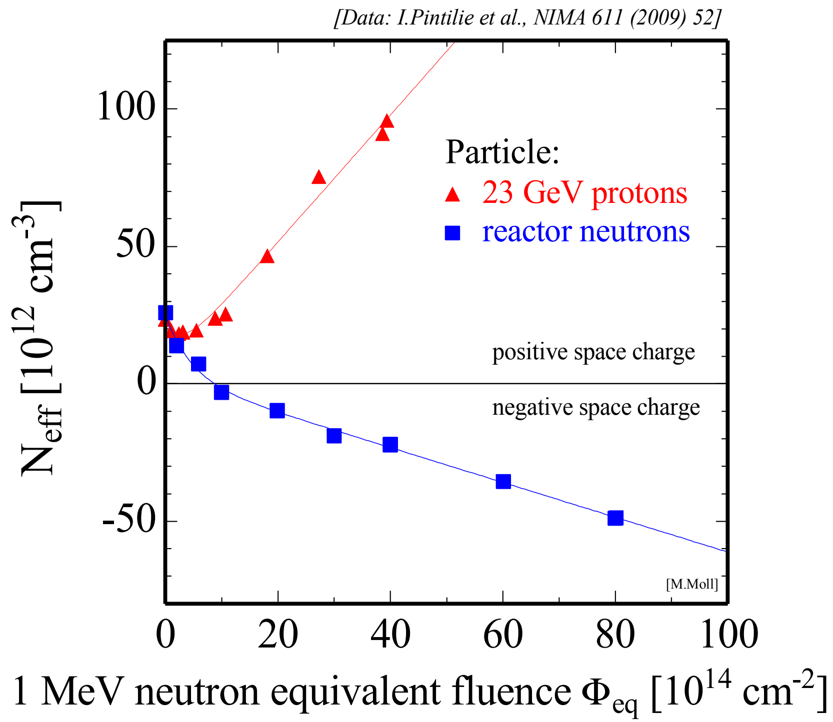


- **Cz, MCz silicon (is oxygen rich)**
  - "no type inversion" in the overall fluence range
  - *Comment: there is no "real" type inversion, a more clear understanding of the observed effects is obtained by investigating directly the internal electric field; look for ("double junction" effects, see later)*

Oxygen rich Si: neutron vs. proton irradiation

EPI silicon (EPI-DO, 72µm, 170Ωcm) irradiated with 24GeV/c protons and reactor neutrons



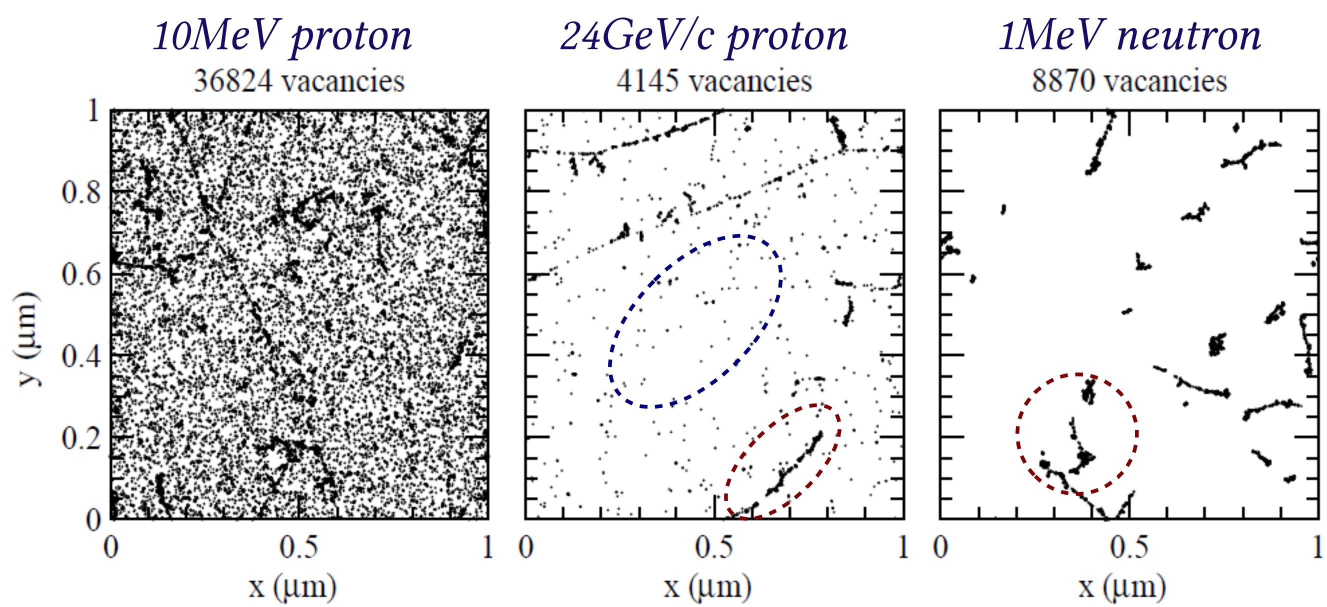


- SCSI ("Type Inversion") after neutrons but not after protons
- Acceptor generation after neutron irradiation (as in standard FZ)
- Donor generation enhanced after proton irradiation (only in oxygen rich Si)

Why the difference in proton and neutron damage?

