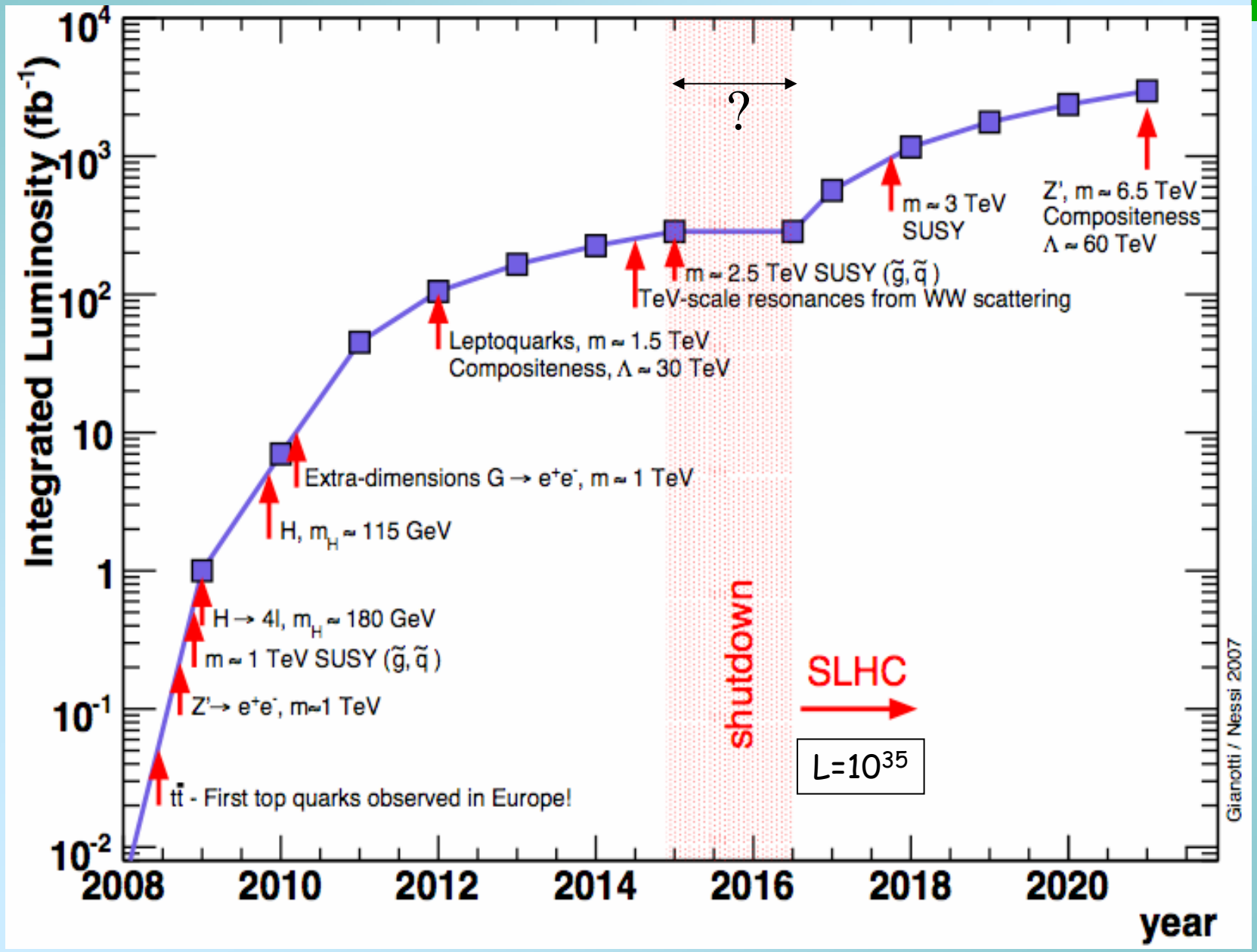
Development of Radiation Hard Tracking Detectors

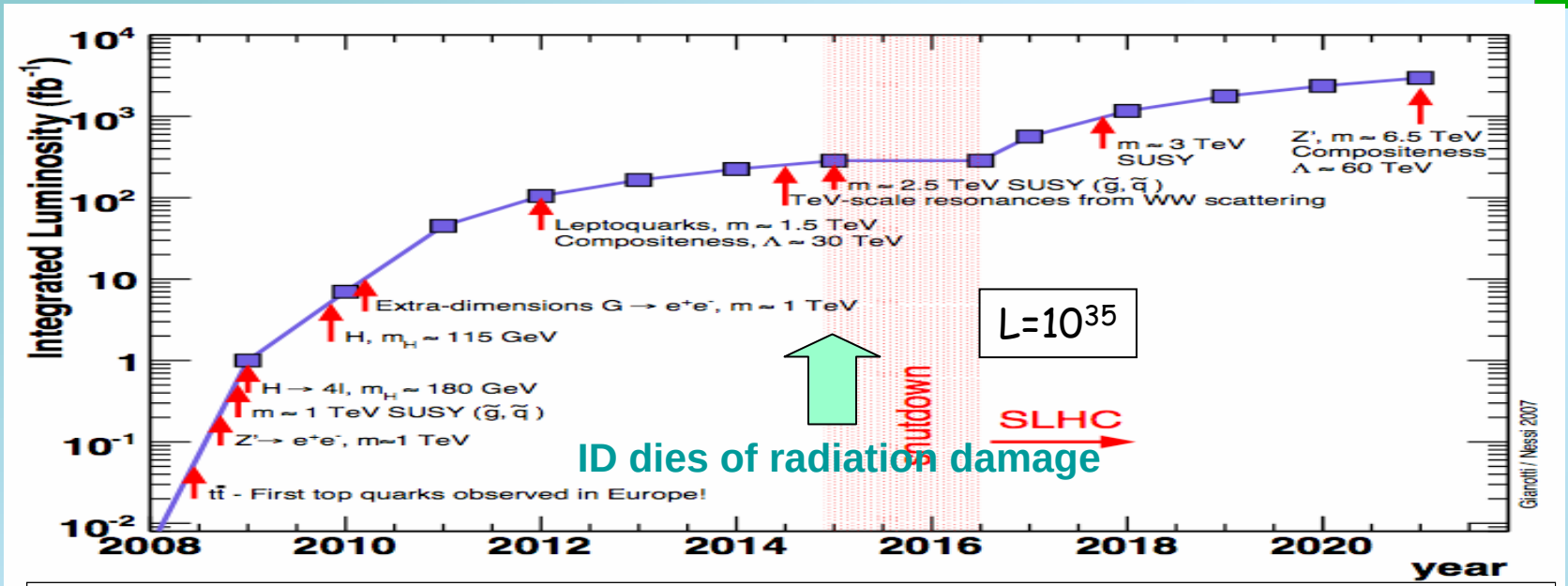
1) LHC Upgrade environment
2) New tracker materials?
3) Radiation damage in Si
    a) Effects
    b) Present microscopic interpretation
4) Bias Dependence of collected charge
5) Thin sensors and Pixel sensors

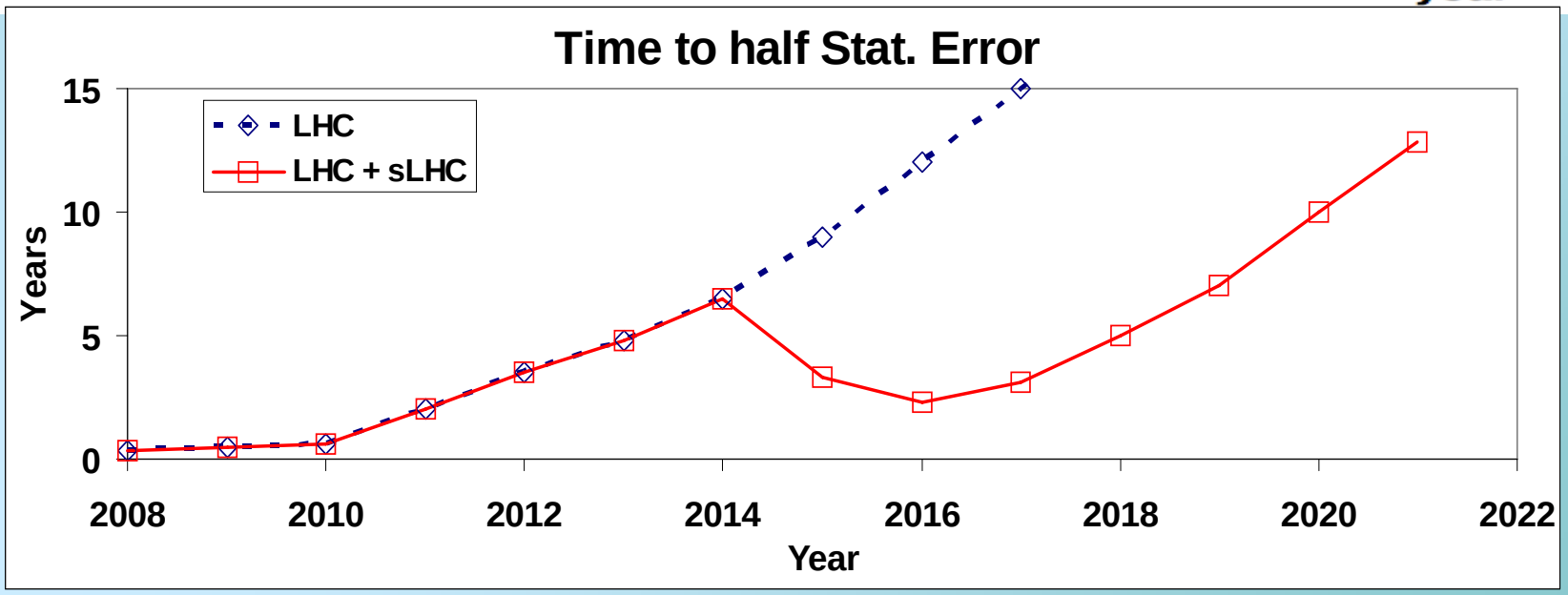
Hartmut F.-W. Sadrozinski,
SCIPP UC Santa Cruz, 1156 High Street, 95064 CA, USA

LHC vs time: a wild guess …



Need to Upgrade





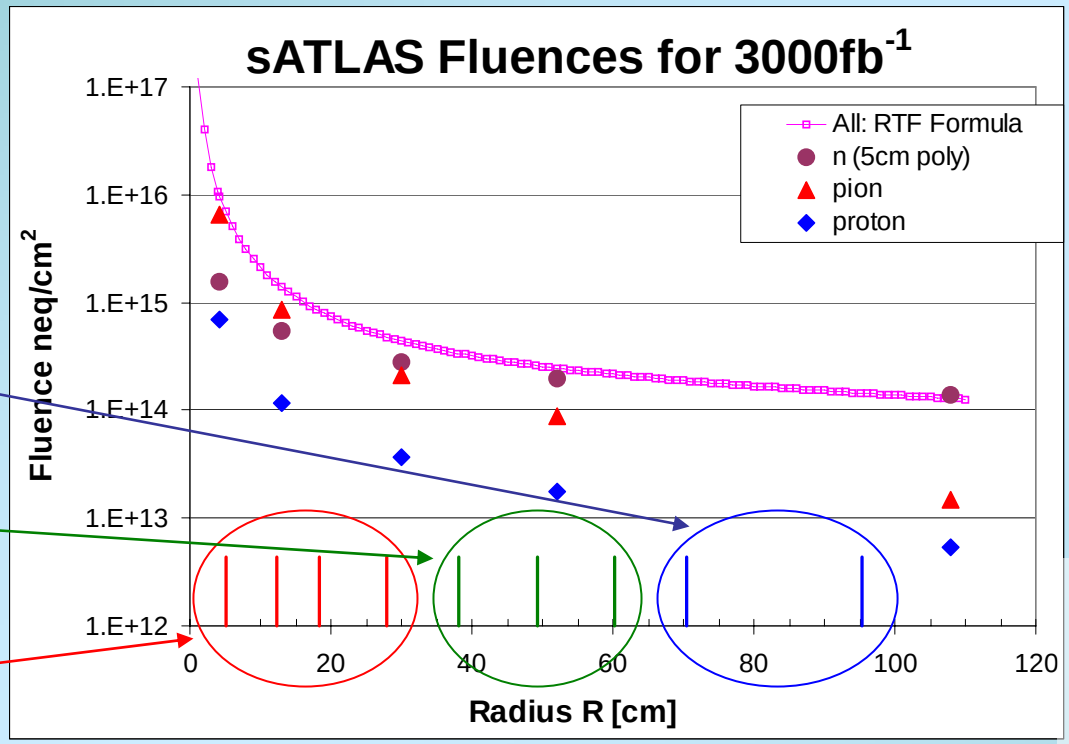
Fluence in Proposed sATLAS Tracker

Radial Distribution of Sensors determined by Occupancy < 2%

Long Strips

Short Strips

Pixels



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

5 - 10 x LHC Fluence

Mix of n, p, π depending on radius R

Strips damage largely due to neutrons

Pixels Damage due to neutrons+pions

Design fluences for sensors (includes 2x safety factor) **:**

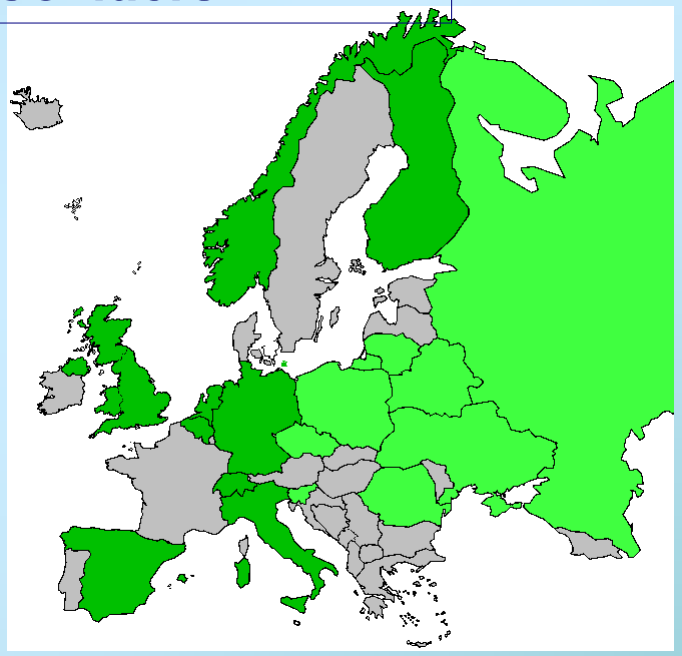
Innermost Pixel Layer:	$1*10^{16}$ neq/cm^2
Outert Pixel Layers:	$3*10^{15}$ neq/cm^2
Short strips:	$1*10^{15}$ neq/cm^2
Long strips:	$4*10^{14}$ neq/cm^2

RD50 – CERN R&D Collaboration

"Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders"

SCIPP

Started in 2002, now 261 Members from 50 Institutes



42 European and Asian institutes

Belarus (Minsk), **Belgium** (Louvain), **Czech Republic** (Prague (3x)), **Finland** (Helsinki) , Laappeenranta), **Germany** (Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe, Munich), **Israel** (Tel Aviv), **Italy** (Bari, Bologna, Florence, Padova, Perugia, Pisa, Torino, Trento), **Lithuania** (Vilnius), **Netherlands** (NIKHEF), **Norway** (Oslo (2x)), **Poland** (Warsaw(2x)), **Romania** (Bucharest (2x)), **Russia** (Moscow, St.Petersburg), **Slovenia** (Ljubljana), **Spain** (Barcelona, Valencia), **Switzerland** (CERN, PSI), **Ukraine** (Kiev), **United Kingdom** (Exeter, Glasgow, Lancaster, Liverpool)

8 North-American institutes

Canada (Montreal), **USA** (BNL, Fermilab, New Mexico, Purdue, Rochester, UC Santa Cruz, Syracuse)

Detailed member list, Progress Reports, Workshop papers etc. :

http://cern.ch/rd50

RD50 : R&D Plan

SCIPP

RD50 started when the design of the LHC tracking detectors based on large-scale silicon strip and pixel sensor were frozen.

The performance of the LHC Si sensors (p-on-n FZ strips, n-on-n oxigenated FZ DOFZ) was limited by radiation damage. The aim of RD50 is to develop Radiation-Hard Semiconductor Devices for High Luminosity Colliders -- like the LHC Upgrade, the Super-LHC (sLHC).

The program of RD50 was laid out and is progressing along these lines:

- **Extend the radiation testing to the predicted sLHC fluences (10^{16}, neutrons!)**
- **Search for alternative sensor materials to Si (more radiation-hard)**
- **Develop new experimental methods to help gaining insight into the radiation damage mechanism**
- **Understand on the microscopic level the observed radiation damage effects**
- **Optimize sensor geometry for radiation tolerance**
- **Start to transfer fabrication to commercial manufacturer in anticipation of large-scale production**

New Materials: Diamond, SiC, GaN

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/cm3]	3.515	6.15	3.22	2.33
Displacem. [eV]	**43**	20	**25**	**13-20**

- Wide bandgap (3.3eV)

⇒ lower leakage current than silicon

- Signal:
  Diamond 36 e/μm
  SiC 51 e/μm
  Si 89 e/μm

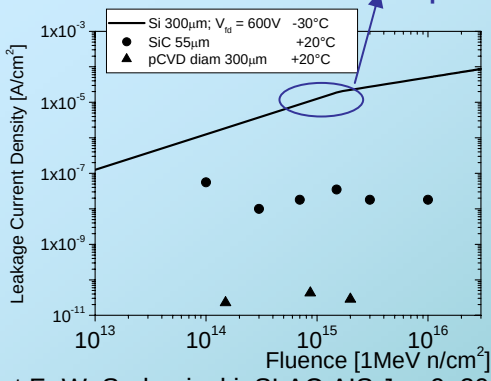
⇒ more charge than diamond

- Higher displacement threshold than silicon

⇒ radiation harder than silicon (?)

