RD50:
Development of Radiation Hard Tracking Detectors

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on behalf of the RD50 Collaboration

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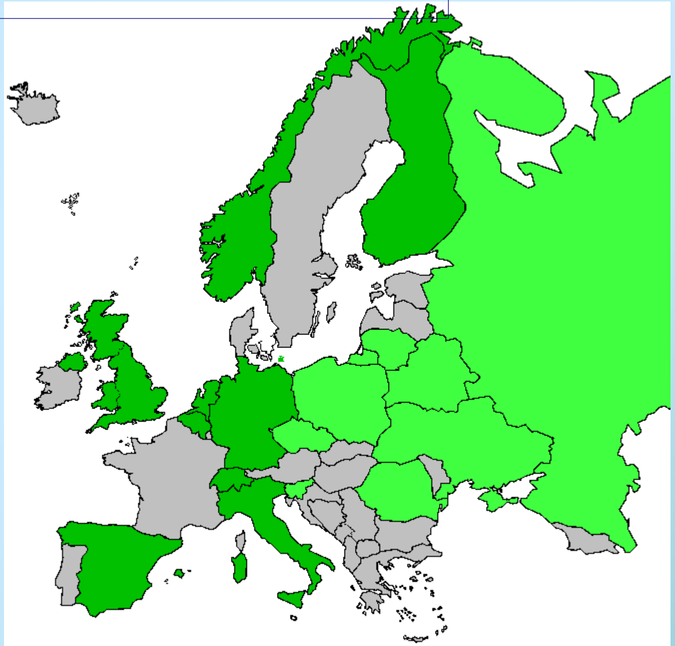
RD50 – CERN R&D Collaboration

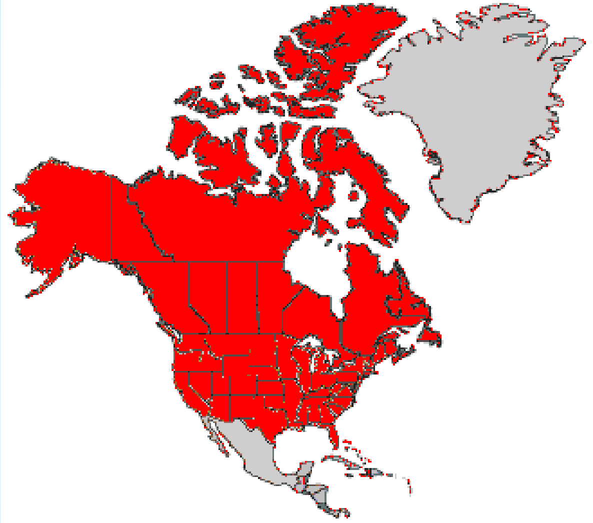
“Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders”

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

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 was limited by radiation damage. The aim of RD50 is to develop Radiation-Hard Semiconductor Devices for High Luminosity Colliders -- which short time later came along in the form of the LHC Upgrade, the Super-LHC (sLHC).

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

- Extend the radiation testing to the predicted sLHC fluences
- Search for alternative, more radiation-hard sensor materials than Si
- Develop new experimental methods to help gaining insight into the radiation damage mechanism
- Understand on the microscopic level the radiation damage observed
- Optimize sensor geometry for radiation tolerance
- Start to transfer fabrication to commercial manufacturer in anticipation of large-scale production

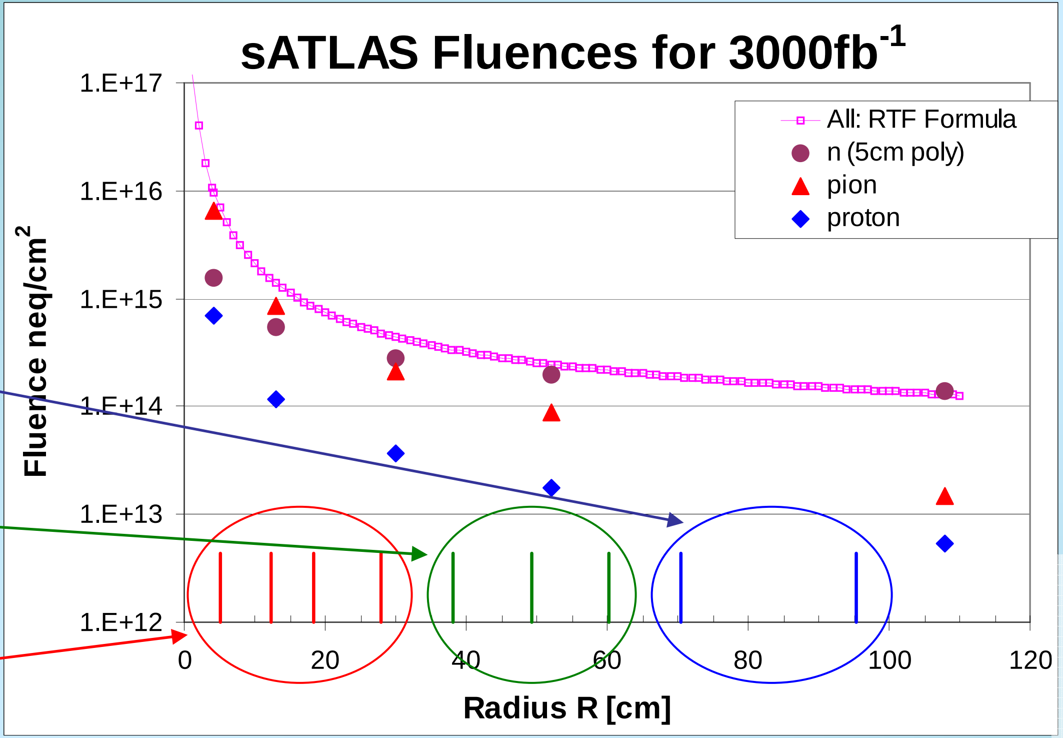
Predicted Fluence in Proposed sATLAS Tracker

Radial Distribution of Sensors determined by Occupancy < 2%

Long Strips

Short Strips

Pixels



5 x LHC Fluence

Mix of n, p, π depending on radius R

Strips Damage largely due to neutrons

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

Design fluences for sensors:

$1*10^{16}$ neq/cm^2 (pixels), $1*10^{15}$ neq/cm^2 (short strips), $4*10^{14}$ neq/cm^2 (long strips) (includes 2x safety factor)

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New materials for Tracking Sensors?