- **Clusters vs. Point defects**:
  - Charged hadrons create less point defects with increasing energy
  - At given particle energy, neutrons create more clusters then protons

Initial distribution of vacancies after incidence of 10^{14}particles/cm^2
[Mika Huhtinen NIMA 491(2002) 194]

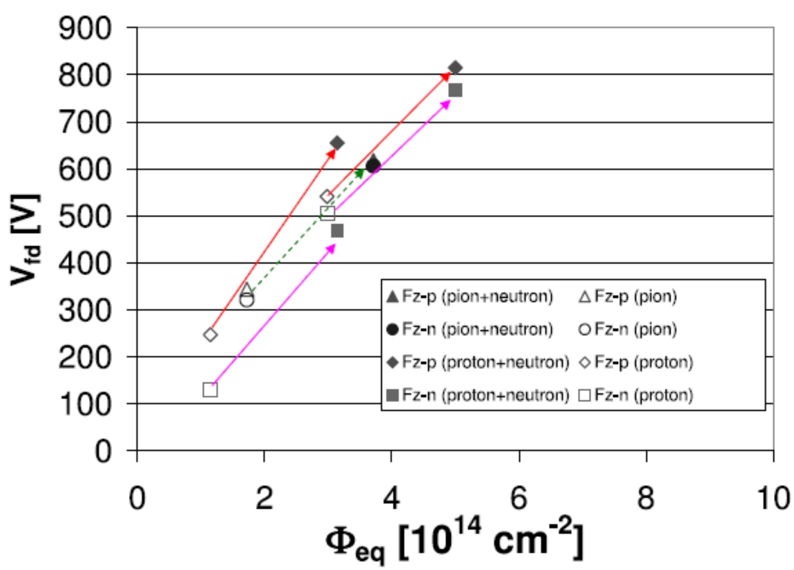


- **A 'simplified' explanation for difference between proton and neutron damage**:
  - Defect clusters produce predominantly negative space charge – acceptors
  - Point defects produce predominantly positive space charge – donors (in 'oxygen rich' silicon)
- Comment: note NIEL violation

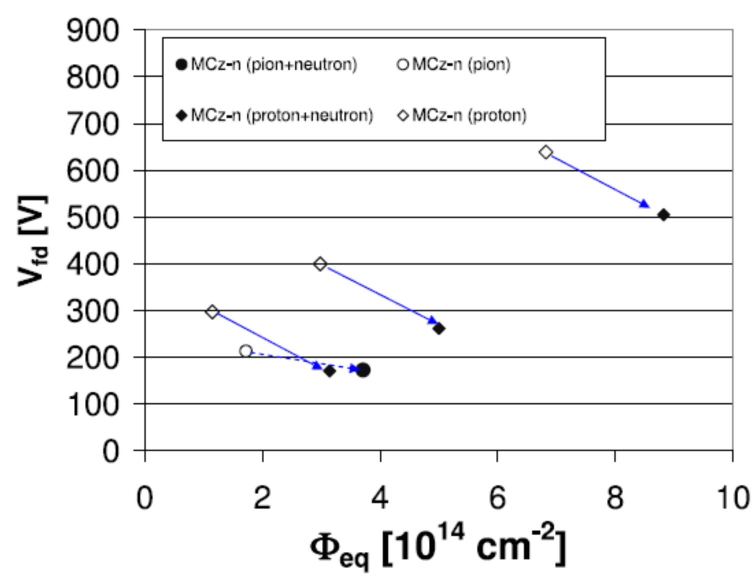
Oxygen rich Si: mixed irradiations

- MCz and Fz n-type devices exposed to mixed irradiations:
  - step 1: proton (or pion) irradiation
  - step 2: neutron irradiation
- Result: damage additive! Can we profit from that in real experiment?

FZ-n (low O concentration)
accumulation of damage



MCz-n (high O concentartion)
compensation of damage

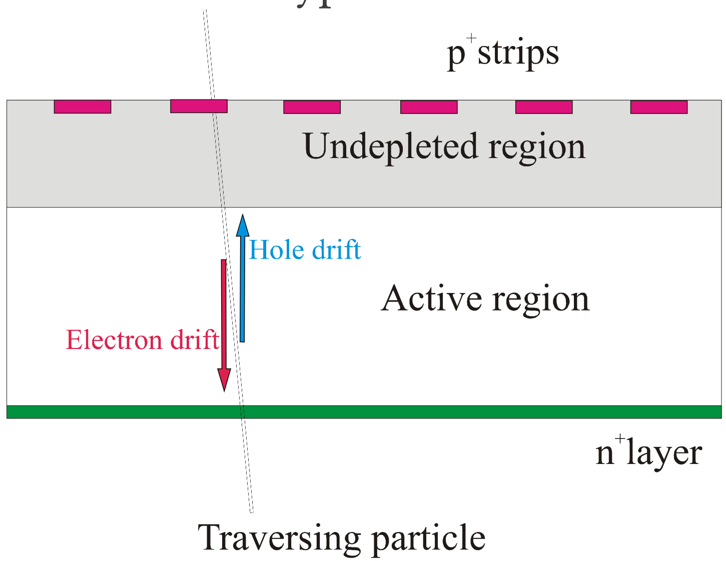


[G.Kramberger et al.,
NIMA, 609 (2009), p142]

