3D SILICON DETECTORS FOR IMAGING APPLICATIONS

Cinzia Da Via', Brunel University, UK

OUTLINE

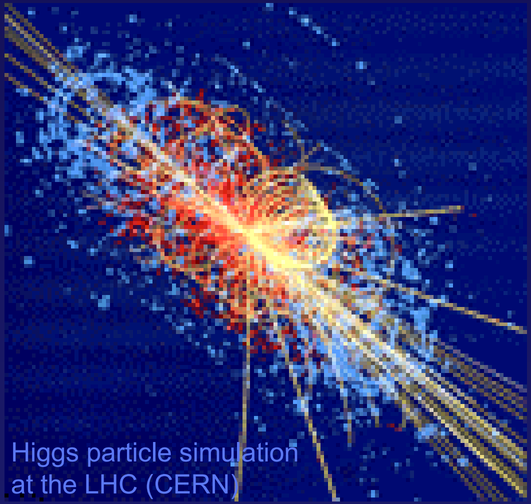
- ❖Introduction
- ❖MEMS and 3D silicon technology
- ❖Active edges and planar/3D
- ❖Response to x-rays
- ❖Conclusions and future

C. Kenney, E. Westbrook, D. Gnani, A. Thompson (Molecular Biology Consortium) J. Hasi, A. Kok, S. Watts (Brunel U.K.) S. Parker (U. of Hawaii) G. Anelli, M. Deile, P. Jarron, J. Kaplon, J. Lozano (CERN) H. Yamamoto (Tohoku U.) E. Mandelli (Lawrence Berkeley Lab) J. Morse (European Synchrotron Radiation Facility), E. Perozziello, V. Bassetti (Genova) and members of the TOTEM Collaboration

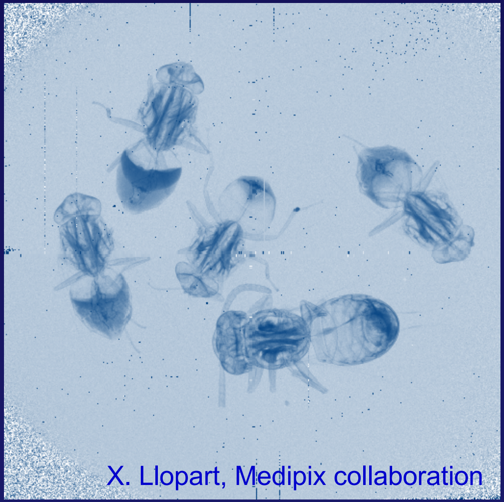
Imaging detectors requirements

- High sensitivity (direct detection)
- Large area coverage
- High spatial resolution
- Speed
- High energy resolution

(NASA/JPL/ASU)



Higgs particle simulation at the LHC (CERN)



X. Llopart, Medipix collaboration

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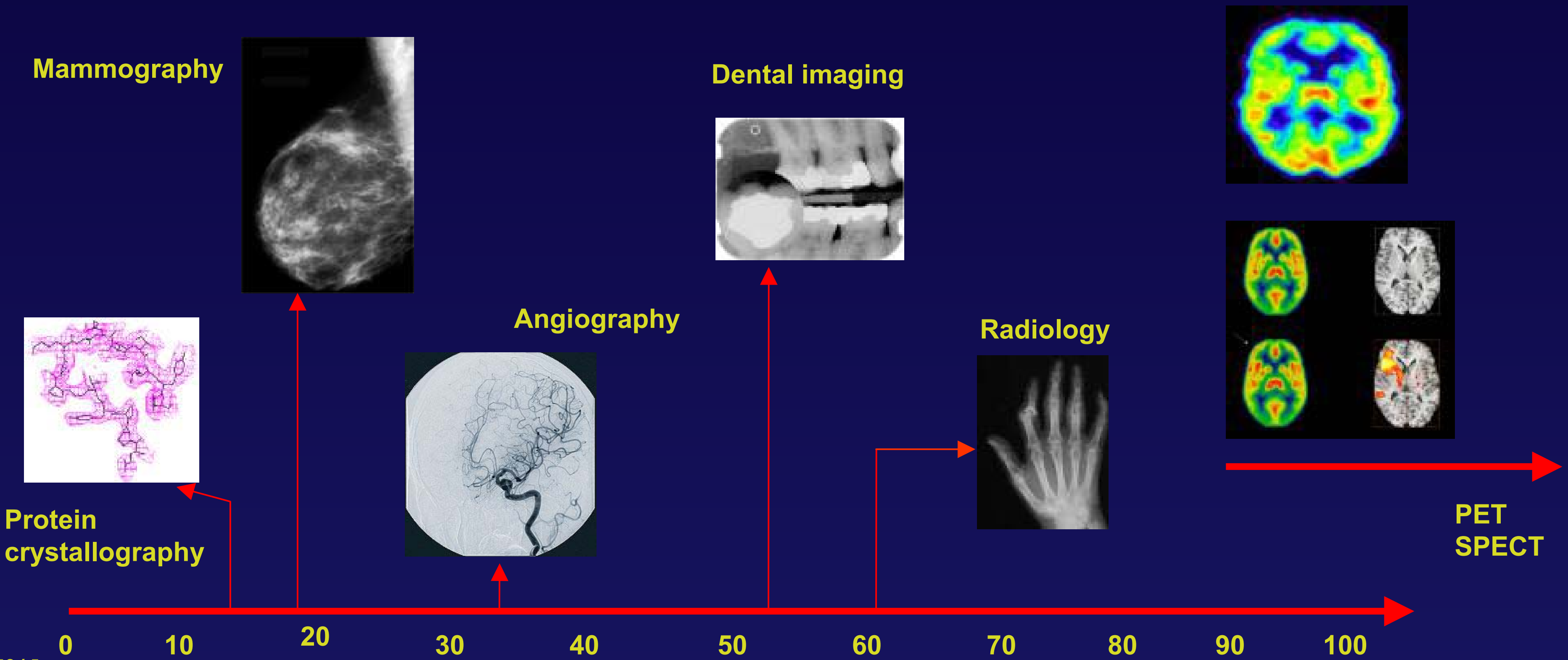
X-ray energy of the most common medical and biological applications and Silicon detectors

3D



Mammography

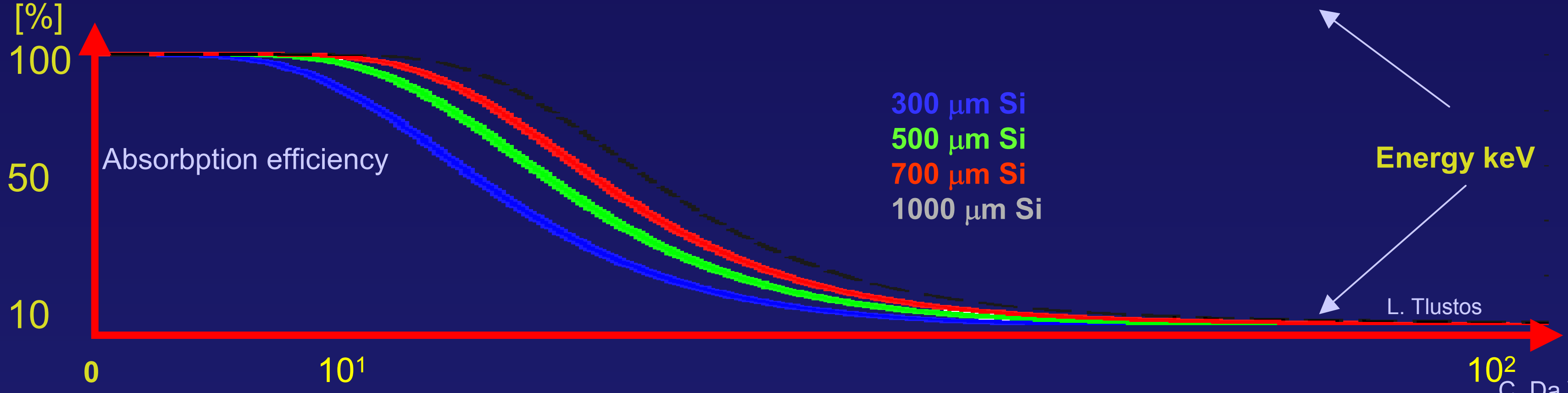
Dental imaging

Angiography

Radiology

Protein crystallography

PET
SPECT



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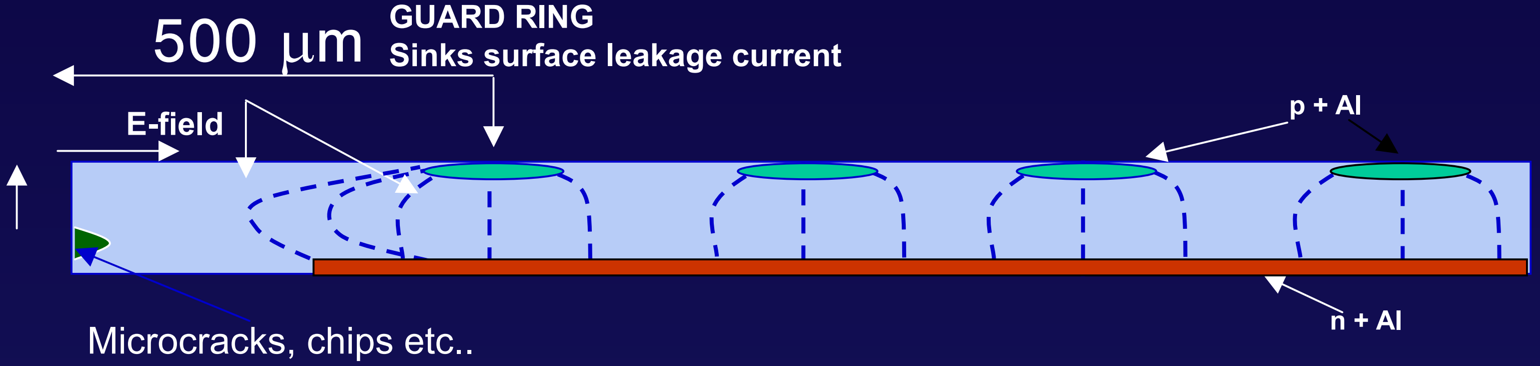
Large area coverage: Why not a traditional planar Si?