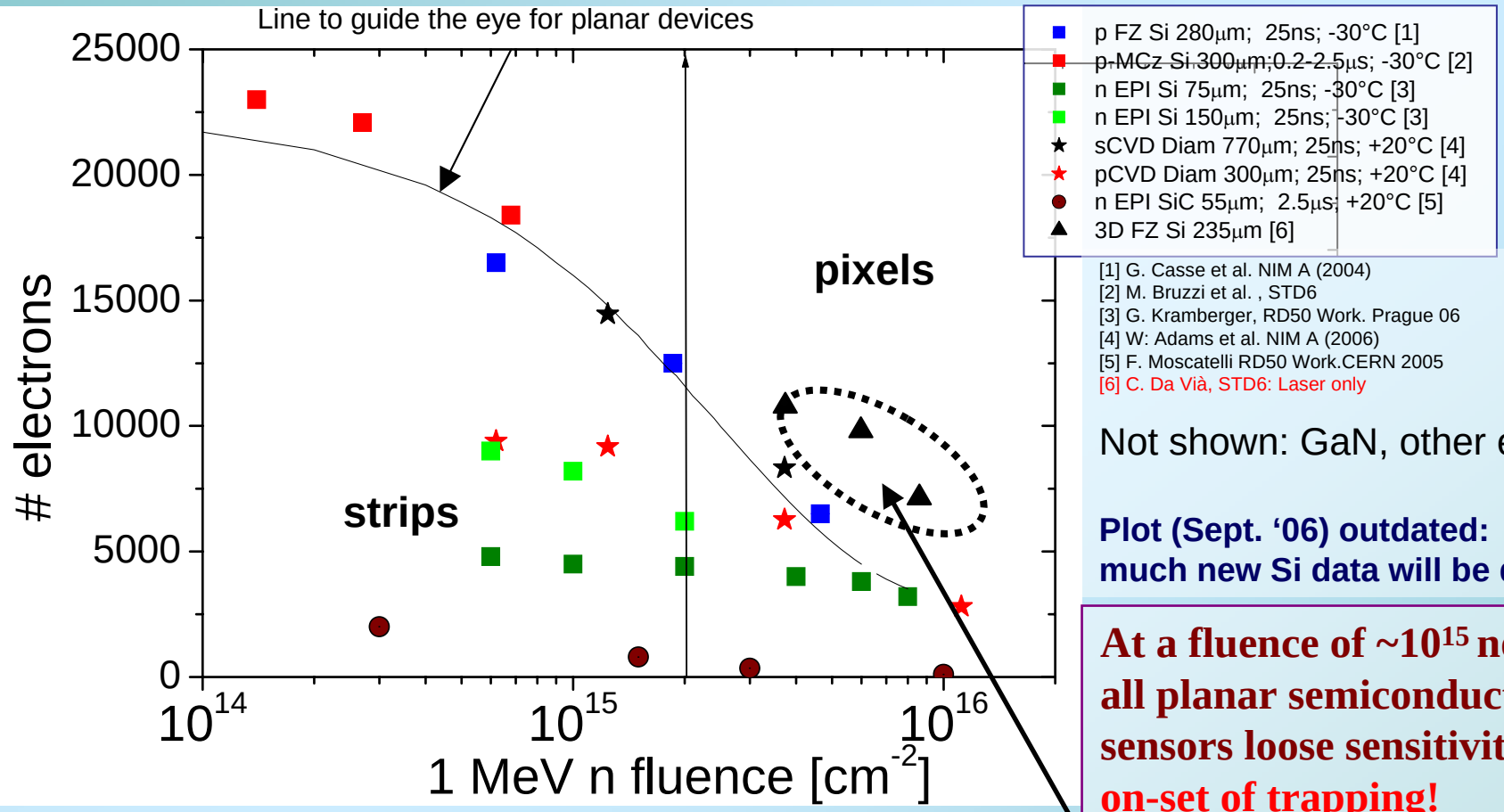
R&D on diamond detectors:
RD42 – Collaboration
http://cern.ch/rd42/

Partial depletion



New materials for Tracking Sensors?

Comparison of measured collected charge on different radiation-hard materials and devices
(M. Bruzzi, H. F.-W. Sadrozinski, A. Seiden, NIM A 579 (2007) 754–761)



[1] G. Casse et al. NIM A (2004)
[2] M. Bruzzi et al. , STD6
[3] G. Kramberger, RD50 Work. Prague 06
[4] W: Adams et al. NIM A (2006)
[5] F. Moscatelli RD50 Work.CERN 2005
[6] C. Da Vià, STD6: Laser only

Not shown: GaN, other excotics

Plot (Sept. '06) outdated: much new Si data will be discussed

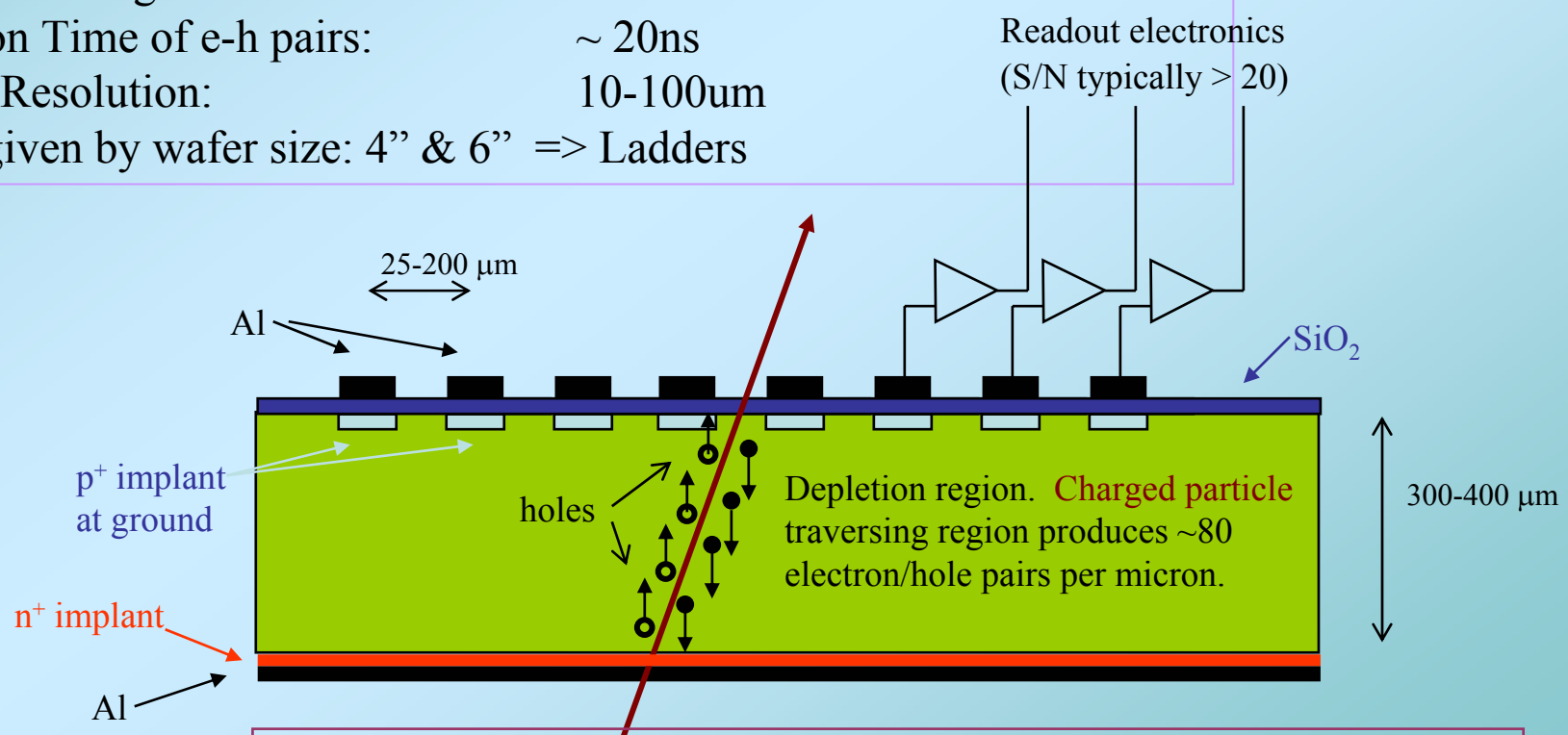
At a fluence of ~10^{15} neq/cm^2, all planar semiconductor sensors loose sensitivity: on-set of trapping!

Solution for Pixels: 3-D sensors, which provide shorter drift distance

No "Wunder" material found, so investigate in depth best known and devloped material: Si.
Erosion of collected charge @ Φ > ~10^{15} neq/cm^2 : is S/N ok?

Properties of Silicon Strip Detectors SSD

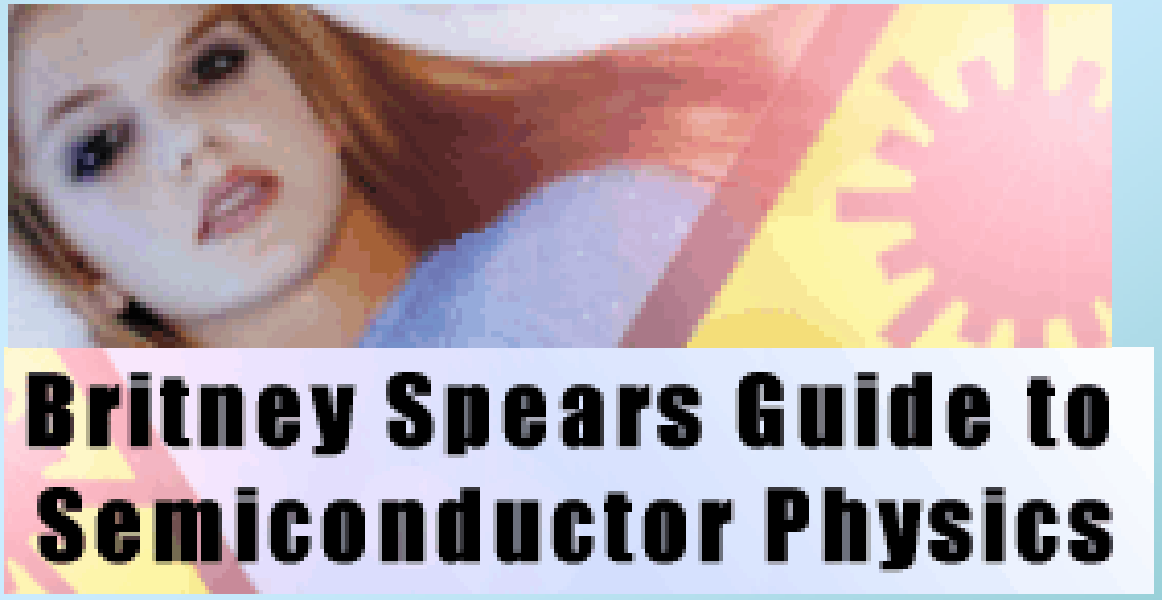
Reverse Bias of junction: only thermal current generation
Scale : Band gap 1.12eV vs. kT = 1/40eV: huge Boltzmann factor
Cooling needed only in ultra-low noise applications.
Wafer thickness 300um = 0.3%RL: 23k e-h pairs (small fluctuations)
Depletion Voltage ~ thickness^2 : < 100V
Collection Time of e-h pairs: ~ 20ns
Position Resolution: 10-100um
Area is given by wafer size: 4" & 6" => Ladders



Determine location of single particles on the micron scale

If you still have Questions…

Visit your Favorite Web Site



http://britneyspears.ac/lasers.htm

RD50

Radiation Damage in Silicon Sensors

SCIPP

- **Bulk (Crystal) damage due to Non Ionizing Energy Loss (NIEL)**
  - displacement damage, built up of crystal defects, proportional to fluence

Influenced by impurities in Si – Defect Engineering is possible!

I. Change of <u>effective doping concentration</u>

⇒ type inversion, higher depletion voltage, under-depletion

⇒ loss of active volume ⇒ decrease of signal, increase of noise

Different for neutron and proton irradiation

~ Same for all tested Silicon materials!

II. Increase of <u>leakage current</u>

⇒ increase of shot noise, thermal runaway, power consumption…

⇒ need for cooling (Diamond has advantage, RD42)

Universal if fluence is scaled according to NIEL

II. Increase of <u>charge carrier trapping</u>

⇒ loss of charge

Different for electrons and holes

- **Surface damage due to Ionizing Energy Loss (IEL**
  - accumulation of +charges in oxide (SiO_2) and the Si/SiO_2 interface, saturates

⇒ interstrip capacitance, strip isolation, breakdown behavior, …

- **Important latent effects:**

Space charge sign inversion (SCSI)

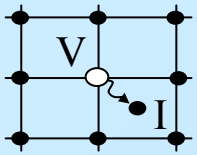
Annealing

Radiation Damage Induced Defects in Bandgap

particle → *Si* → **Frenkel pair** Vacancy + Interstitial

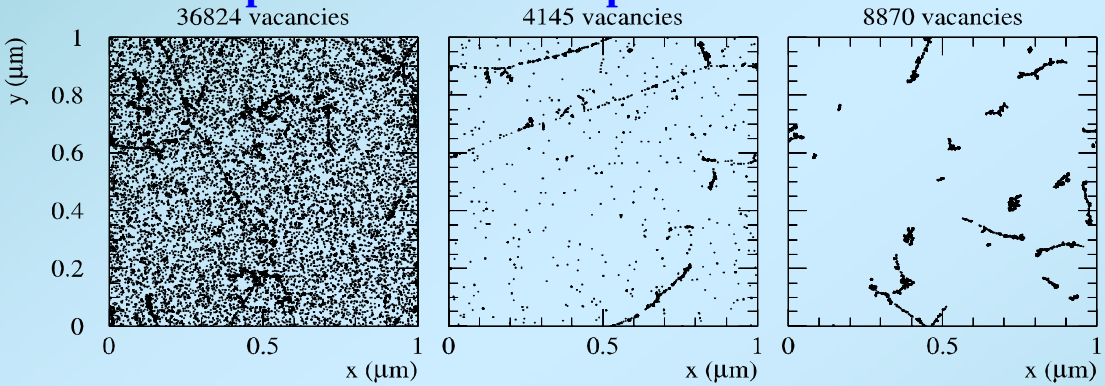
$E_K > 25$ eV → *Point Defects (V-V, V-O ..)*

$E_K > 5$ keV → *clusters*



Initial distribution of vacancies after 10^{14} particles/cm^2

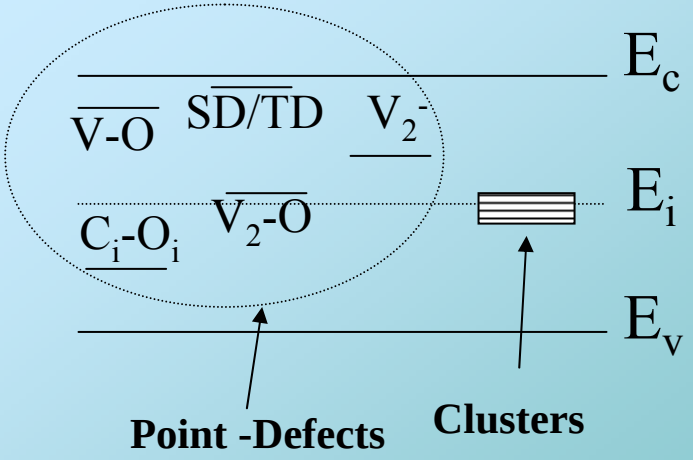
10 MeV protons **24 GeV/c protons** **1 MeV neutrons**



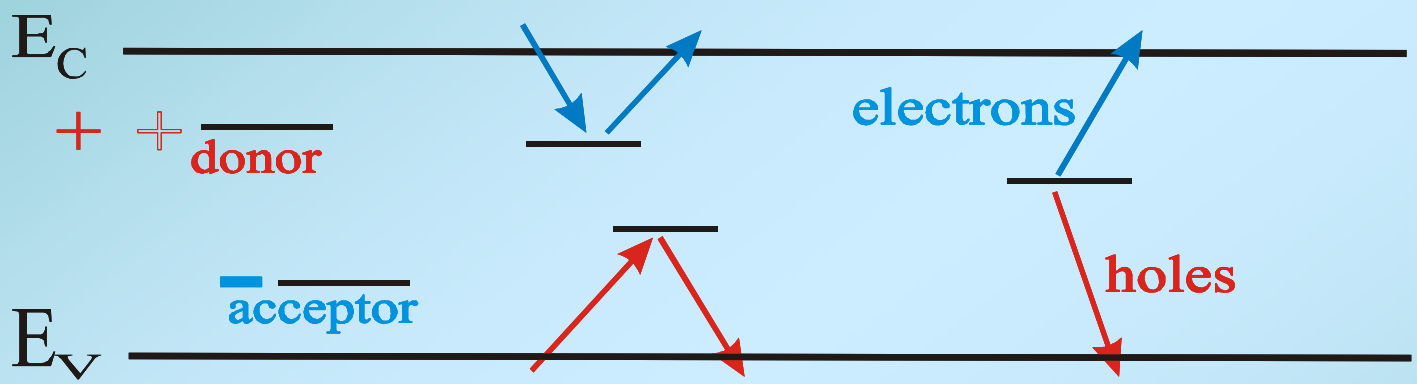
More point defects **Mainly clusters**

[Mika Huhtinen NIMA 491(2002) 194]

Main radiation induced defects in Si



Radiation Damage caused by Defects

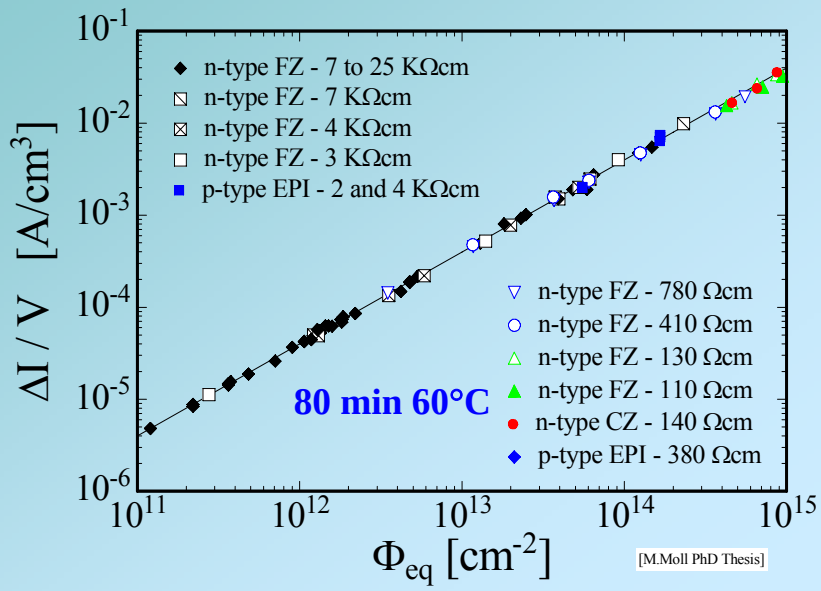


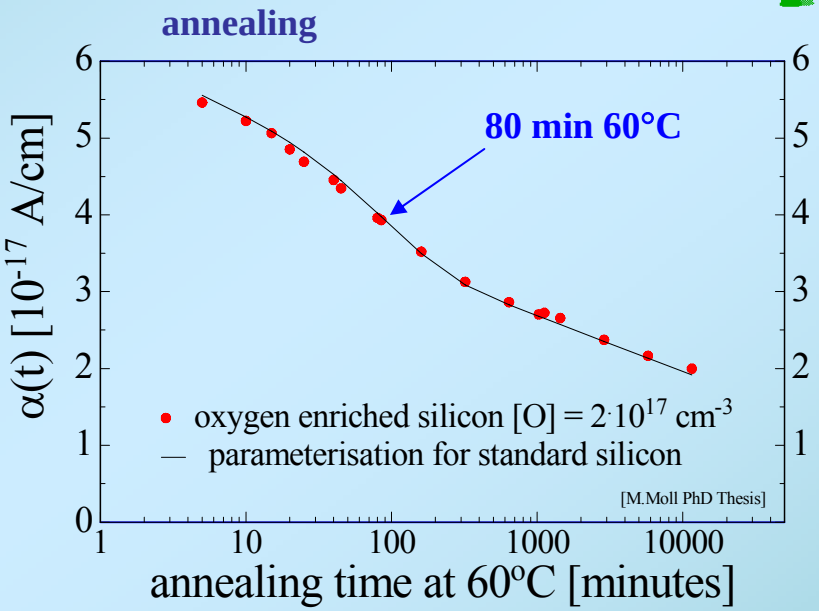
charged defects
⇒ **N_{eff} , V_{dep}**
e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h)
⇒ **CCE**
shallow defects do not contribute at room temperature due to fast detrapping