Device engineering: p-type devices

p^+-n detector

n-type silicon after high fluence
"type inversion"



- High el. field region on the back (non-segmented side)
- Underdepleted
  - charge spread (resolution deterioration)
  - charge loss (CCE deterioration)

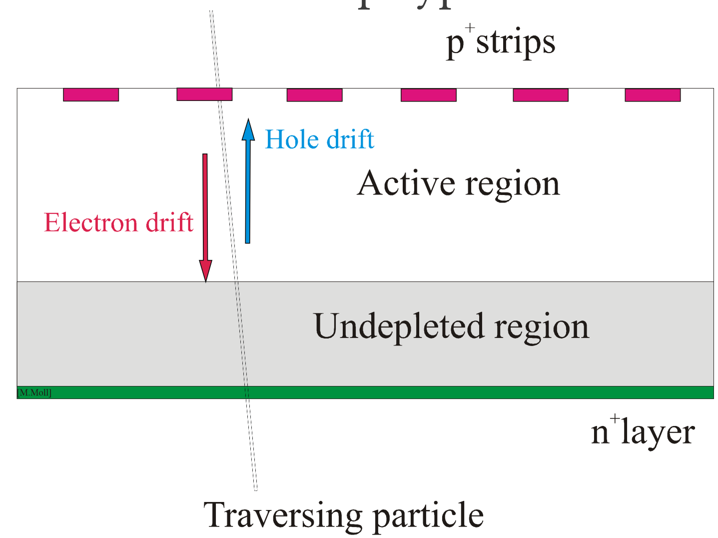
Comment:

✗ *this is just a schematic explanation, reality is much more complex (see next slide)*

✗ *Instead of n-on-p also n-on-n devices could be used*

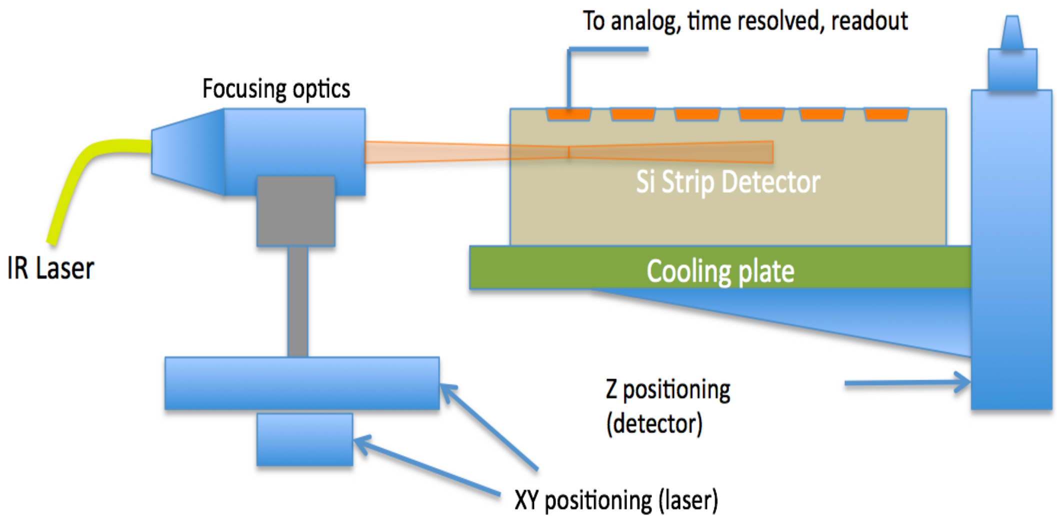
n^+-p detector

p-type silicon after high fluence
still p-type



- High el. field region stays on the front (segmented side ⟶ weighting and real field stay aligned)
- Limited loss of CCE, less deterioration with underdeplition
- Limited deterioration of resolution
- Collecting electrons (3-times faster than holes)

