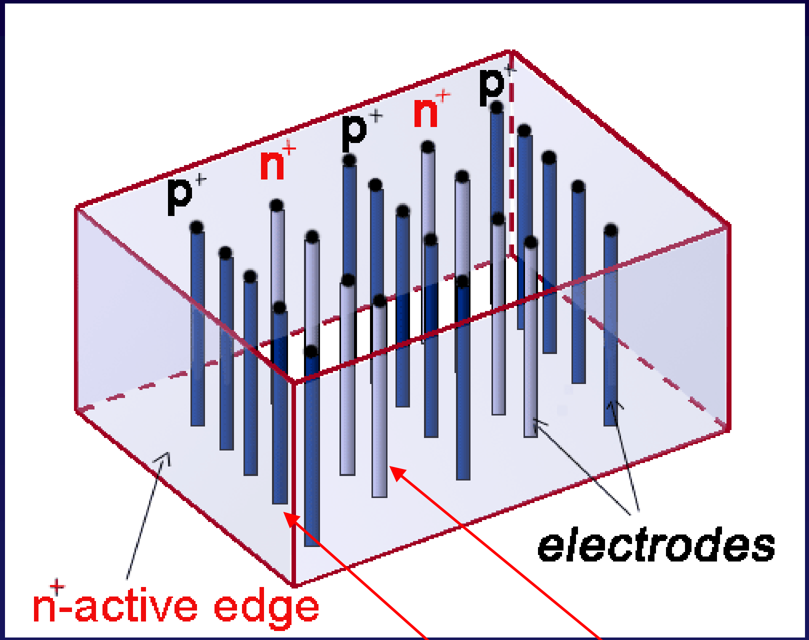
SILICON DETECTORS

Cinzia Da Vià, The University of Manchester, UK

GianFranco Dalla Betta, Marco Povoli ,M. Boscardin, J. Hasi, A. Kok, G. Pellegrini,
C. Kenney, S. Parker, G. Darbo, S. Grinstein, P. Grenier

and the 3DATLAS R&D Collaboration

3D Silicon sensors .. the beginning



Centre for Integrated Systems

Stanford Nanofabrication Facility

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

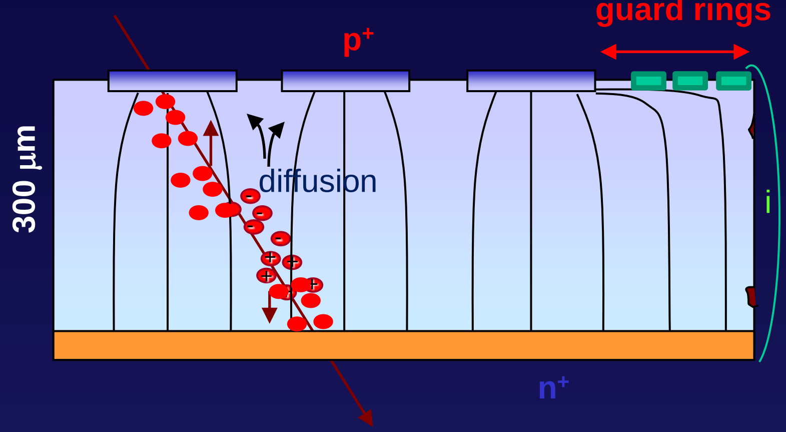
Combine traditional VLSI processing and MEMS (Micro Electro Mechanical Systems) technology.

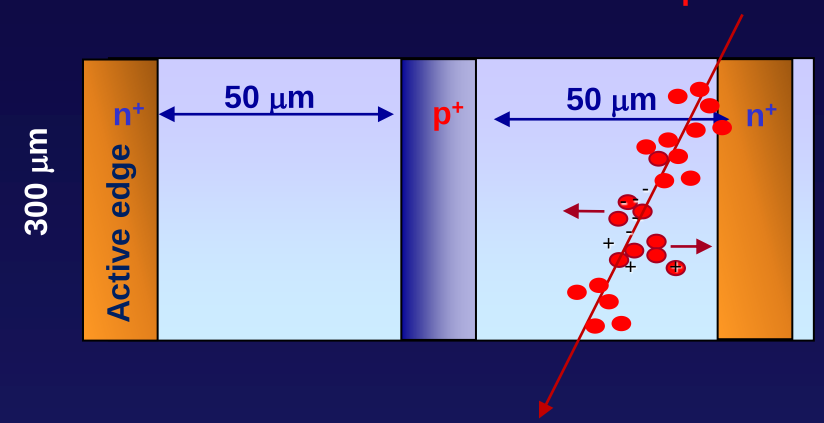
Electrodes are processed inside the detector bulk instead of being implanted on the Wafer's surface.

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

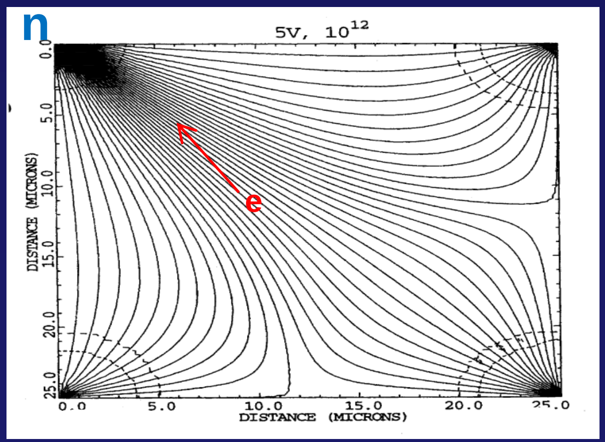
3D versus planar detectors (not to scale)





	3D	planar
❖DEPLETION VOLTAGES	< 10 V	70 V
❖After irradiation	180 V	1000V
❖Power dissipation	goes with V	goes with V
❖EDGE SENSITIVITY	< 5 µm	200 µm
❖CHARGE 1 MIP (300 mm)	$24000e^-$	$24000e^-$
❖CAPA CITANCE	30-50f	~20fF
❖COLLECTION DISTANCE	~50 µm	200 µm
❖SPEED	1-2 ns	10-20 ns

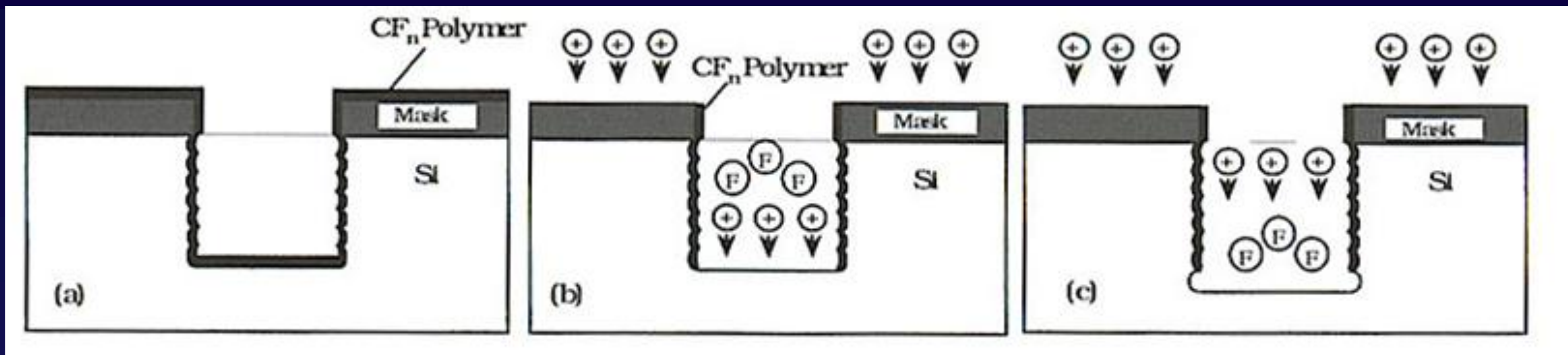
MEDICI simulation of a 3D structure



Drift lines parallel to the surface

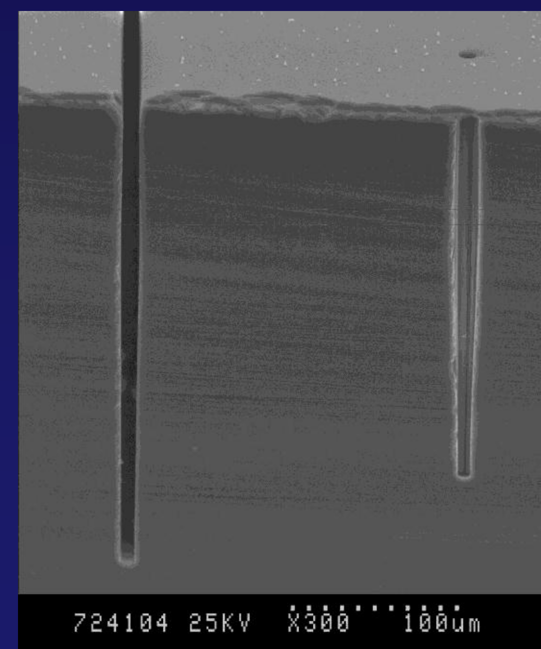
3D has Lower charge sharing probability

The key to fabrication: plasma etching



BOSCH PROCESS: alternating passivation (C_4F_8) and etch cycles (SF_6):

- Within the plasma an electric field is applied perpendicular to the silicon surface.
- The etch cycle consists of fluorine based etchants which react with silicon surface, removing silicon. The etch rates are ~1-5µm/minute.
- To minimize side wall etching, etch cycle is stopped and replaced with a passivation gas which creates a Teflon-like coating homogenously around the cavity. Energetic fluorine ions, accelerated by the e-field, remove the coating from the cavity bottom but NOT the side walls.

