Irradiation studies of CNM double sided 3D detectors

a) Richard Bates, C. Parkes, D. Pennicard, B. Rakotomiaramanana
b) L. Alianelli ,C. Fleta, G. Pellegrini, M. Lozano
c) U. Parzefall
d) X. Blot
e) J. Haerkoenen and E. Tuovinen

a) University of Glasgow, Department of Physics and Astronomy, Glasgow, UK,
b) Instituto de Microelectronica de Barcelona, IMB-CNM-CSIC, Barcelona, Spain,
c) Physikalisches Institut, Universität Freiburg, Germany
d) National Institute of Applied Science of Toulouse, Toulouse, France
e) Helsinki Institute of Physics, Finland

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Outline

- Introduction
  - Motivation
  - CNM Double-sided 3D detectors
- Alibava system
  - Set-up
  - Calibration
- Charge collection
  - Response to Sr-90 electrons
  - High bias operation
- Summary

Radiation-hard detectors for the (s)LHC

- ATLAS Forward Physics programme (2012)
  - Fluence ~ **1×10^{15} 1MeV n_{eq}/cm^2**
- Inner pixel layer (IBL) replacement for ATLAS (2014)
  - Fluence of **4.4×10^{15} 1MeV n_{eq}/cm^2**
- Super-LHC (2017)
  - 10 * luminosity upgrade on present LHC
  - Fluence up to ~ **1×10^{16} 1MeV n_{eq}/cm^2**
- LHCb VELO upgrade
  - Integrated fluence ~ **1×10^{16} 1MeV n_{eq}/cm^2**
- **Design fluences for ATLAS sensors** (includes 2x safety factor) **:**

Innermost Pixel Layer ~ 5cm radius : **1.6×10^{16} 1MeV n_{eq}/cm^2** = 500 Mrad
Outer Pixel Layers ~ 30cm radius : 3×10^{15} 1MeV n_{eq}/cm^2 = 150 Mrad

CNM Dounble-sided 3D Detectors

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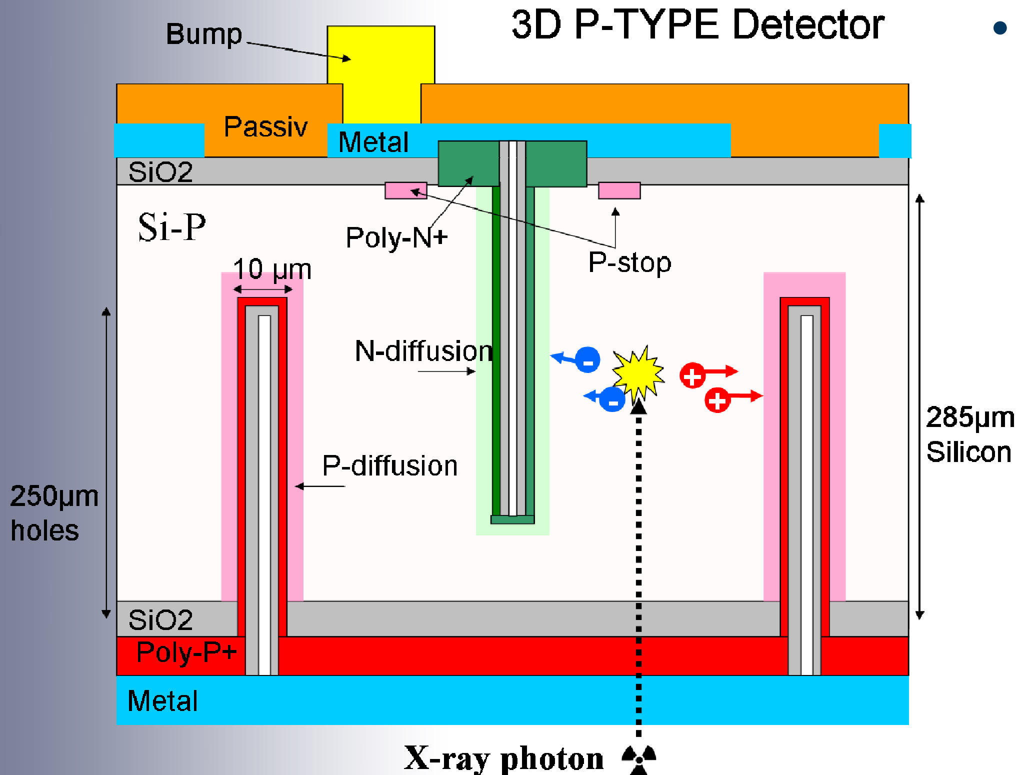
Double sided 3D



- Substrate 285µm thick
- Holes 250µm deep
- p^- type bulk
- n^+ readout columns
- p stop rings around n^+ columns

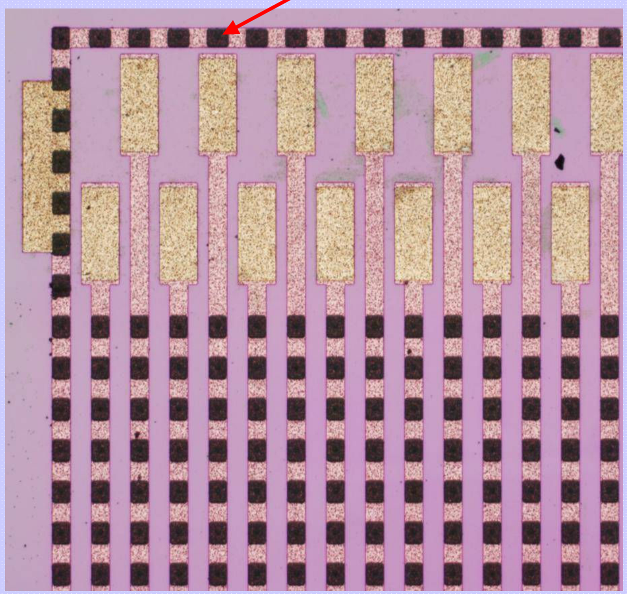
CNM Double-sided 3D fabrication runs

Hole aspect ration 25:1
10µm diameter, 250µm deep
Substrate 285m thick

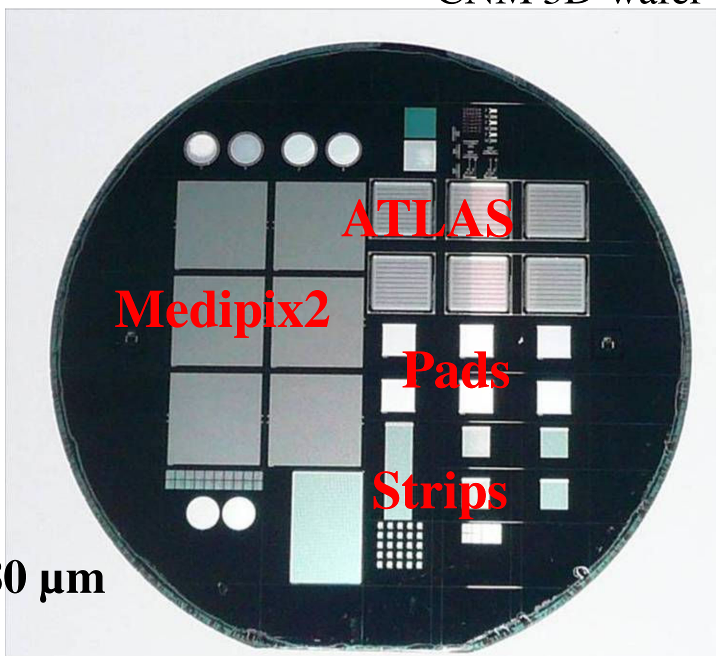
Devices designed at Glasgow & CNM
Fabricated at CNM

50 strips
DC coupled
50 electrodes/strip
4mm long strips

Devices
- » n^+ strips
- » p^- bulk
- » p^+ back contact



CNM 3D-wafer

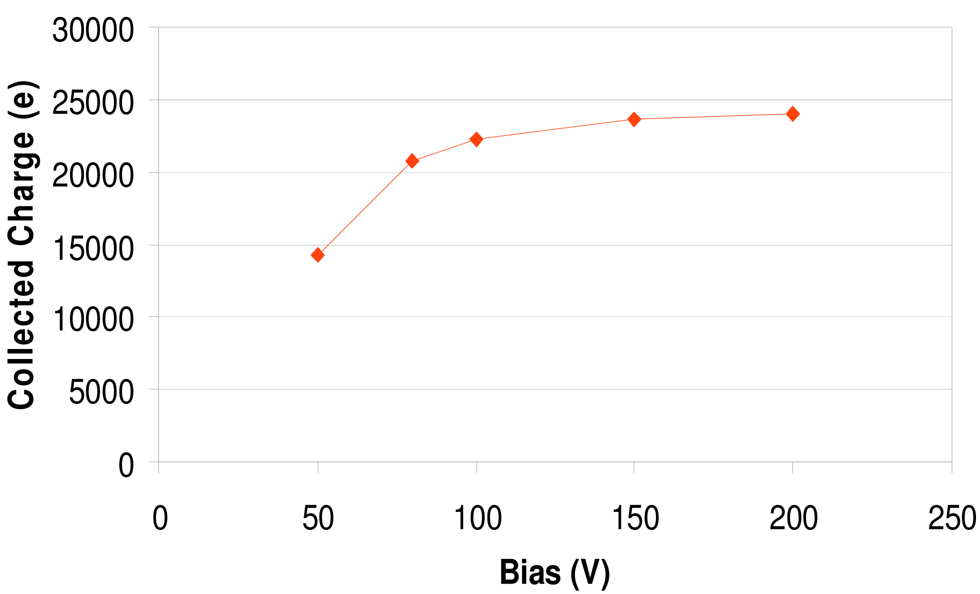


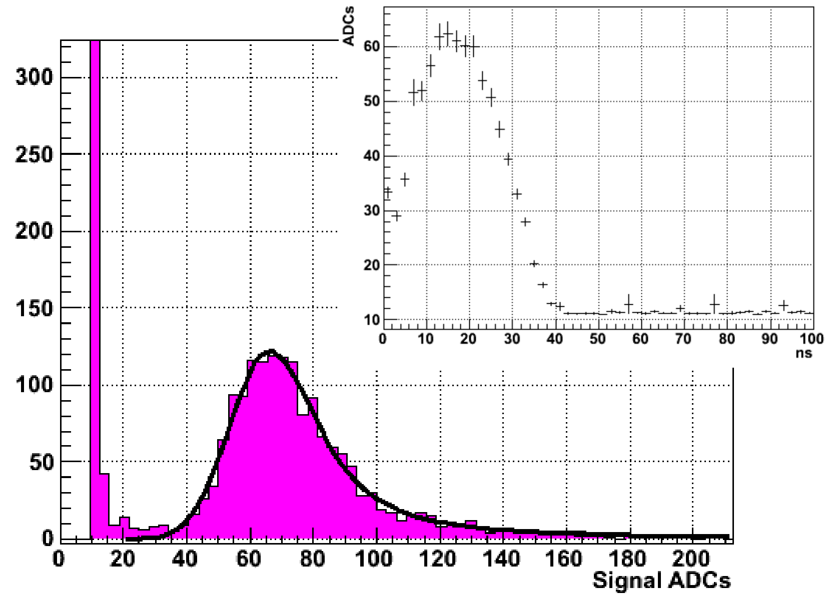
4 inch wafer

ICP is a reliable and repeatable process (many test runs always successful).
Yield: Strip detectors = 88%. ATLAS pixels = 50%

Calibration

- Planar strip detector
  - SCT Barrel miniature
    - p$^+$ readout strips, n$^-$ bulk
    - 300 µm thick
    - 80 µm pitch, 1 cm long AC coupled strips
  - Hole collection
  - Plateau value taken as full charge collection in planar device





Double side 3D
Strip detectors tested

- Short strip detectors
  - Electron collecting,
    n^+ readout columns
- Irradiated at Karlsruhe with 26 MeV protons.
- No intentional annealing
  - max 5 days RT
- Detectors glued to Ceramic base boards
  - RC pitch adaptors from VTT/Helsinki Institute of Physics

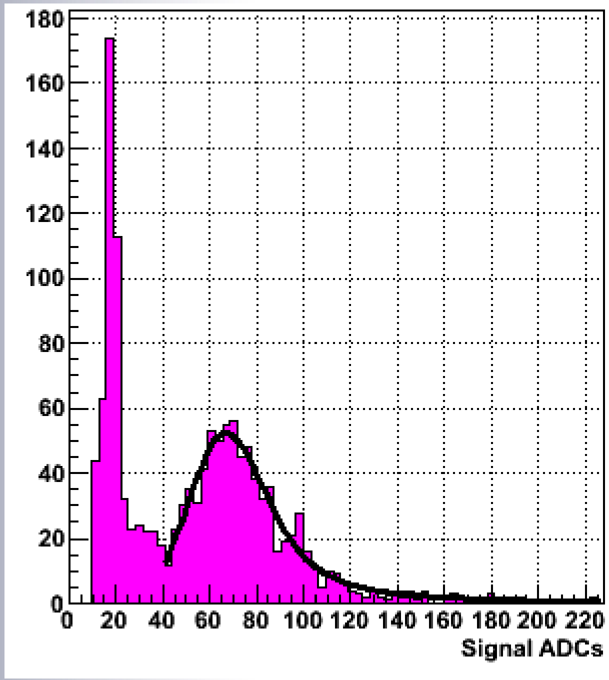
Fluence (1 MeV neq/cm2)

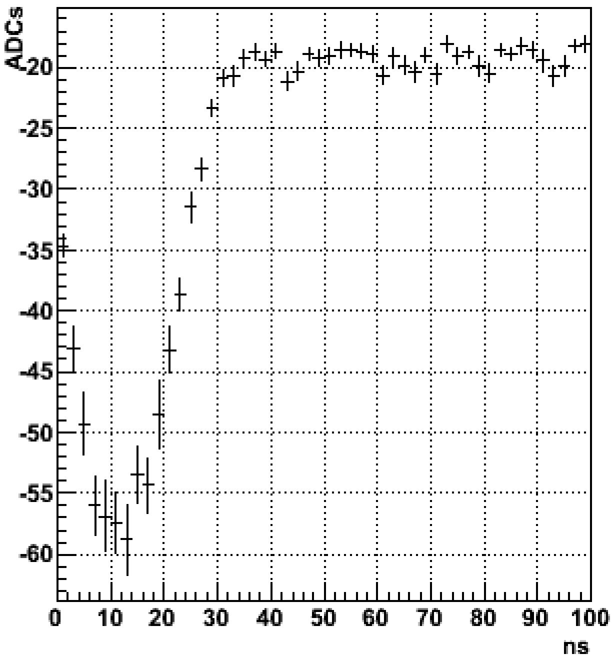
5E14
1E15
2E15
5E15
1E16
2E16

26 MeV protons scaled to
1 MeV neutron equivalent fluence
with a hardness factor of 1.85

Zero fluence data

- 100% Charge Collection from all non-irradiated devices
  - Scaled to 285 µm full device thickness
- Capacitance is higher ~ 3pF for 3D c.f 2pF for planar
  - Noise is higher ~ twice as much
  - Gain should fall a little
  - Still need to fully understand this!