Determination of electric field



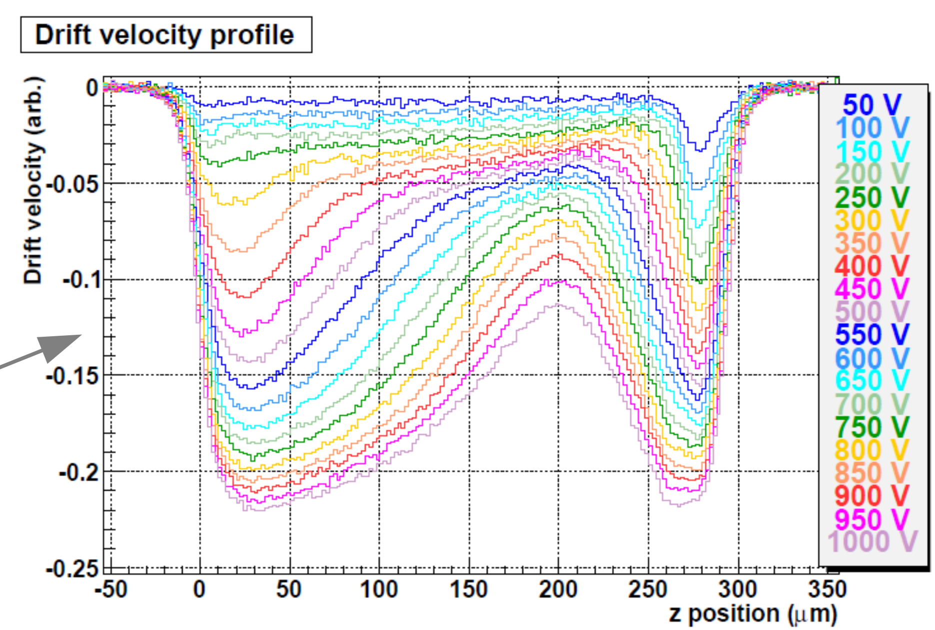
Edge-TCT (transient current technique)

- Technique pioneered by Gregor Kramberger, Ljubljana [1]
- Sensor (strip detector) is illuminated with pulsed IR laser from the side, light focused under one of the strips
- Scan across detector thickness and record induced current signal waveforms as function of depth
- Reconstruction of drift velocity electric field, detector efficiency (also trapping probability ?) profile across the detector thickness

[1] G. Kramberger et al., IEEE TNS, vol. 57, no. 4, August 2010, p 2294

Highly irradiated detectors:

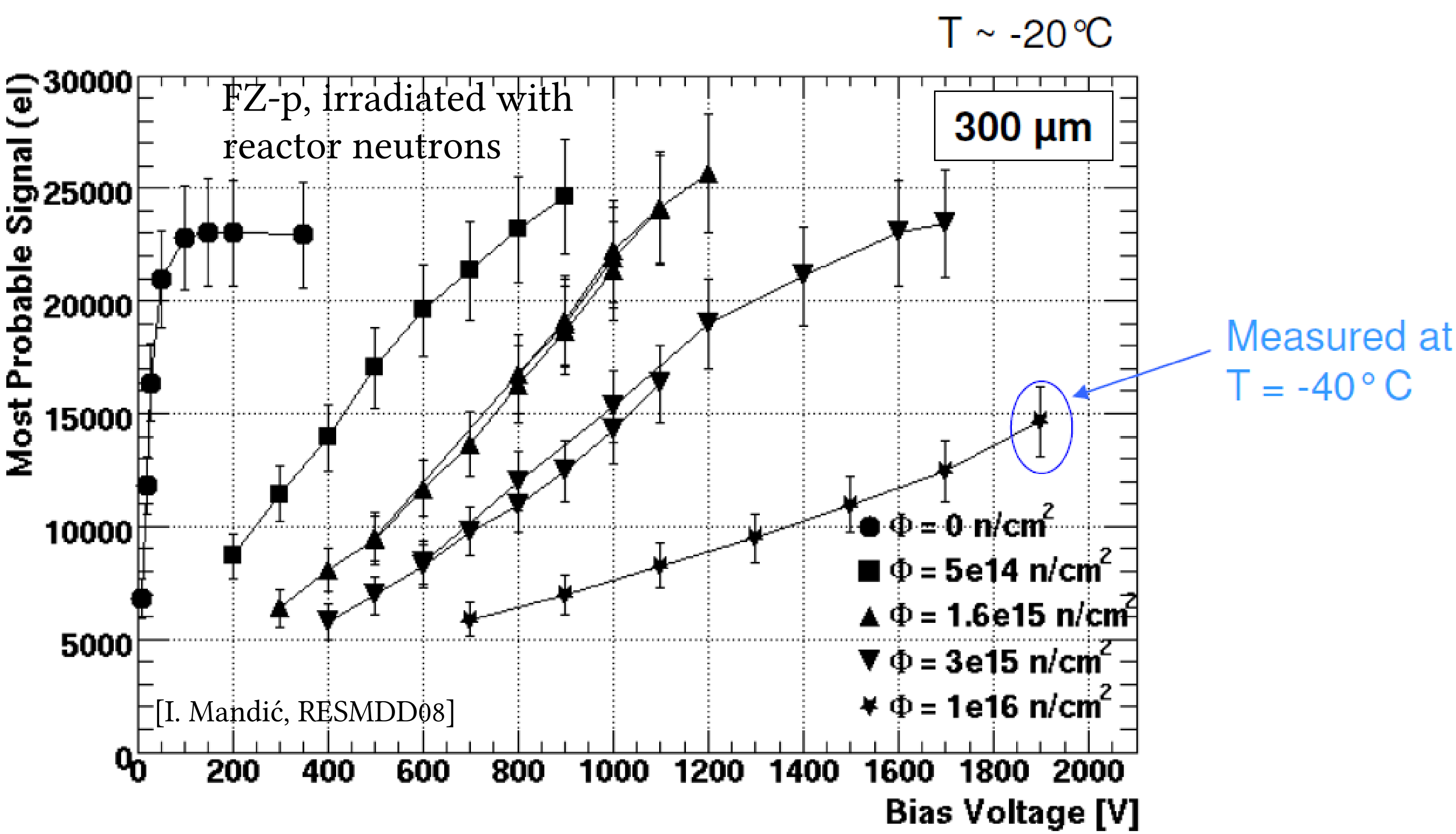
- "Double junction" form of electric field can be observed: field peak both on the back and front
- Example of drift velocity profile in: MCz-p, irradiated with 24GeV/c protons ($\Phi_{eq}=6.2\times10^{15}n_{eq}/cm^2$)