500 µm

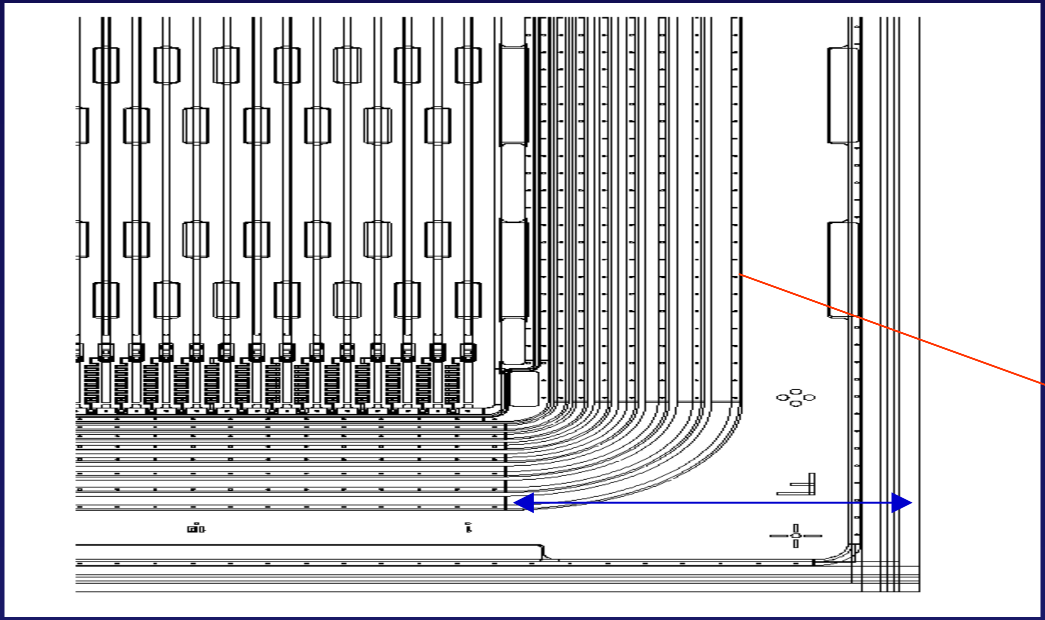
GUARD RING
Sinks surface leakage current

E-field

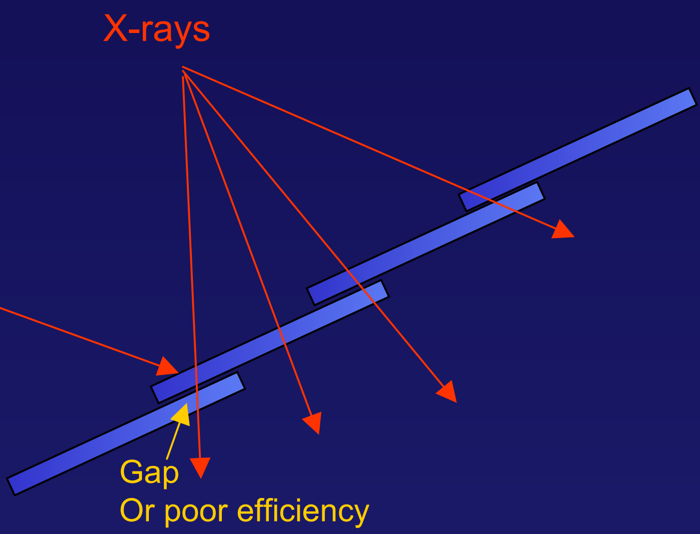
p + Al

n + Al

Microcracks, chips etc..

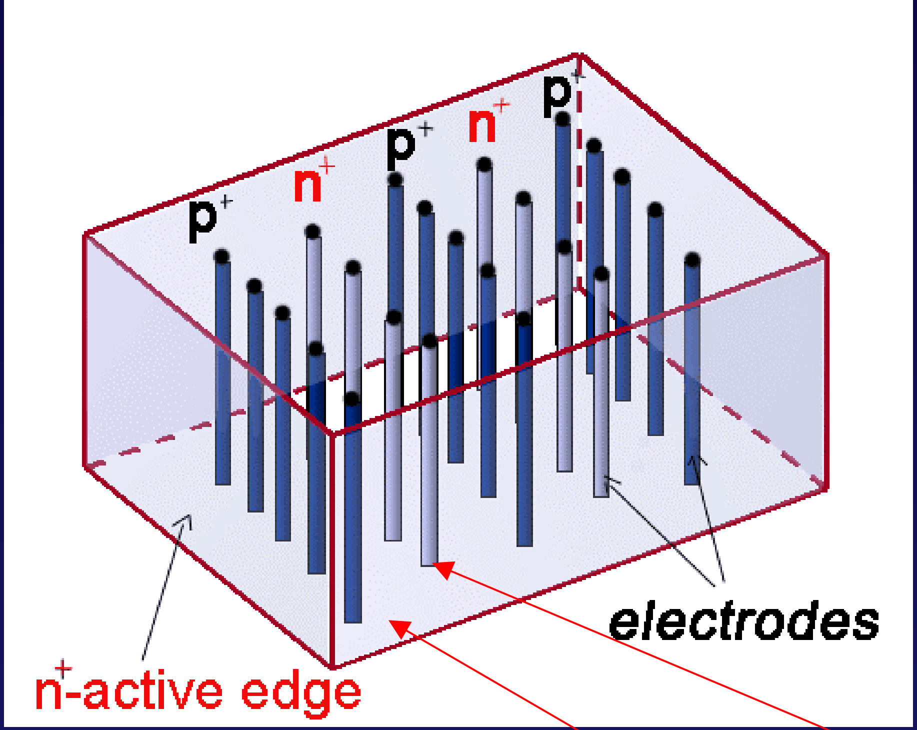

Atlas microstrips

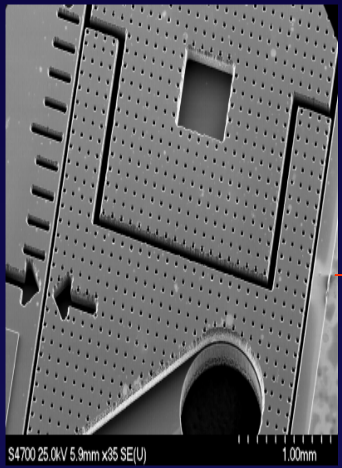
1 mm !!!!

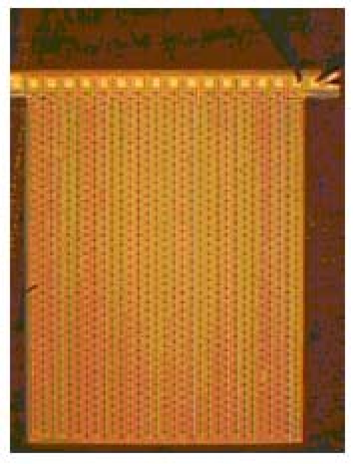

X-rays

Gap
Or poor efficiency

Silicon 3D detectors







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

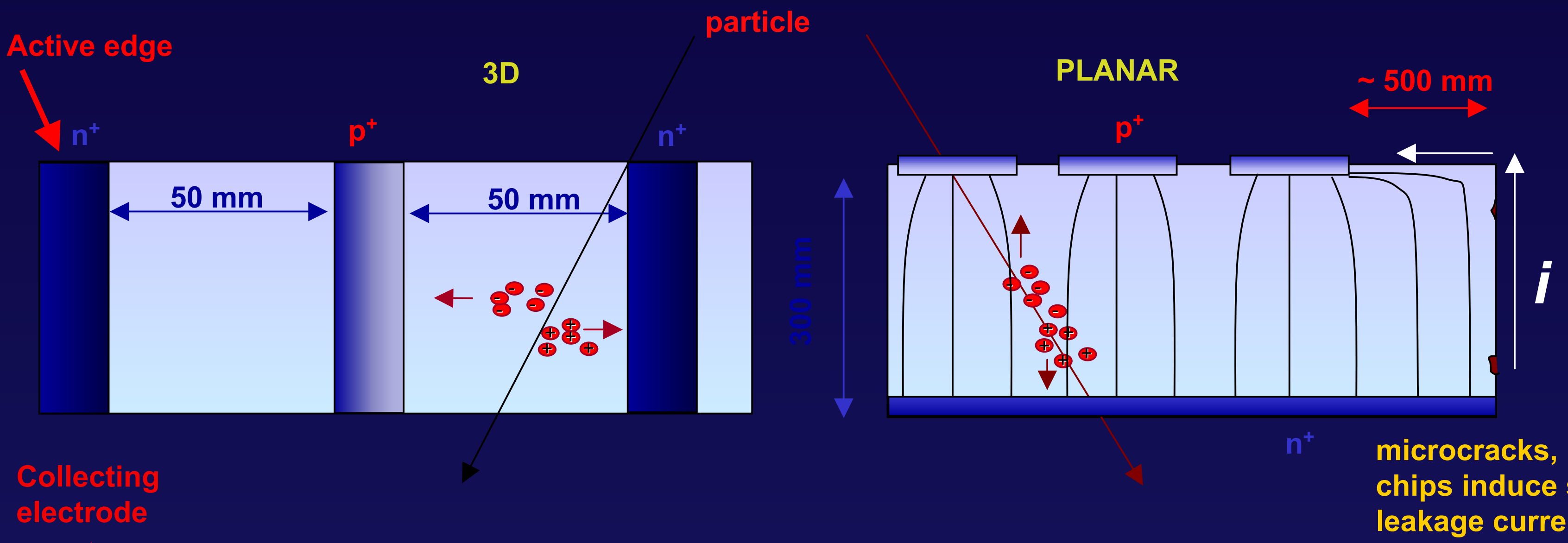
Combine traditional VLSI processing and MEMS (Micro Electro Mechanical Systems) technology.

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 464 (1999) 1224
3. IEEE Trans Nucl Sci 482 (2001) 189
4. IEEE Trans Nucl Sci 485 (2001) 1629
5. IEEE Trans Nucl Sci 48 6 (2001) 2405
6. CERN Courier, Vol 43, Jan 2003, pp 23-26

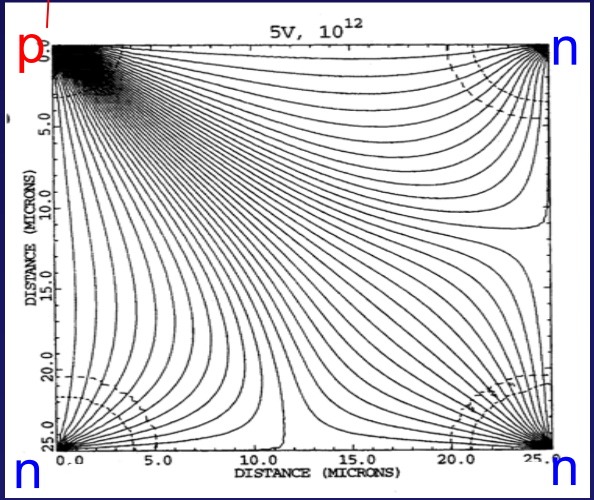
3D versus planar detectors (not to scale)



Active edge

Collecting electrode

microcracks,
chips induce surface
leakage current



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 μm)	$24000e^-$	$24000e^-$
❖CAPACITANCE (121 μm)	200fF	50-200fF
❖COLLECTION DISTANCE	50 μm	300 μm
❖SPEED	1-2ns	10-20 ns

Processing

Currently performed at the Stanford-Nanofabrication-Facility (CIS) Stanford USA

C. Kenney (MBC), J. Hasi (Brunel)

Micromachining (DRIE)

