3D Silicon Detectors for High Energy Physics and Imaging Applications

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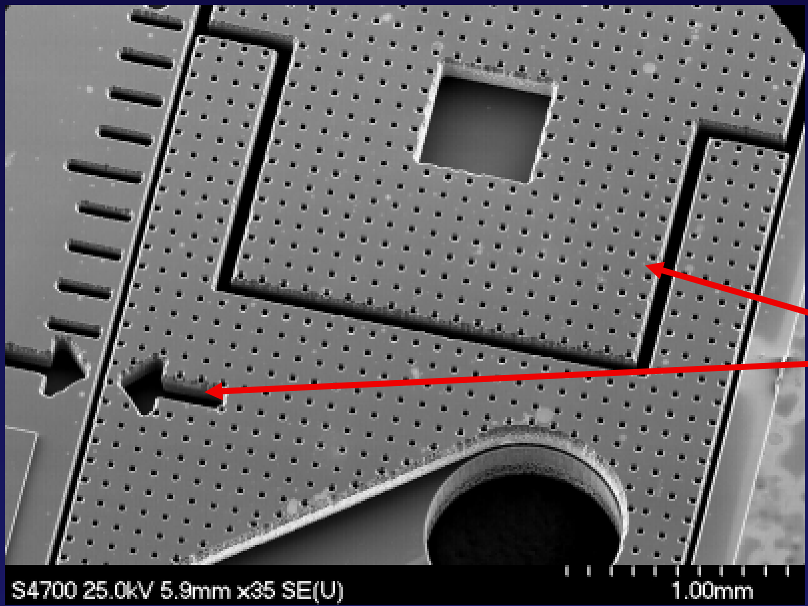
- Introduction
- 3D silicon technology and key properties
- Applications to HEP
- Applications to Medicine and Biology
- Summary and Perspectives

Micro-machining → MEMS



Micro-Electro-Mechanical Systems

MEMS refers to the integration of mechanical elements, and electronics on a common silicon substrate through micro fabrication technology

↓

"micromachining"

↓

process that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electro-mechanical structures

Communications

High frequency circuits will benefit considerably from the advent of the RF-MEMS technology. Electrical components such as inductors and ‘tunable ‘capacitors can be improved significantly compared to their integrated counterparts if they are made using MEMS technology.

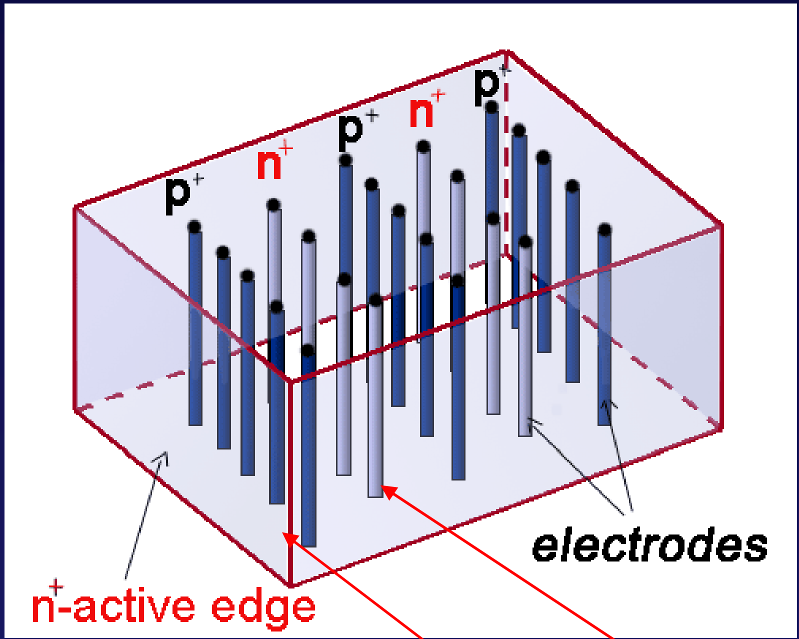
Accelerometers

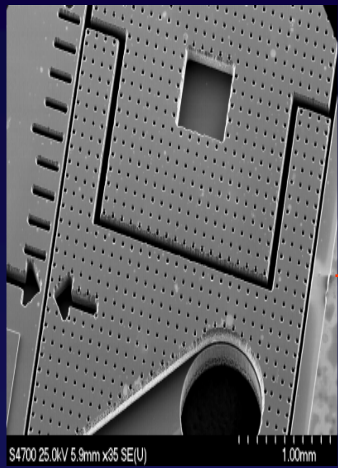
MEMS accelerometers are quickly replacing conventional accelerometers for crash air-bag deployment systems in automobiles.

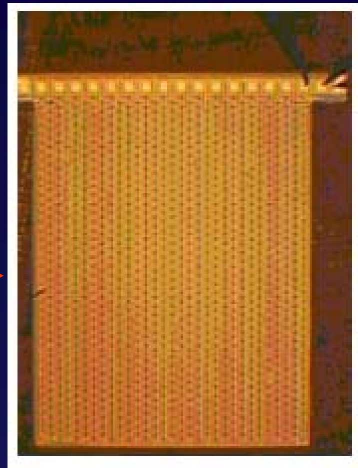
Biotechnology

Polymerase Chain Reaction (PCR) micro-systems for DNA amplification and identification, micro-machined Scanning Tunnelling Microscopes (STMs), biochips for detection of hazardous chemical and biological agents, and micro-systems for high-throughput drug screening and election.

3D Silicon detectors







3D silicon detectors were proposed in 1995 by S. Parker, and active edges in 1997 by C. Kenney.

Combine traditional VLSI processing and MEMS (Micro Electro Mechanical Systems) technology.

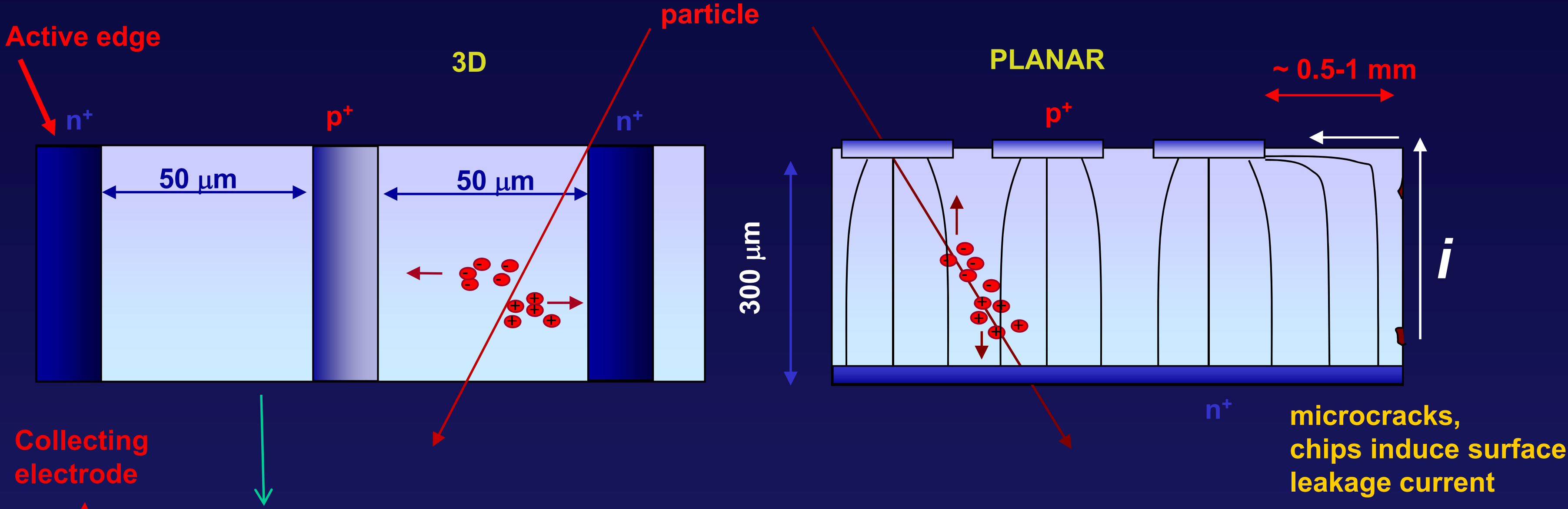
Electrodes are processed inside the detector bulk instead of being implanted on the Wafer's surface.

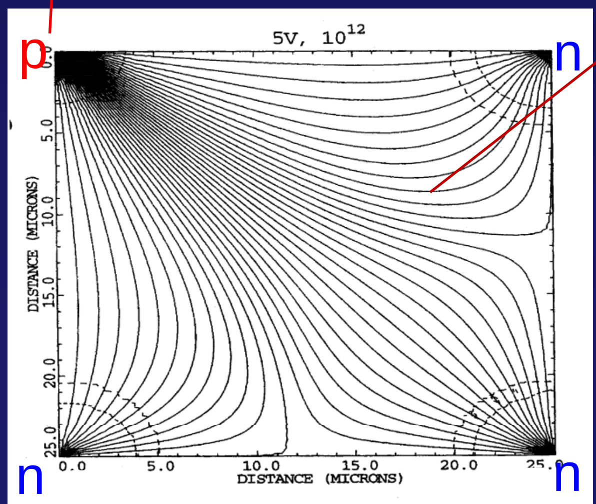
The edge is an electrode! Dead volume at the Edge < 5 microns! Essential for

1. NIMA 395 (1997) 328
2. IEEE Trans Nucl Sci 46 (1999) 1224
3. IEEE Trans Nucl Sci 48 (2001) 189
4. IEEE Trans Nucl Sci 48 (2001) 1629
5. IEEE Trans Nucl Sci 48 (2001) 2405
6. Proc. SPIE 4784 (2002)365
7. CERN Courier, Vol 43, Jan 2003, pp 23-26
8. NIM A 509 (2003) 86-91
9. NIMA 524 (2004) 236-244
10. NIM A 549 (2005) 122
11. NIM A 560 (2006) 127
12. NIM A 565 (2006) 272
13. IEEE TNS 53 (2006) 1676
14. NIM A 587(2008) 243-249

Recent papers not included

3D versus planar detectors (not to scale)





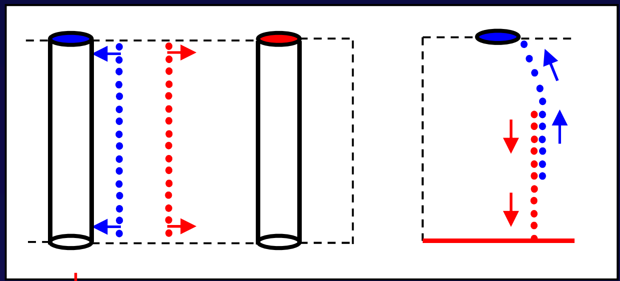
MEDICI simulation of a 3D structure

Drift lines parallel to the surface

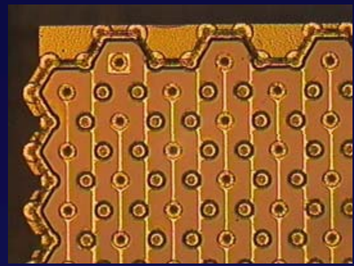
	3D	planar
❖DEPLETION VOLTAGES	< 10 V	70 V
❖EDGE SENSITIVITY	< 5 µm	500 µm
❖CHARGE 1 MIP (300 mm)	24000e-	24000e-
❖CAPACITANCE	30-50f	~20fF
❖COLLECTION DISTANCE	50 µm	300 µm
❖SPEED	1-2 ns	10-20 ns

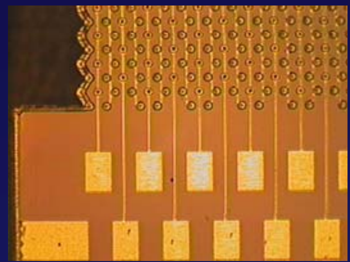
Full-3D speed properties

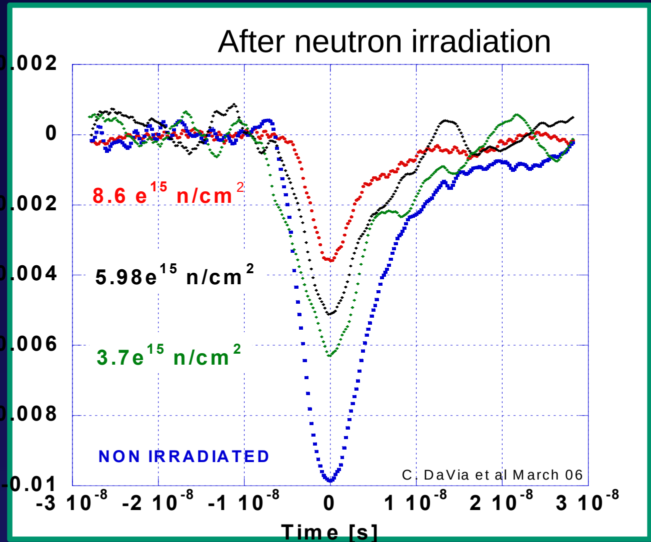
3D Tests with 0.13 μm CMOS Amplifier chip
(A Kok, S. Parker, C. Da Viá, P. Jarron,
M. Depeisse, G. Anelli), fabricated at Stanford
By J. Hasi, C. Kenney

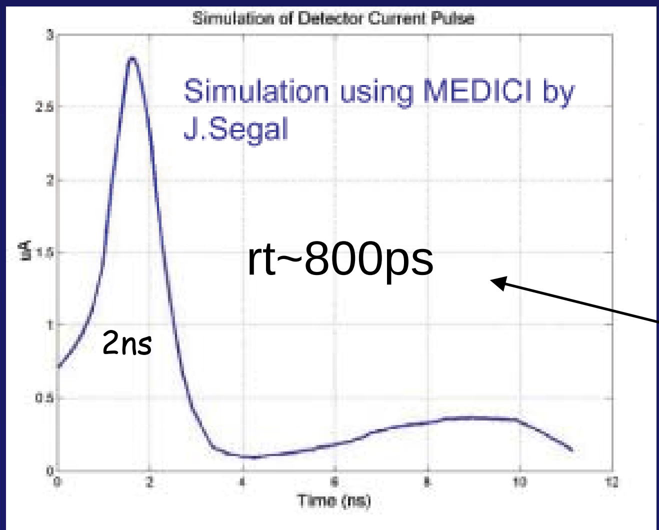


- Short collection distance
- High average e-field at low V_{bias}
- Parallel charge collection



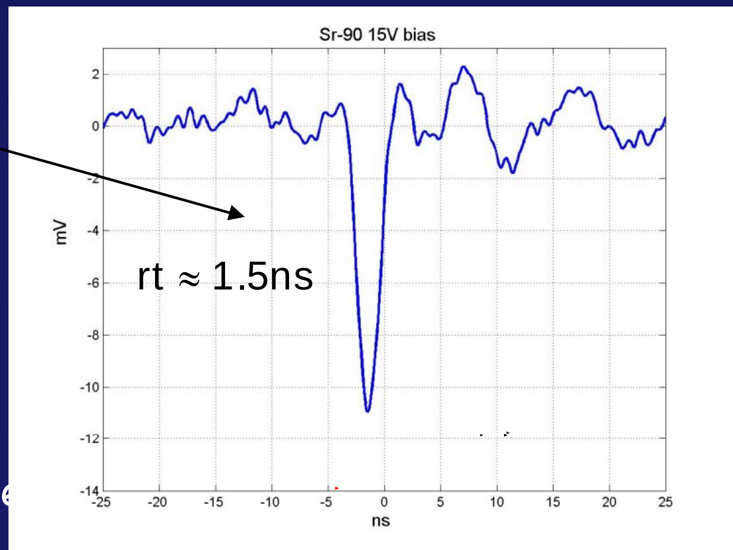




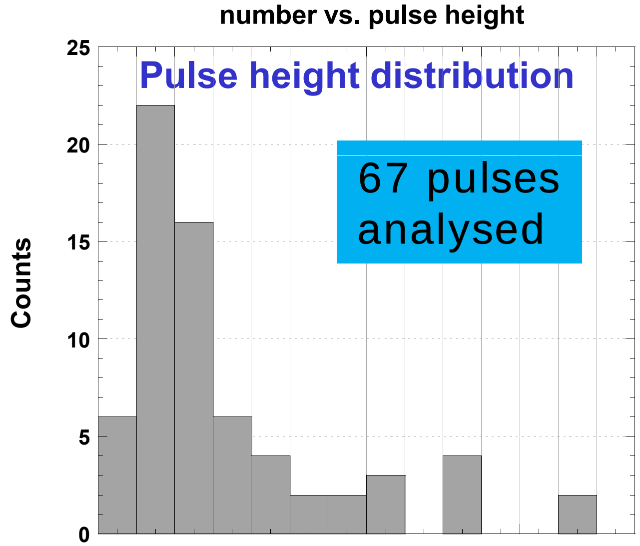


Raw oscilloscope trace

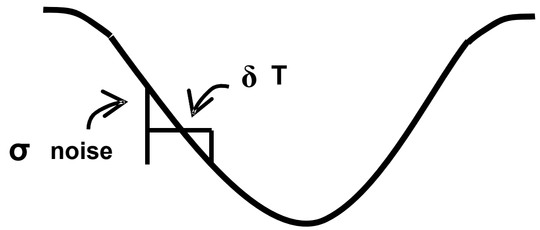
3D signal simulation

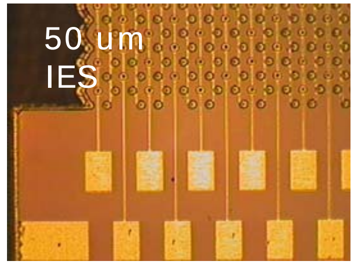


3D Inter-electrode spacing = 50 μm



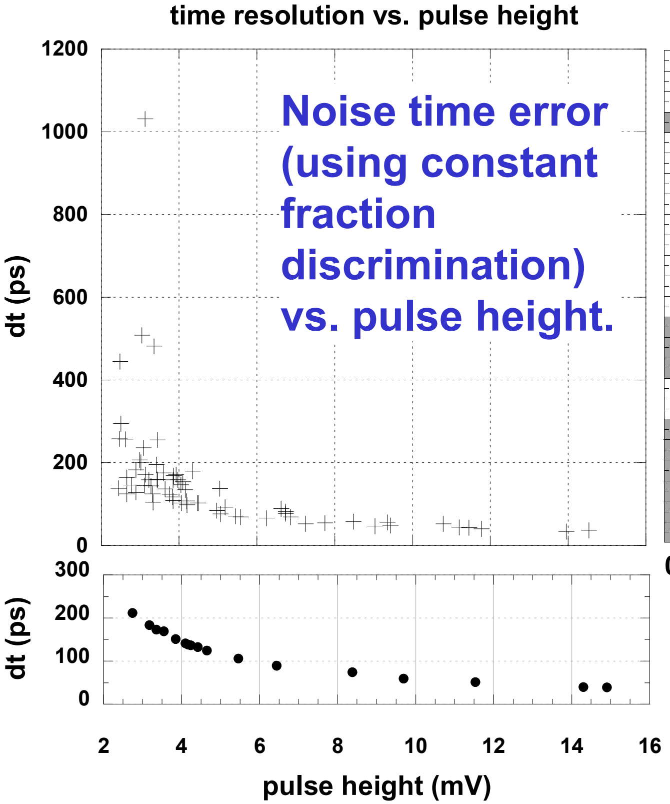
Constant Fraction Discrimination

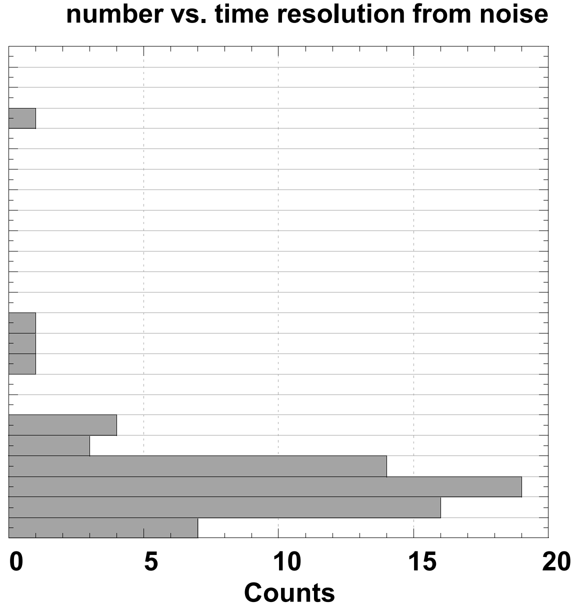




Analysis from S. Parker

Expected noise-induced time-error distribution





average dt
scatter plot:
155 ps
bottom plot:
134 ps

dt distribution from ~ noise-free signal added repeatedly to separate noise segments.

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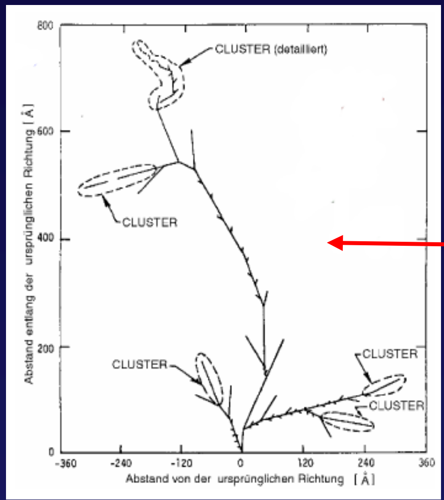
Radiation Induced Bulk Damage in Silicon

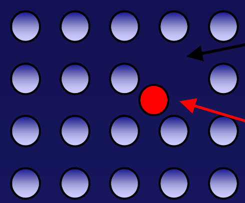
From RD48/ROSE

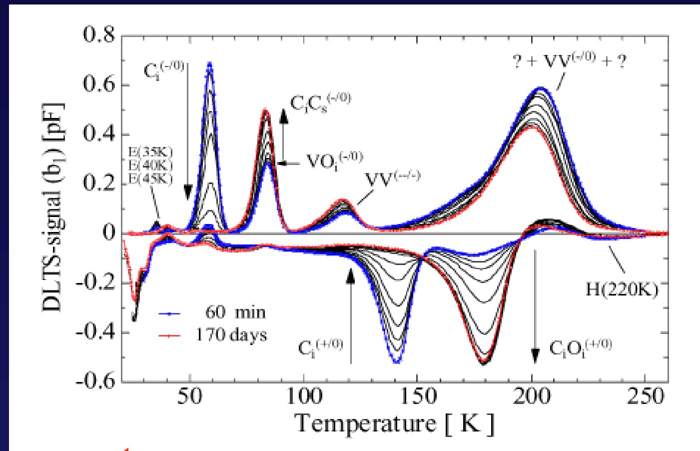


Van Lint 1980

Primary Knock on Atom

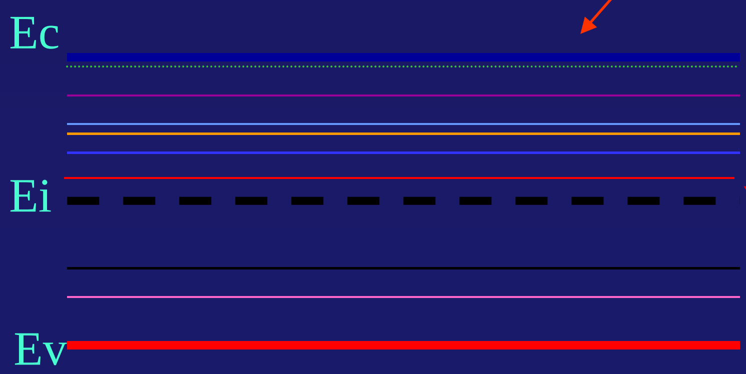
Displacement threshold in Si:
Frenkel pair E~25eV
Defect cluster E~5keV





V,I MIGRATE UNTIL THEY MEET IMPURITIES AND DOPANTS TO FORM STABLE DEFECTS

Effect on sensors



V6

VO^- Ec - 0.17eV

$V2^{(=/-)}$+Vn Ec-0.22eV

$V2^{(-/0)}$+Vn Ec-0.40eV

V_2O

$C_IO_I^{(0/+)}$ Ev+0.36eV

CHARGED DEFECTS==>N_{EFF}, V_{BIAS}

DEEP TRAPS, RECOMBINATION CENTERS ==>CHARGE LOSS

DEEP TRAPS, GENERATION CENTERS==>LEAKAGE CURRENT

Joint Instrumentation Seminar
of the Particle Physics and Photon Science communities
at DESY, Hamburg University and XFEL
- 26 March 2010 -

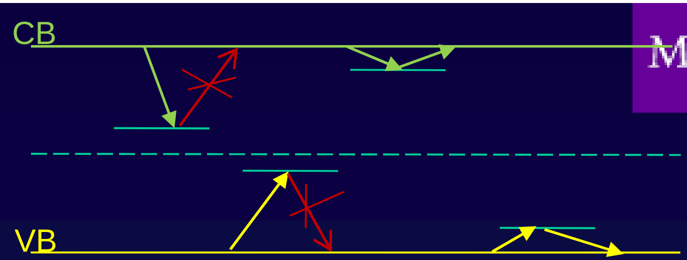
Development of radiation tolerant silicon detectors for the Super - LHC

... with strong focus on the results of the RD50 collaboration

Michael Moll (CERN/PH)

For details on LHC radiation environment and radiation effects on silicon please look at this talk

The effect of trapping

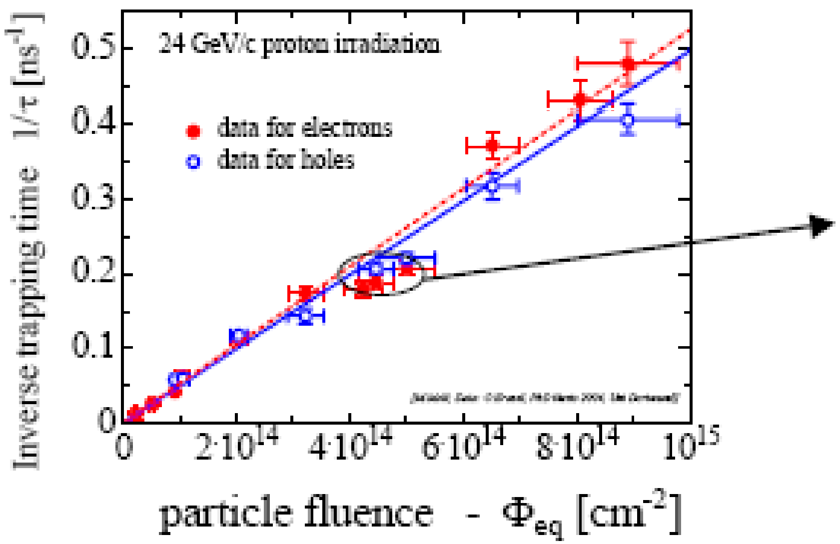


The carriers move less → less signal since the signal is formed when charges move