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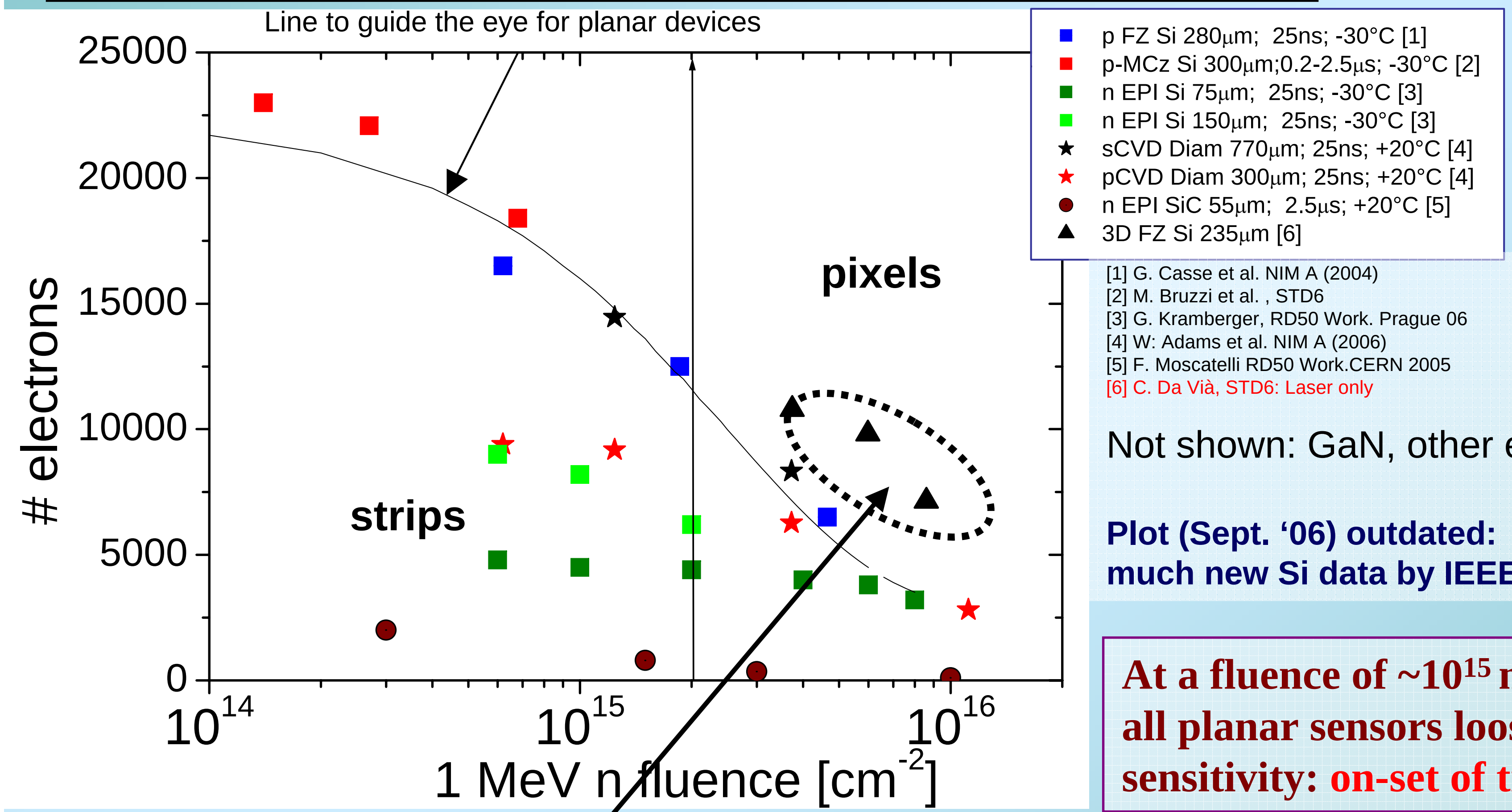
Comparison of measured collected charge on different radiation-hard materials and devices
(M. Bruzzi, H. F.-W. Sadrozinski, A. Seiden, NIM A 579 (2007) 754–761)



[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 by IEEE07!

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

Strips: S / N > 10 → Planar Si SSD ok , Pixels: S / N > 15 → need new approach

Solution for Pixels: 3-D sensors, which decouple drift distance from active depth

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Radiation Damage in Silicon Sensors

- **Bulk (Crystal) damage due to Non Ionizing Energy Loss (NIEL)**

  - displacement damage, built up of crystal defects –

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)

III. 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 the oxide (SiO_2) and the Si/SiO_2 interface –

  ⇒ interstrip capacitance, breakdown behavior, …

- **Important latent effects:**

  Space charge sign inversion (SCSI)

  Annealing

Mitigation of Radiation Damage in Si

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- **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**

All these effects can be probed with a variety of methods, but at the end the measurement of the collected charge in a segmented sensor at sLHC speed is decisive.

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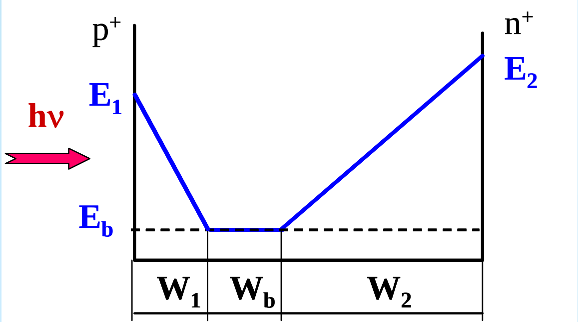
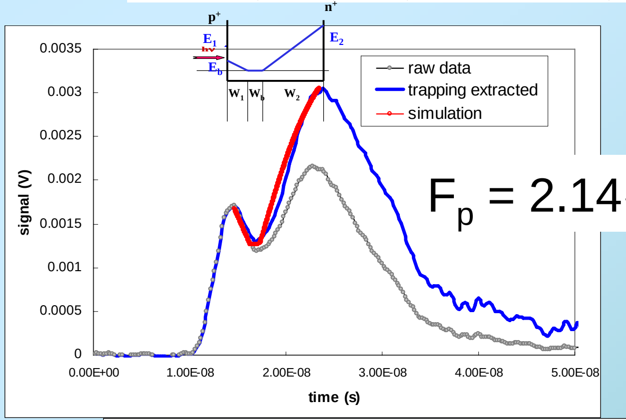
Investigation of E-Field Profile: TCT

Transient Current Technique (TCT) probes the E-field within the sensor by recording the time profile of the collected charge generated by a red laser pulse.



The pulse shows a characteristic double peak structure, proof for a double-junction in the sensor, in addition to the undepleted bulk, which at large fluences becomes highly resistive.

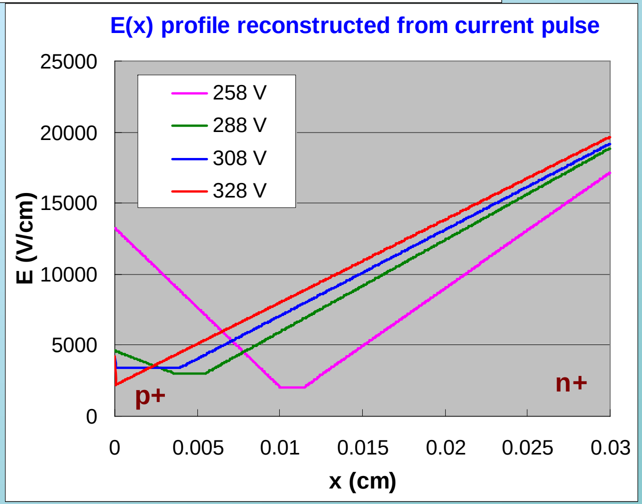
The 2nd peak is reduced by trapping, and needs to be corrected for.



$F_p = 2.14 \cdot 10^{14}\ \mathrm{cm}^{-2}$

The E-field distribution is governed by space charge due to trapped charges, leading to rapid changes depending on the bias voltage.

E. Verbitskaya et al. NIM A 557 (2006) 528



Paper at IEEE NSS'07 :

Z. Li et al. N44-3.

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Investigation of E-Field Profile: C-V

The E-field in the sensor can be probed with Capacitance-Voltage (C-V) measurements, which determine the depleted thickness x.

Since C(V) ~ 1/x, the reciprocal capacitance 1/C(V) carries the information about the depletion history.

