Radiation hardness of p-type detectors: overview

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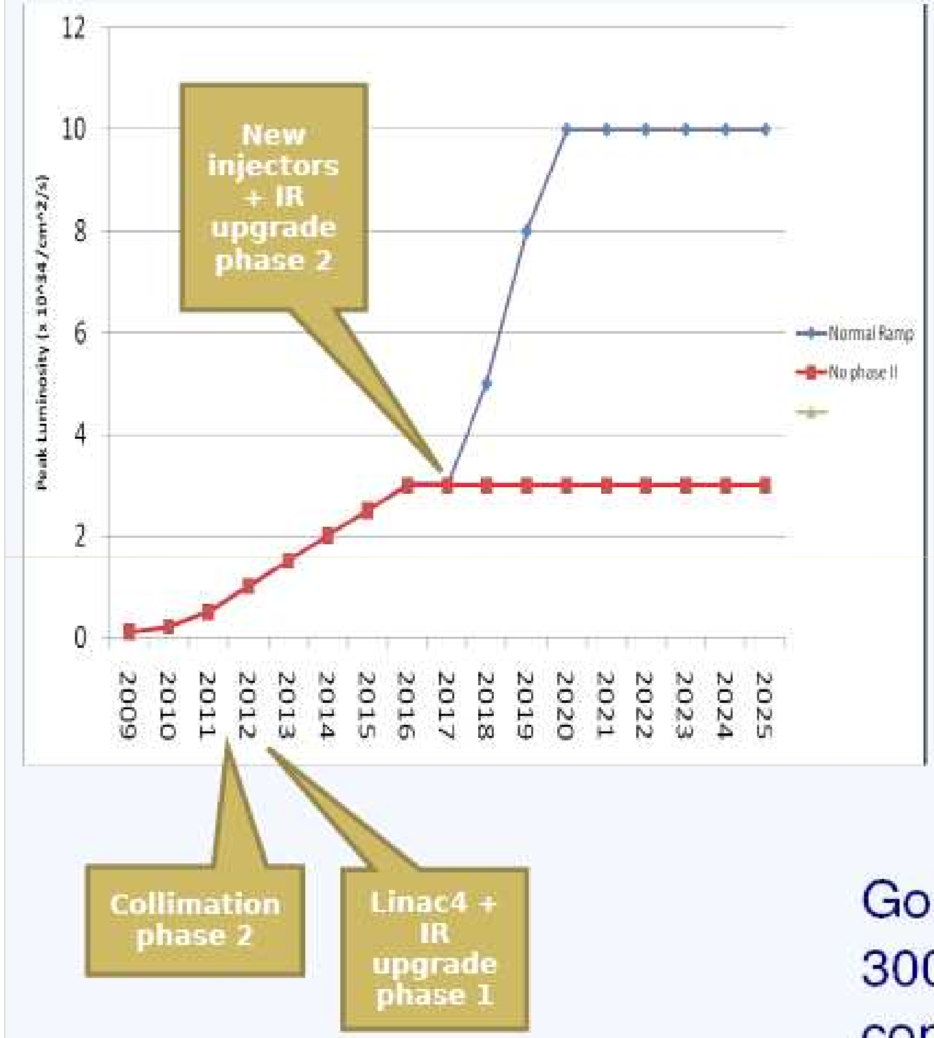
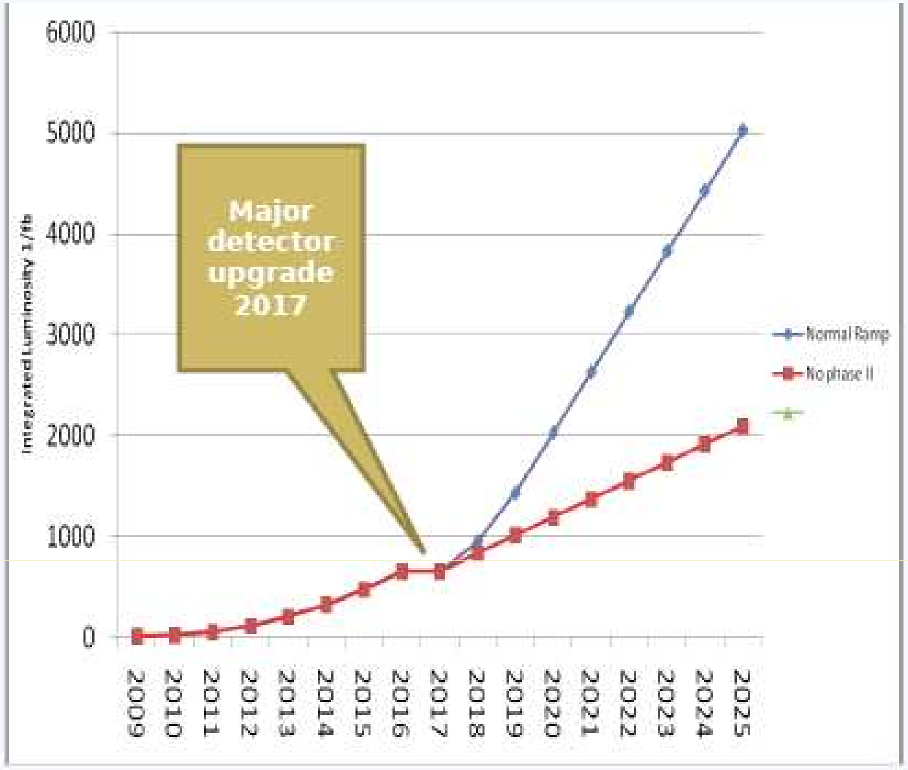
7th RESMDD, October 15 -17, 2008 - Florence - Italy

This overview is based on results from early work in Liverpool in the framework of the ATLAS-SCT and dedicated R&D and on the systematic activities within RD50.

- Future requirements on sensors for SLHC
- Motivations for using n-side readout in high radiation environments
- Charge Collection Efficiency results up to 1×10^{16} n cm^{-2}
- Effect on thickness on the CCE and reverse current of irradiated Si sensors.
- A word on annealing behaviours
- Summary

LHC expectations: peak and integrated Luminosity



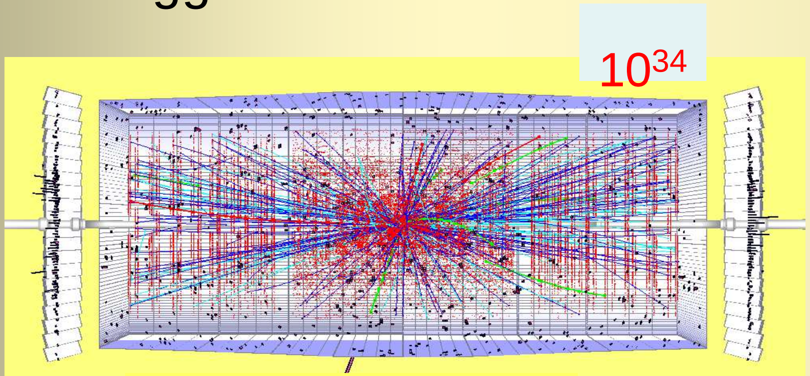


Goal for ATLAS Upgrade:
3000 fb^{-1} recorded
cope with ~400 pile-up events each BC

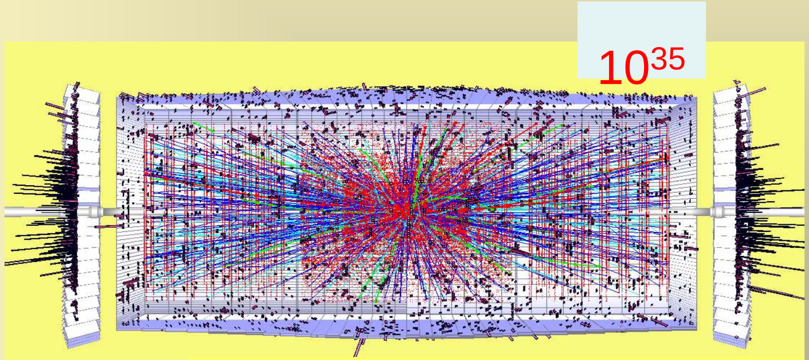
- Ref: LHCC 1/4/2008 – Roland Garoby
  - http://indico.cern.ch/conferenceDisplay.py?confId=36149

How the tracker will improve for the SLHC?

- The SLHC planning assumption
  - Phase I to 2 x 10^{34} around 2013
  - Phase II to 10^{35} incrementally from ~2017
- The structure of the physics events are determined by the centre-of-mass energy and will not change, while the backgrounds from minimum bias events will increase by a factor >10 (>10 x track density and ~10 x radiation).
- No physics reason to improve spatial and momentum measurement precision
  - Key point is to maintain tracking and vertexing performance
- Possibly more involvement of tracker in the trigger
  - CPU-effective track finding
  - Trigger contributions



Full LHC luminosity
~20 interactions/bx



Proposed SLHC luminosity
~300-400 interactions/bx

Power estimates (from CMS)