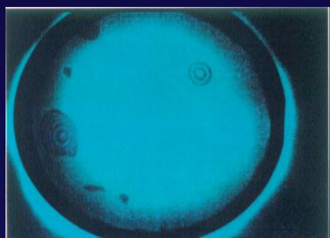


Slide from J. Hasi

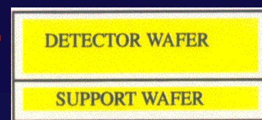
Further micro-fabrication steps

1- etching the electrodes 2-filling them with dopants

Aspect ratio: D:d = 11:1

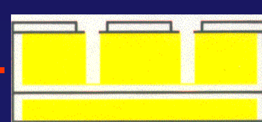


WAFER BONDING
(mechanical stability)
Si-OH + HO-Si -> Si-O-Si + H_2O

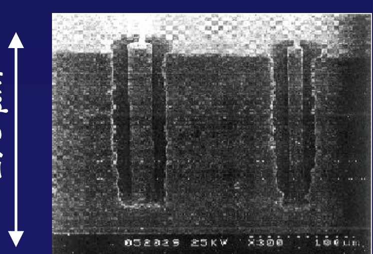


Step 1-3 oxidize and fusion bond wafer

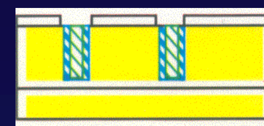
Step 4-6 pattern and etch p^+ window contacts



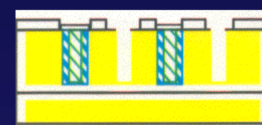
Step 7-8 etch p^+ electrodes



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

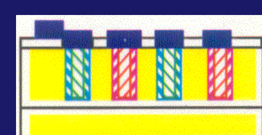


Step 9-13 dope and fill p^+ electrodes

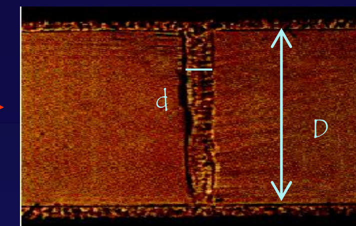


Step 14-17 etch n^+ window contacts and electrodes

Step 18-23 dope and fill n^+ electrodes

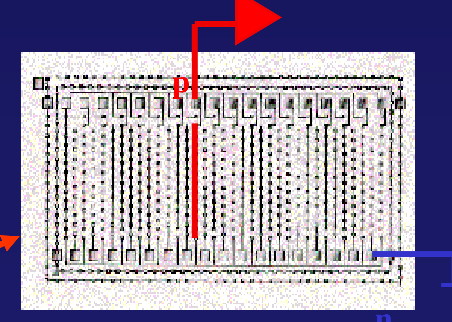


Step 24-25 deposit and pattern Aluminum



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

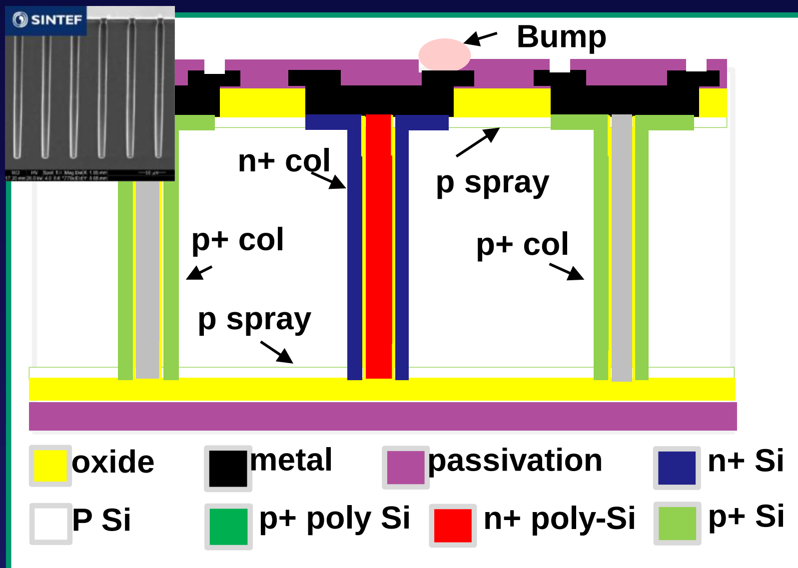
Both electrodes appear on both surfaces



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

Cinzia Da Vià, Manchester, Pisa Meeting 2012, La Biodola, 24 May 2012

Existing 3D designs:

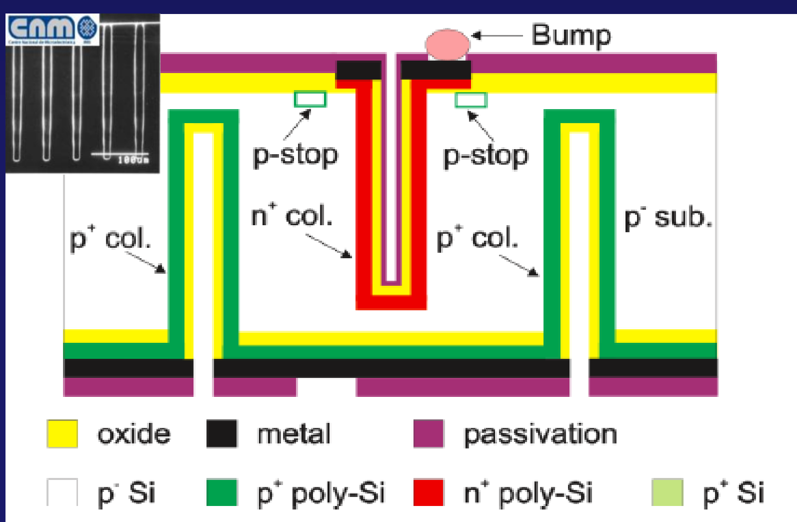


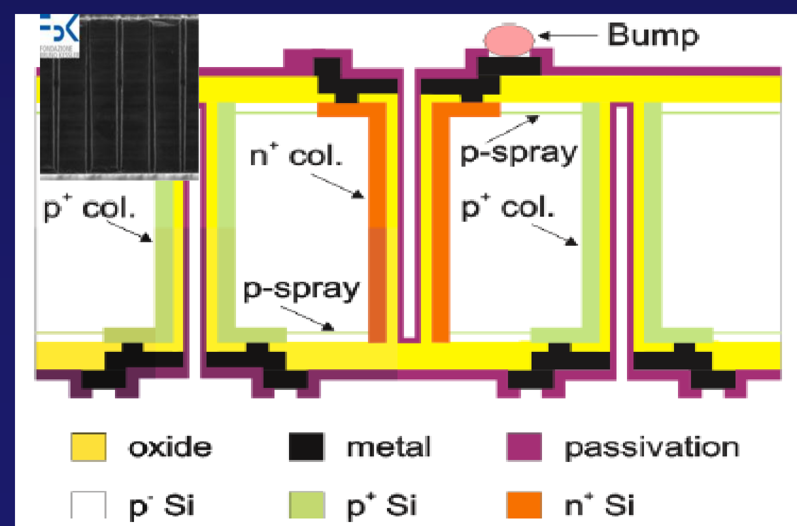
The Stanford Nanofabrication Facility
SINTEF

Single side, full 3D with active edges requires a support wafer which is removed later

ITC irst
FONDAZIONE BRUNO KESSLER
CNM
Centre Nacional de Microelectrònica

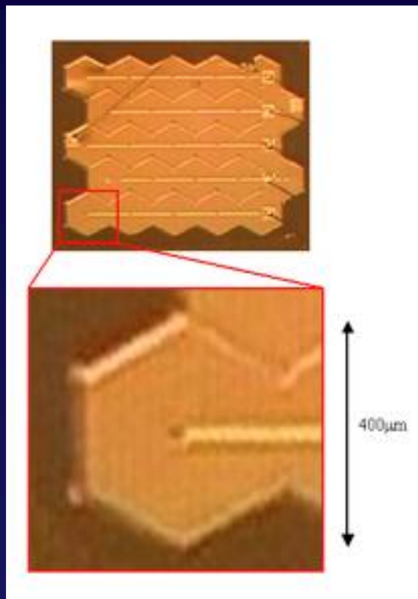
Double sided full or partially through3D with slim-fences (~200um)