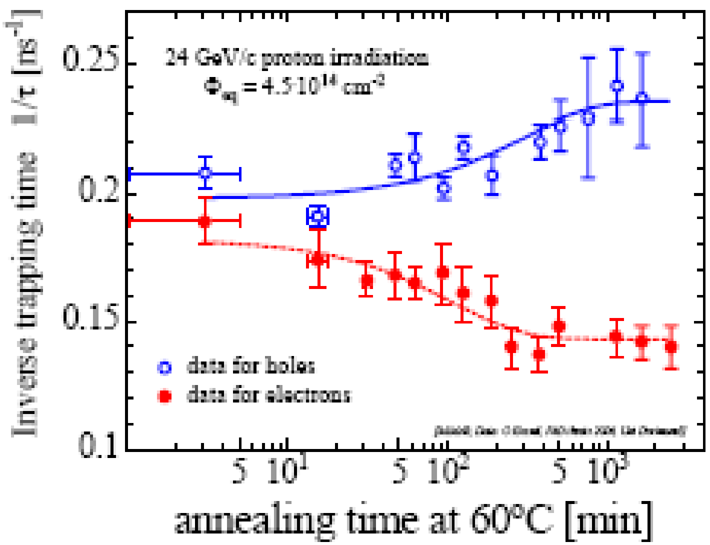
Trapping is characterized by an effective trapping time τ_{eff} for e^- and h:

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

Increase of 1/τ with fluence



1/τ changes with annealing



Trapping has been measured for electrons and holes by G. Kramberger (Ljiubliana) NIMA 481 (2002) 100

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Signal Efficiency and Signal Charge in 3D Structures

SE=signal after irradiation/signal before irradiation

Ramo's theorem with trapping

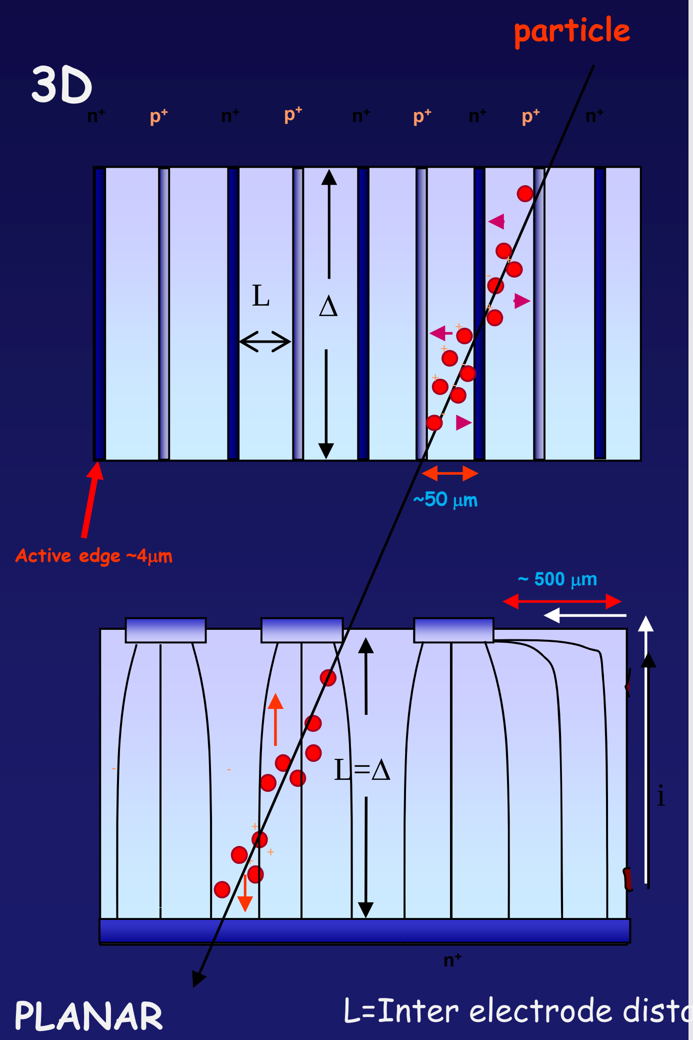
$$\frac{dS}{dt} = q\frac{dV_W}{dx}\frac{dx}{dt}\exp(-\frac{x}{\lambda})$$

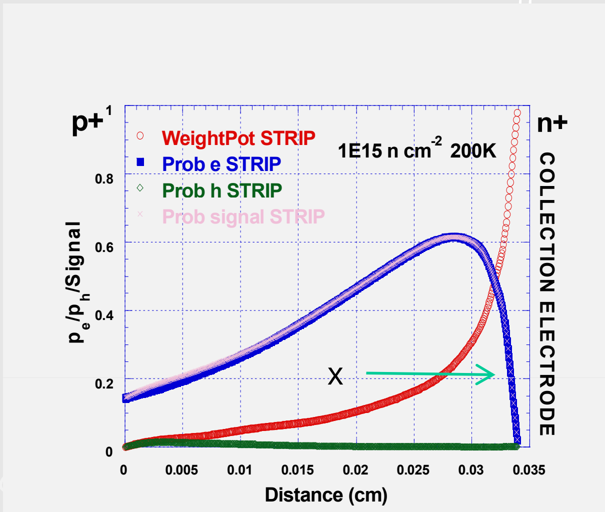
← Effective drift length

$$S = \frac{\lambda}{L}\left[1-\exp(-\frac{x}{\lambda})\right]$$

$$SE = \frac{\lambda}{L} - \left(\frac{\lambda}{L}\right)^2 + \left(\frac{\lambda}{L}\right)^2 \exp(-\frac{L}{\lambda})$$

$$SE = \frac{1}{1+0.6L\frac{K_\tau}{v_D}\Phi}$$



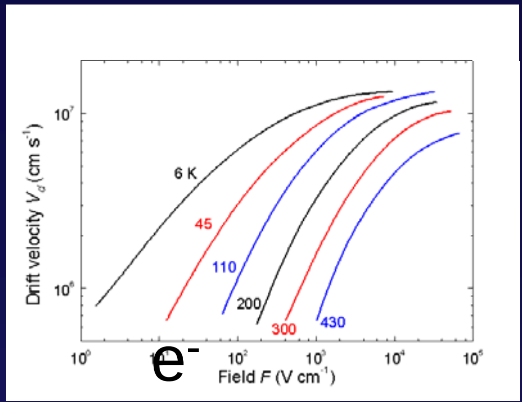


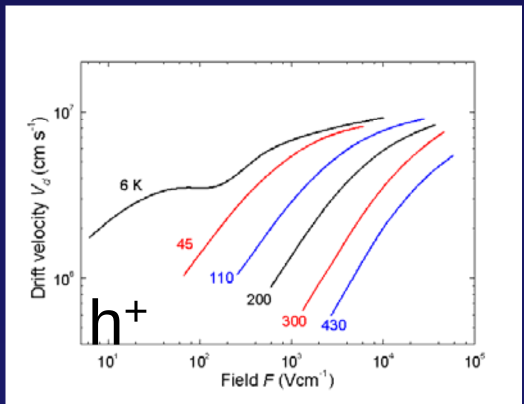
L=inter electrode distance
λ= effective drift length
V_D= v_{drift} (saturated)
Φ= fluence
Kτ=trapping time damage constant
Δ= substrate thickness (determines the amount of generated charged by a MIP)

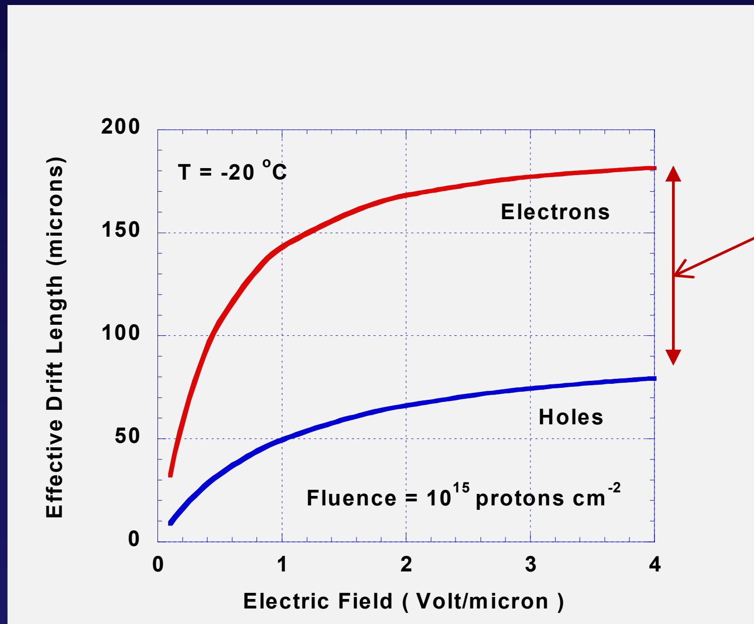
Trapping times from G. Kramberger et al.
NIMA 481 (2002) 100
NIM A 501(2003) 138 (Vertex 2001)

Effective drift length due to trapping

$\lambda = v_{drift} \times \tau_{trap}$







e^- mobility 3 times bigger!

For max signal:

❖Collect e^-

❖Work at V_{drift} Saturated
-> e-field >2V/μm

Ottaviani, Canali et al.

Trapping times from Kramberger et al. NIMA 481 (2002) 100
Simulations CDV and S.Watts NIM A 501(2003) 138 (Vertex 2001)

3D electrodes configurations

Cinzia Da Viá , the University of Manchester-UK. Hamburg 9 April 2010

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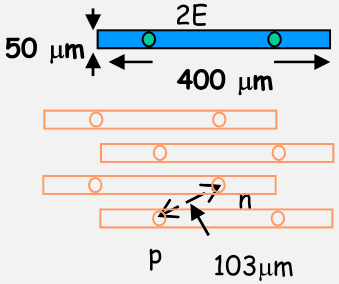
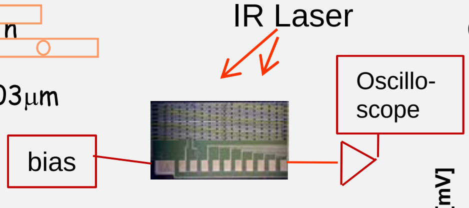
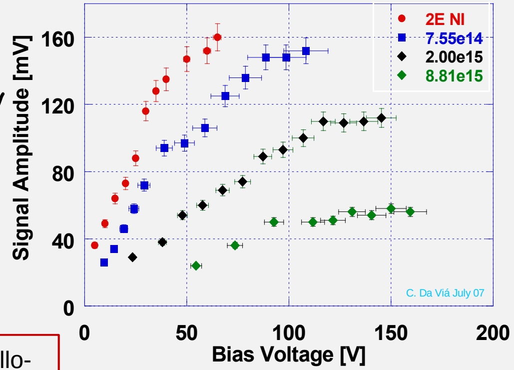
8.81×10^{15} n/cm^2
1.73×10^{16} p/cm^2

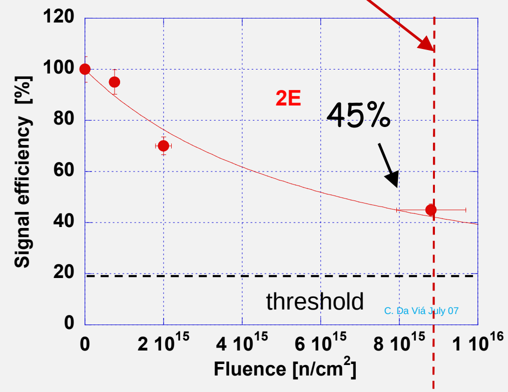
Irradiation and measurements performed in Prague
C. Da Viá, T. Slaviceck, V. Linhart, P. Bem, S. Parker, S. Pospisil, S. Watts (process J. Hasi, C. Kenney)

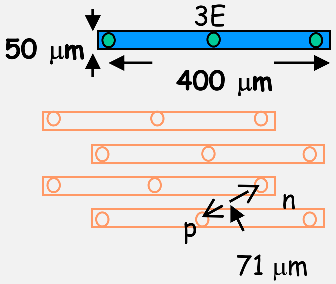


2E
9000e-
V_b~130V

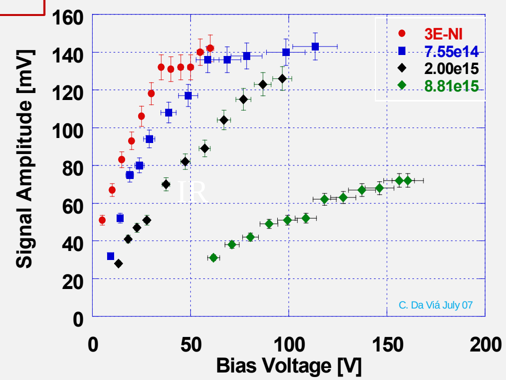


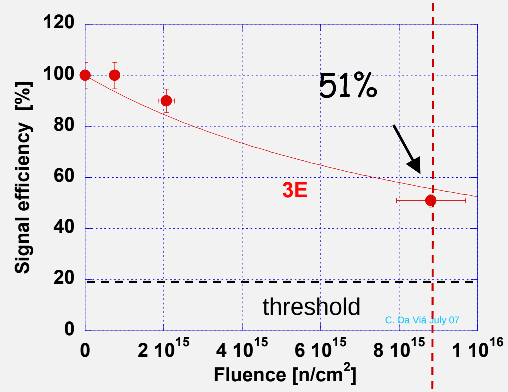


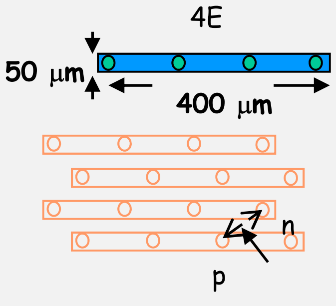




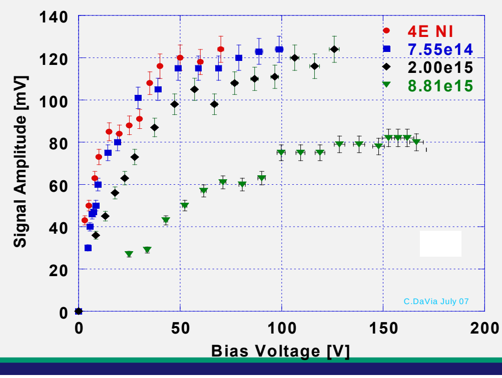
3E
10200e-
V_b~112V

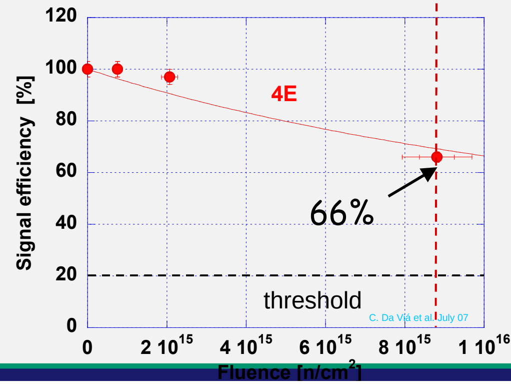






4E
13200e-
V_b~94V

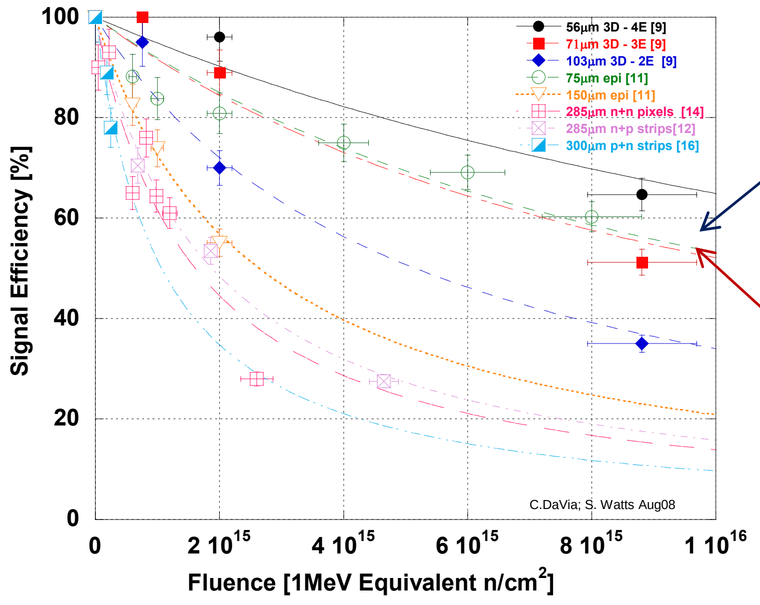




Signal efficiency and signal charge

[9] C. Da Via et al.", (NIMA-D-08-00587)
[10] G. Kramberger at al., Nucl. Instr. Meths. A 554 (2005) 212-219
[11] G. Kramberger, Workshop on Defect Analysis in Silicon Det, Hamburg, August 2006. http://wwwiexp.desy.de/seminare/defect.analysis.workshop.august.2006.html
[12] G. Casse et al., Nucl. Instr. Meths. A (2004) 362-365
[14] T. Rohe et al. Nucl. Instr. Meths. A 552 (2005) 232-238
[16] F. Lemeilleur et al., Nucl. Instr. Meths. A 360 (1995) 438-444

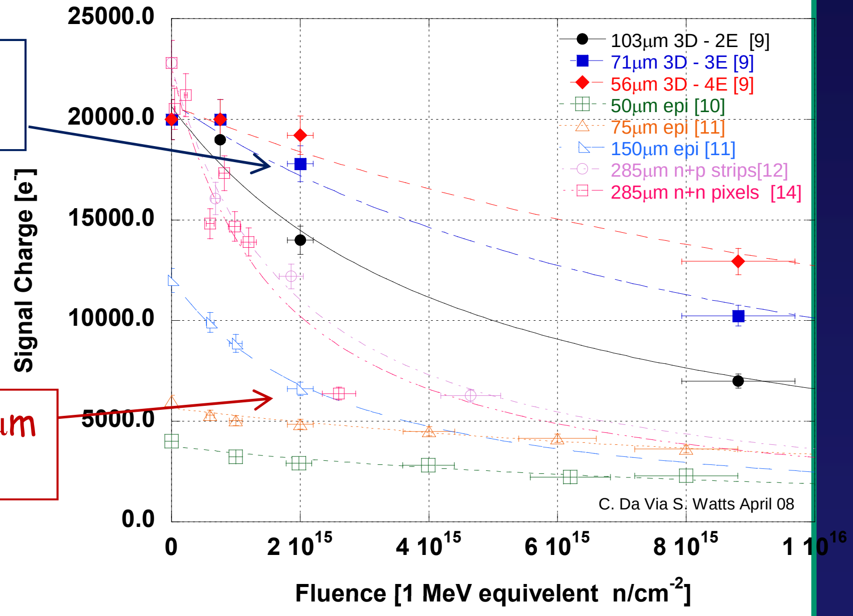
Signal Efficiency (prop 1/L)



71μm 3D

75μm epi

Signal charge (depends on Δ)



Example at 10^{16} ncm^2

S_{MIP} planar ~ 80 (λ/~~L~~) x ~~Δ~~ ~ 80λ ~ 80x30 ~ 2400e$^-$

S_{MIP} 3D ~ 80λ x (Δ/L) ~ 2400 x 210/(71-22$_{\text{electrode implant}}$) ~ 10290e$^-$

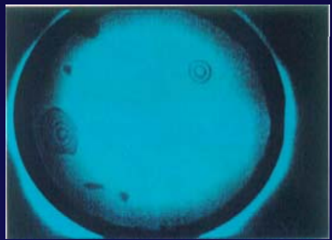
3D wins because Collection distance and substrate thickness are decoupled

Key processing steps (25-32)

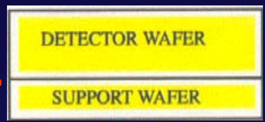
1- etching the electrodes

2-filling them with dopants

Aspect ratio: D:d = 11:1



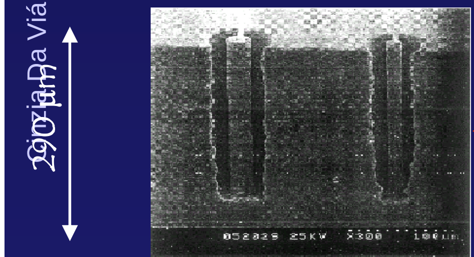
WAFER BONDING
(mechanical stability)
Si-OH + HO-Si -> Si-O-Si + H_2O



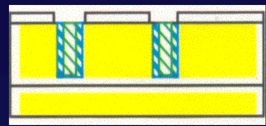
Step 1-3 oxidize and fusion bond wafer

Step 4-6 pattern and etch p^+ window contacts

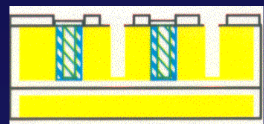
Step 7-8 etch p^+ electrodes



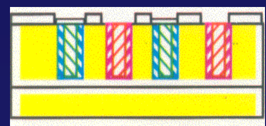
DEEP REACTIVE
ION ETCHING (STS)
(electrodes definition)
Bosh process
SiF_4 (gas) +C_4F_8 (teflon)



Step 9-13 dope and fill p^+ electrodes

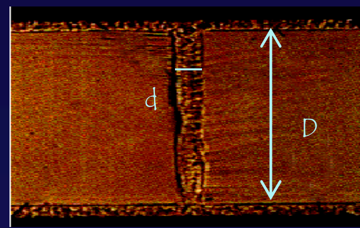


Step 14-17 etch n^+ window contacts and electrodes



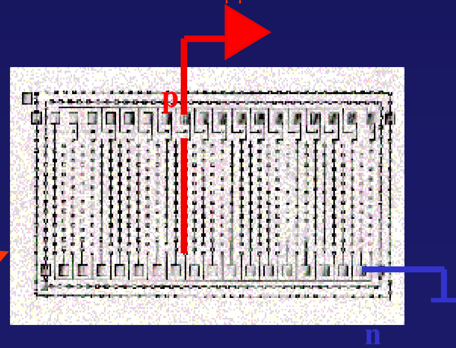
Step 18-23 dope and fill n^+ electrodes

Step 24-25 deposit and pattern Aluminum



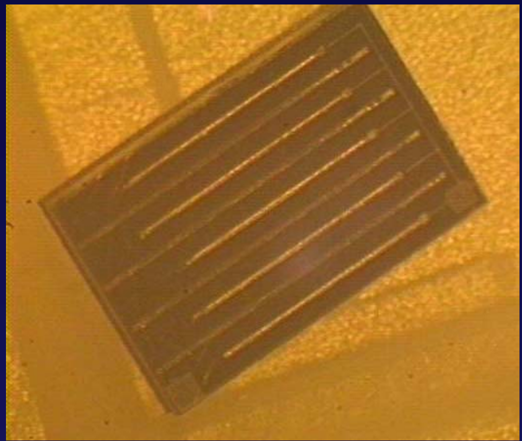
LOW PRESSURE
CHEMICAL VAPOR
DEPOSITION
(Electrodes filling with
conformal doped polysilicon
SiH4 at ~620C)
$2P_2O_5$ +5 Si-> 4P + 5 SiO_2
$2B_2O_3$ +3Si -> 4 B +3 SiO_2

Both electrodes appear on both surfaces

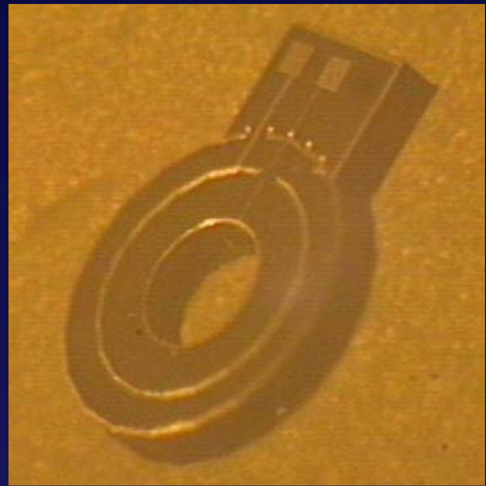


METAL DEPOSITION
Shorting electrodes of the same type
with Al for strip electronics readout
or deposit metal for bump-bonding

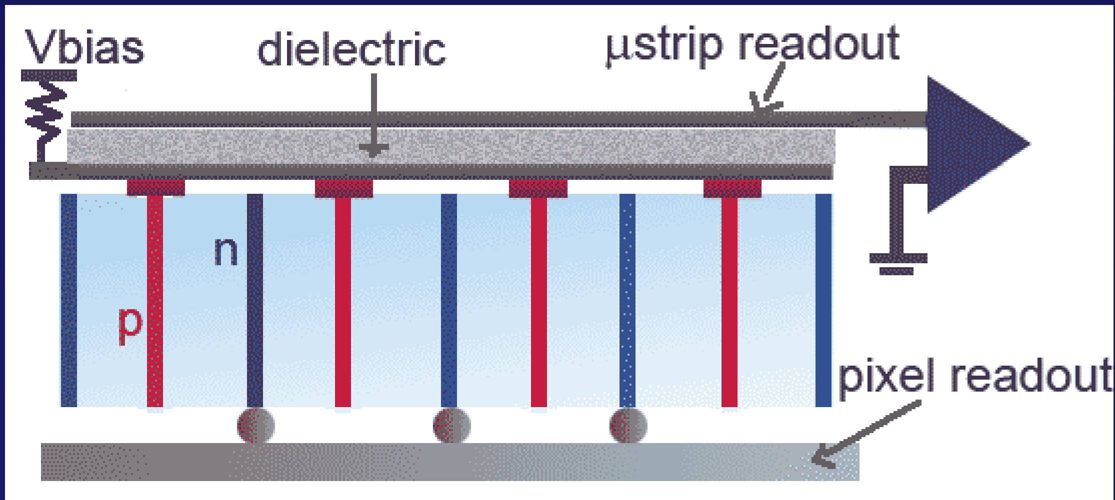
Other structures already fabricated at STANFORD (C. Kenney, J. Hasi) to improve speed and detection properties



3D Parallel trenches



3D coaxial layout



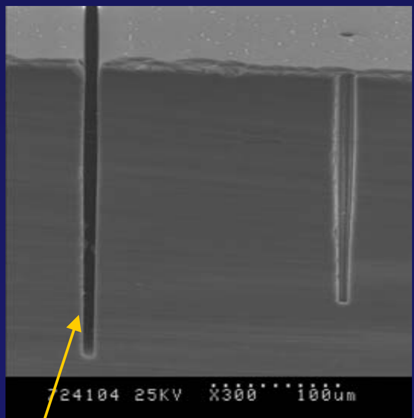
C. Da Via et al., "Dual readout – strip/pixel systems", NIM A594, pp. 7-12 (2008).