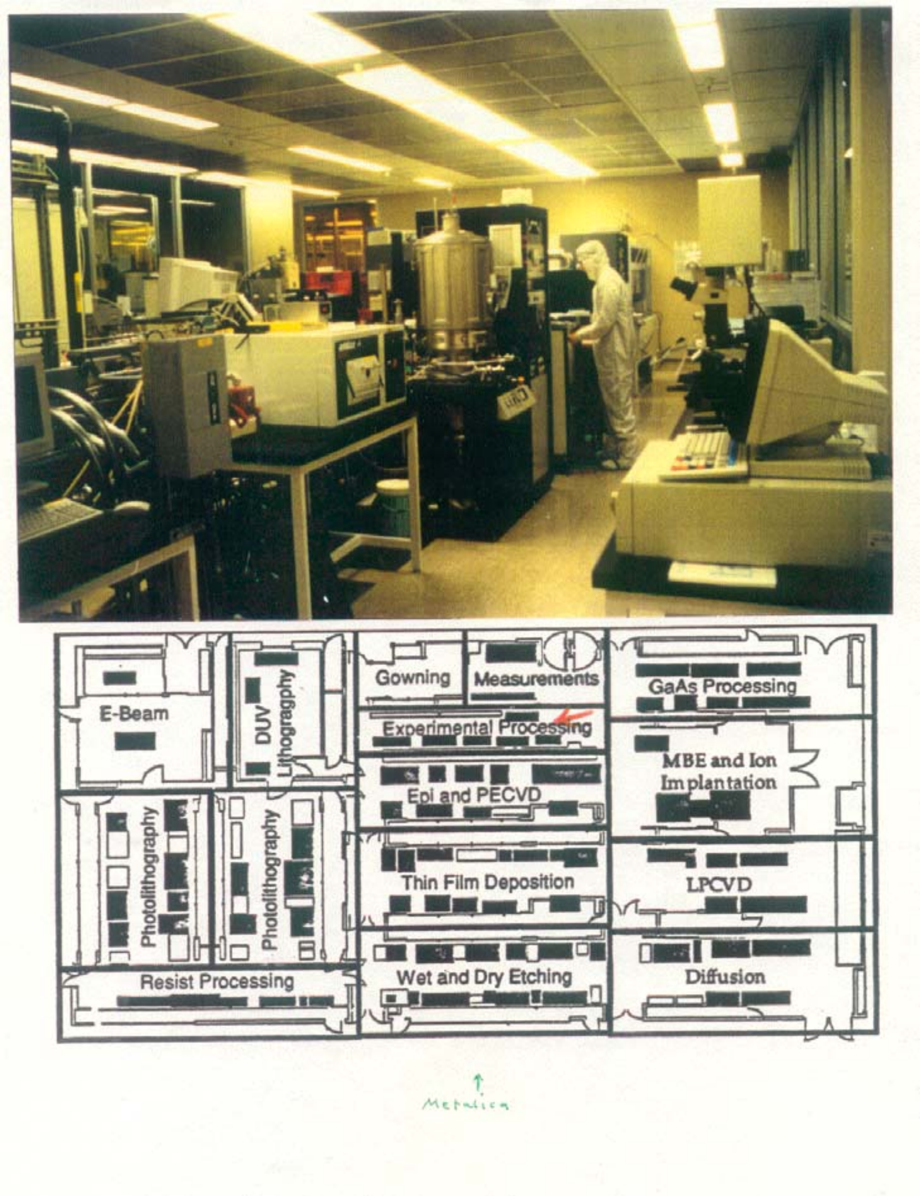
LPCVD

Photolithography

ION implantation

Etc.

1000 m^2 →



BRUNEL – HAWAII –
STANFORD (Molecular Biology Consortium)

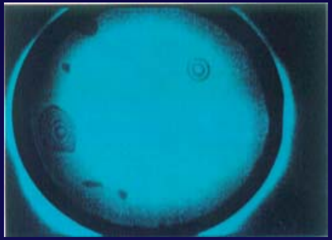
Key processing steps (25-32)

3D

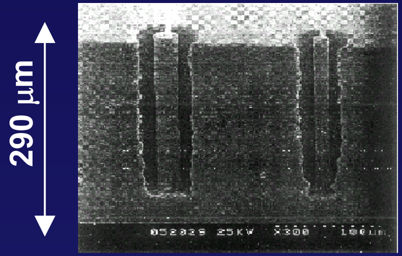
1- etching the electrodes

2-filling them with dopants

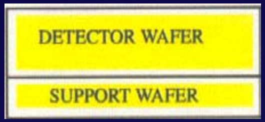
Aspect ratio:
D:d = 11:1



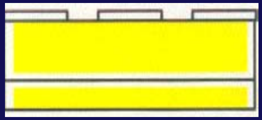
WAFER BONDING
(mechanical stability)
Si-OH + HO-Si -> Si-O-Si + H_2O



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

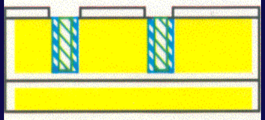


Step 1-3
oxidize and
fusion bond
wafer

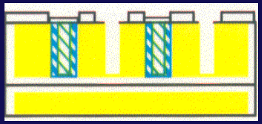


Step 4-6 pattern
and etch p^+ window
contacts

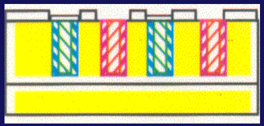
Step 7-8 etch
p^+ electrodes



Step 9-13 dope
and fill p^+
electrodes

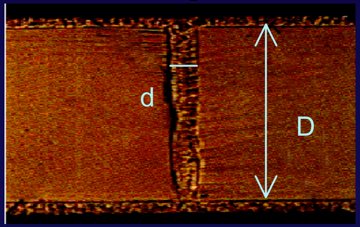


Step 14-17 etch
n^+ window
contacts and
electrodes



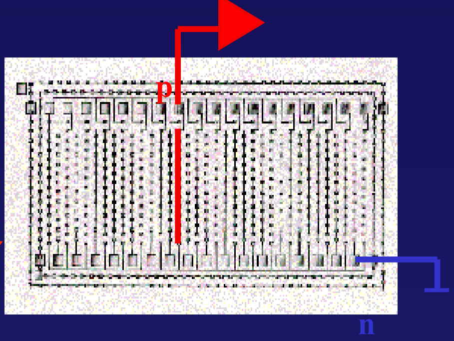
Step 18-23 dope
and fill n^+
electrodes

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



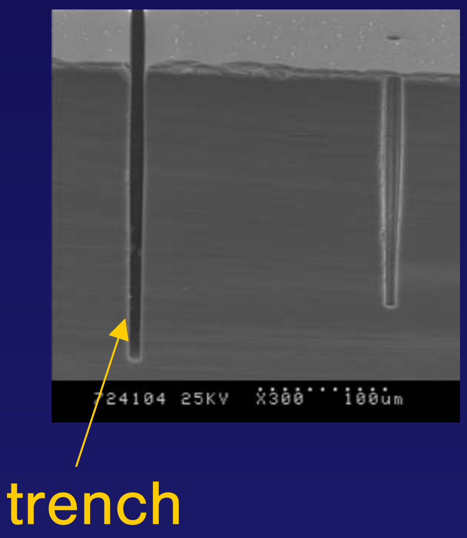
METAL DEPOSITION
Shorting electrodes of the same type
with Al for strip electronics readout
or deposit metal for bump-bonding

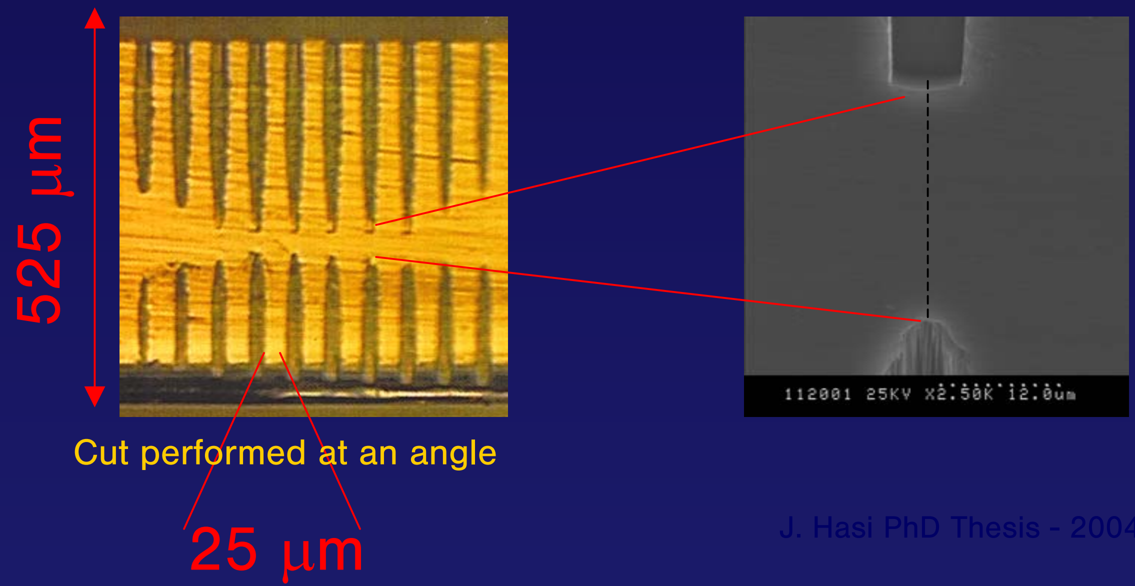
C. Da Via' Sept. 2005

Improving the aspect ratio (D/d) in thick wafers →improving 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 µm – 240 µm
>Double side etching D/d=25:1 etching time = 1.5µm/min
D=525 µm inter electrode spacing = 25 µm

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.)





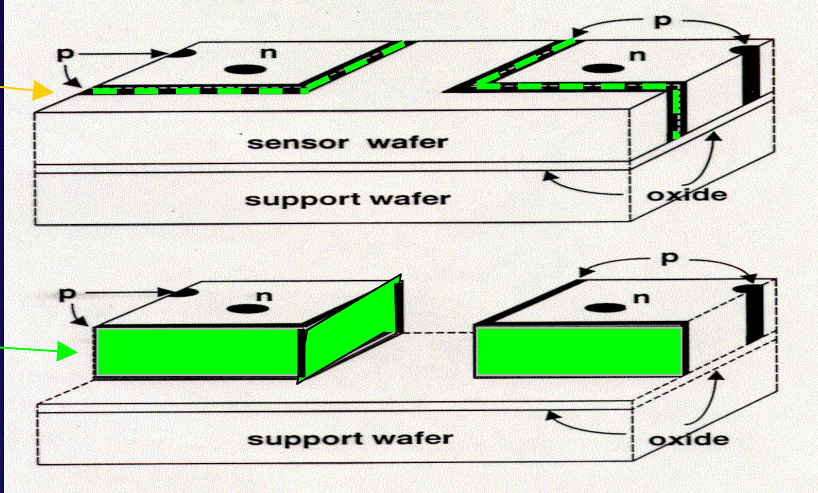
Cut performed at an angle

J. Hasi PhD Thesis - 2004

Active edge processing – a possible large area coverage solution

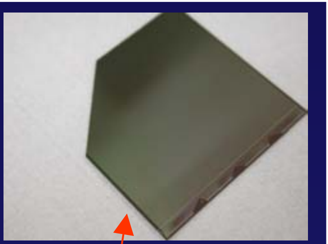
A TRENCH IS ETCHED AND DOPED TO TERMINATE THE E-FIELD LINES

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)