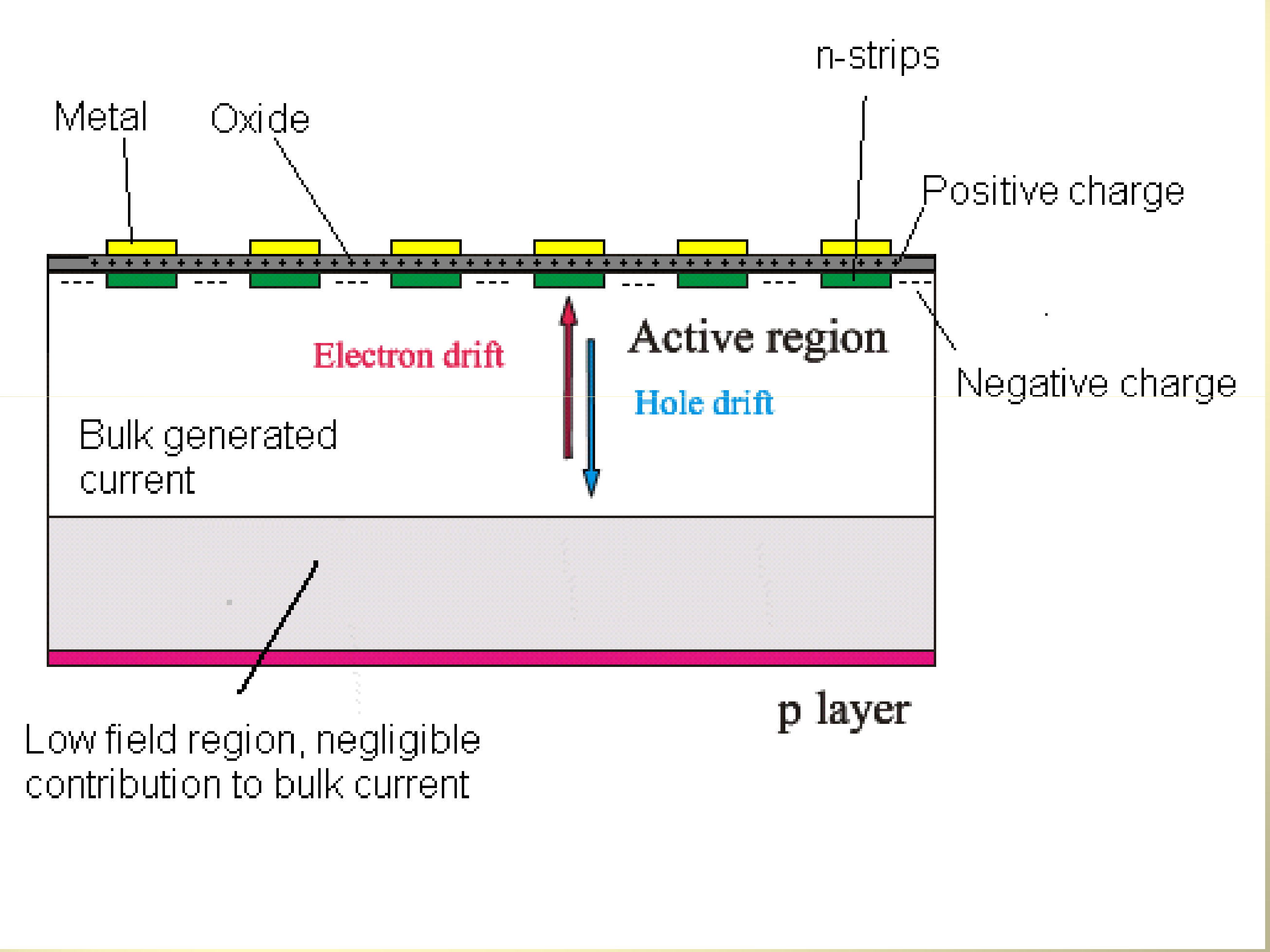
From G. Hall,
VERTEX 2008

- Some extrapolations assuming 0.13µm CMOS
  - Pixels 58µW -> 35µW/pix
    - NB sensor leakage will be significant contribution
  - Outer Tracker: 3600 µW -> 700µW/chan
    - Front end 500µW (M Raymond studies)
    - Links 170µW (including 20% for control)
- More detailed studies needed
  - sensor contribution not yet carefully evaluated
  - internal power distribution will be a significant overhead

Power delivery is a critical aspect, Also sensors will contribute significant power dissipation. Would thin sensors help in reducing the power? Radical solutions required

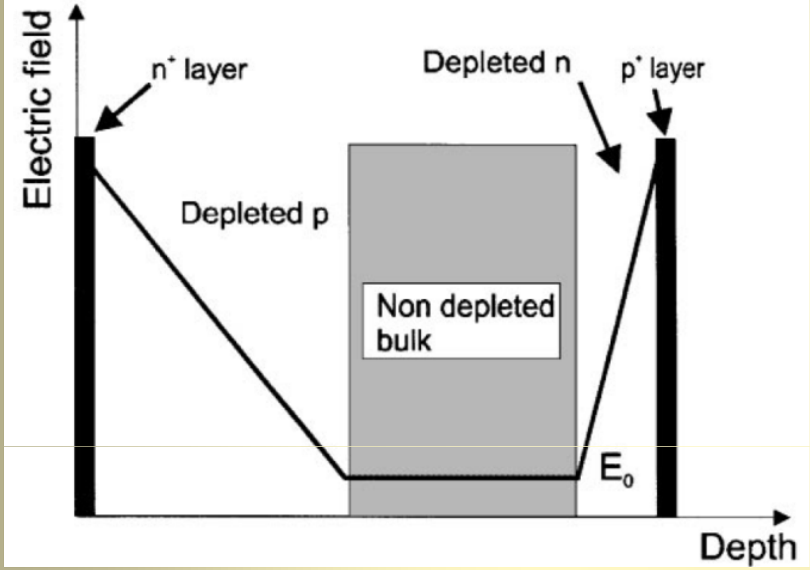
- serial powering or DC-DC conversion
- neither are proven and many problems remain to be solve

Why segmented Si detectors for HEP are usually p-in-n?



n-side Read-out for Tracking in High Radiation Environments

Schematic of Electric field after irradiation

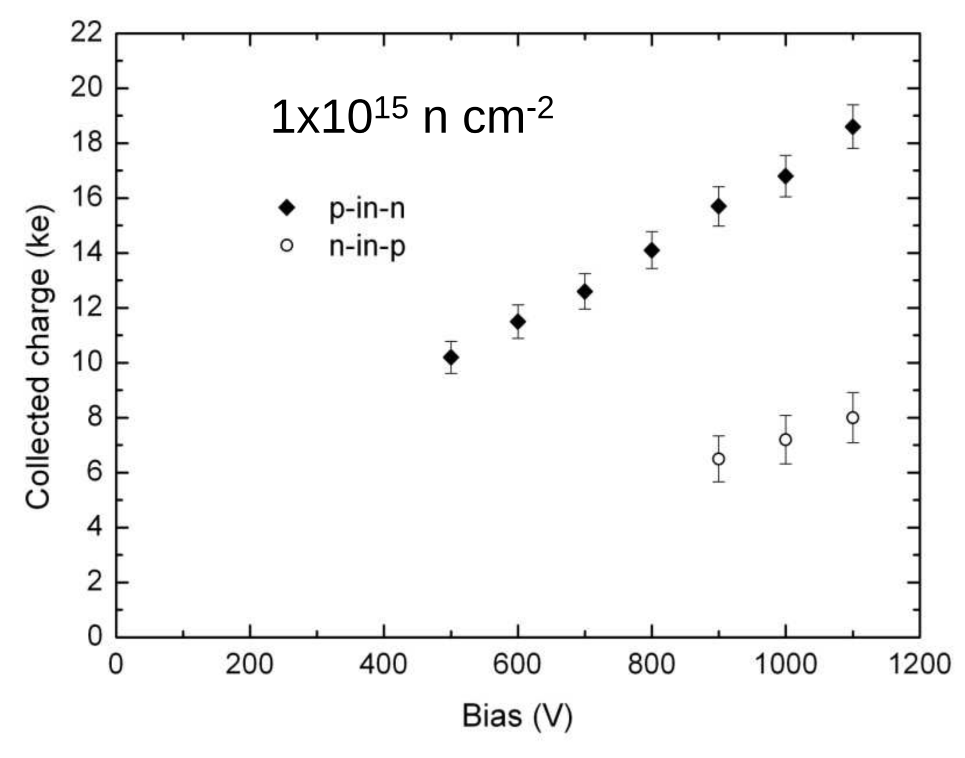


Effect of trapping on the Charge Collection Efficiency (CCE)

$$Q_{tc} \approx Q_0 \exp\left[\frac{-t_c}{\tau_{tr}}\right]$$

$$\frac{1}{\tau_{tr}} = \beta\Phi.$$

n-side read out →
lower collection time, t_c

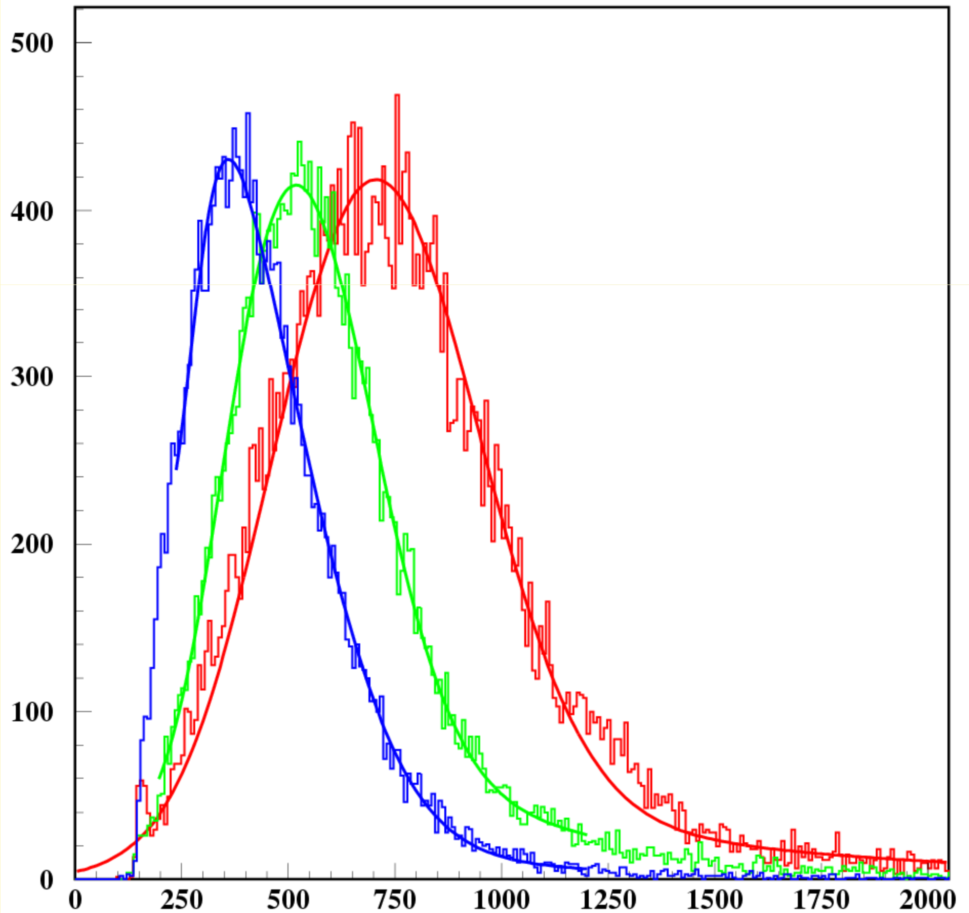


Collecting electrons provides advantage w.r.t. holes due to much shorter t_c.

p-type detectors most natural solution for *e* collection on segmented side.

Method: measure the charge collection of the segmented devices using an analogue electronics chip (SCT128) clocked at LHC speed (40MHz clk, 25ns shaping time). The system is calibrated to the most probable value of the m.i.p. energy loss in a non-irradiated 300µm thick detector (~23000 e^-).

Fast electron source: ^{90}Sr, triggered with scintillators in coincidence.



Motivation for *p*-type:

n-side read-out can be implemented on *n*-type substrates (many successful examples).

But, requires double sided processing (backplane guard ring patterning). Will be effective after space charge sign inversion to *p-type*.

p-type substrate more natural choice

ADVANTAGES

No type inversion.

No backplane processing.

Easier to handle (no need to take care of special gluing on the backside due to the presence of guard-rings. Possibility of operating under-depleted before irradiation)

Further considerations:

With single sided processing more manufacturers can bid for contract (*eg* Hamamatsu) → further price reduction, mitigation of project risks.