Improving the aspect ratio (D/d) in thick wafers →better x-ray detection efficiency

>Original production D/d=12:1 etching time = 5µm/min D=121 µm
>Present production D/d=19:1 etching time = 5µm/min
D=180 mm – 240 mm
>Double side etching D/d=25:1 etching time = 1.5µm/min
D=525 mm inter electrode spacing = 25 µm

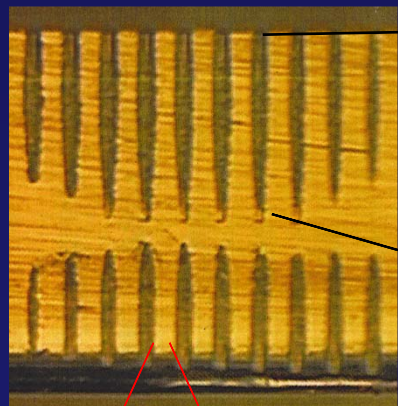
J. Hasi PhD Thesis

Tests made with the original STS etcher. (Newer ones by Alcatel, STS, and others have a number of design changes. Etching should be faster. It should be possible to make narrower trenches and holes.)

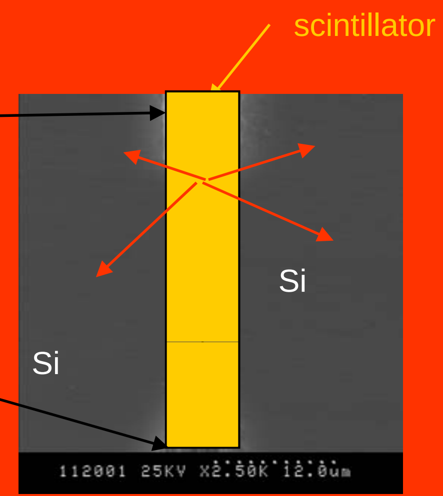


trench

525 µm



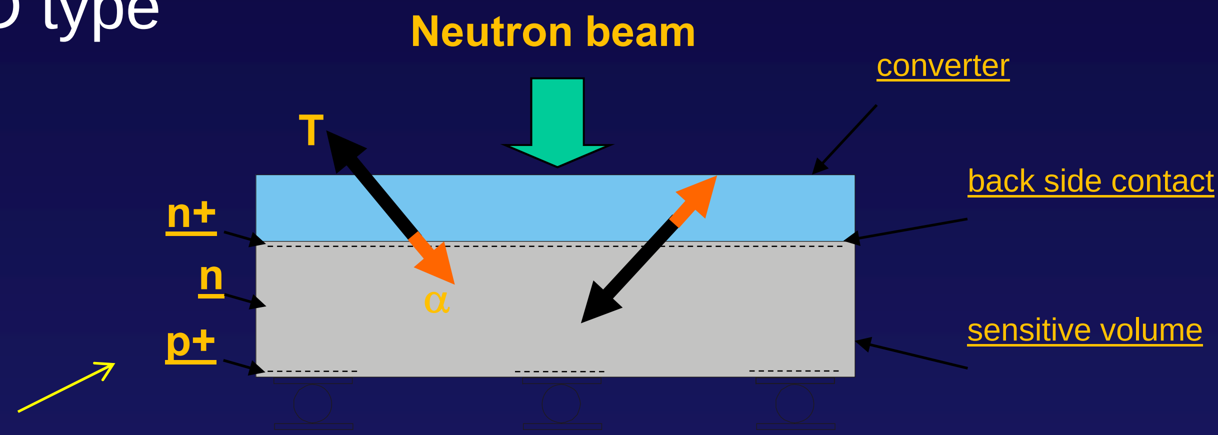
25 µm



Optimised aspect ration for gamma detection

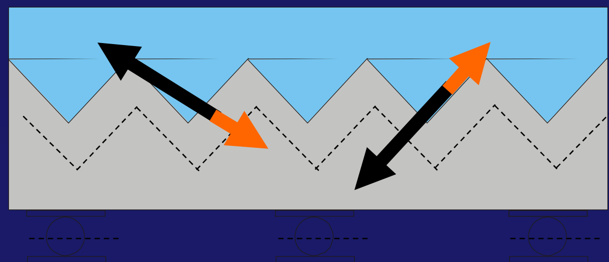
Using the 3D feature for special detection: inserting converting materials in the electrodes to enhance efficiency 2D neutron array modification J Huler, Prague-

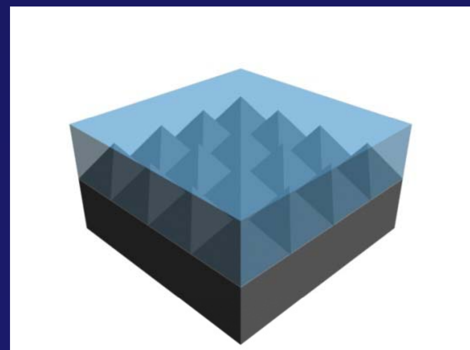
“Standard” 2D type



EFFICIENCY = 5%!!!

“Egg plate” 2D type
(with enlarged surface to increase
 the detector efficiency)



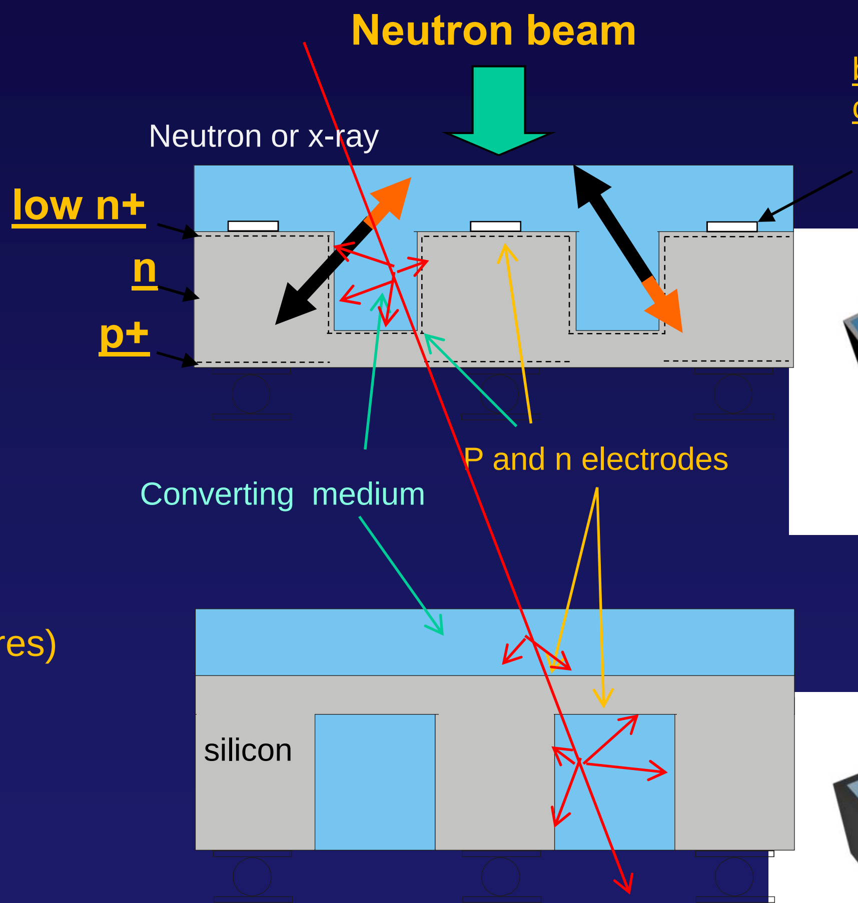


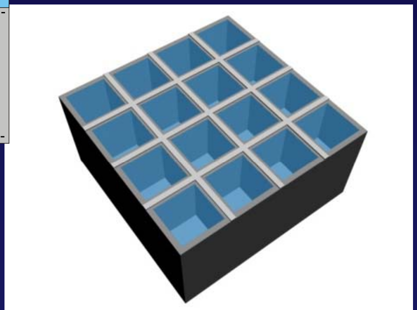
Neutron array modification combine detection and conversion

Cinzia Da Viá , the University of Manchester-UK. Hamburg 9 April 2010

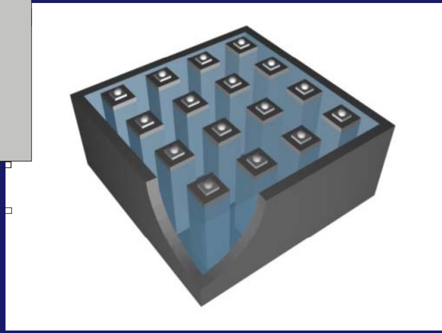
"Channel" 2D type
(maximized filling)

"3D inverse" structure
(there are pillars instead of pores)





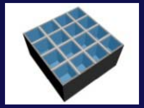
bottom view

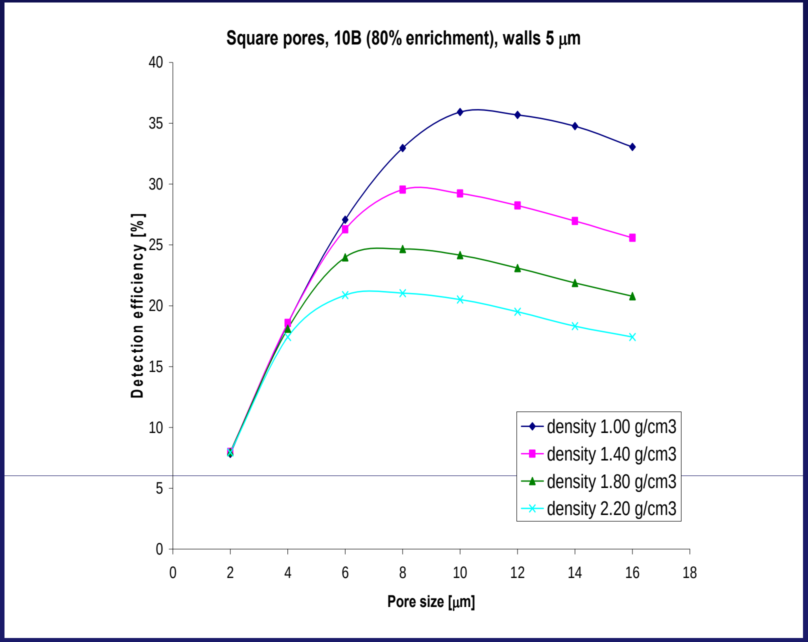


3D geometry arrays
- comparison of cylindrical vs. square ^{10}B converter

Fixed wall thickness – variance in the converter / cell size

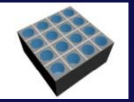
Square

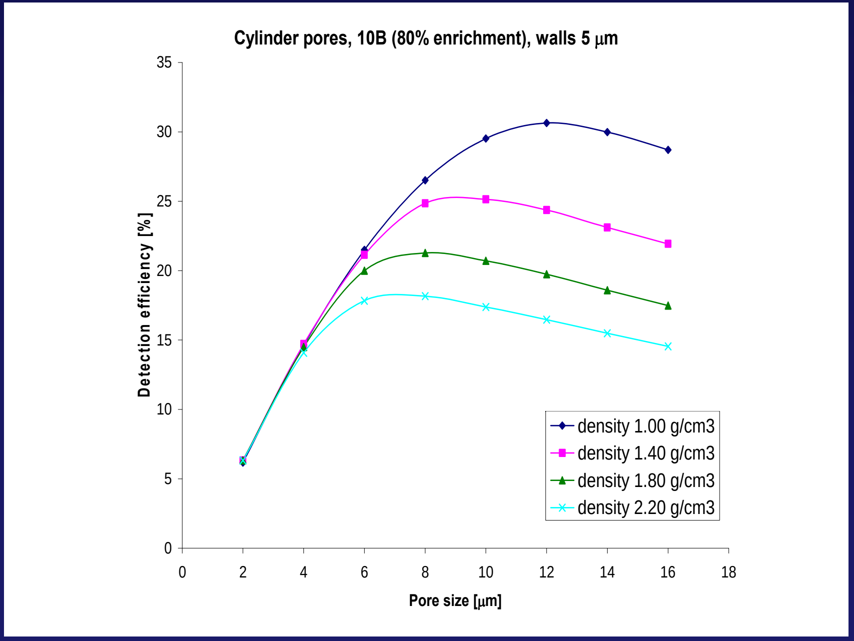




Maximal efficiency: ~36%

Cylinder





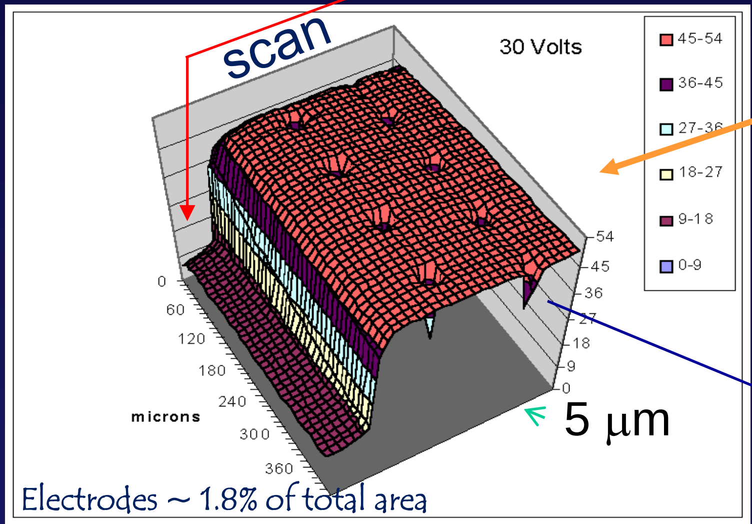
Maximal efficiency: ~31%

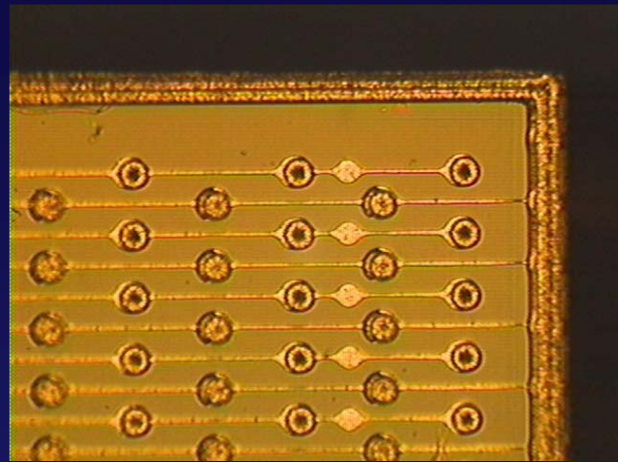
Covering big areas :

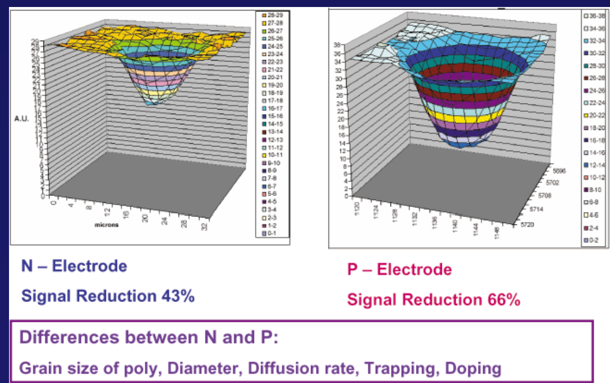
→Active edge and electrode response of 3D sensors

Fabricated at Stanford, J. Hasi (Manchester PhD thesis)

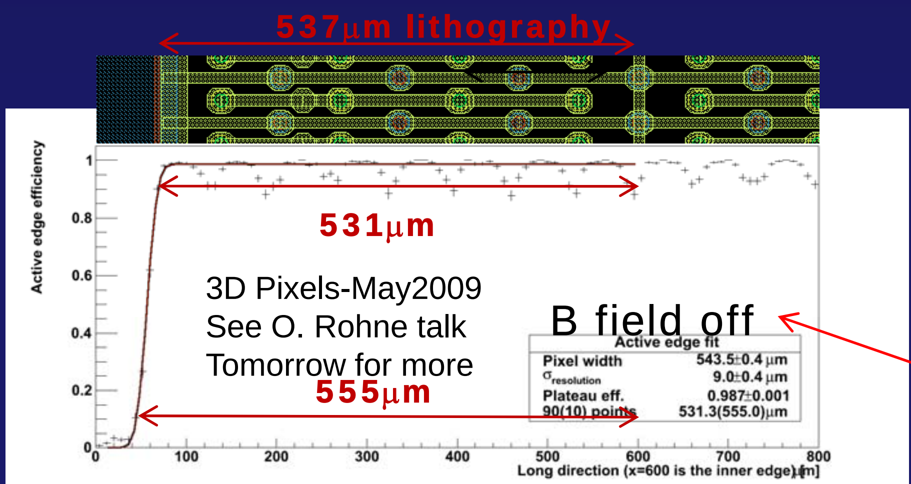
X-ray micro-beam scan, in 2 μm steps, of a 3D, n bulk and edges, 181 μm thick sensor. The left electrodes are p-type







Electrode response

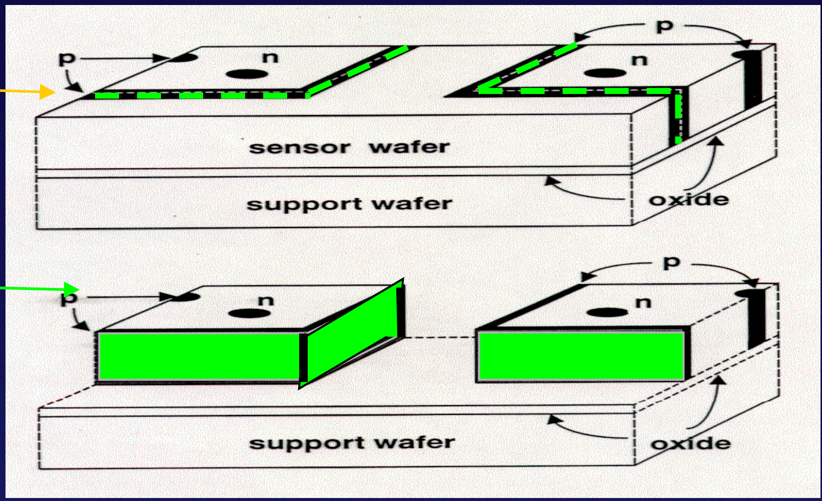


Edge = 543-537=6±9.8 μm
Measured with 1.4T B field
In SPS H8 beamline

Active edge: how does it work?

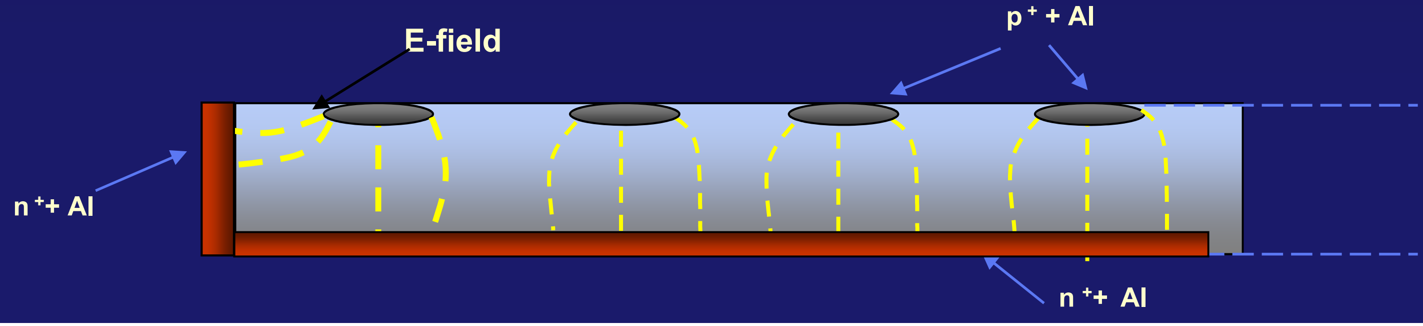
A TRENCH IS ETCHED AND DOPED TO TERMINATE THE E-FIELD LINES

AFTER THE FULL PROCESS IS COMPLETED THE MATERIAL SURROUNDING THE DETECTORS IS ETCHED AWAY AND THE SUPPORT WAFER REMOVED : NO SAWING NEEDED!!!
(NO CHIPS, NO CRACKS)



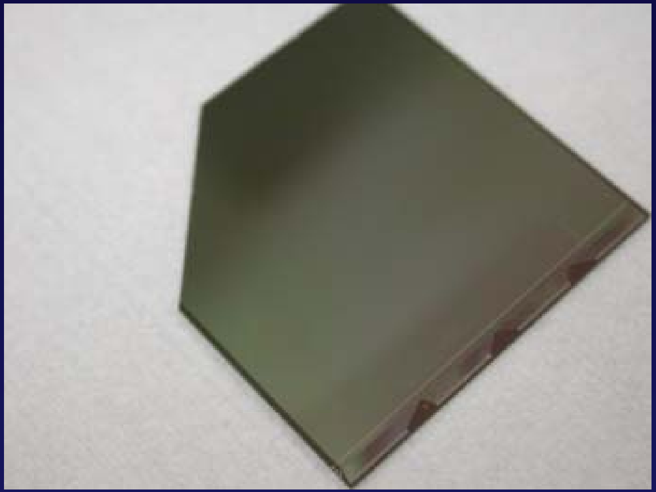
Natural development → PLANAR+3D = planar/3D

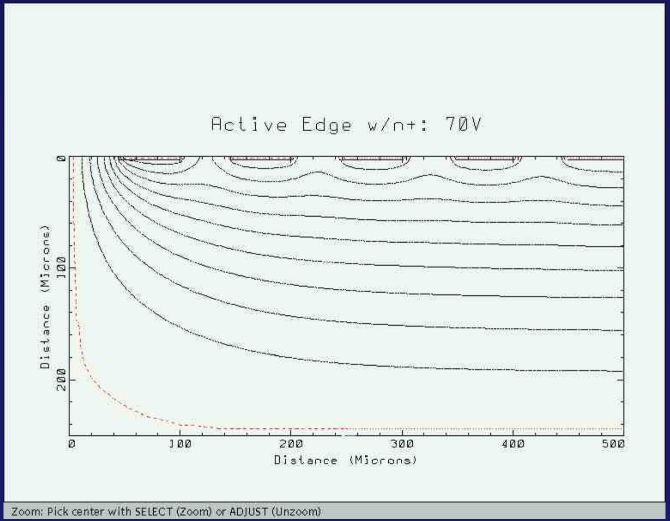
PLANAR DETECTOR + DOPANT DIFFUSED IN FROM DEEP ETCHED EDGE THEN FILLED WITH POLYSILICON (C. Kenney 1997)



❖PLANA (C. Kenney 1997)

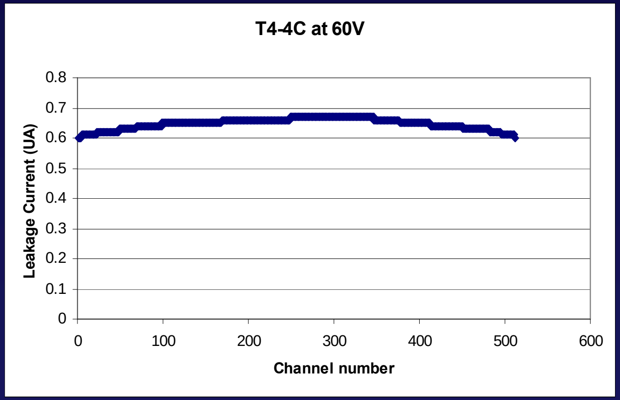
Planar sensors with active edge
Performance of a fabricated sensor



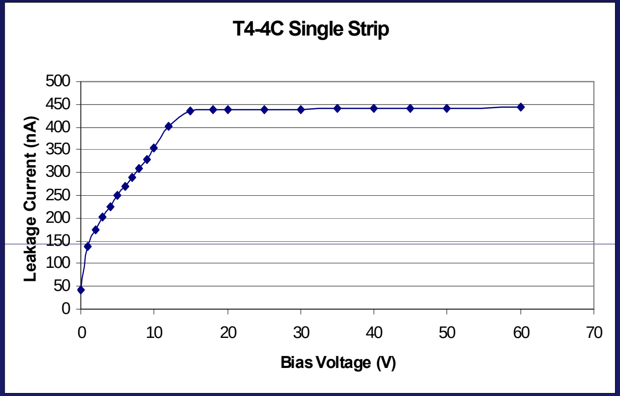


Medici simulation of the equipotential lines of a p on n planar/3D structure (J. Segal)

TOTEM detectors
3x4cm^2 512 μstrips



all the 512 strips at 60V



IV of one strip

IV of one of the pre-production detectors.