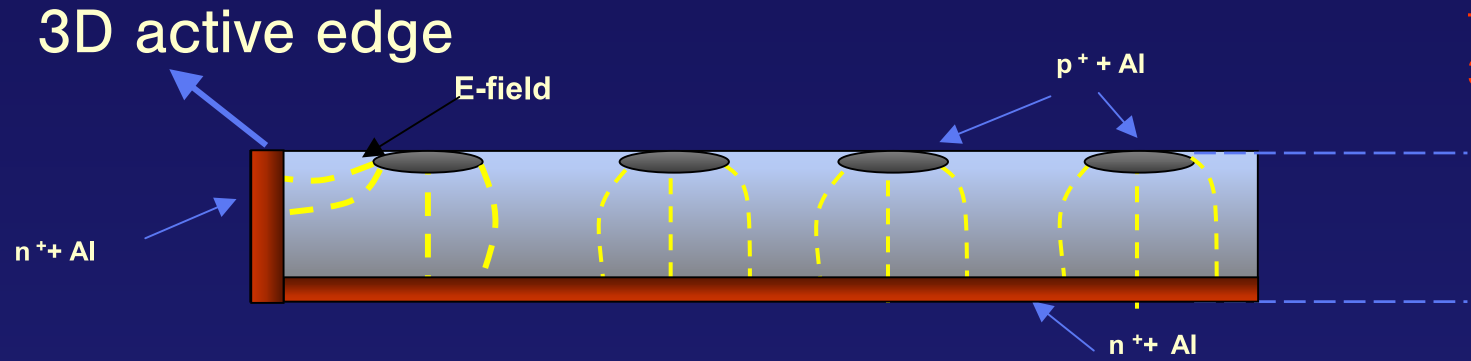


Natural developement → PLANAR+3D = planar/3D

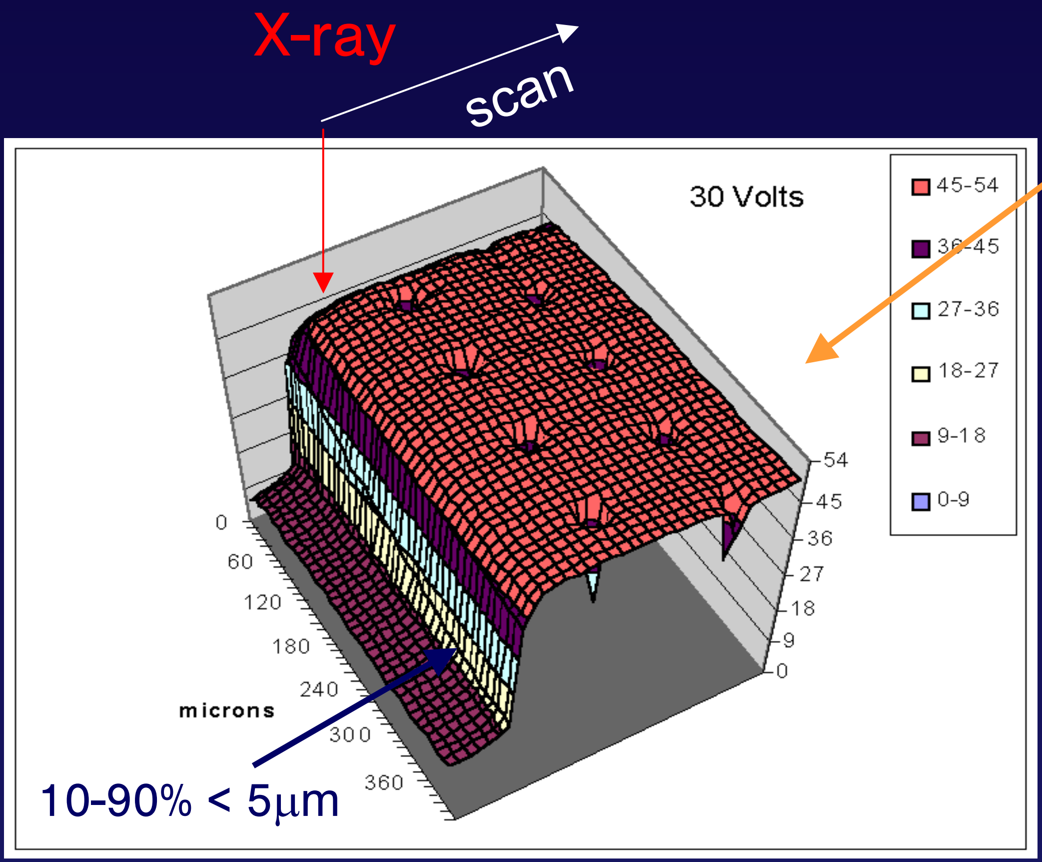
PLANAR DETECTOR + DOPANT DIFFUSED IN FROM DEEP ETCHED EDGE THEN FILLED WITH POLYSILICON (C. Kenney 1997)

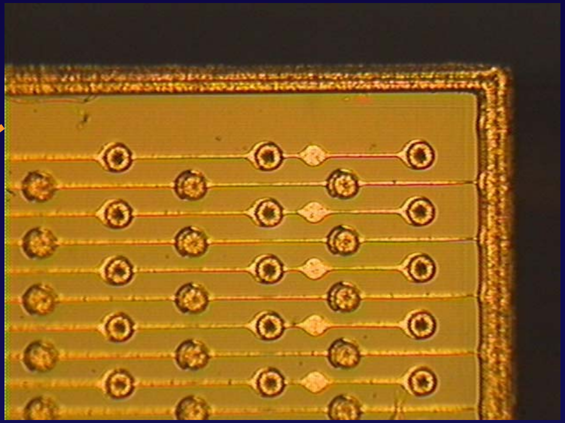


TOTEM detectors
3x4cm^2 512 μstrips



3D uniformity response:
X-rays at ALS-Berkeley





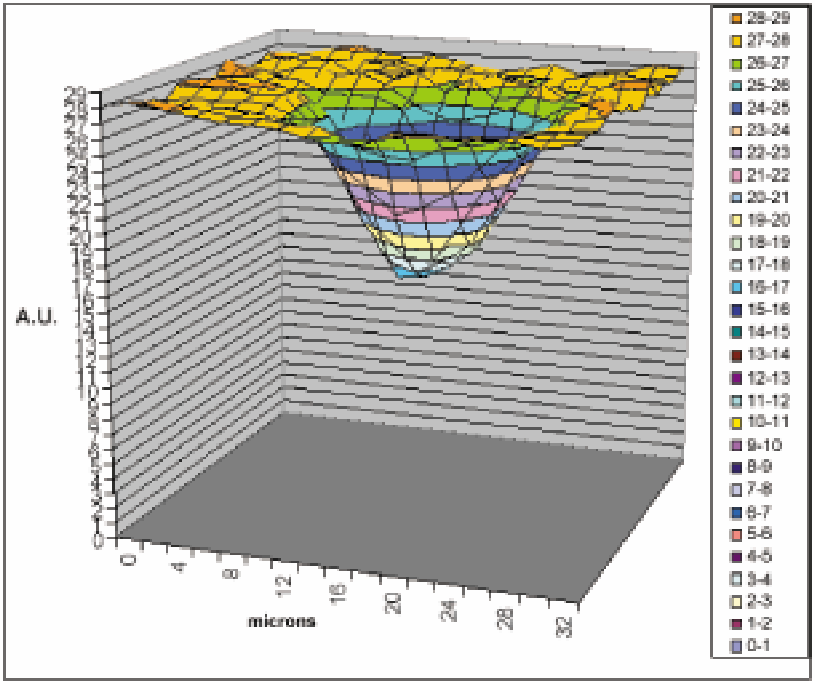
Measurement Performed using a 2 μm 13 KeV x-ray beam

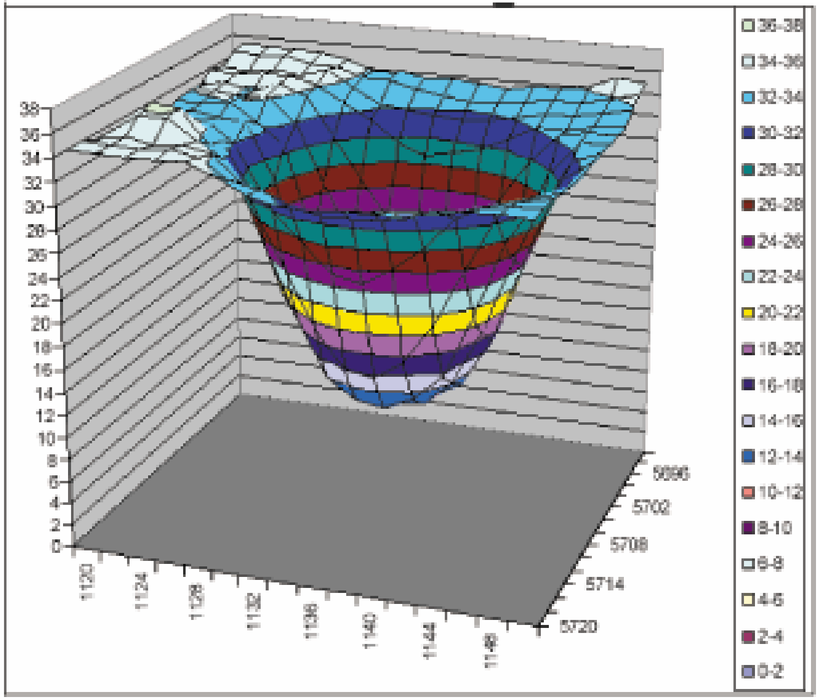
J. Hasi, C. Kenney,
J. Morse, S. Parker

Electrodes ~ 1.8% of total area

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

3D Electrodes response





N – Electrode

Signal Reduction 43%

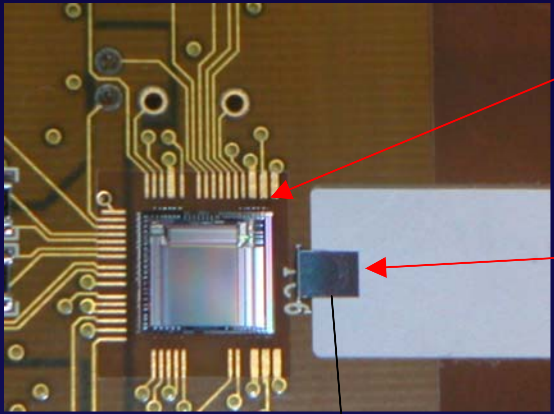
P – Electrode

Signal Reduction 66%

Differences between N and P:

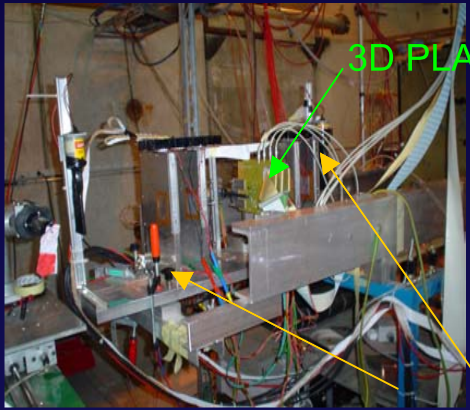
Grain size of poly, Diameter, Diffusion rate, Trapping, Doping

FULL 3D Response to particles: 120 GeV muon beam +0.25 μm LHC compatible readout (CMS/Totem)