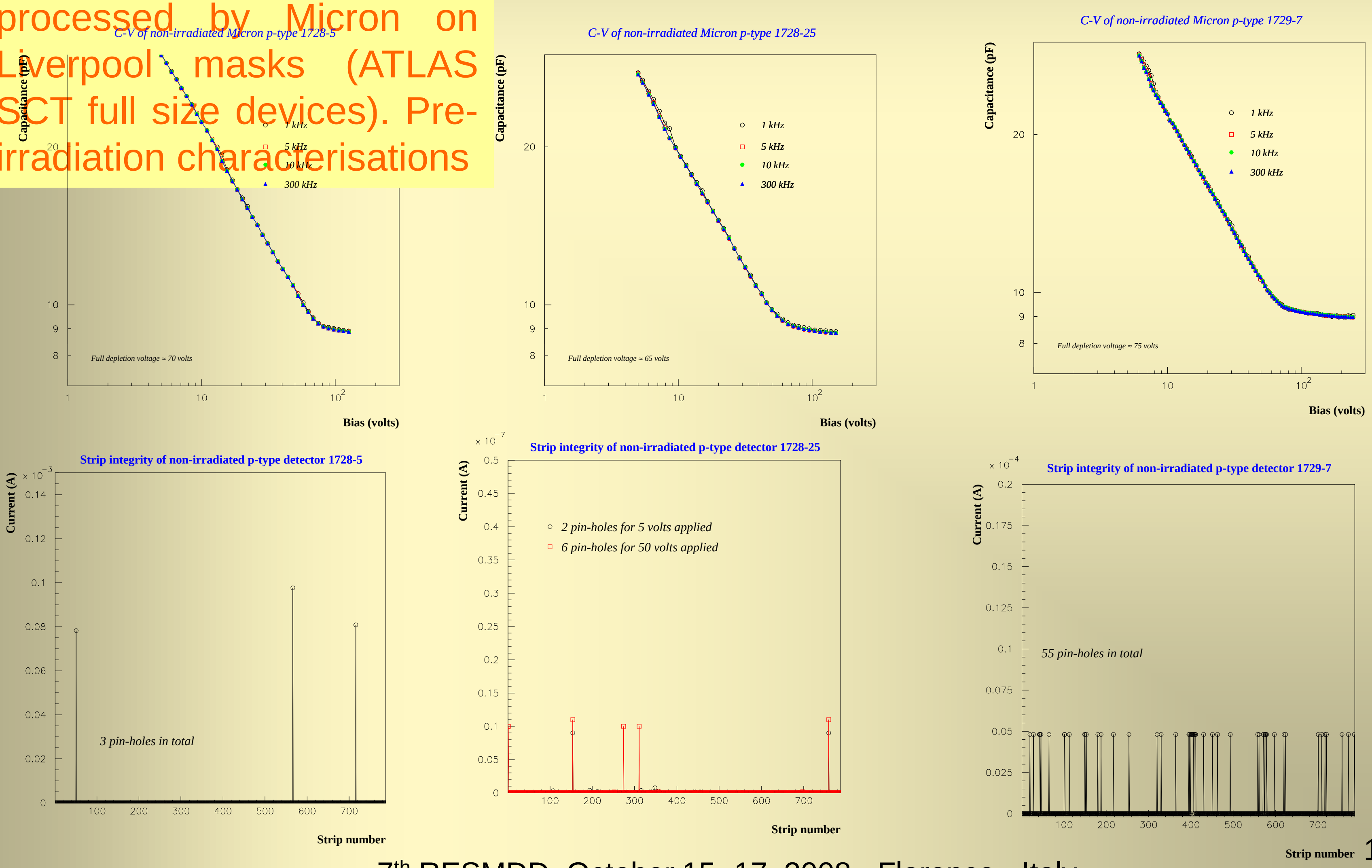
Easier to process thin wafers (possible requirement for reducing material budget in pixel systems).

….and, up to 60% discount with respect to n-in-n!

… a bit of history …….

P-type detectors with individual p-stops processed by Micron on Liverpool masks (ATLAS SCT full size devices). Pre-irradiation characterisations

The development of p-type silicon detectors for the high radiation regions of the LHC, M. D. Hanlon, PhD thesis, Liverpool University1998.

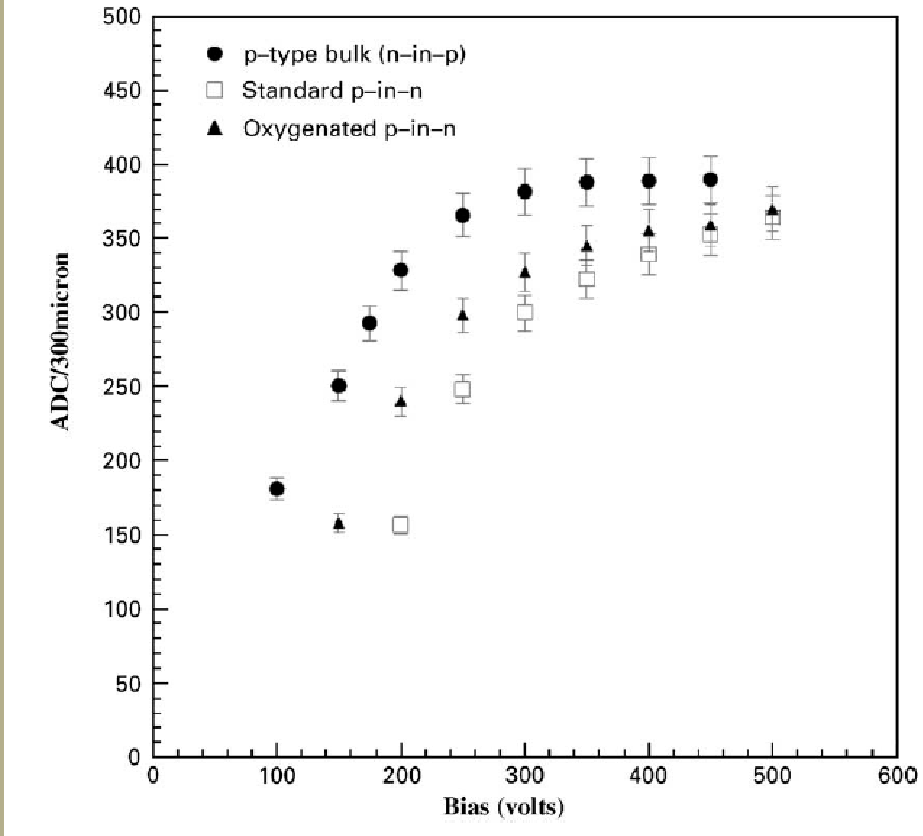


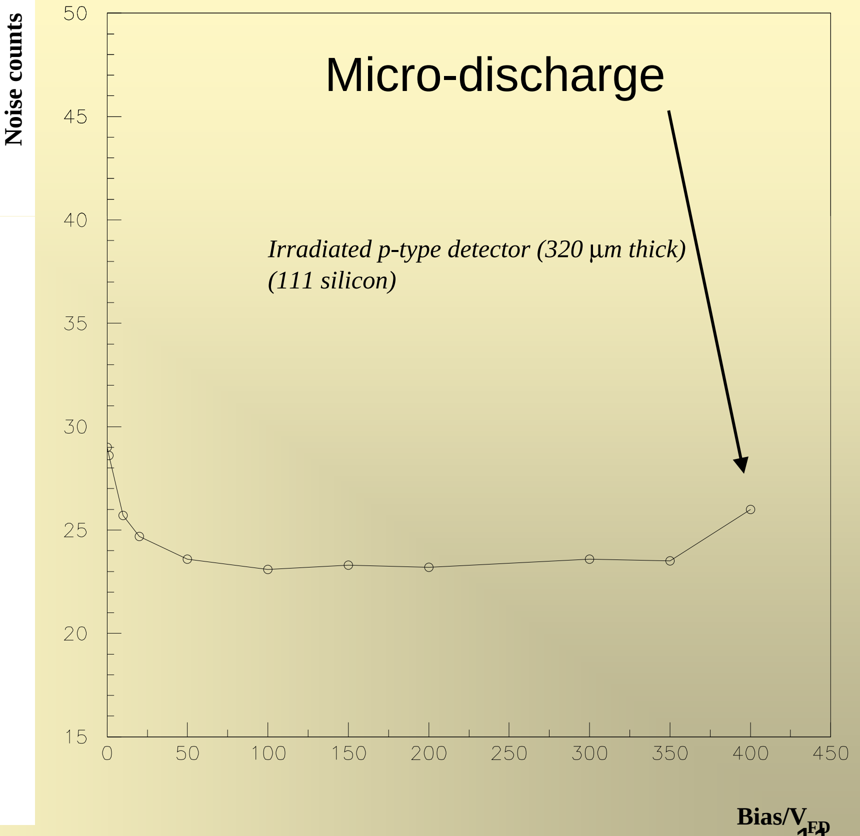
Early results

……. and signal and noise performances after 3.10^{14} cm^{-2}

Signal vs V of p-type, std and oxy. n-type

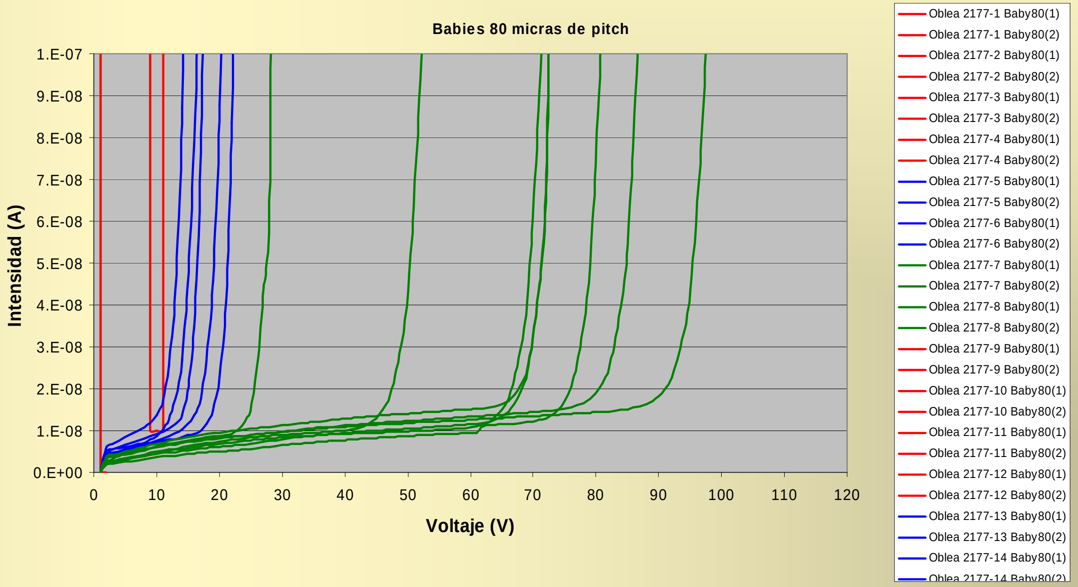
G. Casse, P.P. Allport, T.J.V. Bowcock, A. Greenall, M. Hanlon, J.N. Jackson, "First results on the charge collection properties of segmented detectors made with p-type bulk silicon", Nuclear Instruments and Methods in Physics Research vol. 487/3 (Jul. 2002) 465-470.