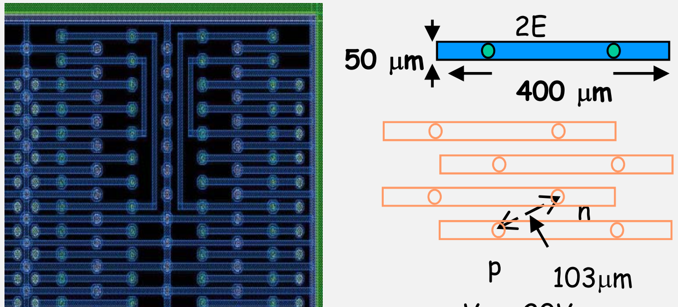
Electrodes configuration

Financial support:
STFC-UK for the FP420 project
DOE, USA for ATLAS Upgrade

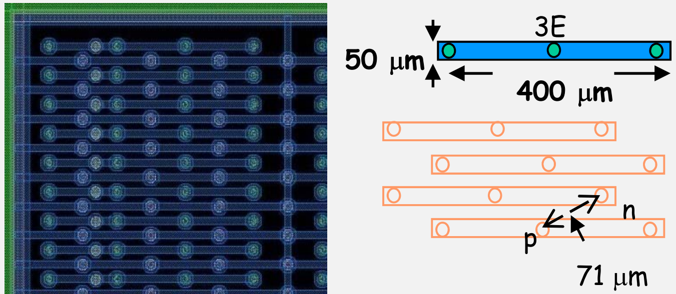
MANCHESTER 1824

Design and fabrication by:
J. Hasi, Manchester
C. Kenney, MBC at CIS-Stanford

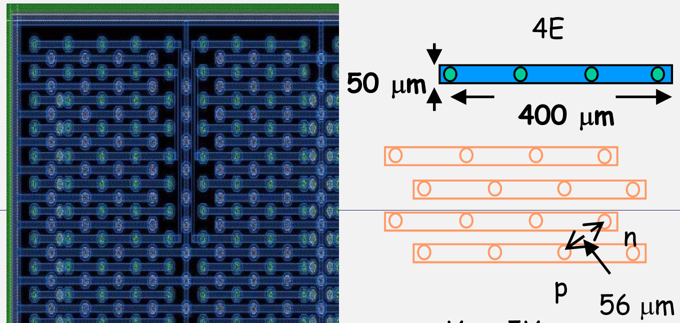
Thickness <250 μm>
p-type substrate 12kΩcm



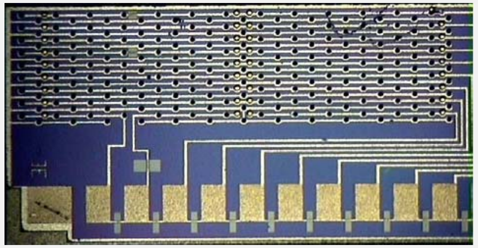
V_{fd} ~20V



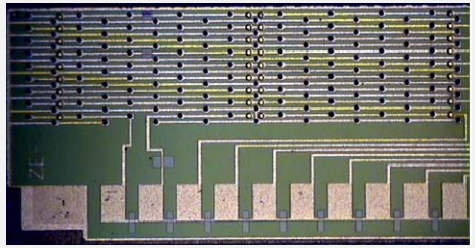
V_{fd} ~8V



V_{fd} ~5V



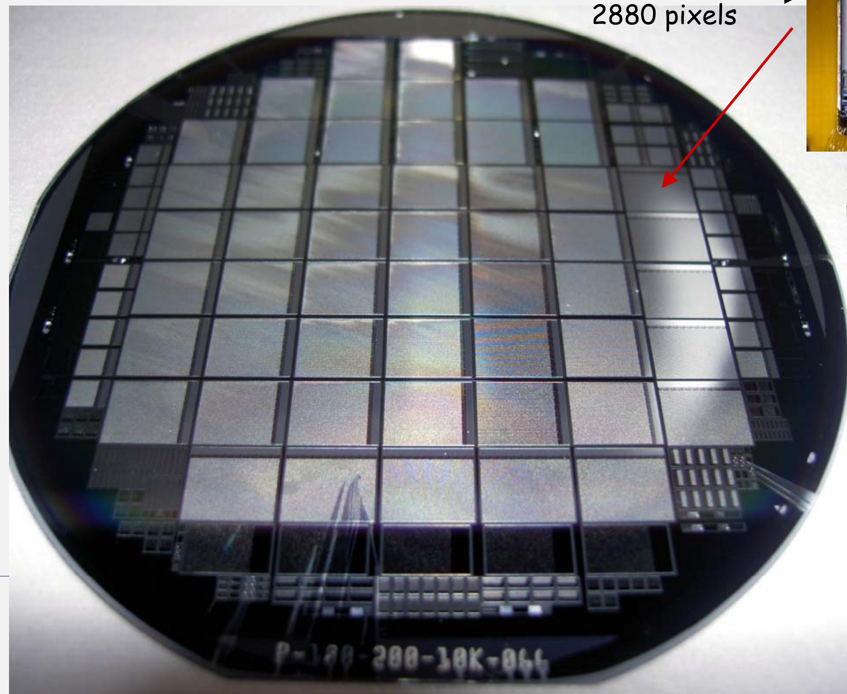
Baby-2E



Baby-3E

ATLAS pixel chip
7.2 x 8 mm²
2880 pixels

Atlas chip picture from Bekerle Vertex03

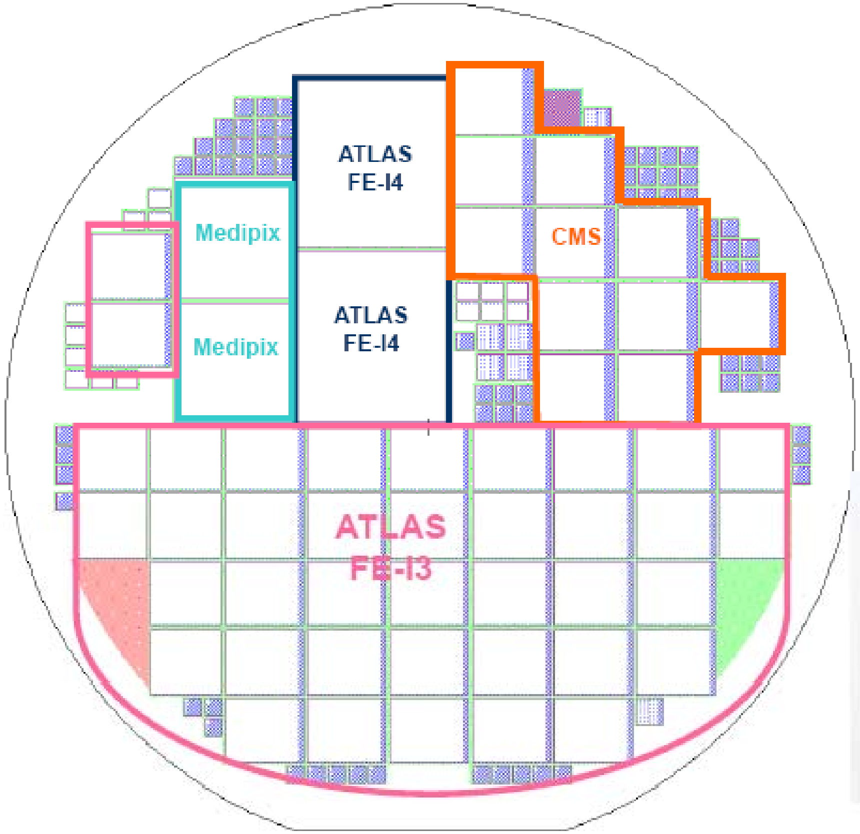


10 wafers competed. Yield~80% (1 wafer)

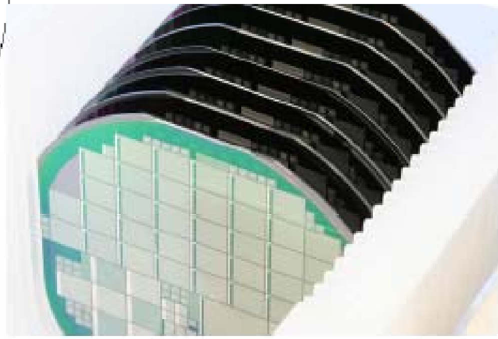
3DC transferred the original 3D design to SINTEF/Norway

From A. Kok (Manchester , Feb. 2010)

3D at MiNaLab

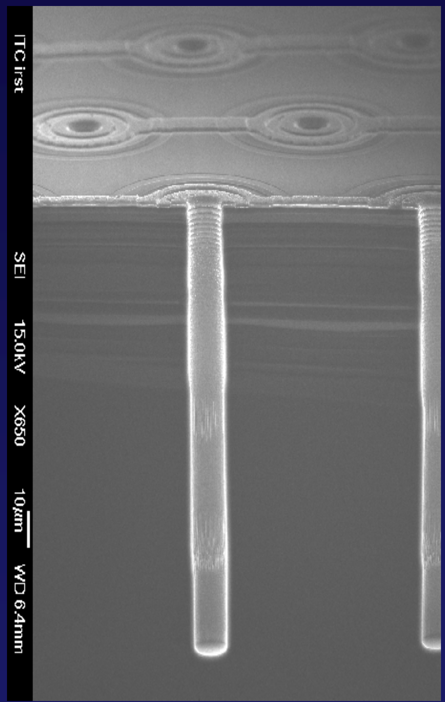


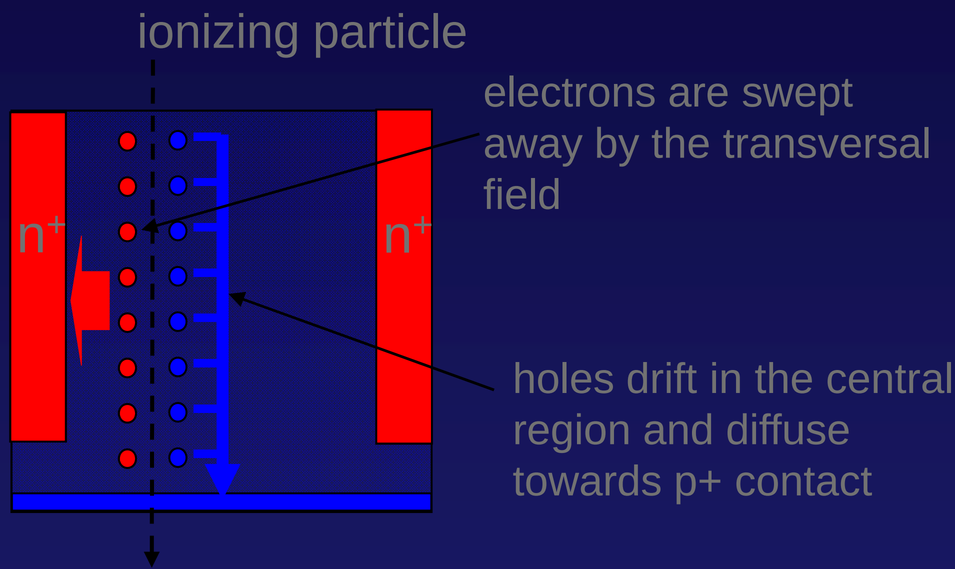
- Second series (B)
- Collaboration with ATLAS, CMS, Medipix and SNF
- Aim to improve yield and stability



Alternative 3D designs:
Single-Type-Column - IRST , CNM VTT

[C. Piemonte et al NIMA 541 (2005)]





Fabrication process is much simpler:

- column etching and doping performed only once
- holes not etched all through the wafer

…**BUT** collection mechanism is less efficient and no active edges

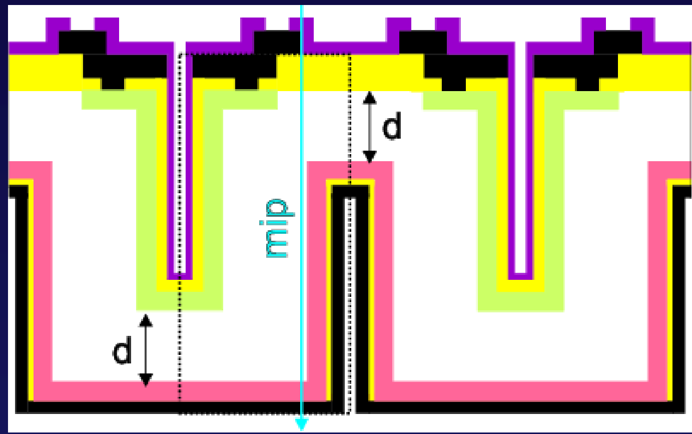
Modified 3D at FBK-IRST: Double Type Column

Cinzia Da Viá , the University of Manchester-UK. Hamburg 9 April 2010

- 3D-DDTC concept

(Double-side Double Type Column)

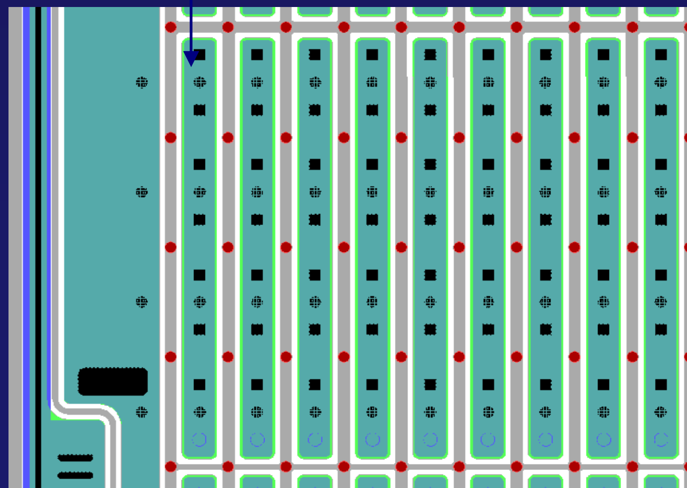
- Expected to have performance comparable to standard 3D detectors (if d is small enough)
- 2 batches under fabrication
- Will be ready for testing in common test beam This Autumn



Batch	DDTC 1	DDTC 2
Substrate type	n-type	p-type
Subst. thickness (μm)	300	205 – 255
Column depth (μm)	200 (not optimized)	180 – 200 (optimized)
Strip design and pitch (μm)	AC/DC coupled, 80 – 100	AC/DC coupled, 80 – 100
Pixel design	ALICE, MEDIPIX	**ATLAS**, CMS
Due by	August 2007	September 2007

ATLAS pixel, single-chip

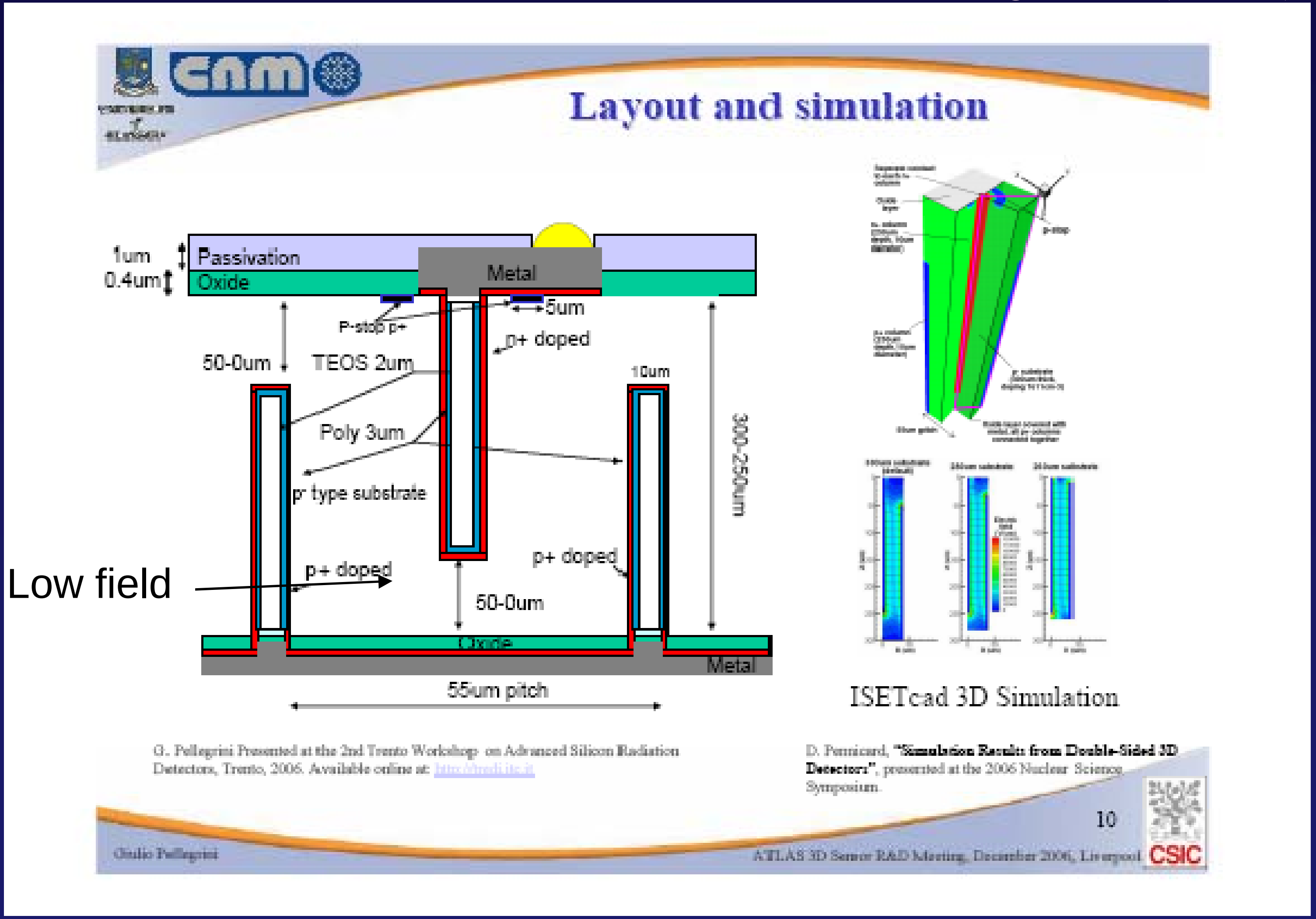
(2, 3, 4 or 7 columns/pixel)



Modified 3D at CNM/ Glasgow : production of partial-and full-double column design

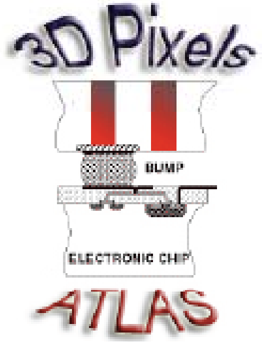
Celeste Fleta Richard Bates, Chris Parkes, David Pennicard – University of Glasgow

Manuel Lozano, Giulio Pellegrini – CNM (Barcelona)



Since 2007 all 3D processing facilities Are jointly pursuing a common goal for the ATLAS IBL

Atlas 3D Pixel Collaboration



- Atlas Upgrade R&D project
  "Development, Testing and Industrialization of Full-3D Active-Edge and Modified-3D Silicon Radiation Pixel Sensors with Extreme Radiation Hardness for the ATLAS experiment"
- 15 institutions
  Barcelona, Bergen University, Bonn University, Calabria University, CERN, Czech Technical University, Freiburg University, INFN Genova, Glasgow University, The University of Hawaii, Lawrence Berkeley National Laboratory, The University of Manchester, The University of New Mexico, Oslo University, SLAC, Stony Brook University, University of Udine, University of Trento
- 4 processing facilities
- Common goal:
  Demonstrate performance requirements and production capabilities for Atlas upgrades

→ VTT joined in November 2009

Performance of the considered 3D designs

Simulations and data shows that
The response of full 3D and
3D-DDTC is very close if the
electrode penetration
stops 25 mm from the surface
Before and after irradiation

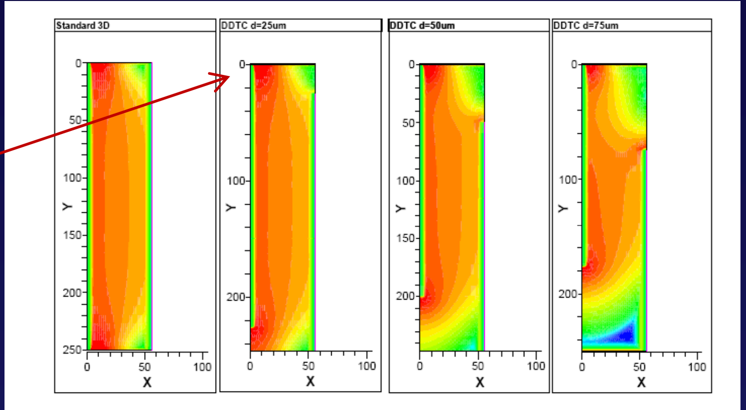


Figure 6.2: Electric field distribution taken from a 2-D cross section of the 3-D structure along the diagonal that connects two columns of opposite doping types. Four cases are here represented: one standard 3D detector and three 3D-DDTC detectors with d spacing of 25, 50 and 75 μm.

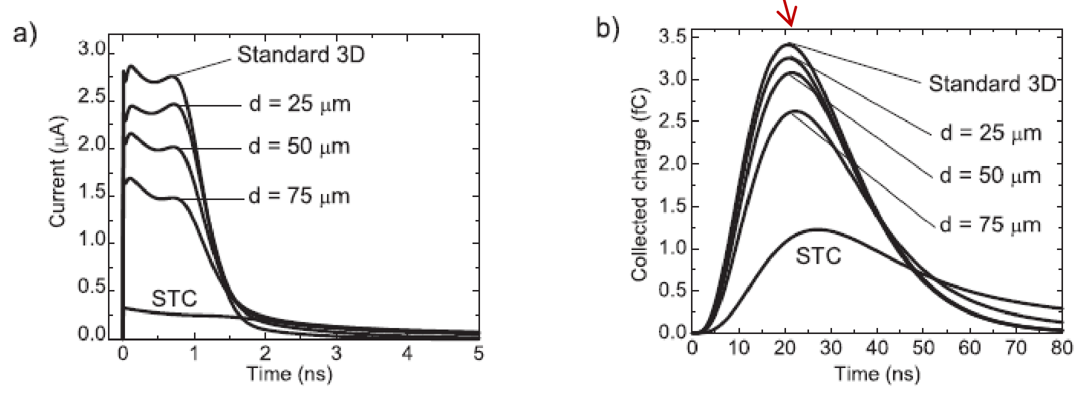
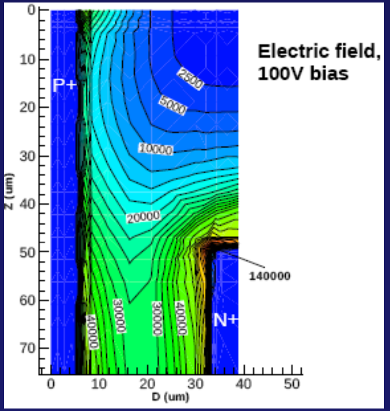


Figure 6.3: Simulated transient signals in 3D detectors of different geometries, biased at 16V, in response to a MIP particle: a) current signal; b) equivalent charge signal at the output of a semi-gaussian shaper with 20ns peaking time.