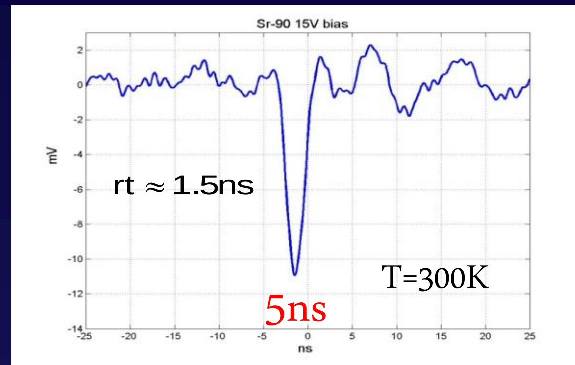


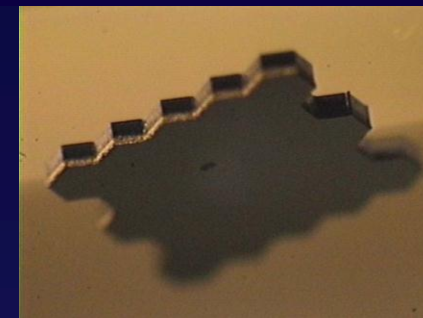


Different shapes depending on applications

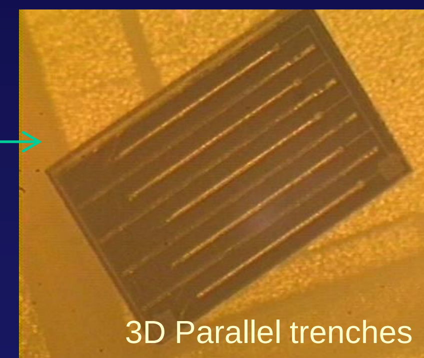
Test with -.130nm fast amplifier designed at CERN by G.(Anelli)

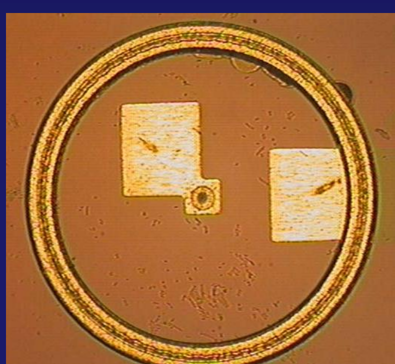


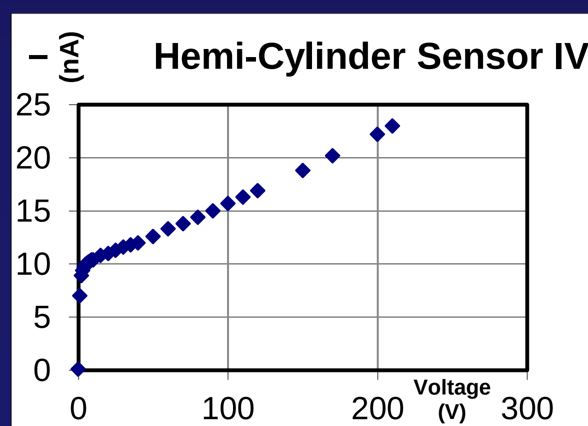


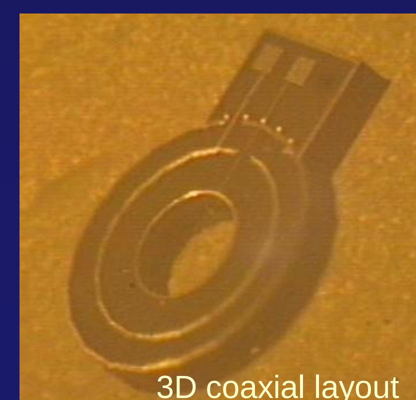


Hexagonal or parallel trench shapes:
Enhanced speed









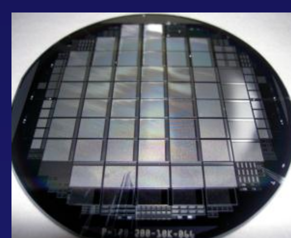
Fabrication J. Hasi and C. Kenney, SLAC/Stanford

3D sensors bump-bonded with pixel frontends

G. Pellegrini et al.Nucl. Instr. Meth. In Phys. Res. Volume 504, Issues 1–3, 21 May 2003, Pages 149–153

Fabricated at CNM Now also being fabricated at FBK and SINTEF applications is synchrotron light sources and Neutron imaging

Medipix2 and Timepix (see LHCb upgrade talk on Monday)



FE-I3 wafer from Stanford also fabricated At SINTEF, CNM, FBK

ATLAS FE-I3

P. Hansson et al. Nucl. Ins. And Meth. In Phts Res. A 628 (2011) 216–220

CMS (see poster by M. Obertino et al.)

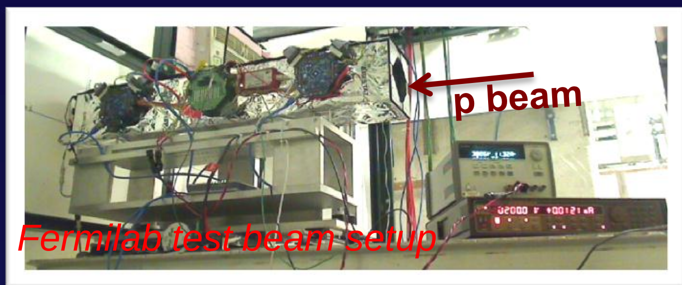
3D pixel sensors with CMS readout

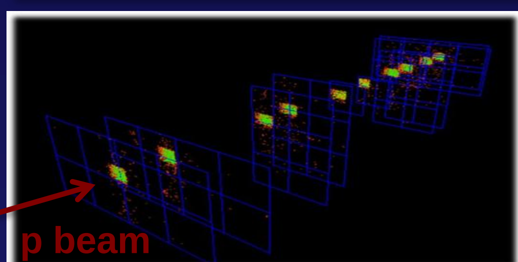
3D pixel sensors compatible with the CMS PSI46 readout chip were first fabricated at SINTEF (Oslo, Norway), and more recently at FBK (Trento, Italy) and CNM (Barcelona, Spain). Collaboration with ATLAS for the sensor production.

S. Kwan, A. Prosser, R. Rivera, L. Uplegger E. Alagoz, K. Arndt, G. Bolla, D. Bortoletto, M. Bubna, A. Krzywda, I. Shipsey. M. Obertino, A. Solano, A. Vilela Pereira, M. Boscardin, G-F. Dalla Betta, M. Povoli, D. Menasce, L. Moroni, J. Ngadiuba, S. Terzo, A.Kumar, R. Brosius I. Osipenkov, P. Tan, L. Perera, S. Wagner F. Jensen J. Andresen MC Lei

Strong collaboration among different institutions to test 3Ds with the aim of choosing a technology for pixel upgrade and forward tracking detectors at CMS.

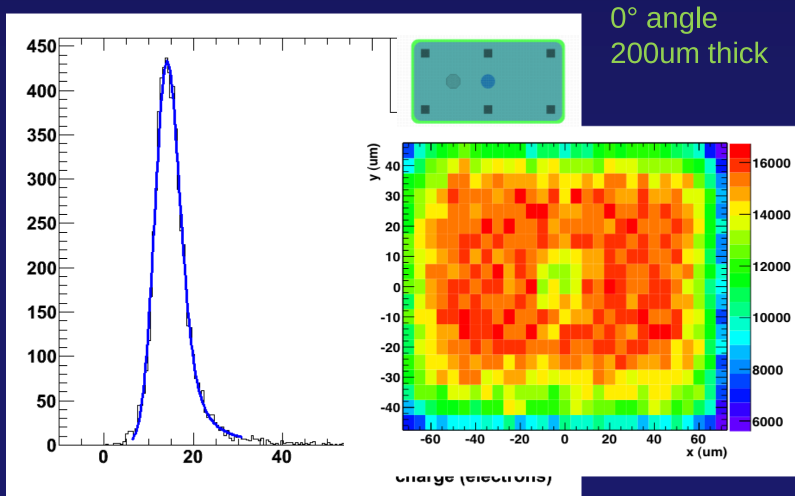
Cinzia Da Viá , Manchester, Pisa Meeting 2012, La Biodola, 24 May 2012





Purdue cold setup

Detectors tested at Fermilab with 120 GeV/c proton beam before and after irradiation



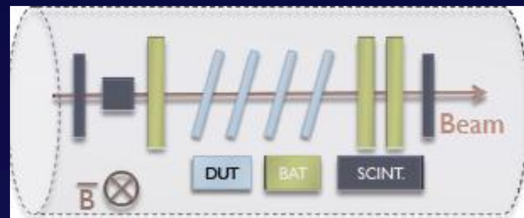
0° angle
200um thick

Charge collection
As expected in 200 mm thick silicon (~16 ke^-) when the track hits the central part of the pixel; elsewhere reduced by the combined effect of charge sharing and readout chip threshold (~2500-3000 e^-).