Micro-discharge

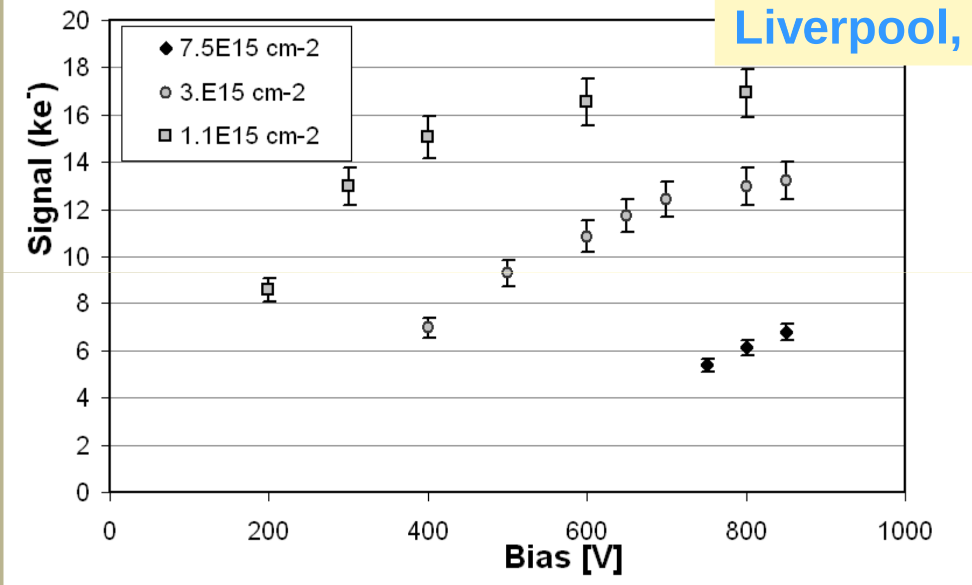
P-type miniature detectors from CNM

This was the very first attempt at p-type silicon manufacturing from CNM. Various p-stop doses were tried with miniature (1x1 cm^{-2}) detectors made with a masked designed by Liverpool. The measurements on non-irradiated devices were disappointing in term of break-down properties. Only the higher p-stop doses were able to guarantee sufficient edge isolation and lower currents to reach about full depletion.

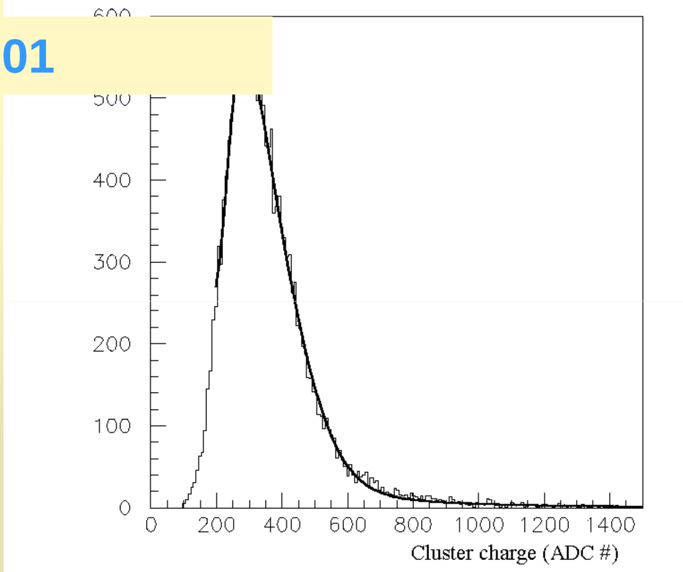


P-type miniature detectors from CNM

Nevertheless, extremely good performances in term of charge collection after unprecedented doses (1., 3.5., and 7.5 10^{15} p cm^{-2}) were obtained with these devices!!



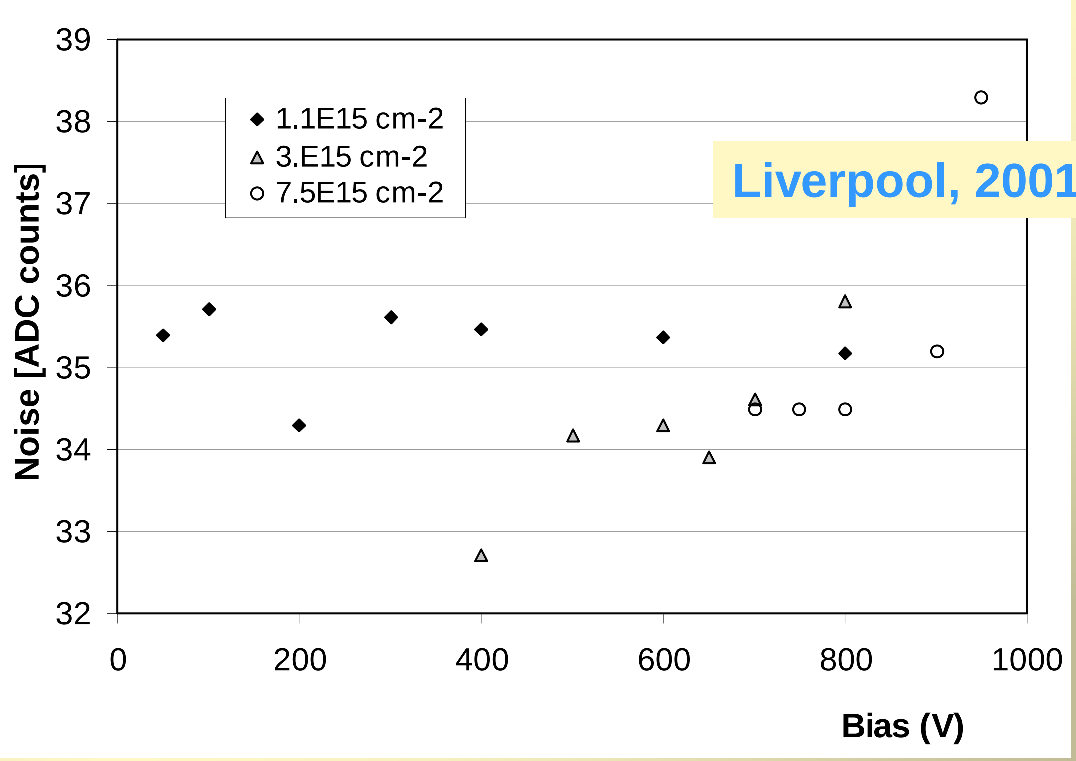
Liverpool, 2001



But: results very likely affected by the relatively high reverse current in the detectors. The air cooling system has been improved since, and now more stable currents are measured and bias up and above 1000V is possible. CCE seems affected by unstable current regime (see later talk on new heavy irradiation results from A. Affolder).

P-type miniature detectors from CNM

Despite the rather poor pre-irradiation characteristics, all the devices (~300µm thick) show a remarkable robustness, after irradiation, both in term of breakdown voltage and noise. A value of about 34 ADC counts was the typical one measured with similar geometry standard ATLAS non-irradiated miniature sensors.



Liverpool, 2001

P-type miniature detectors from CNM

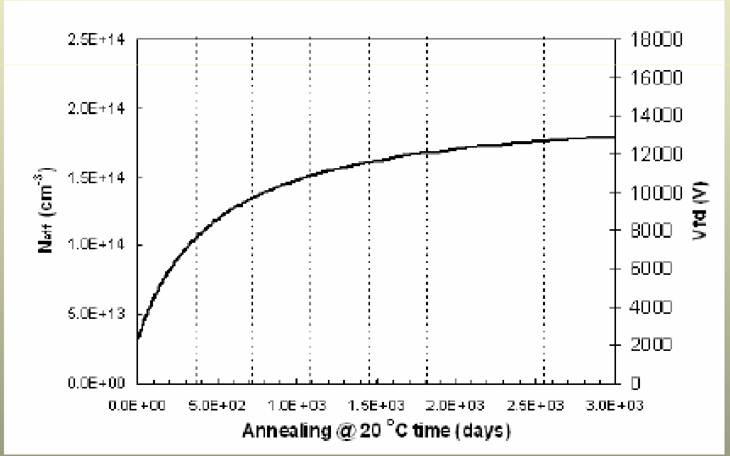
Another effect that has changed the way to regard at the reverse annealing has been measured on these devices. The reverse annealing has been always considered as a possible cause of early failure of Si detectors in the experiments if not controlled by mean of low temperature (not only during operations but also during maintenance/shut down periods). This was originated by accurate measurements of the annealing behaviour of the full depletion voltage in diodes measured with the CV method.

Liverpool, 2001

Expected changes of full depletion voltage with time after irradiation (as measured with the C-V method) for detector irradiated to 7.5 10^{15} p cm^{-2}.

Please notice that according to CV measurements the so called V_{FD} changes from <3kV to >12kV!

Initial V_{FD} ~ 2800V



Predictions from RD48 parameters for Oxygen enriched devices (best scenario: after 7 RT annealing years the V_{fd} goes from ~2800V to ~12000 V!

P-type miniature detectors from CNM

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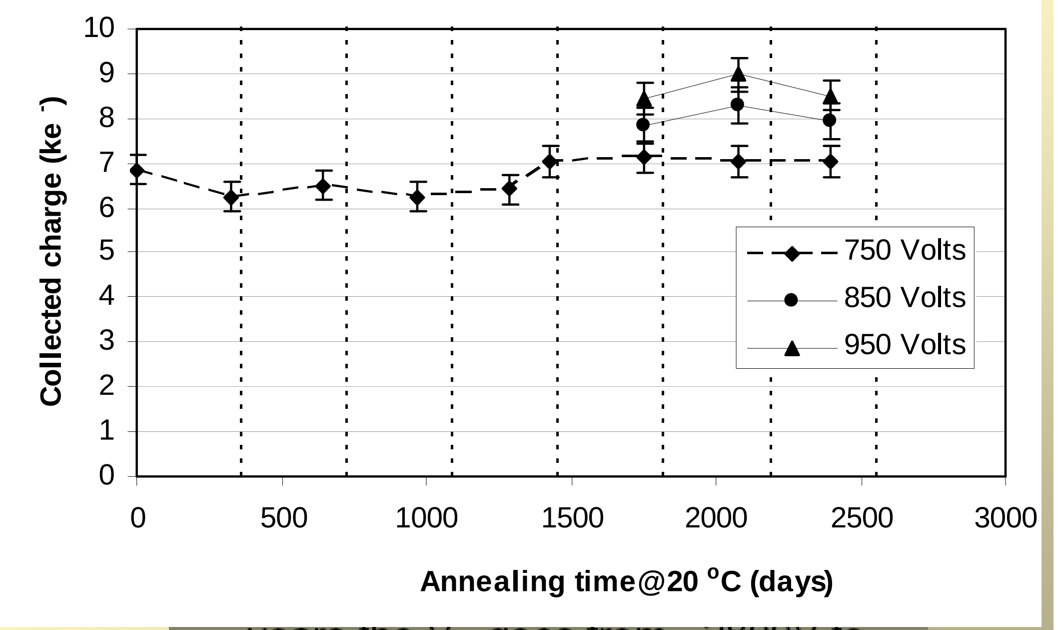


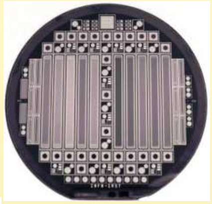
years the V_{fd} goes from ~2800V to ~12000 V!