generation
⇒ **leakage current**
Levels close to midgap most effective

Radiation Damage – Leakage Current





- **Damage parameter α (slope in figure)**

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

Leakage current per unit volume and particle fluence

$$\alpha(60°C, 80\,\mathrm{min}) = (3.99 \pm 0.03) x 10^{-17} \frac{A}{cm}$$

- **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:**

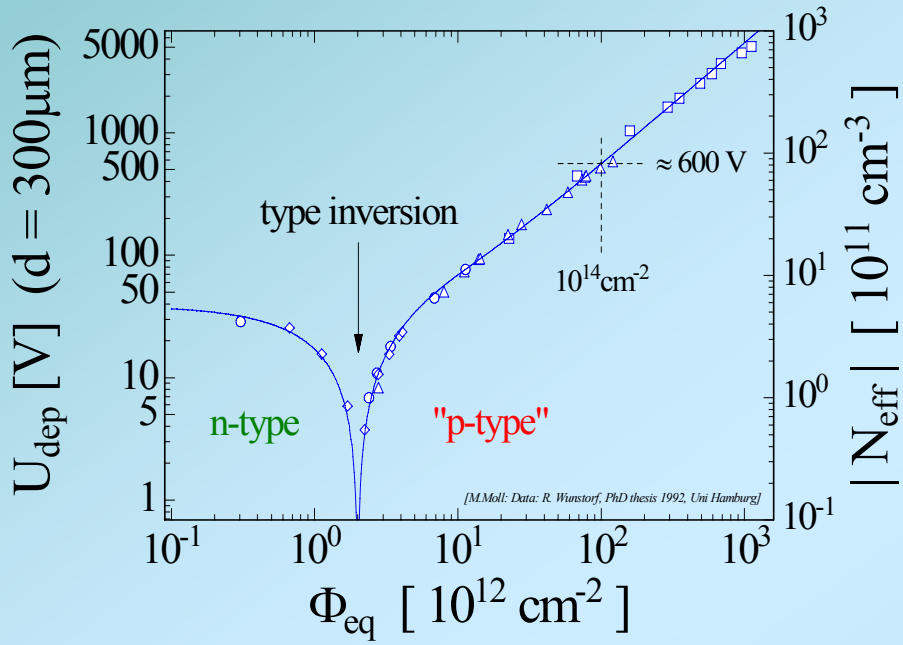
$$I(T) \;\alpha\; T^2 \exp\left(-\frac{E_g}{KT}\right)$$

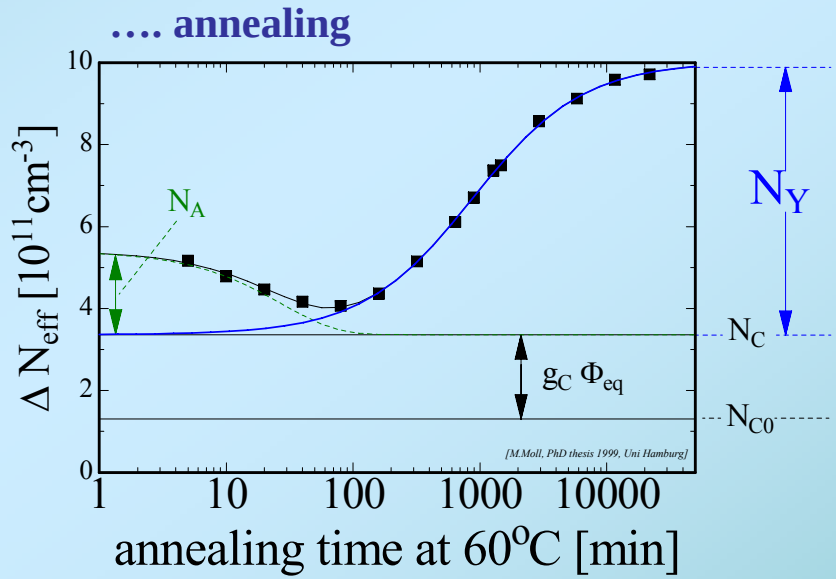
Consequence:

Cool detectors during operation!

Radiation Damage – Effective Doping

- **Change of Depletion Voltage V_{dep} in high resistivity n-type FZ Si** $V = q\frac{Neff}{2\varepsilon}x^2$.





Short term: "Beneficial annealing"
Long term: "Reverse annealing"3x stable component

- time constant depends on temperature:
  - ~ 500 years (-10°C)
  - ~ 500 days (20°C)
  - ~ 21 hours (60°C)
- **Consequence:** Detectors must be cooled even when the experiment is not running!

- Full depletion voltage too high to fully deplete detectors at very high fluences (>1000V @ 10^{15}cm^{-2}
- "**Type inversion**": N_{eff} changes from positive to negative (**Space Charge Sign Inversion**)

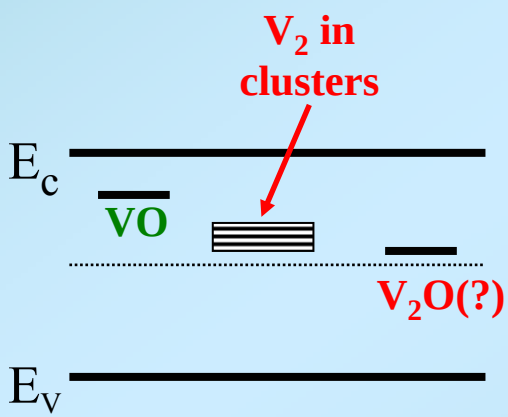
Defect Engineering of Silicon

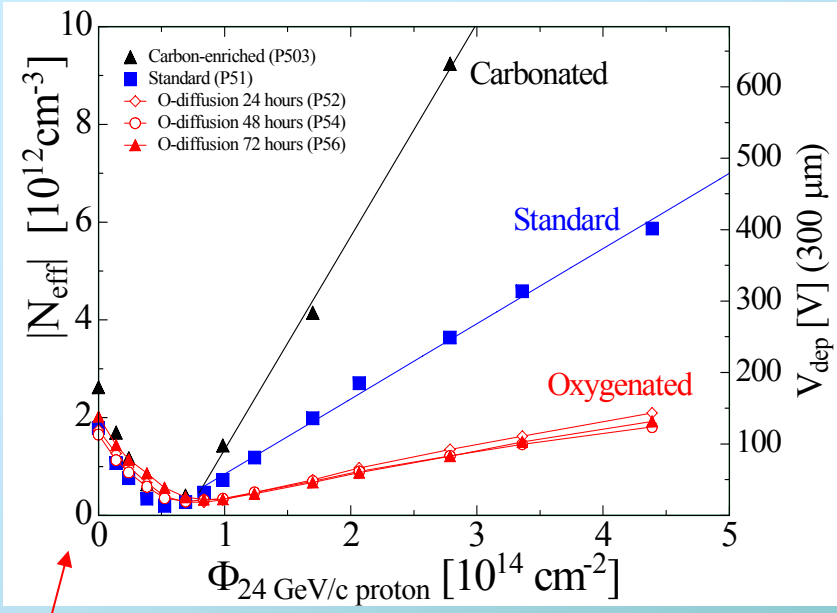
Influence the defect kinetics by incorporation of impurities or defects: <u>Oxygen</u>

Initial idea: **Incorporate Oxygen to getter radiation-induced vacancies**
⇒ **prevent formation of Di-vacancy (V_2) related deep acceptor levels**

•Higher oxygen content ⇒ less negative space charge
One possible mechanism: V_2O is a deep acceptor

V → O → VO (not harmful at RT)
V → VO → V_2O (negative space charge)

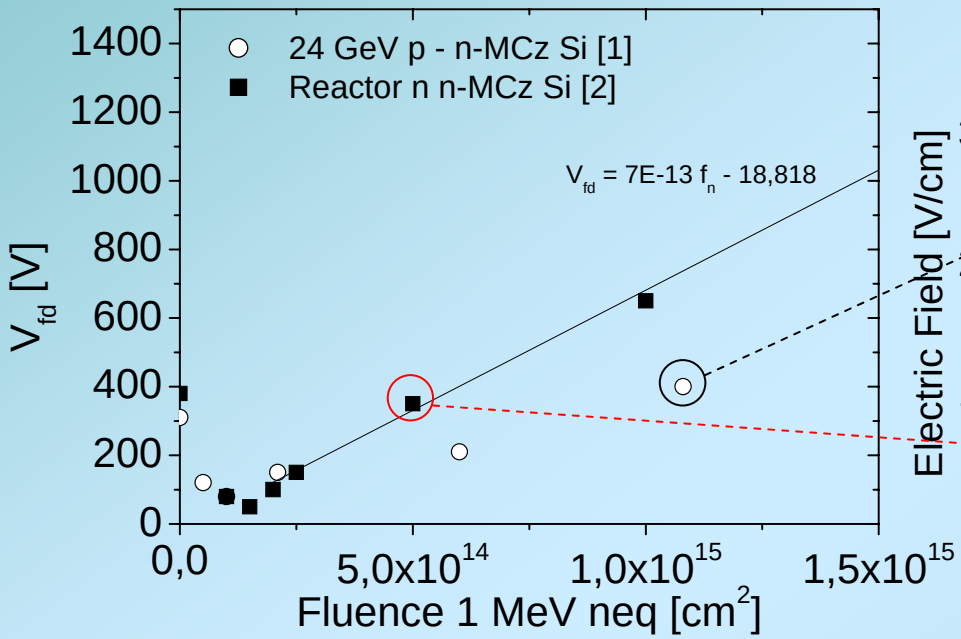




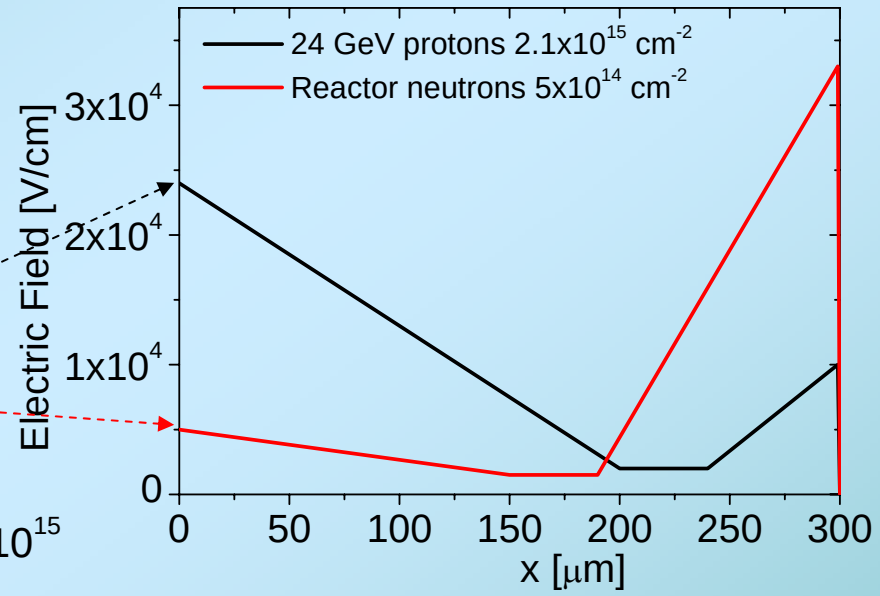
DOFZ (Diffusion Oxygenated Float Zone Silicon) RD48 NIM A465 (2001) 60
MCz (Magnetic Czochralski) has even higher O content NIM A568, 1, (2006), 83-88

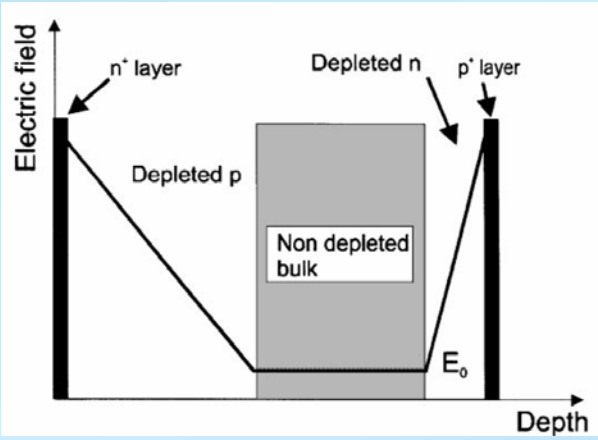
Difference in p and n irradiation in n-type Si

n-type MCz Si after 24GeV p and after reactor neutrons:
Oxygen not effective for neutrons



Electric field distribution by TCT (Ioffe-St Petesburg on SMART n-MCz Si single pad diodes)





"Double Junction" develops mostly from back in neutron irradiated silicon, probably due to a high generation of cluster, behaving as a source of quasi-midgap acceptors.

M. Bruzzi 6th International "Hiroshima" Symposiumk STD06, Carmel Sept. 06

Charge Trapping

Collected Charge is limited by:

- **Partial depletion**
- **Trapping at deep levels**

Collected Charge: $Q = Q_o \cdot \varepsilon_{dep} \cdot \varepsilon_{trap}$

$$\varepsilon_{dep} = \frac{x}{W} = \sqrt{V_{bias} / V_{dep}}$$

$$\varepsilon_{trap} = e^{-\frac{\tau_c}{\tau_t}}$$

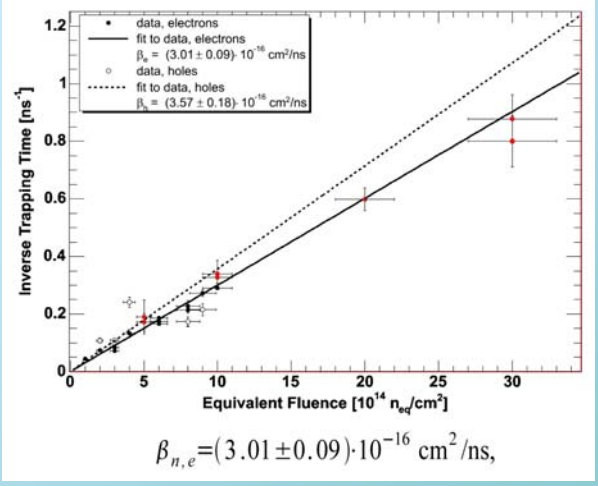
W: Detector thickness
x: Active thickness
τ_c : Collection time
τ_t : Trapping time

$$1/\tau_{e,h} = \beta_{e,h} \cdot [\Phi_{eq}/10^{16}\ \mathrm{cm}^{-2}]$$

$\beta_{e,h} = 3$

$\tau_t = 3$ ns for $\Phi = 10^{15}\ \mathrm{cm}^{-2}$,

$\tau_t = 0.3$ ns for $\Phi = 10^{16}\ \mathrm{cm}^{-2}$



J. Weber, XI RD50 Workshop, CERN, Nov '07

Annealing favorable for electrons
not favorably for holes

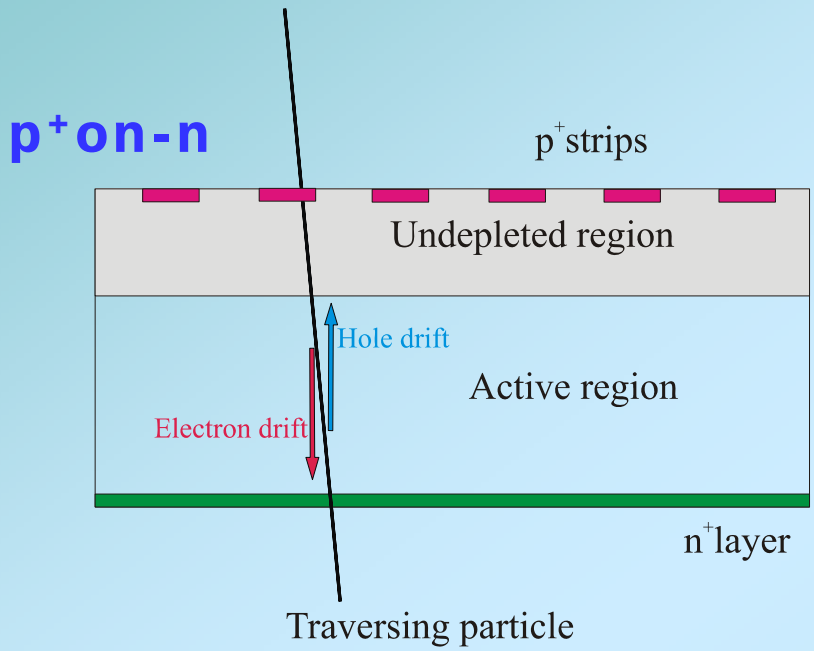
Bias dependence of charge collection:
increase depleted region & speed up collection

Trapping is the ultimate limitation for the active region in all semiconductors
(even for Diamond!)

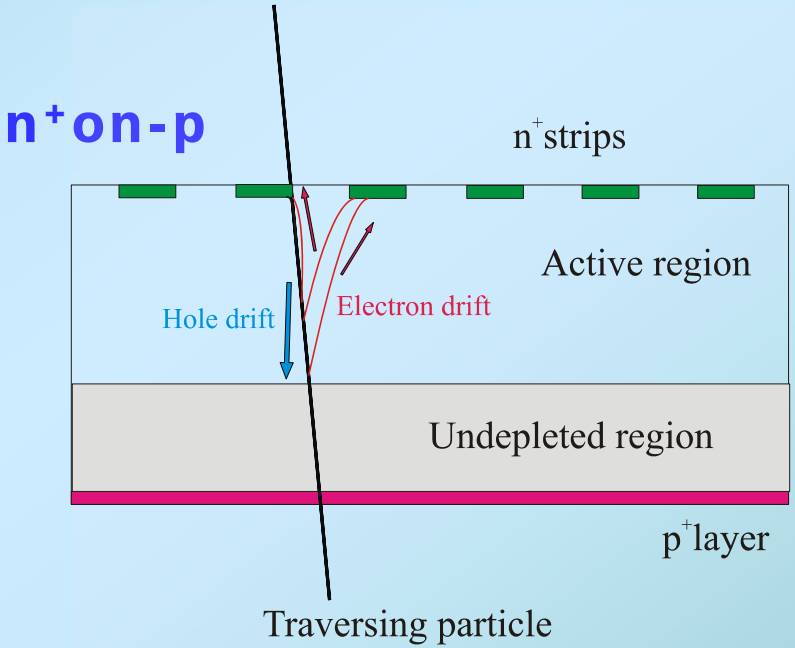
Device engineering: Collection at junction

p-on-n versus n-on-p (or n-on-n) SSD

n-type silicon after high fluences:



p-type silicon after high fluences:



p-on-n silicon, under-depleted:

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

n-on-p silicon, under-depleted:

- **Limited loss in CCE**
- **Less degradation with under-depletion**
- **Collect electrons (fast)**

Be careful, this is a very schematic explanation, reality is more complex, e.g. DJ!