Efficiency
97.5% at 0°; increasing by tilting the sensor of 20° with respect to the beam

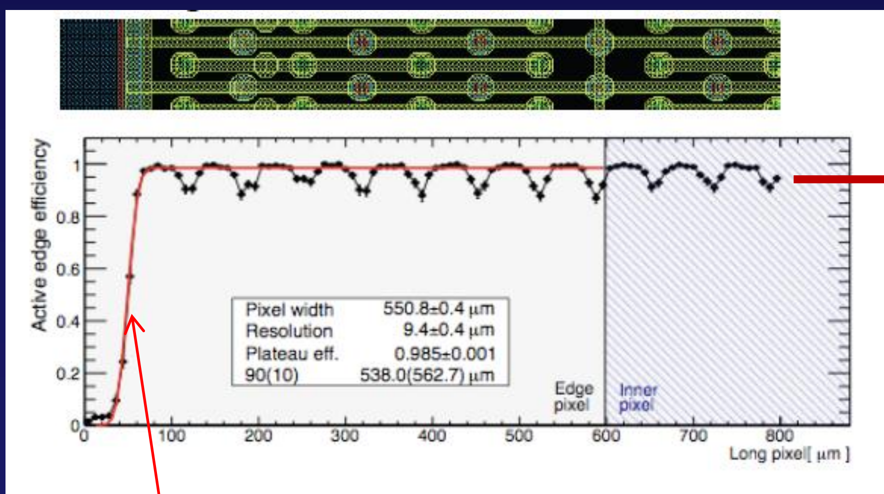
Spatial resolution
~11 (~13) mm in the best (worse) direction at 20°

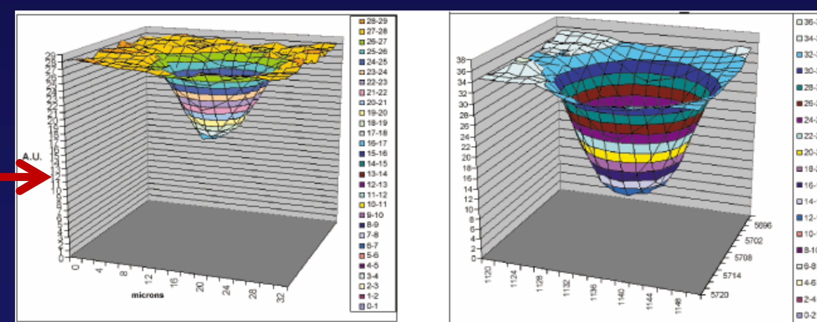
Full 3D with active edges FE-I3 ATLAS



2 um, 14 KeV X-Rays beam at ALS (Berkeley)

120 GeV pions at CERN SpS





N – Electrode

Signal Reduction 43%

P – Electrode

Signal Reduction 66%

Differences between N and P:

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

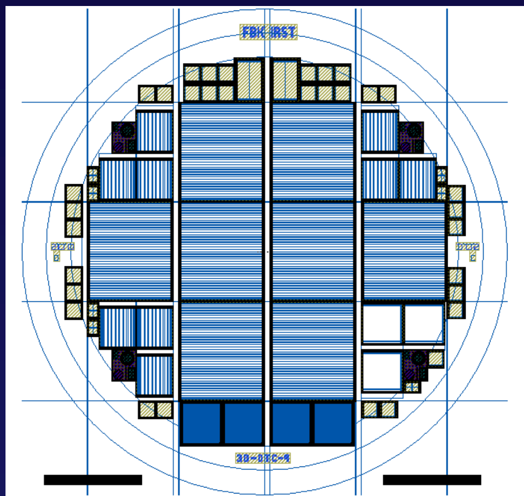
Active Edge = 543-537= 6±9.8 μm

Electrodes response is not zero if filled with poly-silicon

P. Hansson et al. Nuclear Instruments and Methods in Physics Research A 628 (2011) 216–220

J. Hasi PhD Thesis

Industrialization strategy: common floorplan

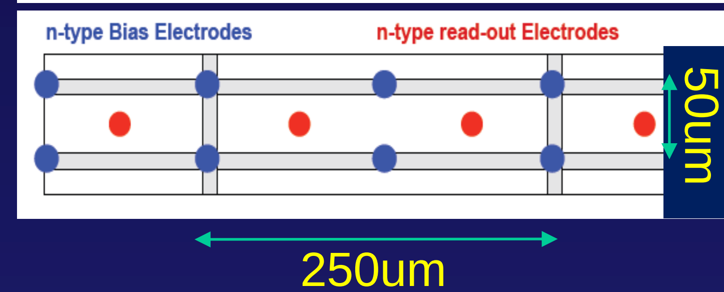


8 FE-I4
3 FE-I3
9 FE-I3
Other structures

Qualification made at FBK-CNM, SINTEF Stanford

Final selection due To limited timescale CNM and FBK

Item	Sensor Specification
Tile type	single
Number of n^+ columns per 250 μm pixel	2 (so-called 2E layout)
Sensor thickness	230 ± 20 μm
n^+-p^+ columns overlap	> 200 μm
Sensor active area	18860 μm $\times$ 20560 μm (including scribe line)
Dead region in Z	< 200 μm guard fence $\pm$ 25 μm cut residual
Wafer bow after processing	< 60 μm
Front-back alignment	< 5 μm

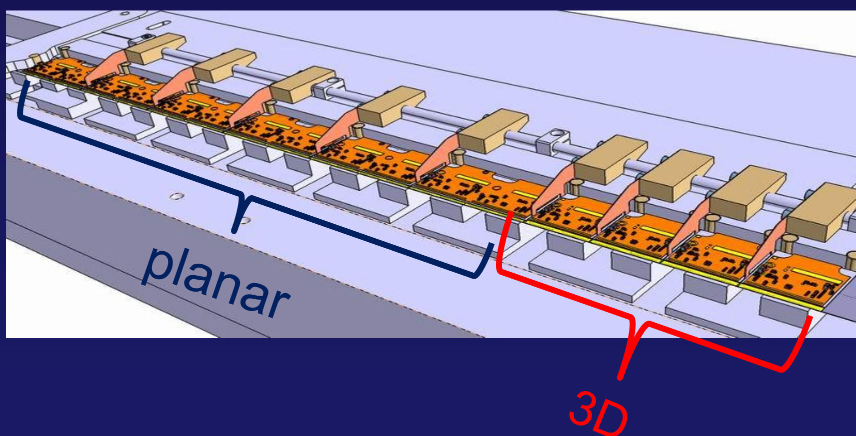


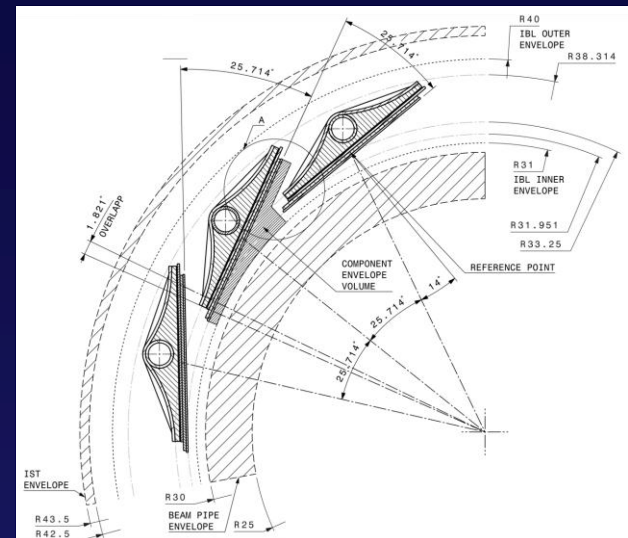
4 runs were completed in February 2012 by CNM and FBK
With 306 good chips. And a total of ~ 100 wafers

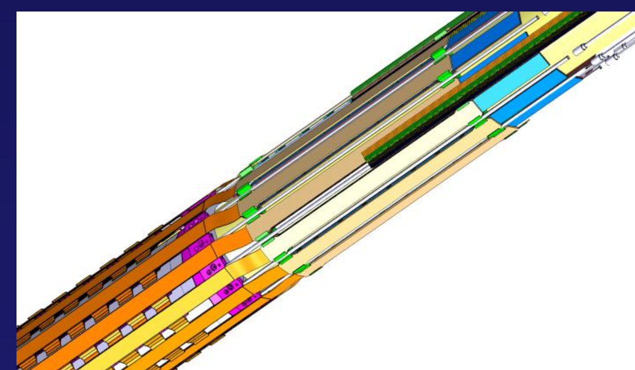
2 more runs are being completed for extra spares and the Atlas Forward Physics (AFP) project in LHC PH1

Atlas IBL see talk from D. Ferrere

- **Baseline layout approved**
  - **14 Staves,**
  - **32 FE chips/stave**
  - **For 3D single chips**
  - **(224 to build 25%)**
  - **For planar double chips (448 to build 75%)**