Continuity of potential, E-field and measured leakage current connect the different areas of depletion.

A model with two trapping centers, one each for acceptors and donors, describes the general features of the data. This is based on the extensive work on **Defect Analysis** within RD50.

Voltage Dependence of Space charge

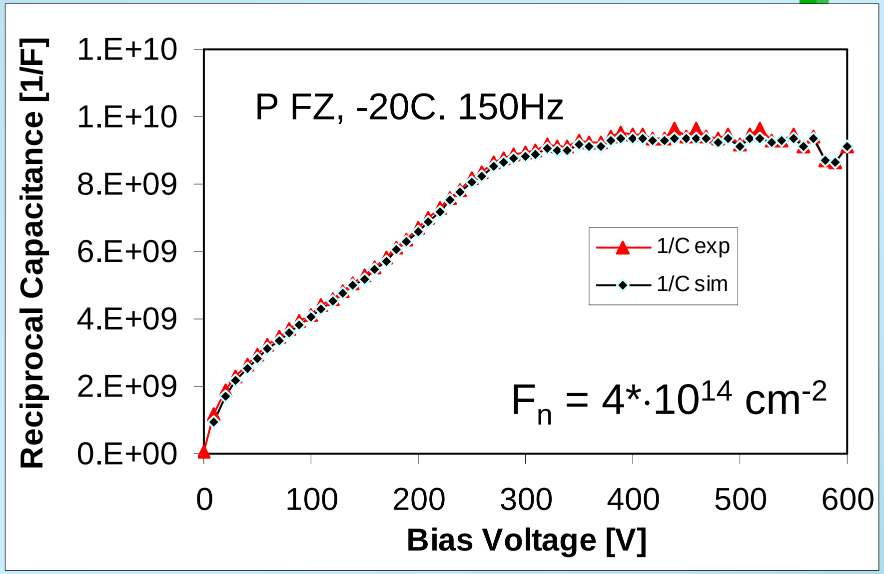
(200um n-on-p- FZ, $\Phi_n = 4^{*}\cdot 10^{14}$ cm^{-2}) :

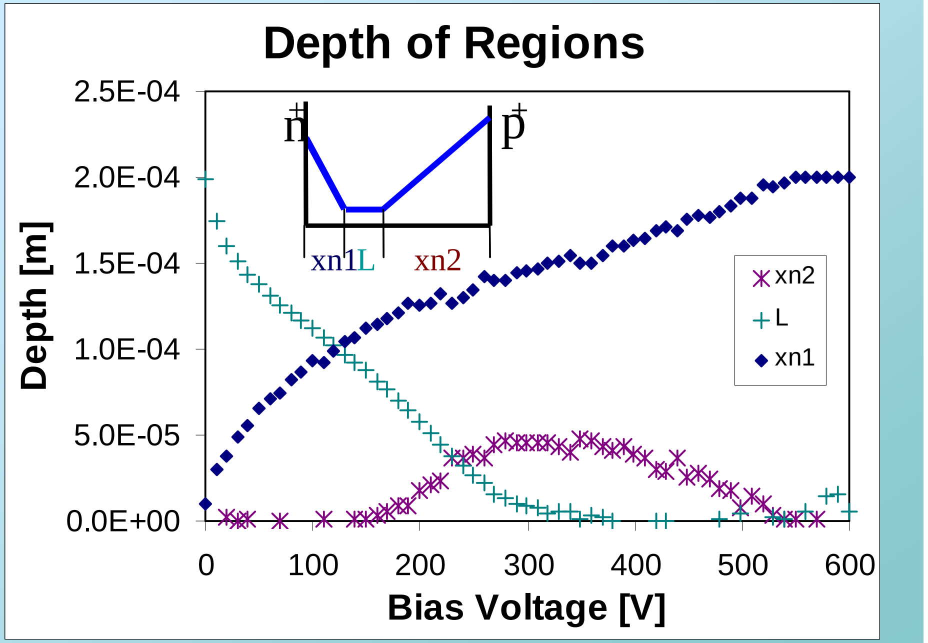
V <150V: depletion from n-side (~100um)

150V< V <350V:	n- and p-side depletion
350V< V <550V:	shift of p- to n-side
V > 550V:	only p-bulk

Papers at IEEE NSS’07 :

M. Bruzzi et al. N24-162





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Depletion: C-V vs. Charge Collection CCE

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Both C-V and CCE(V) depend on the depth of the depleted region x:

C(V) ~ 1/x

CCE(V) ~ x

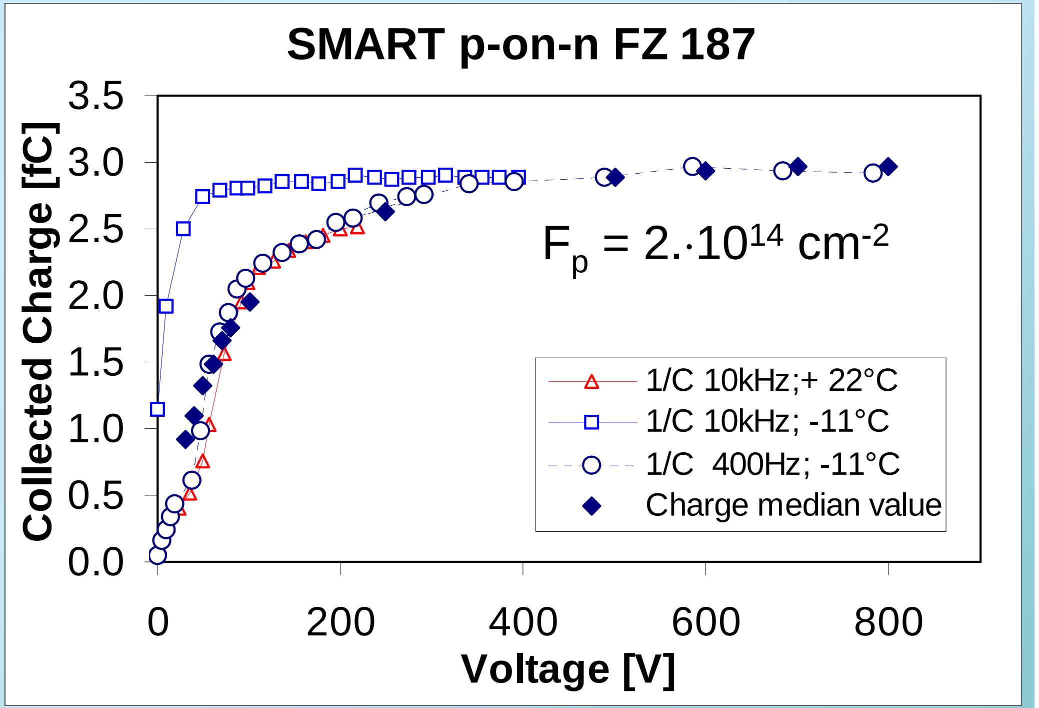
Calculate the expected collected charge = (3.5 fC)*C_o/C(V)

(Can we measure trapping as the ratio between CCE and 1/C?)

At low temps, use low frequency!

RT:	**10 kHz,**
-10º C:	**~400 Hz,**
-20º C:	**~250 Hz**

Low frequency-low temperature C-V permits absolute prediction of charge collection!