RD50 Test Sensor Production Runs (2005/2006)

- **Recent production of Silicon Strip, Pixel and Pad detectors (non exclusive list):**

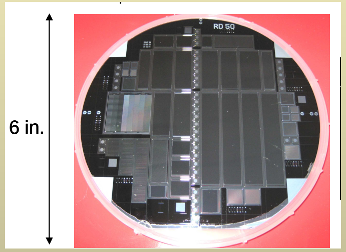
- CIS Erfurt, Germany
  - 2005/2006/2007 (RD50): Several runs with various epi 4” wafers only pad detectors

- CNM Barcelona, Spain
  - 2006 (RD50): 22 wafers (4”), (20 pad, 26 strip, 12 pixel),(p- and n-type),(MCZ, EPI, FZ)
  - 2006 (RD50/RADMON): several wafers (4”), (100 pad), (p- and n-type),(MCZ, EPI, FZ)
- HIP, Helsinki, Finland
  - 2006 (RD50/RADMON): several wafers (4”), only pad devices, (n-type),(MCZ, EPI, FZ)
  - 2006 (RD50) : pad devices, p-type MCz-Si wafers, 5 p-spray doses, Thermal Donor compensation
  - 2006 (RD50) : full size strip detectors with 768 channels, n-type MCz-Si wafers



- IRST, Trento, Italy
  - 2004 (RD50/SMART): 20 wafers 4” (n-type), (MCZ, FZ, EPI), mini-strip, pad 200-500μm
  - 2004 (RD50/SMART): 23 wafers 4” (p-type), (MCZ, FZ), two p-spray doses 3E12 amd 5E12 cm^{-2}
  - 2005 (RD50/SMART): 4” p-type EPI
  - 2006 (RD50/SMART): new SMART mask designed

- Micron Semiconductor L.t.d (UK)
  - 2006 (RD50): 4”, microstrip detectors on 140 and 300μm thick p-type FZ and DOFZ Si.
  - 2006/07 (RD50): 93 wafers, 6 inch wafers, (p- and n-type), (MCZ and FZ), (strip, pixel, pad)



- Sintef, Oslo, Norway
  - 2005 (RD50/US CMS Pixel) n-type MCZ and FZ Si Wafers

- Hamamatsu, Japan
  - In 2005 Hamamatsu started to work on p-type silicon in collaboration with ATLAS upgrade groups

- **M.Lozano, 8th RD50 Workshop, Prague, June 2006**
- **A.Pozza, 2nd Trento Meeting, February 2006**
- **G.Casse, 2nd Trento Meeting, February 2006**
- **D. Bortoletto, 6th RD50 Workshop, Helsinki, June 2005**
- **N.Zorzi, Trento Workshop, February 2005**

RD50 activity:

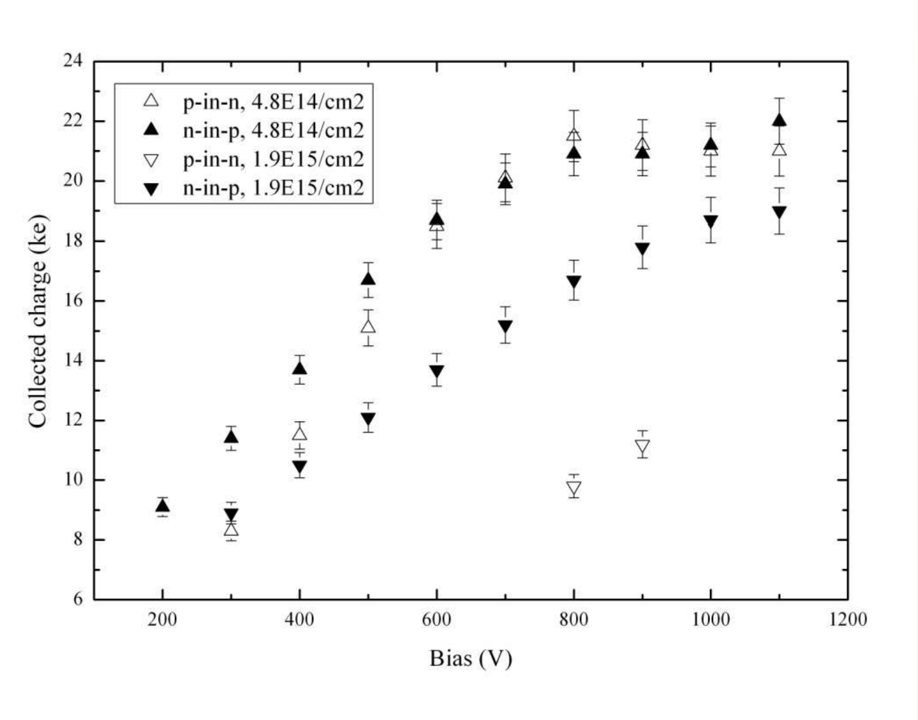
Systematic studies of n-in-p devices by comparison with p-in-n and n-in-n.

Systematic comparison of the effect of the substrate on radiation hardness: MCz, FZ and Epi n and p Si crystals, with n-side readout.

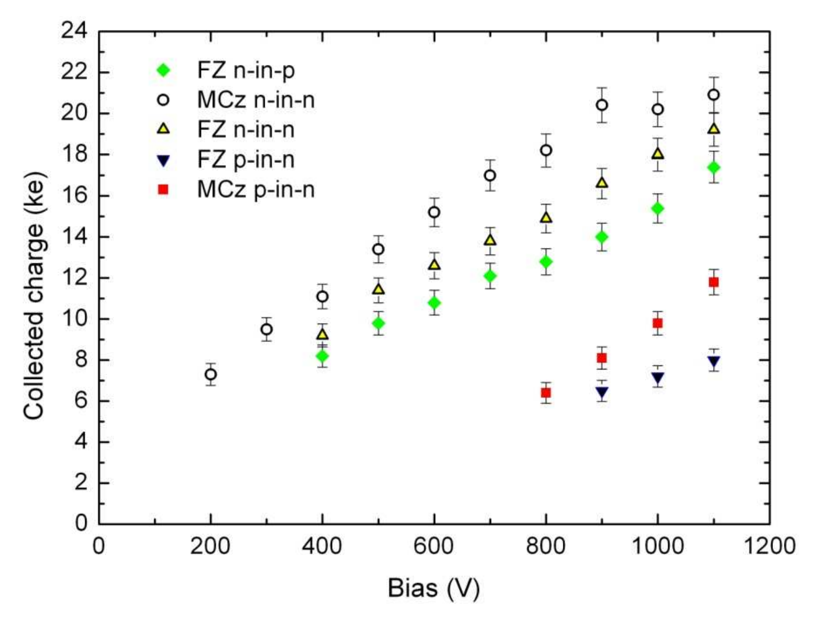
The MCz and FZ comparison will be presented in this conference by A. Affolder.

P-in-N would not work:

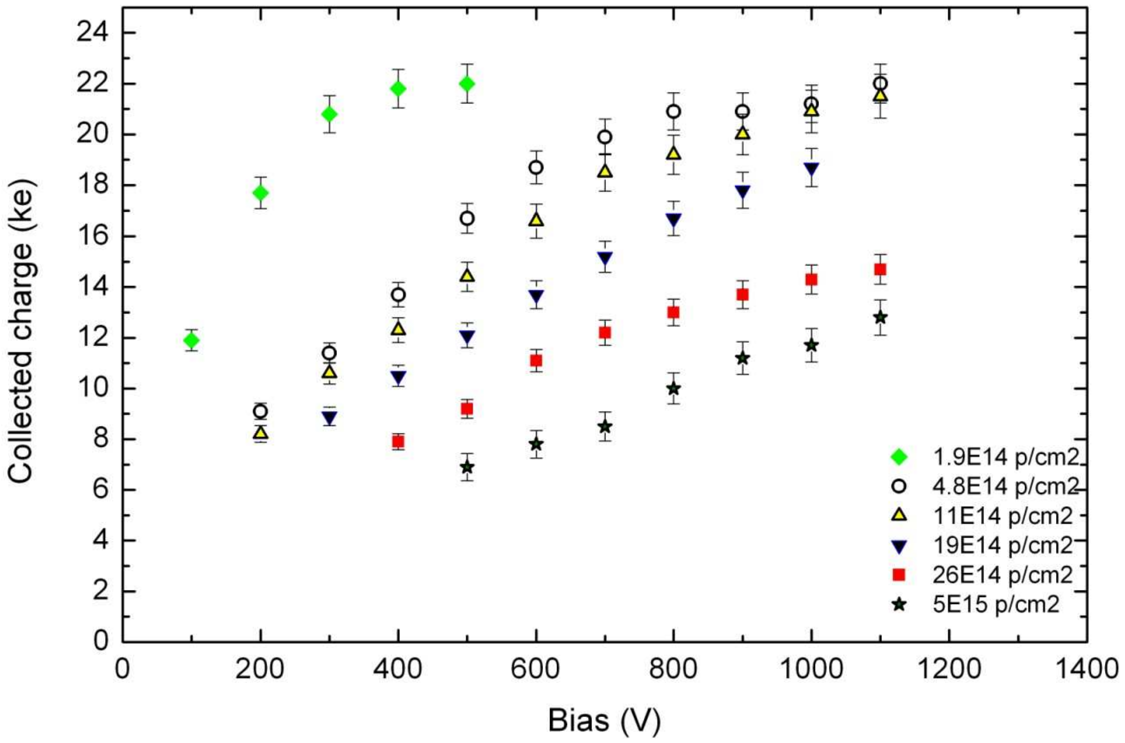
Proton irradiations, 4.8 and 19x10^{14} cm^{-2}.



Neutron irradiations, 1x10^{15} cm^{-2}.