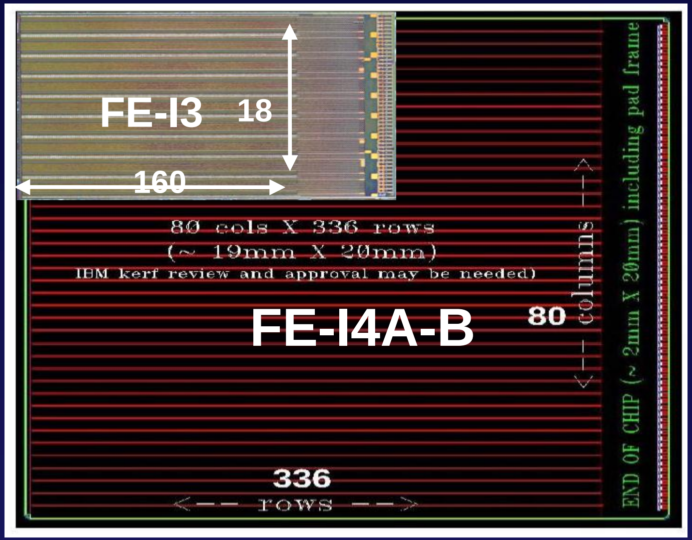


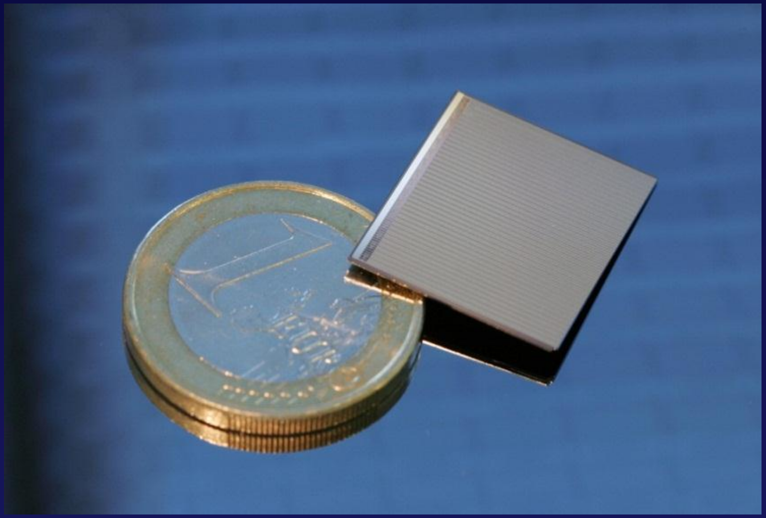


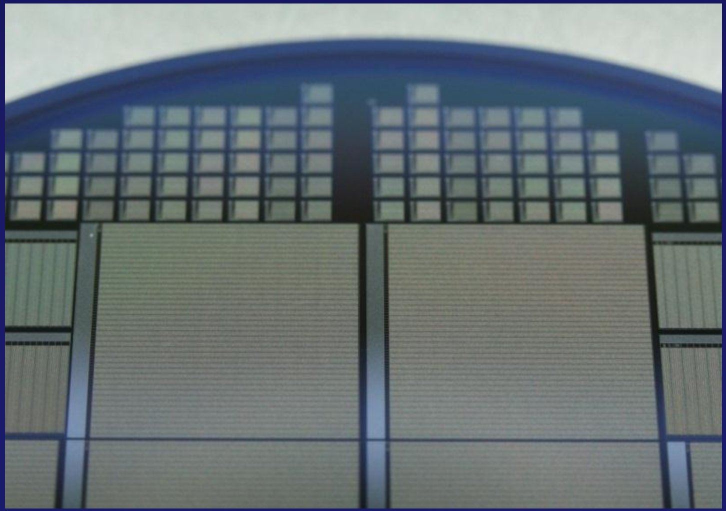
Layout parameters:
- IBL envelope: 9 mm in R
- <R> = 33 mm.
- Z = 60 cm (active length).
- η = 2.5 coverage.

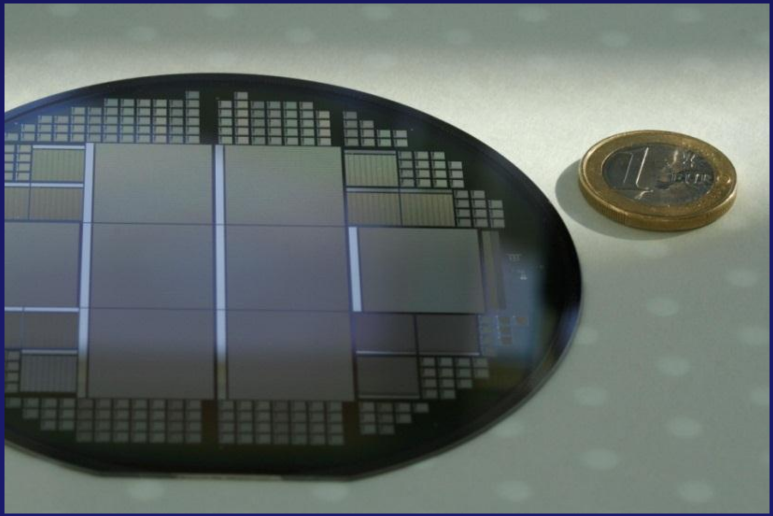
ATLAS FE-I4

pixel size: 250x50um2
total dimension FE-I4: 20.2x19.0mm2
total pixel number: 26880
Total number of holes/chip : >100.000







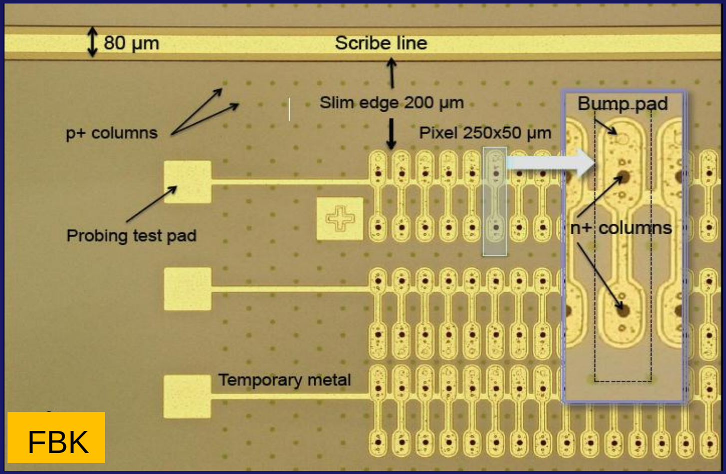


3D sensors Selection Parameters

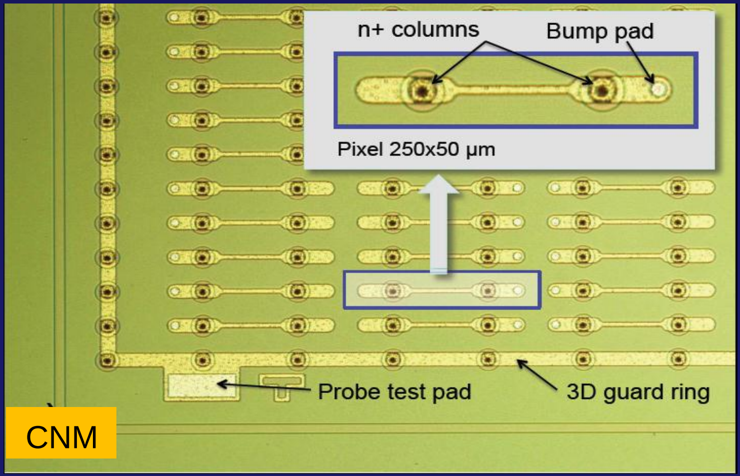
The following specifications are required to qualify a 3D device as functioning correctly before bump-bonding:

- Operation at room temperature (20–24 °C)
- Vdepl ≤ 15V
- Vop ≥ Vdepl +10V where Vdepl is the full depletion voltage.
- Current at 20 – 24 °C at operation voltage: I (Vop) < 2μA per sensor
- For GR measurement (CNM): IGR (Vop) < 200nA per sensor
- Breakdown voltage: Vbd > 25V
- Slope: [I(Vop)/I(Vop-5V)] < 2

I-V measurements are performed on each sensor on wafer with a probe station by the manufacturer using either a temporary metal or by probing the guard ring current



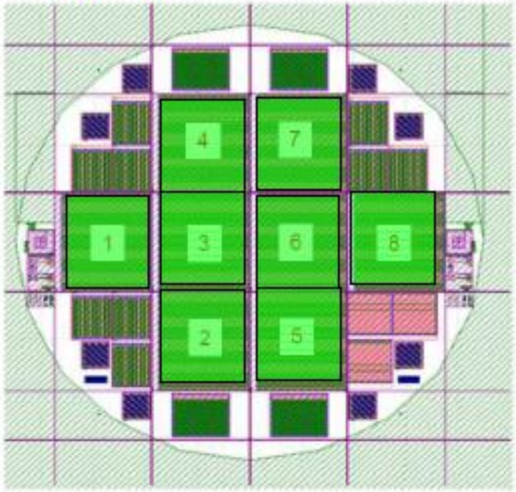
FBK temporary metal probes 336 pixels in each of the 80 rows

