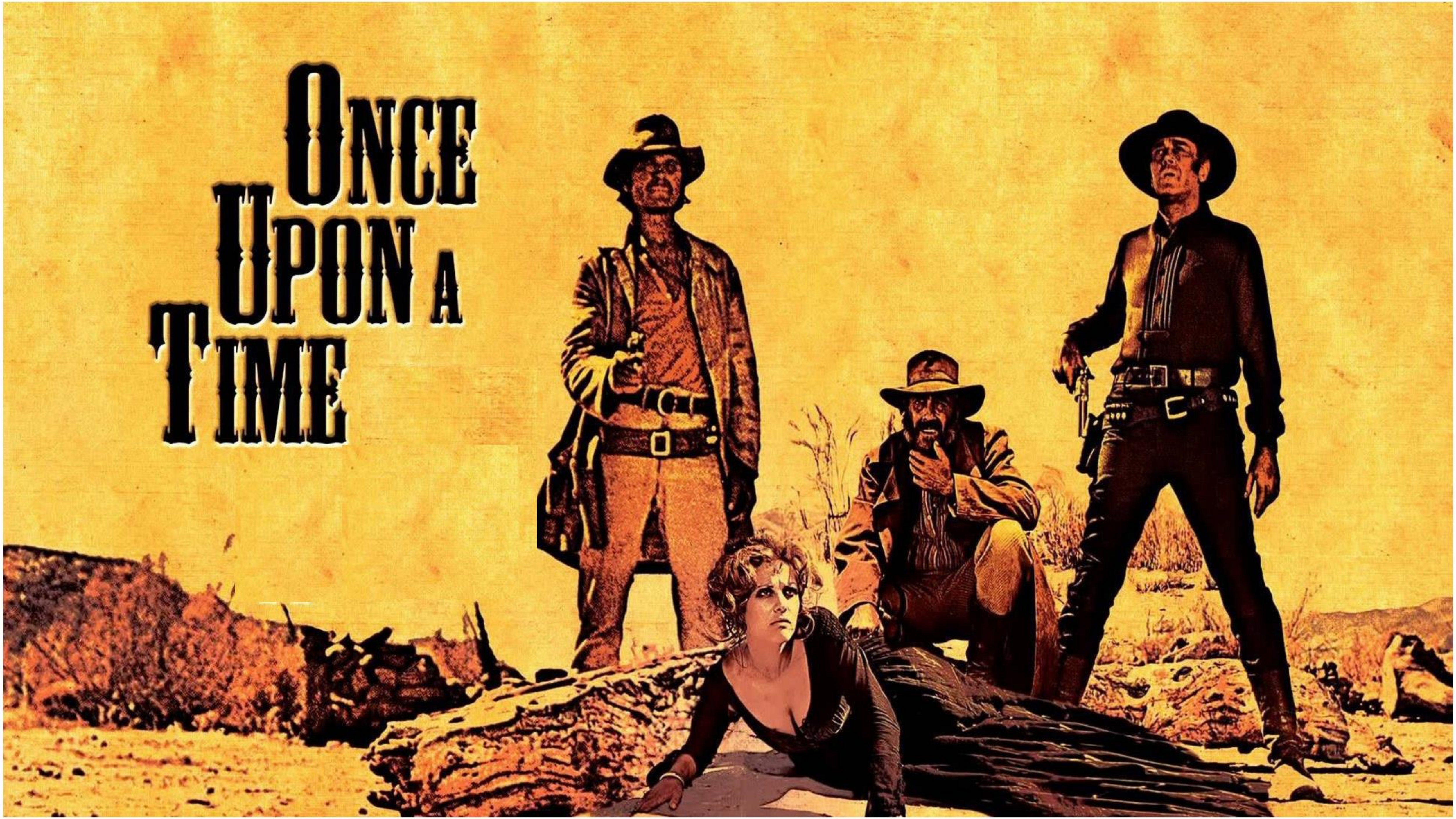
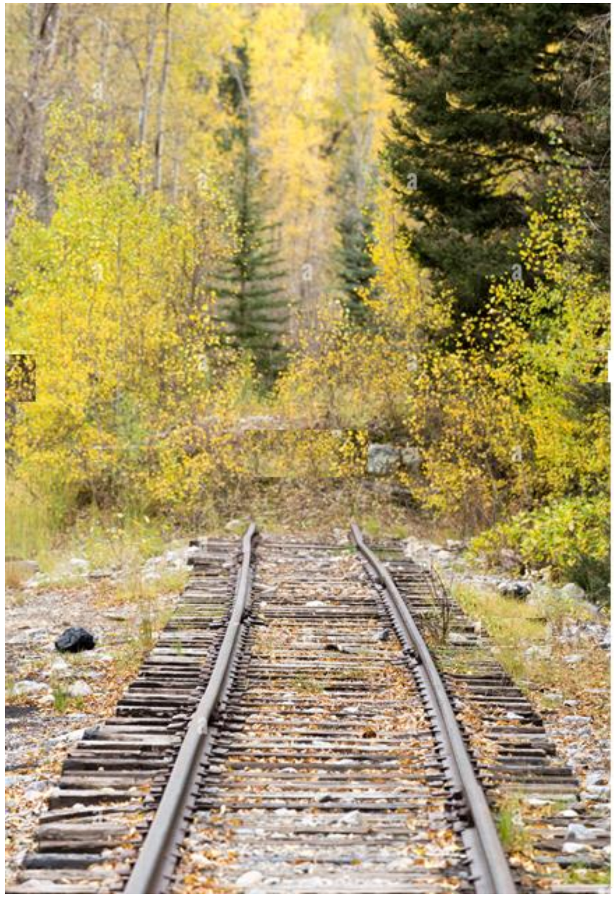
P-type: radiation tolerant sensors for physics experiments

G. Casse

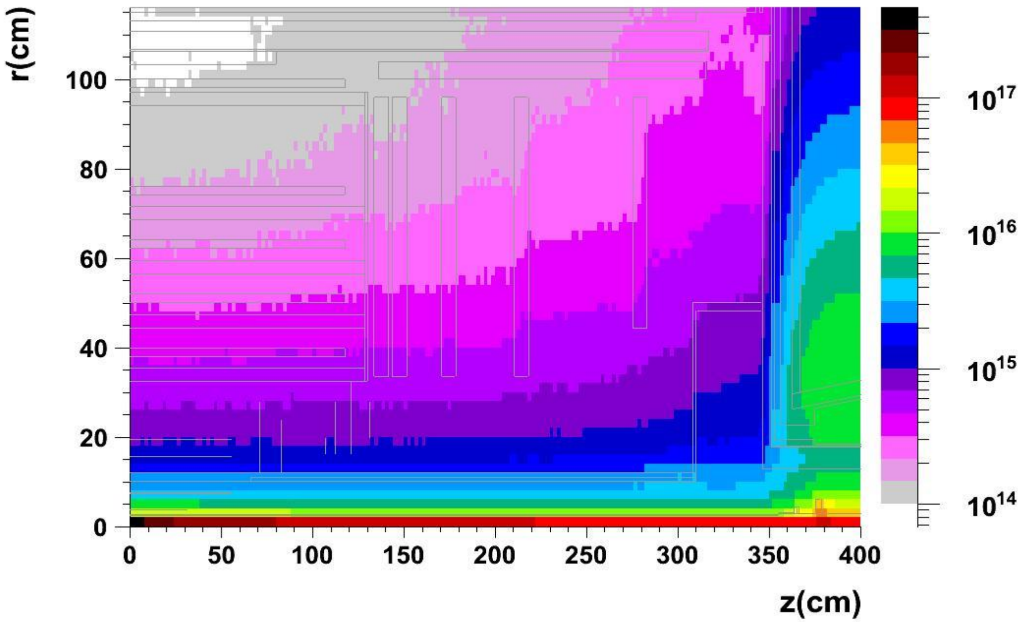

ONCE UPON A TIME

. . . . people were striving to build detectors for the LHC . . . . .

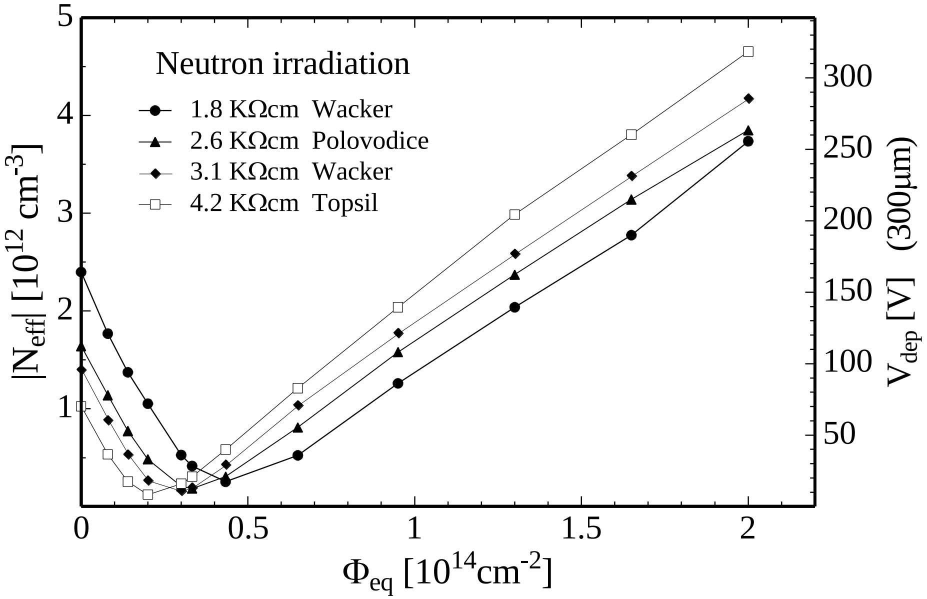


. . . . but there were questions . . . . .