24 GeV/c proton irradiations of p-type FZ sensors

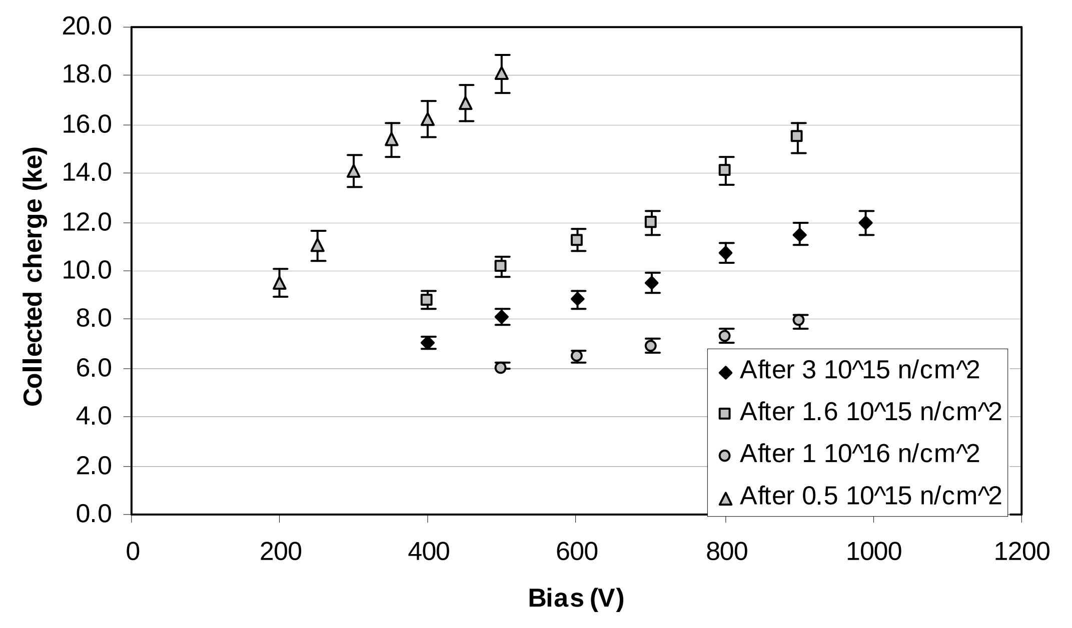


Results with neutron irradiated Micron detectors

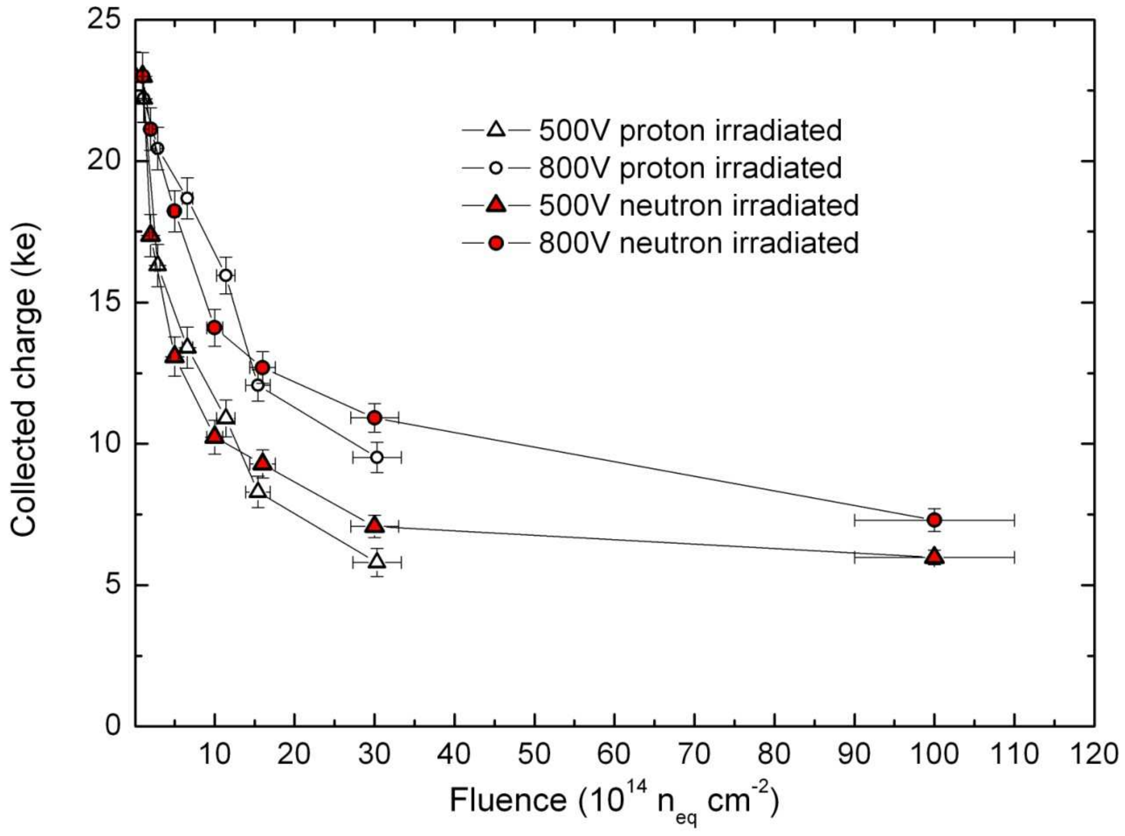
Here µ-strip detector CCE measurements up to 1x10^{16} n cm^{-2}!!

Now, even further

(see talks from A. Affolder and I. Mandic)

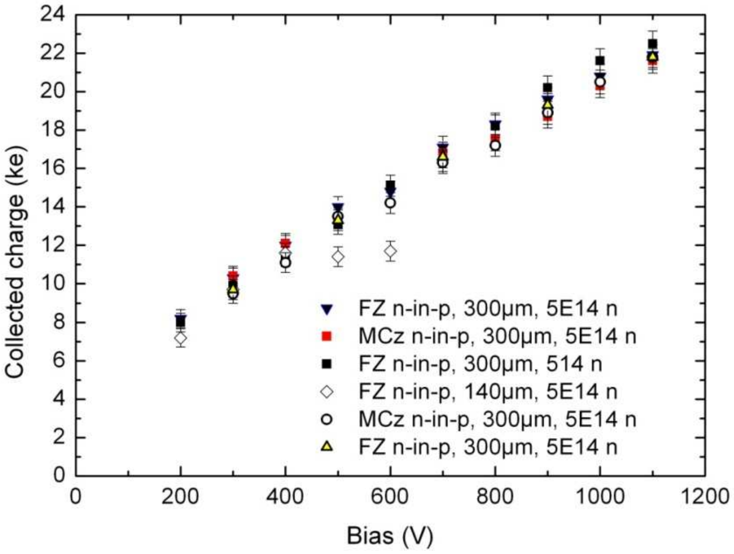


24GeV/c proton irradiations vs neutron (normalised with NIEL)