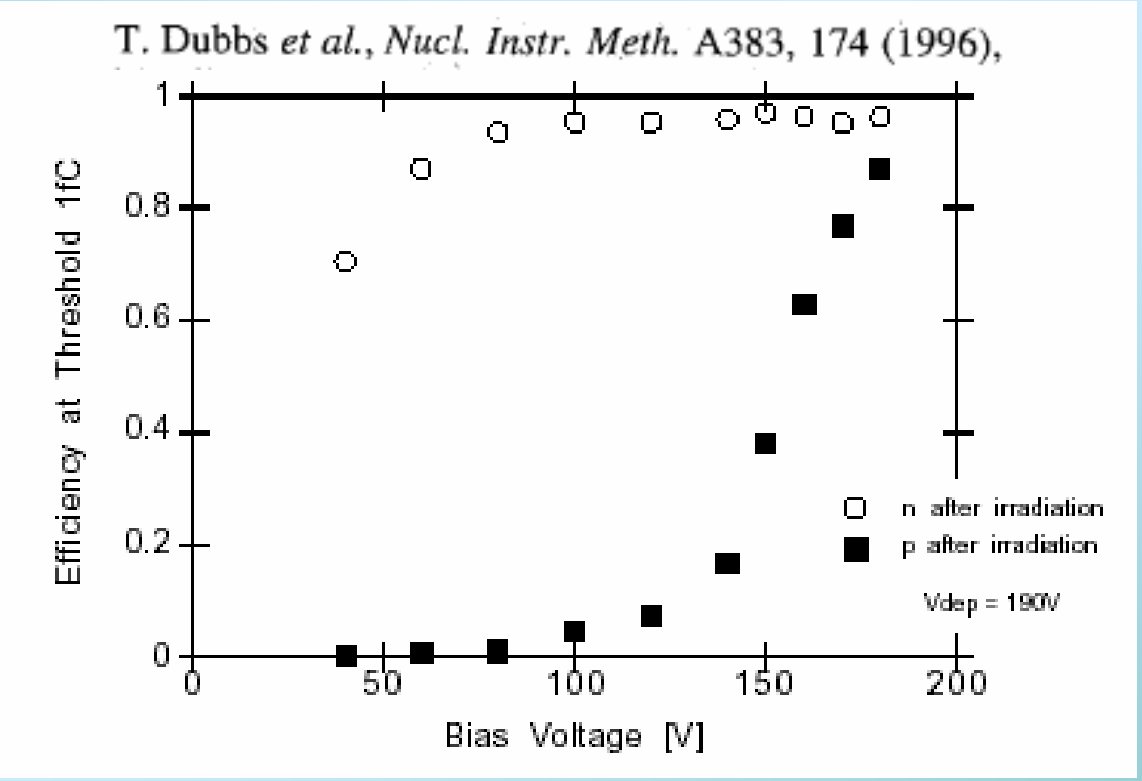
Charge collection efficiency CCE on p- and n-side after Inversion

Advantage of collecting on the n-side after inversion was established long time ago:

Double-sided n-type SSD

106 Ru telescope

(5.10^{13}p/cm^2)



This motivated the

n-on-n development for (ATLAS SCT), ATLAS & CMS Pixels, LHCb Velo

Paradigm Change for Upgrade Tracker:

Collect electrons, use n-on-p sensors (expect be much cheaper than n-on-n)

SSD Development for ATLAS Upgrade Tracker

ATLAS project	Development of non-inverting Silicon strip detectors for the ATLAS ID upgrade		
ATLAS Upgrade Document No:	Institute Document No.	Created: 28/12/2005	Page: 1 of 11
		Modified: 18/05/2006	Rev. No.: 1.04

Institution	P-type SSD	Strip Isolation	HV design	Modules constr.	Mech. Structures cooling	Hybrids,Readout	Electr. Ch	Laser CCI	CCE	Trapping	Oper. Par
KEK	x	x	x	x	x	x	x	x	x	x	
Tsukuba						x	x	x	x	x	x
Liverpool	x	x		x	x		x	x	x	x	
Lancaster							x		x		x
Glasgow				x			x	x?	x	x?	
Sheffield					x	x	x		x		
Cambridge						x	x		x		
QML				x			x				
Freiburg				x		x		x	x		
MPI	x	x	x				x				
Ljubljana							x	x	x	x	
Prague							x	x	x		
Barcelona	x	x	x	x		x	x		x		
Valencia	x	x		x		x	x		x		
Santa Cruz									x	x	x
BNL	x	x	x								
PTI	x	x					x	x		x	

Investigation of p-type Sensors

Ljubljana Univ., SCIPP - UC Santa Cruz, Univ. of Liverpool

- **What collected charge can we expect at fixed bias 500 V for different materials?**
  (ATLAS wants / needs to continue the use of present cables which are rated to 500V!)
- **How much does charge collection depend on different readout (pads, strips, binary, analog)**
- **What is the most promising Si wafer material ?**

•All detectors studied are with n^+ readout (n-on-p and n-on-n) – "electron collection"

Bias Voltage Dependence of Depletion after Neutron irradiation

The depleted sensor thickness x: can be measured two ways:

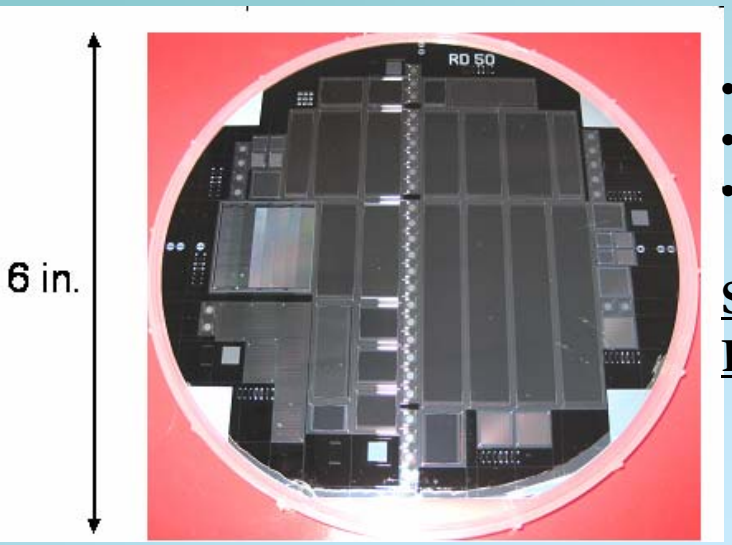
Capacitance-Voltage C-V measurement:

$$C(V) = \varepsilon \frac{A}{x(V)}$$ **for un-irradiated sensor:** $$V = q\frac{Neff}{2\varepsilon}x^2 \rightarrow 1/C^2 \sim V$$

Collected Charge vs. Bias Q(CCE) – V measurements

$$Q(V) \sim x(V)$$ **for un-irradiated sensor** $$Q(V) \sim \sqrt{x}$$

RD50 MICRON 6” project



- 36 processed , 20 received
- Fz (topsil) and MCz (Okmetic) wafers of p&n type material
- n-on-n, n-on-p, p-on-n structures (pixels, strips, diodes)

Strips: ATLAS strips geometry 80 μm pitch (w/p~1/3)
Pads: 2.5 x 2.5 mm^2 , multiple guard rings

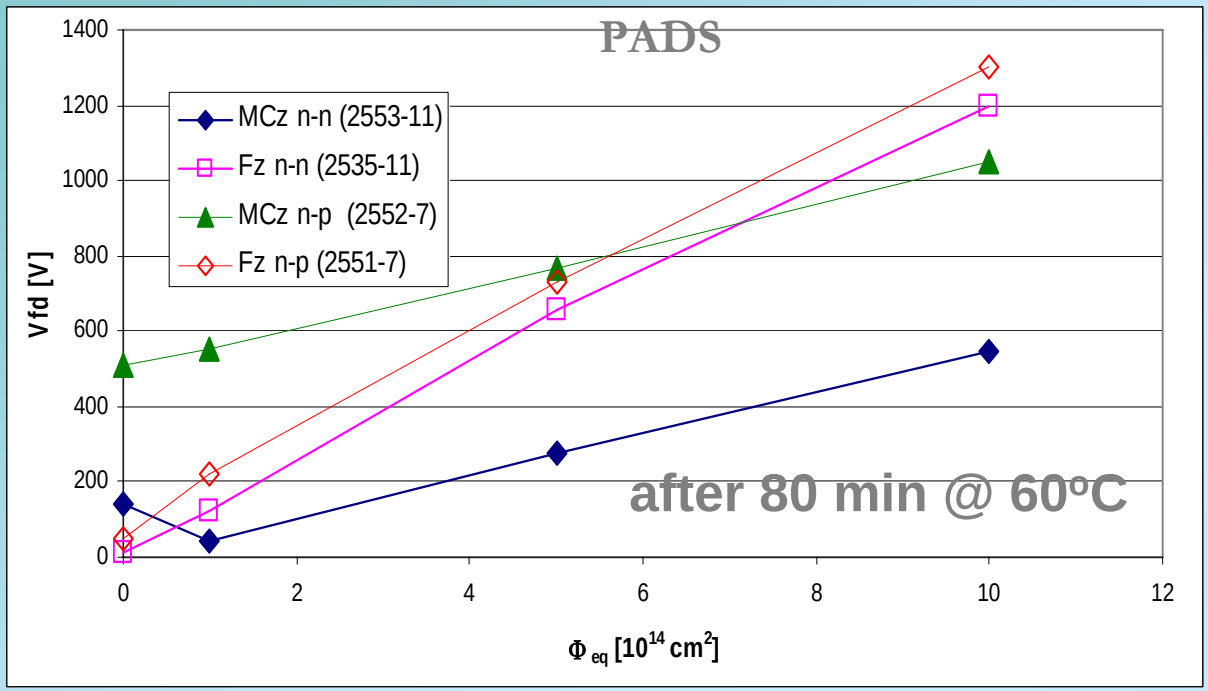
MCz wafers have very high oxygen content

	MCz (n-p)	MCz(n-n)	Fz (n-p)	Fz (n-n)
Wafer	2552-7	2553-11	2551-7	2535-11
Resitivity	1.5 Ωcm	2 kΩcm	14 kΩcm	~20 kΩcm
Orientation	<100>	<100>	<100>	<100>

Neutron and Proton and Pion (Aug. ’07) irradiation of SSD and Diodes

- **Liverpool:** CCE with SSD and diodes
- **UCSC:** CCE with SSD, both p-type and n-type, C-V, i-V on SSD and Diodes
- **Ljubljana:** CCE with Diodes, C-V, i-V on SSD and Diodes

C-V Measurements after Neutron Irradiation



- all detectors have negative space charge (decrease of V_{fd} during short term annealing)
- Leakage current agrees with expectations (α~3.5-5.5•10^{-17}A/cm)

G. Kramberger
ATLAS Tracker Upgrade Workshop, Valencia 12th-14th Dec. 2007

Defect Introduction Rate consistent with microscopic picture:

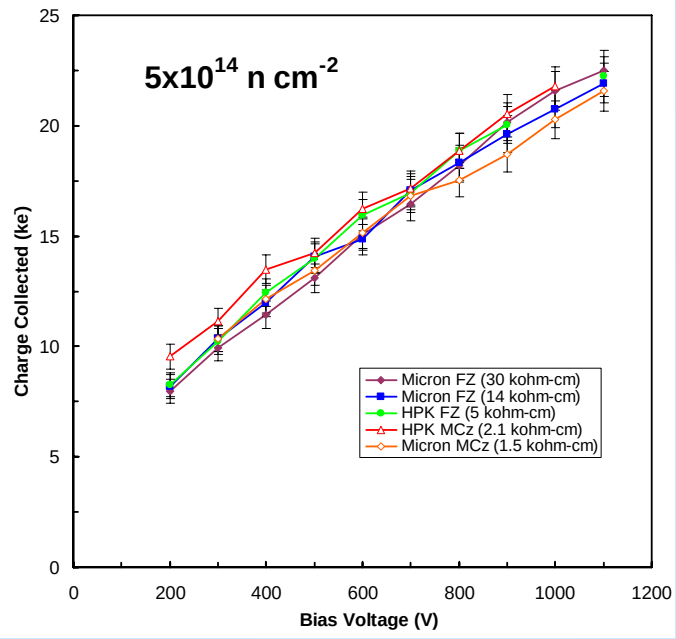
- MCz (p and n type): 55 V/10^{14} cm^{-2} (g_c~0.8 cm^{-2}) – **lower stable damage than seen before ?**
- Fz (p and n type): 125 V/10^{14} cm-2 (g_c~1.8 cm^{-2}) – in agreement with previous results

Charge collection (CCE) in all p-type wafers and n-type FZ should be similar at these fluences.
Expect that n-type MCz should perform better – do we see this performance in CCE?
Expect that MCz should be advantageous at very high fluences.

Charge Collection CCE for p-type Sensors

$\Phi = 5\times10^{14}$ n cm^{-2}

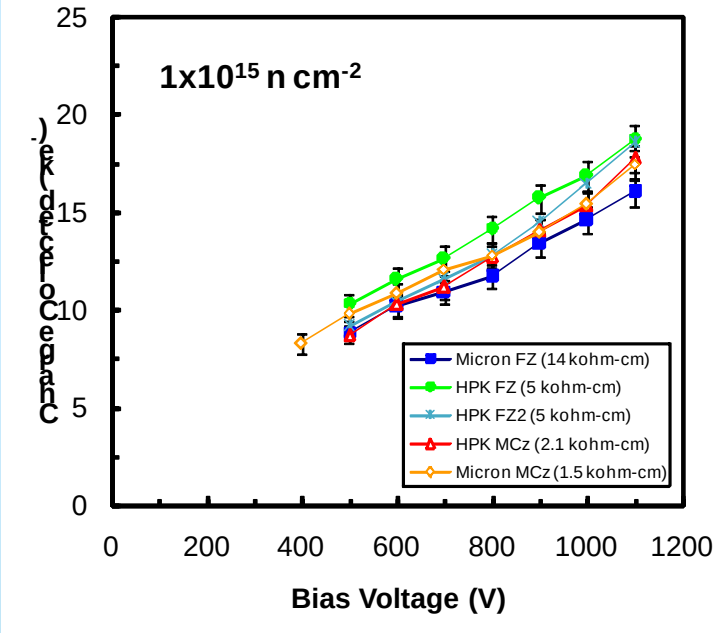
fluence motivated by long strip (10 cm) region of straw-man design



13-14 ke$^-$ collected at 500V

$\Phi = 1\times10^{15}$ n cm^{-2}

fluence motivated by short strip (2.5 cm) region of straw-man design

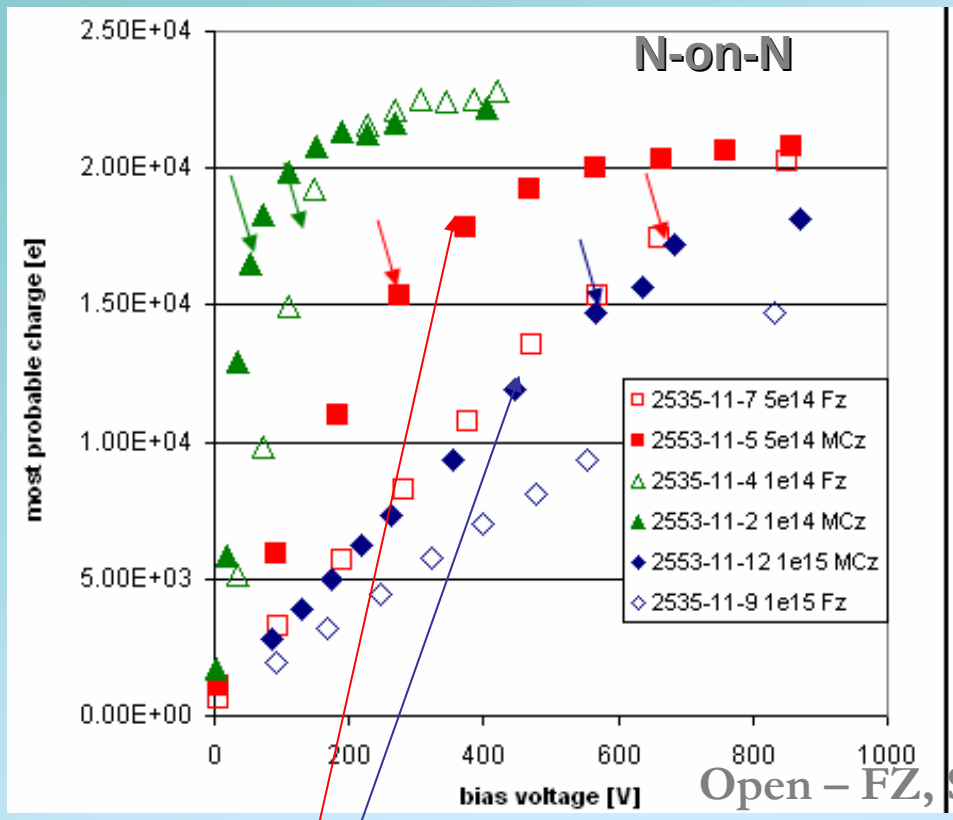


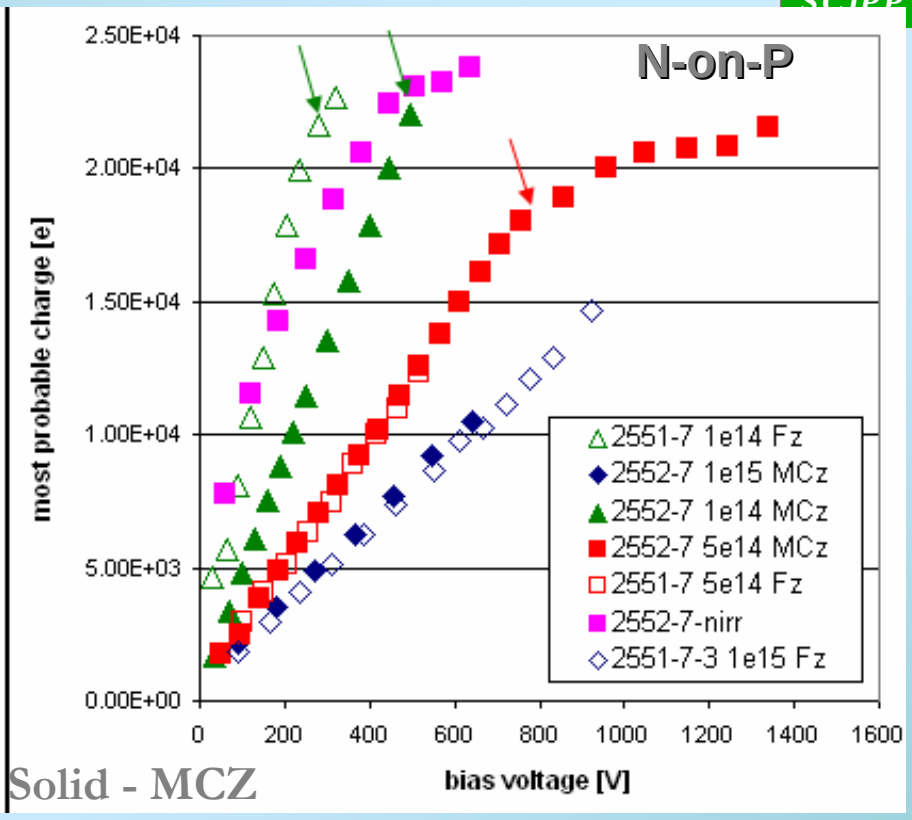
8.5-10 ke$^-$ collected at 500V

No effect on CCE seen for different resistivities or FZ/MCz (as expected)