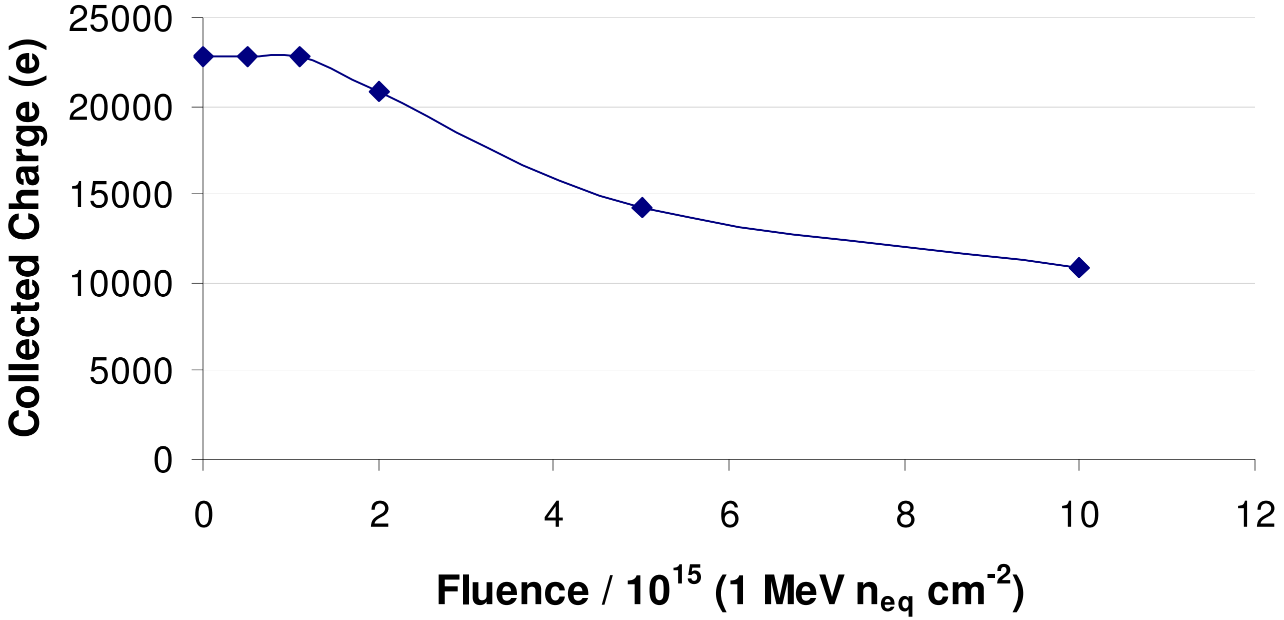




Note: This is a 4mm long strip detector
The noise is large due to the capacitance.
Pixels detectors are only 50 - 500µm long

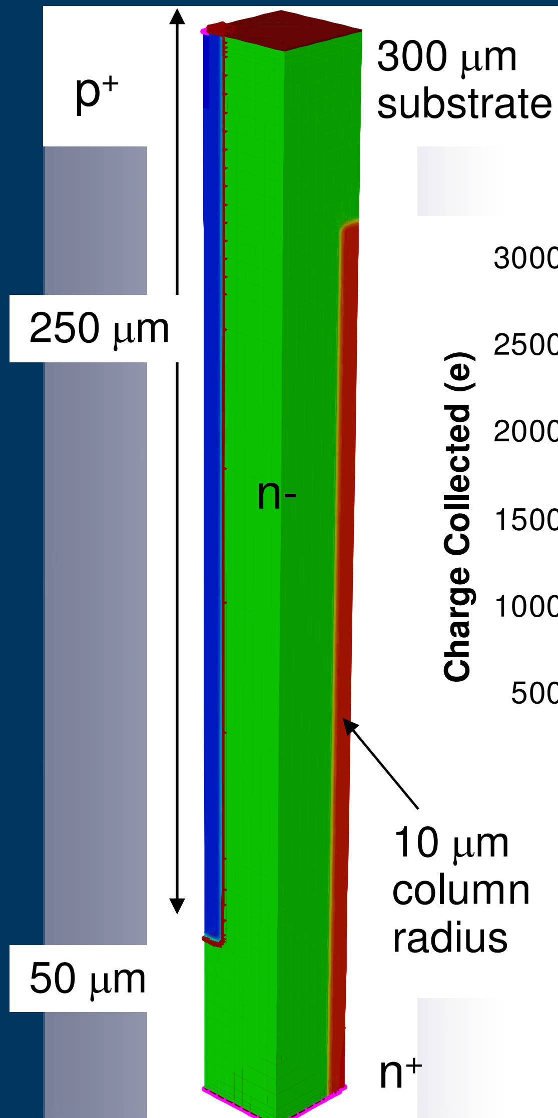
Collected charge for irradiated devices

Electron collecting strip detectors



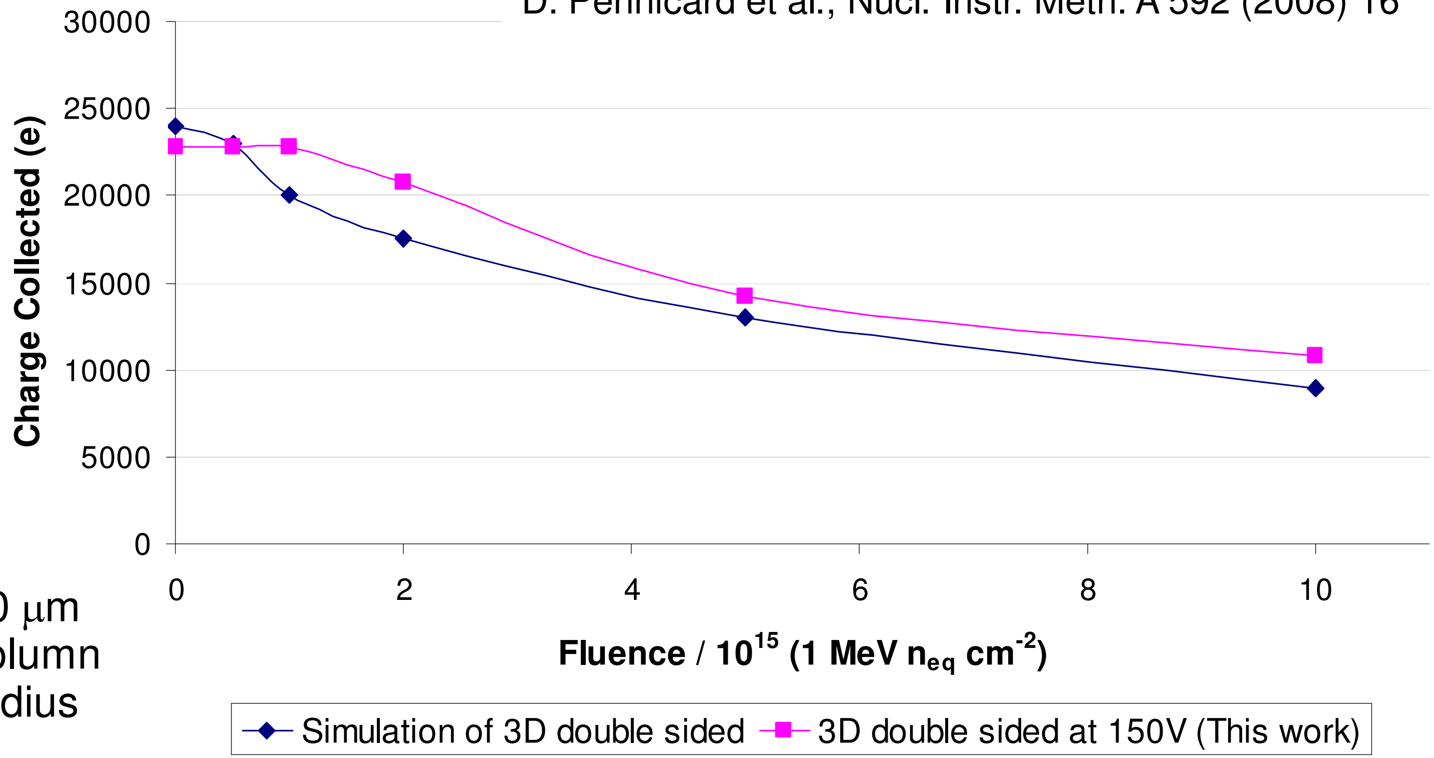
- Bias Voltage fixed at 150V for all irradiated samples
- Non-irradiated sample biased at 18V
- Detector's ceramic based board temperature between -10℃ to -15℃

Simulation – ISE TCAD



Charge collection simulation

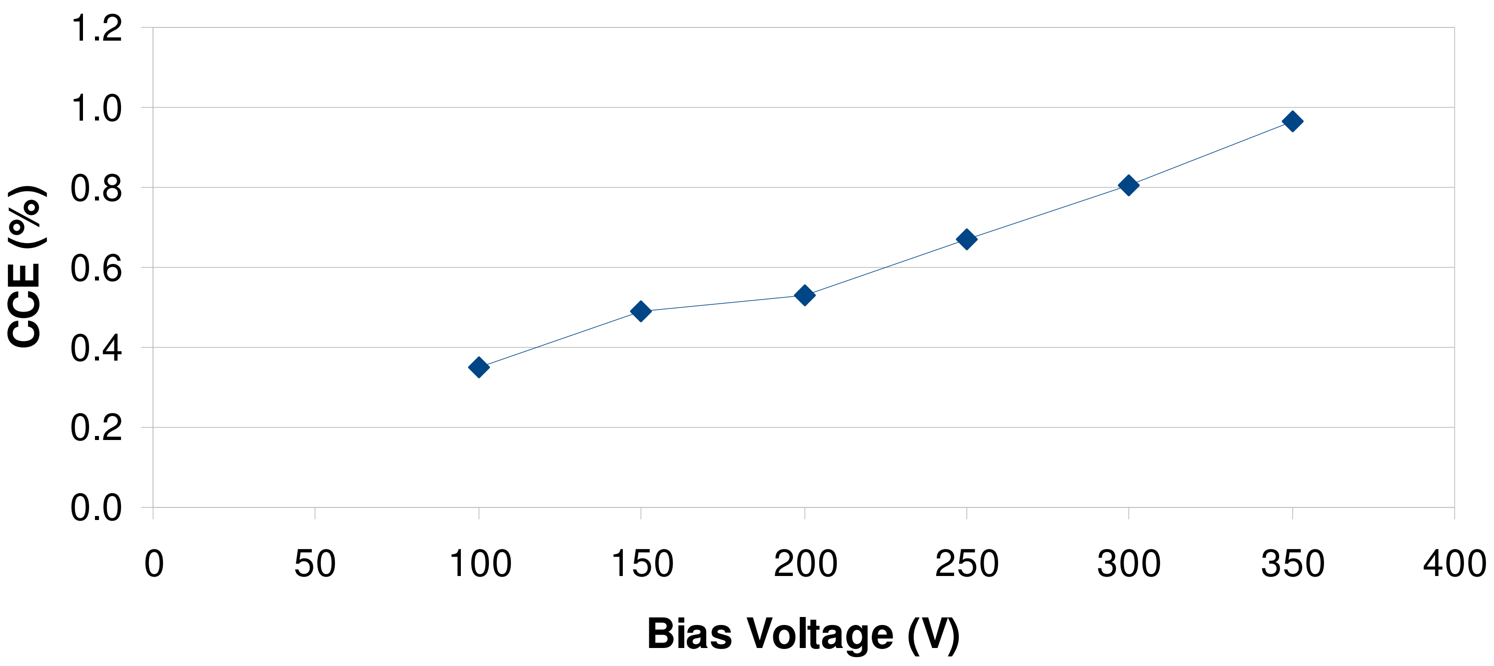
D. Pennicard et al., IEEE Trans. Nucl. Sci. 54, 4 (2007)
D. Pennicard et al., Nucl. Instr. Meth. A 592 (2008) 16



NB – simulation assumes n+ readout for detectors, and 55µm pixels, experimental results have n+ readout and 80µm pixels

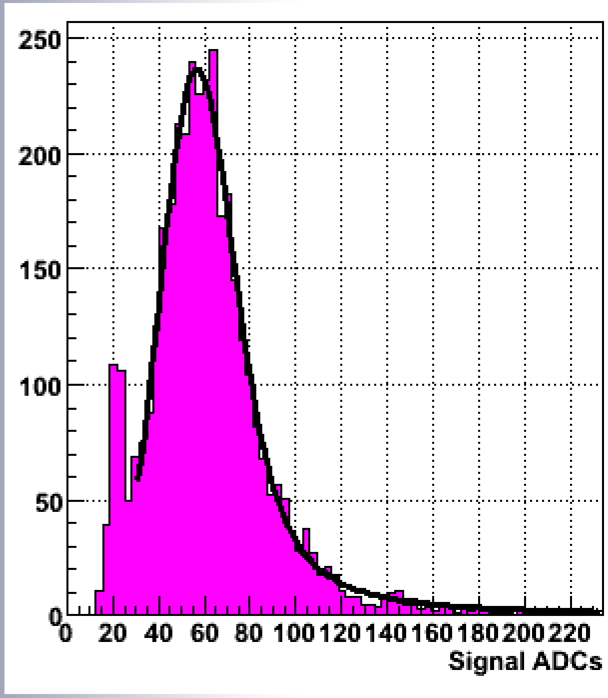
CCE with increasing bias voltage

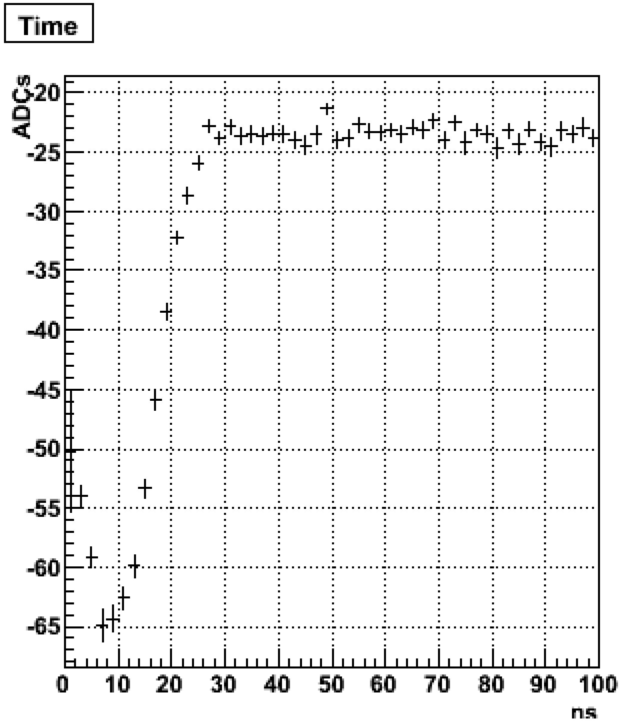
- Detector response after a fluence of 1 x 10^{16} 1 MeV n_{eq} cm^{-2}