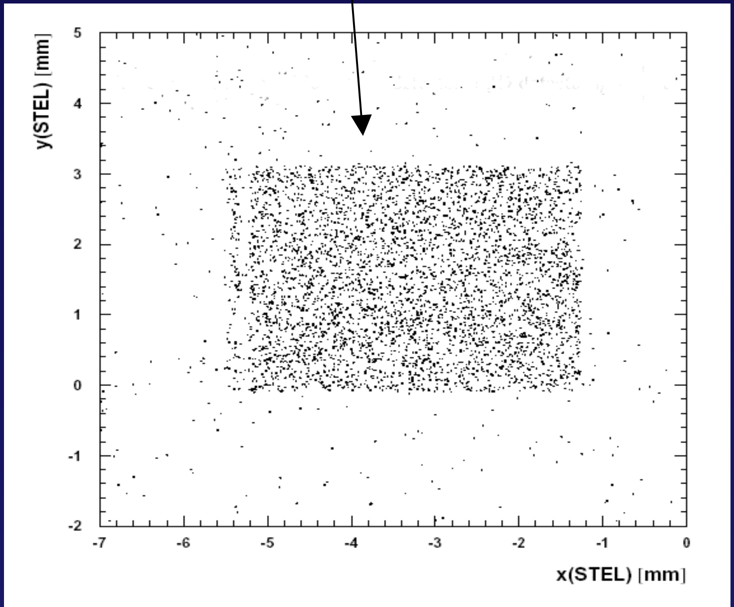


SCTA READOUT CHIP*

3.195 x 3.9 mm^2
3D SENSOR
Thickness=180 μm
n-type Si 4kΩ-cm

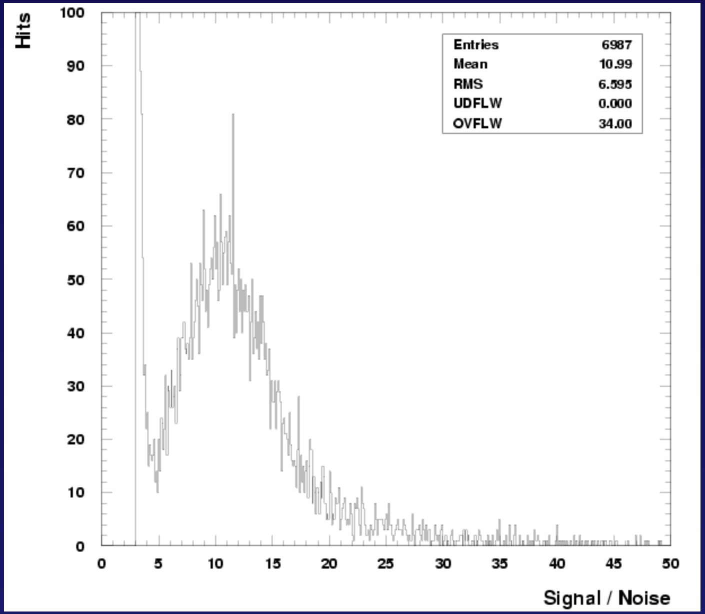


REFERENCE TELESCOPE



Telescope track position at 3D if 3D has a hit

S:N=14:1
Efficiency= 98%



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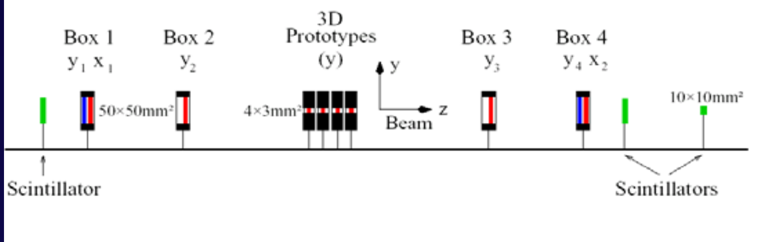
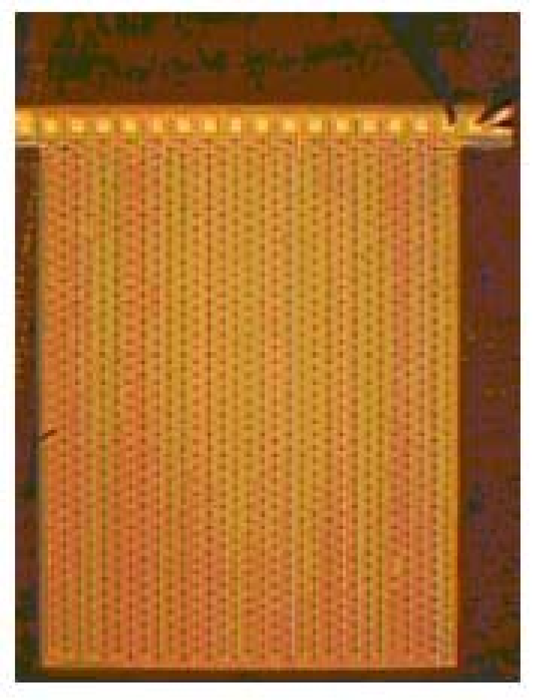
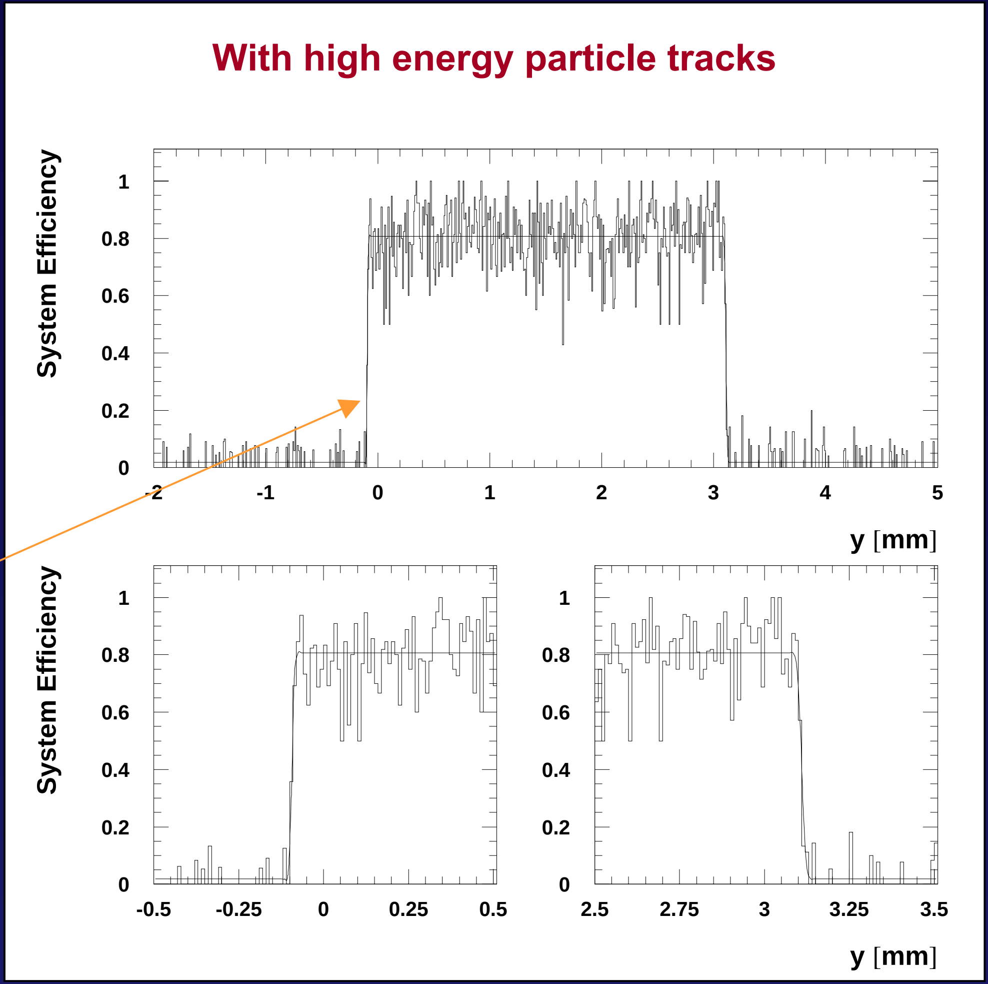
* IEEE Trans.Nucl.Sci.44:298-302,1997
-TOTEM TDR-CERN