p-type devices: CM

CCE measurements of irradiated FZ p-type strip devices

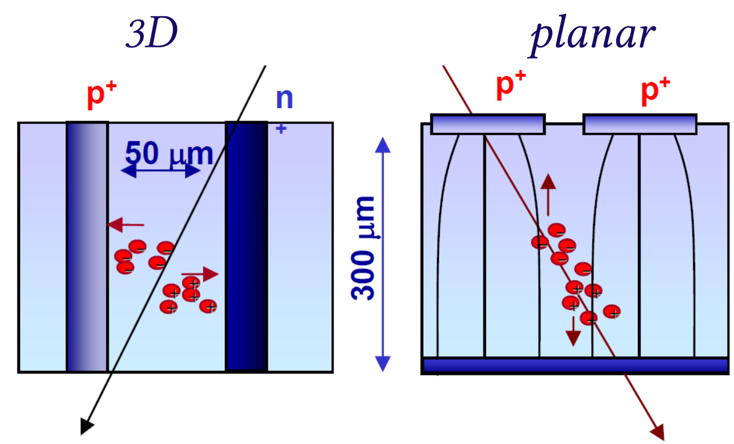
- 100% CCE observed even after 3×10^{15} n/cm2, also even CCE > 100% was observed
- Extrapolation of charge trapping parameters obtained at lower fluences would predict much lower signal
- Origin: 'Charge multiplication effects' due to high electric fields close to the strips

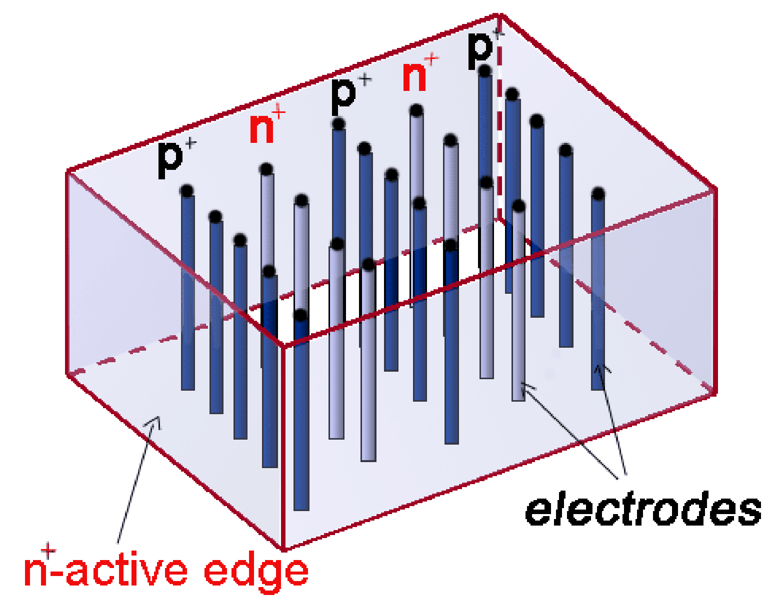


Device engineering: 3D Si sensors

- Electrodes:
  - narrow columns along detector thickness,
  - diameter: 10mm, distance: 50 – 100mm
- Lateral depletion:
  - lower depletion voltage needed
  - thicker detectors possible
  - fast signal
  - radiation hard (short drift path minimizes the trapping)

- promising results
- processing of 3D sensors challenging, though many good devices with reasonable production yield produced
- main drawback is the resulting high channel capacitance
- 3D sensors will be part of ATLAS IBL detector!





first proposed by S.I. Parker et al. [NIMA 395(1997) 328]