Spectra after 1 x 10^{16}

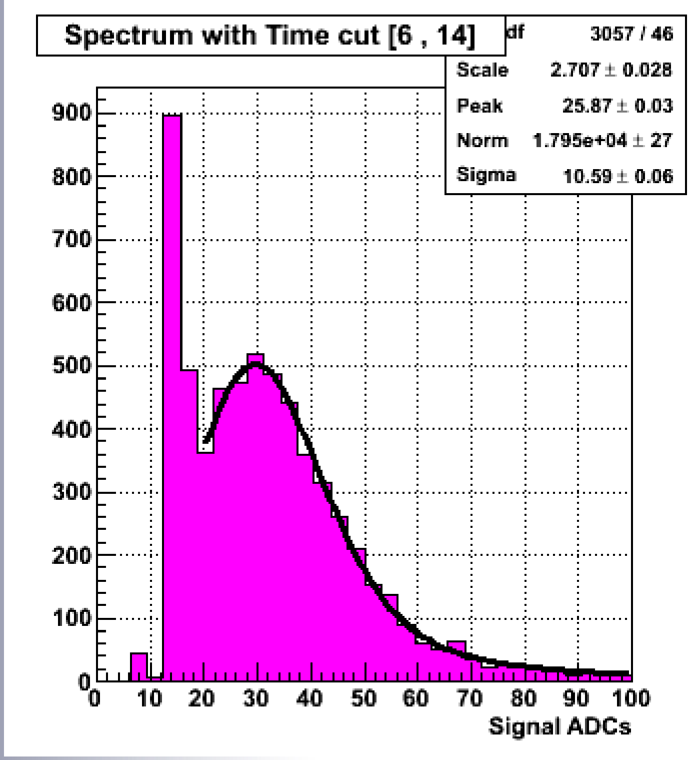
Bias Voltage is 300V

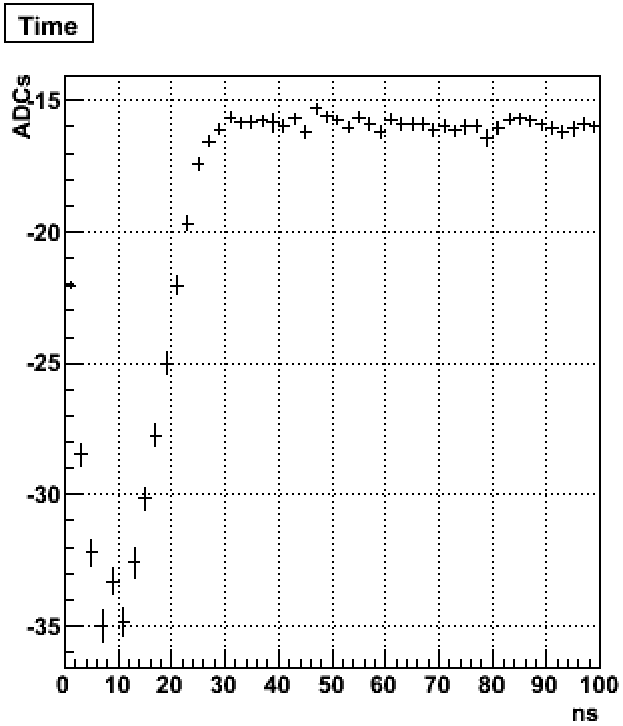




Spectra after 2 x 10^{16}

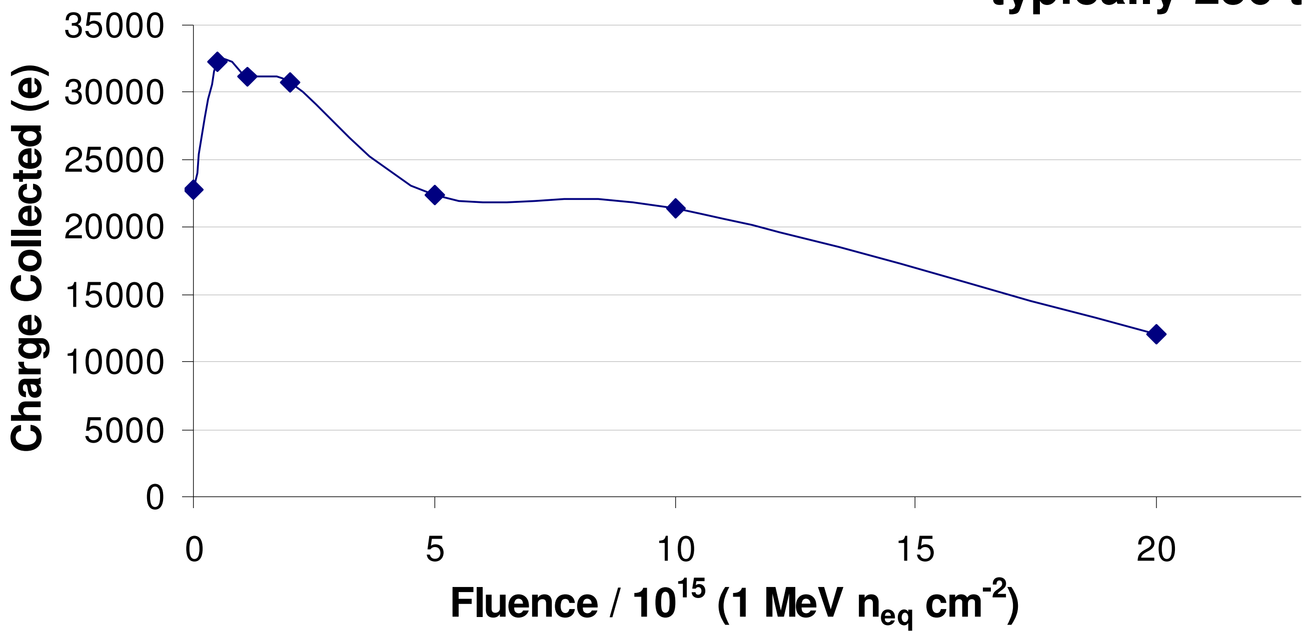
Bias Voltage is 250V





High bias operation

Bias voltage applied maximum possible before excess current or noise typically 250 to 350V



- Increased CCE for high fluences > 5 x 10^{15}

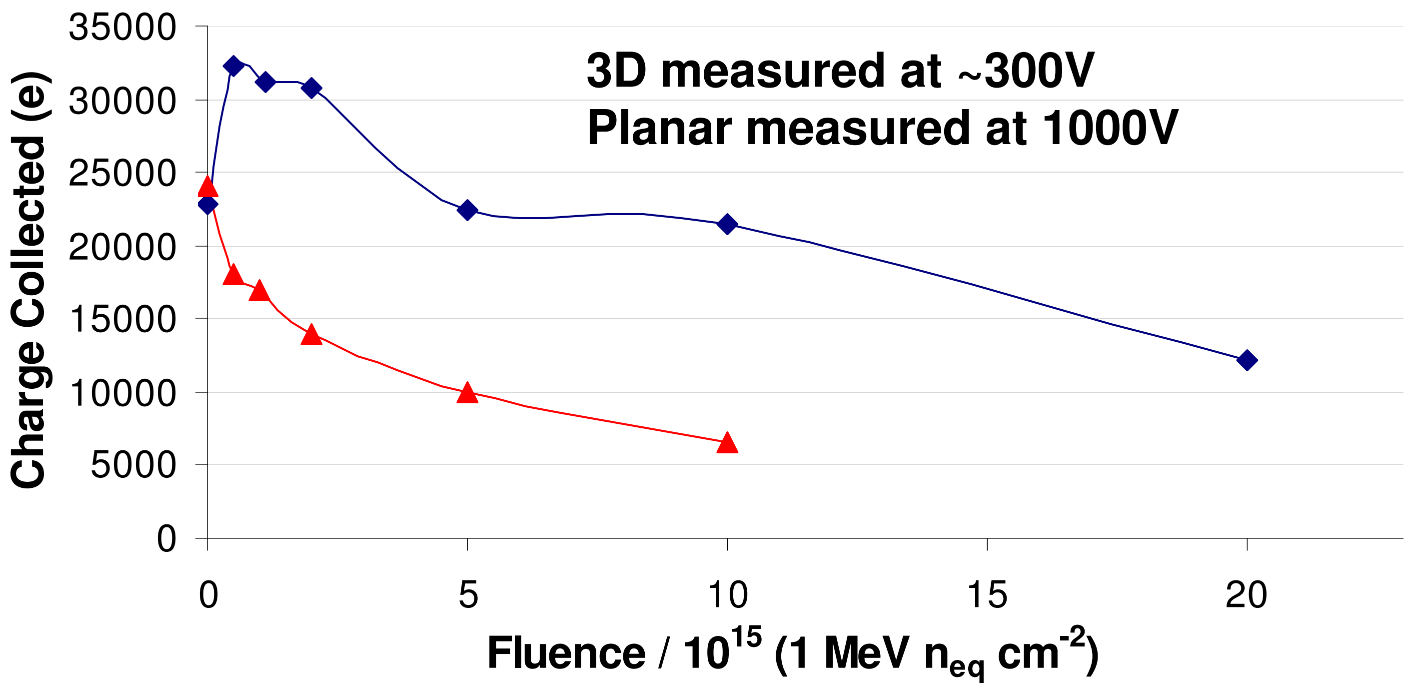
  Close to 100% CCE for 10^{16} 1 MeV n_{eq} cm^{-2}

- More than 100% CCE for fluences 0.5 to 2 x 10^{15} 1 MeV n_{eq} cm^{-2}
- Possible charge multiplication observed

  Observed in heavily irradiated planar devices with kV bias

Comparison of 3D with Planar devices

- 3D results compared to Planar results complied from published work



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Summary

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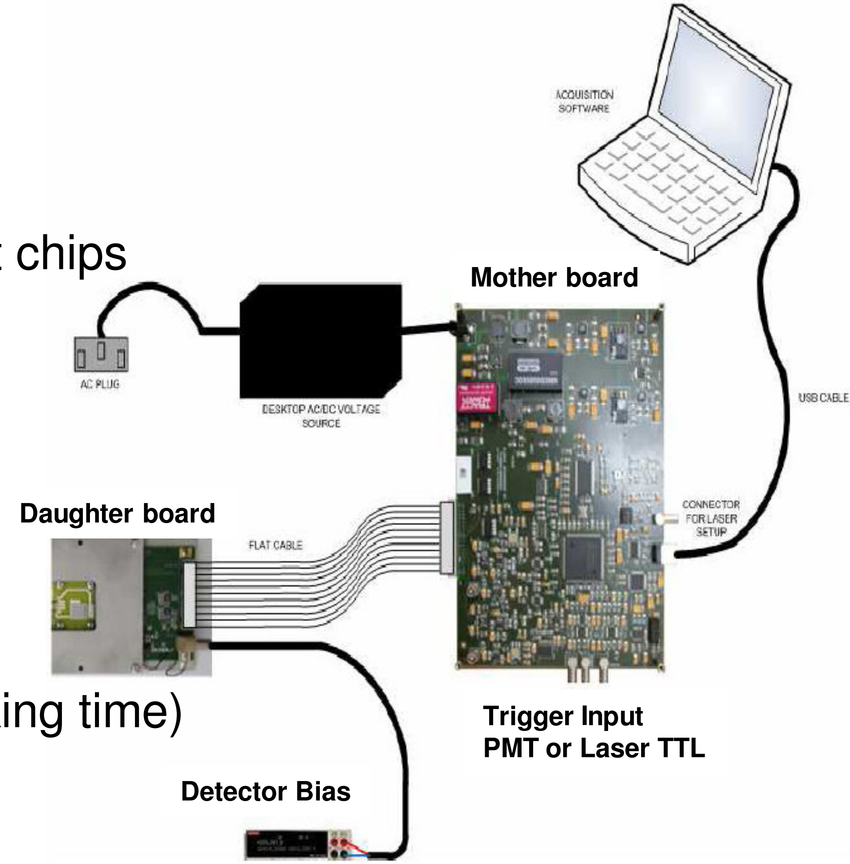
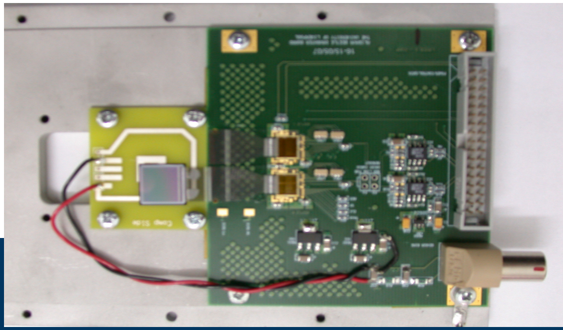
- Non-irradiated 3D double sided devices show 100% CCE
- Post irradiation CCE, measured at 150V, falls
  - CCE of 62% : 14000 e^- after 5×10^{15}
  - CCE of 47% : 11000 e^- after 1×10^{16}
- Charge collection agrees well with simulation prediction
- Enhanced charge collection with high bias
  - Possible charge multiplication in high electric fields
  - 30000 e^- for 200V bias up to a fluence of 2×10^{15}
  - CCE of 98% : 22500e^- after 5×10^{15} measured at 250V
  - CCE of 94% : 21500e^- after 1×10^{16} measured at 350V
  - CCE of 53% : 12000e^- after 2×10^{16} measured at 300V
- Sufficient charge for ATLAS front-end chip
- Operation at -10°C to -15°C fine