M.K. Petterson et al., RESMDD06, in print NIMA

Trapping

Collected Charge as a function of bias voltage

$$Q\,(V) = Q_o * \varepsilon(\text{depletion}) * \varepsilon(\text{trapping}) = Q_o*(x/w)*\exp(-\tau_c/\tau_t)$$

Depletion: x: depleted width, w: sensor width,

Uniform doping density: $V_{bias} = q*Neff/(2\varepsilon)*x^2$, $\varepsilon(x) = x/w = \mathrm{sqrt}(V_{bias} / V_{dep})$

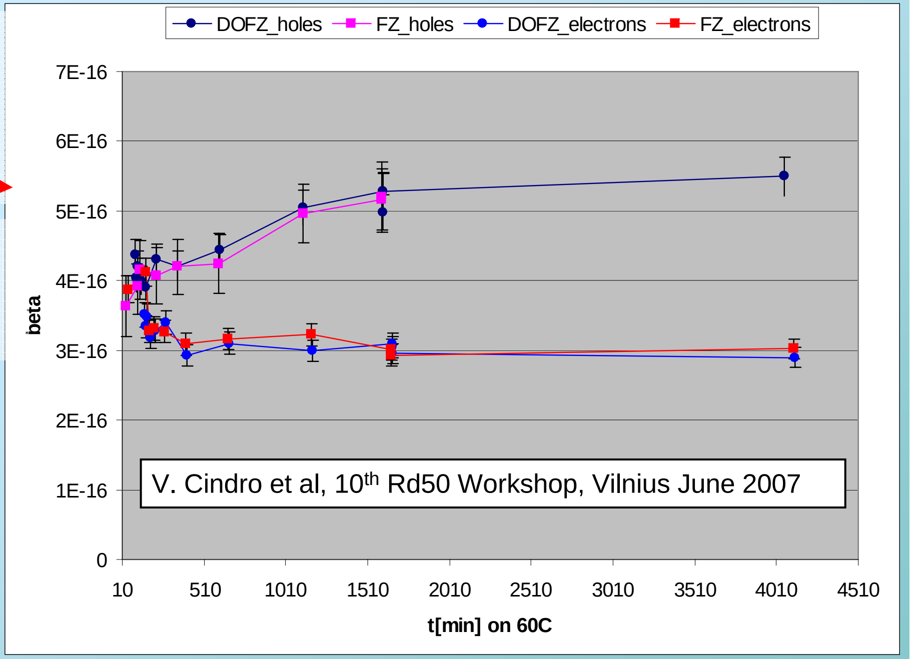
Trapping depends on the ratio collection time τ_c / trapping time

Trapping time $1/\tau_t = \beta*(\Phi/10^{16})\ \mathrm{ns}^{-1}$, $\beta = 5$ at $\Phi=10^{14}$

i.e $\tau_t = 2$ ns for $\Phi = 10^{15}\ \mathrm{cm}^{-2}$, $\tau_t = 0.2$ ns for $\Phi = 10^{16}\ \mathrm{cm}^{-2}$

N.B. β not constant, seems to decrease with fluence: good!

Electrons anneal favorably: good!



V. Cindro et al, 10th Rd50 Workshop, Vilnius June 2007

Explanation of dependence of charge collection: increase depleted region & speed up collection!

Trapping is the ultimate limitation for charge collection in semiconductors

(even for Diamond!)

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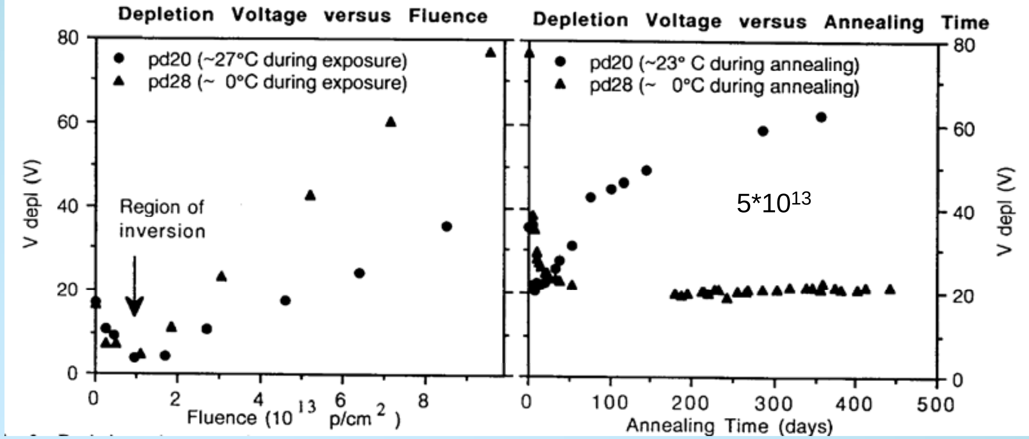
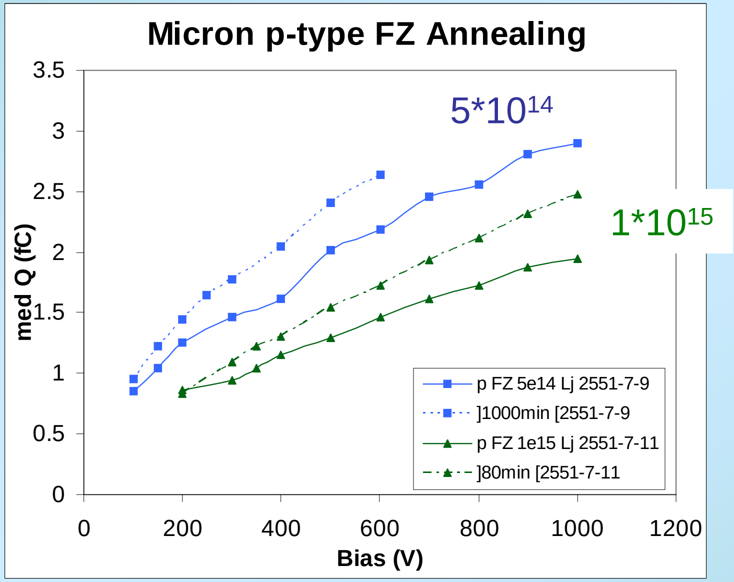
Annealing

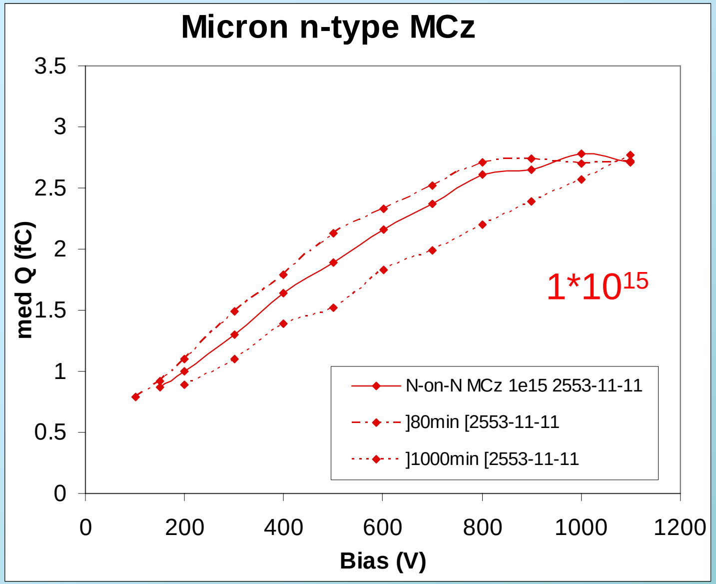
For p-on-n LHC sensors, annealing during and after irradiation was a major source of engineering and operational difficulties, since the sensors needed to be kept cold to prevent detrimental “anti”-annealing.