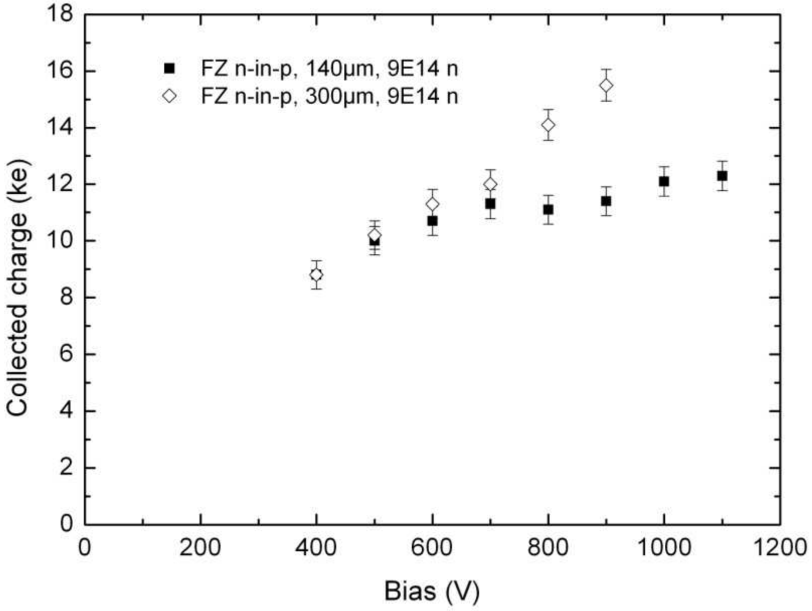


Effect of thickness: CCE

5×10^{14} n cm^{-2}

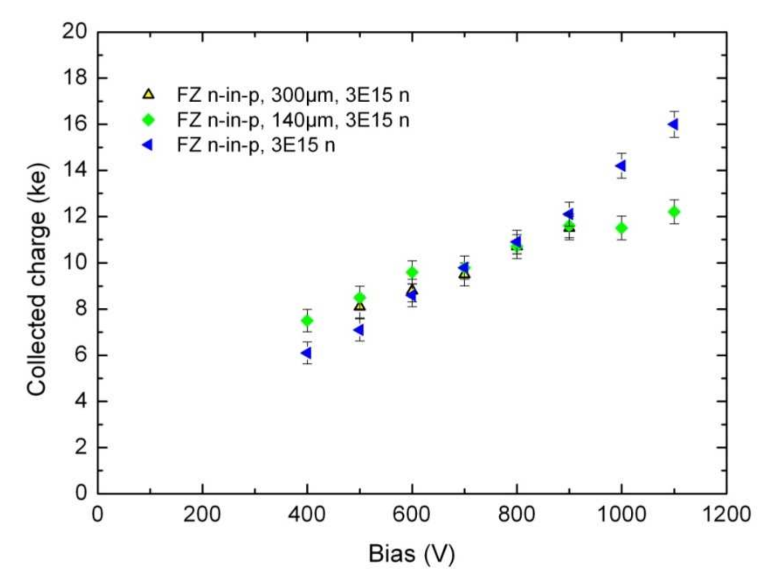


9×10^{14} n cm^{-2}

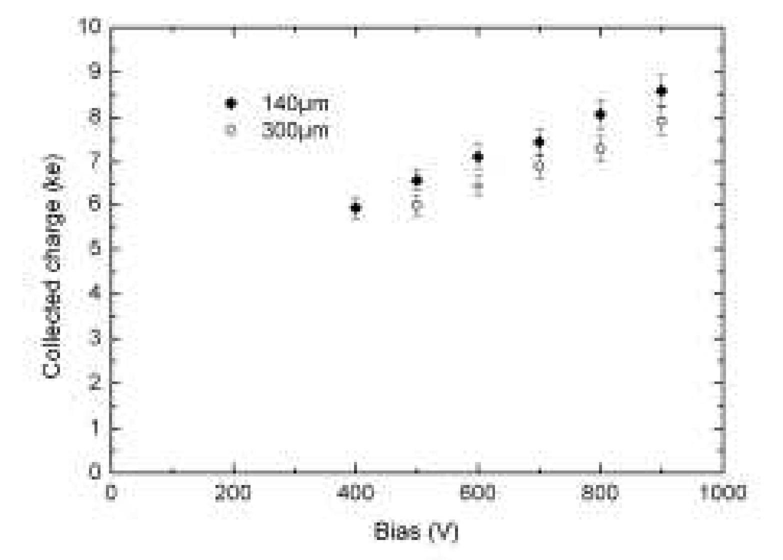


Effect of thickness: CCE

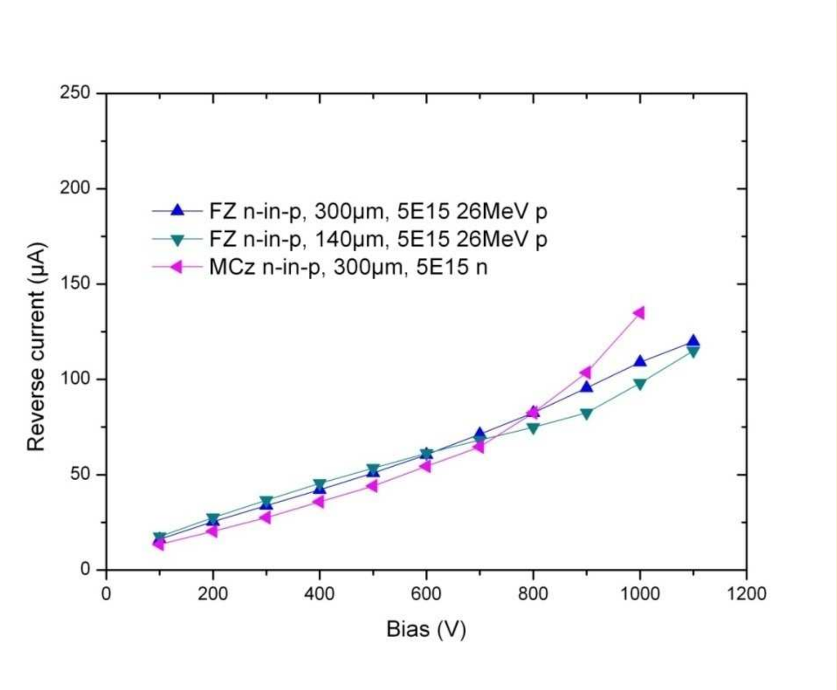
$3\text{x}10^{15}$ n cm^{-2}

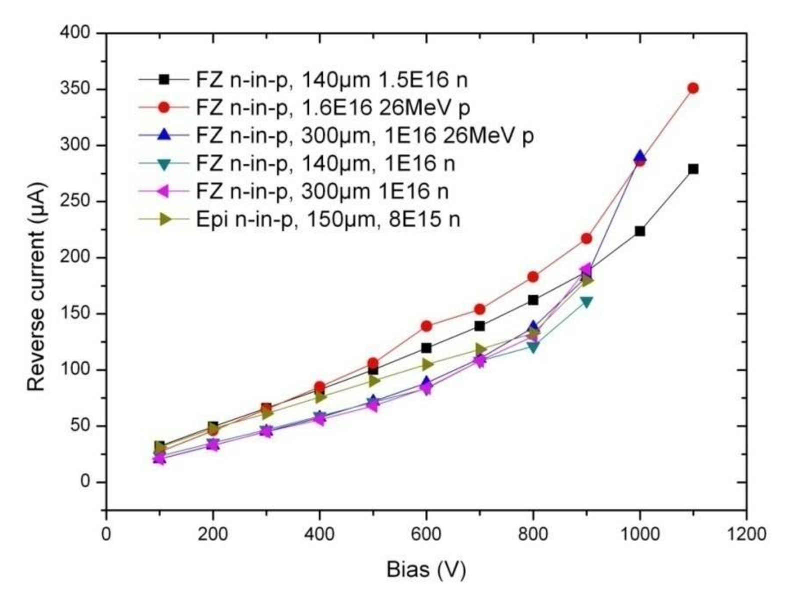


$1\text{x}10^{16}$ n cm^{-2}



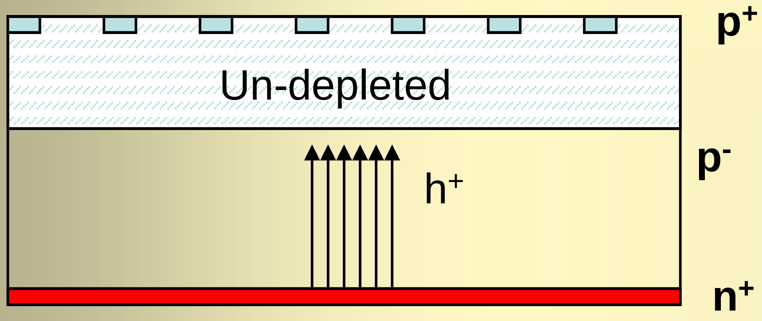
Effect of thickness: reverse current



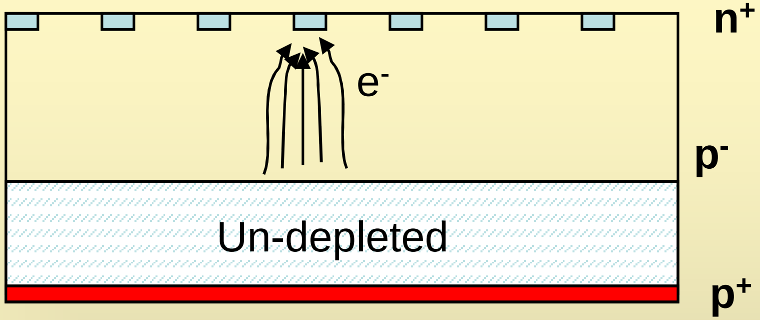


Why this happens? Remember: P-strip vs N-strip Readout

- **“Standard” p-on-n after type inversion**



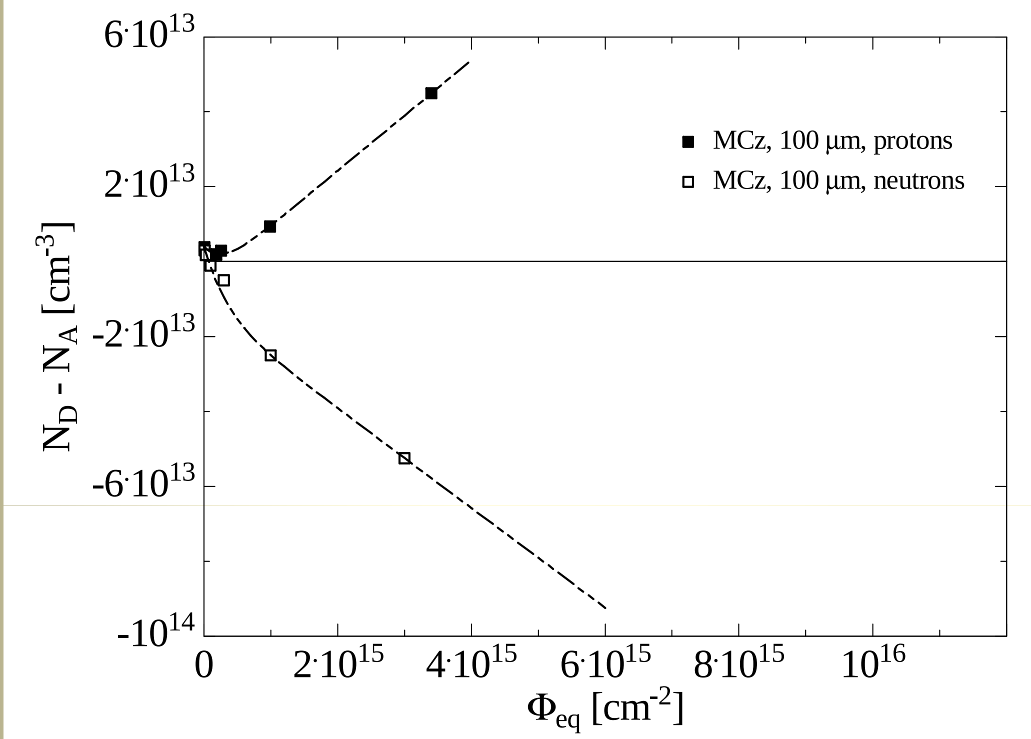
- **“New” n-on-p before/after type inversion**



Type inversion turns lightly doped material to “p” type

Is there any other substrate behaving significantly better than n-in-p sensors made on FZ material?

Special effects: mixed irradiations (neutrons + protons)

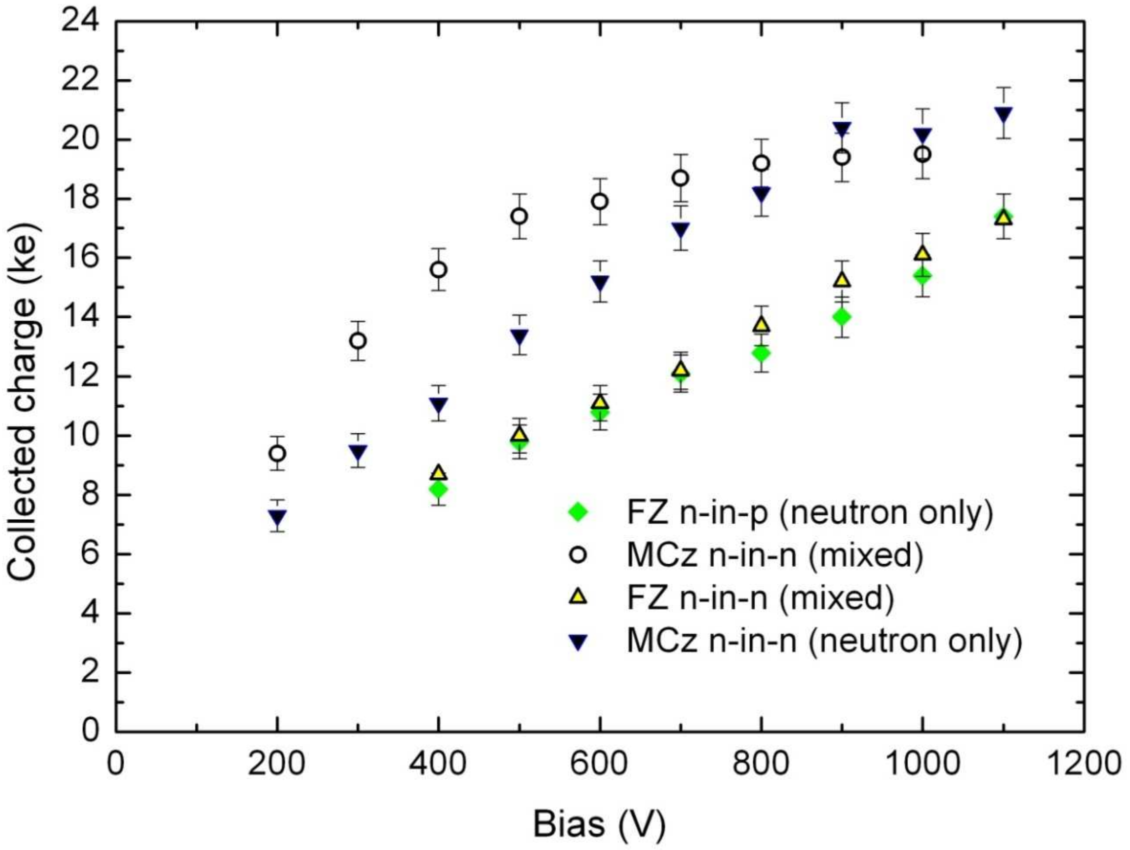


E. Fretwurst et al., 11th RD50 workshop

Practical outcome: possible partial compensation of N_{eff}, therefore **better CCE at low voltages**?