A. Affolder ATLAS Tracker Upgrade Workshop, Valencia 12th-14th Dec. 2007

Bias Dependence of Charge collection CCE





Open – FZ, Solid - MCZ

G. Kramberger

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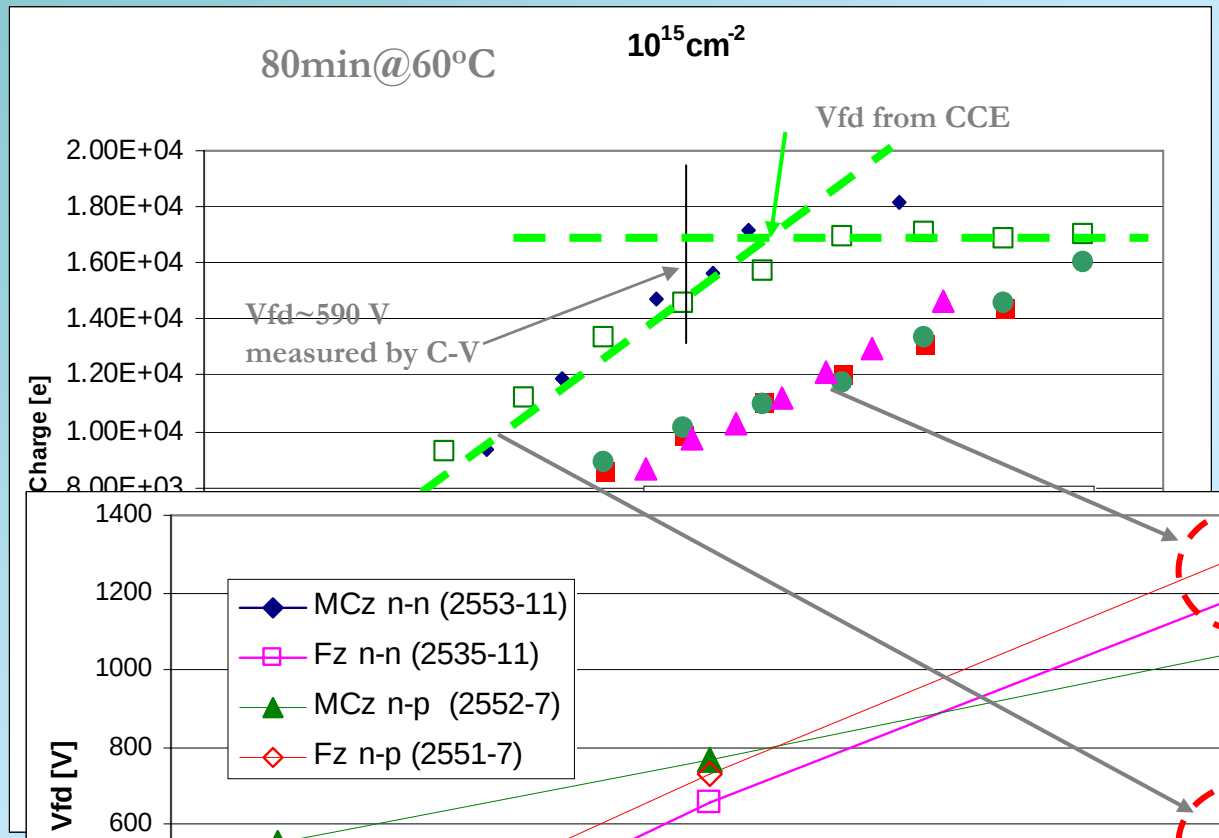
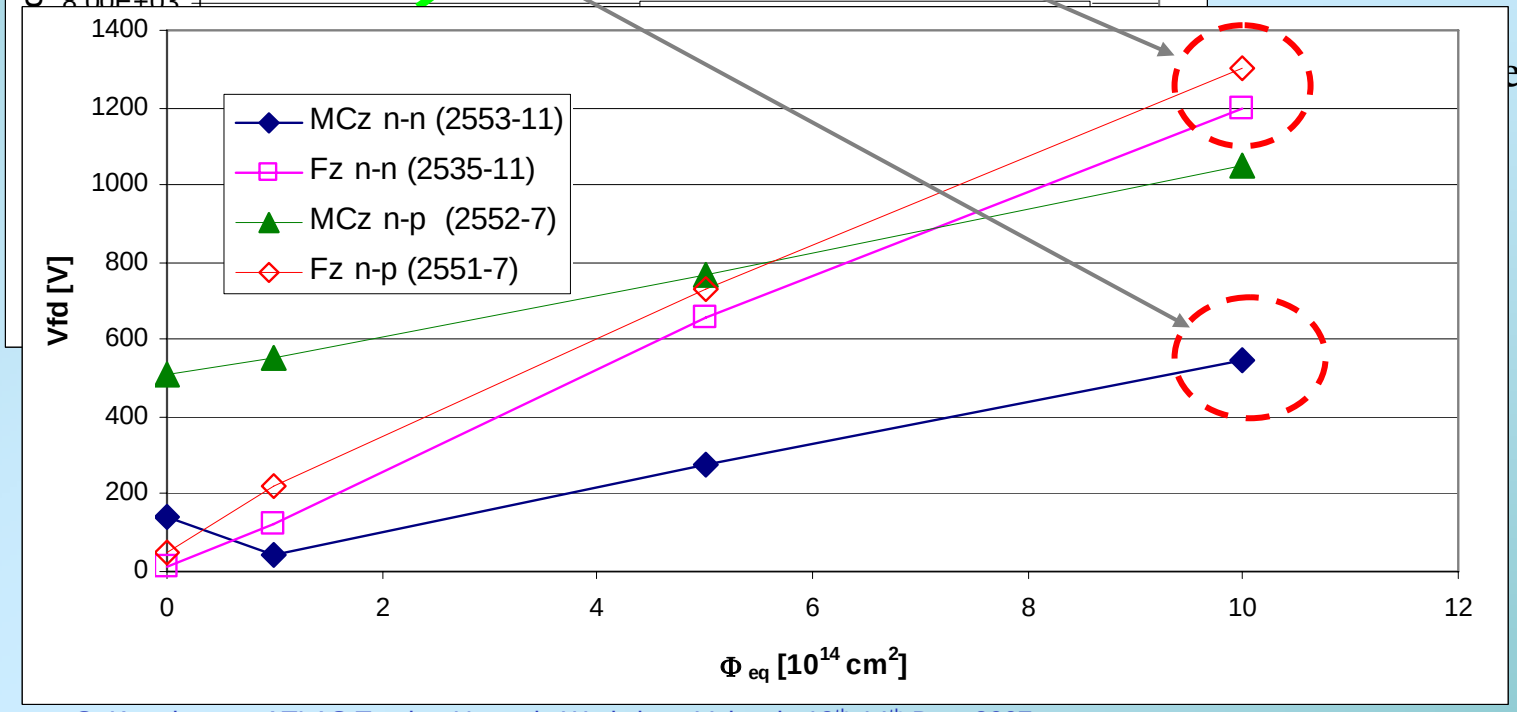
- V_{fd} from CV (denoted by arrows) agrees well with the kink in CCE
- The slope of charge increase with voltage is directly related to V_{fd}:
  - increase of V_{fd} can be measured by the change of slope and vice versa
  - Similar V_{fd} = similar slope -> same E field
- High resistive non-depleted bulk is well reflected in linear increase of charge – different from un-irr.
- N-type FZ and all P-type show similar behavior, and N-type MCz has best depletion characteristics, as predicted from C-V

Fz-p vs. MCz-n Difference due to Depletion Voltage





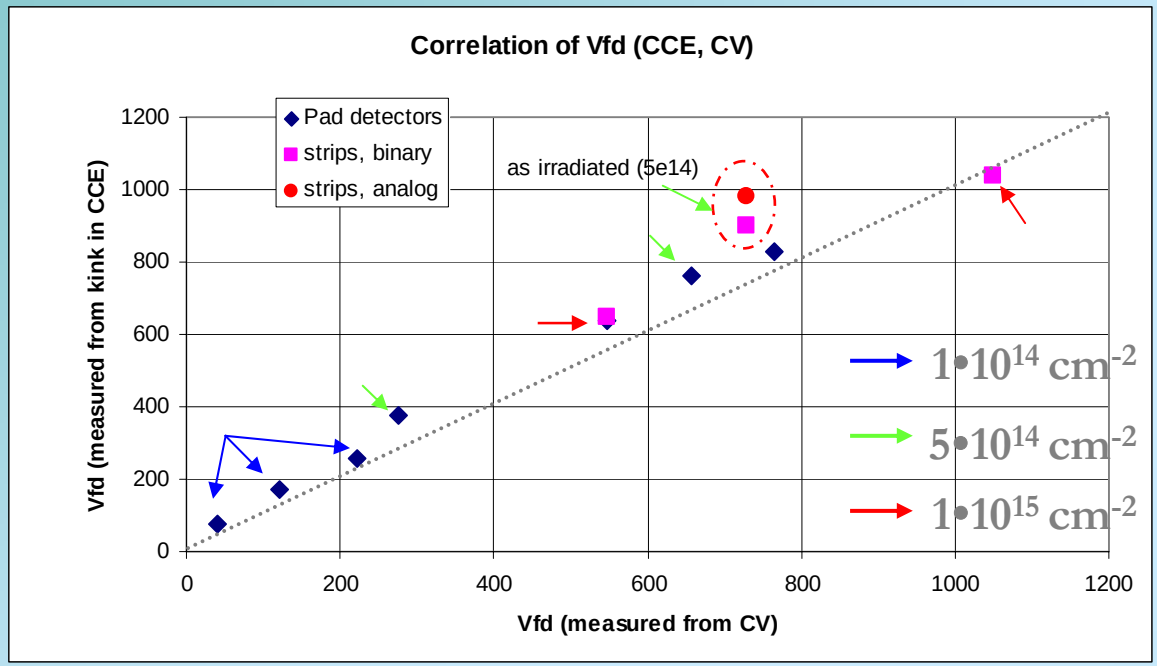
Big difference in the charge collection between MCz n-n and Fz n-p
~14000 e vs. ~8000 e at 500V!

Fully depleted detector – one can see kink in Q-V plot

e in CCE is difference in V_{fd}

G. Kramberger, ATLAS Tracker Upgrade Workshop, Valencia 12th-14th Dec. 2007

Depletion Voltage from C-V vs. from Q(CCE)-V



V_{fd} from saturation in C-V and Q(CCE)-V curves (80min @ 60°C – end of beneficial annealing)

The correlation holds for all investigated fluences in range of full depletion voltages up to 1000V!

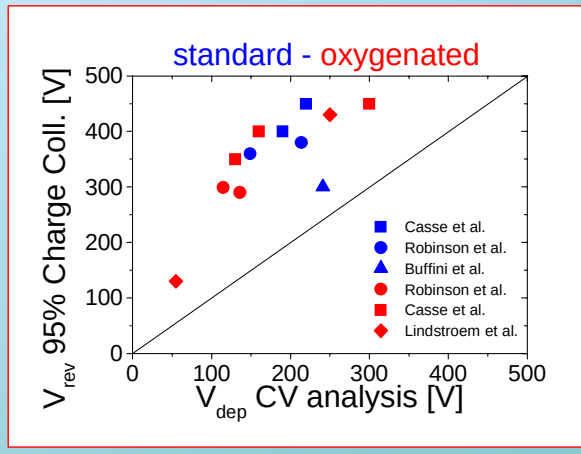
G. Kramberger

ATLAS Tracker Upgrade Workshop, Valencia 12th-14th Dec. 2007

V_{fd} from CV underestimates the onset of saturation in CCE by max. 100-150 V!

- after V_{fd} the collected charge continues to increase due to shorter drift
- due to growth of depletion depth from electrode side the offset is smaller than in inverted p-on-n!

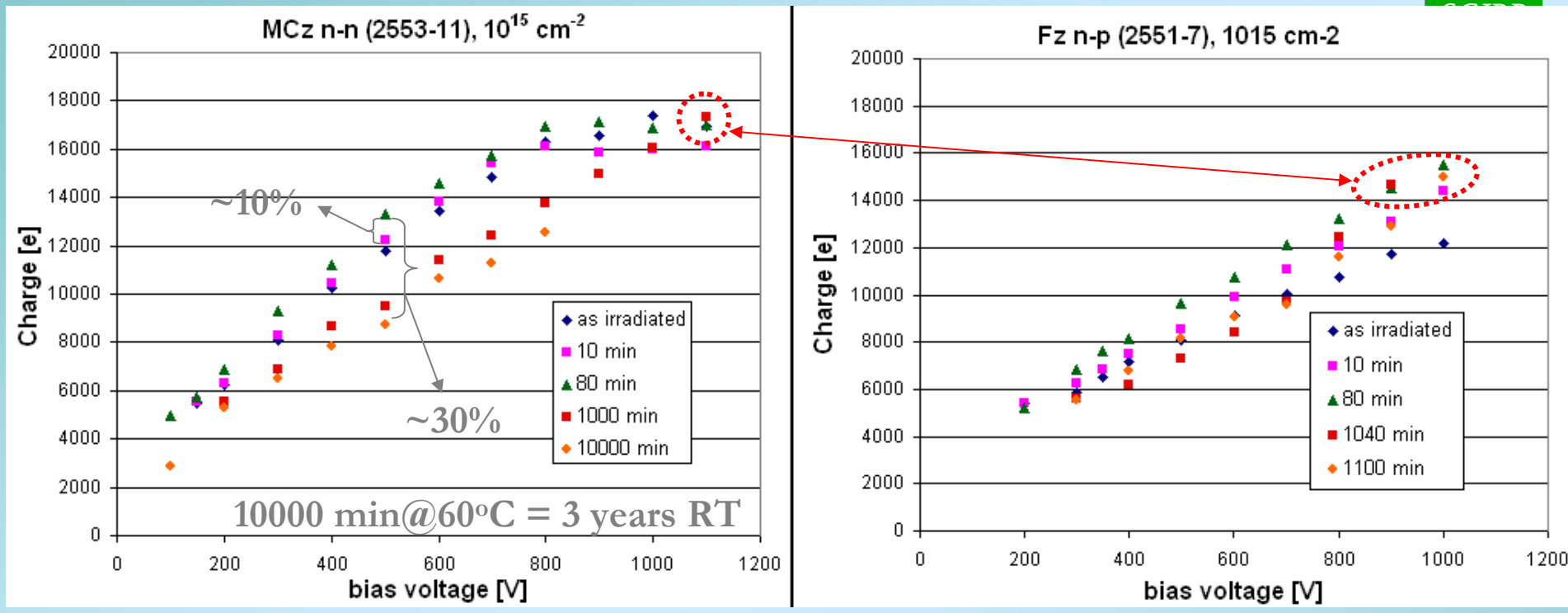
Advantage of charge collection on the junction



M. Bruzzi, H. F.-W. Sadrozinski

STD6 Carmel, Sept. 07

Long term annealing of charge collection



G. Kramberger, ATLAS Tracker Upgrade Workshop, Valencia 12th-14th Dec. 2007

The CCE for n-type MCz follows the annealing trend of the depletion Voltage V_{fd}:

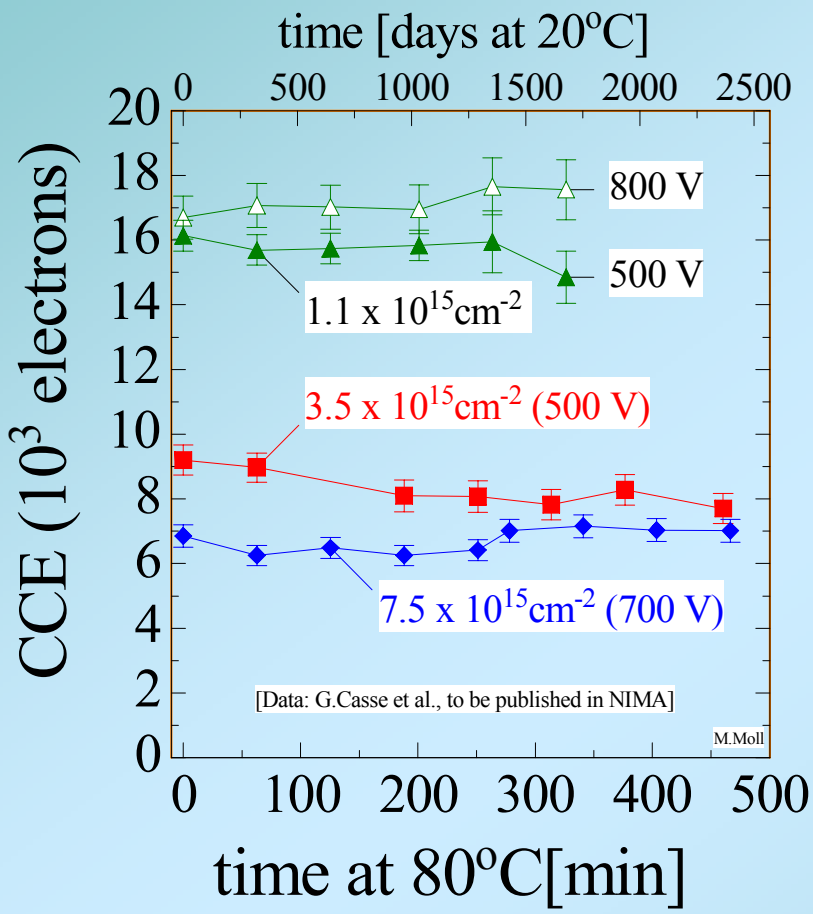
- initial rise (beneficial annealing) increase in collected charge by ~10% (@500V)
- decrease by again 20-30% (@500V) during the reverse annealing 10000 min

Increases for p-type FZ-p by 30% and then slow decrease to the pre-anneal value

After depletion annealing of trapping visible

Annealing of p-type FZ and DOFZ sensors

(p irradiated)



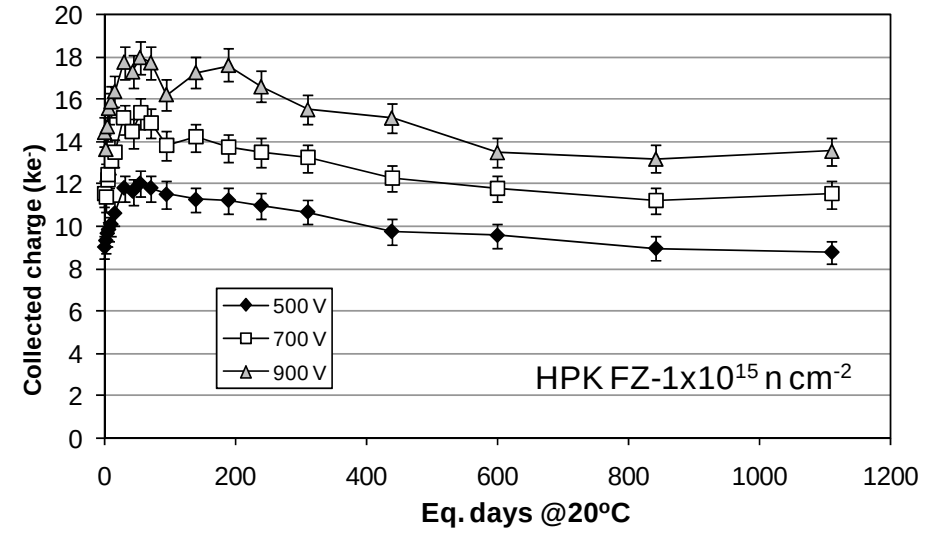
- p-type strip detector (280μm) irradiated with 23 GeV p (7.5×10^{15} p/cm^2)
- expected from previous CV measurement of V_{dep} on n FZ:
  - before reverse annealing: $V_{dep} \sim 2800$V
  - after reverse annealing $V_{dep} > 12000$V
- no reverse annealing visible in the CCE measurement !