H.J. Ziock at al, IEEE TNS 40, 344 (1993)

At sLHC fluences, these effects are much less pronounced, and open 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





Accelerated annealing at elevated temperature 1000min @60 ºC = 514 days @RT

Thin Detectors

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

The “MCZ - type inversion riddle”

- Sign of effective space charge after high levels of irradiation

	MCz-n Cz-n	MCz-p	Epi-n (ρ>150Ωcm)	Epi-n (ρ=50Ωcm)	Epi-p (ρ~1KΩcm)	STFZ-n STFZ-p	DOFZ-n DOFZ-p
24 GeV/c protons	positive	negative	positive	positive	positive	negative	negative
26 MeV protons	negative	--	positive	--		negative	negative
neutrons	negative	negative	negative	positive		negative	negative

Why ?
Are MCZ- n and MCZ-p different?

The only n-type material that never inverts.

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

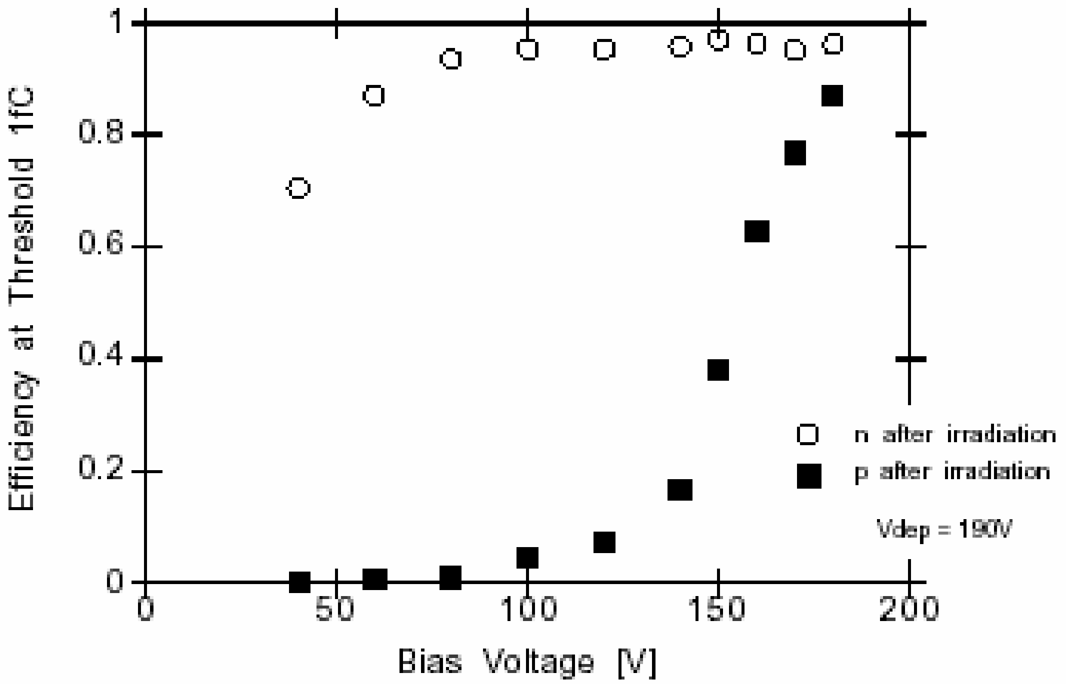
Advantage of collecting on the n-side after inversion was established long time ago:

Double-sided n-type SSD

106 Ru telescope

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

T. Dubbs *et al.*, *Nucl. Instr. Meth.* A383, 174 (1996),



This motivated the

n-on-n development for ATLAS SCT, LHCb

Paradigm Change for RD50:

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

Papers at IEEE NSS'07 : G. Casse et al. N07-06, M. Petterson et al. N24-160.

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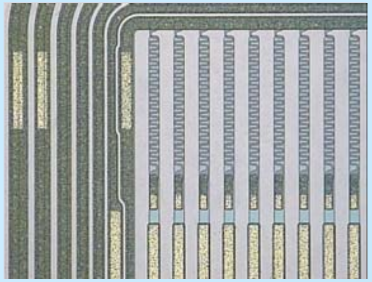
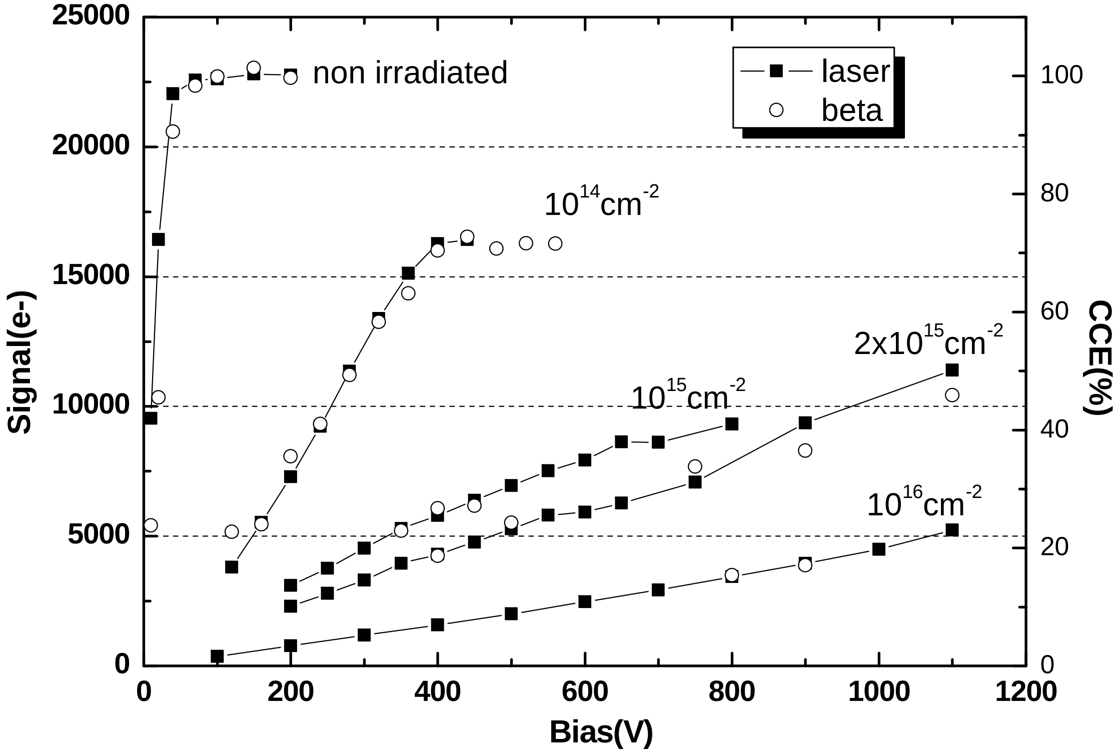
CCE on p-type SSD – MIPs & Laser

- Wafers <100>, P type FZ, 300 µm, ρ=20 kΩ·cm
- N strips on P-type material
- Manufactured at CNM (Barcelona)
- RD50 mask set
- 130 strips, 80 µm pitch, 1cm^2
- AC coupled, poly resistor bias
- P-spray isolation