3D Edge Sensitivity







Fit width = (3.203 ± 0.004) mm

Phys. width = (3.195 ± 0.001) mm

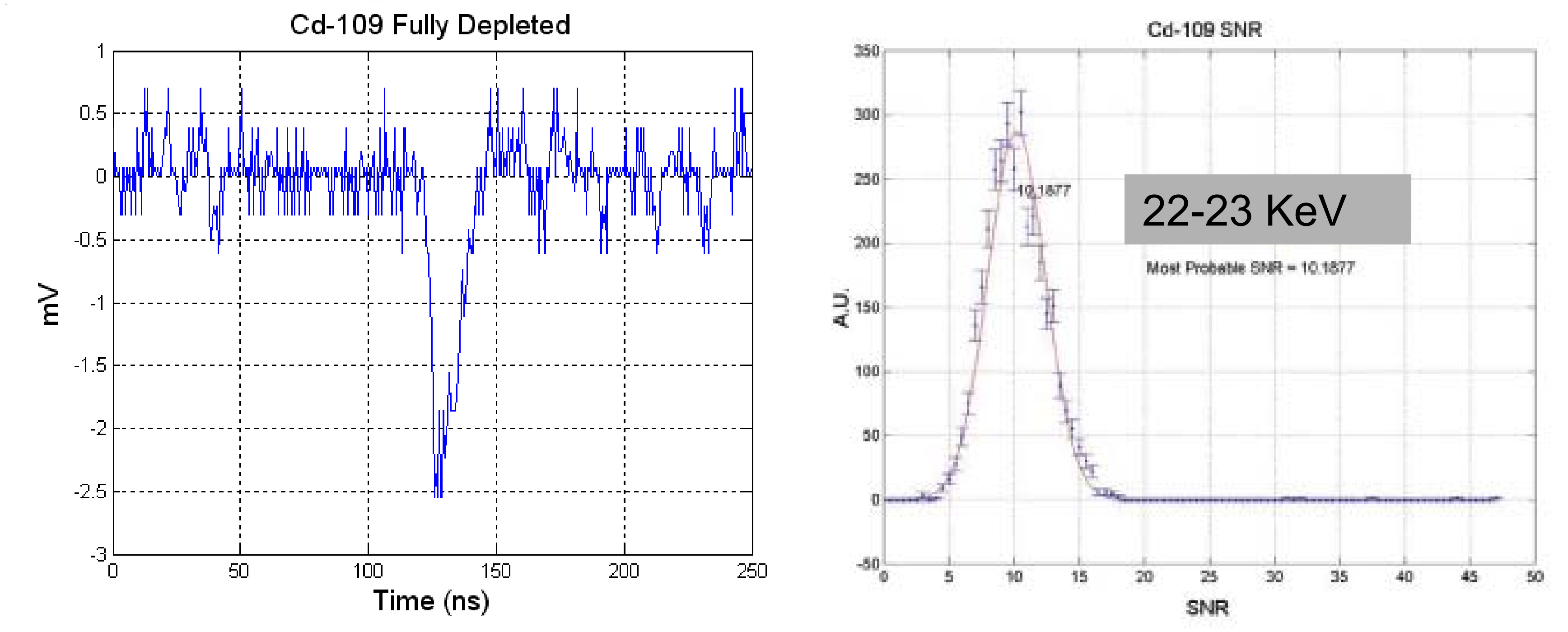
C. Da Via' Sept. 2005

Response to ^{109}Cd

Pitch	200 um
Thickness	**121 um**
Dimensions	0.0121 x 0.36 x 0.195 cm^3

S:N=13:1

Typical oscilloscope trace



22-23 KeV

Most Probable SNR = 10.1877

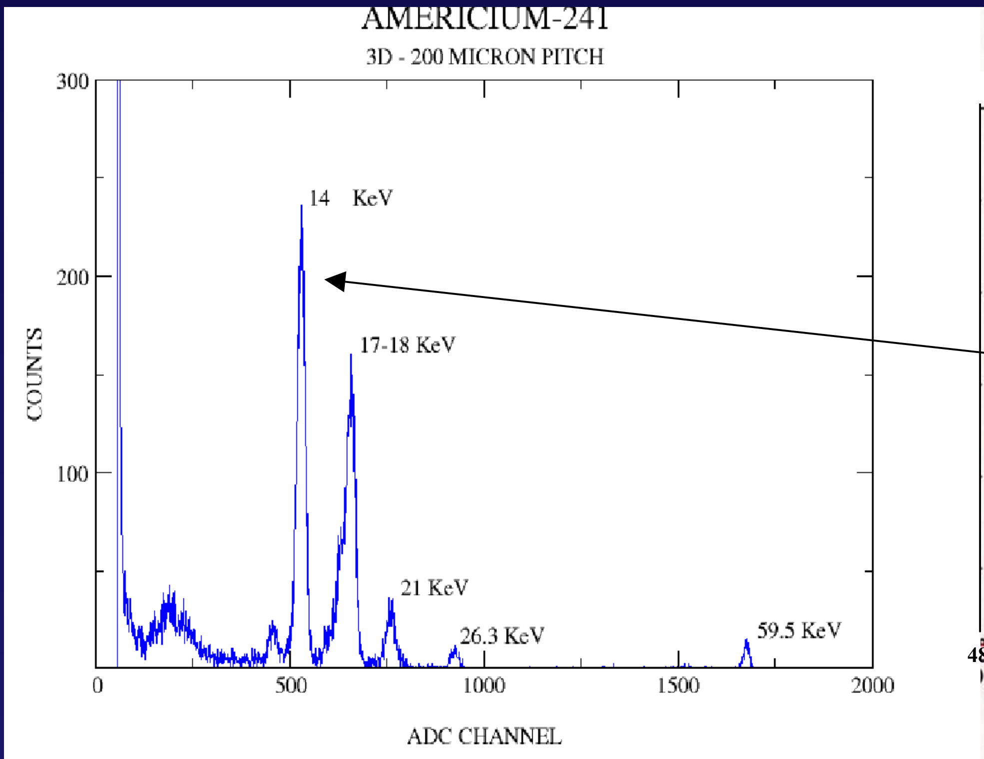
Measurements by A. Kok- Brunel

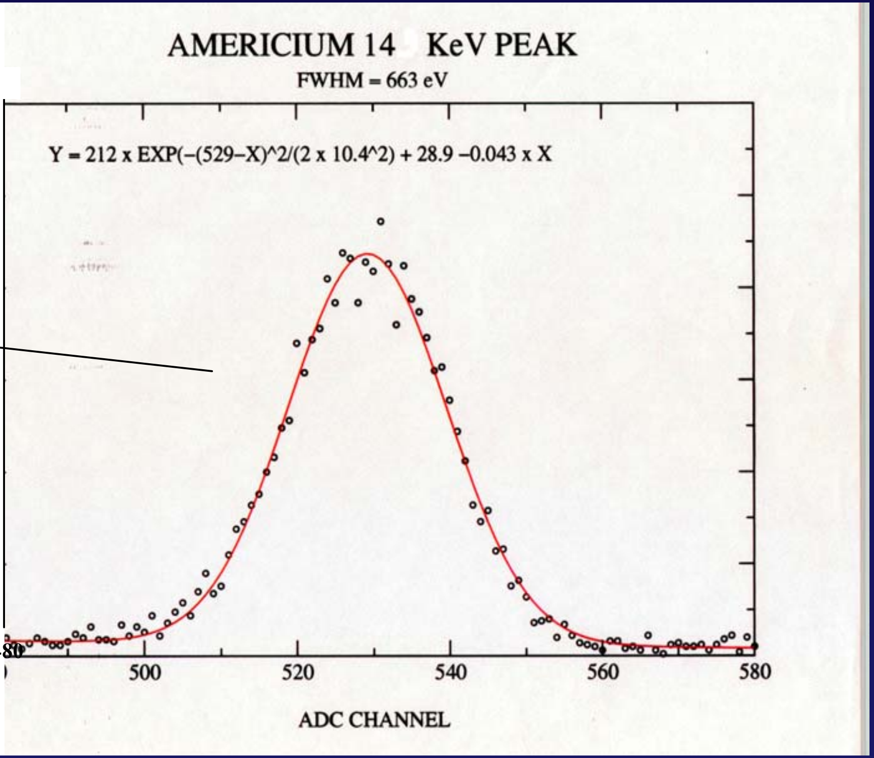
*Fast Electronics CERN MIC :G. Anelli, P. Jarron et al. NIM A 377 (1996) 435

3D spectral response

I_{leak} = 0.45 nA (average) 200 μm
I_{leak} = 0.26 nA (average) 100 μm
C = 0.2 pF per electrode
Thickness = 120 μm

Gaussian response

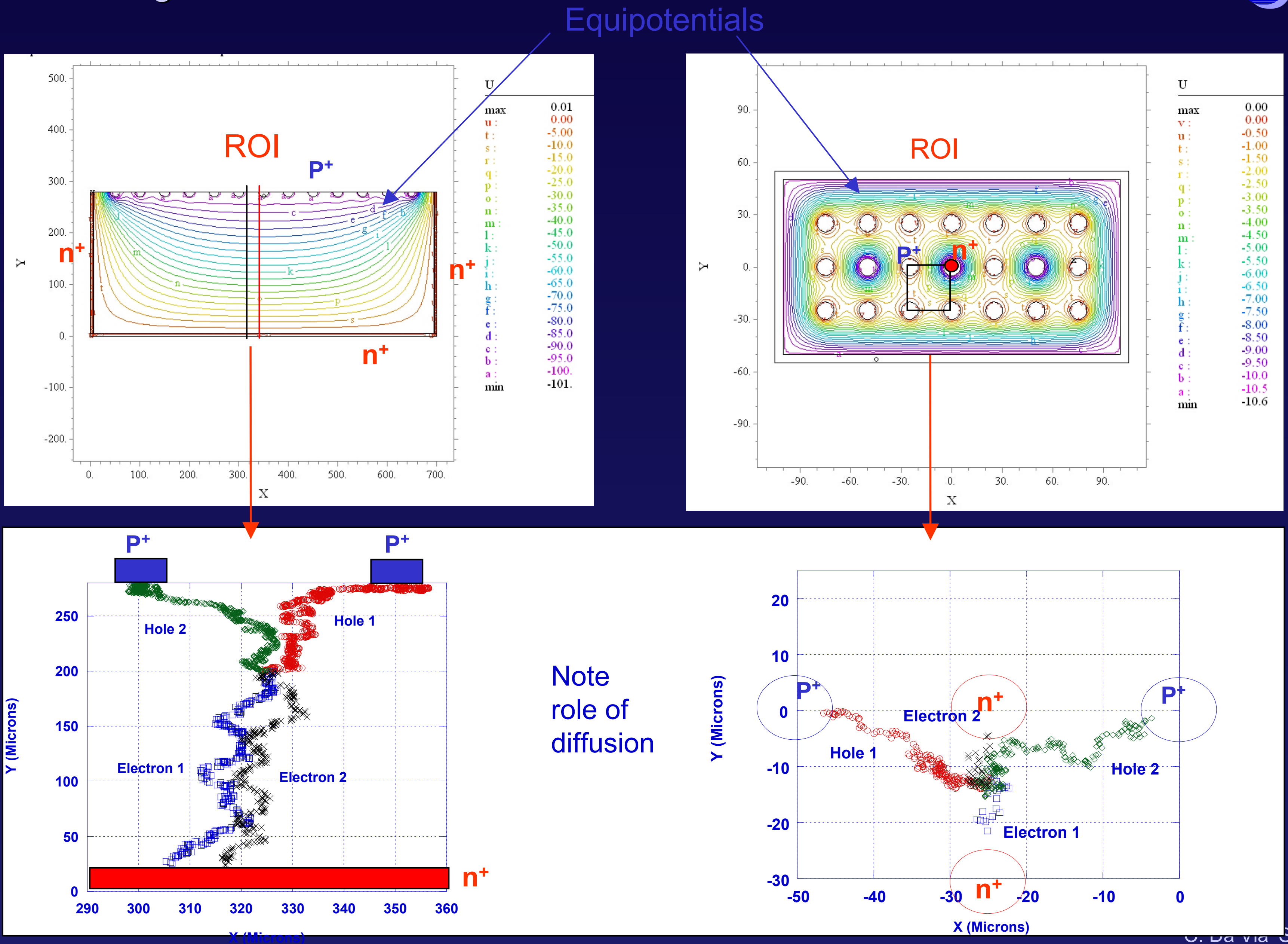




$\sigma/E=2\%$

CHARGE SHARING – PLANAR vs 3D - p-type, p-on-p 50 μm pitch

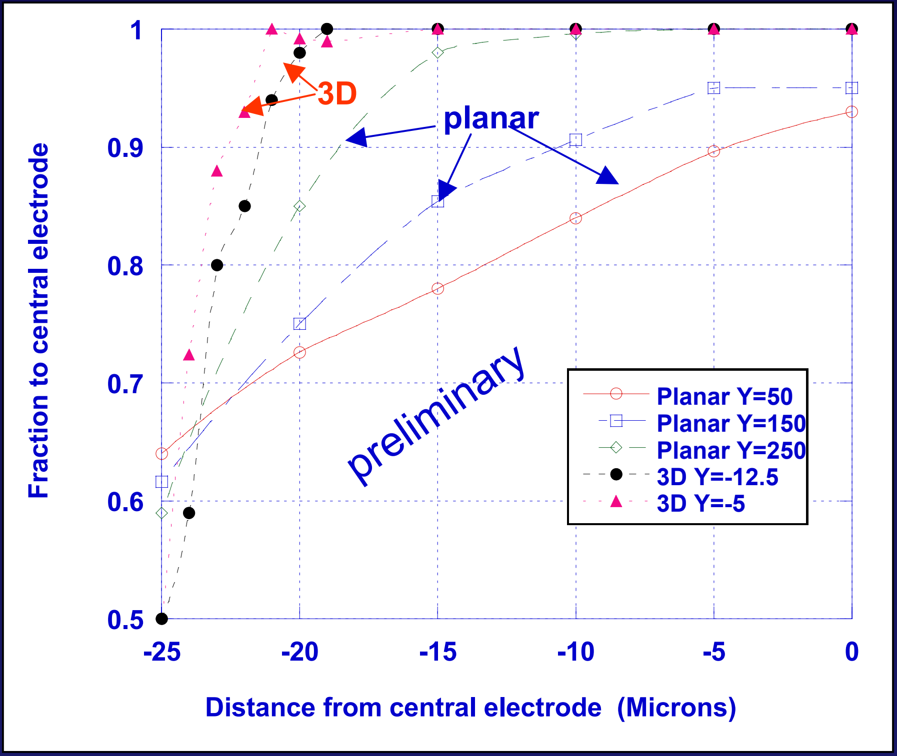
ROI = Region of interest

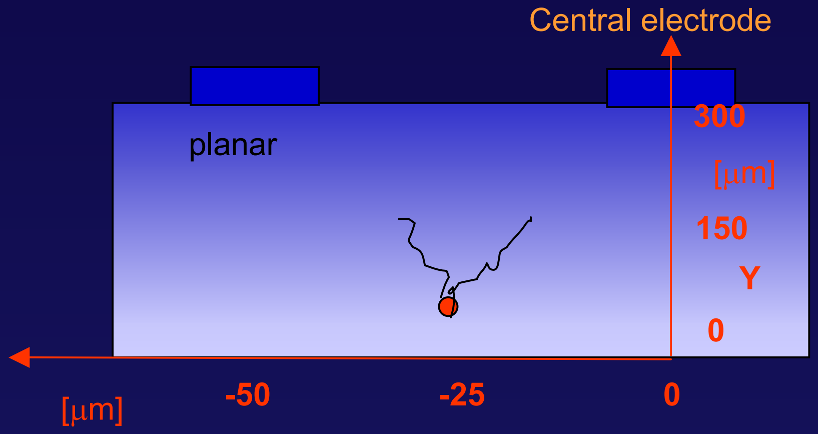


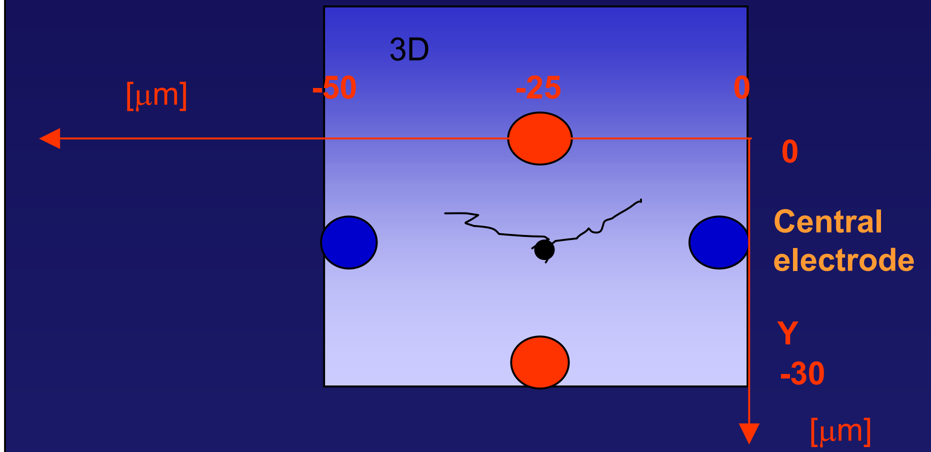
Note
role of
diffusion

Probability of charge sharing : planar vs 3D 3D collects all charge on 1 electrode in most cases → Better Energy resolution