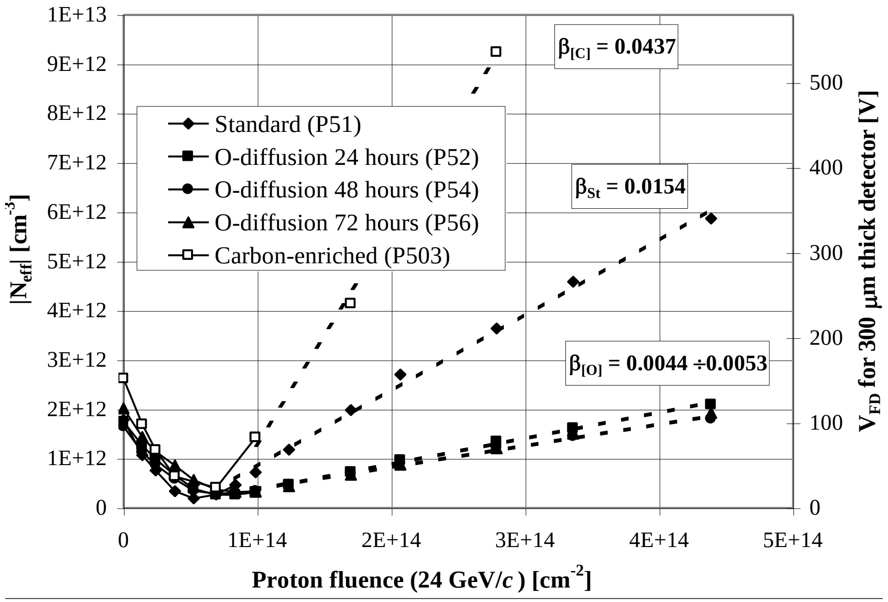
1 MeV neutron eq fluence

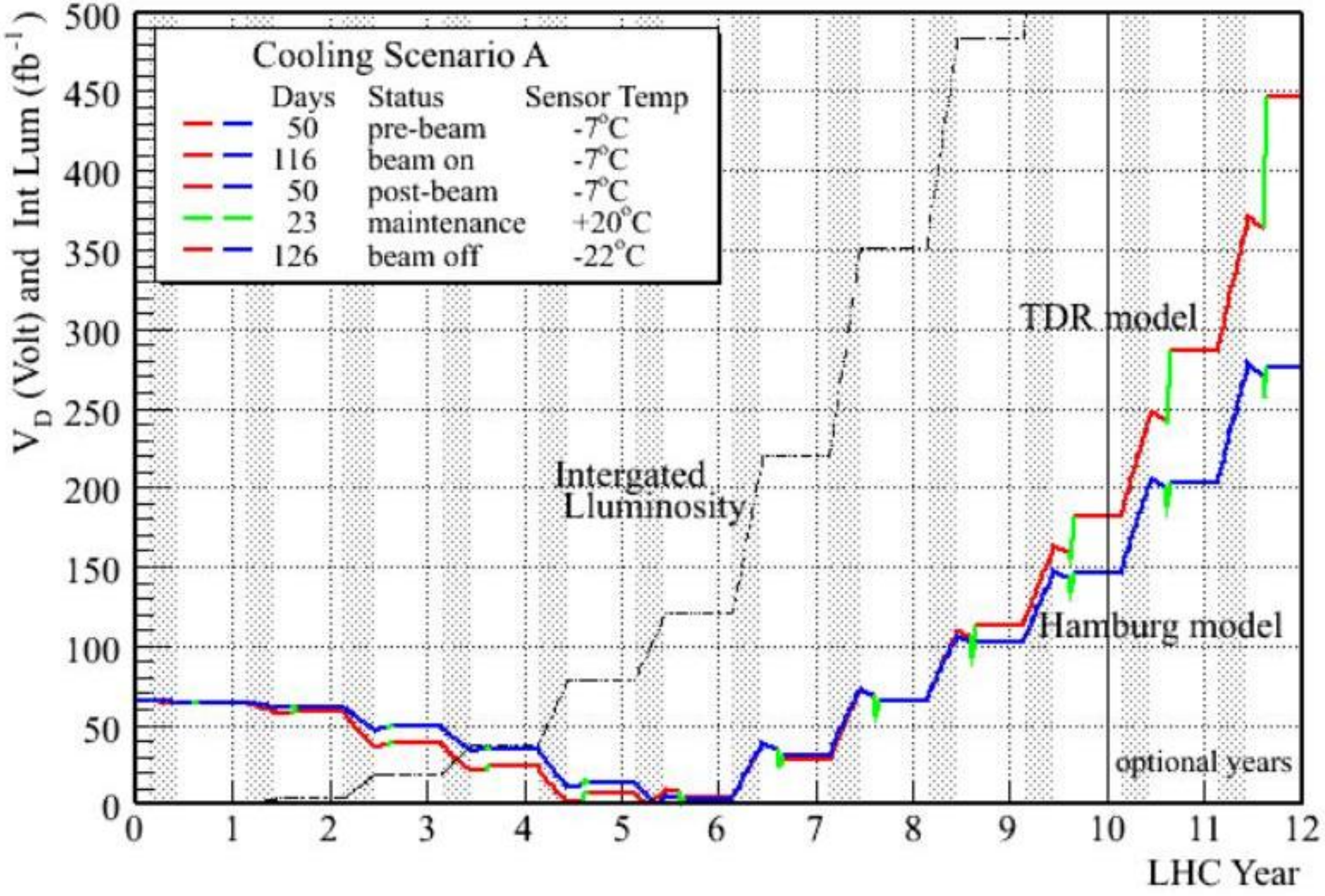


Radiation tolerance prediction: "old" method



"Good" operation of sensors was based on the ability to provide a bias voltage corresponding to 120-130% of the full depletion voltage. But the VFD would be well over 10000V at HL-LHC doses ....




Cooling Scenario A
Days Status Sensor Temp
50 pre-beam -7°C
116 beam on -7°C
50 post-beam -7°C
23 maintenance +20°C
126 beam off -22°C
V_D (Volt) and Int Lum (fb^{-1})
0
50
100
150
200
250
300
350
400
450
500
0
1
2
3
4
5
6
7
8
9
10
11
12
LHC Year
Intergated
Lluminosity
TDR model
Hamburg model
optional years

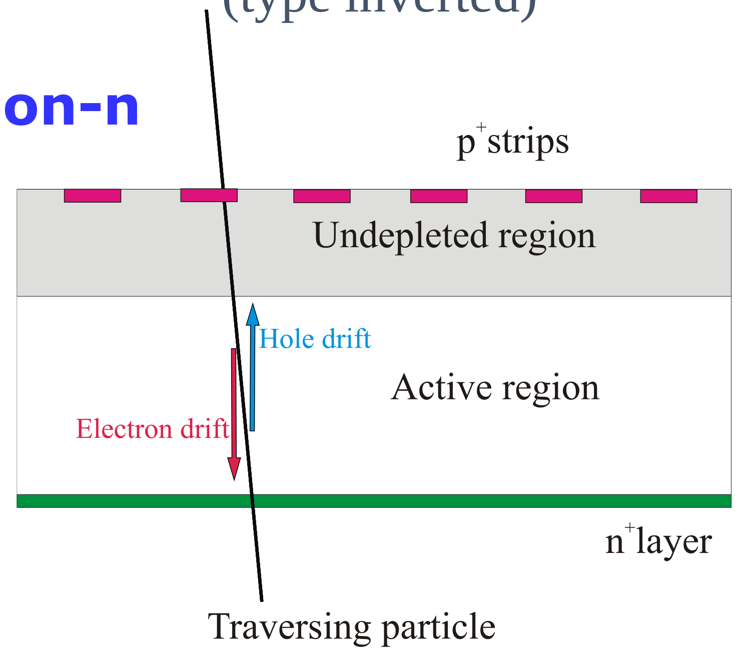
RD50: Device engineering

p-in-n versus n-in-p (or n-in-n) detectors

n-type silicon after high fluences:

(type inverted)

p^+on-n



p-on-n silicon, under-depleted:

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

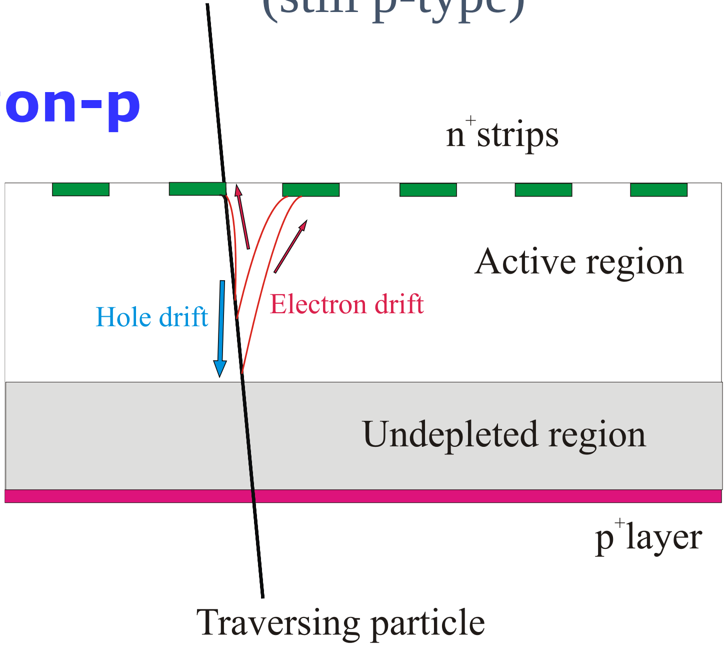
Comments:

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

p-type silicon after high fluences:

(still p-type)

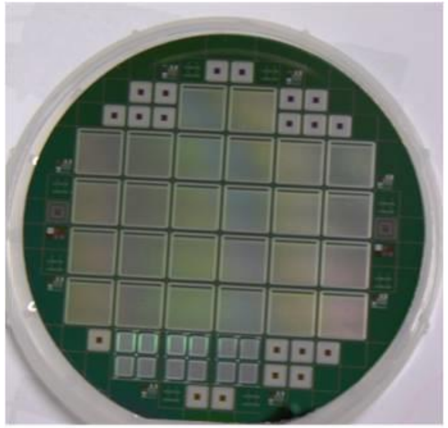
n^+on-p



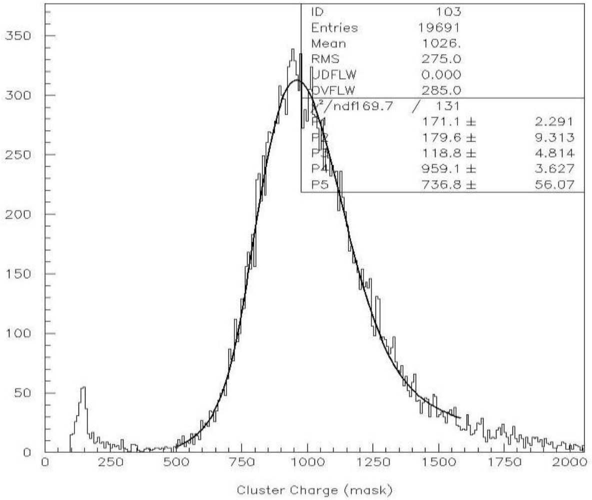
n-on-p silicon, under-depleted:

- Limited loss in CCE
- Less degradation with under-depletion
- Collect electrons (3 x faster than holes)

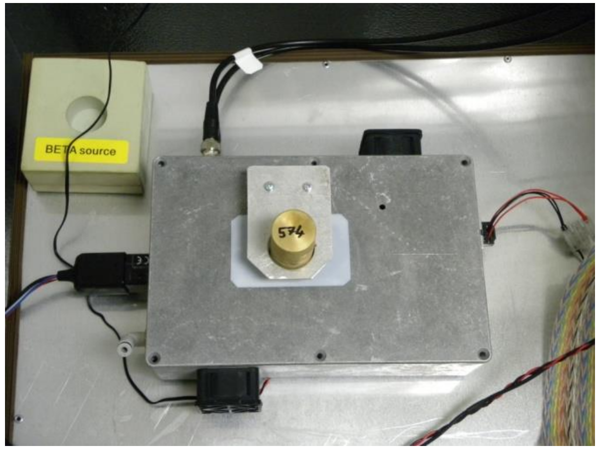
More relevant method: analogue readout with LHC speed electronics

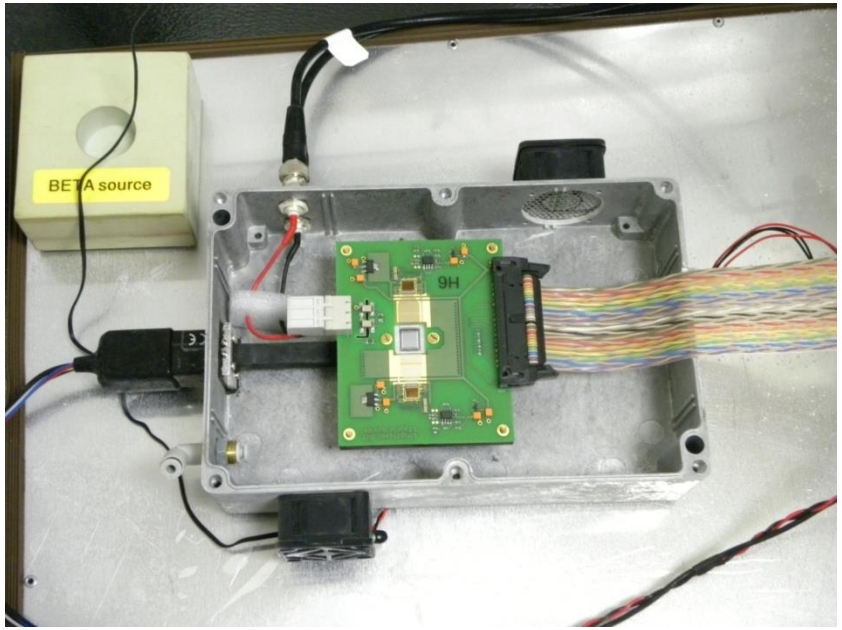


Mip signal from ^{90}Sr source



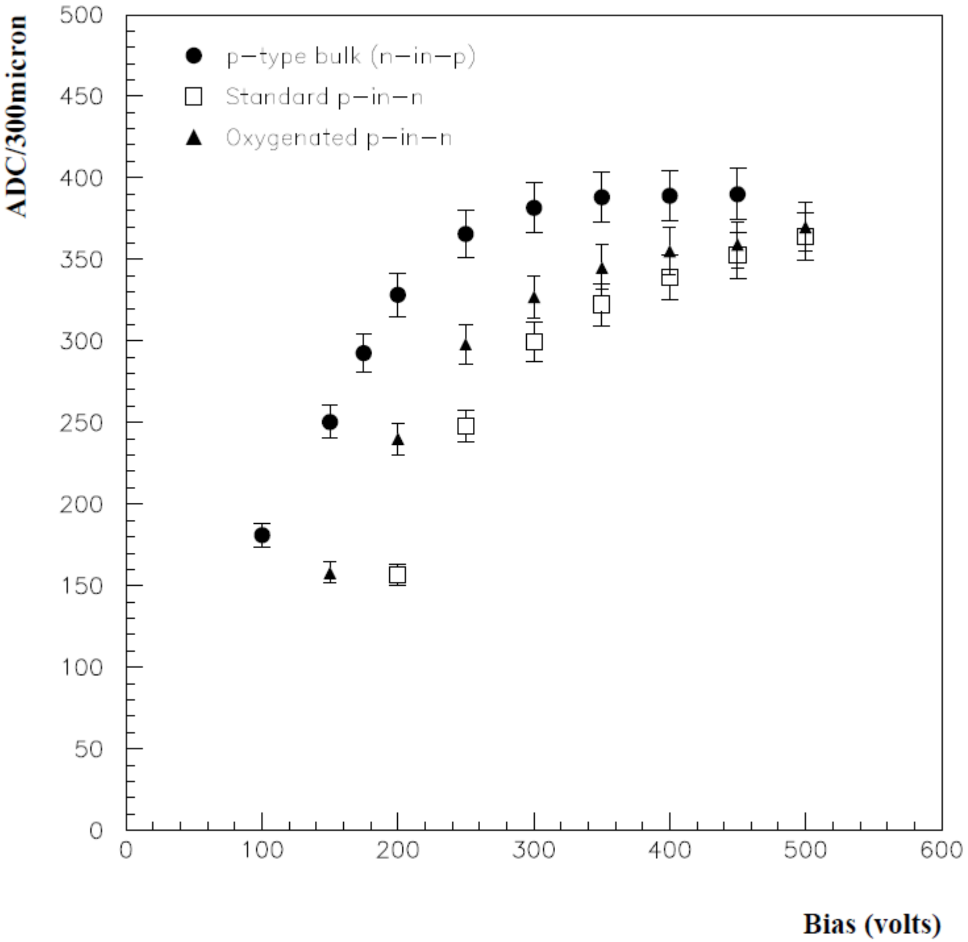
Analogue information from the Alibava board (equipped with Beetle chip)





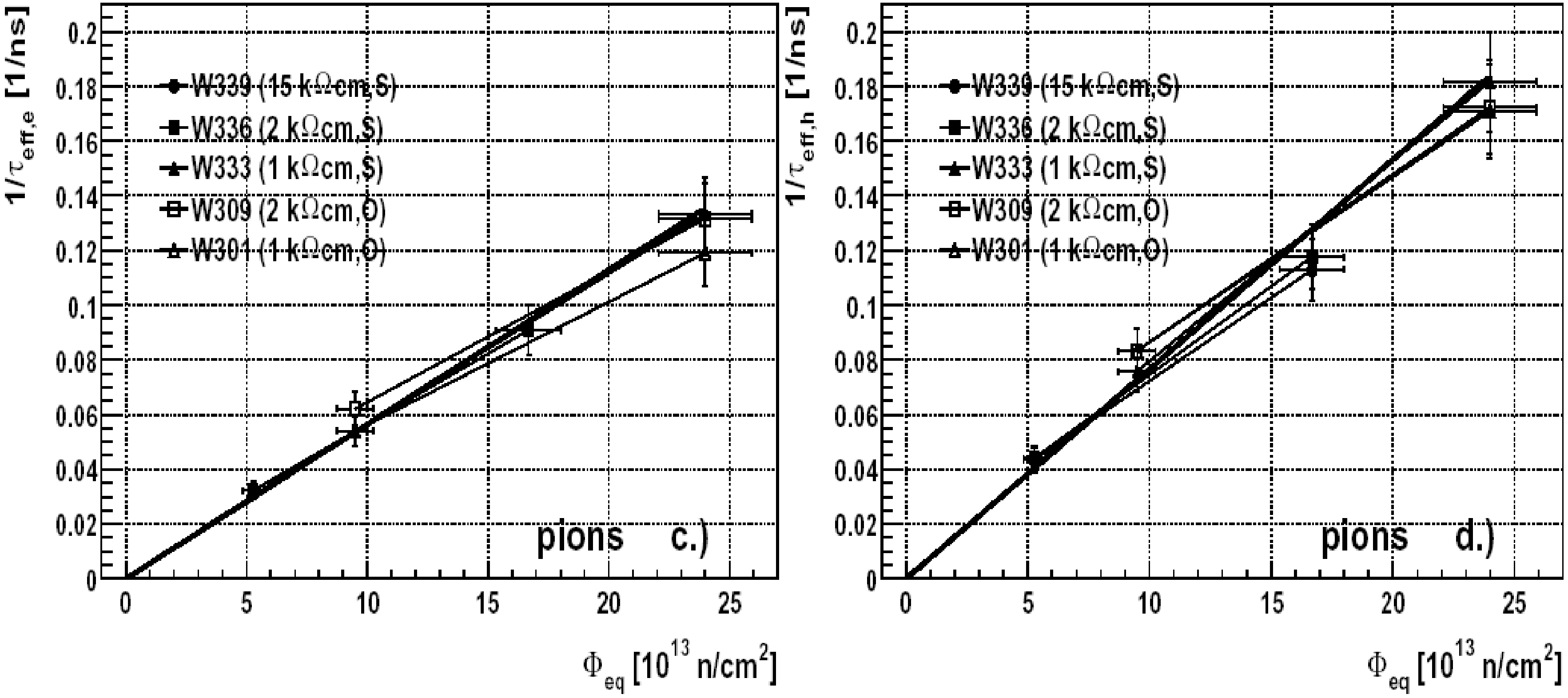
The readout side yields remarkable improvement.

Comparison of n-in-p µ-strip sensor (irradiated to 4E14 n_{eq} cm^{-2}) and p-in-n (irradiated to 3E14 n_{eq} cm^{-2}).



G. Casse et al., 2000

Charge trapping



The Charge Correction Method (based on TCT) for determination of effective trapping times requires fully (over) depleted detector – so far we were limited to 10^{15} cm^{-2}.

Effect of trapping on the Charge Collection Distance

$$Q_{tc} \cong Q_0 \exp(-t_c/\tau_{tr}),\ 1/\tau_{tr} = \beta\Phi.$$

$$v_{sat,e} \times \tau_{tr} = \lambda_{av}$$

$\beta_e = 4.2\text{E}{-}16\ \text{cm}^{-2}/\text{ns}$

$\beta_h = 6.1\text{E}{-}16\ \text{cm}^{-2}/\text{ns}$

G. Kramberger et al., NIMA 476(2002), 645-651.

After heavy irradiation the charge collection distance (CCD) of thin detectors should have a similar (better?) charge collection efficiency (CCE) as thicker ones.