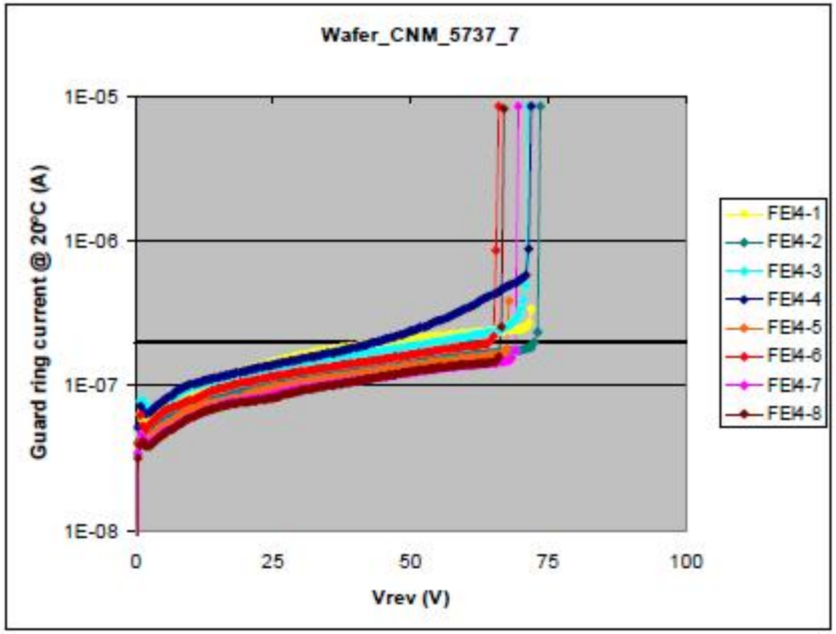


CNM probes the guard ring current

3D IBL production QA

Batch: 5737
Wafer: 7





	Class	GR current @ 25 V (nA)	I(25V) / I(20V)	Breakdown V (V)
S1	A	145.18	1.13	71
S2	A	102.12	1.10	72
S3	A	132.70	1.09	69
S4	A	139.88	1.10	71
S5	A	96.12	1.14	67
S6	A	116.11	1.09	65
S7	A	86.76	1.09	69
S8	A	82.57	1.07	66

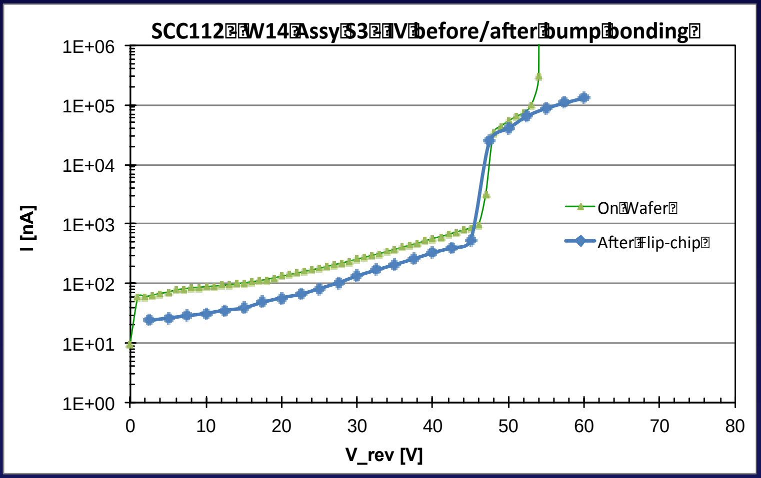
bowing

Wafer curvature: 60.8µm

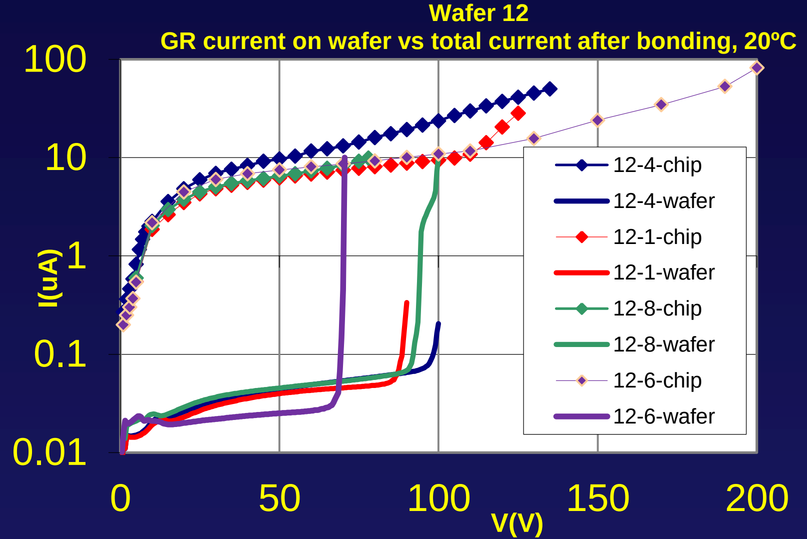
class A detectors: 8
class B detectors: 0
class C detectors: 0

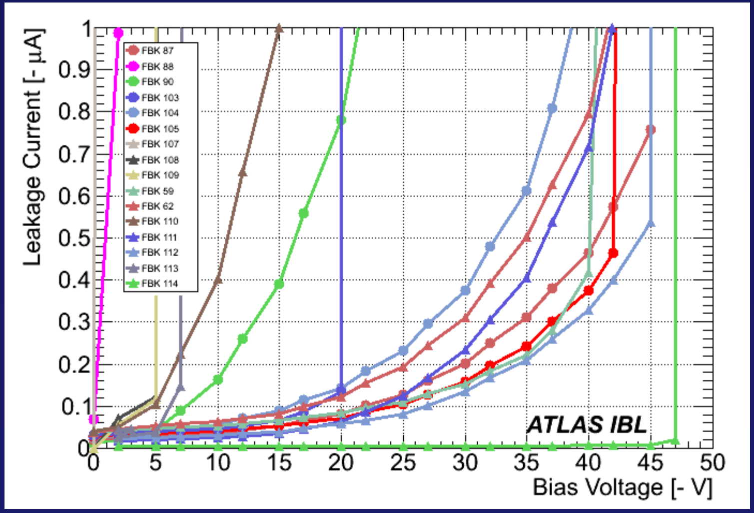
IV before and after bump-bonding

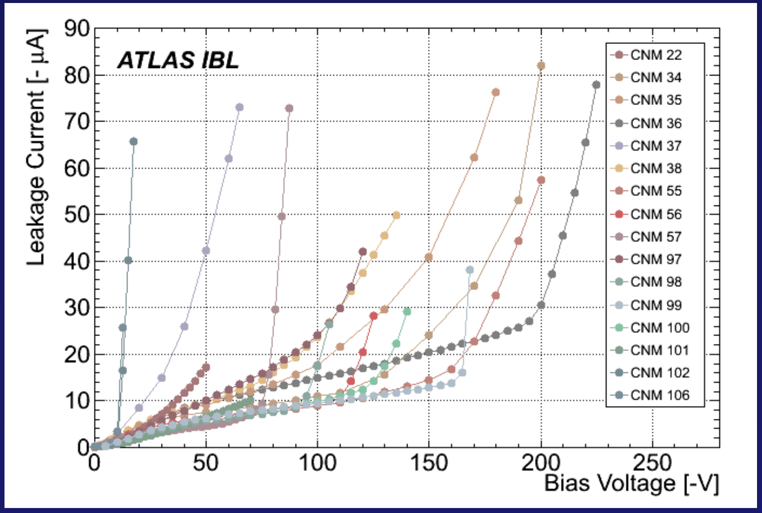
N. Zorzi, G. Giacomini, D-L. Pohl, G. Darbo



C. Fleta. S. Grinstein, G. Pellegrini







Cinzia Da Viá , Manchester, Pisa Meeting 2012, La Biodola, 24 May 2012

Radiation Hardness of 3D sensors

$\lambda = \tau \times v$

Drift length = Trapping time × Drift Velocity (saturated)

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

L= Inter-Electrode Spacing

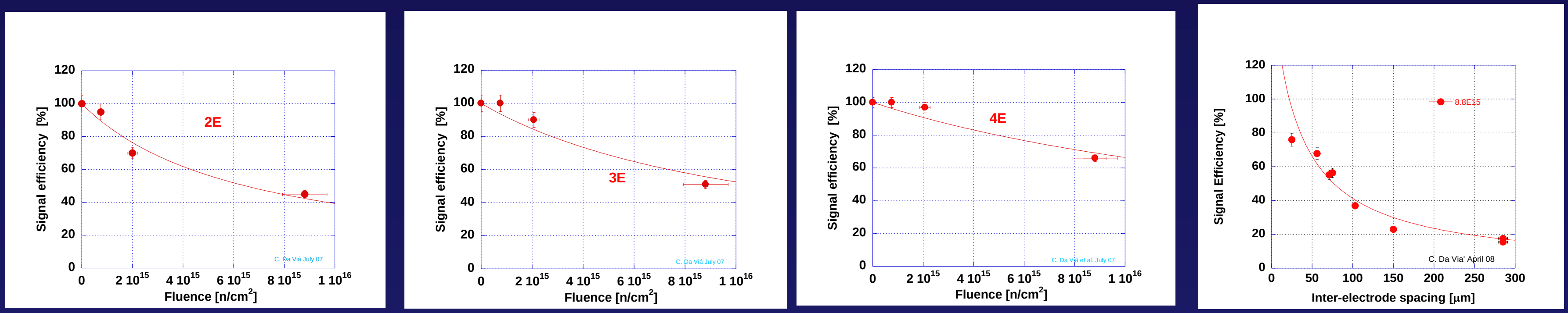
Cinzia Da Viá , Manchester, Pisa Meeting 2012, La Biodola, 24 May 2012

2E = 103um

3E= 71um (IBL DESIGN)