No annealing





Routine CCE measurements after neutron fluence in excess of 10^{16} n/cm^2

Bias dependence of collected charge in good agreement between Laser and MIP

CCE is low because of "diode" configuration

Ultimate limits for the radiation hardness of silicon strip detectors for sLHC. M. Lozano et al. NIM A, In press

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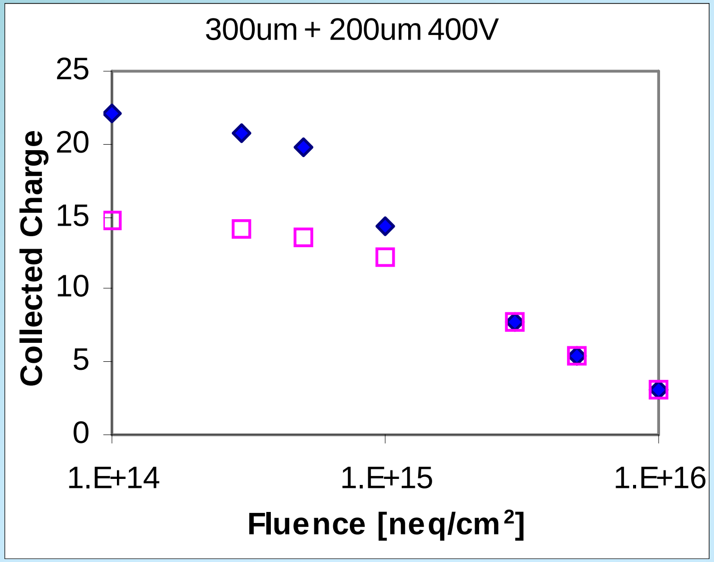
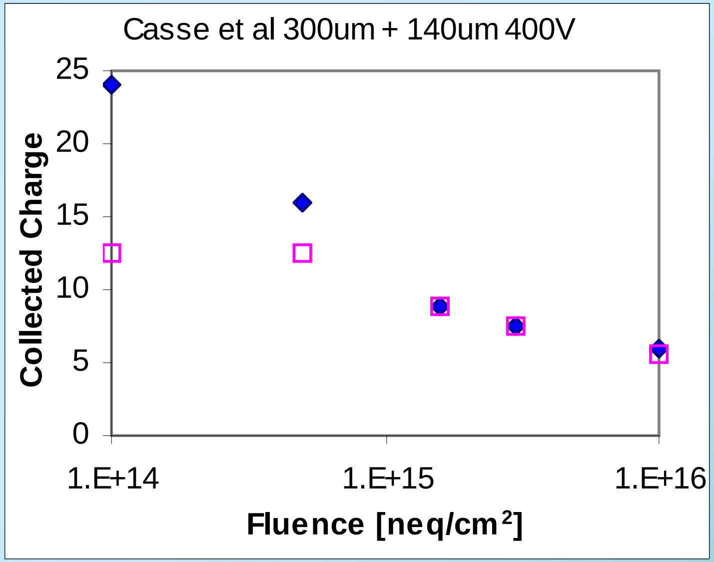
Simulations vs. Measurements

The improved understanding of the charge collection as a function of bias permits refined predictions of the performance during operations at the sLHC.

Example: questionable benefit of thin sensors:



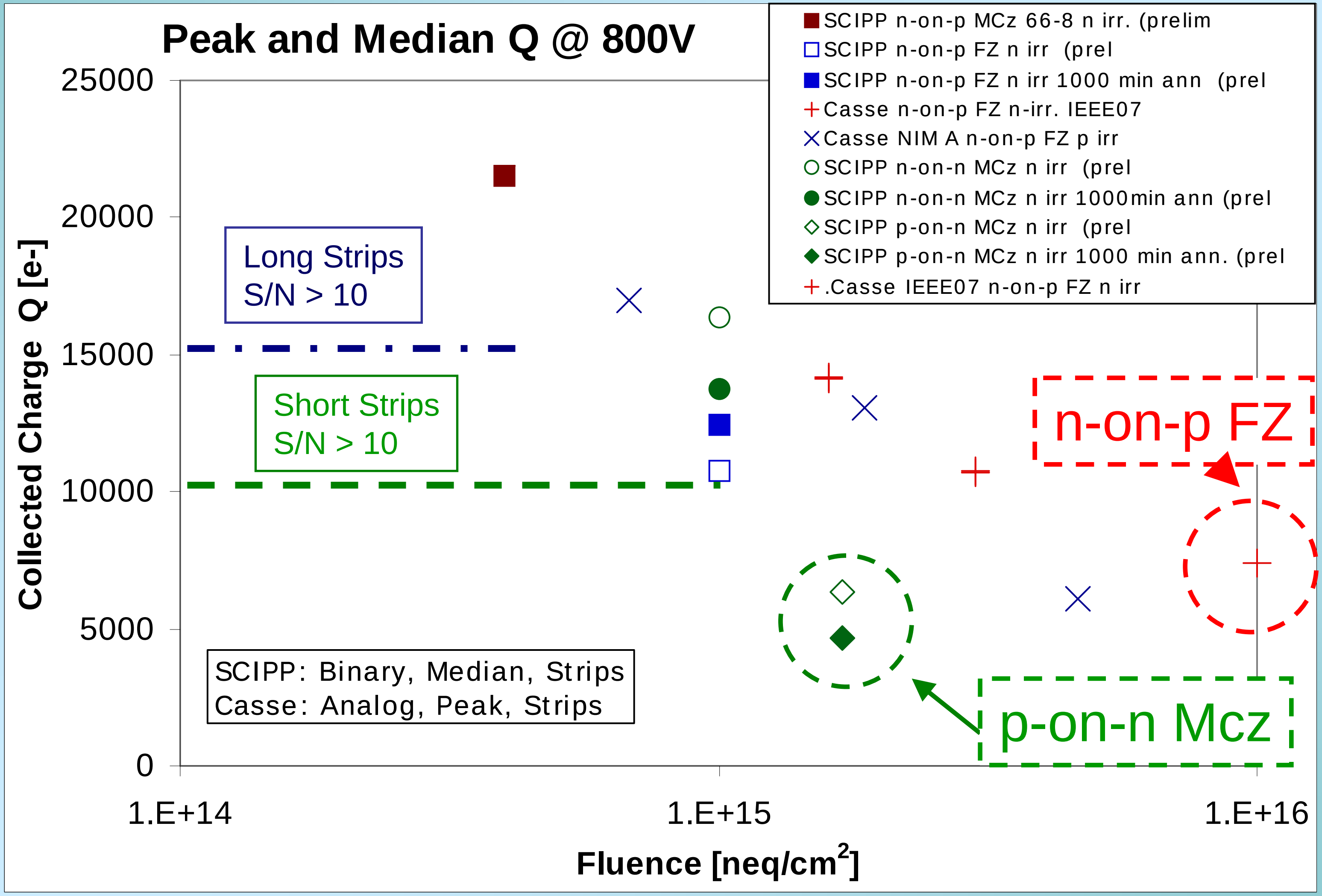


Simulations 2005:
(M. Bruzzi, H. F.-W. Sadrozinski, A. Seiden, NIM A 579 (2007) 754–761)

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

A few details are still not understood: e.g. the bias effect after irradiation to 10^{14} neq/cm^2.

Charge Collection in Upgrade Strips



N-on-p strip sensors are sufficiently radiation-hard for the sLHC
No obvious advantage for MCz over FZ.