Back-up slides

Alibava system - Hardware

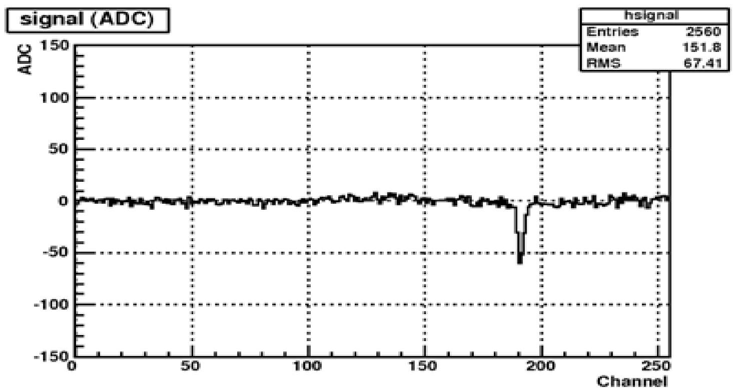
- Mother Board
  - Control Beetle chips
  - Trigger on PMT signal
  - Process analogue data from readout chips
  - Communicate with a PC via USB.
- Daughter board
  - Two Beetle readout chips
  - Re-bondable fan-ins
  - H.V. filter operational to 1kV
- Beetle front end (from LHCb)
  - LHC speed bi-polar amplifier (25ns peaking time)
  - Full analogue readout
- Rest of hardware
  - Collimated Sr-90 source above the detector
  - Scintillator with PMT trigger below the detector
  - Everything in a freezer with dry air and monitoring



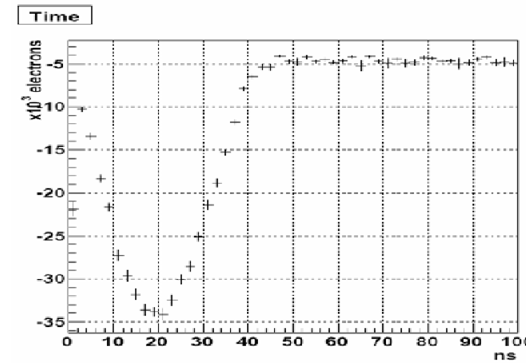


Alibava system - Software

- RAW data
- Pedestal corrected
- Common mode noise corrected
- S/N cuts applied
- Pulse shape
- Signal spectrum

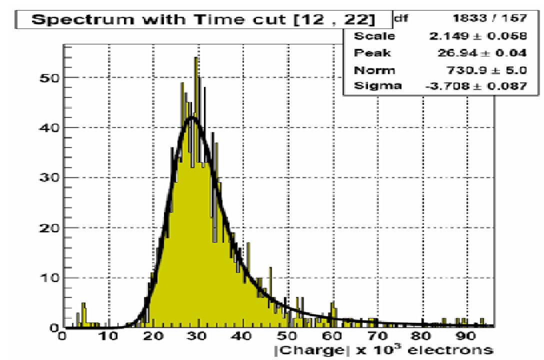


Signal corresponding to an event (trigger): ADC counts vs channel number



Pulse shape:

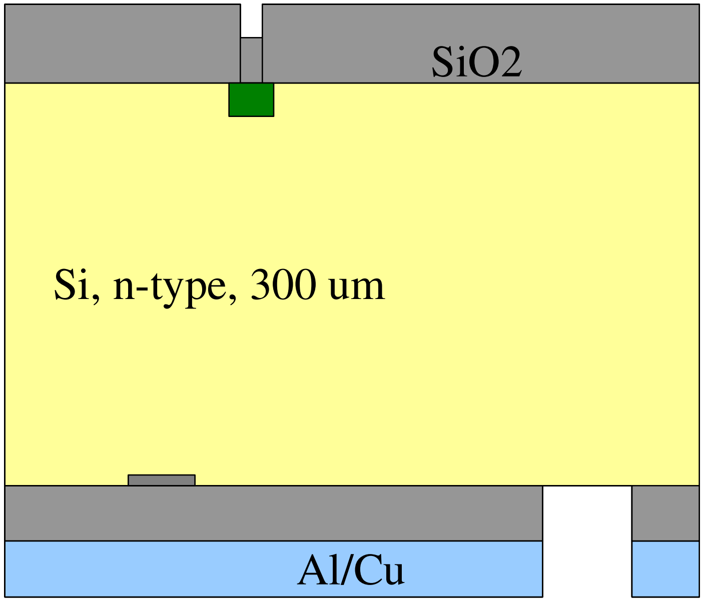
collected charge vs. delay



Signal spectrum with in time cut: number of events vs. collected charge

Double-sided 3D Detector production

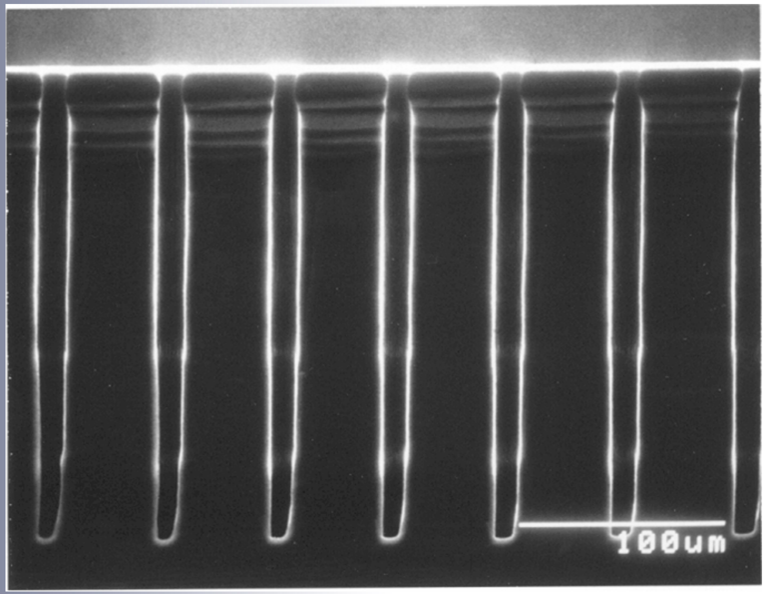
- Column fabrication introduces extra steps
- Begin with columns on back side

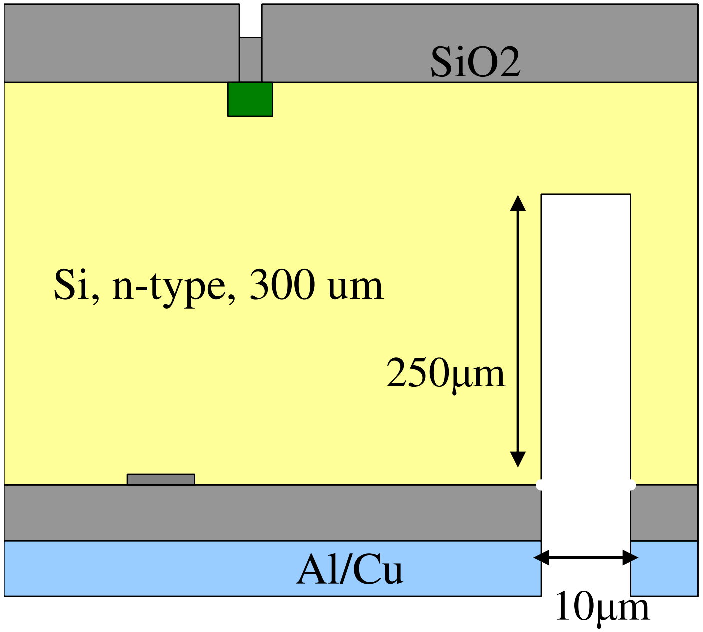


Double-sided 3D Detector production

Hole etching

- Deep Reactive Ion Etching
  - F plasma etches away base of hole
  - CF_2 coating protects sidewall
  - Limit on depth : diameter ratio
  - 250μm depth, 10μm diameter

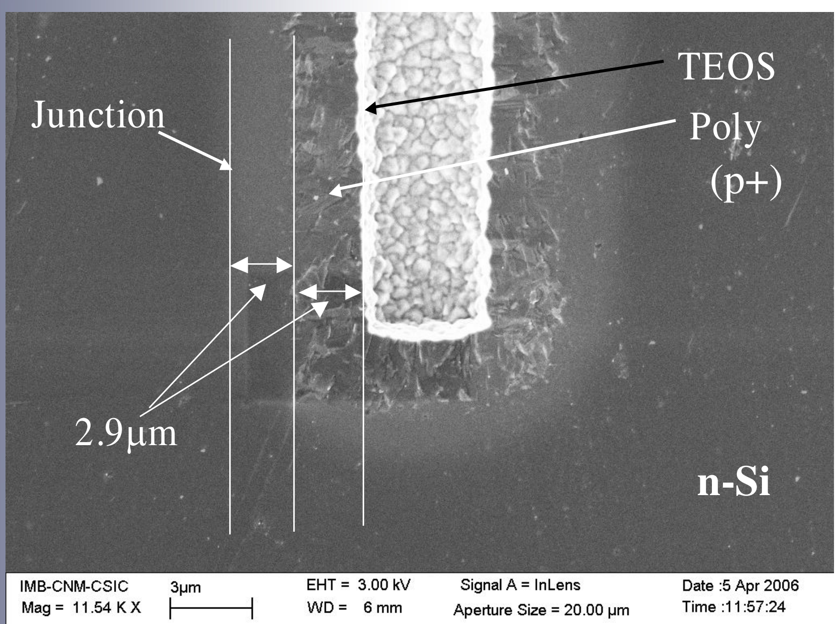


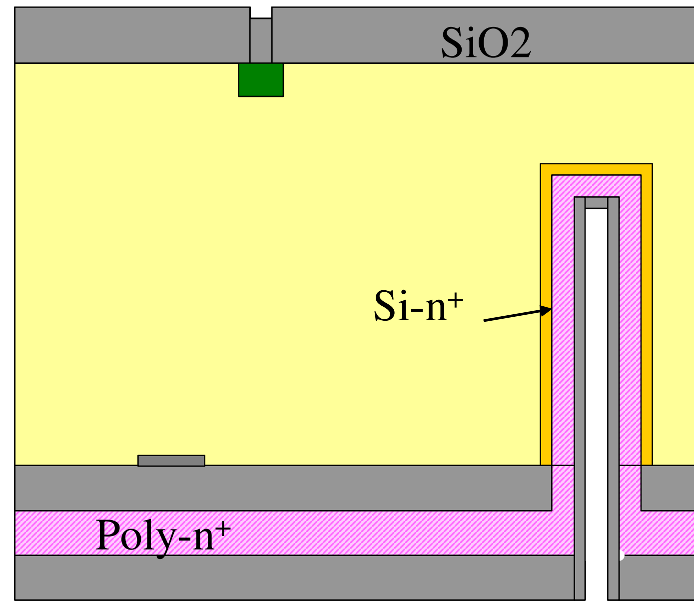


Double-sided 3D Detector production

Column filling and doping

- Deposit 3µm poly-silicon
- Phosphorus doping through poly
- Passivate inside of column with SiO_2

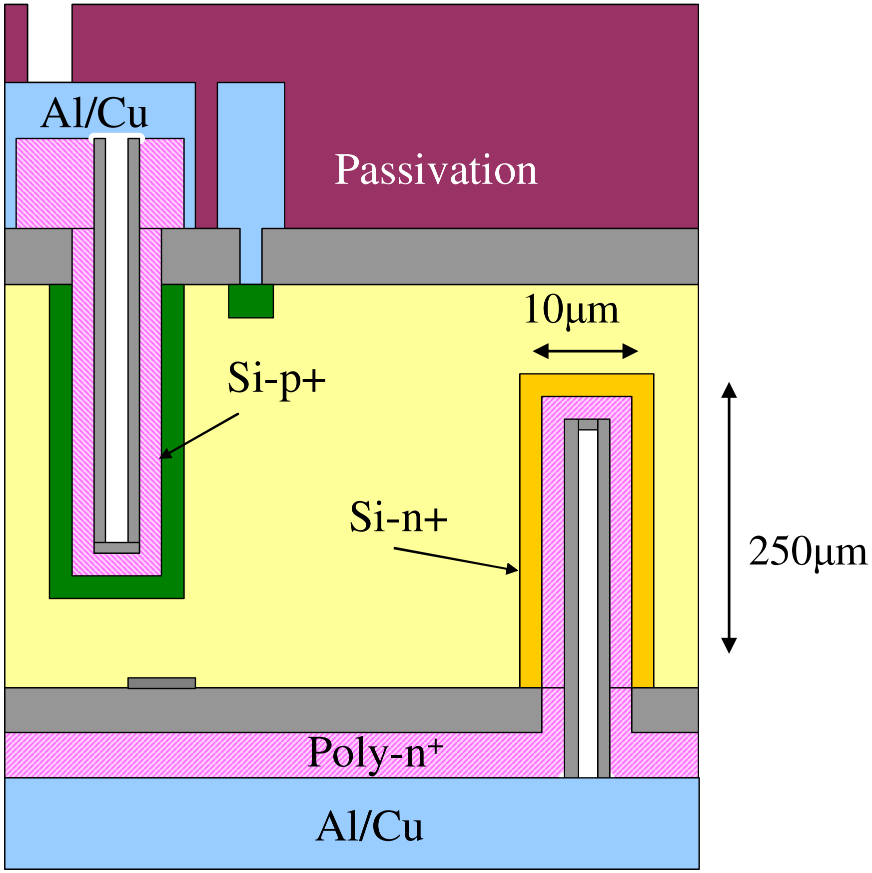




Double-sided 3D Detector production

Finished detector

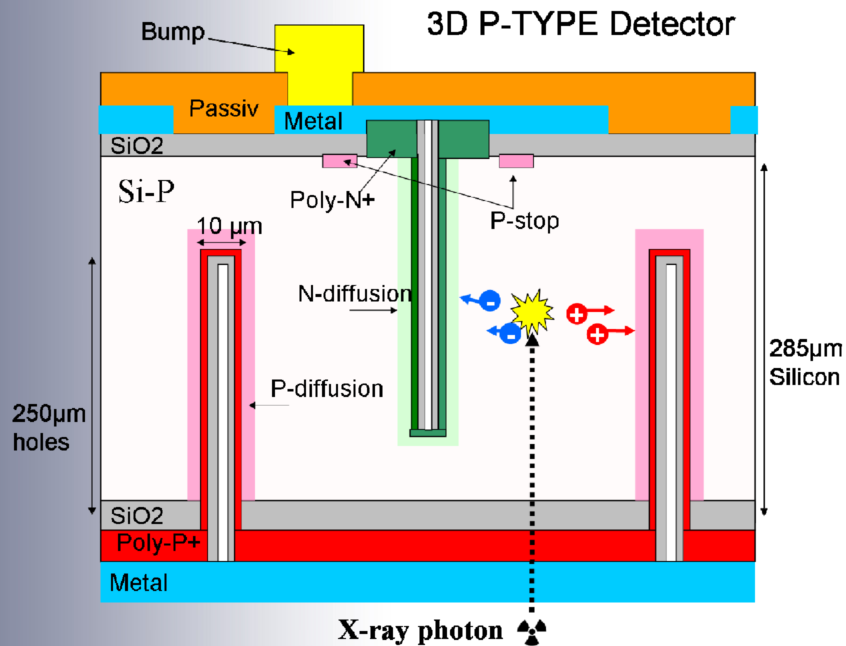
- P+ columns fabricated on front side
- Contacts on front
- Backside coated with metal for biasing