Simulations (from A. Zoboli
PhD thesis, Trento, March 2009)
D. Pennicard, Glasgow IEEE/NSS 08

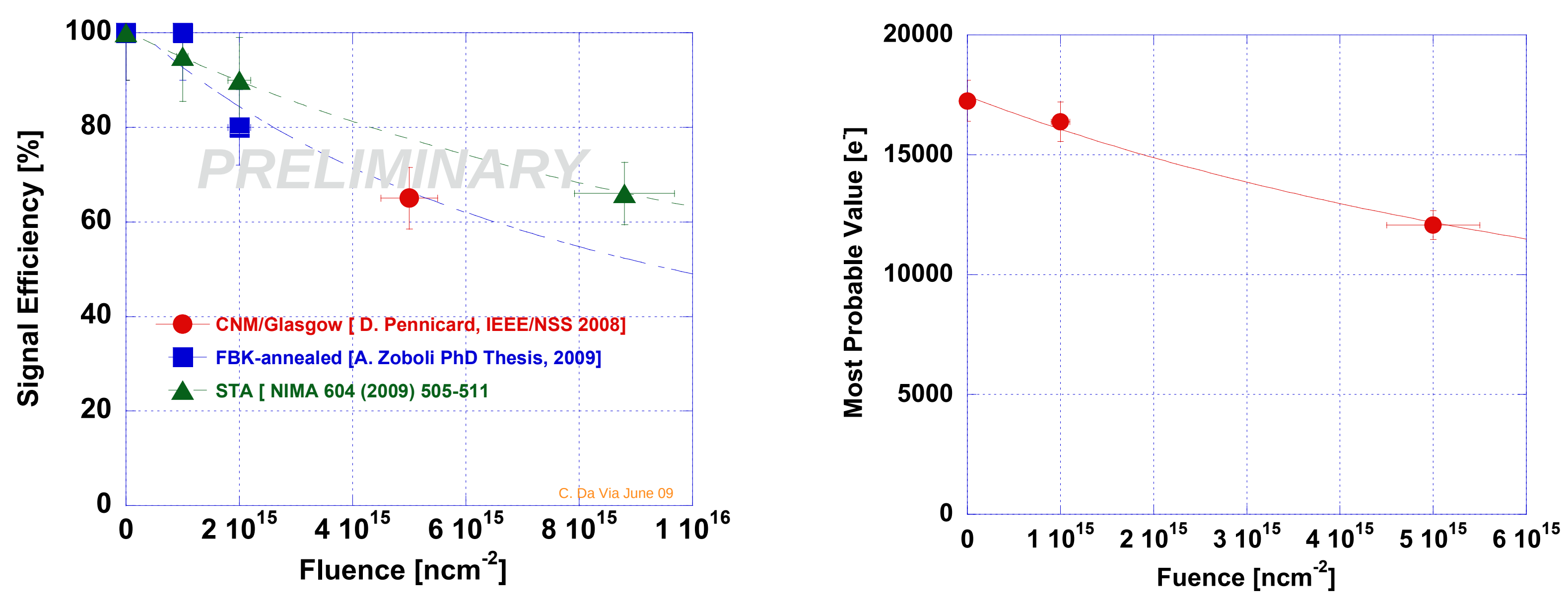
Most probable signal after IBL fluence

Compilation of Stanford, CNM,FBK

LAST SUMMER STATUS

MPS=230μm x 75e$^-$ = 17 250

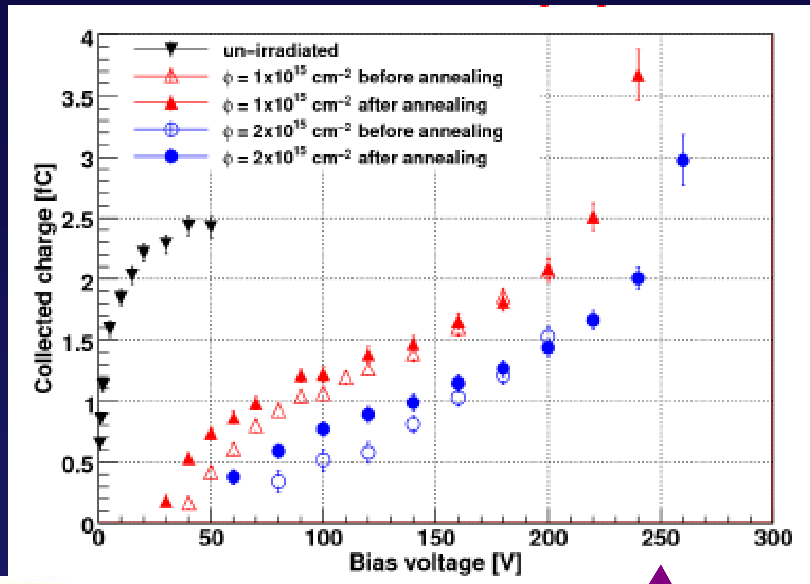
Fluence [ncm^{-2}]	MPS [e$^-$]
0	17250
$1x10^{15}$	16380
$5x10^{15}$	12075



FBK devices measured at Freiburg using MIPs

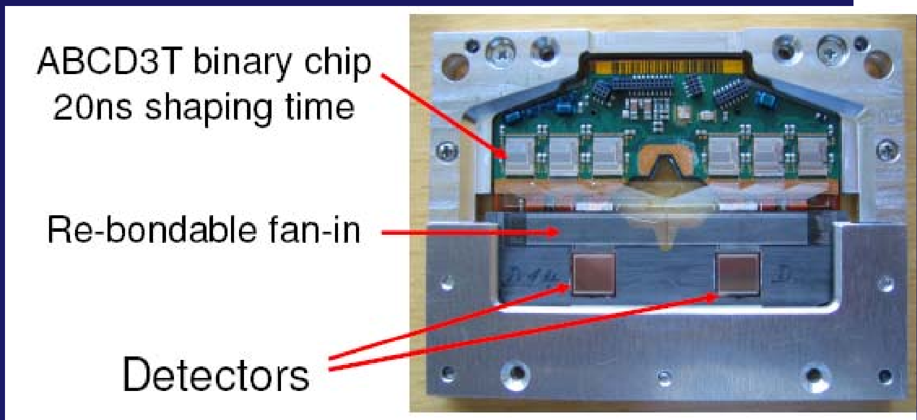
Evidence for multiplication effect (A. Zoboli, Trento)

substrate	n-type
Thickness	300 µm
Read-out column depth	190 µm
Ohmic column depth	160 µm



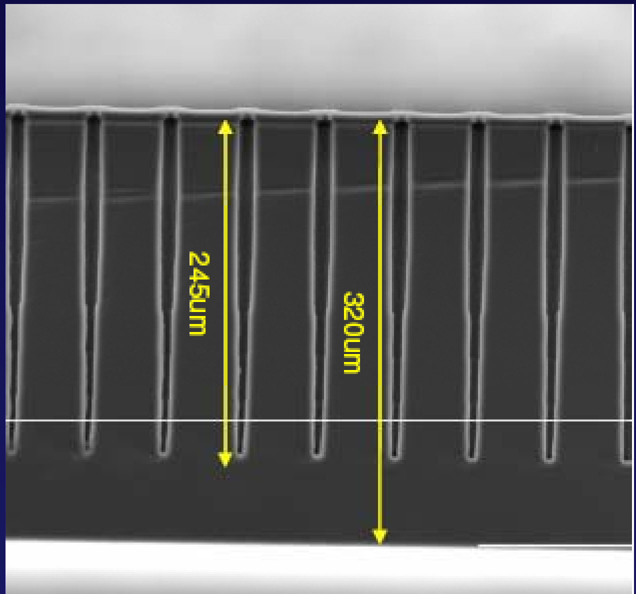
T= -11°C

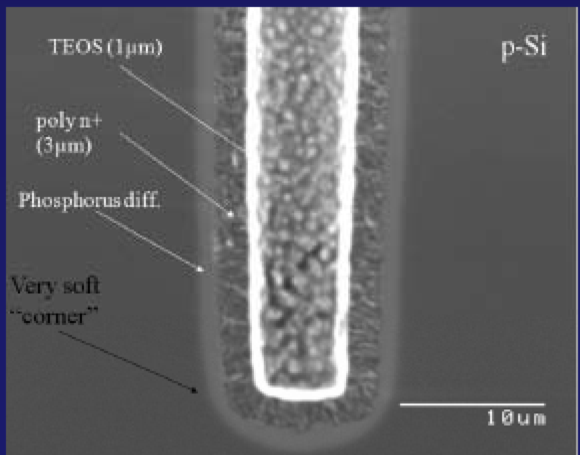
BEFORE AND AFTER ANNEALING
CERN SCENARIO



Latest Irradiation results from CNM 3D sensors

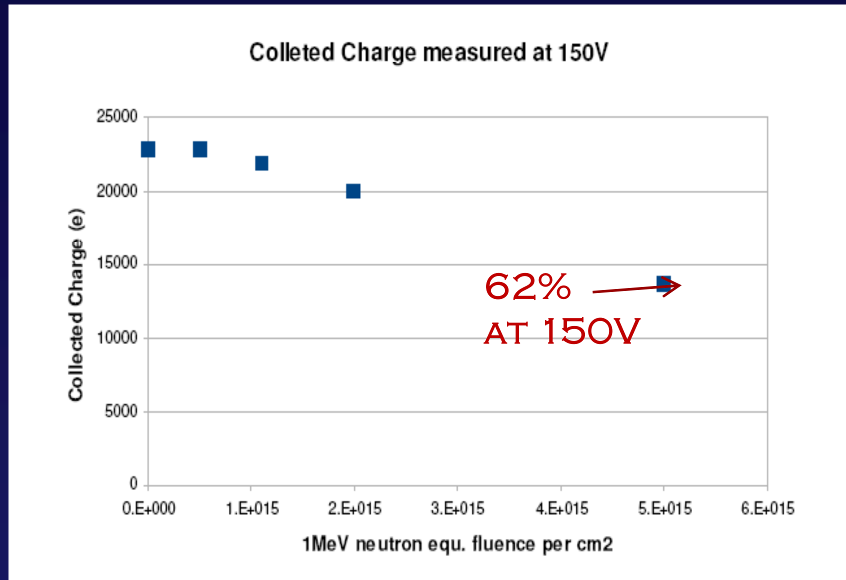
Measured in Glasgow using the ALIBAVA system +**MIPs**
(presented by G. Pellegrini, 3D General meeting 25/9/09)

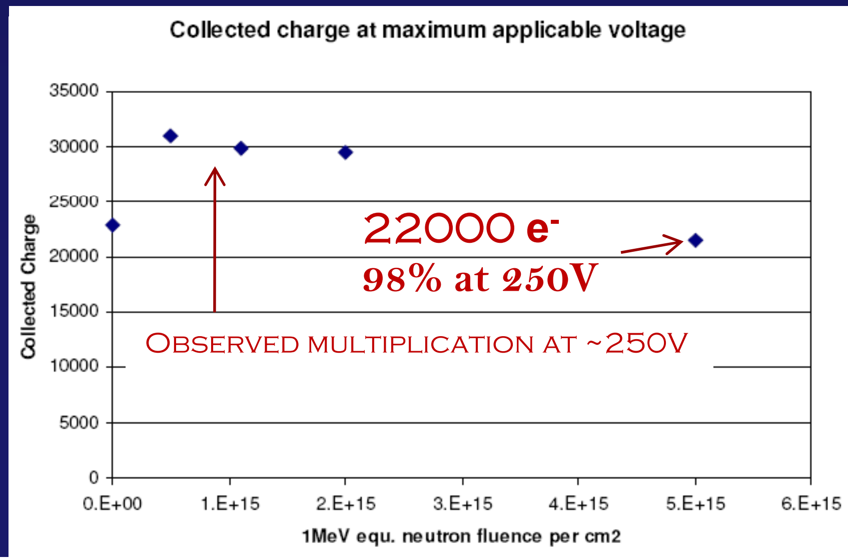




Aspect ratio 25:1

10 µm electrode diameter





Common Floor-Plan Design

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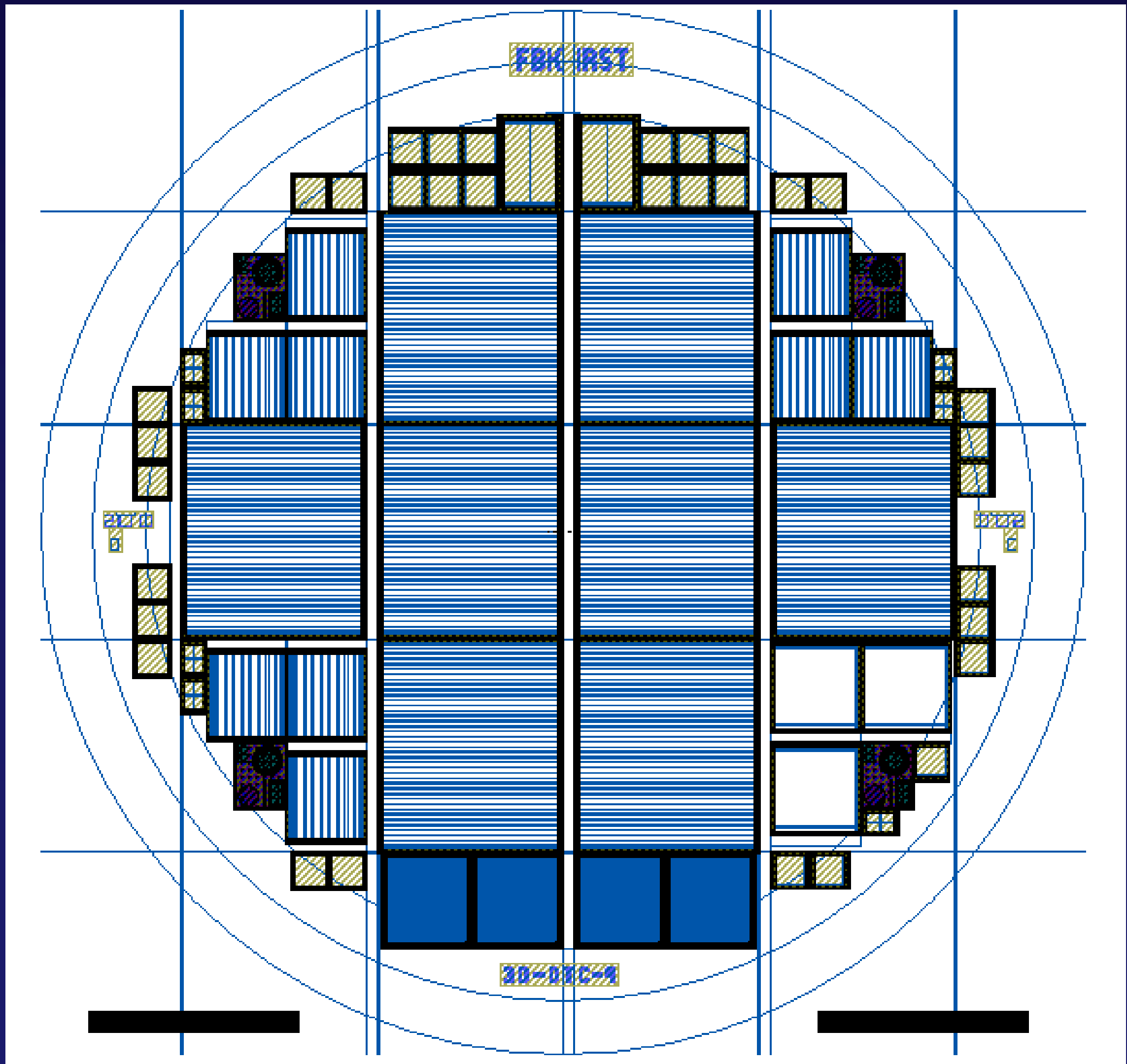
Design by GF Dalla Betta, C. Kenney, A. Kok, G Pellegrini



- 8 x FE-I4
- 9 x FE-I3
- Other test structures

•120 wafers x 8 = 960 FE-I4

Of which:

•480 full 3D with active Edges

•320 double sides with slim fences

And :

1080 x FE-I3

MANCHESTER 1824

Where could 3D Si be applied?

3D features:

Active edges
Low voltage
High speed
Shape adaptation

HEP

❖Vertex
-active edge
-spatial resolution
-radiation hardness

❖Forward Physics

Medical-Biological

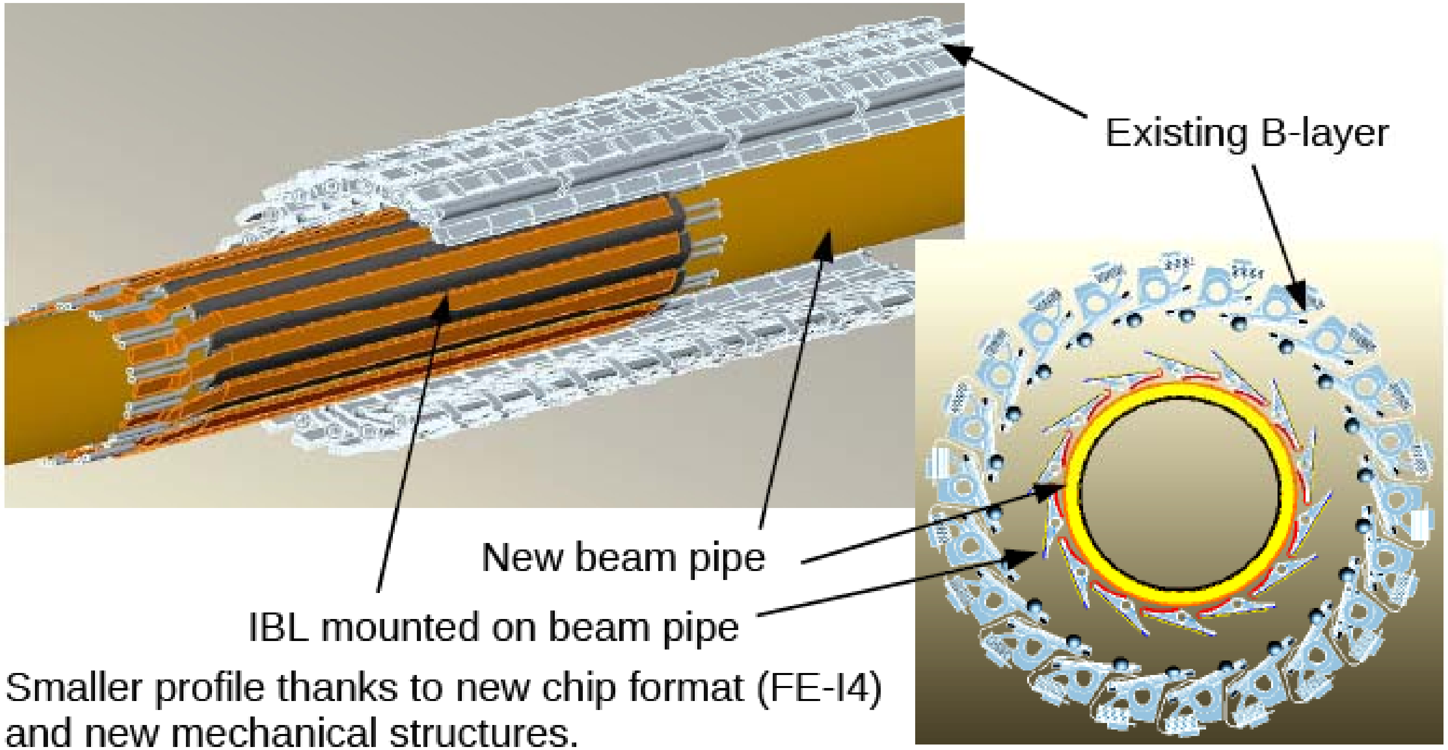
❖Micro structures: endoscopy, dosimetry
❖Large area imagers (mammography, synchrotron)
❖Focal planes (diffracted x-rays)
❖Spectroscopy
❖Edge-on scanned imaging (synchrotron mammography)

❖PET (embedded crystals)
– photo-multiplication

❖TOF-PET (above + speed)

Atlas IBL – timescale 2014-15 (3D is one of the Considered technologies with new-planar and diamond)

IBL design



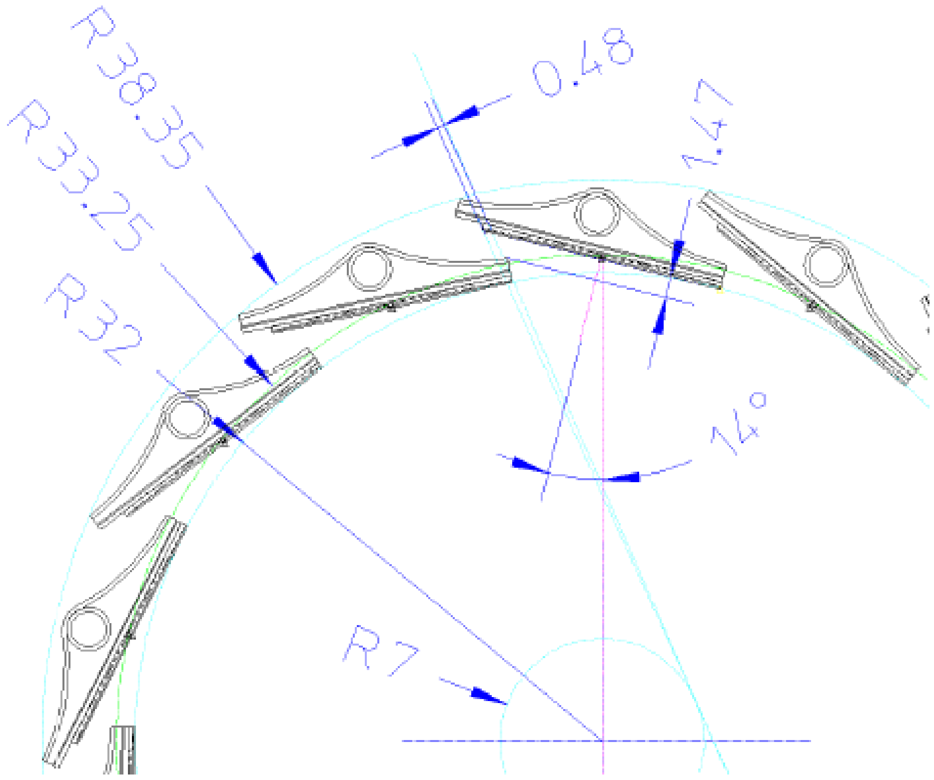
Smaller profile thanks to new chip format (FE-I4) and new mechanical structures.
New sensors with higher radiation tolerance
Smaller pixels and new readout architecture for higher rate operation

MANCHESTER 1824

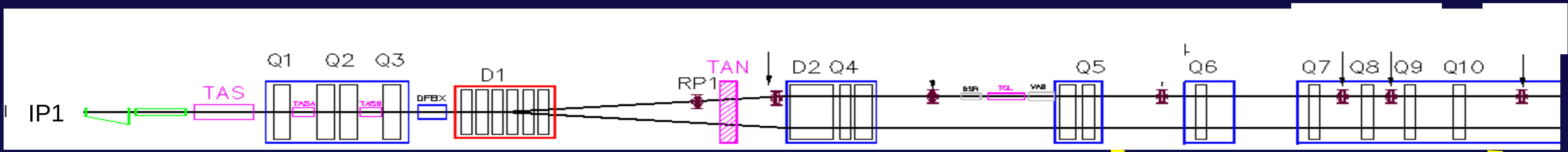
IBL Layout

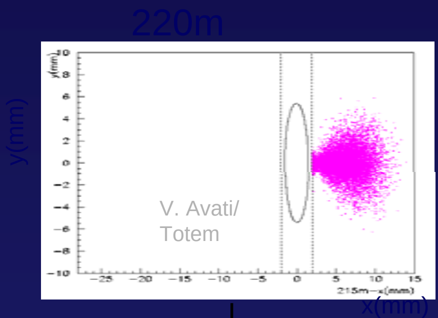
- Several layout under study: Converging on “reverse turbine” layout with 14 staves as baseline layout for engineering studies and TDR:
- Work on others continues at slower pace

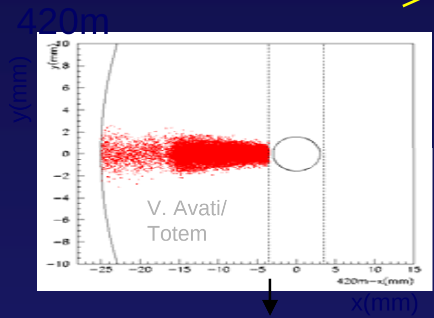
- 14 staves – layout parameters
  - IR 32mm
  - OR (structure) 38.35mm
  - Sensor Radius 33.25mm
  - Sensor Tilt Angle 14 degrees
  - Nominal Internal Clearance ~1.47mm
- Proposed tolerances for the stave assembly
  - Geometry tolerance (+/- 0.1mm)
  - Assembly tolerance (+/- 0.15mm)
  - Total tolerance range ½ mm



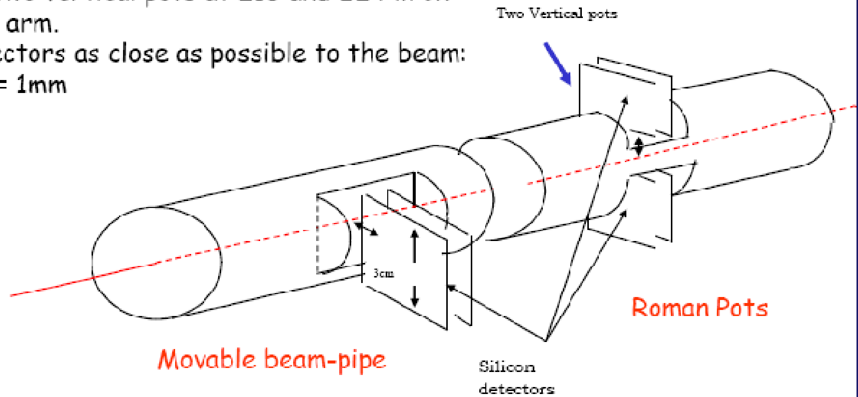
ATLASFP – 2011-2012
Forward Detectors = use LHC beam-line as a spectrometer
Proton energy loss results in proton trajectory horizontal departure

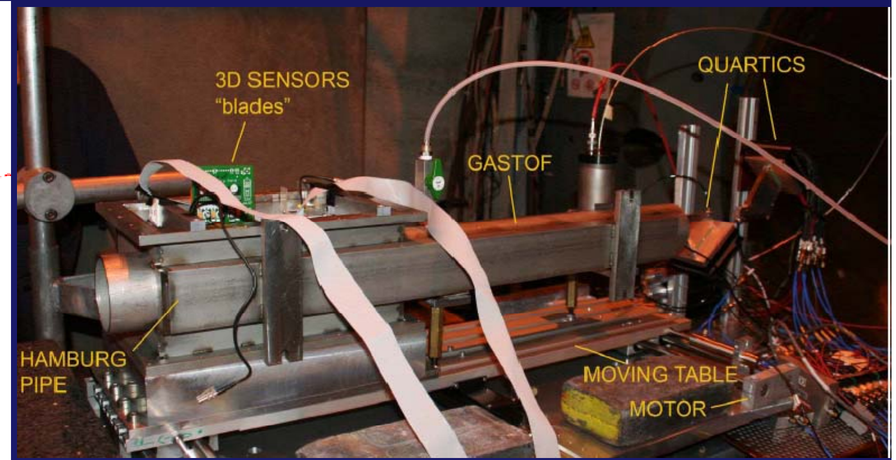






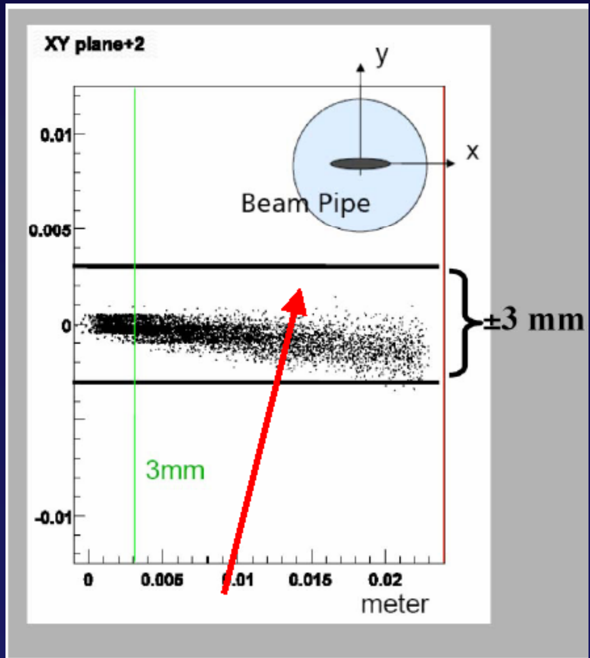
Horizontal detectors in a movable beam-pipe and two vertical pots at 216 and 224 m on each arm.
Detectors as close as possible to the beam:
10σ = 1mm