- **Same behavior holds for thin MCz-diodes reveal no SCSI after proton damage, contrary to neutron damage**
- **β > 0 (dominant donor creation) for protons (more point defects than clusters)**
- **β < 0 (dominant acceptor creation) for neutrons (more clusters than point defects)**

Special effects: mixed irradiations (neutrons + protons): $1x10^{15}$ n_{eq} cm^{-2}

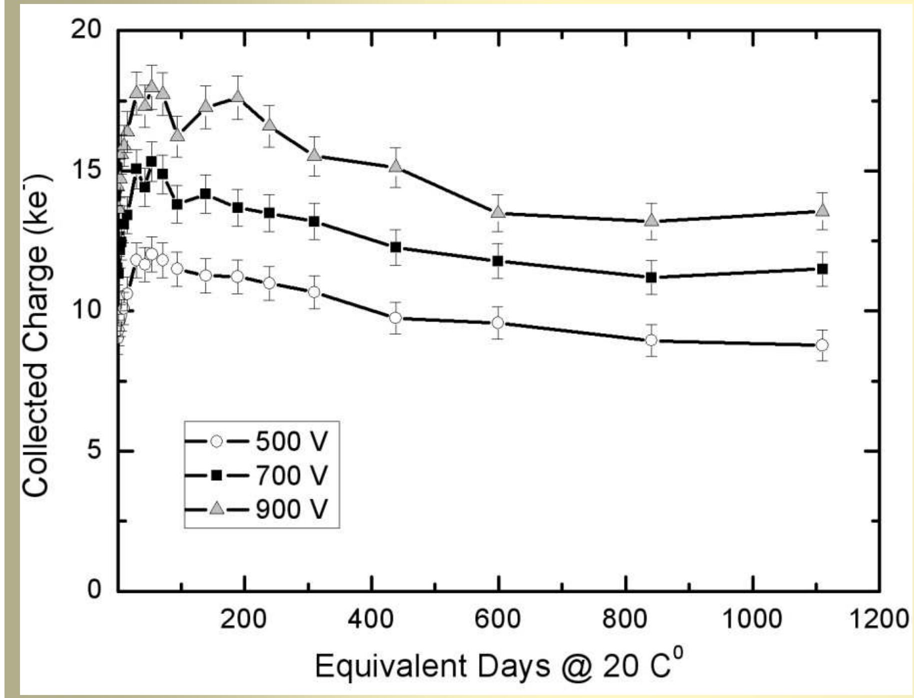


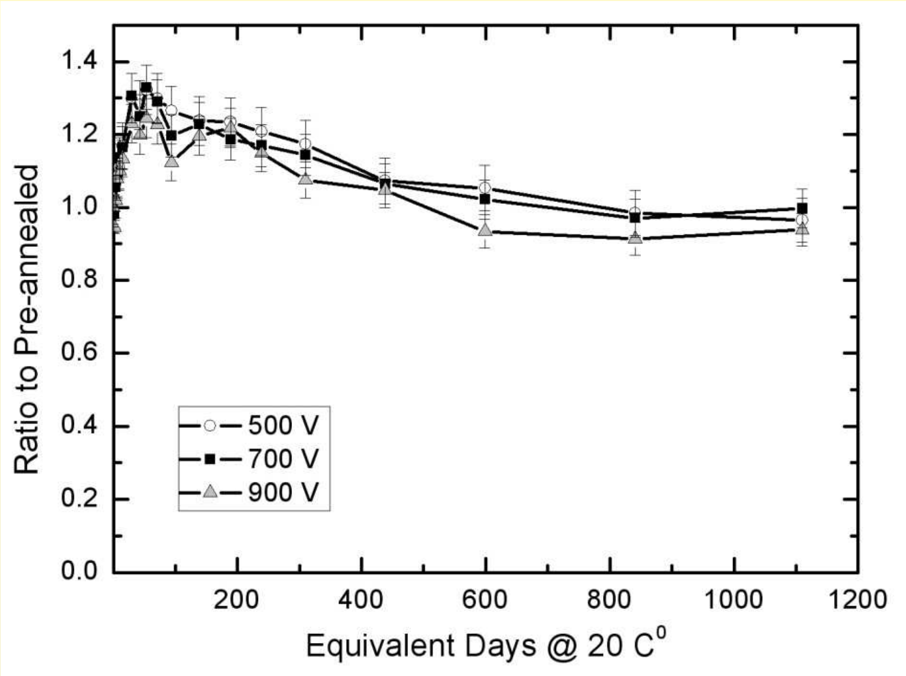
Special effects: mixed irradiations (neutrons + protons): 1×10^{15} n_{eq} cm^{-2}

n-MCz showing significant improvement in the case of neutron and mixed irradiation. Will have similar advantages also with proton irradiation?

Would p-MCz show similar advantages with proton irradiations?

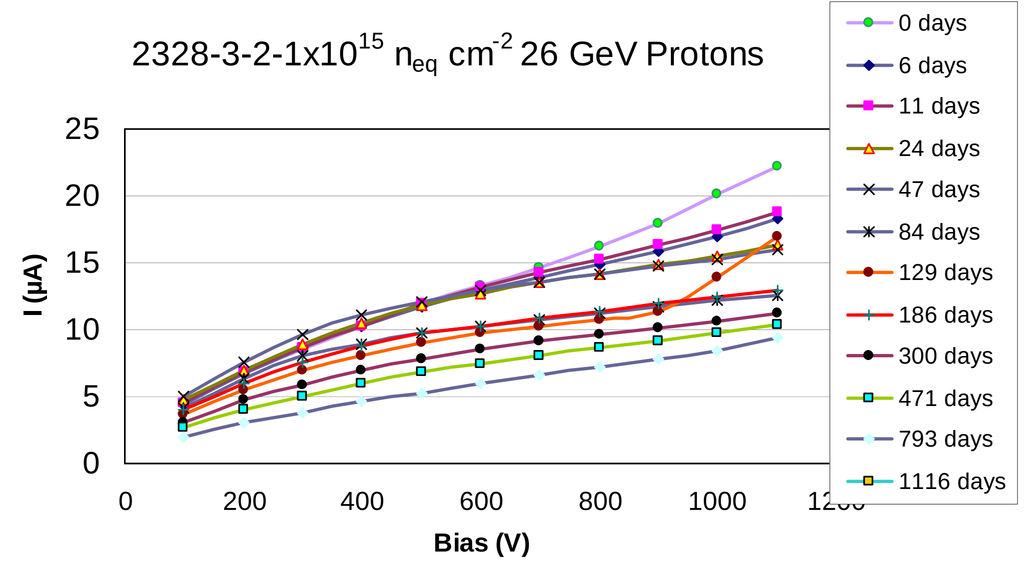
A word on the annealing of the CCE (Neutrons)

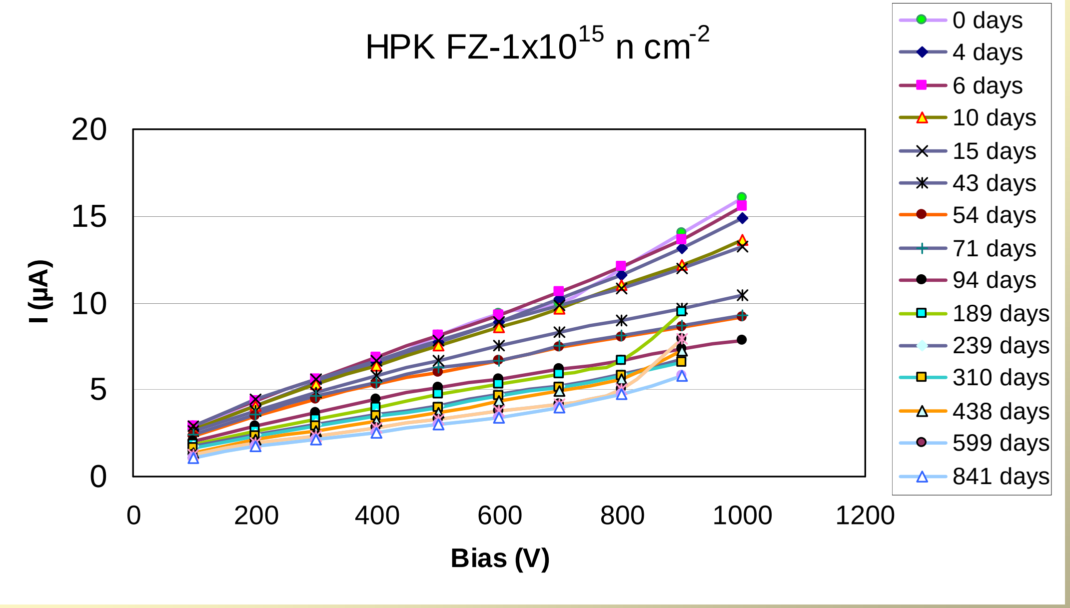




Important operational parameter: temperature management (including shutdown periods).

Annealing of the IV (Neutrons and Protons)





NOTE: this is a very important parameter for SLHC operation!

Would allow to use annealing to optimise the signal size and reduce the reverse current.

SUMMARY

Finely segmented silicon detectors made with n-side readout on p-type substrate have emerged as the most promising choice for the replacement of the tracker systems for the CERN LHC upgrade to higher luminosity. They will replace the present sensors in the LHCb-VELO detector. They have practically assumed the status of baseline devices for the silicon microstrip layers of the upgrades (n-in-p detectors will guarantee a S/N of ~15 after 1×10^{15} n_{eq} cm^{-2} required to qualify the innermost ATLAS-SCT upgraded microstrips). Planar p-type sensors are also now being considered as possible candidates even for the innermost pixel layers, after the impressive results in term of Charge Collection Efficiency after $>1.5 \times 10^{16}$ n_{eq} cm^{-2}.