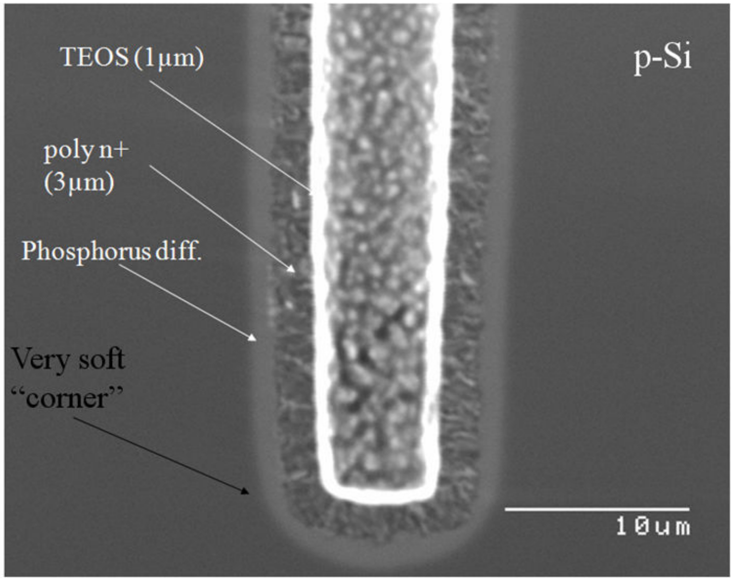


CNM Double-sided 3D Detectors

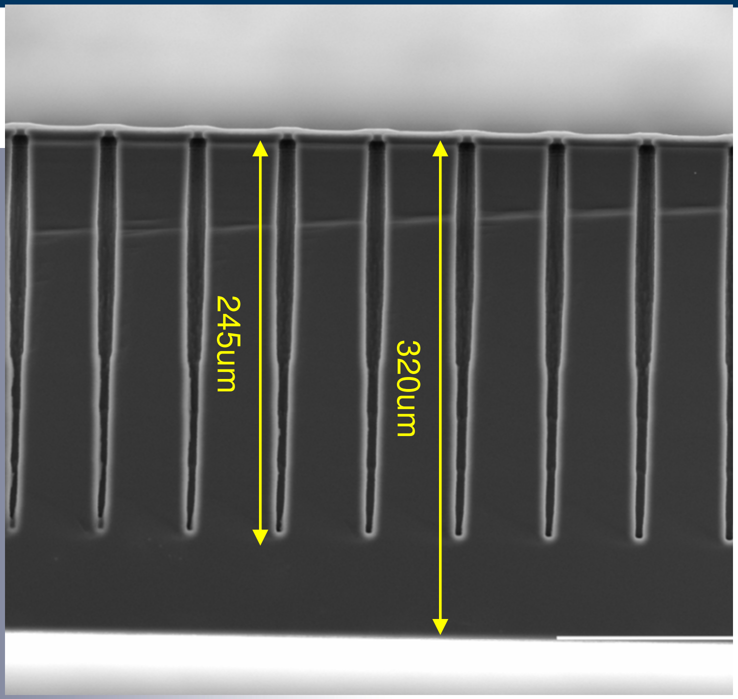
- Devices designed at Glasgow & CNM
- Fabricated at CNM
- Columns are etched from opposite sides of substrate
- Columns don't pass through full substrate thickness

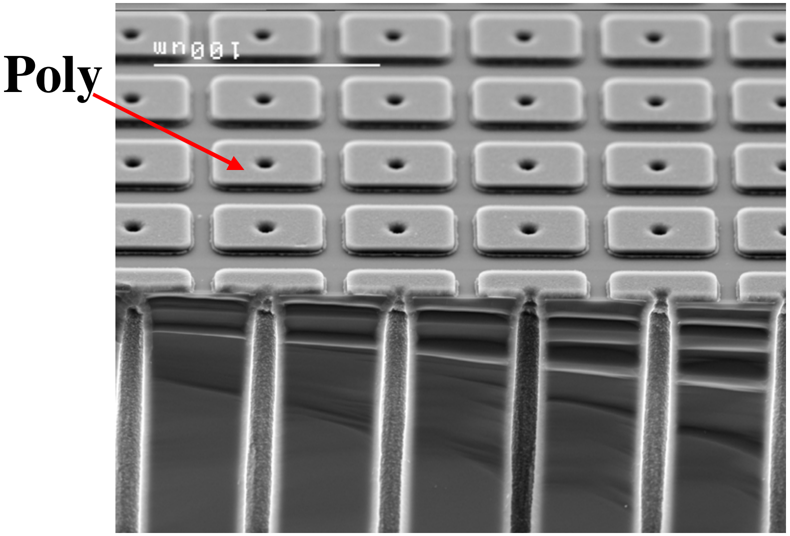
- Column fabrication:
  - ICP etching : BOSCH process
  - Partial filing with 3µm LPCVD polysilicon
  - Doping with P or B
  - Passivation with 1µm TEOS Si_2O

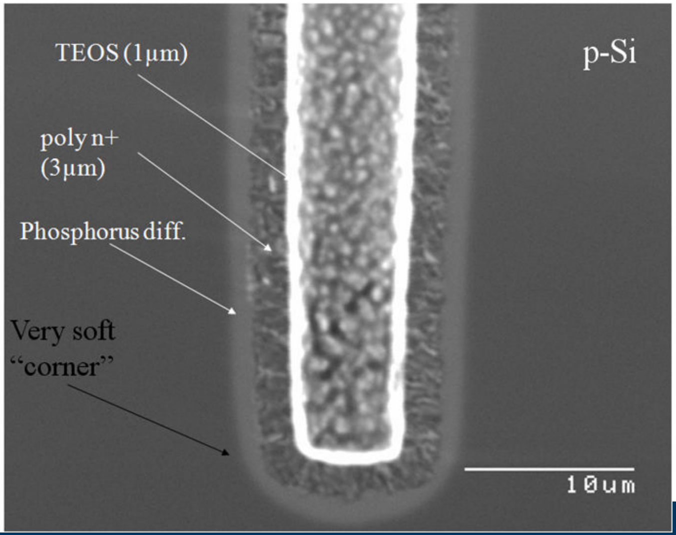




3D Electrodes



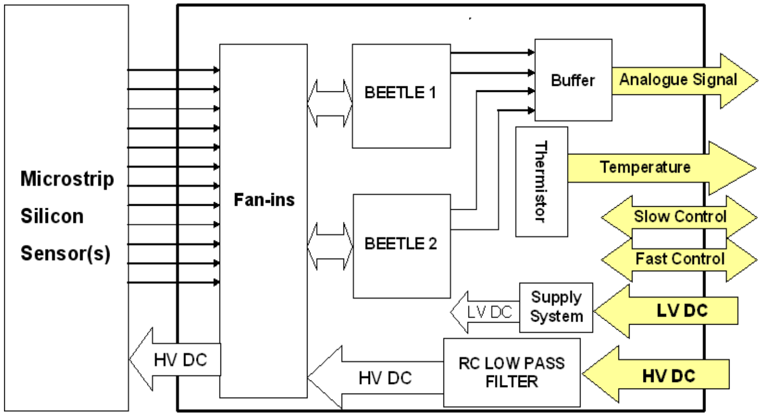


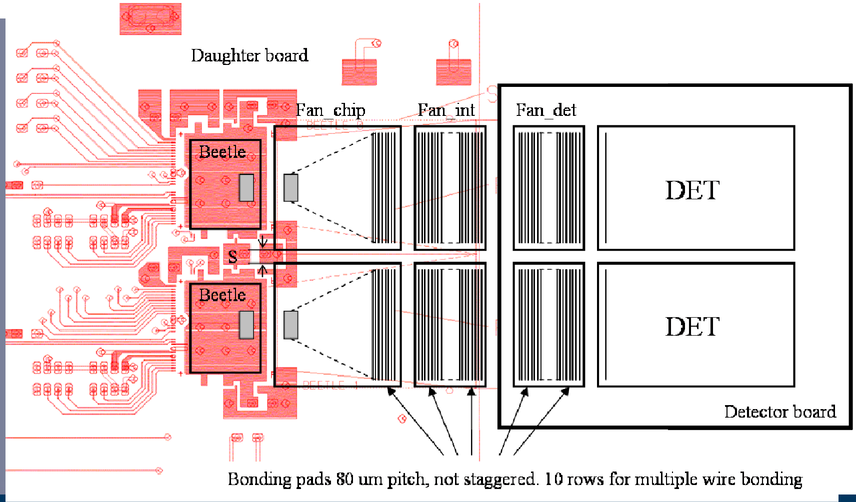


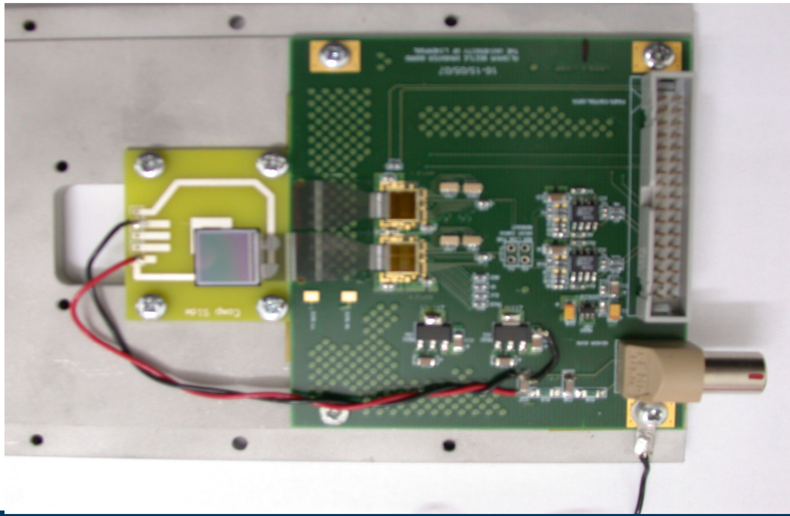
Hole aspect ratio up to 25:1 (columns are 10µm diameter, 250µm deep)

Daughter board

- Two Beetle readout chips in parallel mode.
  - 256 input channels.
  - Analogue front-end with 25 ns of peaking time.
  - Analogue multiplexed readout of each chip.
  - Output dynamic range ~ ±110000 electrons.
- Buffer stage for sending the analogue output signals to the mother board.
- Control signals provided by the mother board and shared by both Beetle chips.
- A thermistor (NTC) for sensing the temperature close the Beetle chips.
- Low voltage DC level (5 V) for Beetle chips (2.5 V) and buffer stage power supply (3 V): provided by the motherboard.
- High voltage DC level for silicon detector(s) bias: external power supply.
- Fan-ins and detector board: multiple wire bonding and two different sensor sizes.