4E= 56um

5E= 47um



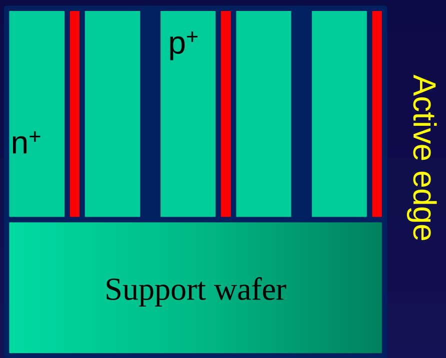
At 9×10^{15} ncm $^{-2}$

L=IES [um]	105	71	56	47
Signal Efficiency %	45	51	66	68
Charge 50um e-	1800	2040	2640	2720
Charge 100um e-	3200	4080	5280	5440

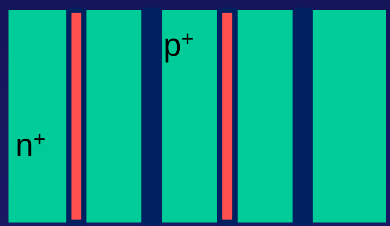
Nucl. Instrum. Meth. A 603 (2009) 319-324

3D sensors signal efficiency compatibility

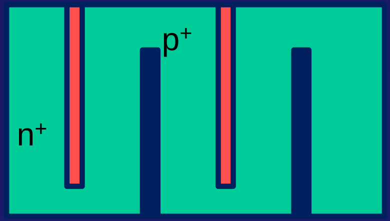
Cinzia Da Viá , Manchester, Pisa Meeting 2012, La Biodola, 24 May 2012



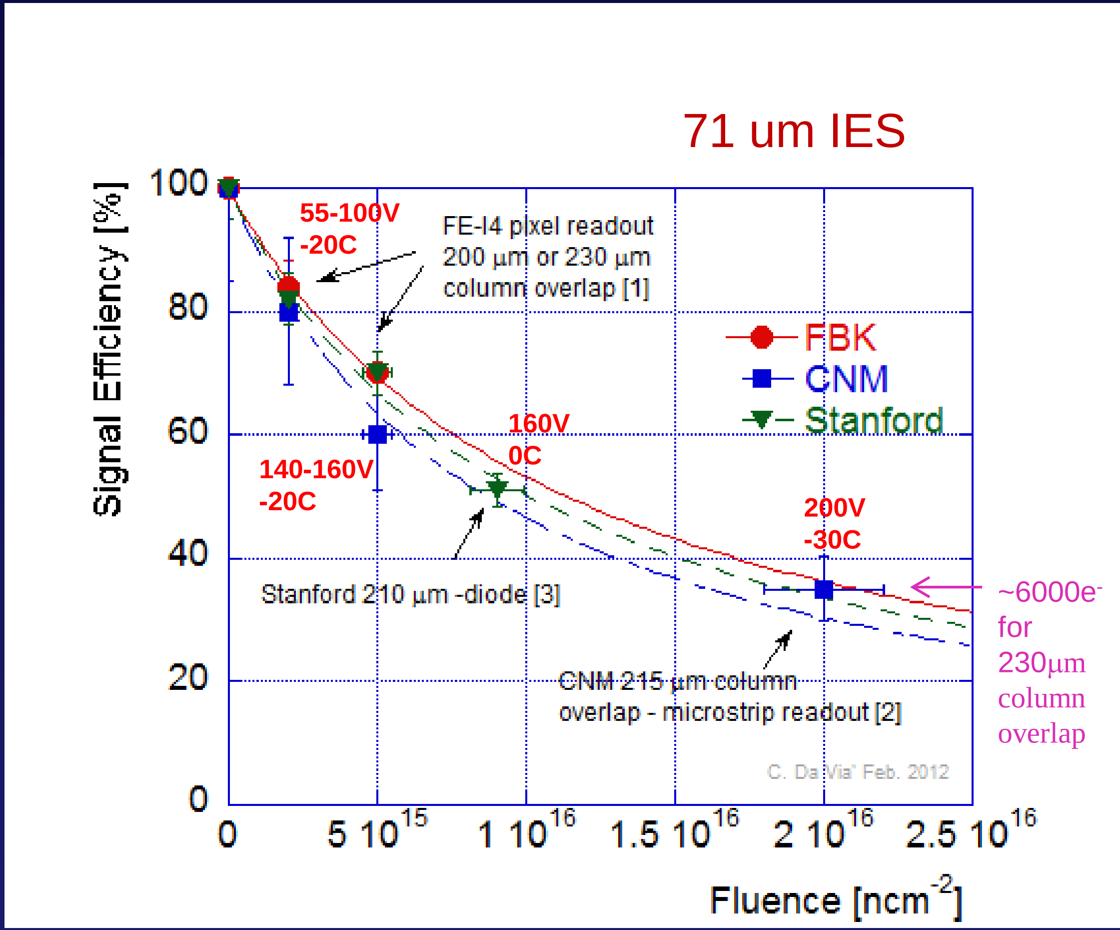
SINTEF/STANFORD



FBK



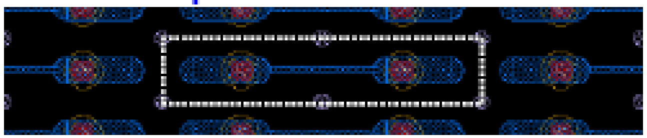
CNM

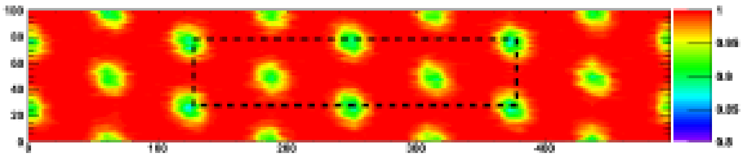


[1] 2011 CNM-FBK IBL Modules. (C. Gemme, A. Micelli, S. Grinstein, lab tests) (test beam coordinated by P. Grenier, J. Wingarted, A. La Rosa) , to be published in JINST.
[2[ ]M. Kohler et al. IEEE Trans. Nucl. Scie. Volume 57, issue 5, 2010
[3] C. Da Via, et al., Nucl.Instrum.Meth.A604:505-511,2009

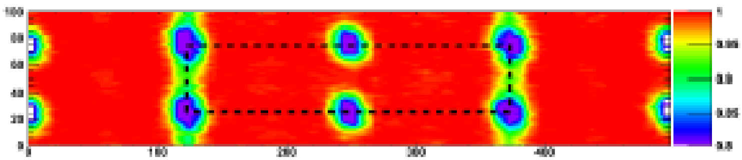
3D Performance after irradiation (see Prototype ATLAS IBL Modules using the FE-I4A Front-End Readout Chip, to be published on Jinst)

3D pixel sensors

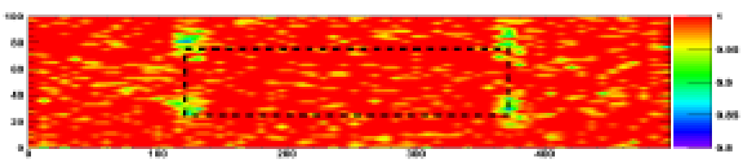




SCC105 FBK-3D, un-irrad, HV=20V, Eff.=98.77%



SCC81 CNM-3D, n-irrad HV=160V, Eff.=97.46%



SCC34 CNM-3D, p-irrad, HV = 160V, Eff.=98.96%

Threshold: 1600 e
p-irrad: 5×10^{15} n_{eq}/cm^2 with 24 MeV protons
n-irrad: 5×10^{15} n_{eq}/cm^2 by nuclear reactor

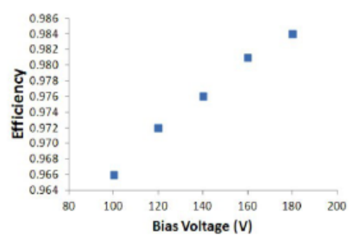
Ref.: IBL GM 2/2012 - Sh. Tsiskaridze / IFAE-Barcelona

Irradiation performed in Karsrhue and Ljubljana
Thanks to the Desy colleagues for the use of the EUDET telescope. Boards from Bonn, mounting in Bonn Genova and

Bias scan of 3D CNM device p-irradiated at 5×10^{15} n_{eq}/cm^2

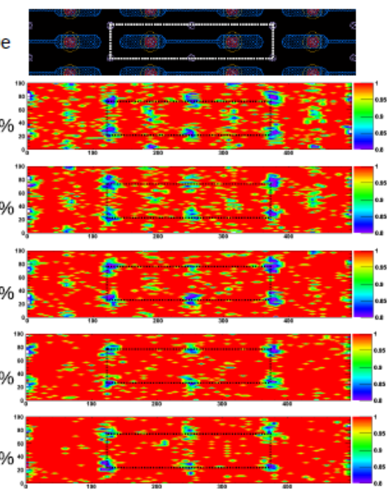
- *Thresh. = 1600e*
- *Angle = 0° (worst case for 3D)*