New materials: diamond

Property	diamond	Si
Band gap [eV]	5.5	1.12
Intrinsic resistivity @ RT [Ωcm]	$>10^{11}$	2.3×10^{5}
e(h) mobility [cm^2/Vs]	1900 (2300)	1350(480)
e(h) sat. velocity [cm/s]	$1.3(1.7)\times10^{5}$	$1.1(0.8)\times10^{5}$
Dielectric constant	5.7	11.9
Displacement energy [eV/atom]	43	13-20
Thermal conductivity [W/m K]	~2000	150
Energy to create e-h pair [eV]	13	3.61
MIP Ionization loss [Mev/cm]	4.7	3.21
Avrg. MIP signal/100μm [e_0]	3602	8892

⇒ low leakage current (low noise, no cooling)

⇒ fast signal

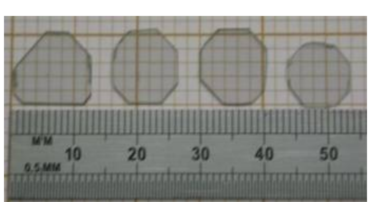
⇒ low capacitance

⇒ radiation hard

⇒ heat spreader

⇒ low signal

poly-CVD (16 chip ATLAS pixel module)



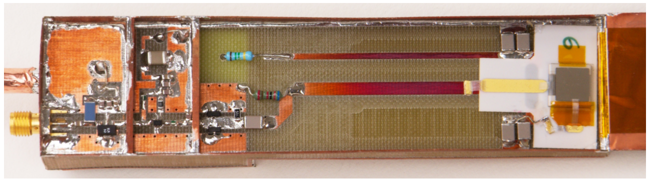
single crystal CVD diamond (few cm)

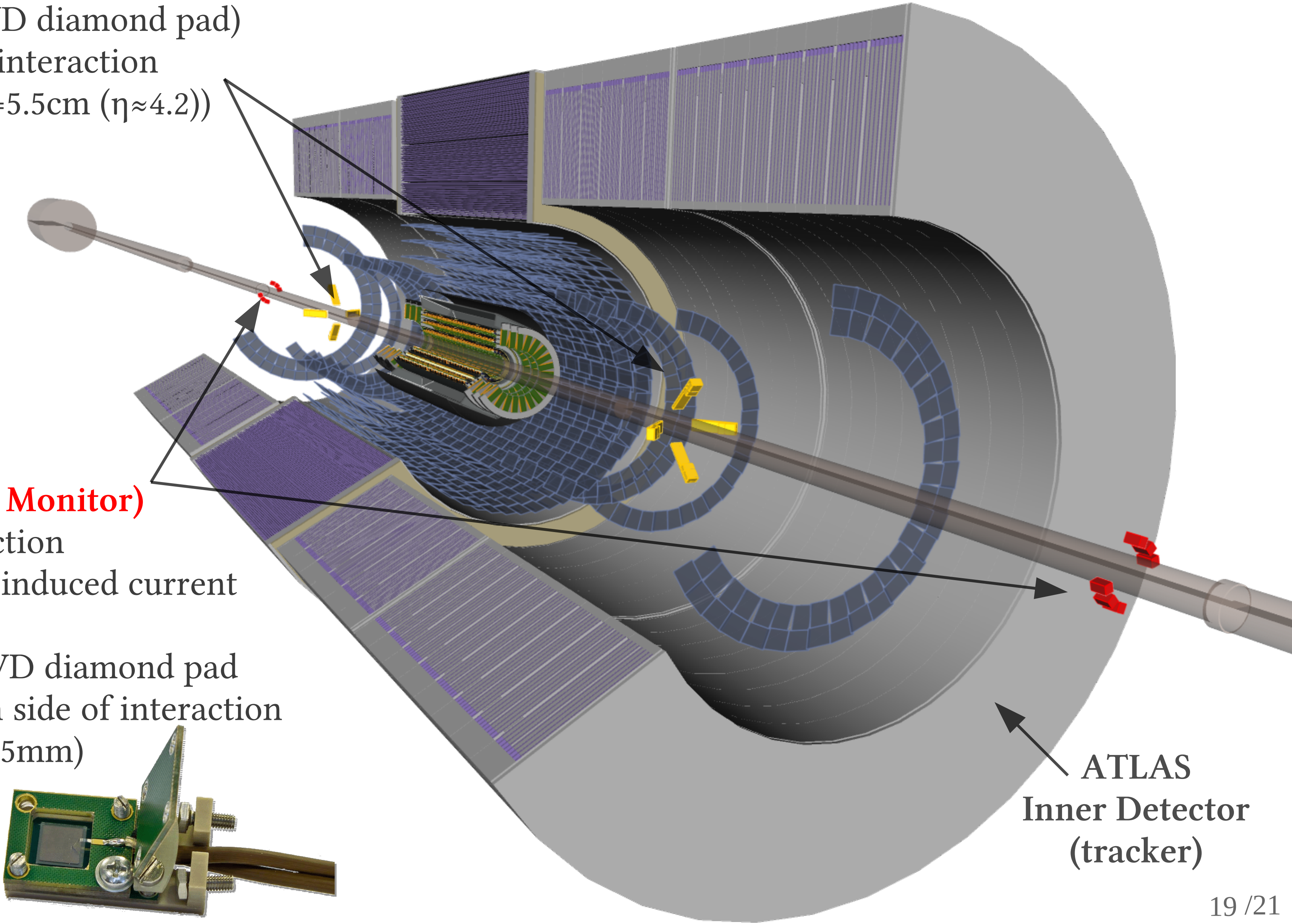
Diamond sensors heavily used in LHC experiments for Beam Monitoring