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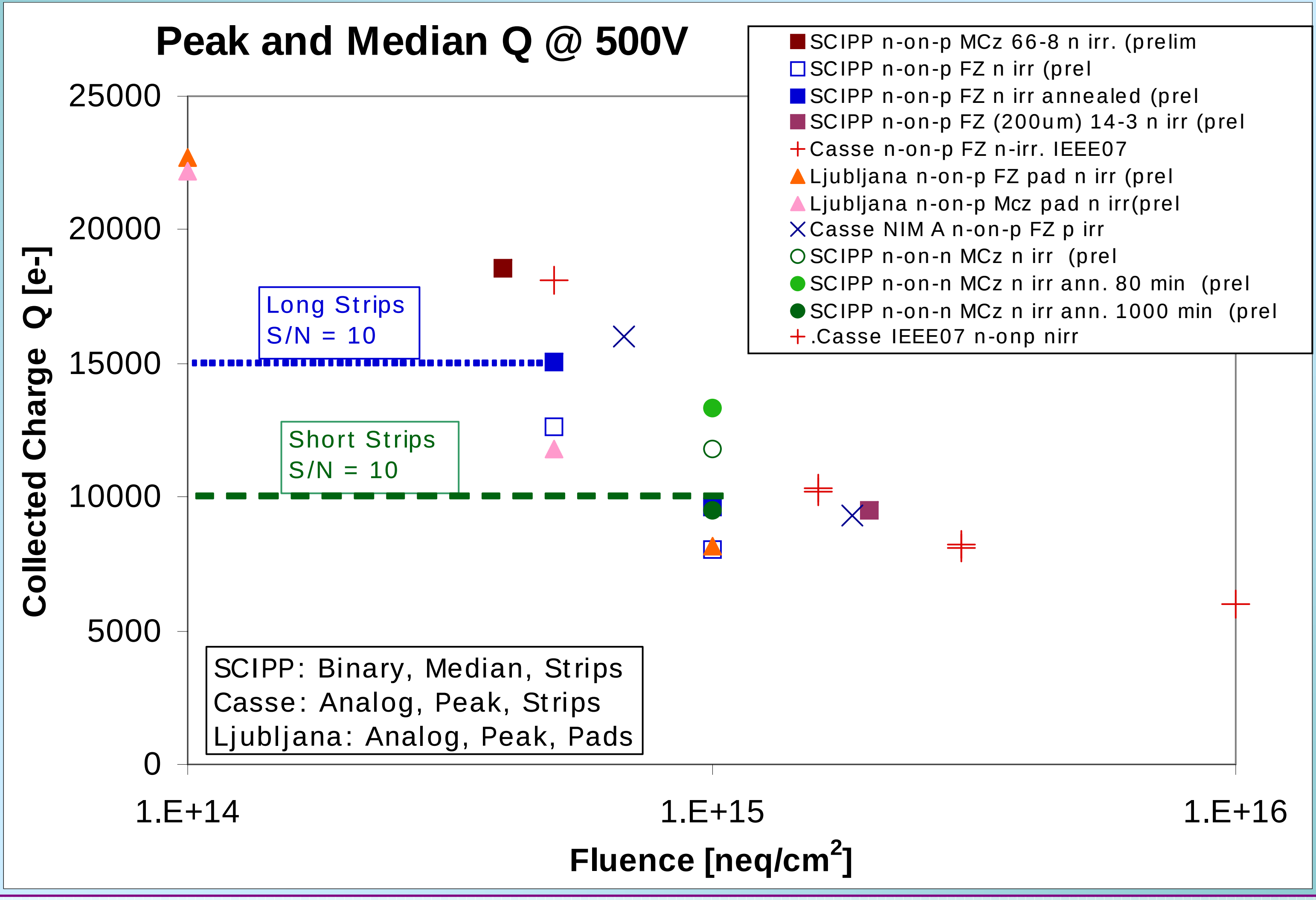
Charge Collection in Upgrade Strips

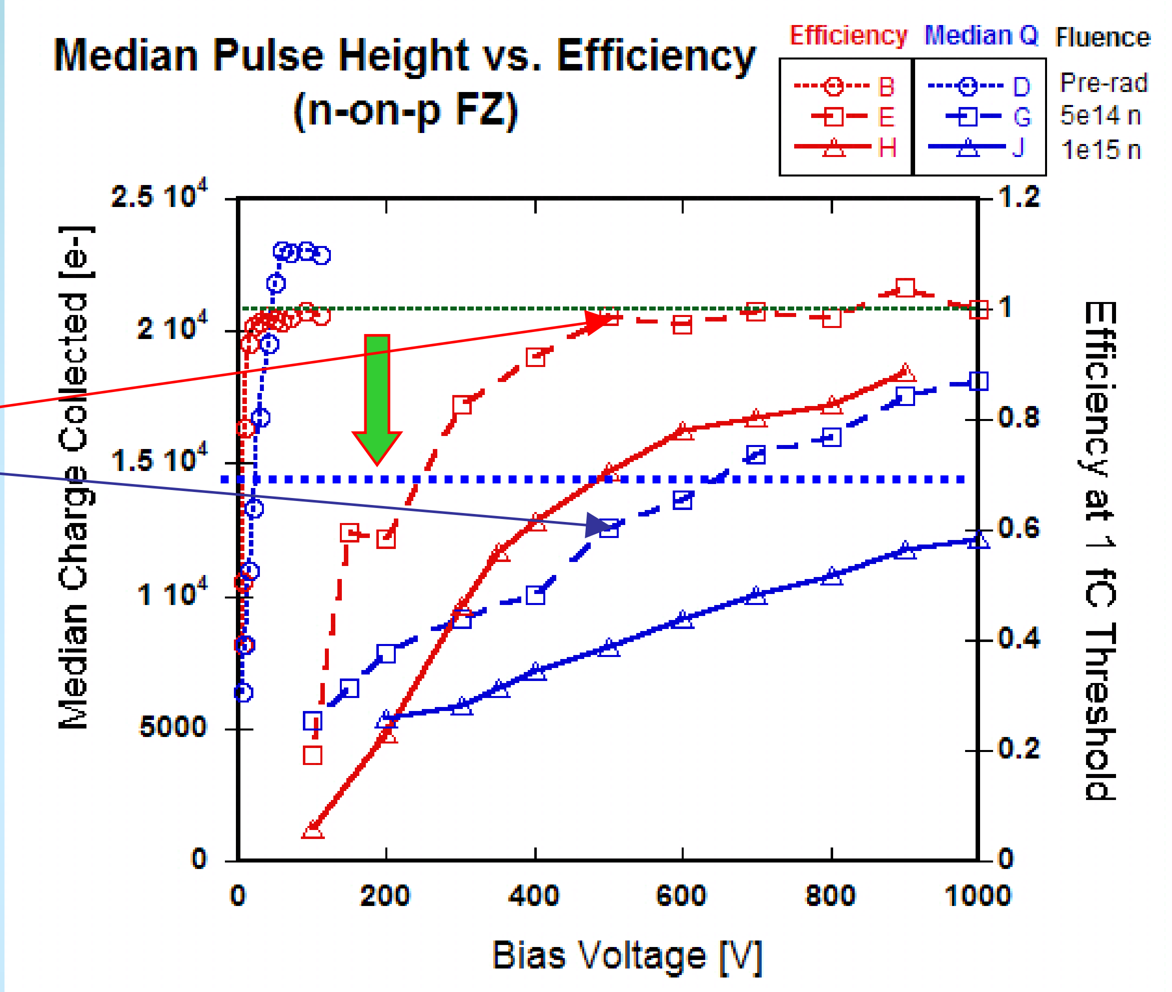
ATLAS bias voltage is constraint to < 500V (cables!).