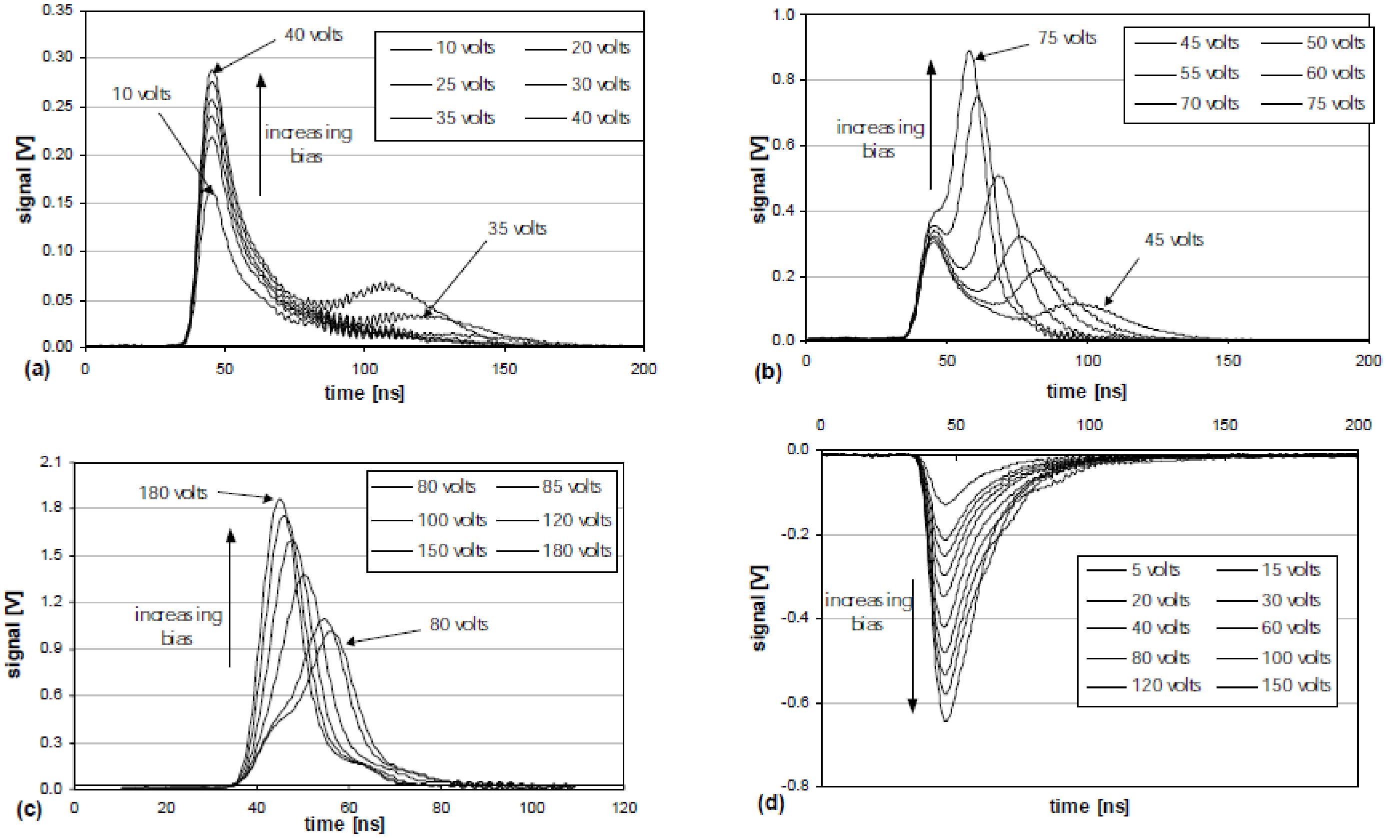
$$\lambda_{Max,n}\ (\Phi=1e14) \cong 2400\mu m$$

$$\lambda_{Max,n}\ (\Phi=1e16) \cong 24\mu m$$

$$\lambda_{Max,p}\ (\Phi=1e14) \cong 1600\mu m$$

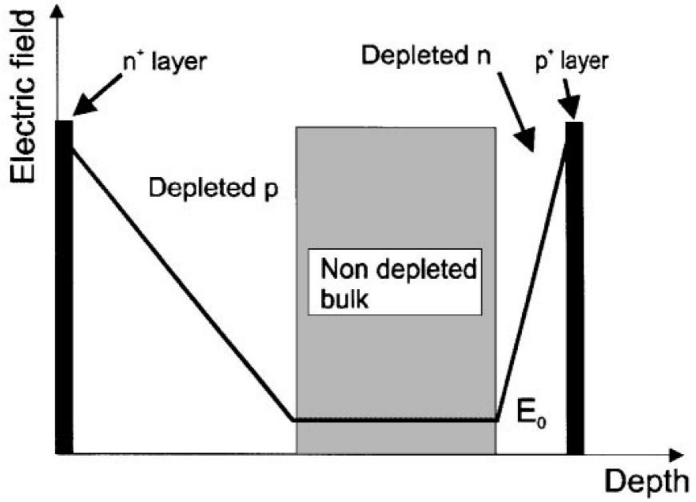
$$\lambda_{Max,p}\ (\Phi=1e16) \cong 16\mu m$$

The reverse current is proportional to the depleted volume in irradiated detectors. Do thin sensors offer an advantage in term of reduced reverse current compared to thicker ones (this aspect is particularly important for the inner layer detectors of SLHC, where significant contribution to power consuption is expected from the sensors themselves)?


(a)
signal [V]
time [ns]
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
50
100
150
200
40 volts
10 volts
increasing bias
35 volts
10 volts
20 volts
25 volts
30 volts
35 volts
40 volts
(b)
signal [V]
time [ns]
1.0
0.8
0.6
0.4
0.2
0.0
0
50
100
150
200
75 volts
increasing bias
45 volts
45 volts
50 volts
55 volts
60 volts
70 volts
75 volts
(c)
signal [V]
time [ns]
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.0
0
20
40
60
80
100
120
180 volts
increasing bias
80 volts
80 volts
85 volts
100 volts
120 volts
150 volts
180 volts
(d)
signal [V]
time [ns]
0
50
100
150
200
0.0
-0.2
-0.4
-0.6
-0.8
increasing bias
5 volts
15 volts
20 volts
30 volts
40 volts
60 volts
80 volts
100 volts
120 volts
150 volts

N-side read-out can make planar segmented Si detectors suitable for tracking in extreme (SLHC levels: 1-2x10^{16} cm^{-2}) radiation environments.

Schematic changes
of Electric field
after irradiation



Effect of trapping on
the Charge Collection
Efficiency (CCE)

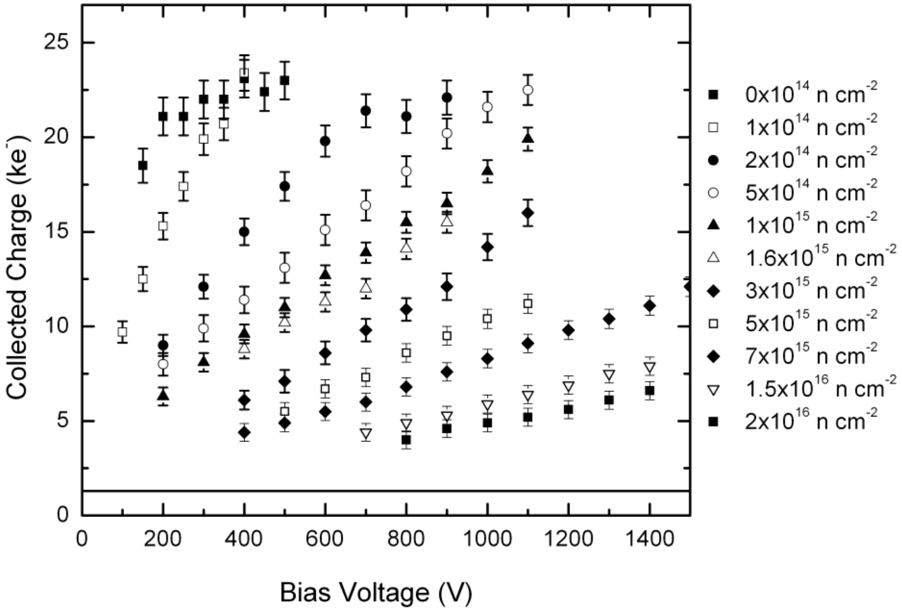
$$Q_{tc} \cong Q_0 \exp(-t_c/\tau_{tr}),\ 1/\tau_{tr} = \beta\Phi.$$

Collecting electrons provide a sensitive advantage with respect to holes due to a much shorter t_c. P-type detectors are the most natural solution for *e* collection on the segmented side.