Fraction of carriers that travel to central electrode versus start position relative to central electrode



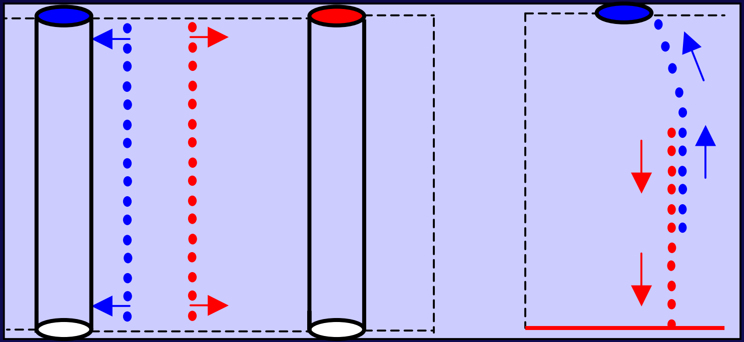




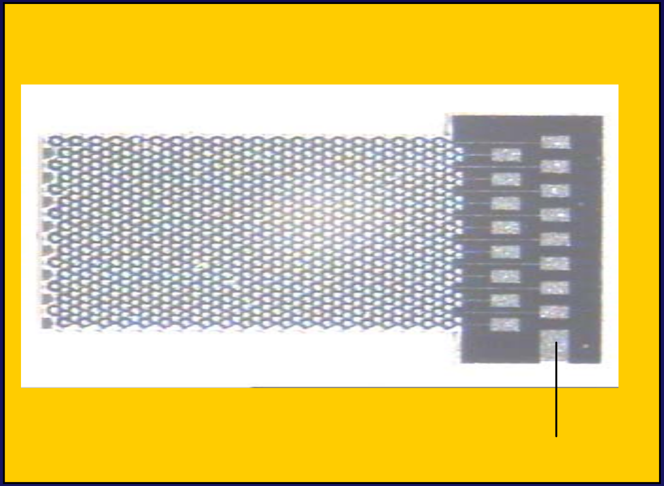
Simulations by S. Watts, Brunel

3D were tested with a 0.13 μm CMOS amplifier chip (designed by Depeisse-Anelli-CERN MIC)

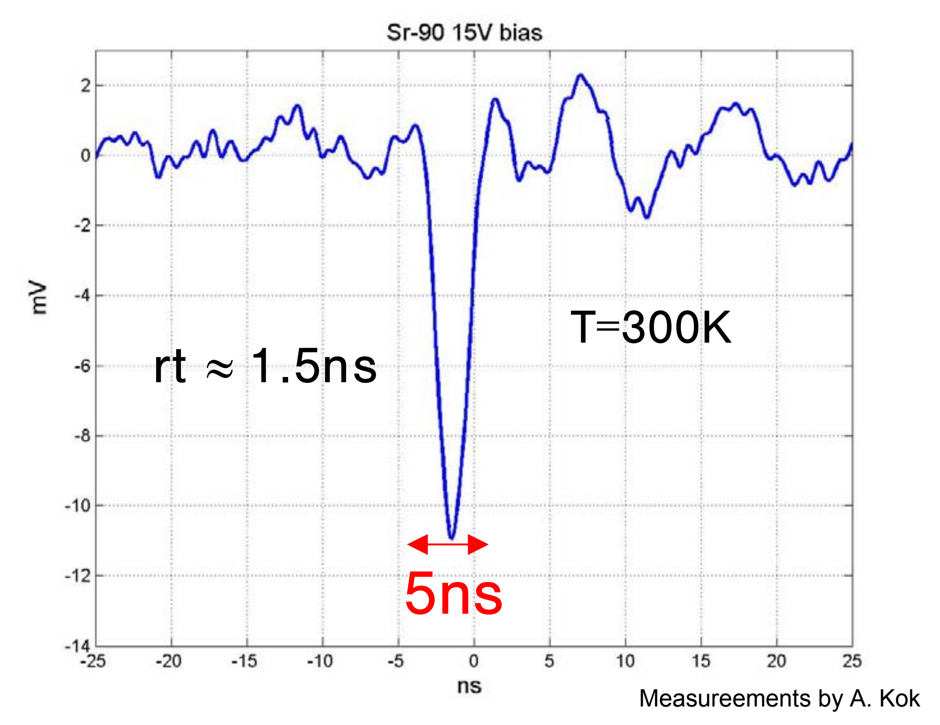
3D



- ❖Short collection distance
- ❖High average e-field with moderate V_{bias}
- ❖Parallel charge collection



3D Inter-electrode distance = 50 μm



Sr-90 15V bias

rt ≈ 1.5ns

T=300K

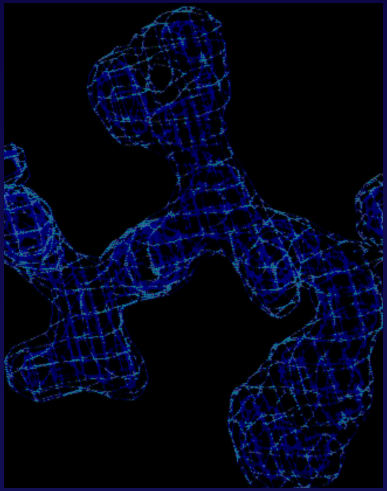
5ns

Measureements by A. Kok

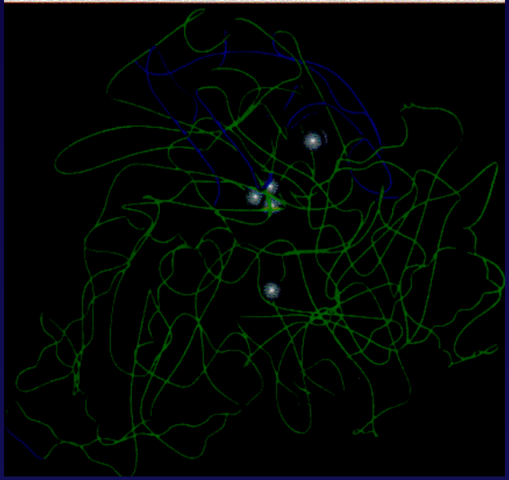
C. Da Via' Sept. 2005

Applications: Protein folding 3DX project (MBC)