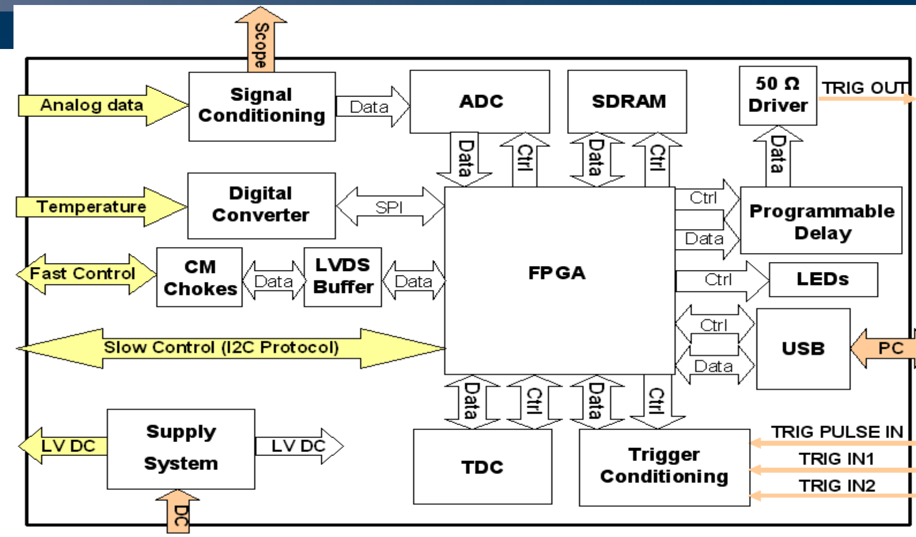


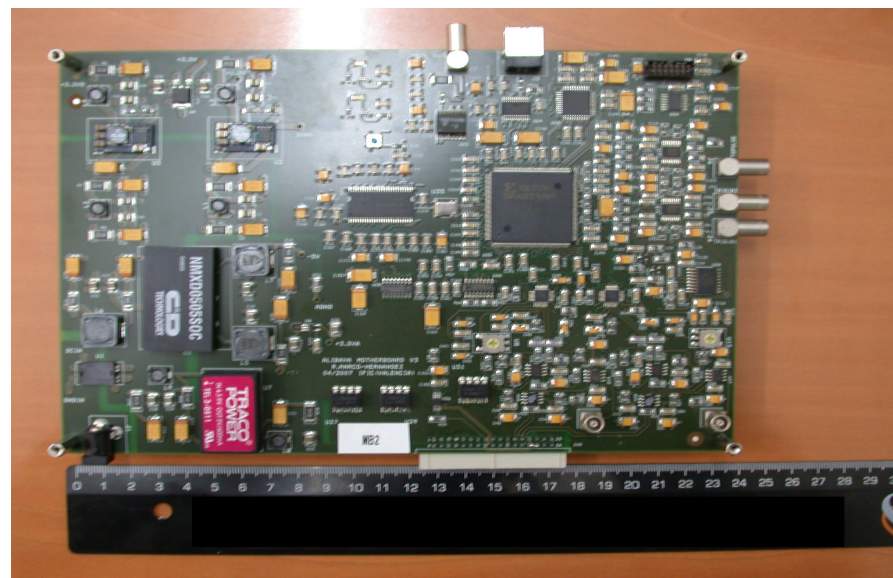




Mother board

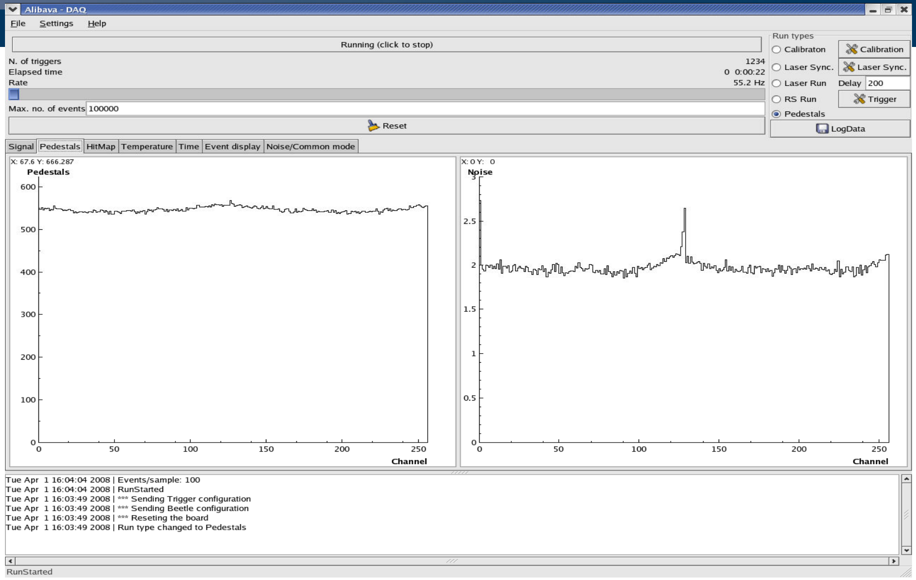
- Analogue signal conditioning:
  - Amplification and filtering: minimization of noise.
  - Buffering: two copies of the Beetle multiplexed analogue outputs for spying with a scope
- ADC: digitalization at 40 MSps of the Beetle analogue multiplexed signals.
- Digital converter: temperature analogue signal digitalization.
- Generation of control signals for Beetle chips by FPGA: DAQ sequences and configuration.
- Trigger conditioning and TDC for obtaining a time stamp of each trigger with radioactive source setup.
- Generation of a trigger output with programmable delay for the laser source.
- USB controller.
- SDRAM (512 Mb) for temporal storage of acquired data.
- FPGA (40 MHz): custom logic and embedded µP.
  - Control of the hardware.
  - Synchronization of DAQ sequences.
  - Generation of Beetle control signals.
  - Communication with the software.
- Supply system: from AC/DC desktop power supply (5V).
  - Generation of MB and DB supply levels.

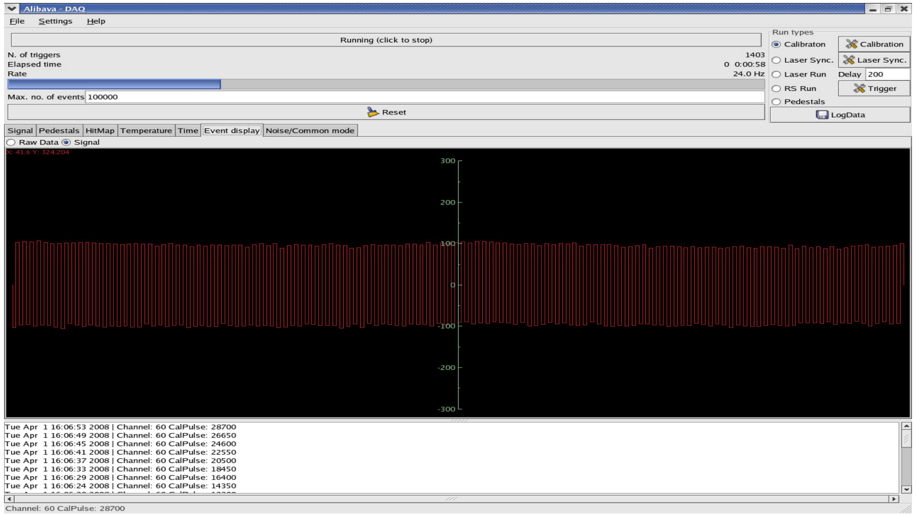




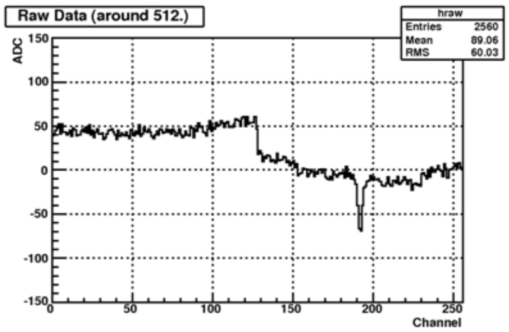
PC software

- Functions:
  - Control the whole system (configuration, calibration and acquisition).
  - Processing and monitoring of acquired data.
  - User interface with the system (GUI).
  - Generation of information (output files).
- Two software levels:
  - Low level:
    - Software/mother board communication by USB: VCP (virtual com port) driver (2.4 Mb/s) used.
    - Processing of acquired data.
  - High level:
    - GUI: control of the system and data monitoring.
    - Output file generation for further processing and analysis.
- Programmed in C++.
- Operating system compatibility:
  - Linux version fully operational.
  - Maybe Windows in the future.
- There are also macros for ROOT in order to process the data acquired with the software.



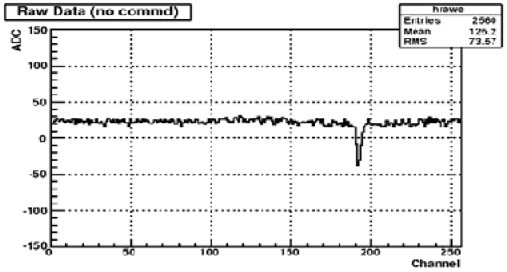


Processing of the acquired data



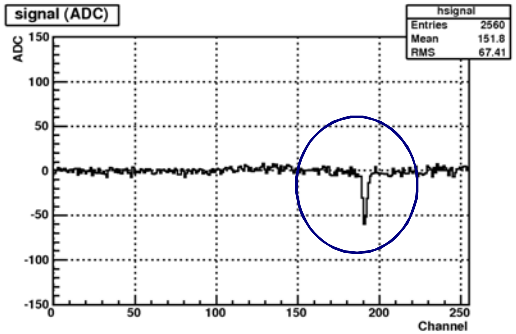
Raw data (ADC counts vs channel number): digitalization of the Beetle analogue multiplexed output signal

Pedestals correction



Raw data with pedestal value for each channel corrected (ADC counts vs channel number)

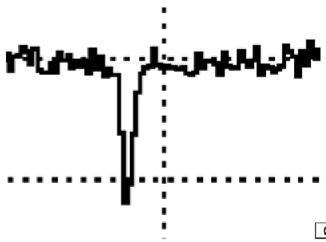
Common mode correction



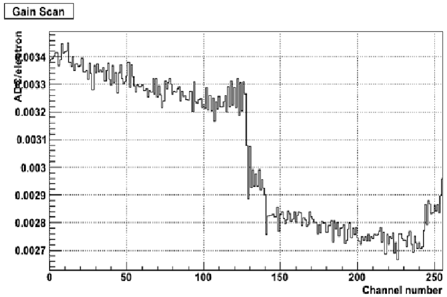
Signal corresponding to an event (trigger): ADC counts vs channel number

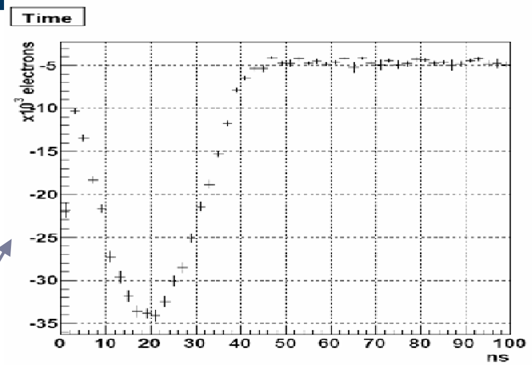
Signal computation of acquired data from each trigger

Signal is computed as the sum of strips in a cluster.
➔Feed S/N > 6.
➔Neighbours S/N > 2.5.

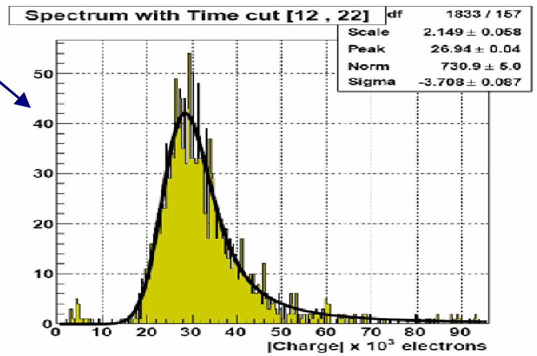


We can obtain different representations of acquired data from a given number of triggers. We use the calibration data for ADC counts to electrons conversion





Pulse shape reconstruction: collected charge (electrons) vs. delay (ns)



Signal spectrum with a time cut: number of events vs. collected charge (electrons)

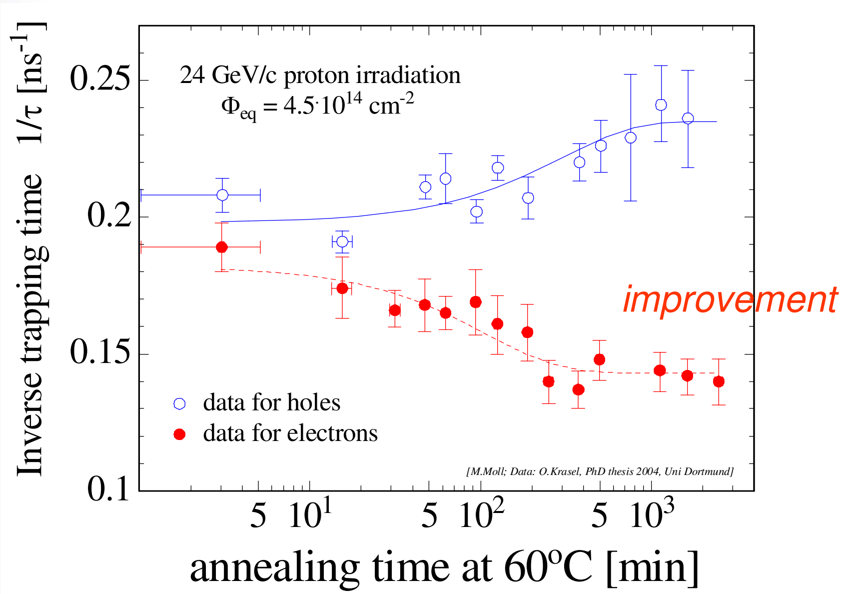
Charge trapping

$$Q_{e,h}(t) = Q_{0e,h} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t\right)$$ **where** $$\frac{1}{\tau_{eff\ e,h}} \propto N_{defects} = \beta_{e,h}\Phi$$

$\beta_e = 4.2\times10^{-16} cm^{-2}/ns$, $\beta_h = 6.1\times10^{-16} cm^{-2}/ns$

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

1/τ changes with annealing



$\tau_{eff}(10^{14}) = 20ns$ $\lambda = v_{sat}\tau_{eff} = (10^7 cm/s)\times 2\times10^{-8} s = 2000\mu m$

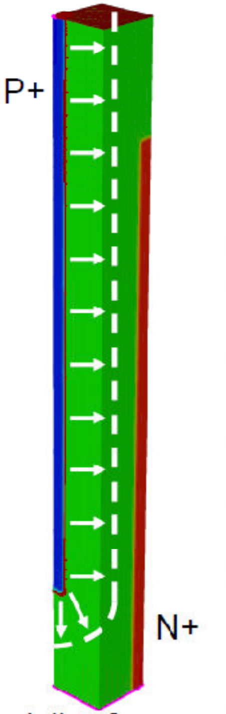
$\tau_{eff}(10^{16}) = 0.2ns$ $\lambda = v_{sat}\tau_{eff} = (10^7 cm/s)\times 2\times10^{-10} s = 20\mu m$

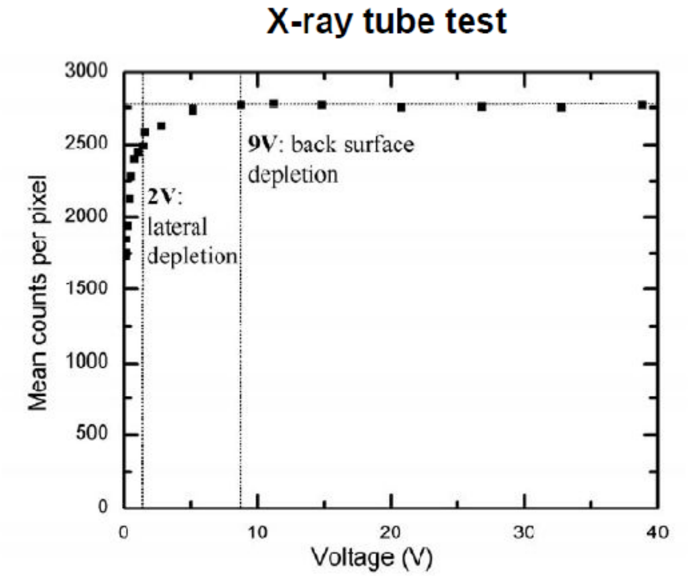
Decrease in CCE.