N-side read out
to keep lower t_c

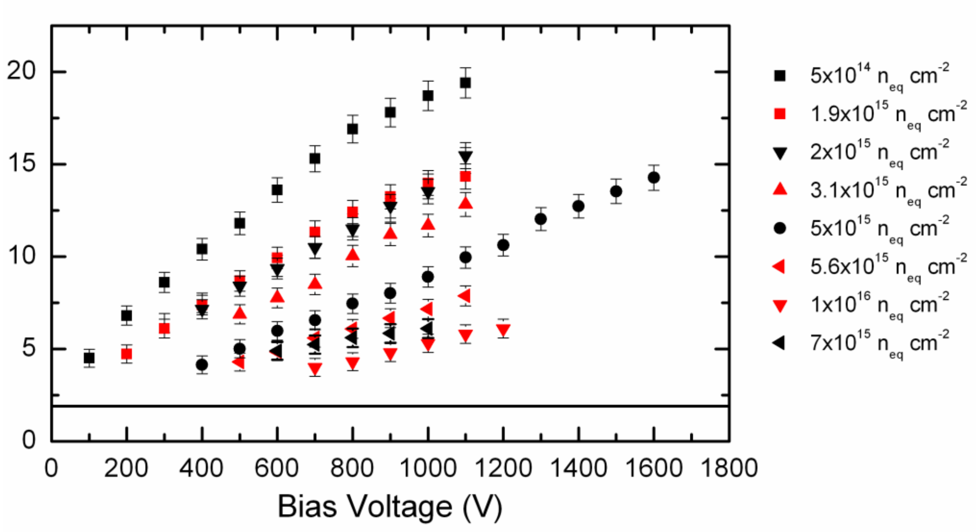
Results with proton irradiated 300 μm n-in-p Micron sensors (up to 1×10^{16} n_{eq} cm^{-2})

Irradiated with reactor neutrons



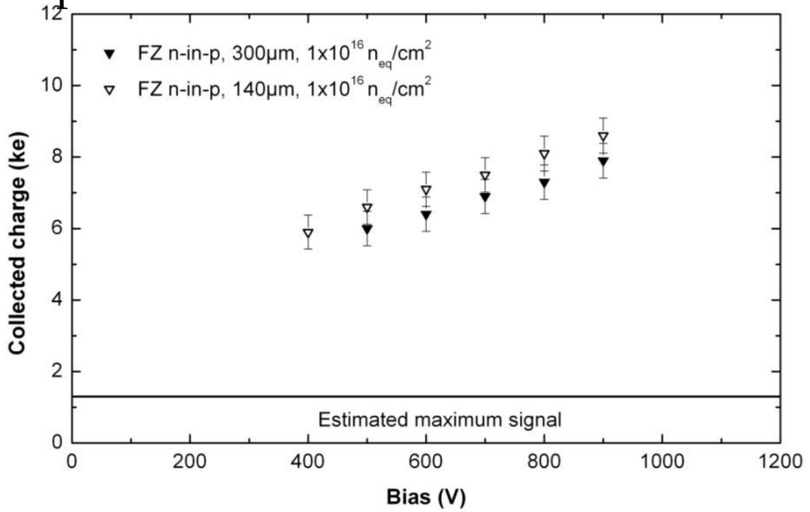
RED: irradiated with 24GeV/c protons

Other: 26MeV protons

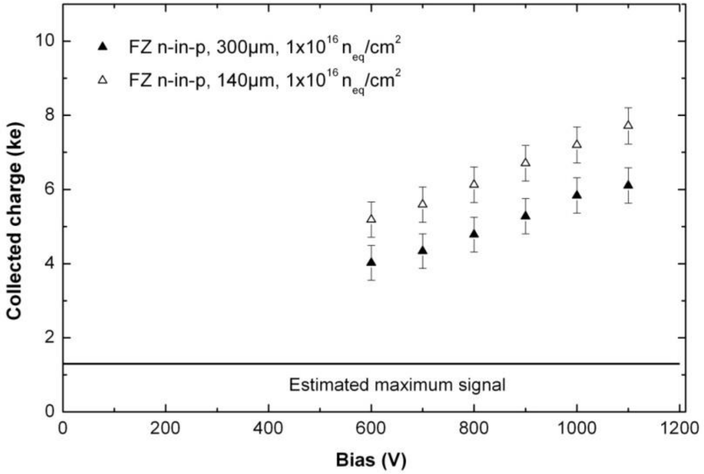


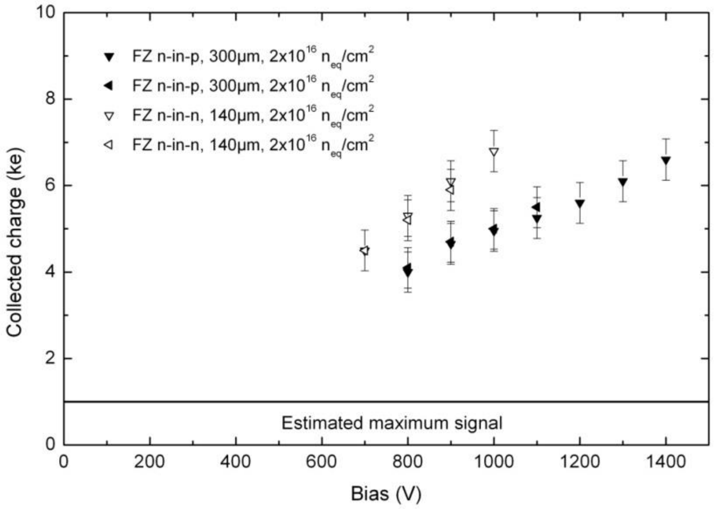
… but there is dependence on the thickness: 140 and 300 μm n-in-p Micron sensors

Cold(0-5 ^{o}C) irradiation to $1x10^{16}$ n_{eq} cm^{-2} with 24 GeV/c protons



Irradiation to $1x10^{16}$ n_{eq} cm^{-2} with 26 MeV protons

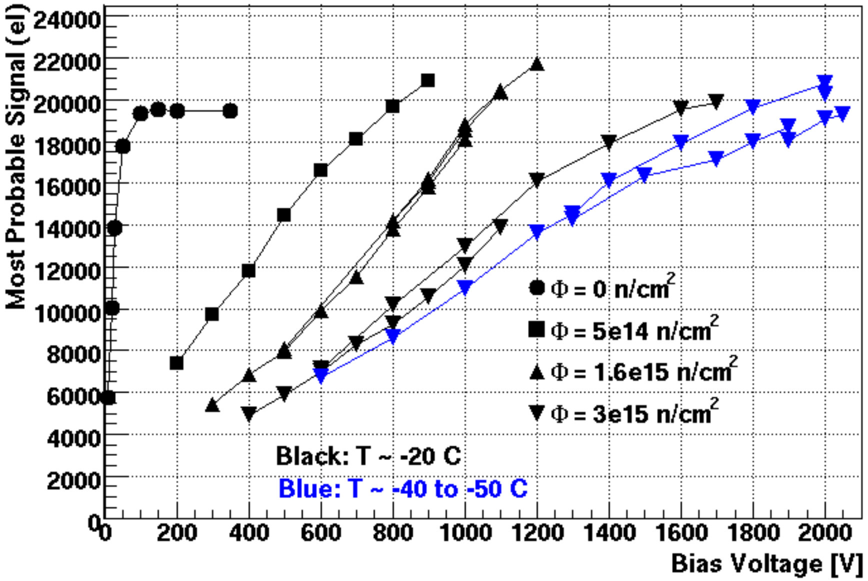




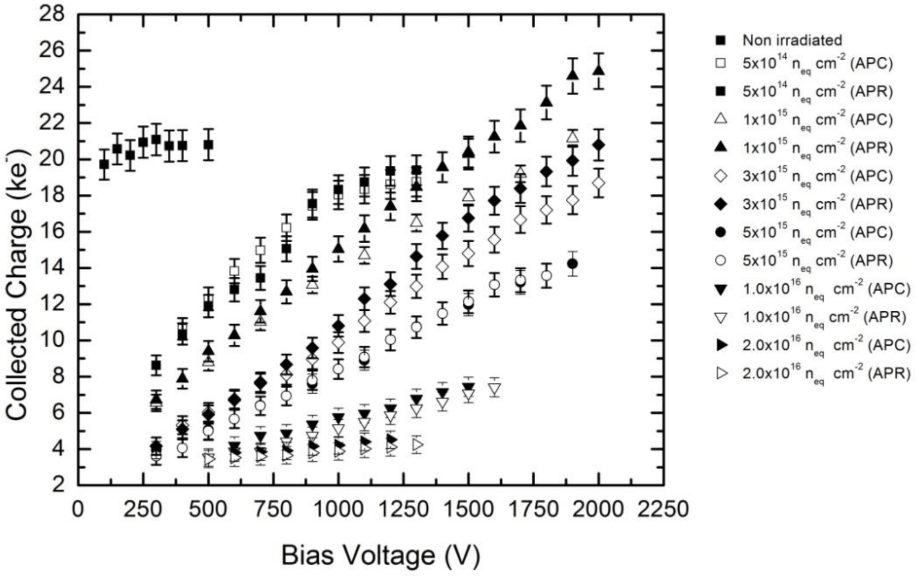
Irradiation to $2x10^{16}$ n_{eq} cm^{-2} with reactor neutrons

The results in the previous slide are a compilation of results obtained by Liverpool. Results from the JSI of Ljubljana show very good agreement with the neutron irradiations. Here they have been pushed to higher voltages and they show a collected charge equal to the charge collected by non-irradiated sensors after heavy irradiation.