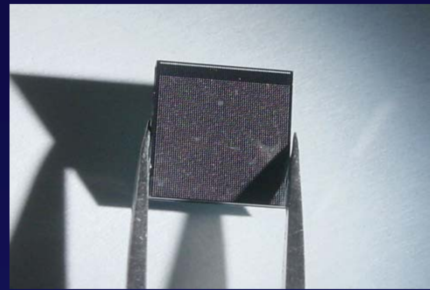


Tracking Detectors: at 420m 25x5mm²

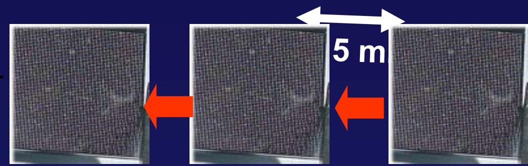
3D silicon with active edges



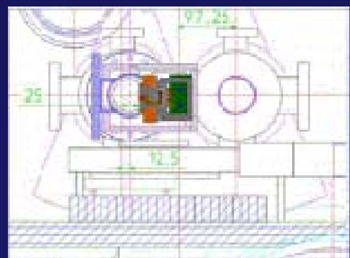
7.2 mm x 24mm (7.2 x 8 mm² sensors)

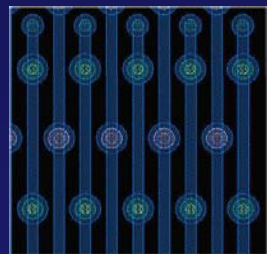


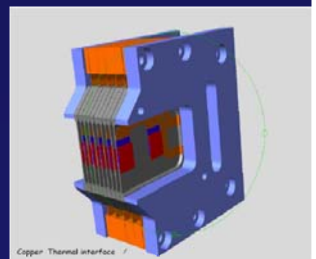
50µmx400µm



R.Thompson
S.Kolya/Manchester







LHC EXPERIMENT	DIMENSIONS	RO SIGNAL	TRIGGER	BUFFER
ATLAS	50x400 µm² 7.2x8mm²	binary and time over threshold	Internal fast-OR	2 - 6.4µs 40 MHz

$$\sigma_{x,y} = \frac{50\mu m}{\sqrt{12}} = 14.4\mu m$$

Operating Voltages

Cinzia Da Viá , the University of Manchester-UK. Hamburg 9 April 2010

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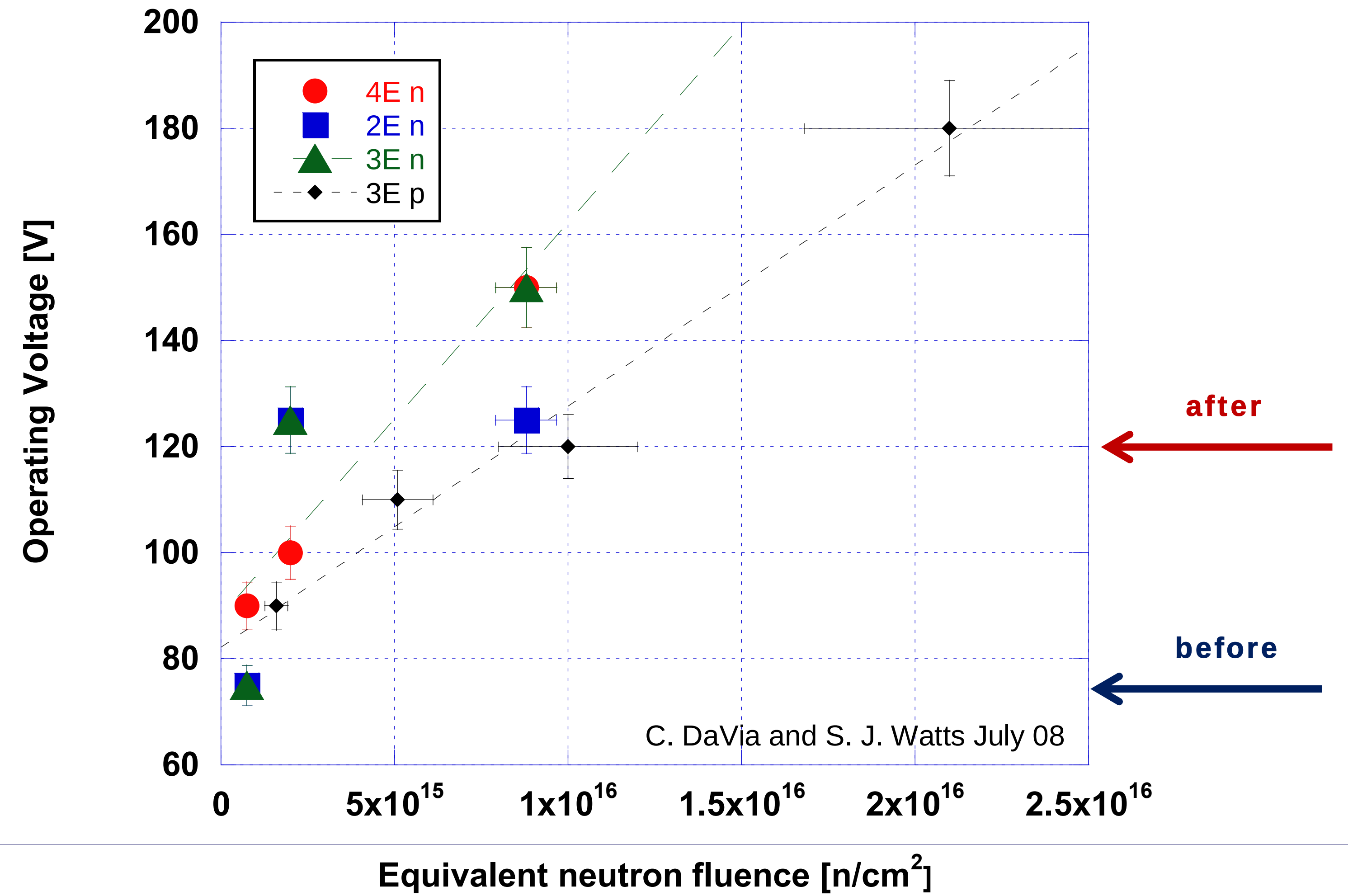
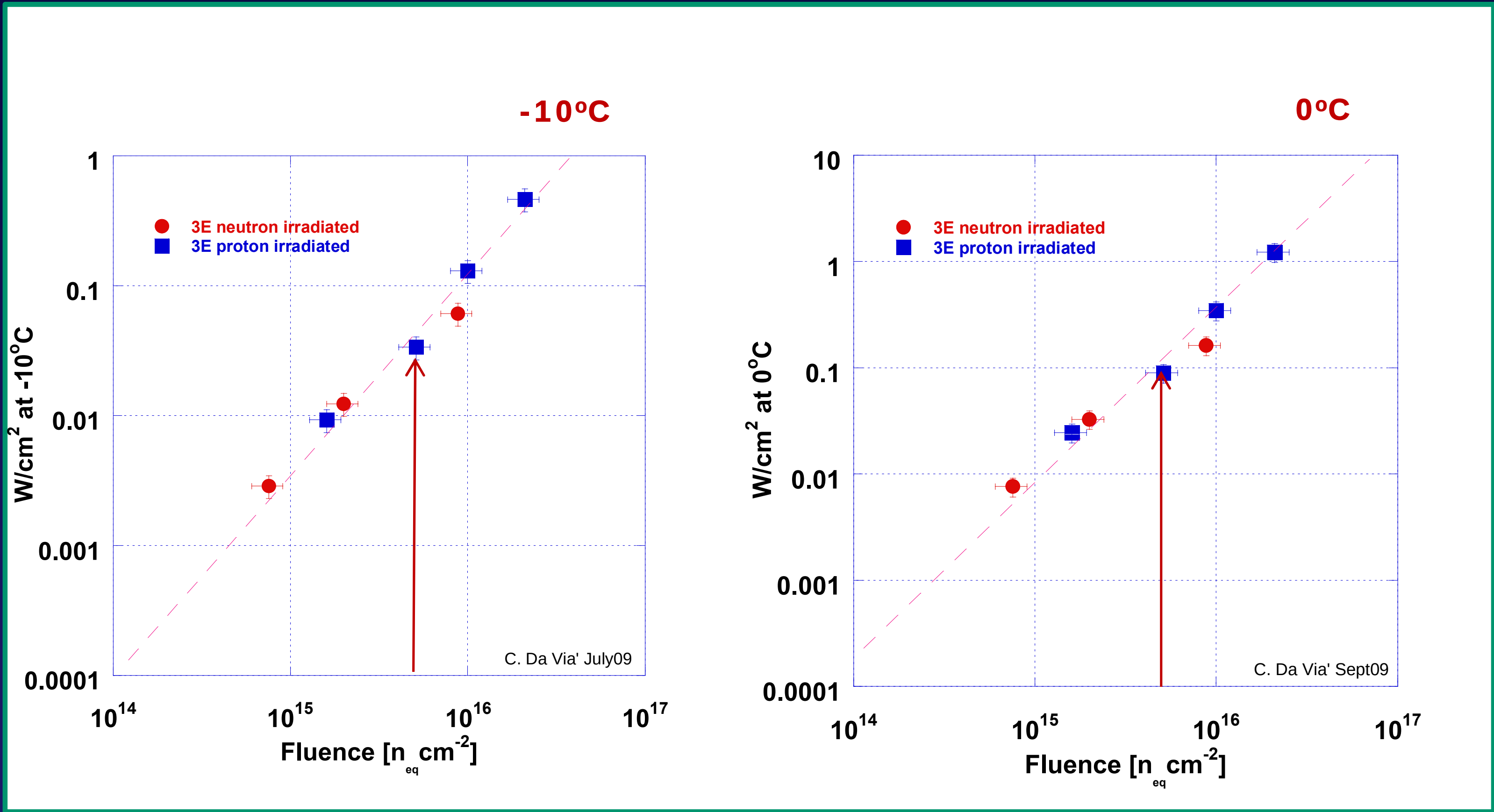


Power dissipation

Current depends on

$T^2 exp(-1.12/2kT)$



-1

T [ºC]	Fluence [ncm⁻²]	Power [Wcm⁻²]
-10	$5x10^{15}$	0.034
0	$5x10^{15}$	0.089

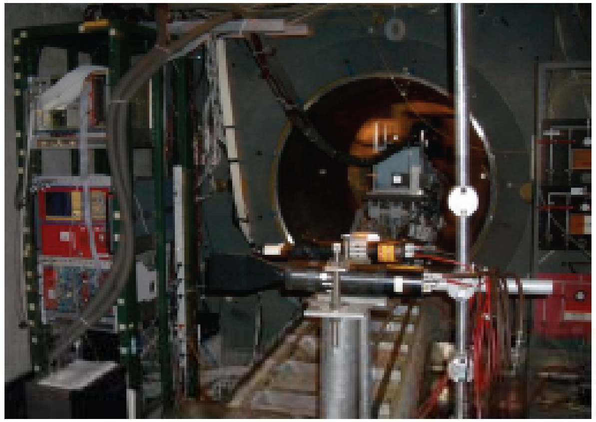
Recent results: October Test Beam

07 October – 02 November 09

PER OLA HANSSON, SLAC
SLIDES FROM VIENNA CONFERENCE

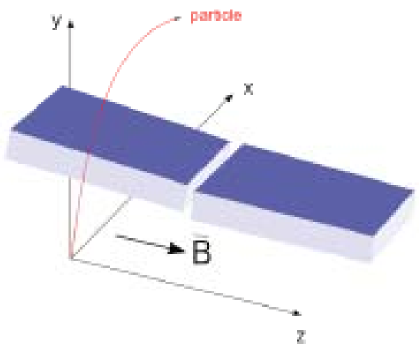
MANCHESTER 1824

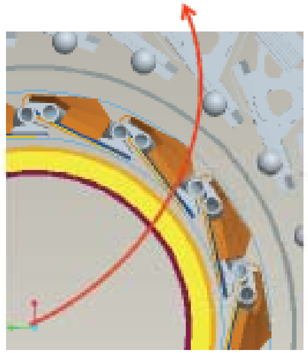
J. Balbuena, C. Barrera, E. Bolle9, M. Borri12, M. Boscardin15, M. Chmeissani, G.-F. DallaBetta14, G. Darbo13, C. DaVià7, B. DeWilde11, S. Dong10, O. Dorholt9, S. Fazio3, C. Fleta, C. Gemme13, M. Giordani, H. Gjersdal9, P. Grenier10, S. Grinstein6, J. Hasi10, K. Helle, F. Huegging2, P. Jackson10, C. Kenney10, M. Kocian10, I. Korolkov, A. La Rosa4, A. Mastroberardino3, A. Micelli, C. Nellist, P. Nordahl9, F. Rivero12, O. Røhne9, H. Sandaker1, D. Silverstein10, K. Sjøbæk9, T. Slaviec5, J. Stupak11, I. Troyano, J. Tsung2, D. Tsybychev11, N. Wermes2, C. Young10

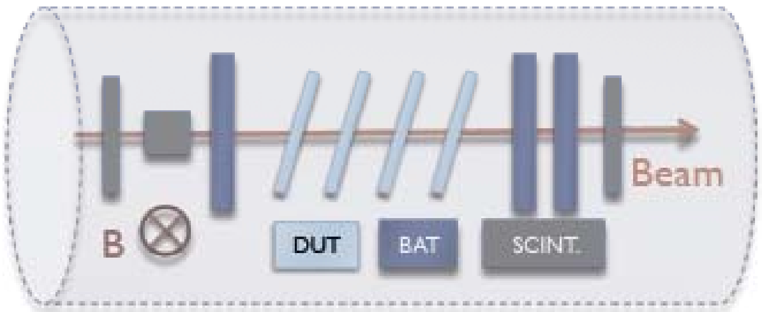


- CERN North Hall
  - 180GeV pions from CERN SPS target
- Bonn Analysis Telescope (BAT)
  - Two-sided Si micro-strips (50um pitch)
  - Analog read-out; integrated DAQ & online DQ
- Trigger: two scintillators (+ veto)
- Morpurgo large superconducting dipole
  - 1.57T measured at DUT's

- Driven by Atlas IBL layout and requirements
  - 2T solenoid magnetic field in beam direction
  - Momentum measurement in transverse direction $r\times\phi$
- Sensor tilt angle between 10-25° degrees







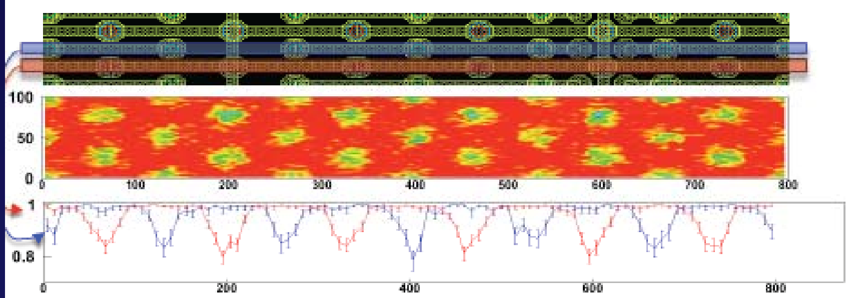
Tracking efficiency

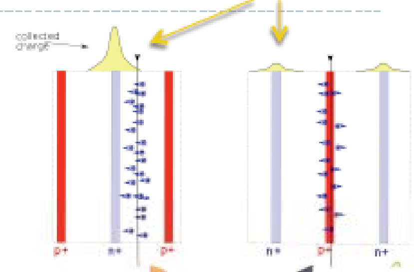
Per Ola Hansson, SLAC
Slides from Vienna conference

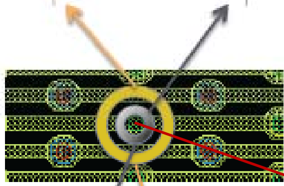
J. Balbuena, C. Barrera, E. Bolle9, M. Borri12, M. Boscardin15, M. Chmeissani, G.-F. DallaBetta14, G. Darbo13, C. DaViá7, B. DeWilde11, S. Dong10, O. Dorholt9, S. Fazio3, C. Fleta, C. Gemme13, M. Giordani, H. Gjersdal9, P. Grenier10, S. Grinstein6, J. Hasi10, K. Helle, F. Huegging2, P. Jackson10, C. Kenney10, M. Kocian10, I. Korolkov, A. La Rosa4, A. Mastroberardino3, A. Micelli, C. Nellist, P. Nordahl9, F. Rivero12, O. Røhne9, H. Sandaker1, D. Silverstein10, K. Sjøbæk9, T. Slaviec5, J. Stupak11, I. Troyano, J. Tsung2, D. Tsybychev11, N. Wermes2, C. Young10

Signal size

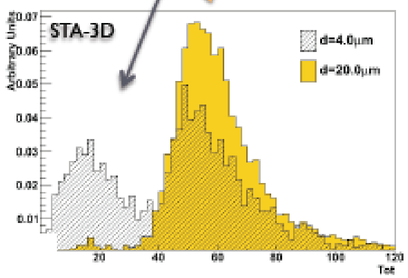
- Electrodes are parallel to track at normal incidence
- Striking feature of 3D design



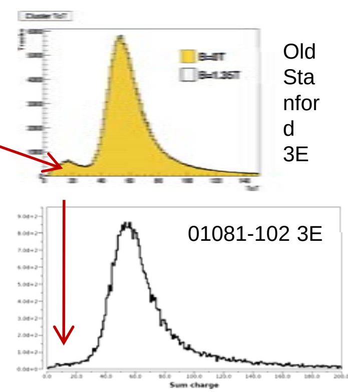


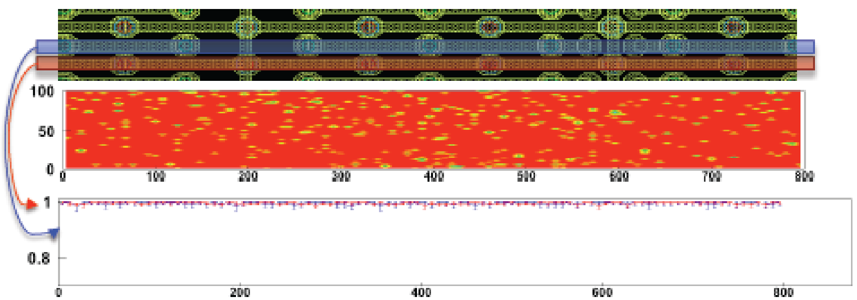


- Holes etched and filled (DRIE)
  - Doped polysilicon or passivation only
- Study charge collection in electrode region
  - Measure 40-60% signal loss J. Hasi, PhD Thesis
- Novel electrode fillings produced; analysis ongoing

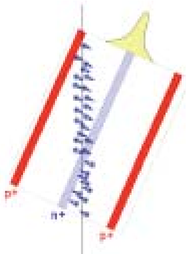


New electrode treatment shows encouraging evidences
Test beam data and X-ray data being analysed





At 15°

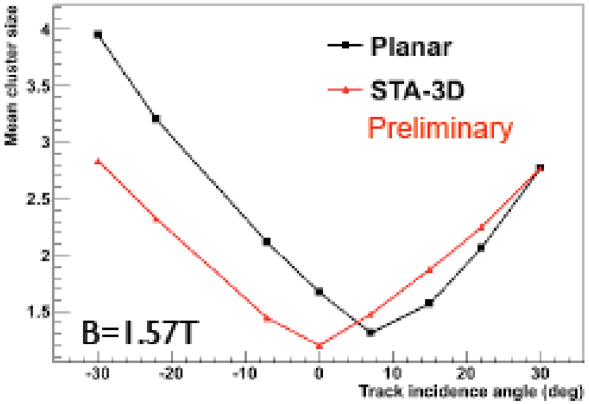


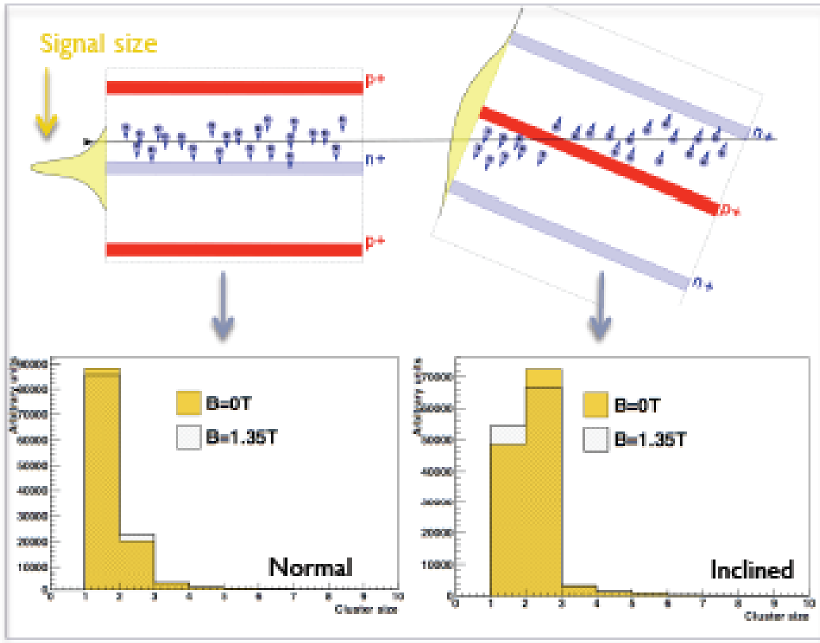
Magnetic field ON

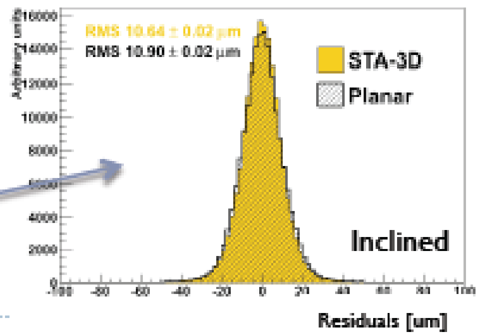
	0°	15°
TA-3D	96.3	99.6
BK-3E7	98.9	99.8
Planar	99.8	99.8

Charge sharing, tracking resolution and Lorentz effect

- Charge sharing between pixels is important
  - Cluster size ~ tracking resolution
  - Signal size ~ operational characteristics after irradiation





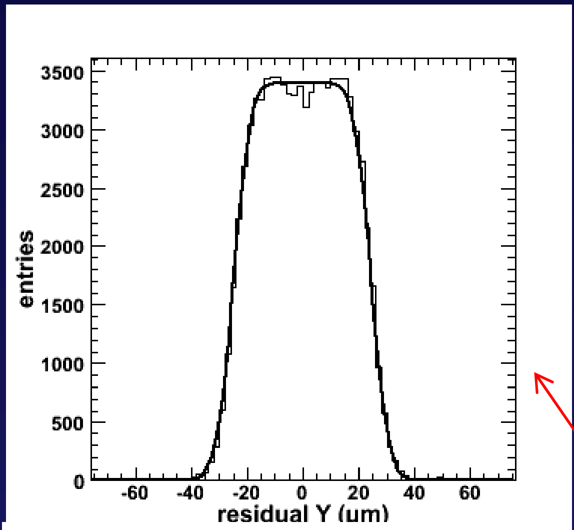


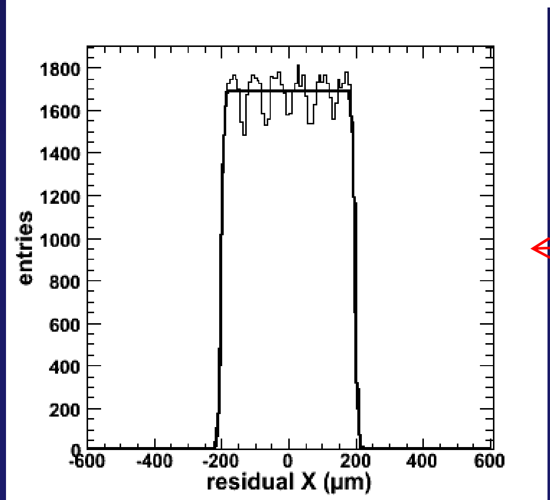
$\sigma = 10.9\ \mu m$

Track resolution not de-convoluted

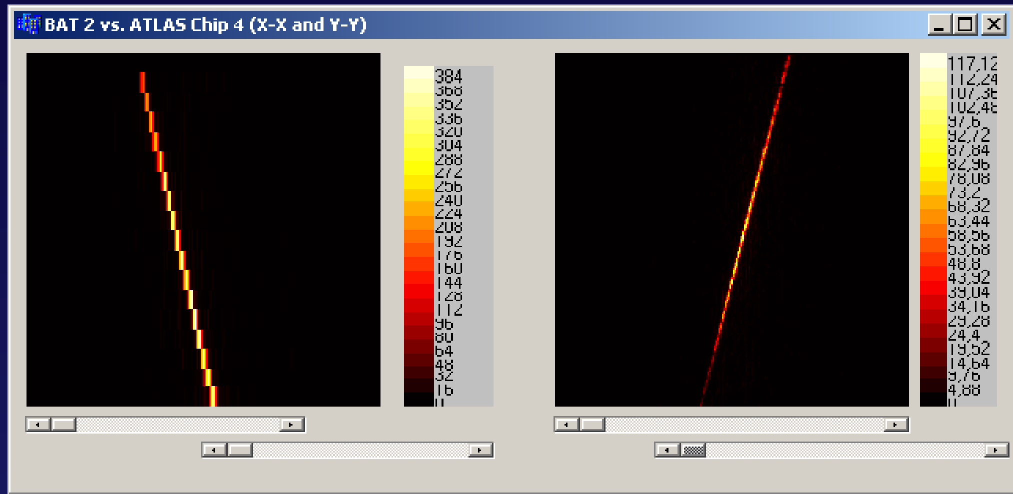
- Tilt angle important for resolution
- Measured resolution similar to planar sensor
- 3D sensors insensitive to magnetic field

Tracking performance 3E configuration





Correlation with telescope planes



50μm direction:
width (49.4±0.1)μm, sigma (4.8±0.1)μm

400μm direction:
width (398.0±0.3)μm, sigma (6.4±0.2)μm

M. Mathes1, C. DaVia2, J. Hasi2, S. Parker3, M. Ruspa4, L. Reuen1, J. Velthuis1, S. Watts2, M. Cristinziani1, K. Einsweiler4, M. Gracia-Sciveres4,K. Kenney5, N. Wermes1

1Bonn, Germany
2Manchester University, UK
3University of Hawaii, USA
4LBL, Berkeley, USA
5Molecular Biology Consortium, Stanford, USA