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

CCE vs. Annealing (n irradiated)

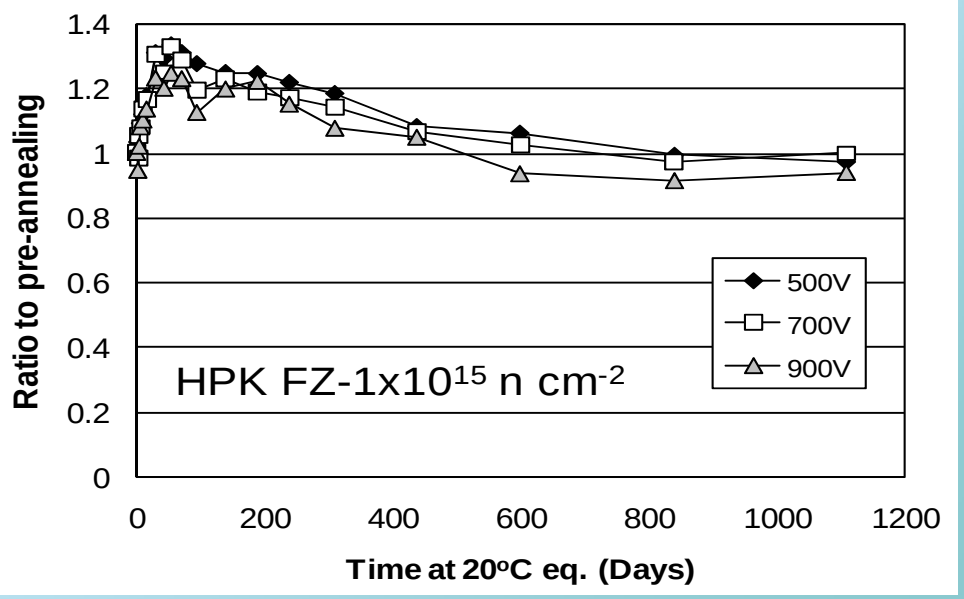
Stable plateau of increased signal between 20-100 days (30% for this piece)

(Current decreases by ~30% over same time period)



At sLHC fluences for p-type sensors, the entire annealing process is much less pronounced. than for n type FZ.

It opens the possibility that sensors need to be cooled only during operations to control the leakage current, but not during beam-off time to prevent anti-annealing



A. Affolder ATLAS Tracker Upgrade Workshop, Valencia 12th-14th Dec. 2007

Mitigation of Radiation Damage in Si

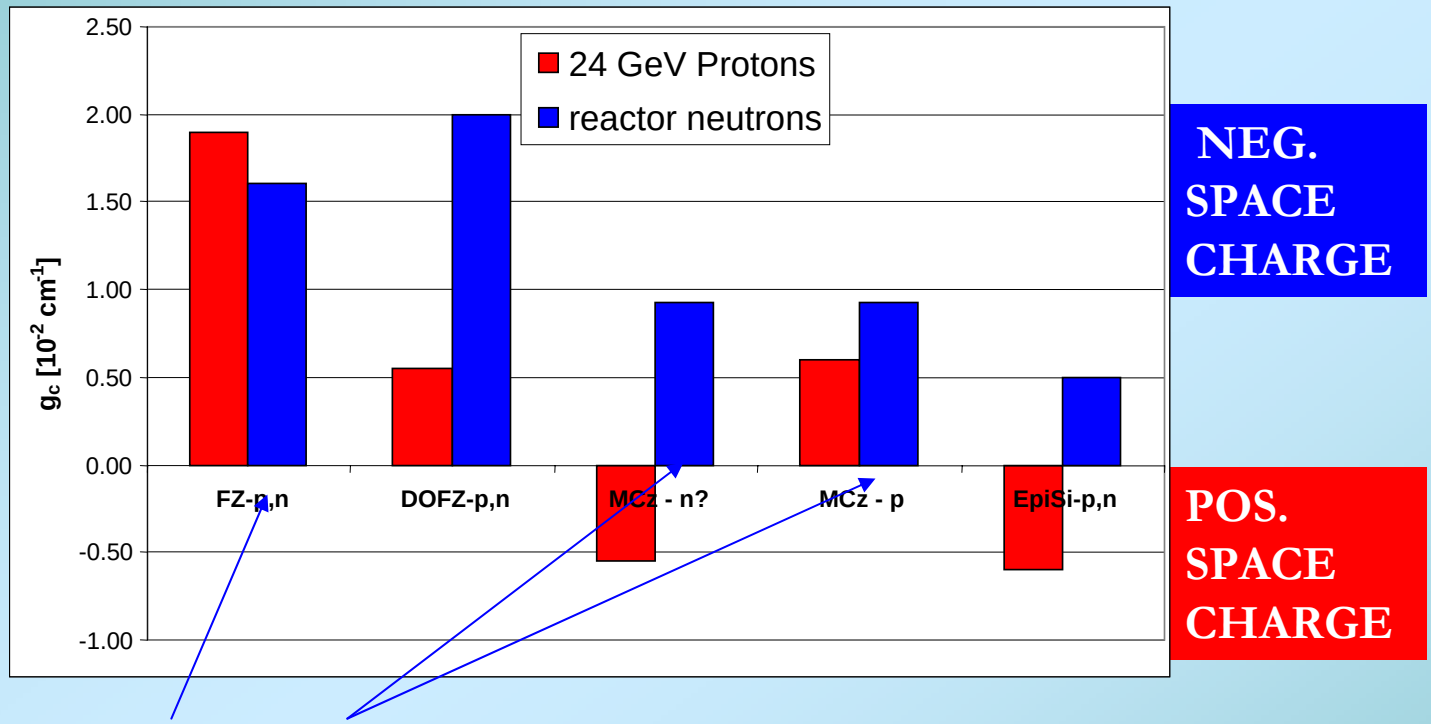
- **Increase depleted region at fixed bias: Wafer materials**
  - Oxygen — But neutrons
  - **Epi — But neutrons, protons**
  - **MCz — But special wafer processing**
  - N-type wafers: low resistivity , — But SCSI, annealing
  - **P-type wafers: high resistivity — Need experience, good annealing**

- **Decrease drift distance to decrease trapping: Geometry**
  - Thin — But inferior at low / medium, no advantage at high fluences
  - **3-D — But high capacitance, need experience**

- **Reduce trapping with beneficial annealing: Carrier**
  - **Collect at (main) junction — n-on-p or** n-on-n
  - **Collect electrons — less trapping, good trapping annealing**

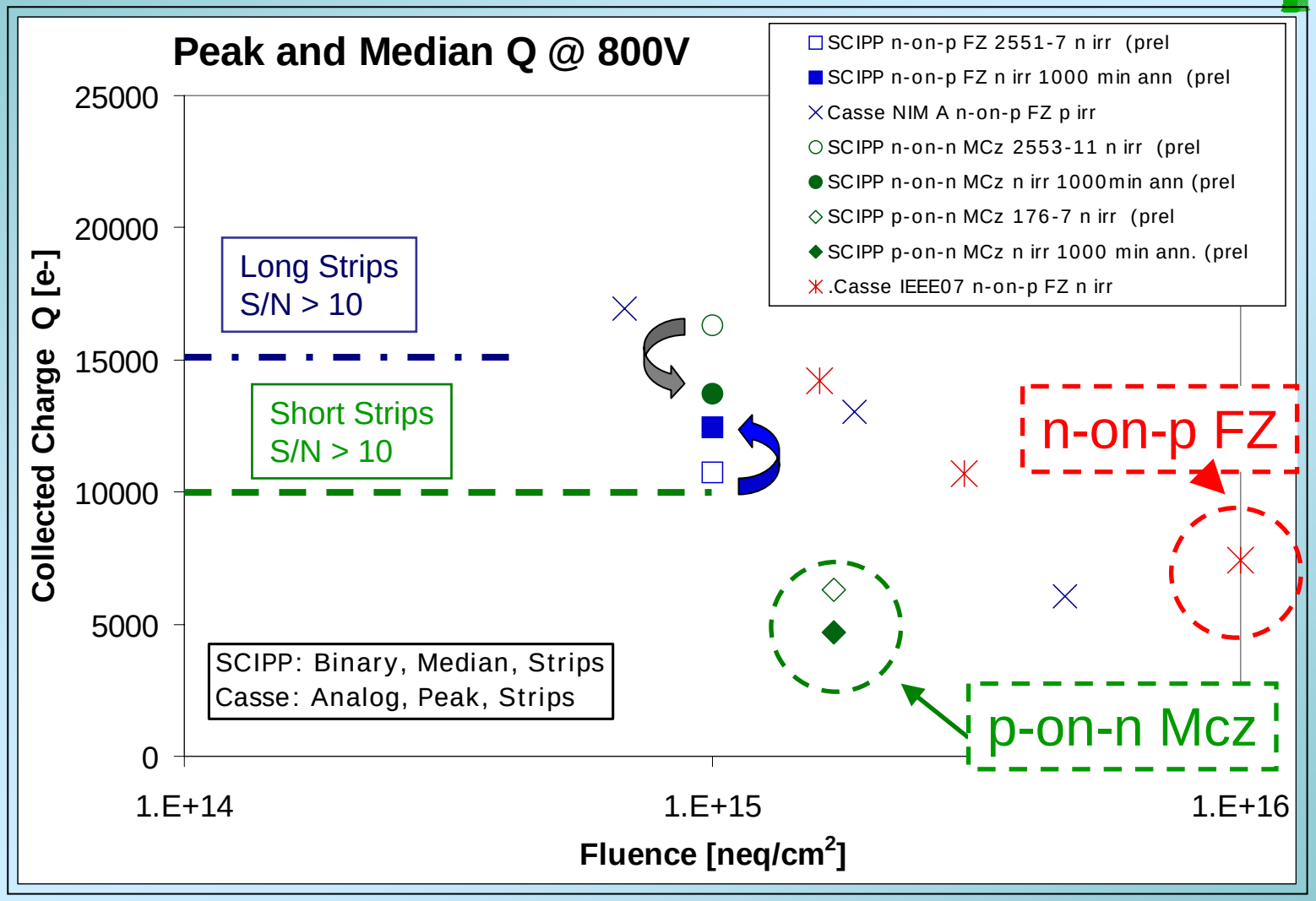
Wafer Scorecard

- Materials: Neff = $Neff_0 + g*\Phi_{eq}$
- For p-type: need $Neff_0$ low: high resistivity
- For n-type, need $Neff_0$ high: low resistivity



FZ and Mcz data verified for neutron irradiation, some proton data puzzling. Will soon have proton and pion data to check the advantage of MCz.

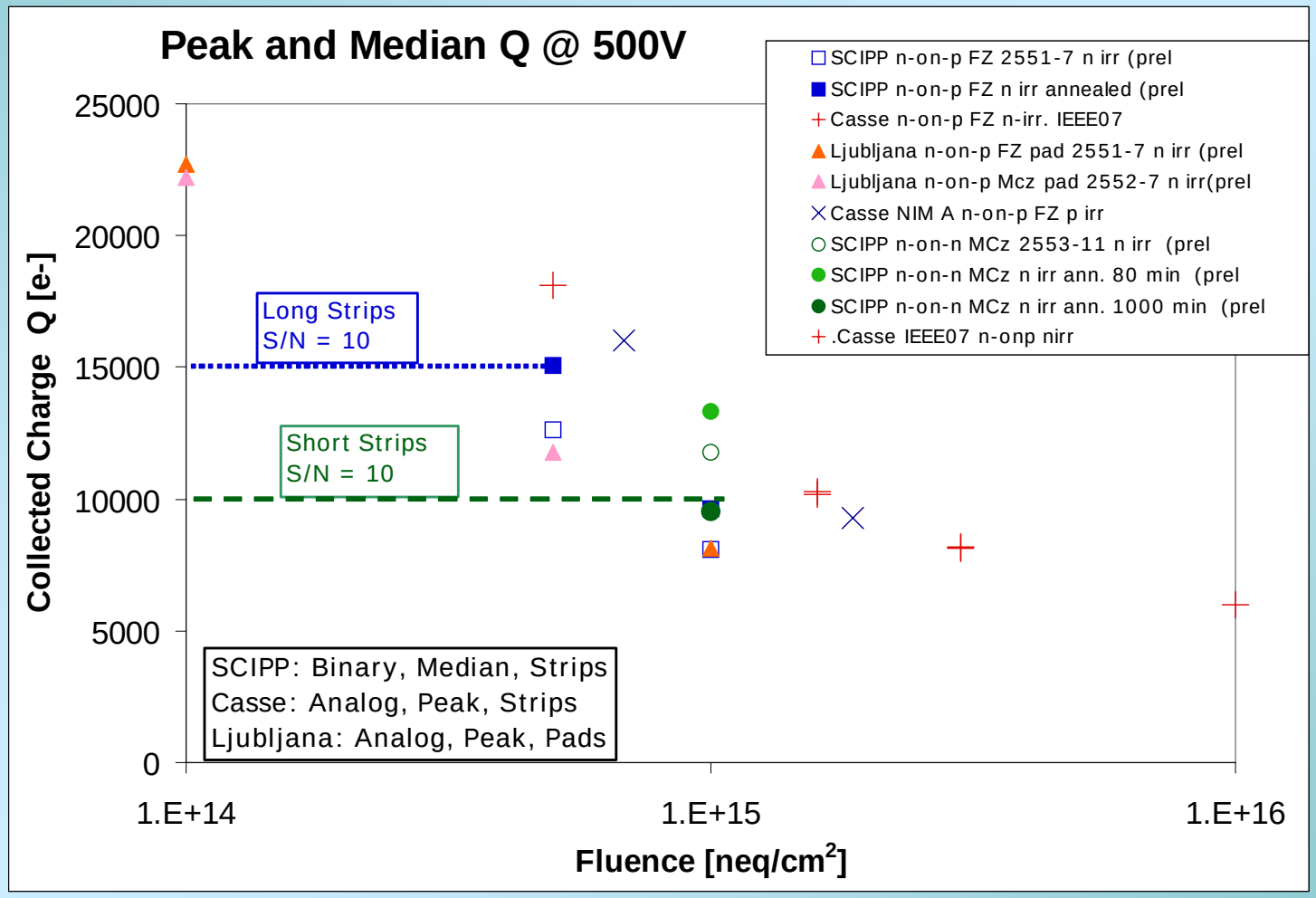
Charge Collection in Irradiated SSD



N-on-p strip sensors are sufficiently radiation-hard for the sLHC
No obvious advantage for MCz over FZ. 7500 e after 10^{16} n/cm^2!

Charge Collection in Upgrade Strips

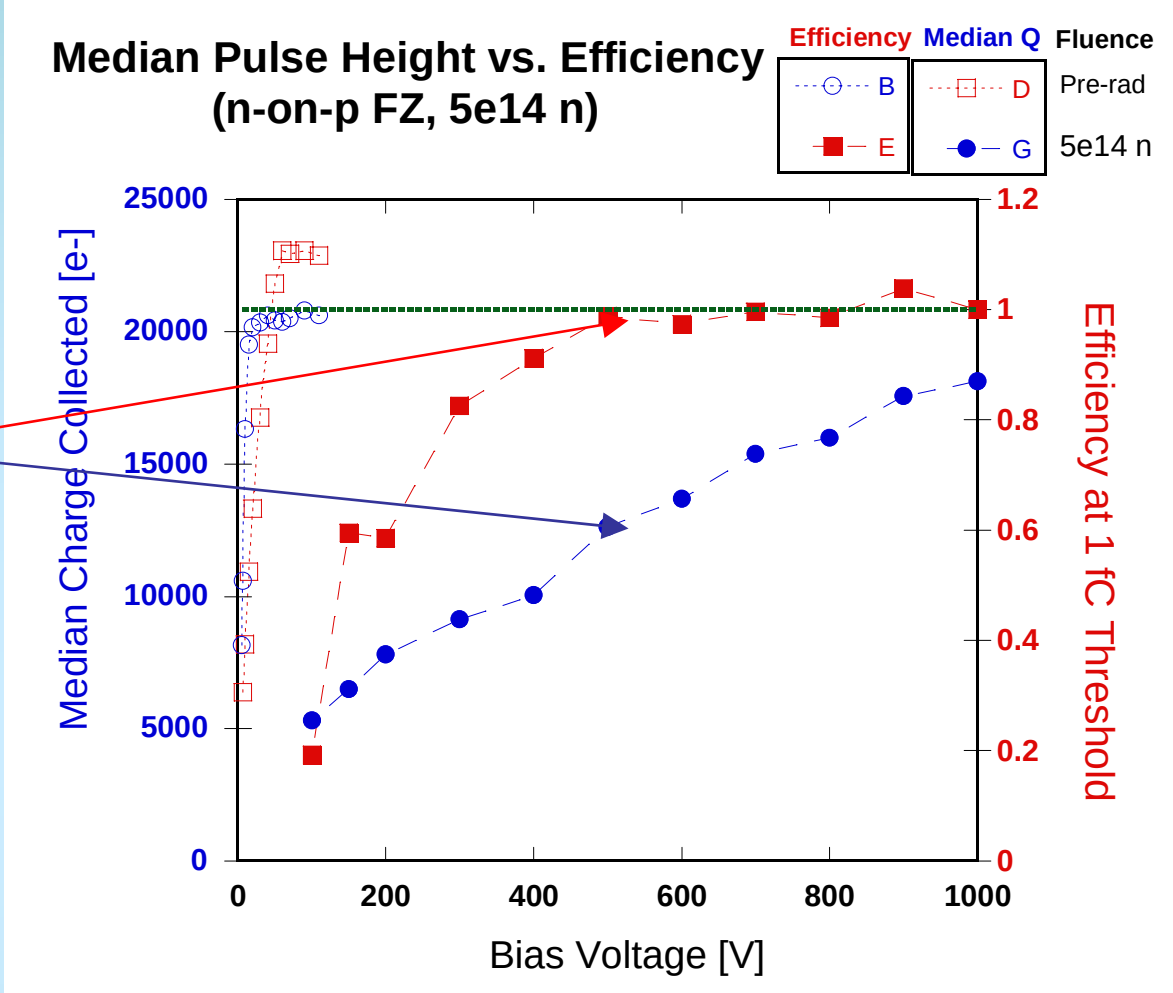
ATLAS bias voltage is constraint to < 500V (cables!).