I. Mandic at the 12th RD50 workshop.

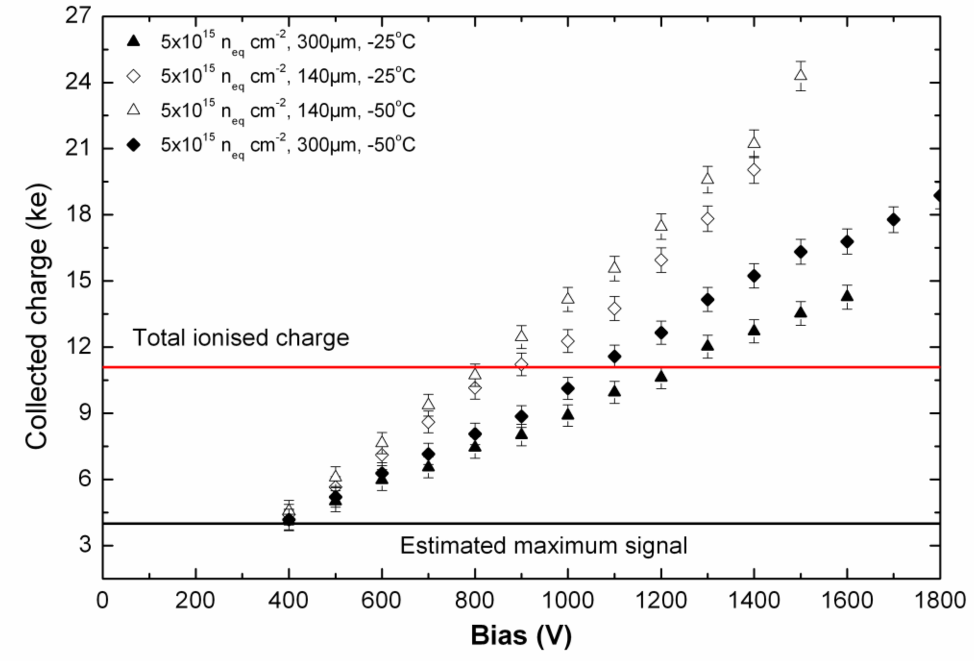


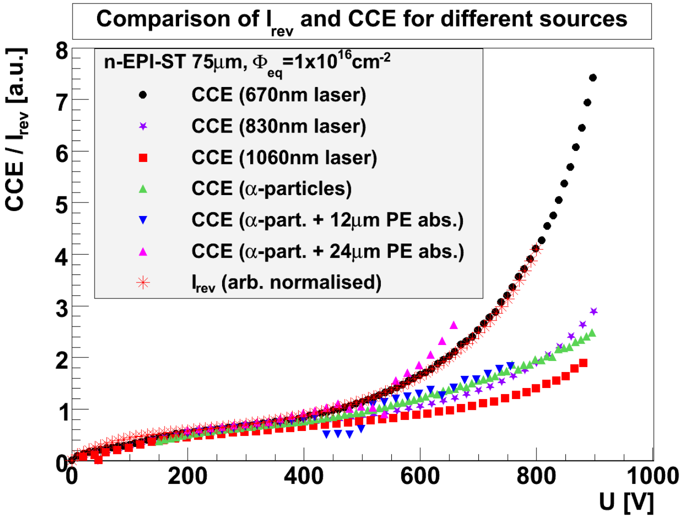
Liverpool



140 and 300 μm n-in-p Micron sensors after 5×10^{15} n_{eq} 26MeV p

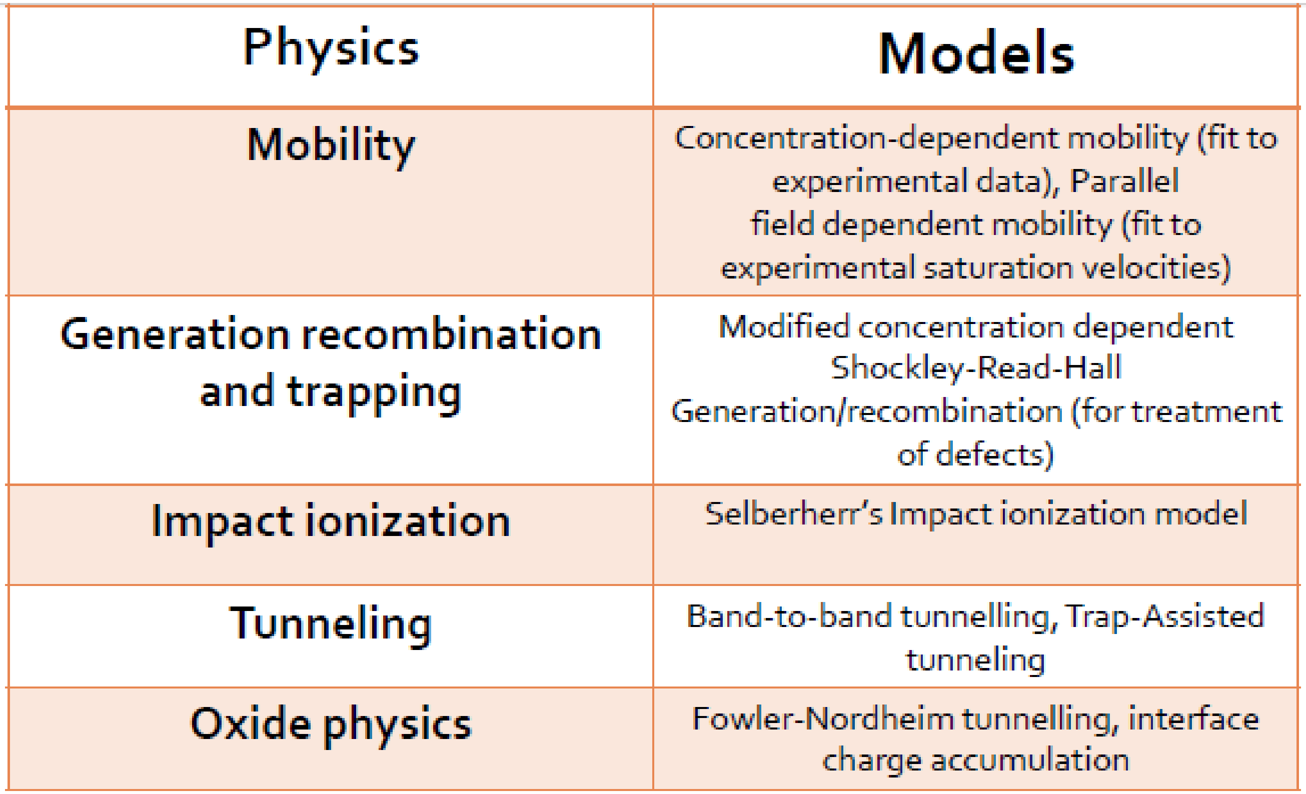
Evidence of a charge multiplication effect: not only the whole charge is recovered, but increased by f = 1.75





Also CM in diodes (J. Lange, 15th RD50 workshop).

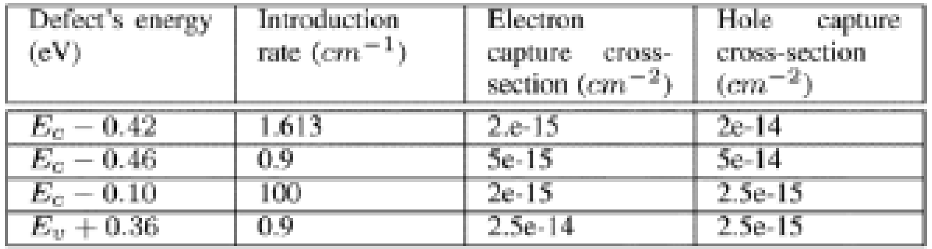
TCAD, M. Benoit et al., presented at the ATLAS Upgrade meeting, DESY, Hamburg, 19/04/2010



Physics	Models
Mobility	Concentration-dependent mobility (fit to experimental data), Parallel field dependent mobility (fit to experimental saturation velocities)
Generation recombination and trapping	Modified concentration dependent Shockley-Read-Hall Generation/recombination (for treatment of defects)
Impact ionization	Selberherr’s Impact ionization model
Tunneling	Band-to-band tunnelling, Trap-Assisted tunneling
Oxide physics	Fowler-Nordheim tunnelling, interface charge accumulation

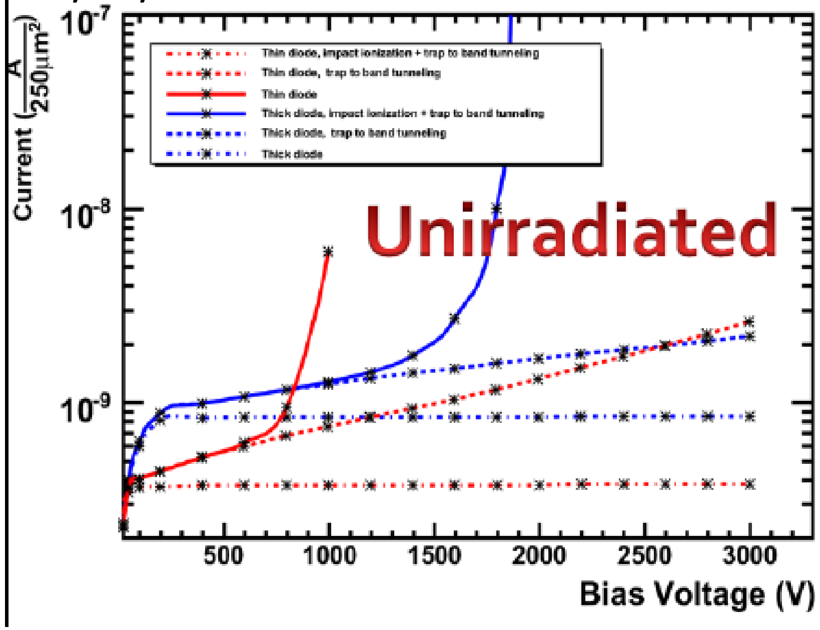
Radiation damage

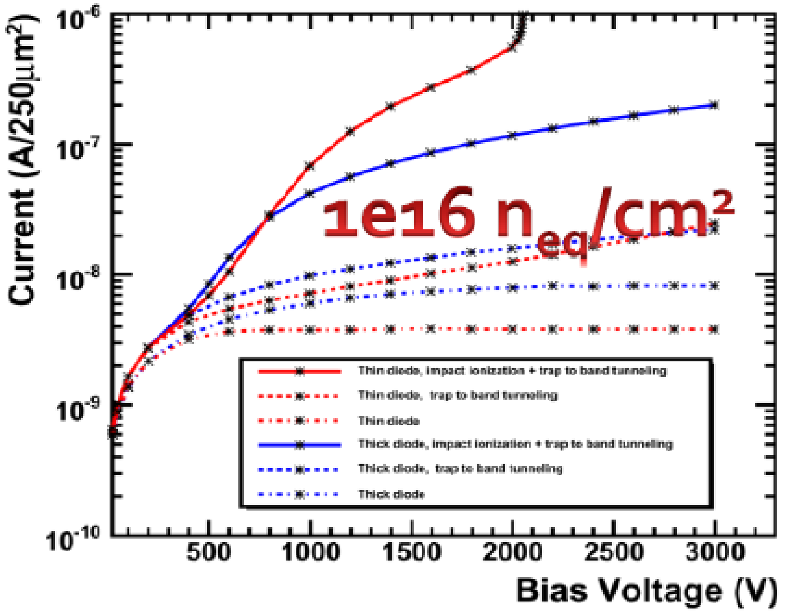
P-TYPE RADIATION DAMAGE MODEL



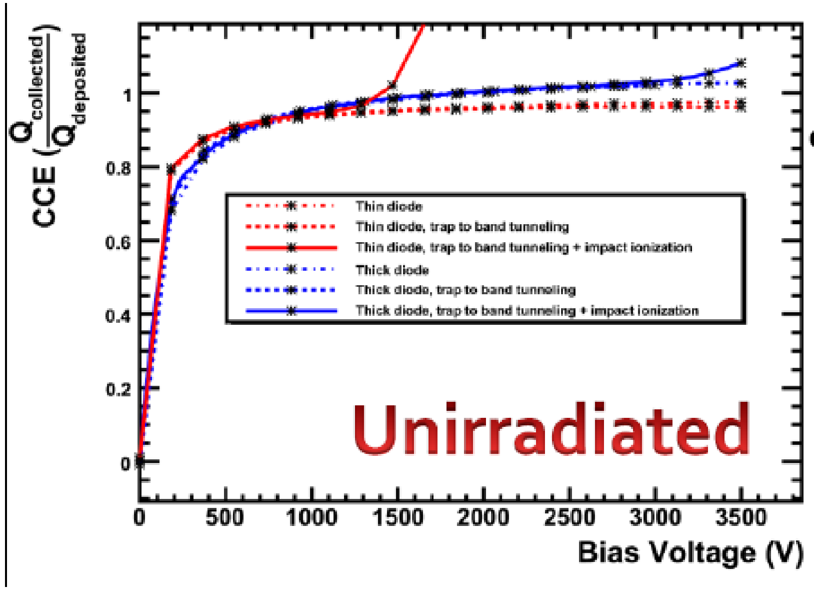
Defect's energy (eV)	Introduction rate (cm^{-1})	Electron capture cross-section (cm^{-2})	Hole capture cross-section (cm^{-2})
$E_c - 0.42$	1.613	2.e-15	2e-14
$E_c - 0.46$	0.9	5e-15	5e-14
$E_c - 0.10$	100	2e-15	2.5e-15
$E_v + 0.36$	0.9	2.5e-14	2.5e-15