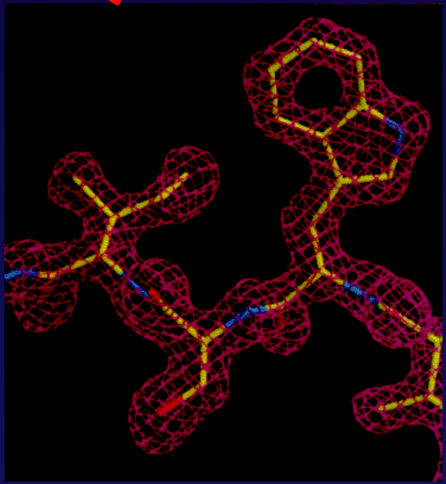
DENSITY

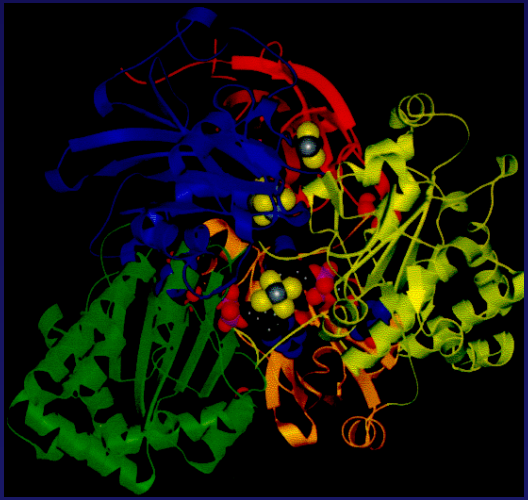


TRACE



SEQUENCE



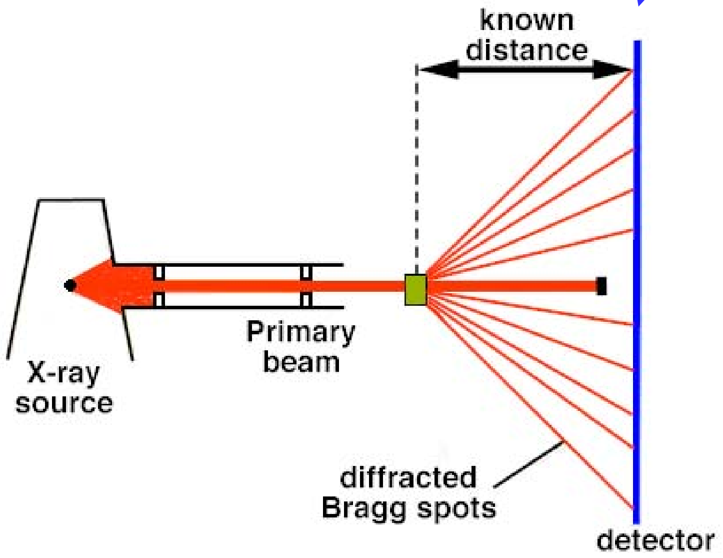


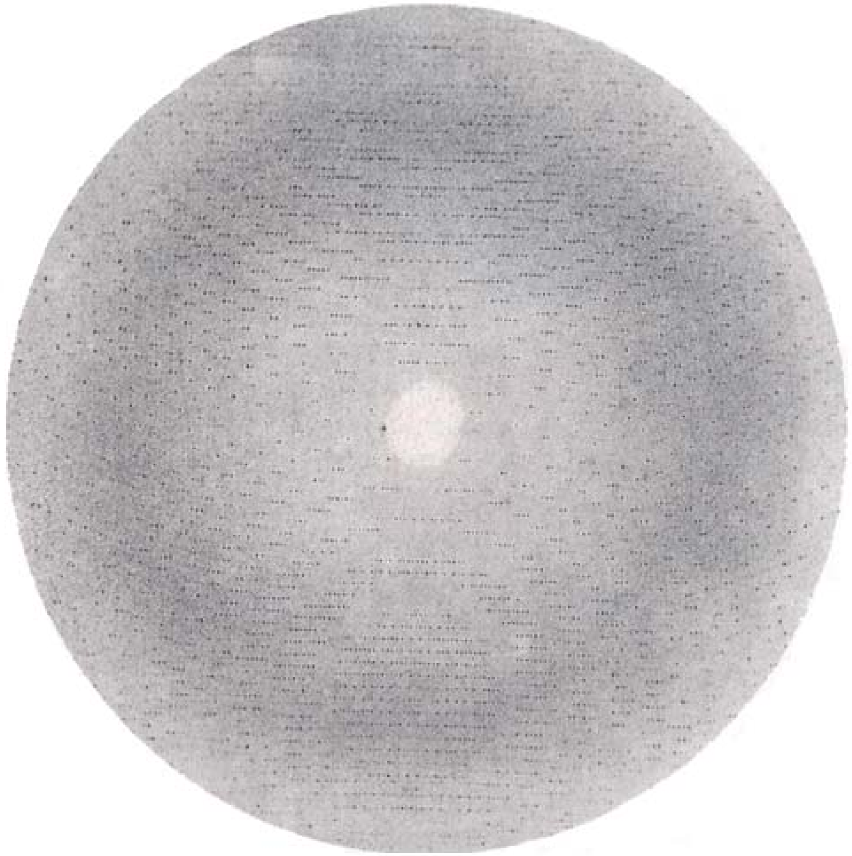
FINAL MODEL

Data from Peter Kuhn/Stanford

More on http://www.brunel.ac.uk/research/rose/3D

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



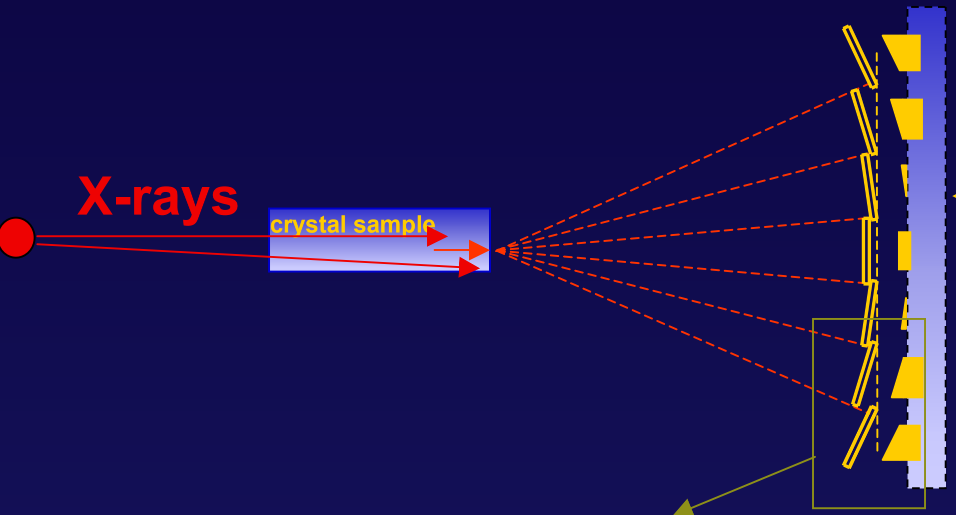


3D pixel detectors x-ray setup (3DX project)

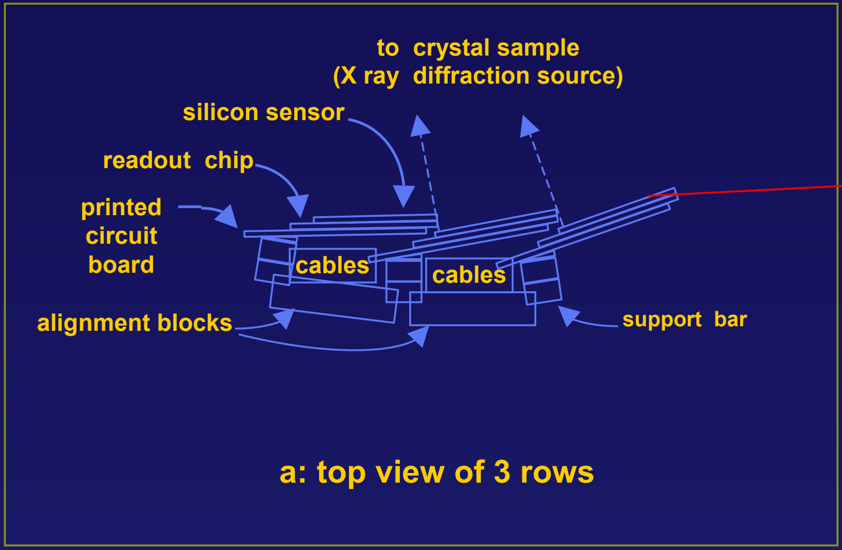
E. Westbrook et al. (molecular biology consortium) USA

3D

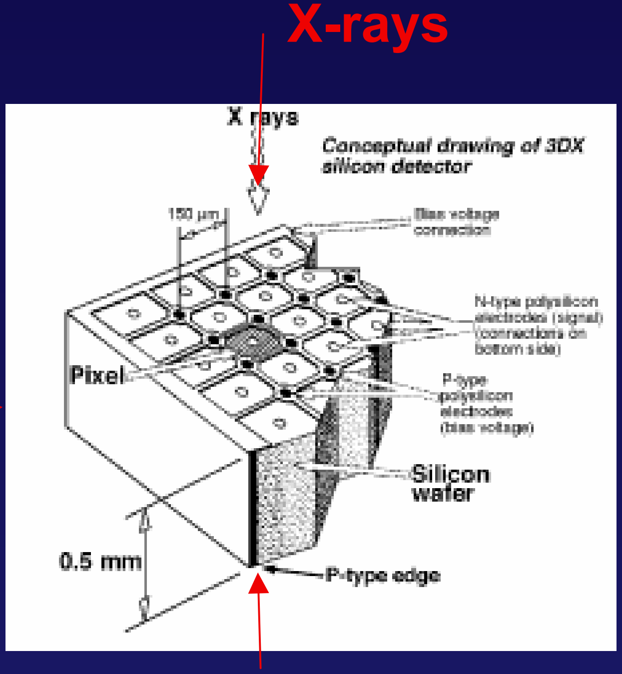
- ❖High signals
- ❖Low noise
- ❖Moderate cost
- ❖High speed



support bar
(behind plane of sensors)



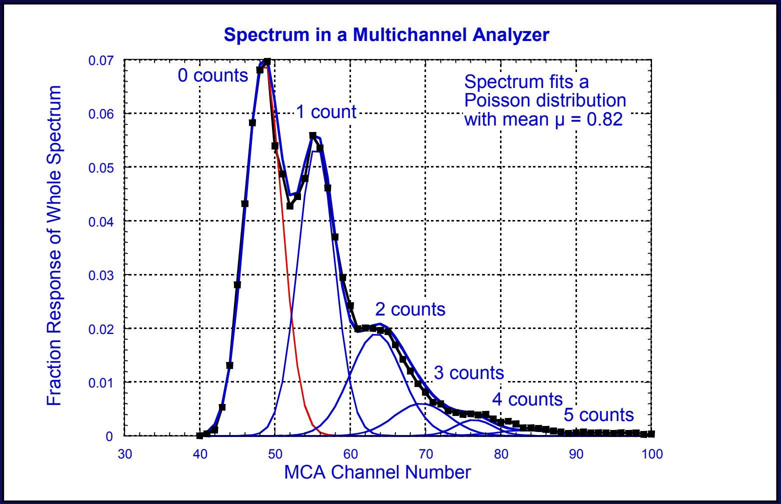
a: top view of 3 rows



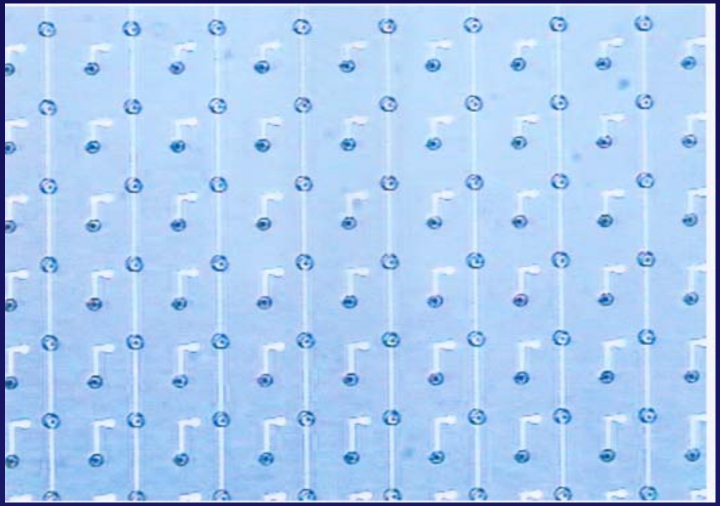
Bump bond to pixel readout electronics

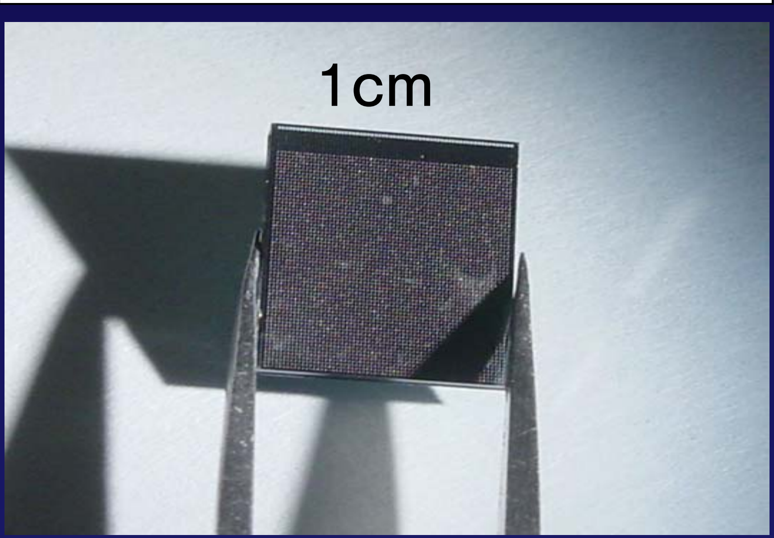
C. Da Via' Sept. 2005

3D sensors 64x64 pixel array designed At LBL- Berkeley (MBC)



Electron micrograph of actual sensor chip, with electrodes and bump-bonding pads





One complete sensor, with indium bumps

Conclusions

3D

- ❖ MEMS TECHNOLOGY SUCCESSFULLY USED TO MANUFACTURE 3D AND PLANAR-3D SILICON DETECTORS
- ❖ FAST (3,5 ns and 1.5 ns RISE TIME AT 20 ^{o}C)
- ❖ LESS CHARGE SHARING-IMPROVED ENERGY RESOLUTION AT ANY SUBSTRATE THICKNESS
- ❖ ACTIVE EDGES MEASURED TO BE < 4 μm WITH X-RAYS AND MIPS – LARGE AREA IS POSSIBLE
- ❖ TEST BEAM RESULTS WITH LHC ELECTRONICS VERY ENCOURAGING
- ❖ WILL BE USED TO STUDY PROTEIN FOLDING (2007) JOINING MEDIPIX COLLABORATION
- ❖ IN THE TOTEM EXPERIMENT AT THE LHC (2007)
  TOTEM-TDR-001 CERN-LHCC-2004-002
  FP420 Candidate for 400m upgrade in 2008-09
- ❖ PROMISING TECHNOLOGY FOR FUTURE LHC UPGRADE DEVICES ALREADY BUMP BONDED TO ATLAS-PIXEL RO