ATLAS: BCM and BLM

BCM (Beam Conditions Monitor)

- purpose: protection, luminosity
- based on TOF measurement
- 4 modules (pCVD diamond pad) on each side of interaction ($z = \pm 183.8$cm, $r = 5.5$cm ($\eta \approx 4.2$))





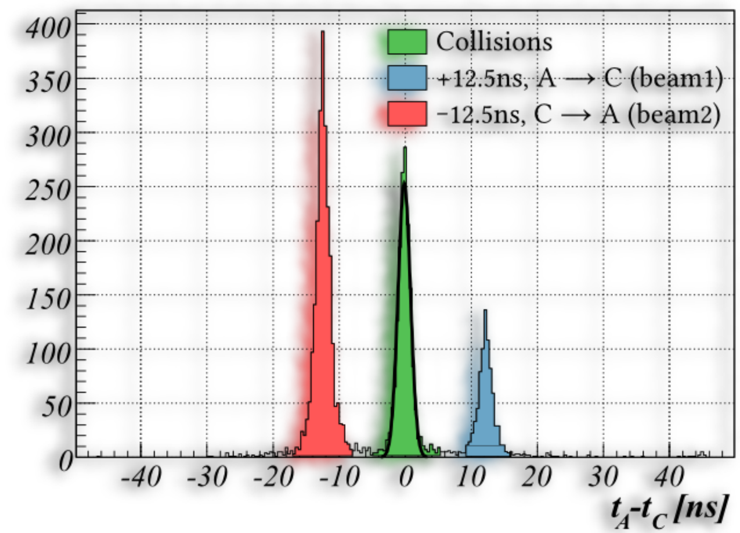
BLM (Beam Loss Monitor)

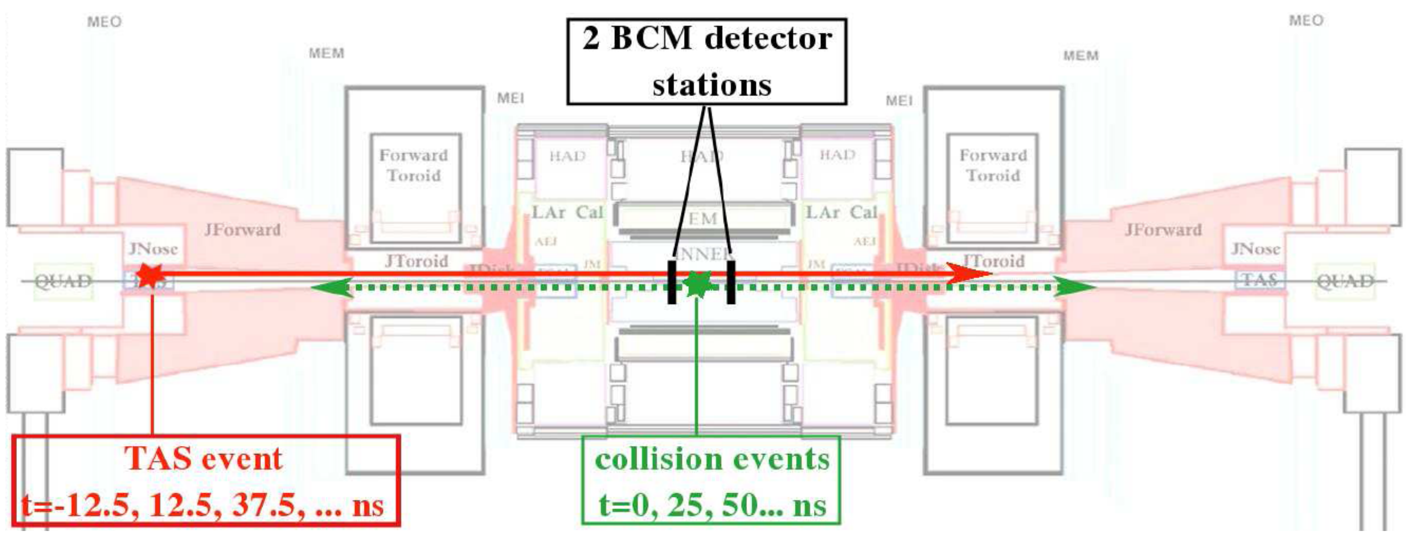
- purpose: protection
- based on beam induced current measurement
- 6 modules (pCVD diamond pad sensor) on each side of interaction (z~3450mm, r~65mm)

ATLAS BCM: principle of operation

Time of flight measurement to distinguish between collisions and background events (beam – gas, halo, TAS scraping)