Back-Up Lateral and Full depletion

Depletion of Medipix2 3D

- Tested count rate vs bias with 60kV tungsten X-ray tube
  - Rapid increase in count rate up to 2V – lateral depletion
  - Count saturates around 9V – full depletion
  - CVs on test structures follow same pattern



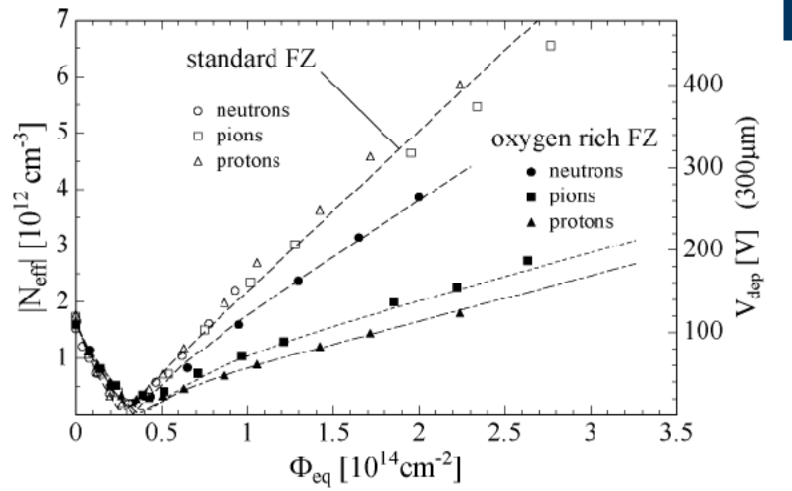


Trento Workshop p-type and 3D detectors
C. Fleta, University of Glasgow

3D Detectors and Radiation Hardness

Increase in effective p-type doping with damage

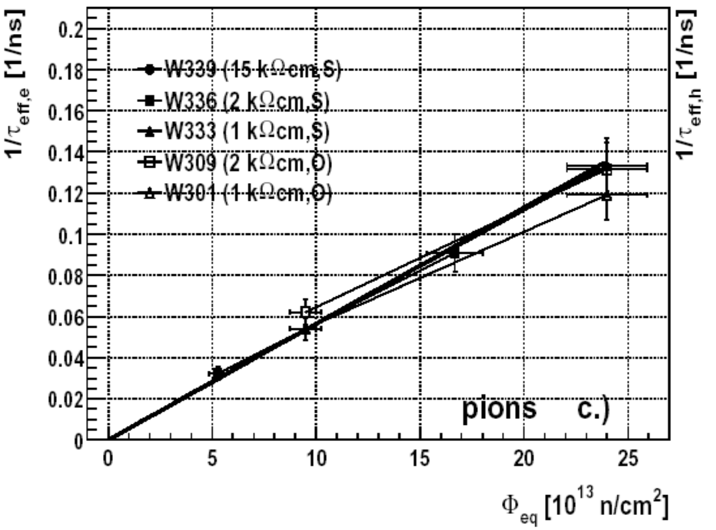
- Increased depletion voltage
- 300µm planar detectors cannot be fully depleted far beyond $10^{15} n_{eq}/cm^2$
- 3D detectors have short depletion distance, reducing V_{dep}



See M. Moll thesis, Hamburg 1999

Charge trapping $\frac{\partial n}{\partial t} = -\frac{n}{\tau_{eff,e}}$

- Free electrons and holes trapped by defects, reducing CCE
- Dominant effect at very high fluences
- 3D structure reduces collection time – less trapping



G. Kramberger, Aug. 23-24, 2006, Hamburg, Germany

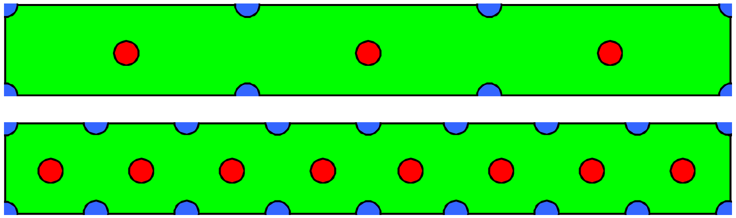
Increased leakage current

- Need to cool detectors

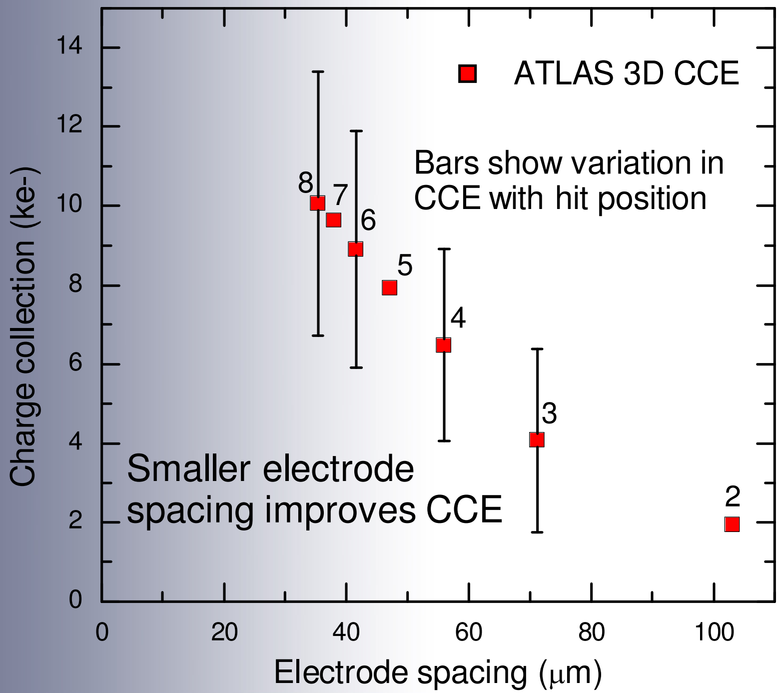
Optimisation of ATLAS 3D structure

ATLAS pixel is 400µm * 50µm

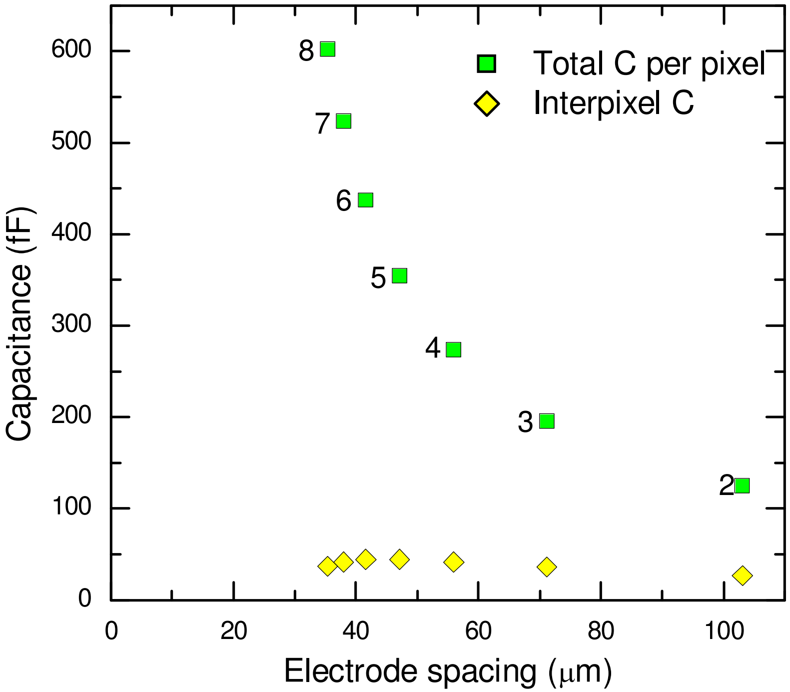
- Different layouts available
- Trade-offs between V_{dep}, CCE, capacitance, column area…



Charge collection with $10^{16} n_{eq}/cm^2$ radiation damage



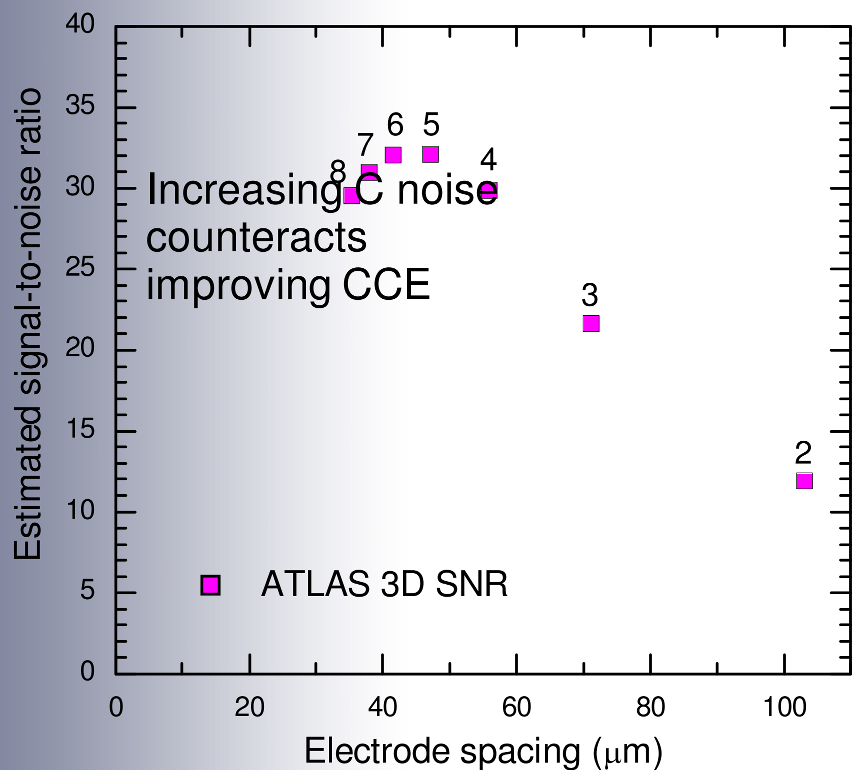
Capacitance at each pixel



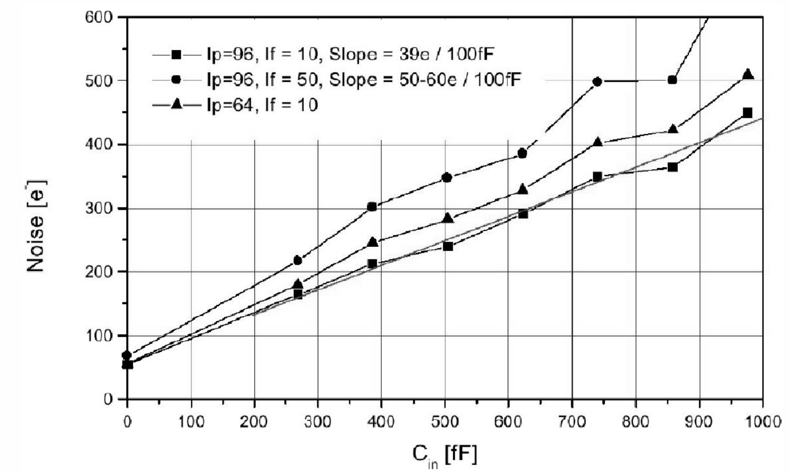
Signal to noise estimate at $10^{16} n_{eq}/cm^2$

Uses noise vs. capacitance data from un-irradiated ATLAS sensors (won't include high leakage current or damage to readout chip)

- Assume 100fF from preamplifier input and bump bond
- Also 70e- threshold dispersion



Noise≈$60e^{-}+39e^{-}/100fF$



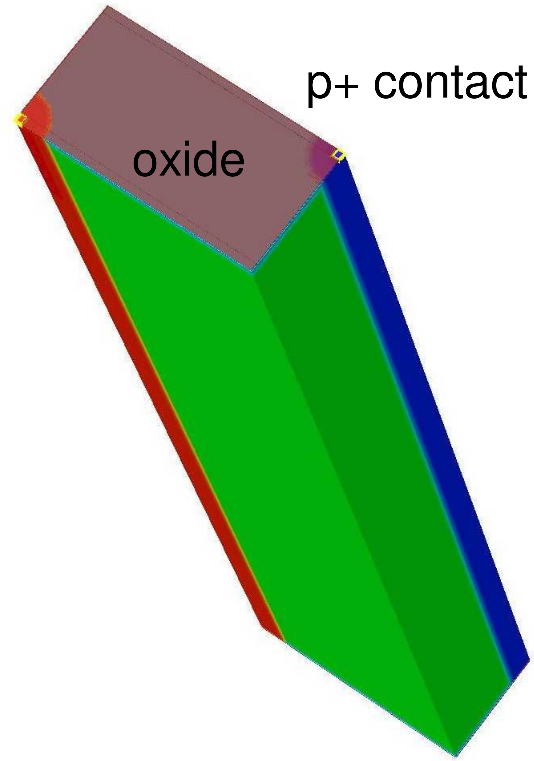
"Progresses on the ATLAS pixel detector", A. Andreazza, *NIMA* vol. 461, pp. 168-171, 2001

Simulation methods

- **See presentation from 10th RD50 meeting**
- Synopsis TCAD finite element simulation

- **Damage model**
  - Trap dynamics modelled directly
  - P-type FZ material
  - Based on work at Uni. Perugia – see M. Petasecca et al., *IEEE Trans. Nucl. Sci., vol. 53, pp. 2971–2976, 2006*
  - Modified to match experimental trap times (V. Cindro et al., IEEE NSS, Nov 2006)