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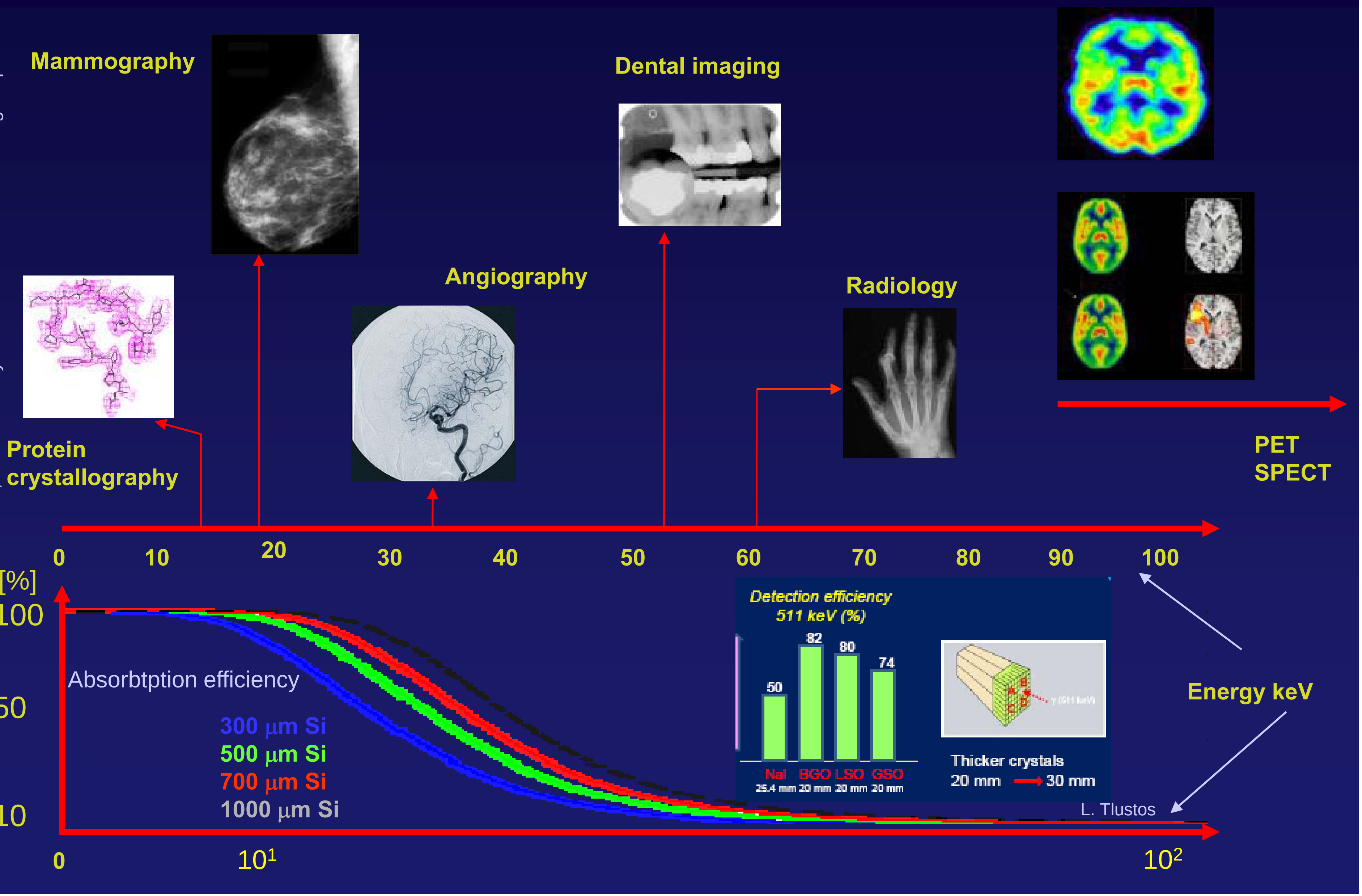
X-ray energy of the most common medical and biological applications



Cinzia Da Viá , the University of Manchester-UK. Hamburg 9 April 2010

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Detection strategy

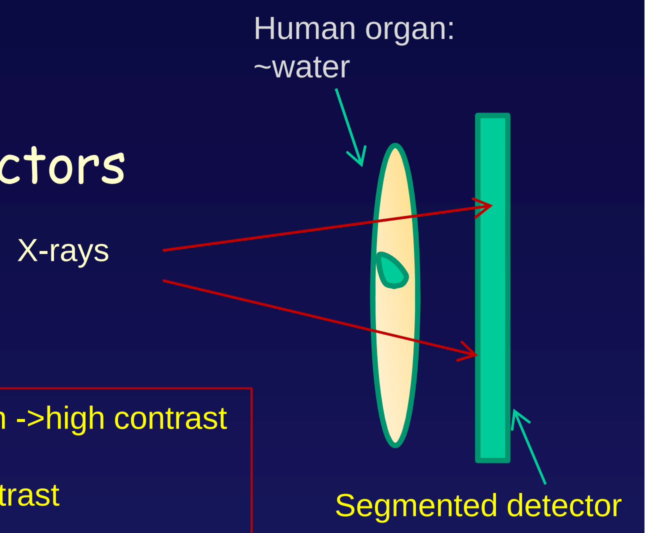
Low energy: Thick silicon or high Z semiconductors

Direct detection: high spatial resolution

Example
Hybrid detector
semiconductor + MEDIPIX

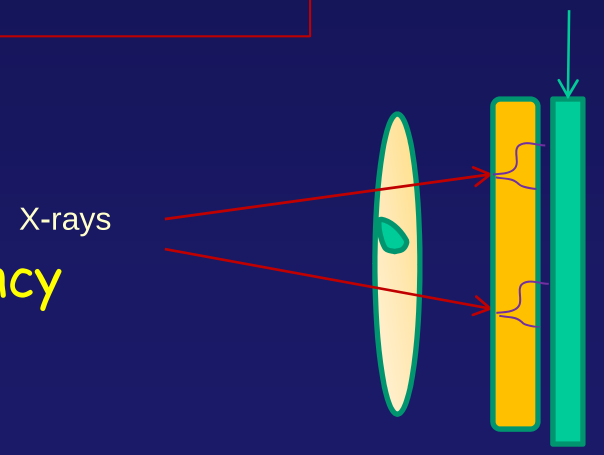
Micro-calcification ->high contrast

Cysts -> low contrast



High energy: crystals +photo detector
or high Z semiconductors

Indirect detection : high detection efficiency but degradation of spatial resolution



scattering, diffusion
Precision degradation
But high detection
Efficiency → low dose to the patient

Direct detection: MEDIPIX + Thick Si or high Z

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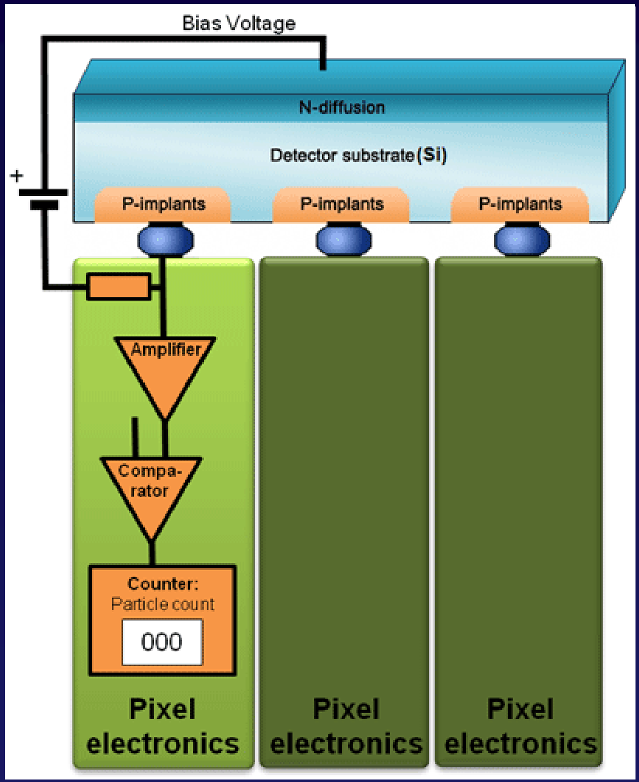
See talk by M. Campbell the 23rd of April

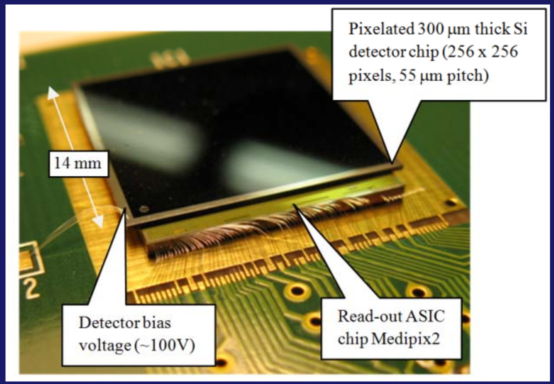


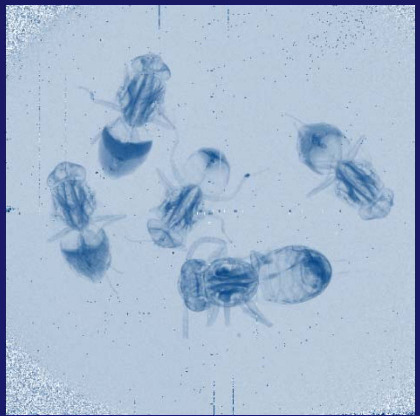
Hybrid structure sensor and electronics a re processed separately. Bump-bonds provide t he electrical connection

❖Medipix 2 and Medipix 3 are collaborations between number of European Universities and Research Institutes.

❖The device consists of a pixellated sensor chip and a read-out chip containing the amplifier, discriminators and counter(s) for each pixel.

❖Applications include Mammography, autoradiography and synchrotron radiation applications

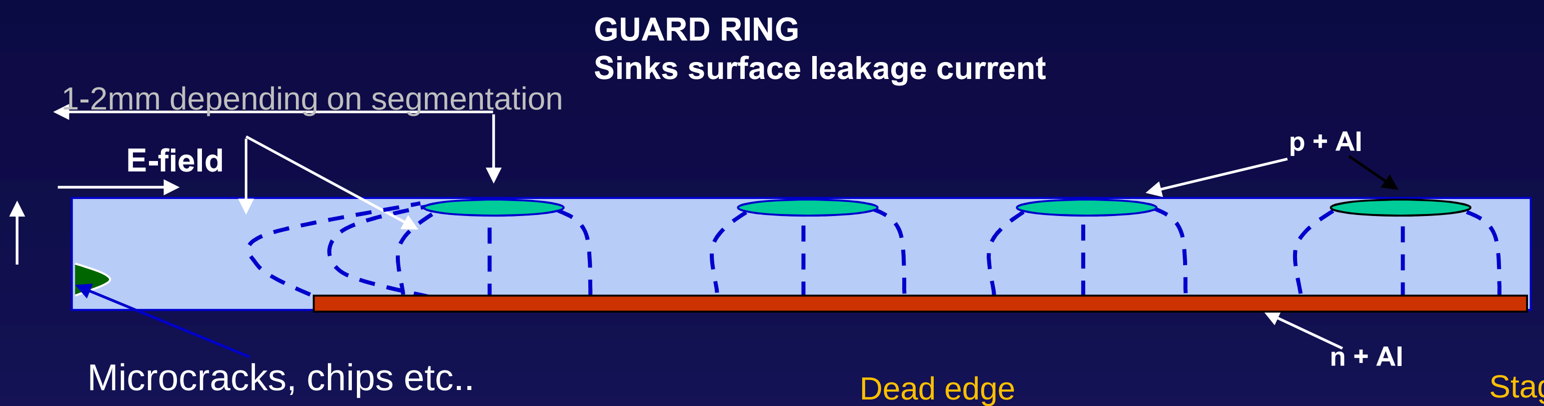




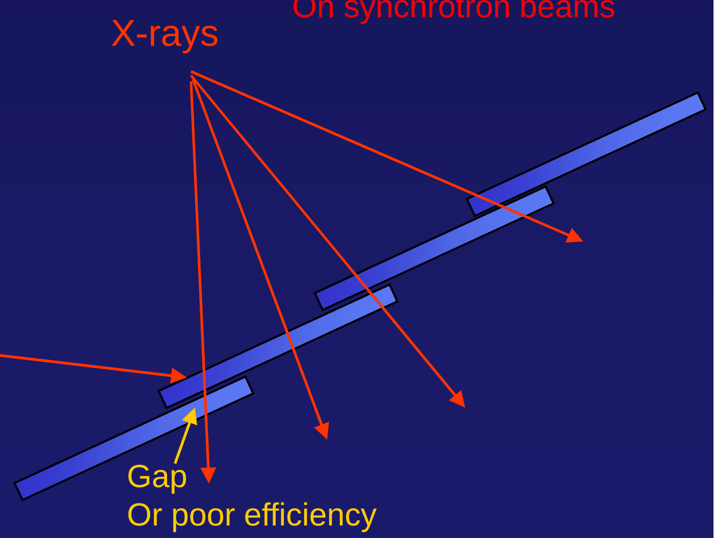
Parameters of Medipix2:

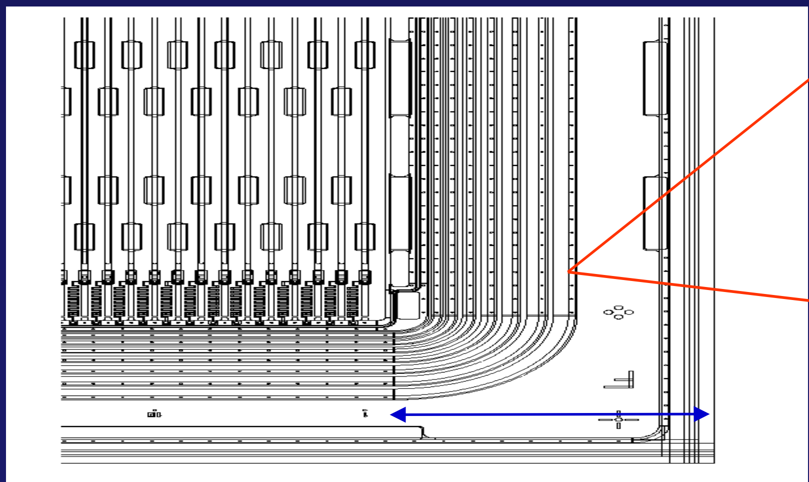
Pixels: 256 x 256
Pixel size: 55 x 55 mm2
Area: 1.5 x 1.5 cm2

Reducing the dead volume in medical imaging: →active edges



Edge-on x-ray imager
Example mammography
On synchrotron beams

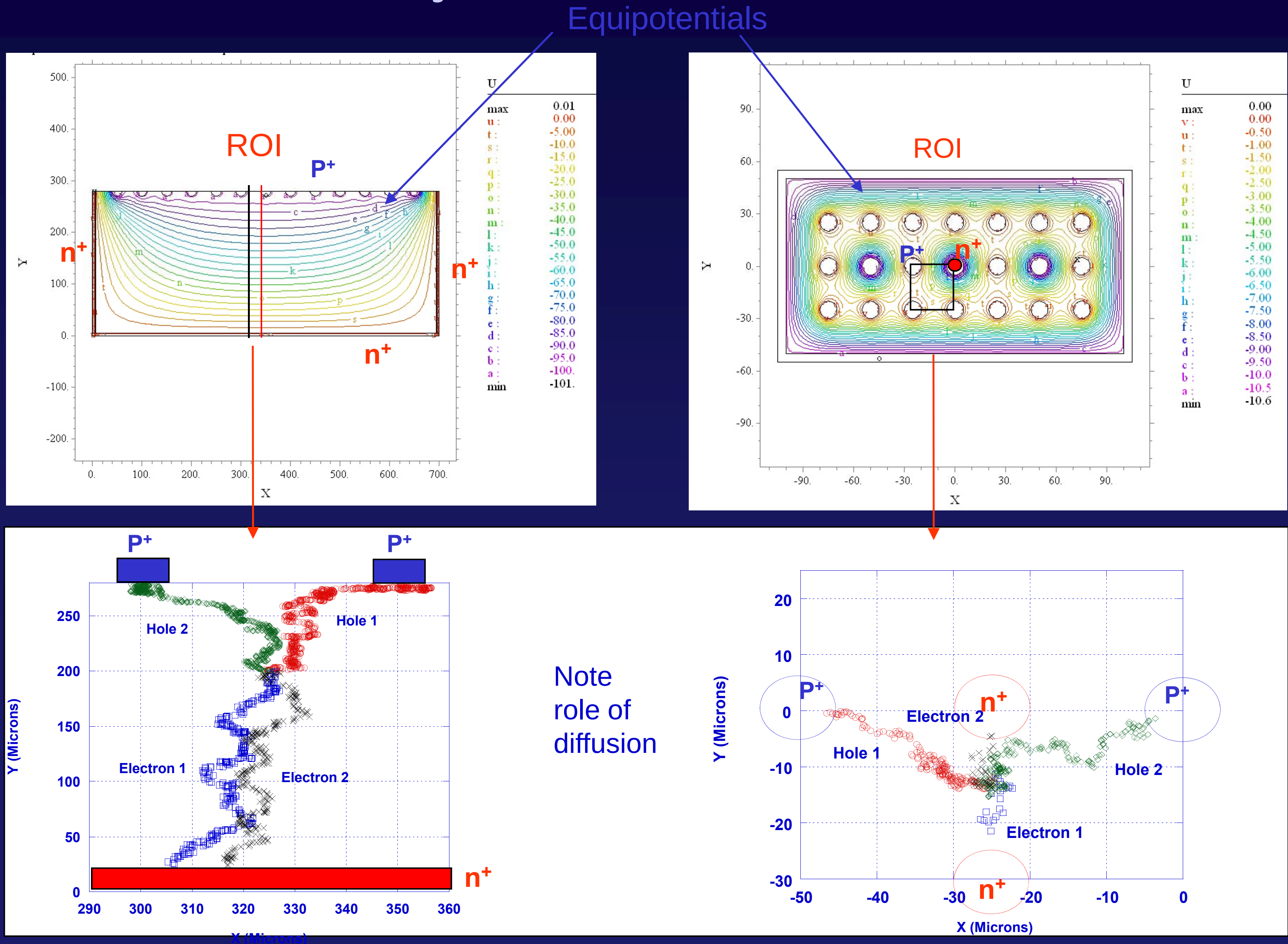




ATLAS microstrips guard rings ~1mm

Spectroscopy

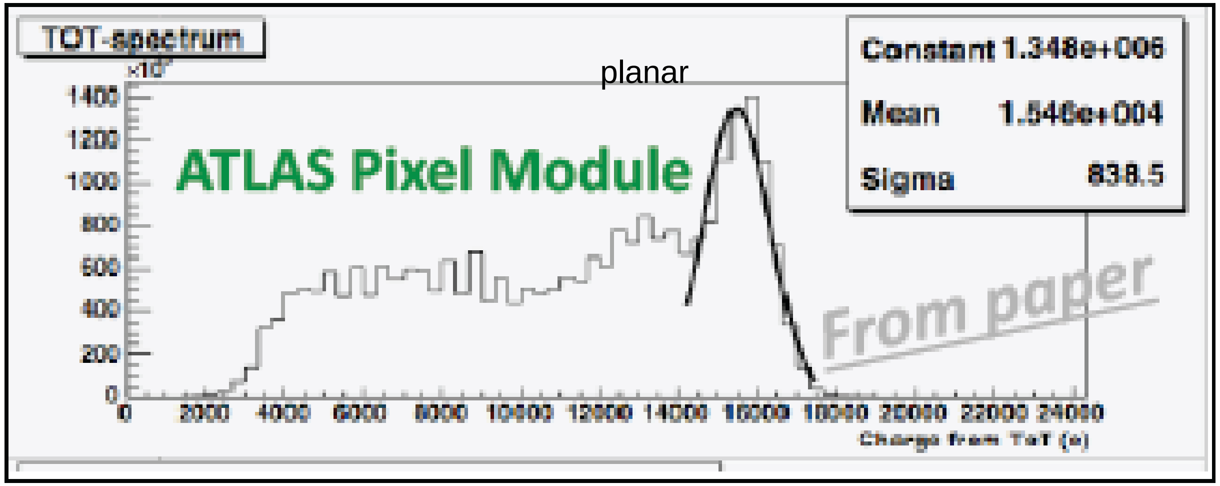
CHARGE SHARING – PLANAR vs 3D – p-type, p-on-p 50 mm pitch
ROI = Region of interest

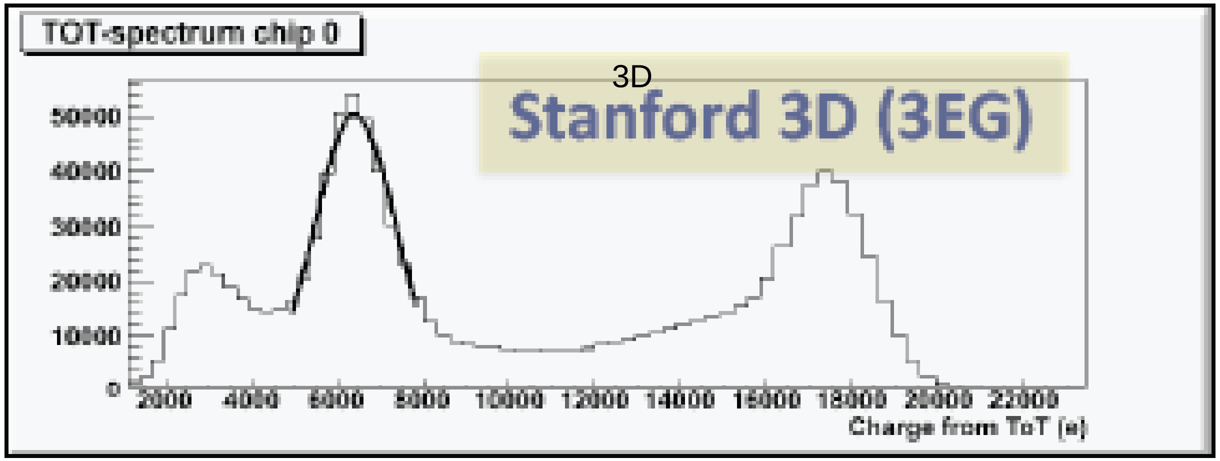


Charge sharing:

^{241}Am .