N-on-p strip sensors are sufficiently radiation-hard for the sLHC ?

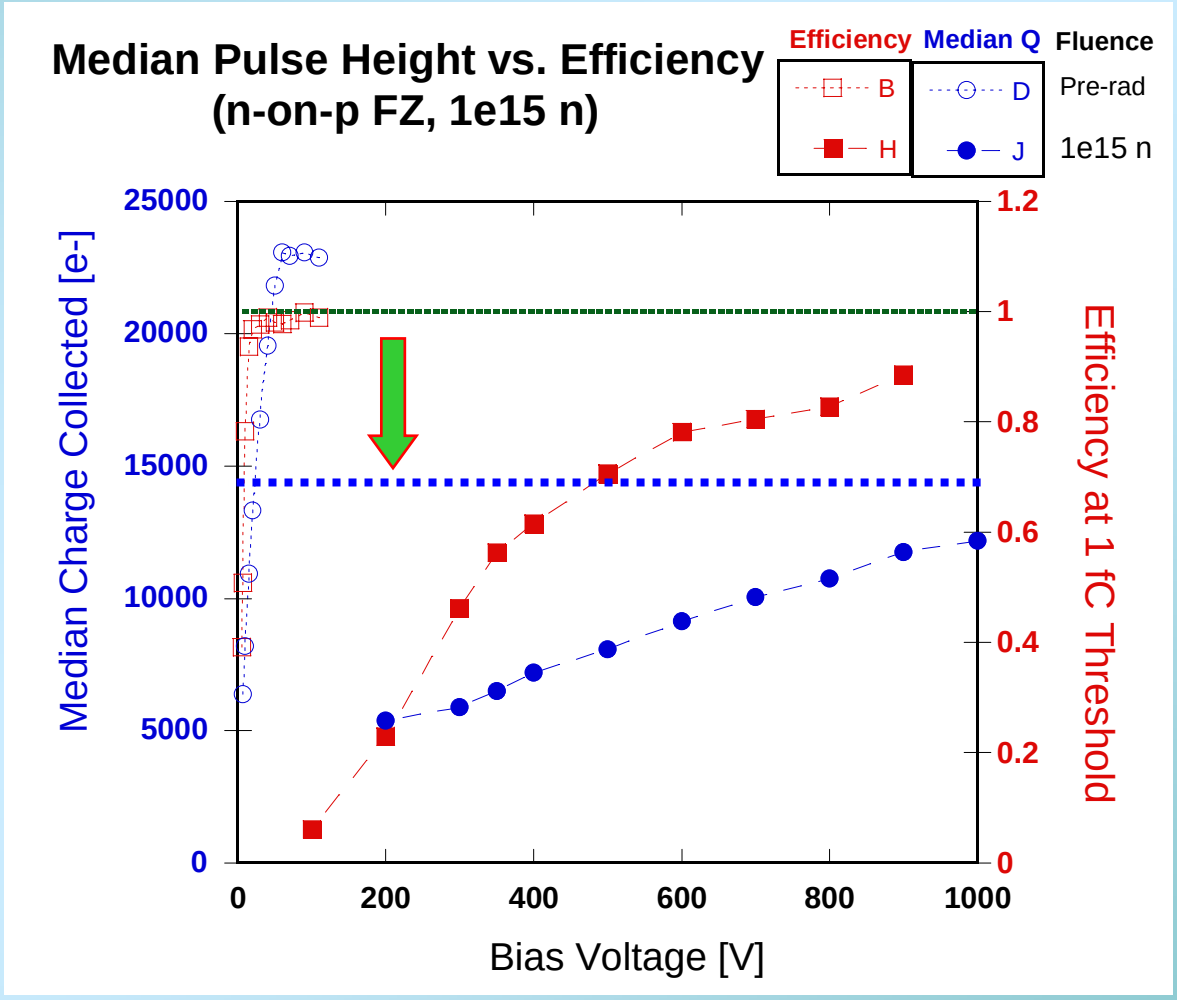
Efficiency vs. Collected Charge

- For tracking sensors with **binary readout**, the **figure of merit** is not the collected charge, but the **efficiency**.
- **100% efficiency** is reached at a signal-to-noise ratio of **S/N ≈ 10**, **S/Thr > 2.5**
- For **long strips** (5e14 cm^{-2}) with a signal of about 14ke, the usual threshold of 1fC = 6400 e can be used.



Long strips efficient at 1fC threshold

Efficiency vs. Collected Charge



- For **short strips** (1e15 cm^{-2}) with a signal of about 8ke, the efficiency at 500V is only 70%.
- The threshold needs to be reduced to about 4500 e, i.e. electronics must be designed for a noise of ~700e.

Short strips efficient if threshold can be lowered

Thin and Pixel sensors

Thin Sensors

Benefits of thin sensors:

Can be fully depleted at high fluences (important for p-on-n sensors ?):

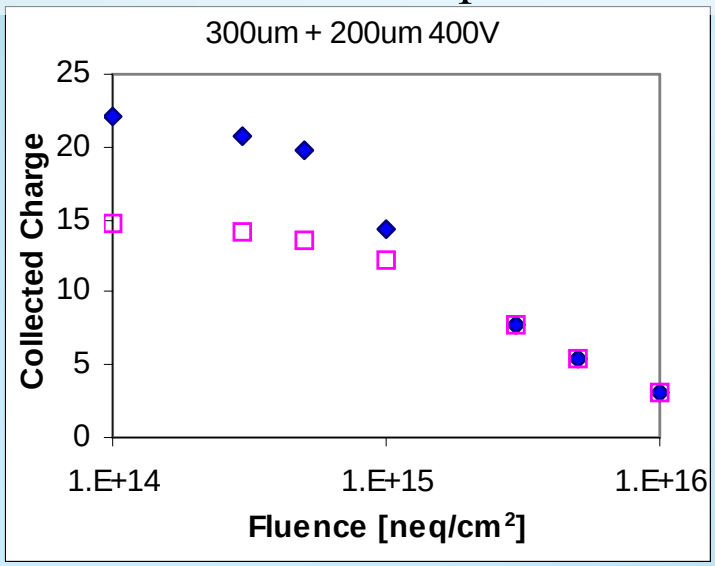
Thin detectors allow very high effective doping densities in n-type detectors and thus "delay" of inversion to very high fluences. $V_{bias} = q*Neff/(2\varepsilon)*x^2$

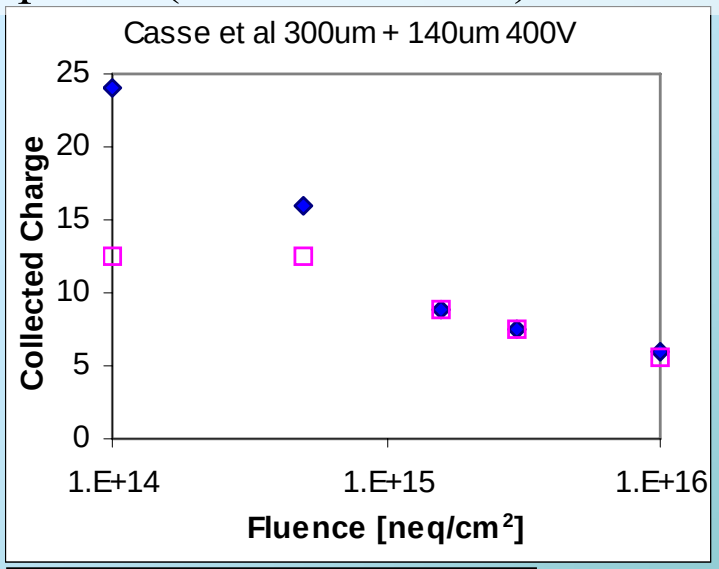
Less material (sensor only a fraction of the total material budget)

Disadvantage of thin sensors:

Signal lower for much of the operation

Thick sensor can be operated under-depleted (current is lower)





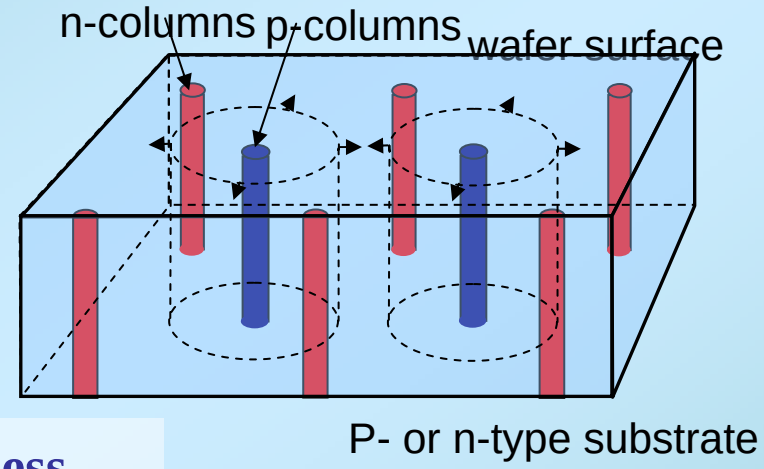
Simulations 2005:
(M. Bruzzi, H. F.-W. Sadrozinski, A. Seiden, NIM A 579 (2007) 754–761)

Measurements 2007
(G. Casse, Affolder, P.P. Allport, IEEE 07, N07-06)

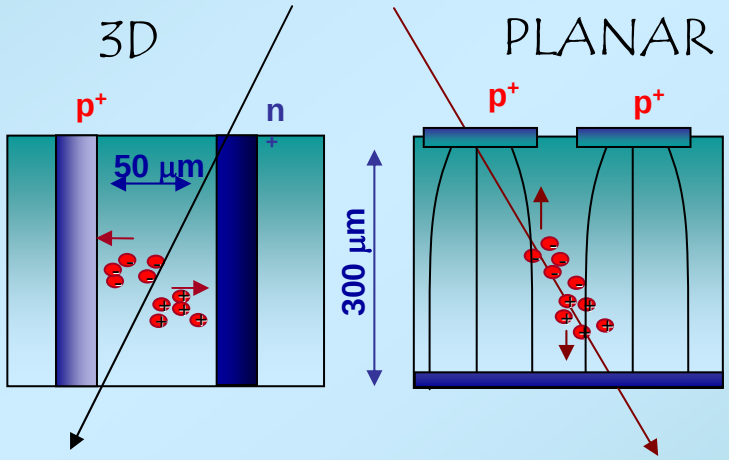
3D Detector - Concept

- **Planar electrodes replaced by columns through the wafer**
  - diameter: 10mm, distance: 50 - 100mm
- **De-couple deposit and charge collection**

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



- **Lateral depletion assures Radiation Hardness**
  - **Low depletion voltage: Increase active thickness**
  - **Short drift distance and fast signal: Decrease trapping**



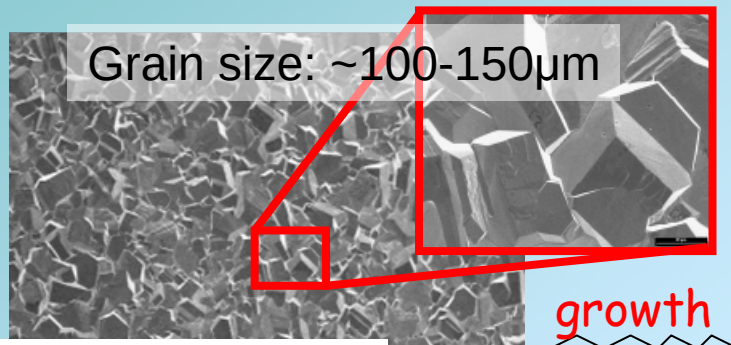
ATLAS project	Development, Testing and Industrialization of Full-3D Active-Edge and Modified-3D Silicon Radiation Pixel Sensors with Extreme Radiation Hardness Results, Plans.		
ATLAS Upgrade Document No:	Institute Document No.	Created: 17/07/2006	Page: 1 of 13
		Modified: 08/03/2007	Rev. No.: 2.00

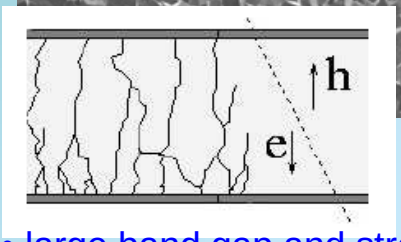
No proton irradiation

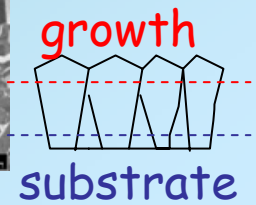
No radiation hardness with MIP (only laser)

pCVD Diamond

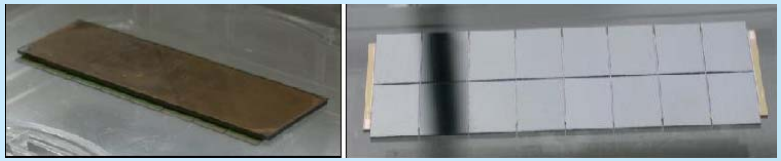
ATLAS project	Diamond Pixel Modules for the High Luminosity ATLAS Inner Detector Upgrade		
ATLAS Upgrade Document No:	*Institute Document No.*	*Created:* 11/05/2007	*Page:* 1 of 12
		Modified:	*Rev. No.:* 1.0



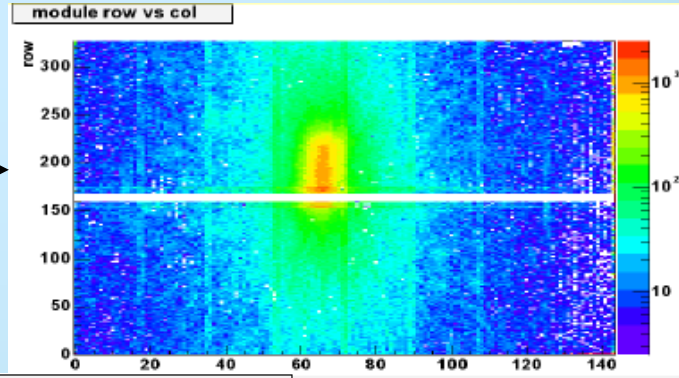




ATLAS pixel module

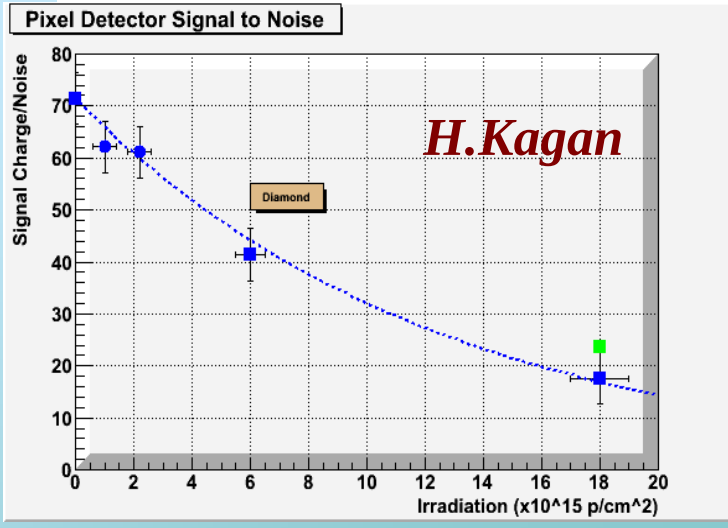


hitmap



- large band gap and strong atomic bonds promise fantastic radiation hardness
- **low leakage current and low capacitance both give low noise**
- **Ionization energy is high: MIP≈ 2x less signal for same X_0 of SI**
  - Diamond: ~13.9ke$^-$ in 361 µm (140 enc; bare threshold ~1500e)
  - SI: ~22.5 ke$^-$ in 282 µm
- Grain-boundaries, dislocations, and defects can influence carrier lifetime, mobility, charge collection distance and position resolution
- Available Size ~2 x 6 cm^2 (12cm diameter wafer; ~2mm thick)

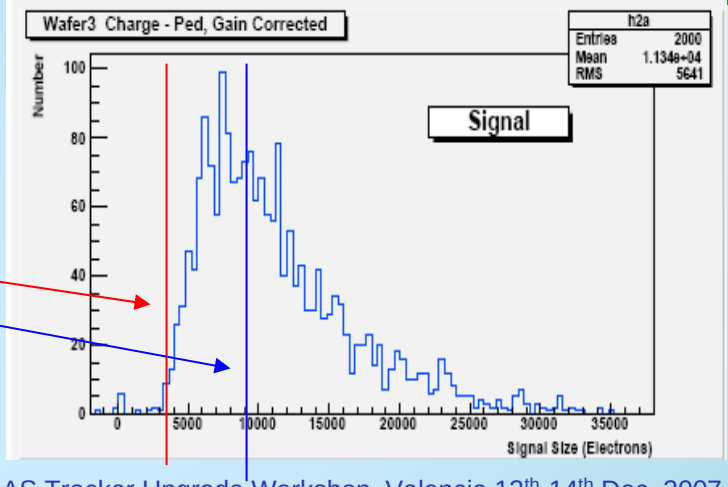
M. Mikuz ATLAS Tracker Upgrade Workshop, Valencia 12th-14th Dec. 2007



Pixel Sensor Efficiency: Signal/Threshold

Signal is Landau (here Diamond):

Efficiency requires
Signal/Threshold > 2



O. Roehne ATLAS Tracker Upgrade Workshop, Valencia 12th-14th Dec. 2007

C. daVia ATLAS B-Layer Workshop, CERN Sep. 28-30. 2007

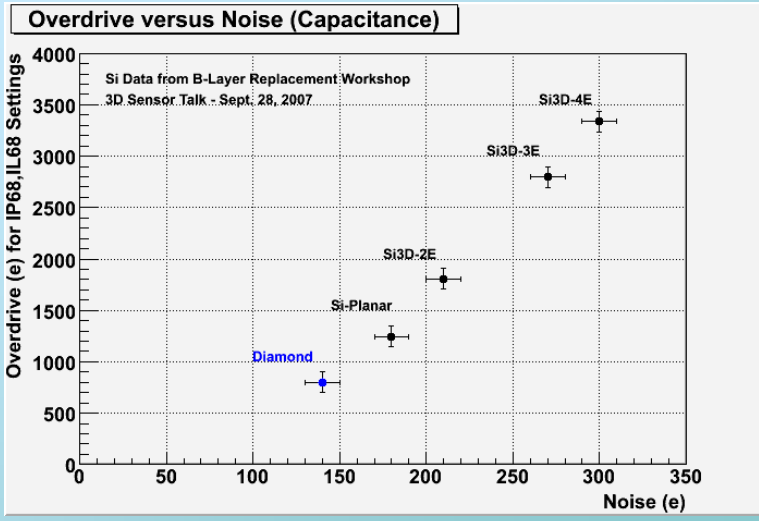
Threshold

"bare" threshold is set as low as the system permits
Bare Threshold ~ 1500e for Diamond
~ 2500e for Silicon
(why does it not scale with noise?)