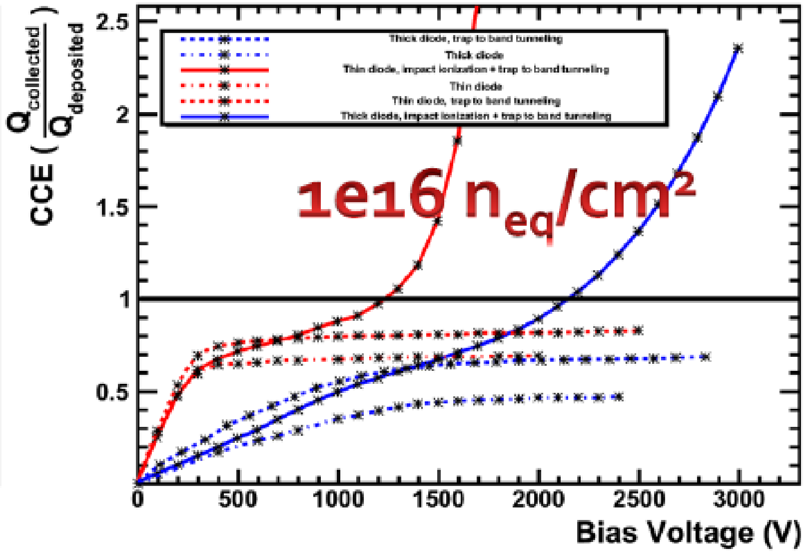
ISE TCAD, M. Benoit et al., presented at the ATLAS Upgrade meeting, DESY, Hamburg, 19/04/2010



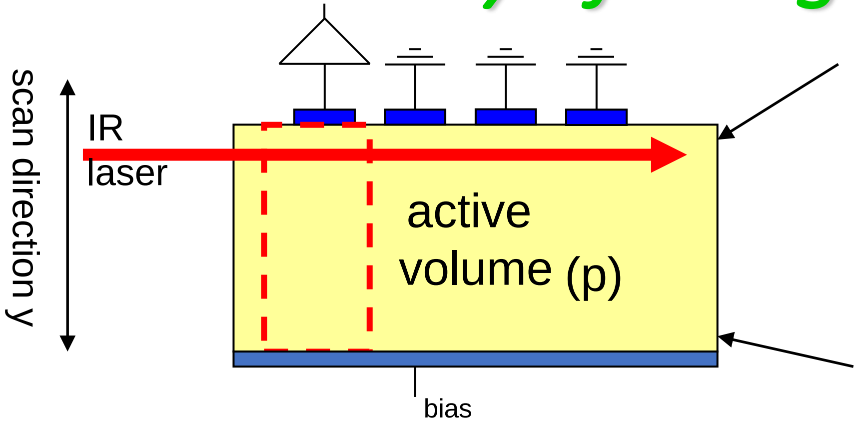


140µm
300µm





“Edge-TCT” a new way of using TCT



Illumination close to strips – hole injection

The same amount of charge injected for close to strip and close to backplane – change of e-h fraction

Illumination close to backplane – hole injection

The idea is to use focused IR laser to simulate grazing technique:

Advantages:

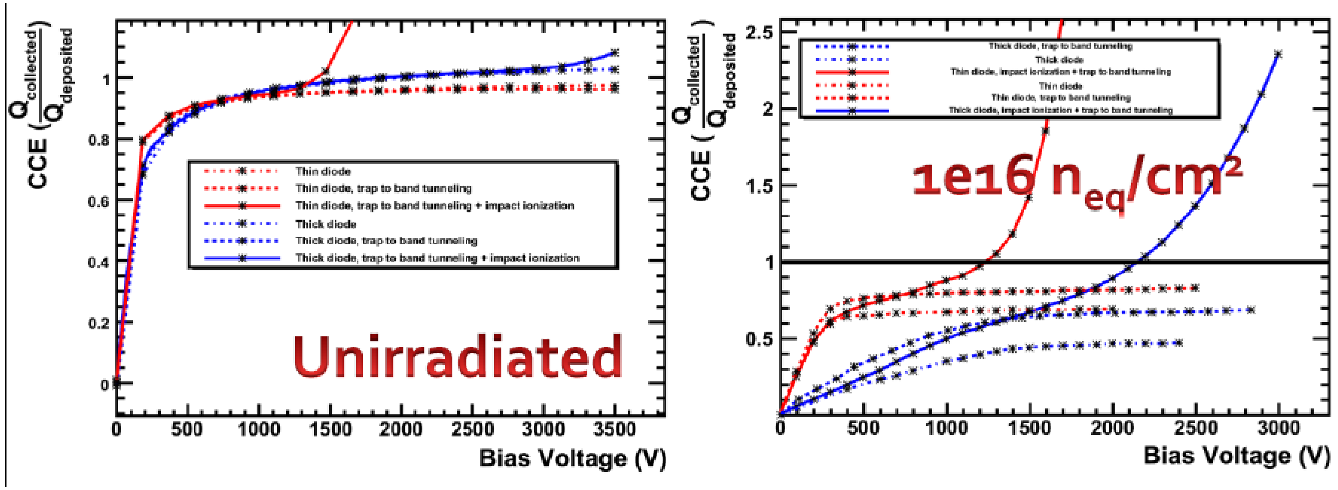
- Position of e-h generation can be controlled by moving tables
- the amount of injected e-h pairs can be controlled by tuning the laser power
- easier mounting and handling
- not only charge but also induced current is measured – a lot more information is obtained

Drawbacks:

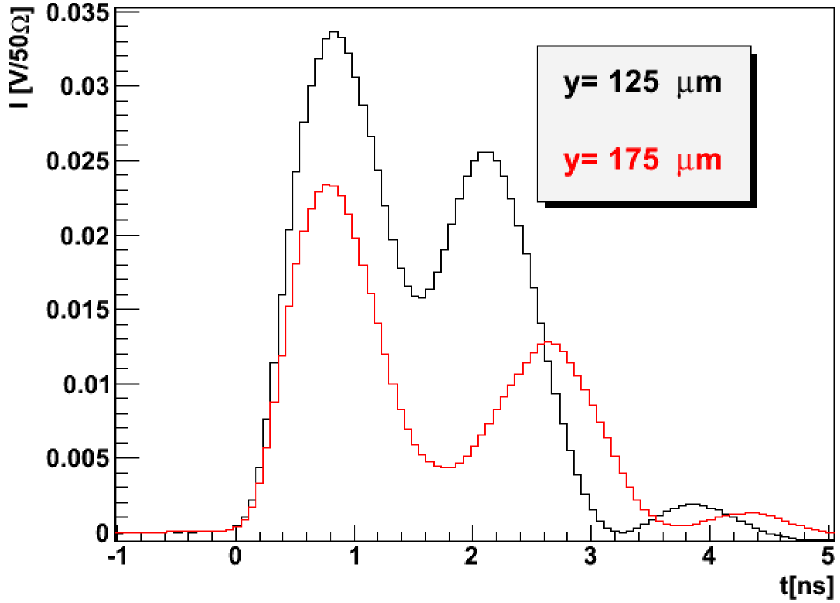
- Applicable only for strip/pixel detectors if 1060 nm laser is used (light must penetrate guard ring region)
- Only the position perpendicular to strips can be used due to widening of the beam! Beam is “tuned” for a particular strip
- Absorption falls with temperature of the sensor – a relatively powerful laser is required for large signal and makes absolute measurements of the charge more difficult
- Light injection side has to be polished to have a good focus – depth resolution
- It is not possible to study charge sharing due to illumination of all strips

CM is a well documented effect, but we are not mastering it yet

We can qualitatively understand it. We are investigating it from various perspectives.



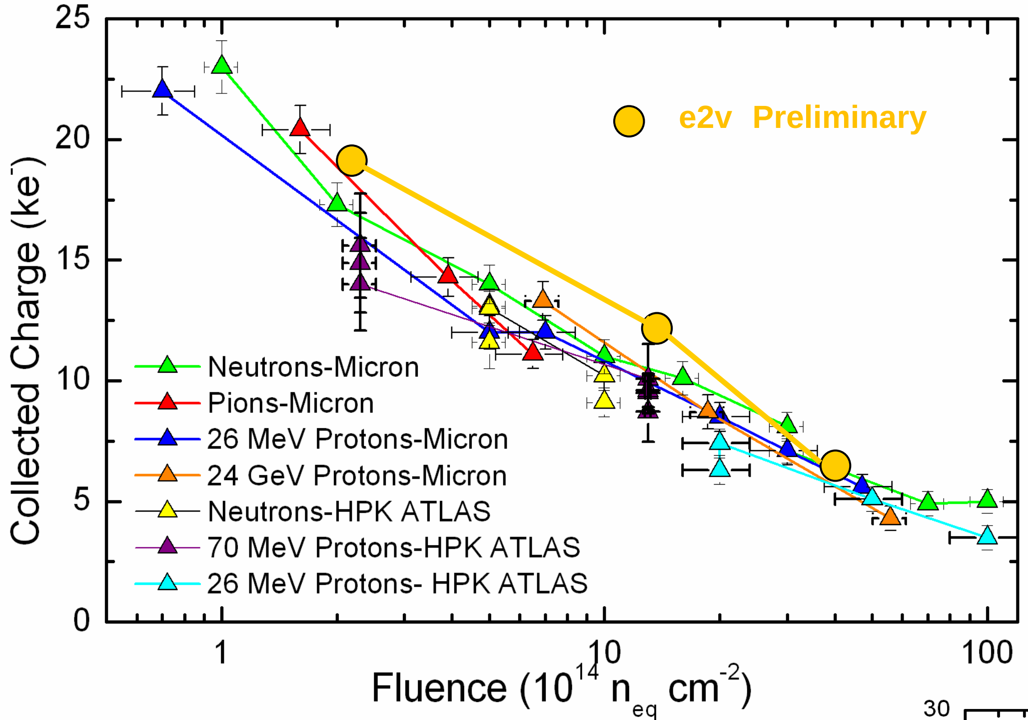
ISE TCAD, M. Benoit et al., presented at the ATLAS Upgrade meeting, DESY, Hamburg, 19/04/2010