Measurements A. La Rosa/CERN





Measurements
By A. La Rosa
CERN

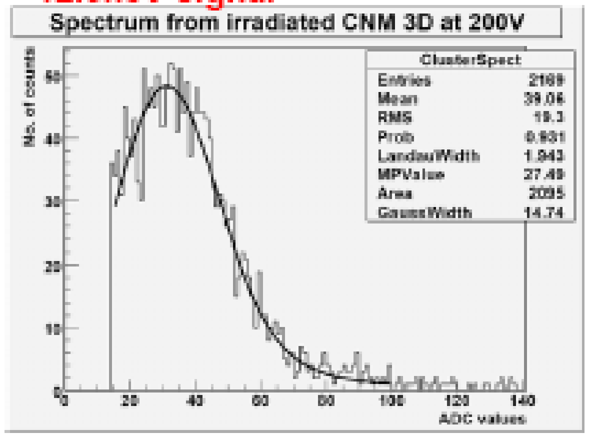
CNM-Freiburg-Glasgow

Freiburg

Testing in Glasgow/Freiburg

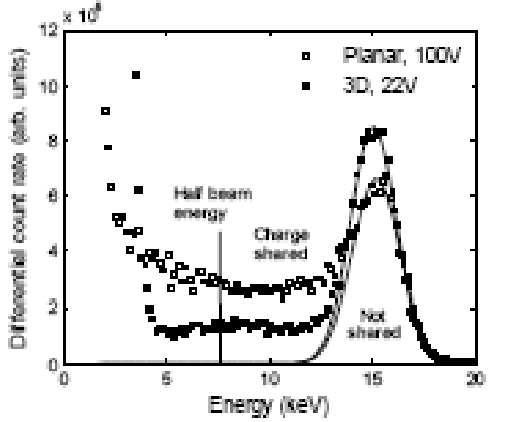
$\Phi = 5 \times 10^{15}$ 1MeV $n_{equ}cm^{-2}$

12.8keV signal



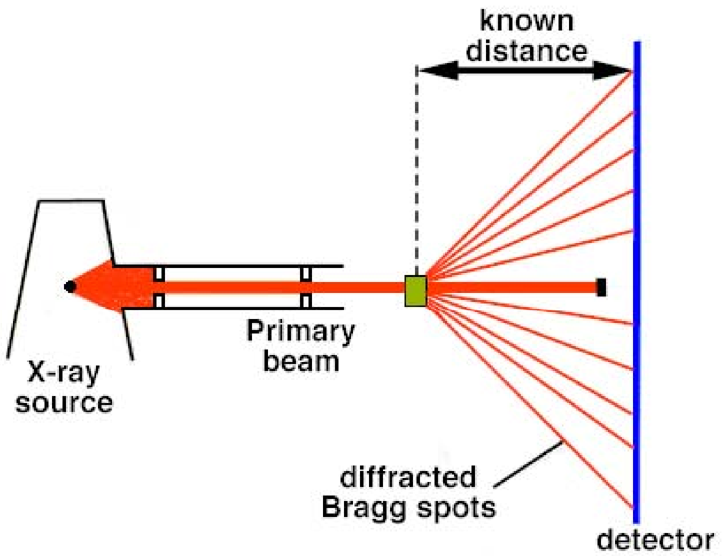
- **Strip detector with LHC readout electronics, hole pitch 80um in x and y**
  - Easier to test functionality of 3D detectors
  - MIP CCE lab tests with LHCb analogue readout and recently CMS APV testbeam
  - Irradiation programme planned with new devices including effect of annealing on signal
- **ATLAS pixel readout**
  - Have 48 ATLAS pixel devices
  - In discussion to Selex for bump bonding
  - Tests to be done with UK/CERN TurboDAQ system
    - Glasgow doesn't have a system at present
- **Medipix2 pixel detectors**
  - X-ray detection
  - Raster scan of micron spot sized Synchrotron beam to study position response
  - Demonstrated behaviour of unirradiated p-column n-bulk pixel detector
  - n-column p-bulk to be bonded and tested soon

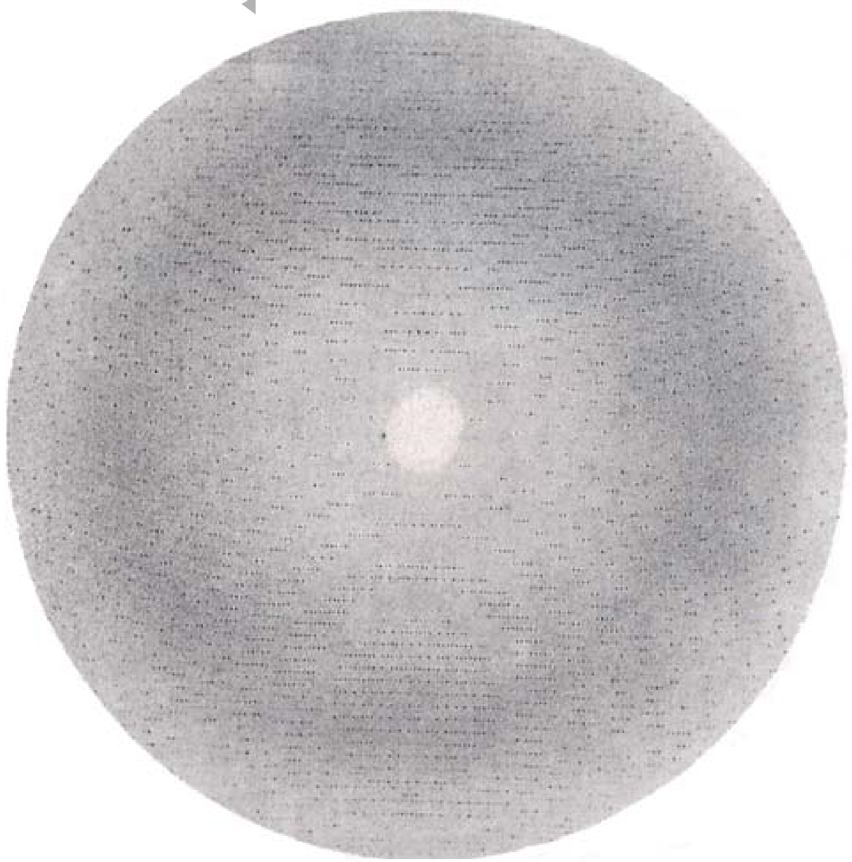
15keV X-ray spectrum



Protein crystallography: 3DX project (MBC)

The Diffraction Pattern of Discrete Bragg Spots is Captured by the Detector





Example of reconstructed structure: Enzyme Active Site (from E. Westbrook MBC)

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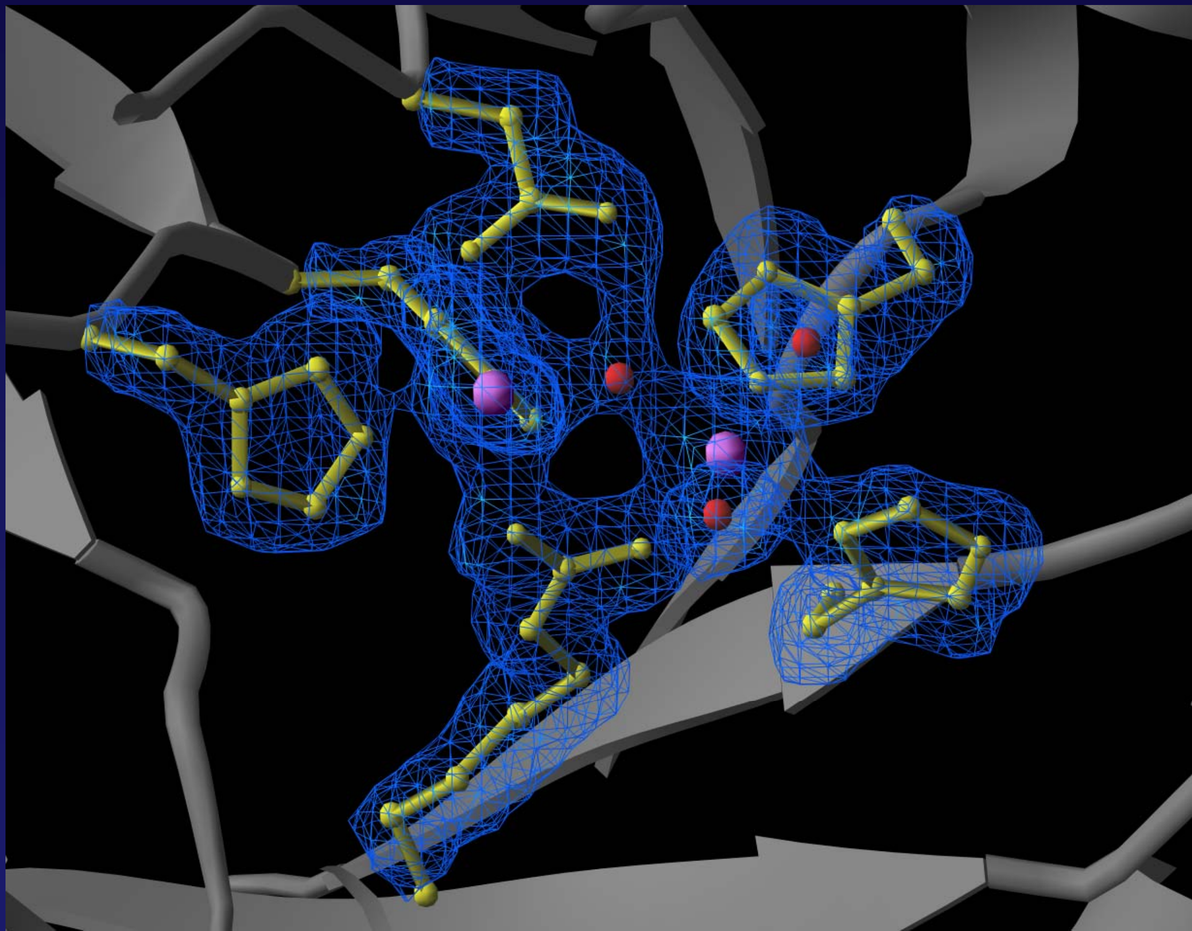
- ***Pseudomonas diminuta* phosphotriesterase**: **This enzyme catalyzes the hydrolysis of organophosphorus pesticides and nerve agents. Its crystal structure is being studied by Hazel Holden's research group at the University of Wisconsin, Madison (see PDB file 1DPM).**
- **Purple atoms: zinc**
- **Red: bound water**
- **Yellow: side chains**
- **1.8 Å resolution map,**

- **Present detectors:**
- **CCDs. Time resolution ms**

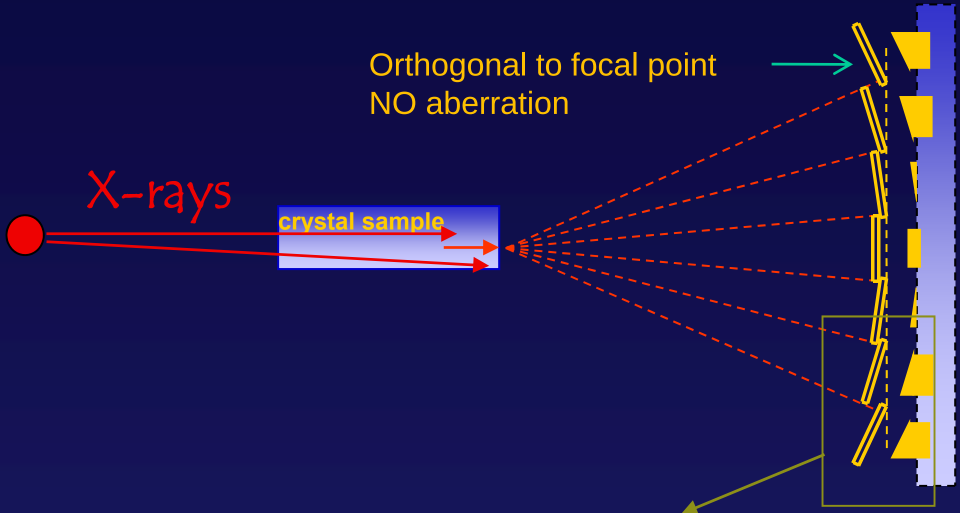
- **Needs faster ASIC for protein folding**

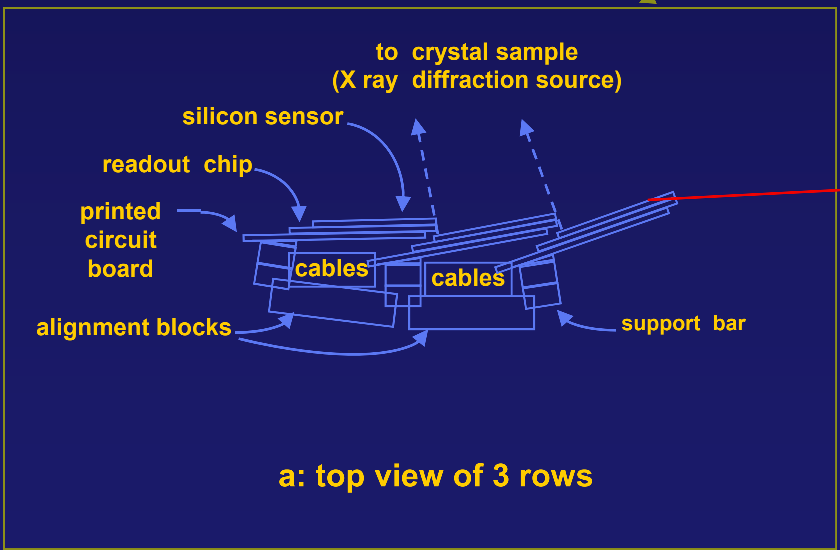


3D pixel detectors x-ray setup (3DX project)

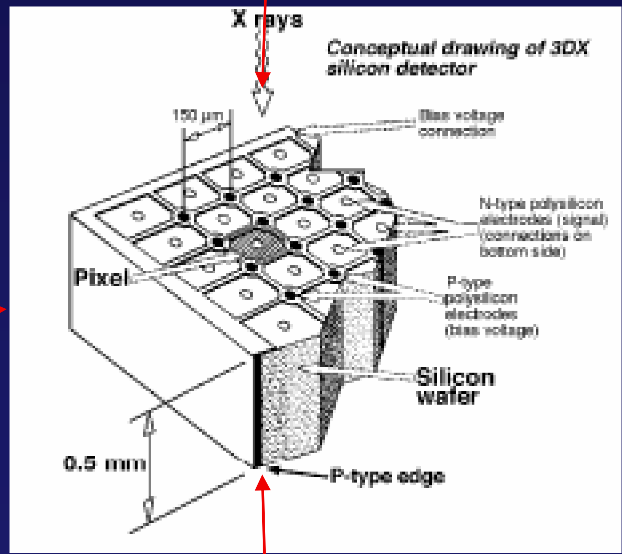
E. Westbrook et al. (molecular biology consortium) USA

- ❖High signals
- ❖Low noise
- ❖Detection efficiency
- ❖High speed → Protein folding





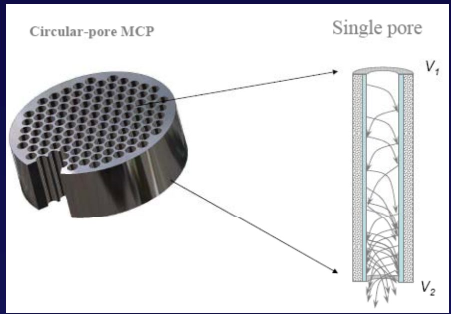
X-rays



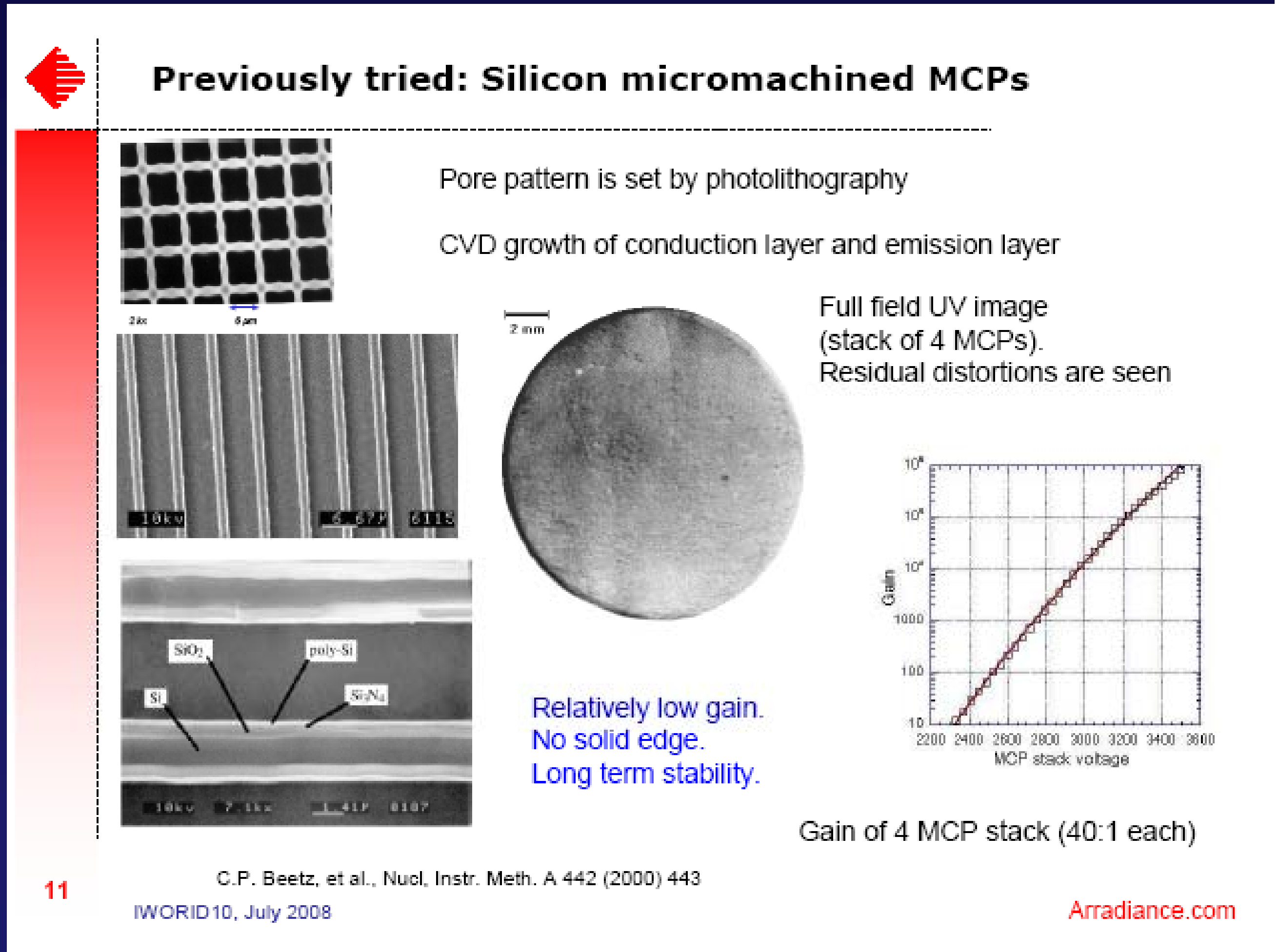
Bump bond to pixel readout electronics

Other Example of 3D processing: Micro-Machined Micro-Channel Plate

From D.R. Beaulieu IWORID 2008



- ❖Fast Photomultiplier Widely used
- ❖Pores normally coated glas
- ❖Various applications
- ❖Aging at high rates is an Issue
- ❖Pores dimension 10μm or less
- ❖Speed depends on pore
- ❖dimension



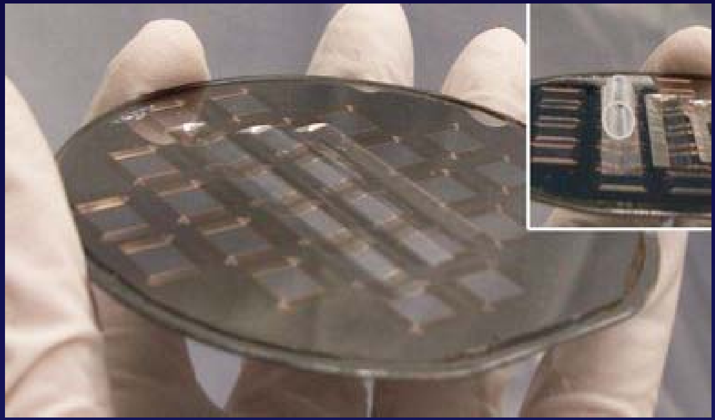
Improvements of gain and lifetime
due to novel emission and conduction layers

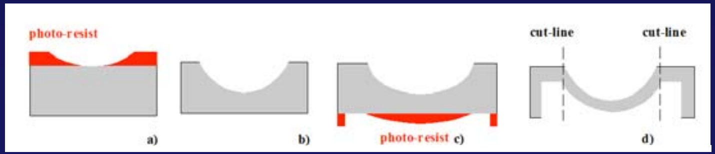
Curved semiconductor detectors

Cinzia Da Viá , the University of Manchester-UK. Hamburg 9 April 2010

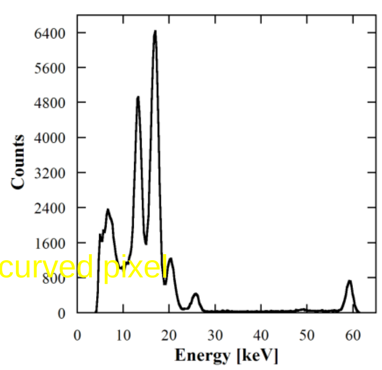
Bernard F. Phlips, *Member, IEEE, and Marc Christophers*
Presented at IEEE-NSS 2008, Dresden Germany

- Done on Si , GaN and SiC already tried
- Uses Deep reaction Ion Etching
- Key to technology:
- Photo Lithography works: pixels and strips made using 'GrayTone Lithography' (selects photoresists differently at different depths)
- Wafer thinning uses standard processing
- Indium bump-bonding still works on curved structure
- Can be used on all material that allow DRIE
- Resist spray coating
- Alternatives to CMP to improve flatness

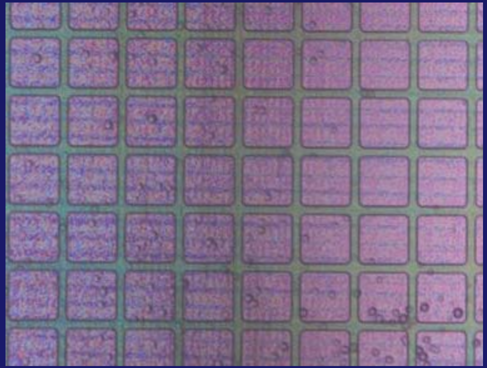




Principle of gray-tone technology: The 3-D resist profile, a) an c), is directly transferred into silicon topography, b) and d).



Am-241 photon spectrum taken with a fully depleted curved pixel detector, half-pipe (1.73 keV FWHM at 59.54 eV).



Top-view optical micrograph of a pixel array on a curved detector(pixel dimensions 150 x

Thin silicon and 3D interconnect an alternative to bump-bonding

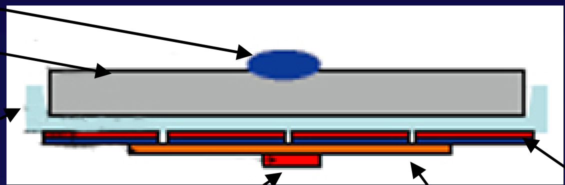
Courtesy R. Nisius, HG Moser
Munich and IZM

Example of detector module

Cooling pipe

Support/heat s preader

Thinned sensor/frame

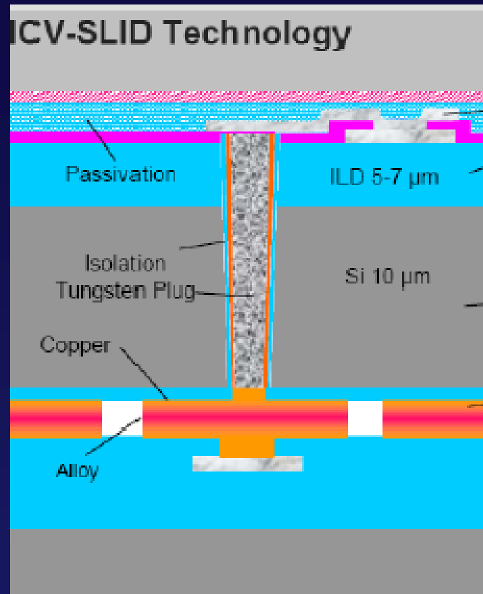


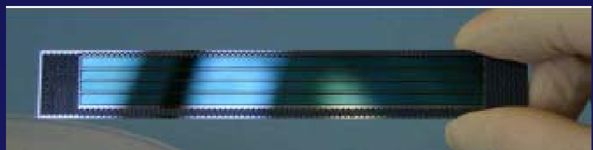
Module control data link

Flex-bus

Multilayer chip

Solid-Liquid Inter Diffusion Connection -IZM

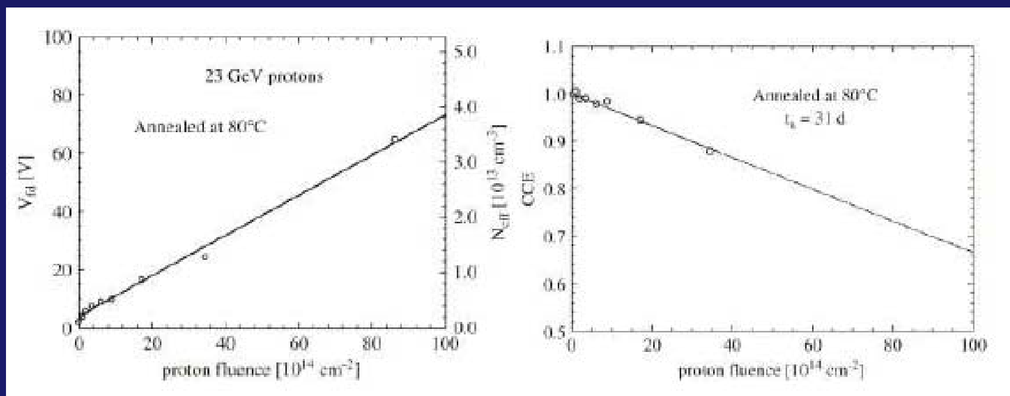


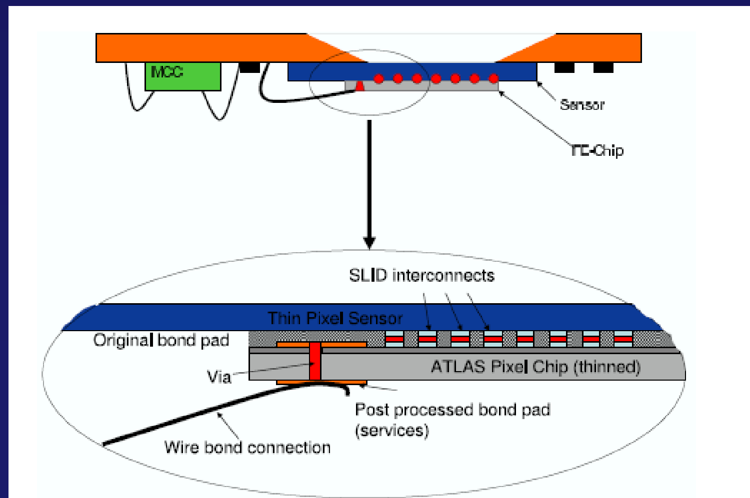


50µm thick prototype
n-type

Behaviour after irradiation

This silicon requires
New ROC development





Summary and perspectives

- 3D technology can be used to fabricate sensors for HEP ,Medicine, Biology....
- Advantages are: flexibility in adaptive shapes and optimised detection Radiation hardness and enhanced speed
- Current Applications include:
- ATLASFP, B-Layer , Vertex Detection
- Structural Molecular Biology 3DX, X-ray imaging
- CNM bonded Double sided 3D to MEDIPIX2
- Curved structures (proposed for vertex purposes)..

Industry is actively responding, industrialisation process on its way..
3D silicon is one of the considered technologies for the ATLAS IBL

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- *Stanford -3D work:*

C. Kenney (MBC), L. Reuen, R. Kohrs, M. Mathes, N. Wermes (Bonn Univ.) S. Parker (U. of Hawaii) G. Anelli, M. Deile, P. Jarron, J. Kaplon, J. Lozano and the TOTEM Collaboration (CERN), V. Bassetti (Genova), M. Garcia-Sciveres, K. Einsweiler (LBL), J. Hasi, A. Kok (now Sintef), S. Watts (Manchester U.K.) V. Linhart, T. Slavicheck, T Horadzof, S. Pospisil (Technical University, Praha), M. Ruspa (Torino), O. Rohne, E. Bolle (Univ. of Oslo).

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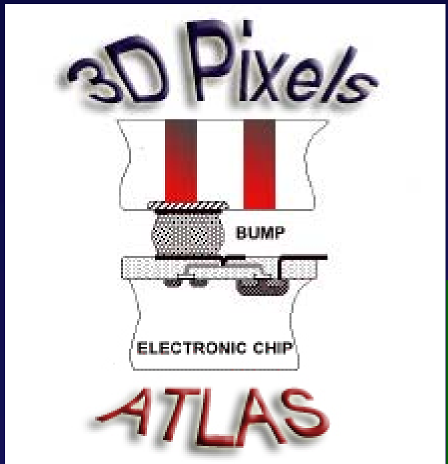
- *Other material from: R. Bates, M. Boscardin,, G. Della Betta, J. Harkonen,, C. Fleta, T-E. Hansen, M. Hoeferkamp,, R. Nisius, H.G. Moser, G. Pellegrini, S. Saidel, U. Parzefall*

References to papers and talks in the transparencies. Apologies if I forgot someone ..

ATLAS 3D Silicon Sensors R&D Collaboration



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18 institutions and 5 processing facilities