In order to fit the hit into the beam crossing of 20 ns, the signal has to exceed the threshold by the "overdrive".

In-time Threshold = bare threshold + overdrive

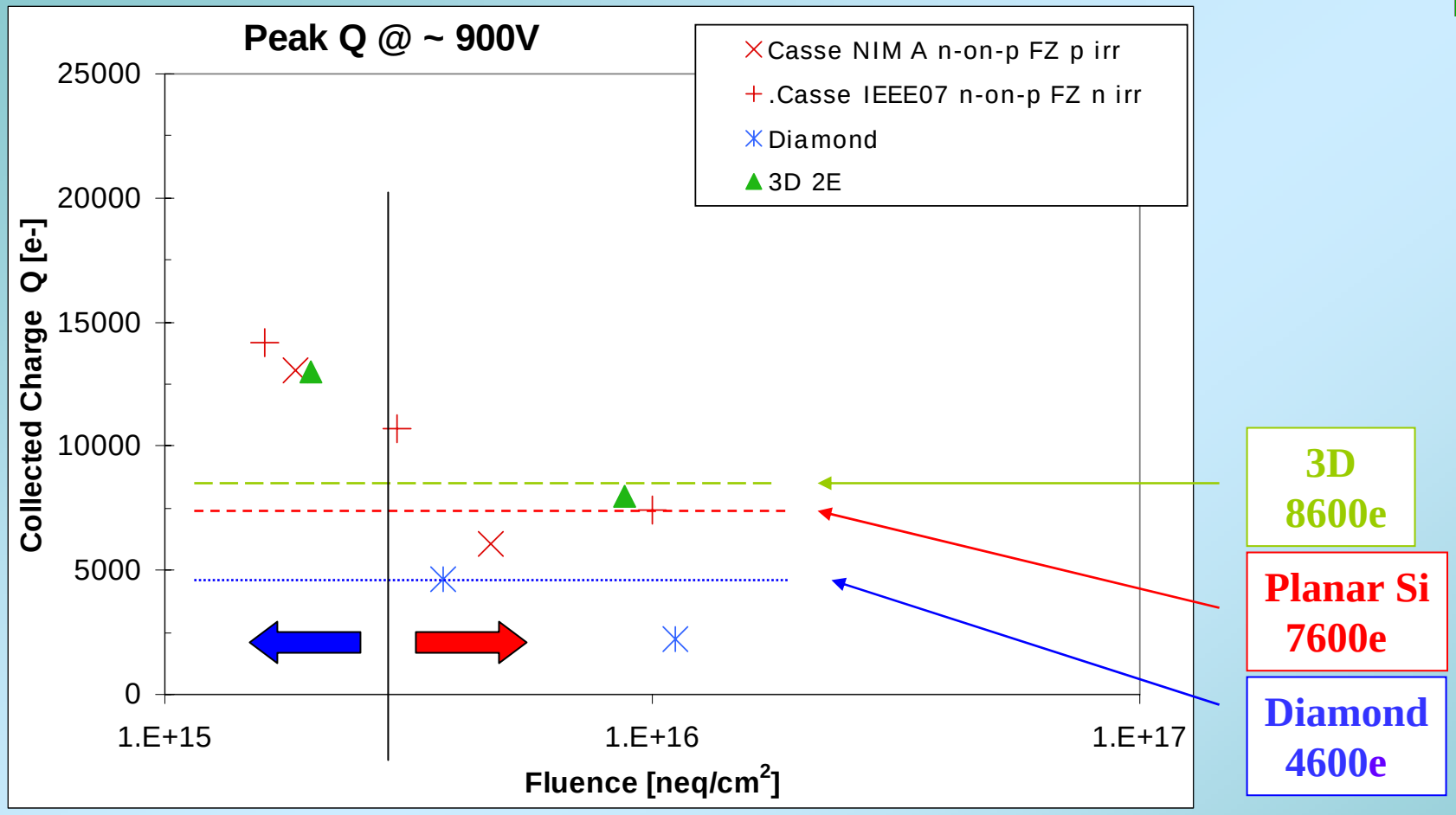
Overdrive scales with noise



Signal needs to be > 2x In-time Threshold:

Sensor	Threshold [e]			Required Signal [e]
	Bare	Overdrive	In-time	
Si planar	2500	1300	3800	7600
Si 3D	2500 (?)	1800	4300	8600
Diamond	1500	800	2300	4600

Pixel S/N -> Signal/Threshold



Need comparisons of CCE(V) with (m.i.p.) and S/N after $10^{16} n_{eq}/cm^2$ of protons
Preliminary results show marginal performance for 3D.
Need to optimize FEE?

Planar n-on-p adequate for all but innermost Pixel Layer

Planar (protons!) and diamond are not adequate for innermost Pixel Layer

Conclusions

RD50 provided the bases for understanding the use of tracking detectors at the LHC upgrade.

No magic new semiconductor tracking material found.

Paradigm change in Si at fluence of about 10^{15} neq/cm^2:

At lower fluences depletion of sensors important.

MCz seems to be favored, at least for neutrons

Strong annealing in n-type FZ, little annealing in p-type and n-type MCz.

Collect electrons in n-on-p (cheaper than n-on-n) because of high mobility.

Collected charge almost independent of wafer type except n-type FZ.

At higher fluences trapping dominates

but high resistivity MCz p-type could have depletion advantage at very high fluences.

A straw-man tracker layout at the sLHC looks like this:

Planar n-on-p sensors with long and short strips at large and medium radius and the outer pixels.

At small radii, the pixel sensors might need to be made from 3D sensors, but we need more high fluence proton data with planar p-type MCz.

Acknowledgments

Thanks to

the foundries and institutes who supplied sensors,

RD50 collaborators in Ljubljana, Liverpool, Louvain, CERN, Karlsruhe, PSI, UCSC for carrying out the irradiations, and analyzing the data.

the many students who spend their evenings and nights taking and analyzing the data.

References

ATLAS Tracker Upgrade Workshop Valencia Dec 11-14 2007

http://indico.cern.ch/conferenceTimeTable.py?confId=21398

ATLAS Upgrade Website

http://indico.cern.ch/categoryDisplay.py?categId=350

RD50 Website

http://rd50.web.cern.ch/rd50/

LHC Machine Operations Website

http://lhc-operation.web.cern.ch/lhc-operation/

ATLAS Inner Detector Replacement

To keep ATLAS running more than 10 years the inner tracker will have to go ...
(Current tracker designed to survive up to 730 fb^{-1} ≈ 10Mrad in strip detectors)

For the luminosity-upgrade the new tracker will have to cope with:

- **much higher occupancy levels 3000 fb-1**
- **much higher dose rates ~ 300Mrad**
- **same performnace**

To build a new tracker for 2015, major R&D program already needed.

Steering group (lead Nigel Hessey) and several working groups.

Formal proposal submittal structure.

Timescales:

- **R&D leading into a full tracker Technical Design Report (TDR) in 2010**
- **Construction phase to start immediately TDR completed and approved.**

The intermediate radius barrels are expected to consist of modules arranged in rows with common cooling, power, clocking and cooling.

The TDR will require prototype super-modules/staves (complete module rows as an integrated structure) to be assembled and fully evaluated

All components will need to demonstrate unprecedented radiation hardness

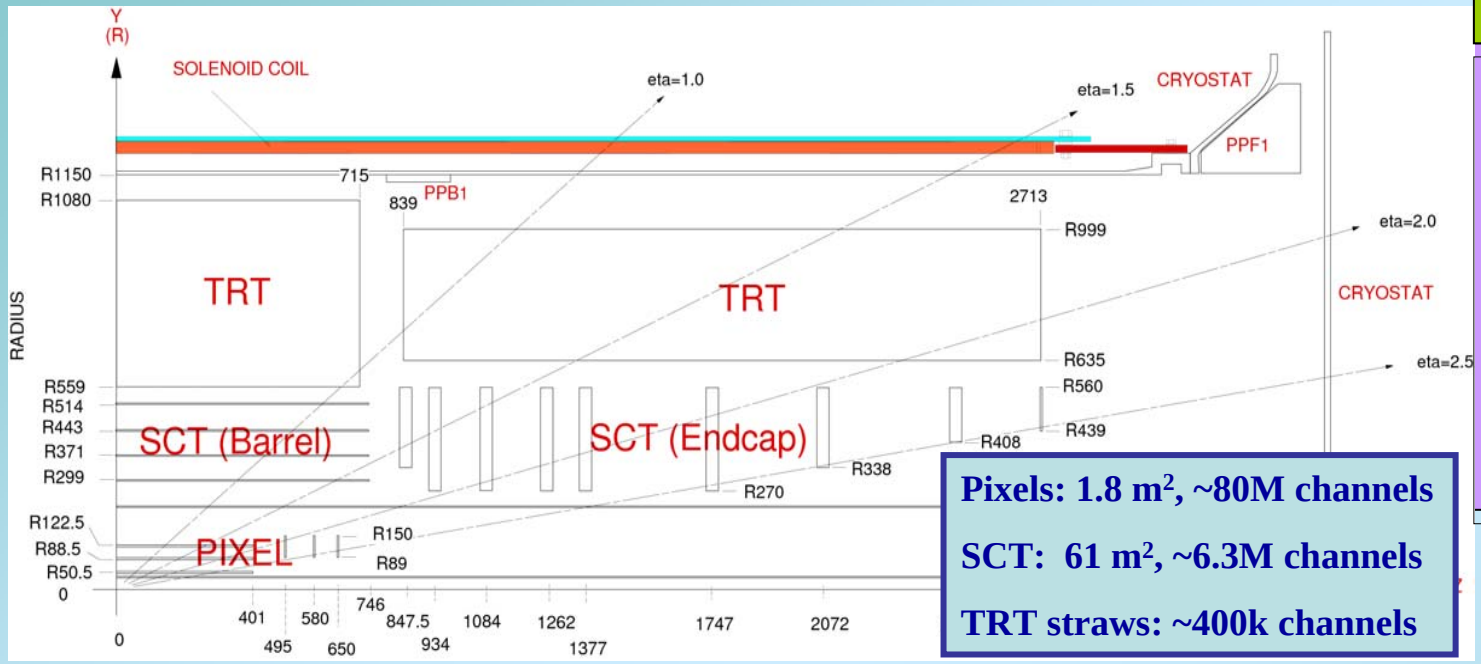
✓many strategies to follow up, new techniques, many unknown parameters .... needs first beam

- 25 ns vrs 50 ns .... 12ns,75ns gone!
- LHC nominal and ultimate L strategy -> new large aperture triplet
- Early separation scheme, magnets inside the detector ... small crossing angle
- Beam-beam effects : unclear can be tolerated, wait for LHC beam
- Luminosity leveling : new .... more fill lifetime, less peak luminosity
- Crab cavities,... : new magic technology, need substantial R&D

✓ ATLAS message is always the same:

we prefer more constant luminosity, less pile up at the start of the run, higher luminosity at the end

Current Inner Tracker Layout

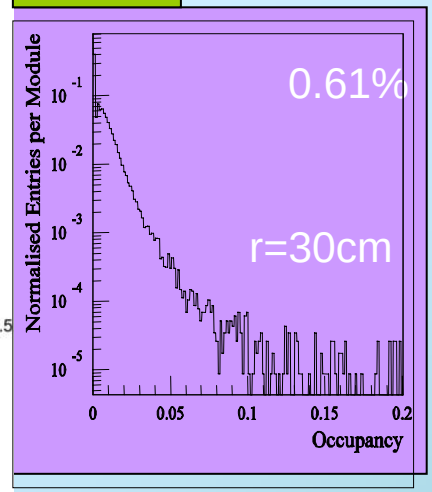


Pixels: 1.8 m², ~80M channels

SCT: 61 m², ~6.3M channels

TRT straws: ~400k channels

ID TDR



Mean Occupancy in Innermost Layer of Current SCT

Pixels (50 μm × 400 μm): 3 barrels, 2×3 disks 5cm < r < 15cm

- Pattern recognition in high occupancy region
- Impact parameter resolution (in 3d)

Radiation hard technology: n^+-in-n Silicon technology, operated at -6°C

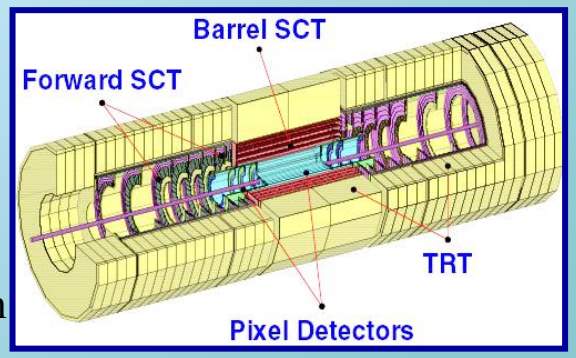
Strips (80 μm × 12 cm) (small stereo angle): "SCT" 4 barrels, 2×9 disks

- pattern recognition 30cm < r < 51cm
- momentum resolution

p-strips in n-type silicon, operated at -7°C

TRT 4mm diameter straw drift tubes: barrel + wheels 55cm < r < 105cm

- Additional pattern recognition by having many hits (~36)
- Standalone electron id. from transition radiation

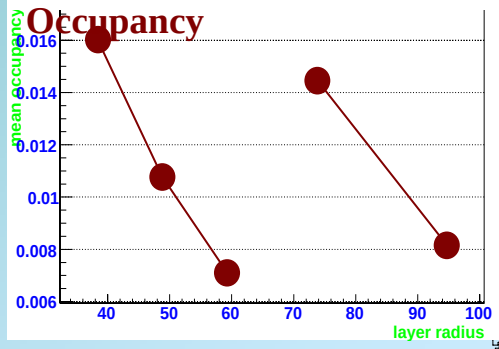


New SLHC Layout Implications

Strawman 4+3+2

Pixels:	**r=5cm, 12cm, 18cm, 27cm**	**z=±40cm**
Short (2.4 cm) μ-strips (stereo layers):	**r=38cm, 49cm, 60cm**	**z=±100cm**
Long (9.6 cm) μ-strips (stereo layers):	**r=75cm, 95cm**	**z=±190cm**

Short and Long Strip Occupancy

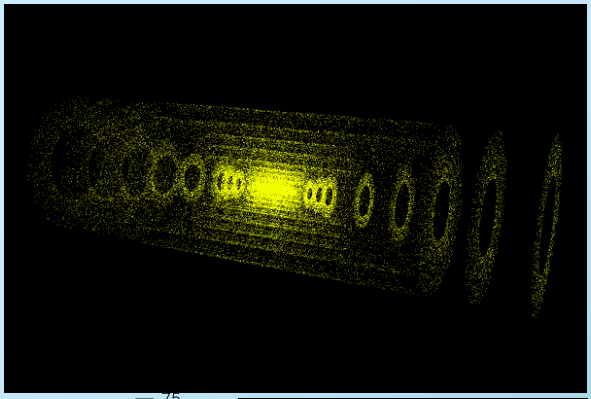


1.6%

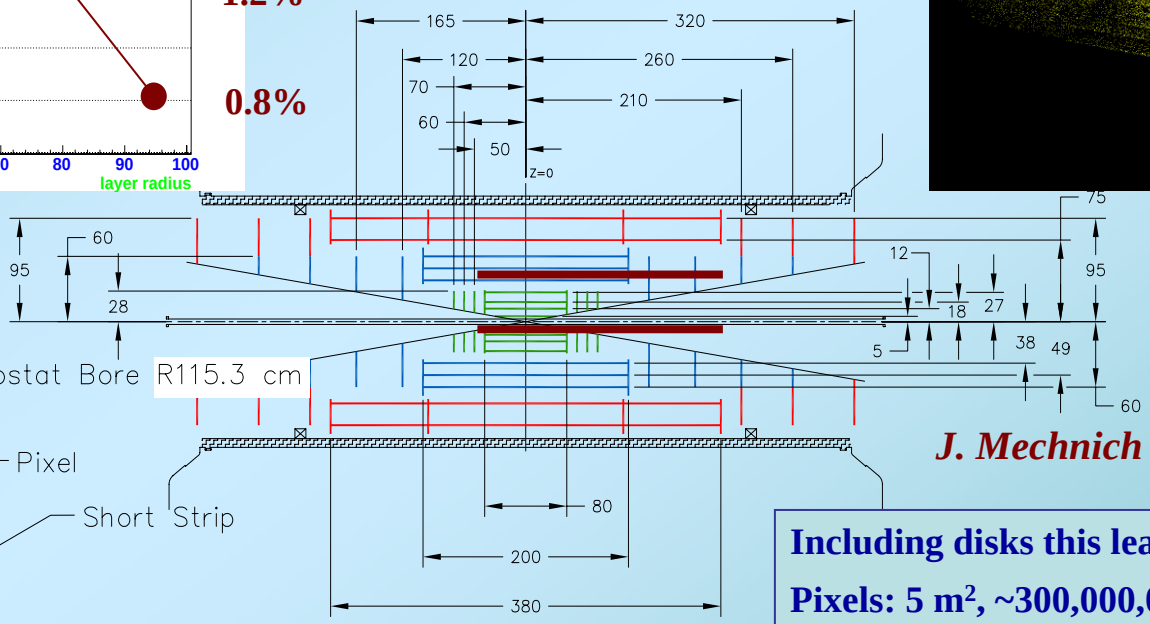
1.2%

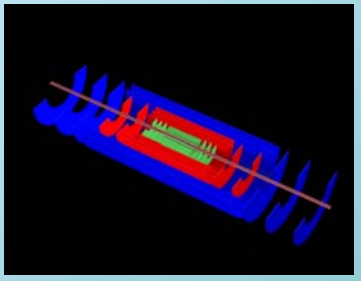
0.8%

Only LO MC (Pythia) . May need to include ×2 safety factor?

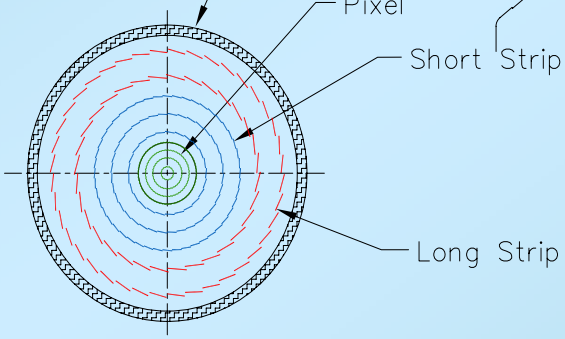


J. Tseng





J. Mechnich



Including disks this leads to:

Pixels: 5 m², ~300,000,000 channels

Short strips: 60 m², ~28,000,000 channels

Long strips: 100 m², ~15,000,000 channels