- measurement every proton bunch crossing (25ns)
- 2 detector stations at z=±1.9m
- particles from collisions reach both stations at the same time (~6ns after collisions)
- secondary particles from downstream background interactions reach nearest station 12.5ns before particles from collisions (~6 ns before collisions)
- use coincident "in time hits" to monitor luminosity
- use "out of time hits" to identify background events





Requirements:

- fast and radiation hard detector & electronics:
  - rise time ~1ns
  - pulse width ~3ns
  - baseline restoration ~10ns
  - ionization dose ~0.5 MGy,
  - 10^{15}particles/cm2 in 10 years
- MIP sensitivity

Sensors for HL-LHC

Fluences $\Phi_{eq} < 10^{15}cm^{-2}$ (outer layers – strip sensors)

- **Underdepletion** is dominant cause for CCE degradation
- **n-MCz silicon detectors**: good performance in mixed fields due to compensation of charged hadron and neutron damage (more work needed)
- **p-type Si microstrip detectors**: encouraging results (“base line option” for the ATLAS SCT upgrade)

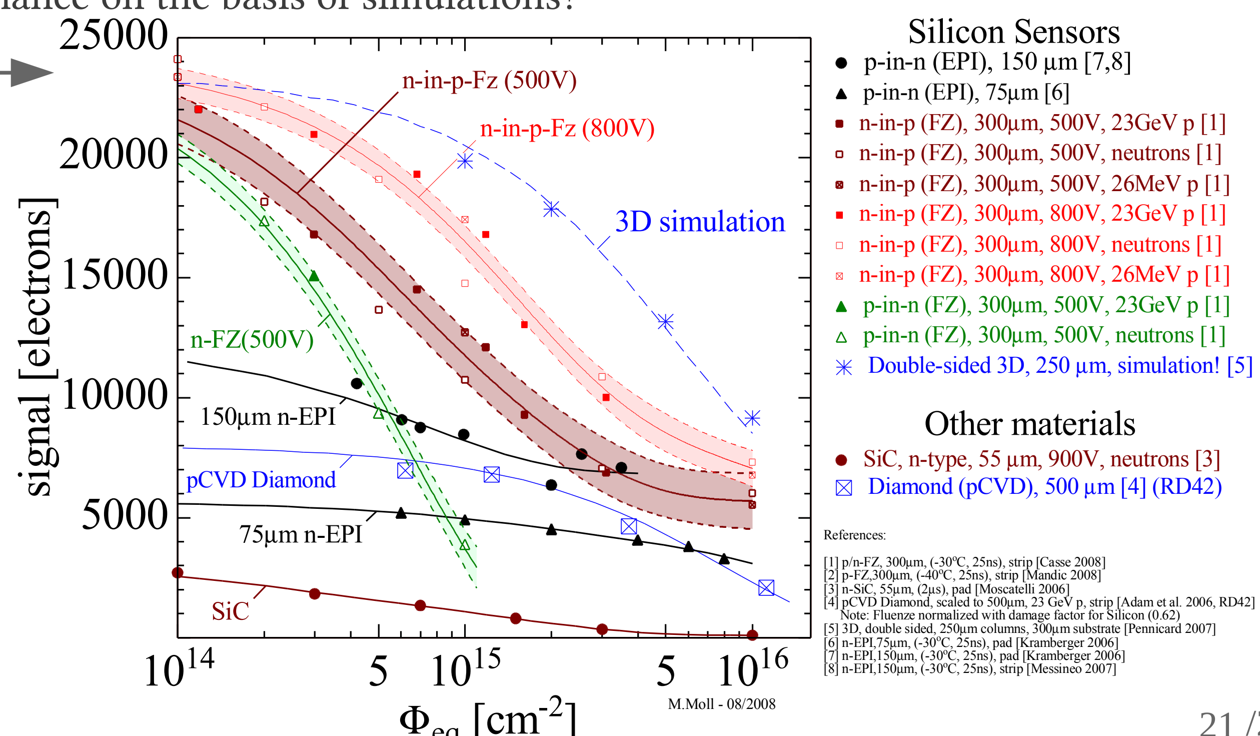
Fluences $\Phi_{eq} > 10^{15}cm^{-2}$ (innermost tracking layers – pixel sensors)

- CCE degradation mostly due to **trapping** -> active thickness is significantly reduced
- Collection of electrons at electrodes essential: Use n-on-p or n-on-n detectors!
- Presently three options under investigation: **planar Si (thin, p-type), 3D Si, Diamond**

Questions to explore:

- Can we control multiplication effects in order to profit from them?
- Can we profit from compensation effects in mixed fields (i.e. MCz-n)?
- Can we understand detector performance on the basis of simulations?

A comparison of technologies in terms of collected charge (signal) →



Note:
- *measurement at partly different conditions...*
- *only an indication of what could be used*
- *for spcific applications SNR crucial! (also important: efficiency, availability, price,reliability, cooling, track resolution...*