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

Efficiency vs. Collected Charge

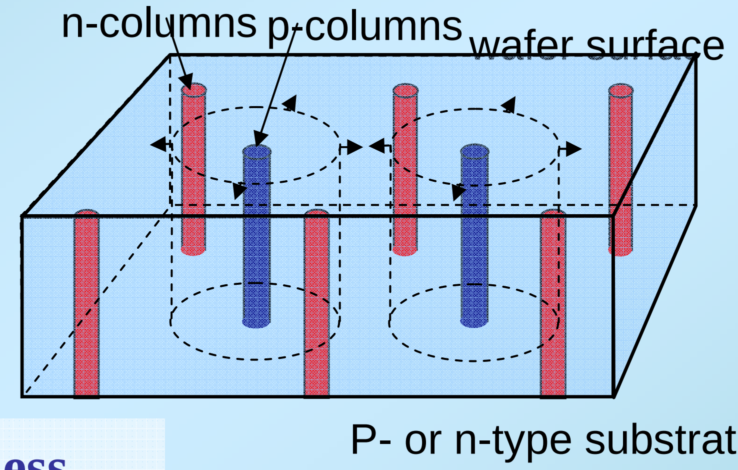
- For tracking sensors with **binary readout**, the **figure of merit** is not the collected charge, but the **efficiency**.
- **100% efficiency** is reached at a signal-to-noise ratio of **S/N ≈ 10**.
- For **long strips** (5e14 cm^{-2}) with a signal of about 14ke, the usual threshold of 1fC = 6400 e can be used.
- For **short strips** (1e15 cm^{-2}) with a signal of about 8ke, 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

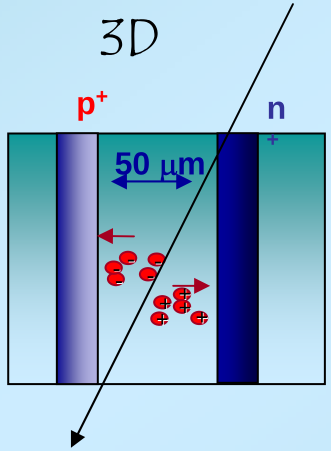
3D Detector - Concept

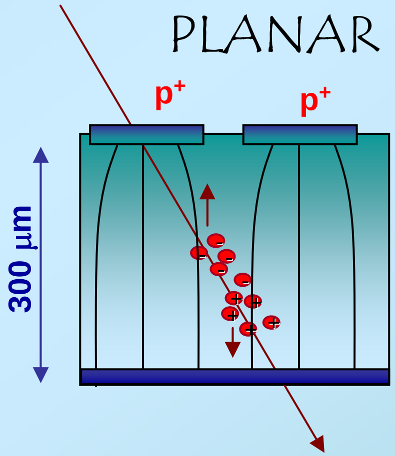
- **Planar electrodes replaced by columns through the wafer**
  - diameter: 10mm, distance: 50 - 100mm
- **De-couple deposit and charge collection**



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**





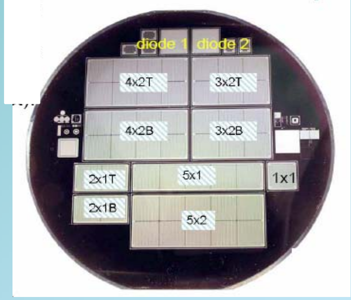
Papers at IEEE NSS'07 :

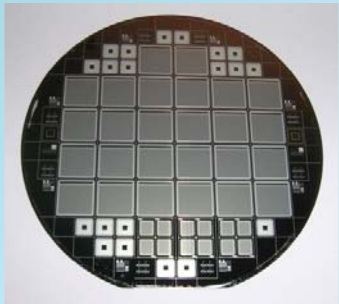
C. Fleta et al. N16-01,
G.-F. Dalla Betta et al. N18-3,
M. Zavrtanik et al. N24-150,
G. Pellegrini et al. N24-250,
S. Kűhn et al. N44-2,
J. Metcalfe et al. N44-2.

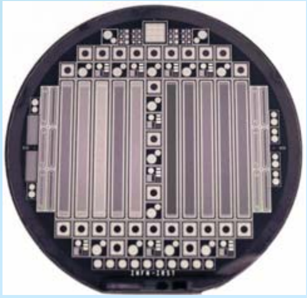
C. Da Via et al. N18-4,
M. Mathes et al. N20-4.

RD50: Towards Commercialization

4" : **Micron** **CNM** **IRST**

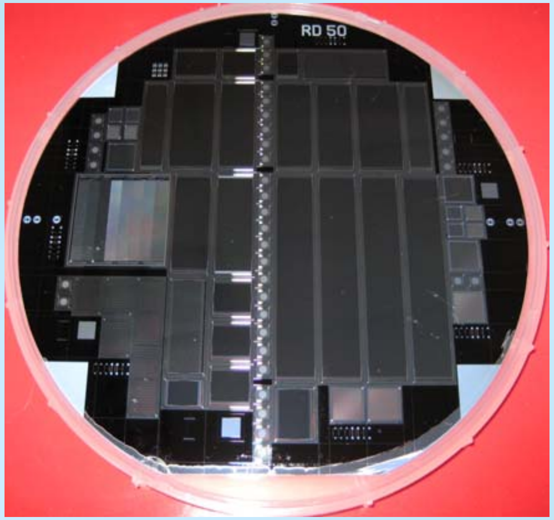




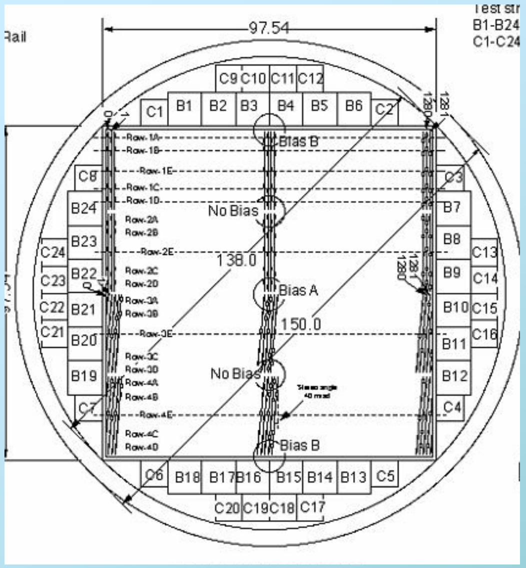


+ Processing at BNL, Helsinki, CSI, ….

6" : **Micron** **HPK (ATLAS07)**



n-on-n, p-on-n, n-on-p
FZ and Mcz



n-on-p, FZ

Conclusions

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

New experimental methods are being developed to allow insight into the details of radiation damage mechanism in semi-conductors.

Charge collection:
Paradigm change at fluence of about 1e15:
At lower fluences depletion of sensors important, and strong annealing
At higher fluences trapping dominates and there is very limited annealing.
Collect electrons in n-onp.

A straw-man tracker layout at the sLHC looks like this:
N-on-p sensors with long and short strips at large and medium radius.
At small radii, the pixel sensors might need to be made from 3D sensors (or not?).

Acknowledgments

Thanks to

the foundries and institutes who supplied sensors,

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

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

and……

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....Waikiki
to be such a
great host!