TCT studies
2nd peak due to avalanche multiplication

the difference in peak amplitude for different y is due to electrons trapped

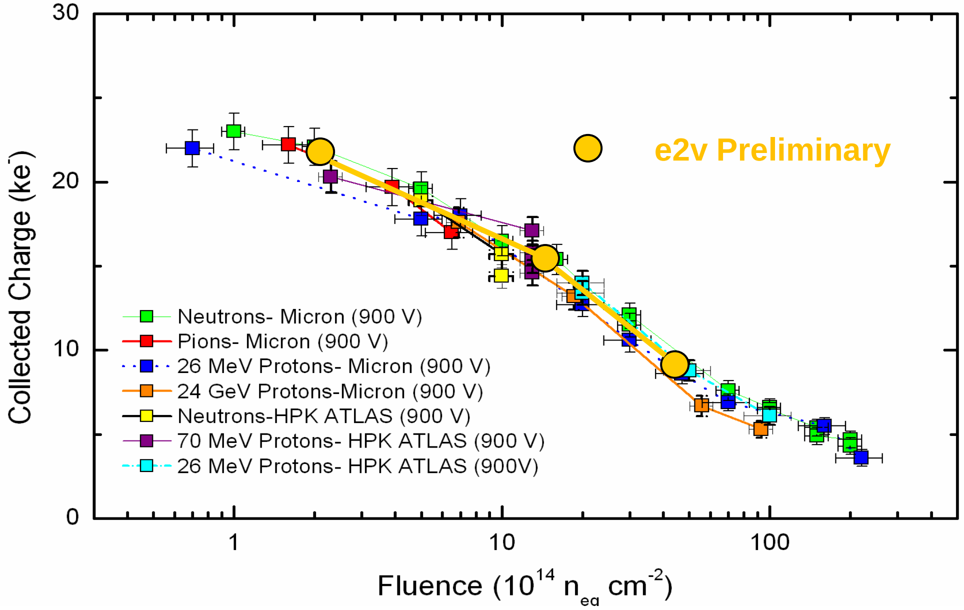
G. Kramberger wt al., 18th RD50 workshop.



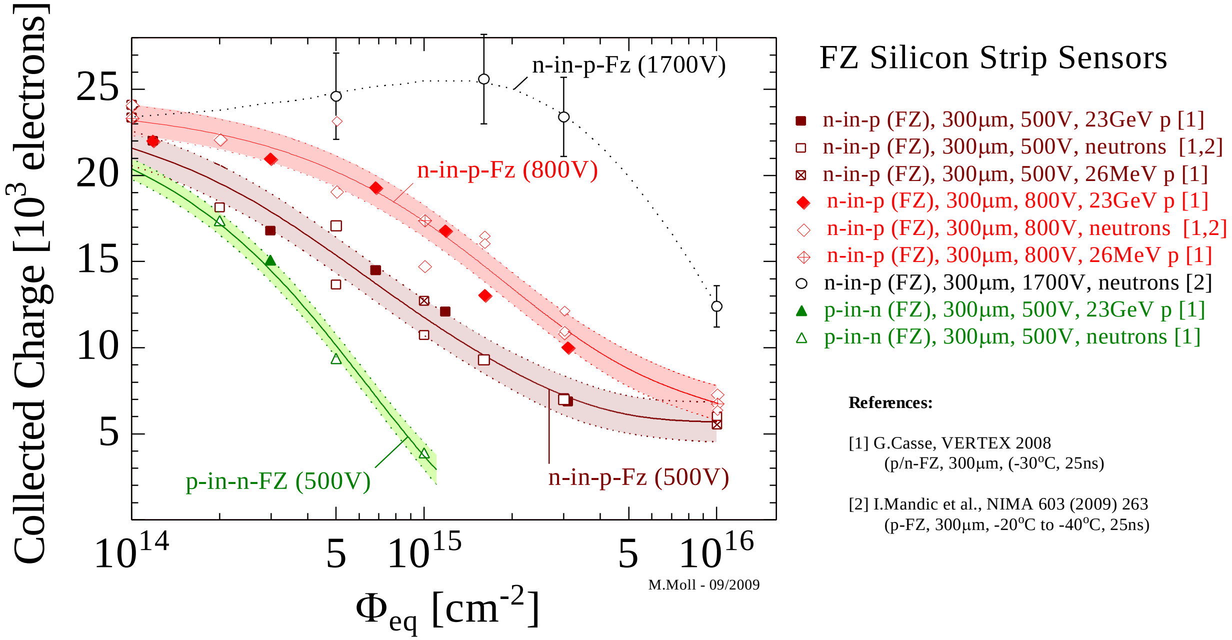
500 V

Nonetheless, Measurements show consistent results from various manufacturers

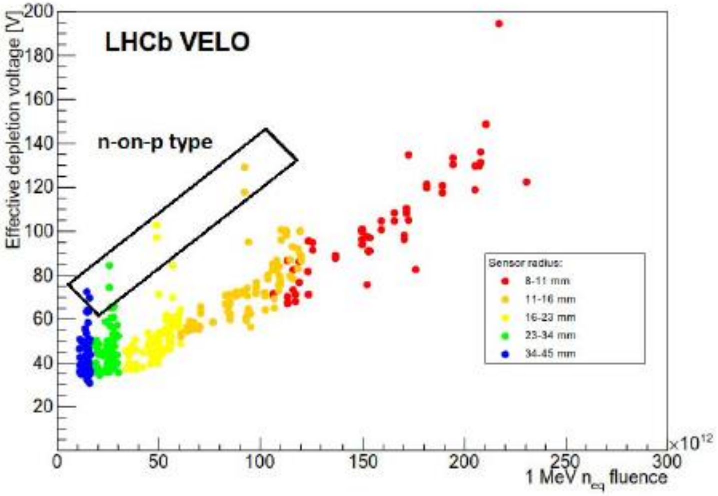
900 V

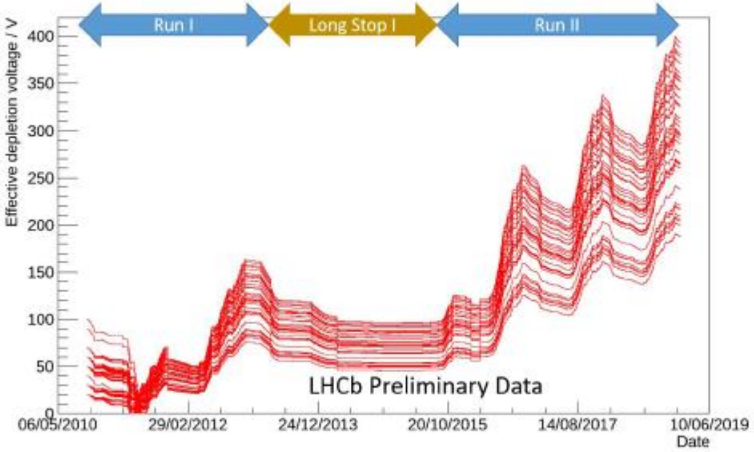


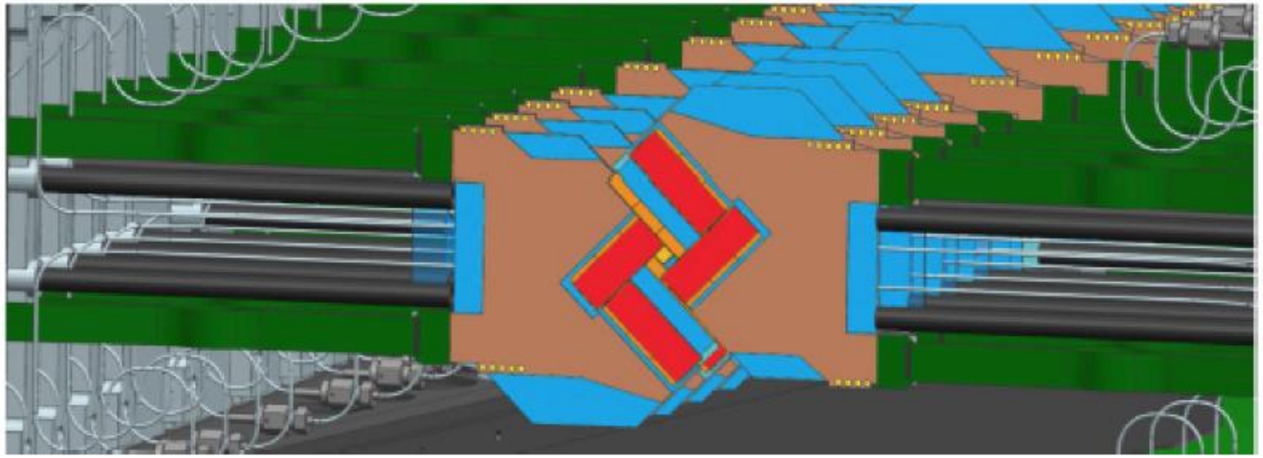
A great margin to gain with extremely high voltage



Compiled by M. Moll


LHCb VELO
n-on-p type
Effective depletion voltage [V]
200
180
160
140
120
100
80
60
40
20
0
50
100
150
200
250
300
$\times10^{12}$
1 MeV n_{eq} fluence
Sensor radius:
8-11 mm
11-16 mm
16-23 mm
23-34 mm
34-45 mm


Run I
Long Stop I
Run II
Effective depletion voltage / V
400
350
300
250
200
150
100
50
0
LHCb Preliminary Data
06/05/2010
29/02/2012
24/12/2013
20/10/2015
14/08/2017
10/06/2019
Date



ATLAS, CMS, LHCb

Tracker and vertex and HG-Calo!! sensors are p-type bulk.

Over 1200 m^2 of silicon sensors are p-type in HL-LHC.