Example of a simulated 3D structure



$\beta_e = 4.0*10^{-7} cm^2 s^{-1}$, $\beta_h = 4.4*10^{-7} cm^2 s^{-1}$,

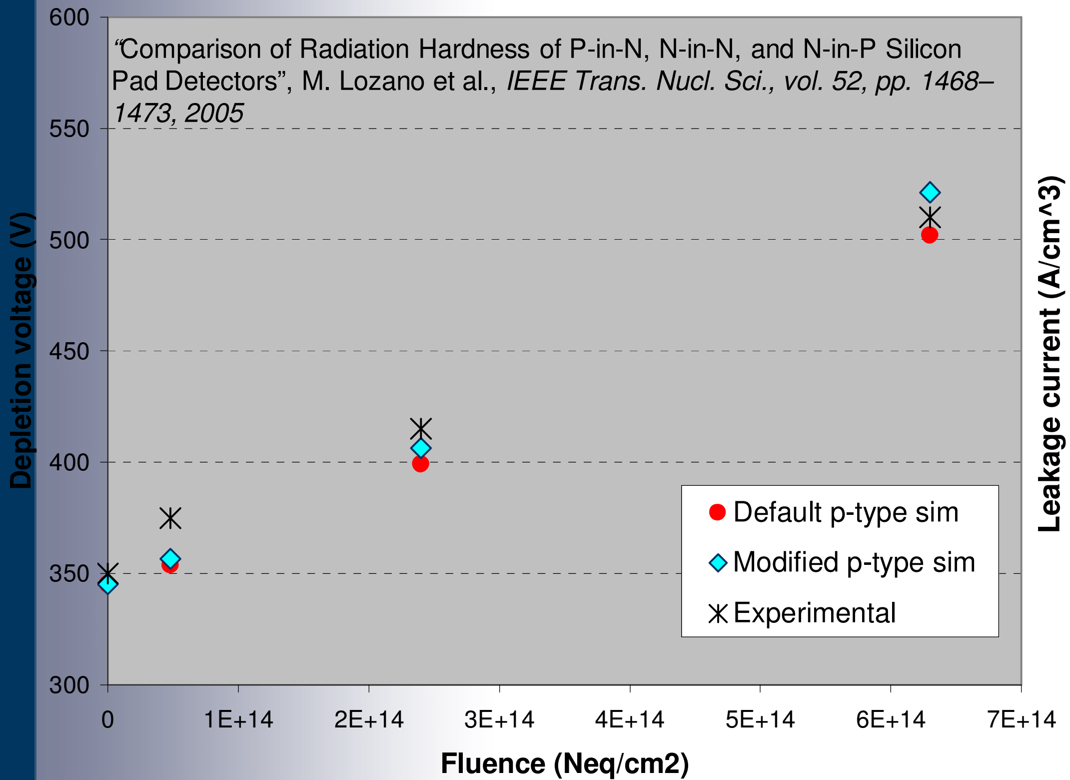
$$\frac{1}{\tau_e} = \beta_e \Phi_{eq}$$

Type	Energy (eV)	Trap	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
Acceptor	Ec-0.42	VV	$9.5*10^{-15}$	$9.5*10^{-14}$	1.613
Acceptor	Ec-0.46	VVV	$5.0*10^{-15}$	$5.0*10^{-14}$	0.9
Donor	Ev+0.36	CiOi	$3.23*10^{-13}$	$3.23*10^{-14}$	0.9

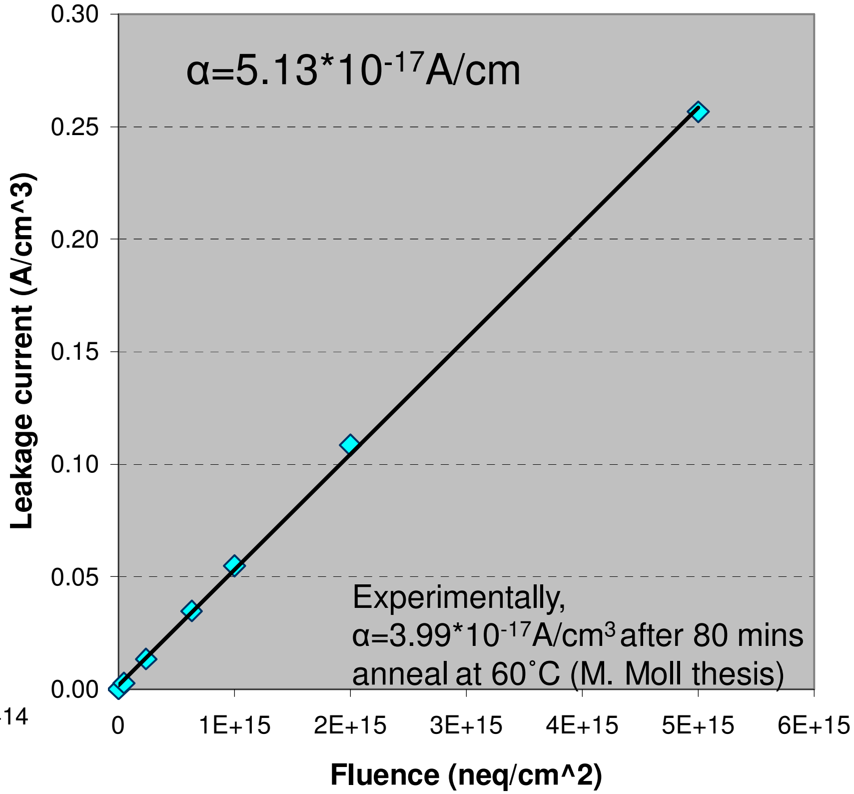
Comparison with experiment

- Compared with experimental results with proton irradiation
- Depletion voltage matches experiment
- Leakage current is higher than experiment, but not excessive

P-type trap models: Depletion voltages

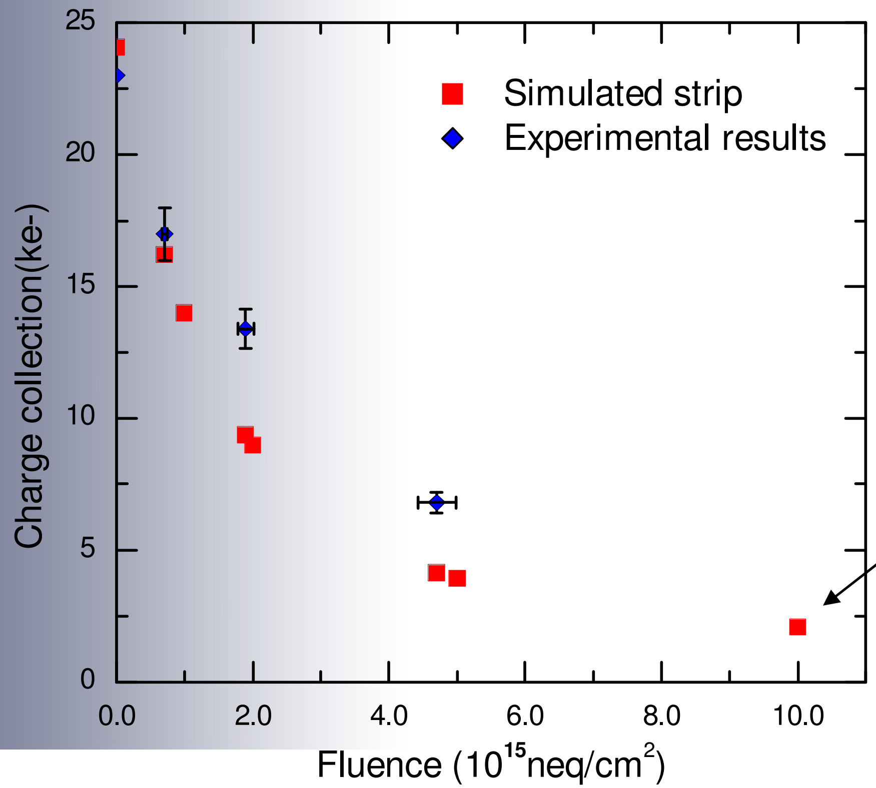


P-type trap model: Leakage Current



N+ on p strip detector: CCE

- At high fluence, simulated CCE is lower than experimental value
  - Trapping rates were extrapolated from measurements below $10^{15} n_{eq}/cm^2$
  - In reality, trapping rate at high fluence probably lower than predicted



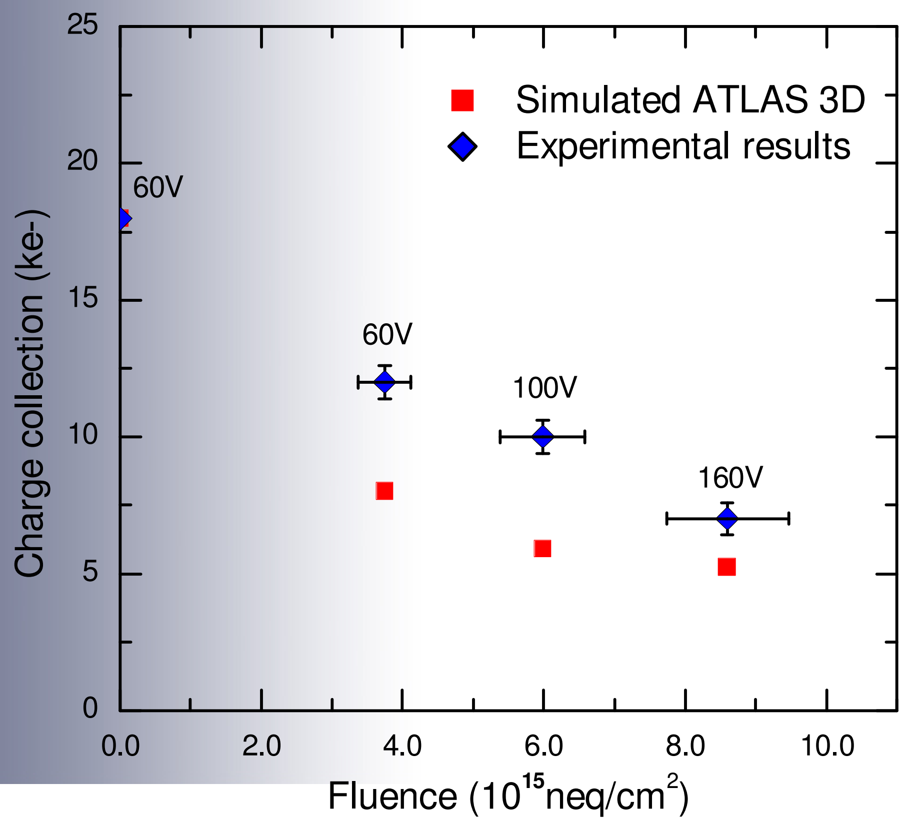
PP Allport et al., IEEE Trans. Nucl. Sci., vol 52, Oct 2005

900V bias,
280μm thick

From β values used, expect 25μm drift distance, 2ke- signal

ATLAS 3D detector: CCE

- Experiment used n+ readout, with 3 n+ columns per ATLAS pixel
- Experiment used defocused IR laser pulse to flood the pixel with charge; the simulation mimics this
- Both experiment and simulation show improved CCE at high fluence



C. da Via et al., Liverpool ATLAS 3D meeting, Nov. 06

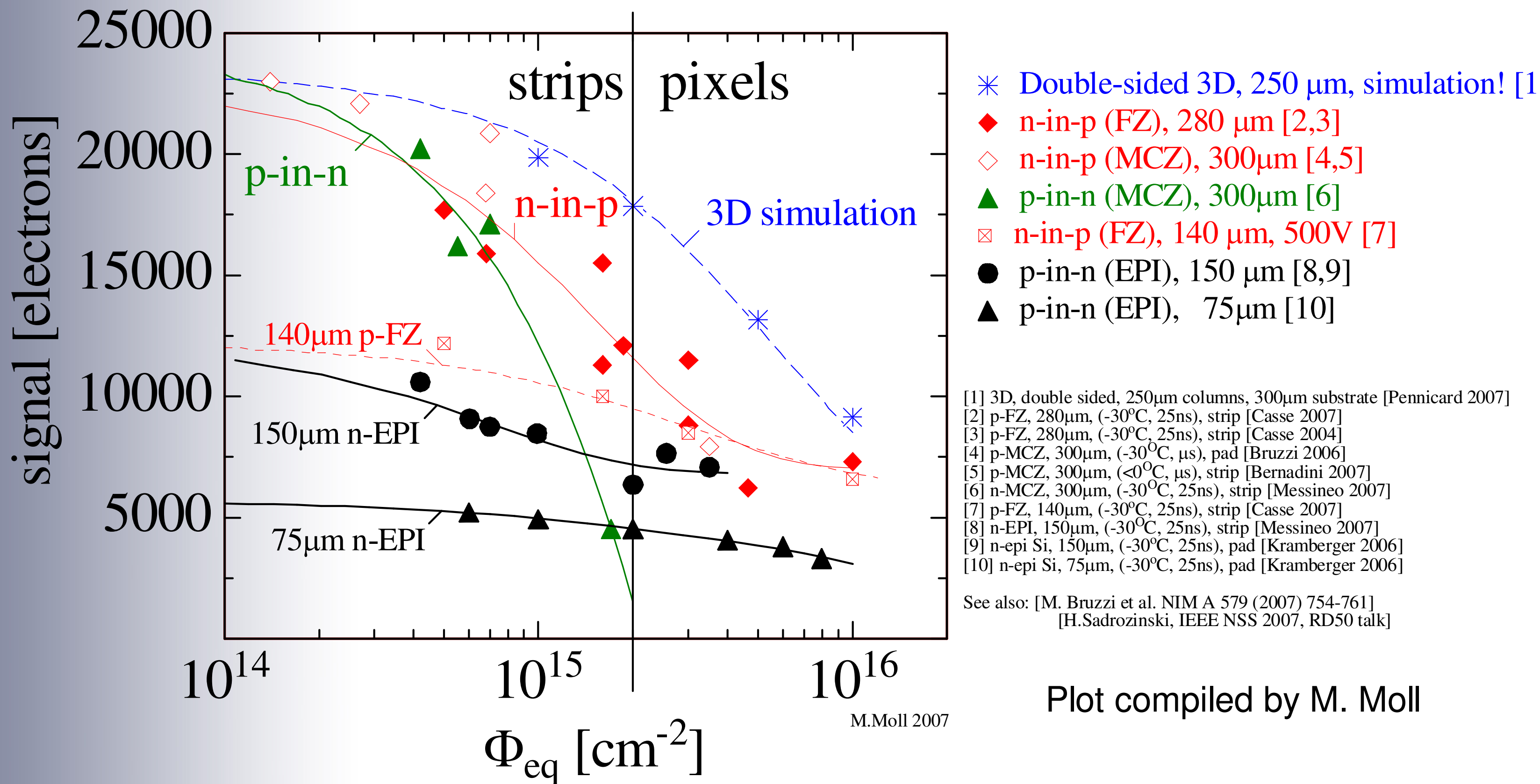
Detectors produced at Stanford

At high fluences, simulated CCE ~2/3 of experimental value (like with planar detector)

Simulations performed using Synopsys TCAD

Predict higher collection efficiency for 3D than for planar sensors

– Model uses pessimistic values for trapping rates



Plot compiled by M. Moll