At ~160V inefficiency area associated to n+ column disappears



SCC34: p-irrad 3D CNM

TH: 1600e



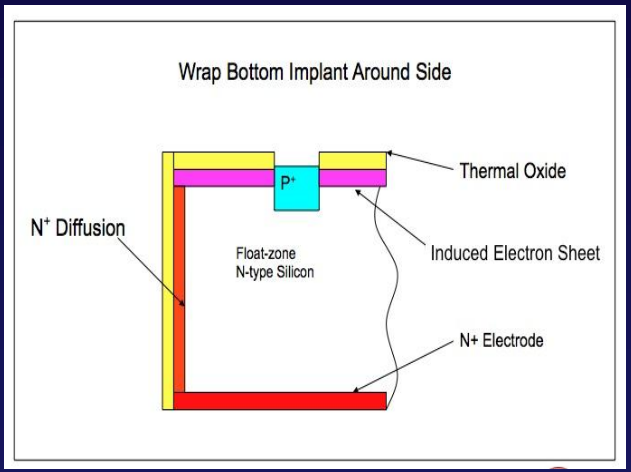
HV=100 Eff=96.6%
HV=120 Eff=97.2%
HV=140 Eff=97.6%
HV=160 Eff=98.1%
HV=180 Eff=98.4%

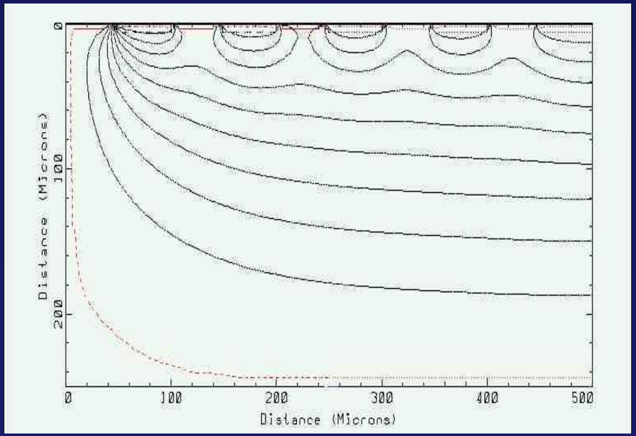
Ref.: IBL GM 2/2012 - Sh. Tsiskaridze / IFAE-Barcelona

Test beam with prototypes planar-active edge sensors for TOTEM data are reported in H. Niewiadomsky (CERN) PhD theisis

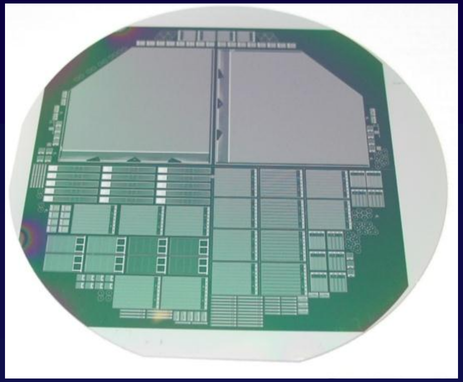
3D edges with planar central electrodes

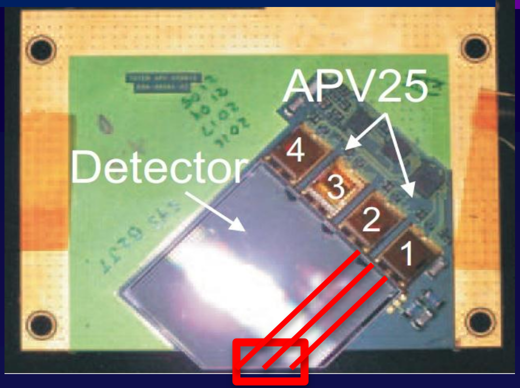
The principle: extend the backside electrode To the side, keeping the central electrodes planar

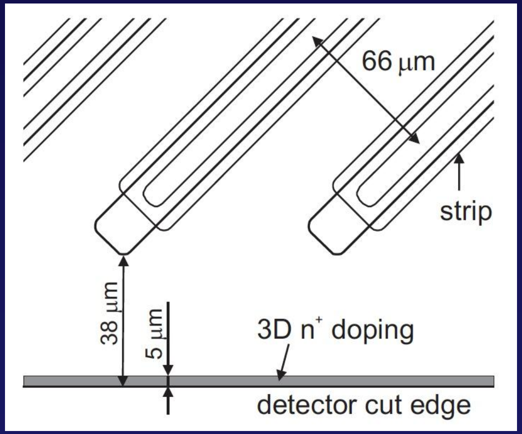


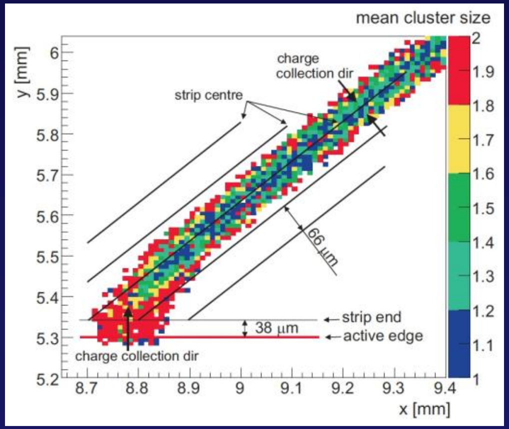


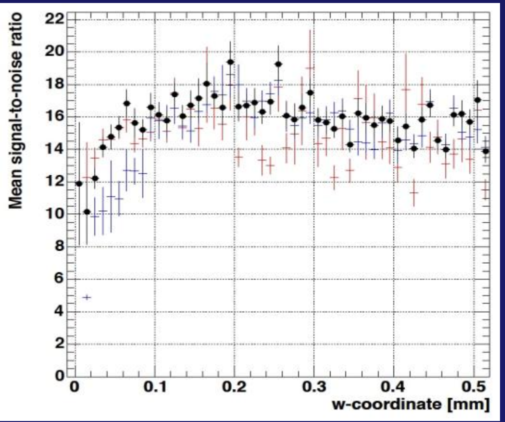
Simulated Equipotential lines: charge at the edge Is shared amongst few pixels











- Proposed by same 3D inventors in 1997. Data of fabricated samples: Nucl.Instrum.Meth.A565:272-277,2006
- Now several other groups/fabs making them:

>>See poster by Marco Povoli on FBK prototype sensors

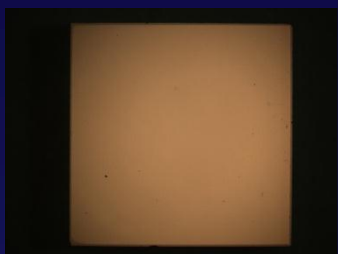
3D structures on diamond substrate

…the benefits of 3D with no noise for monitoring harsh environments

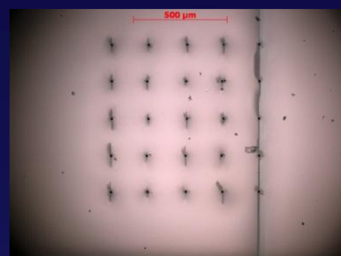
See poster from Benoit Caylar

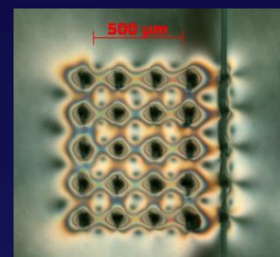
Alexander Oh (Manchester)
Benoit Caylar (CEA Saclay)
Michael Pomorski (CEA Saclay)
Thorsten Wengler (CERN)
Stephen Watts (Manchester)
Iain Haughton (Manchester)

Process flow



Single crystal diamond

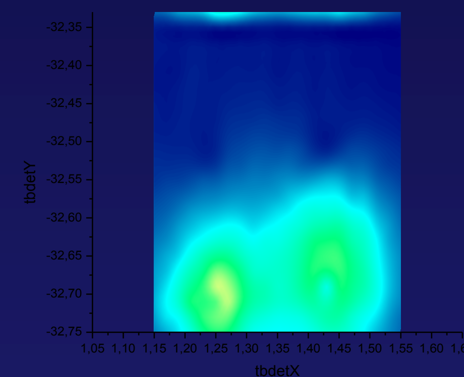




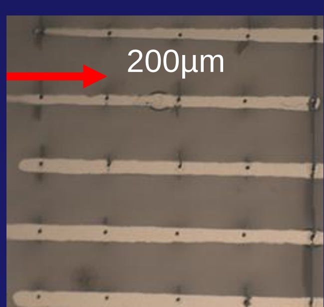
3D electrodes graphitization with an IR high power laser

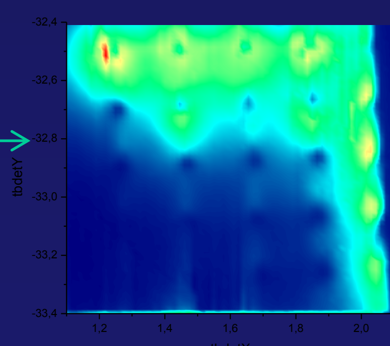
After metallization

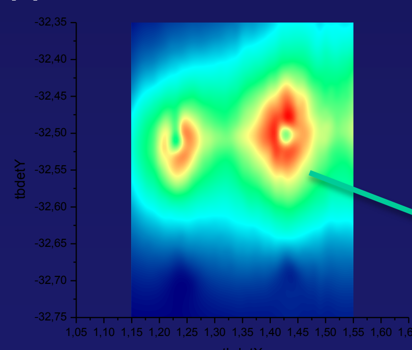
Samples from DDL
Processing made in Saclay and Manchester

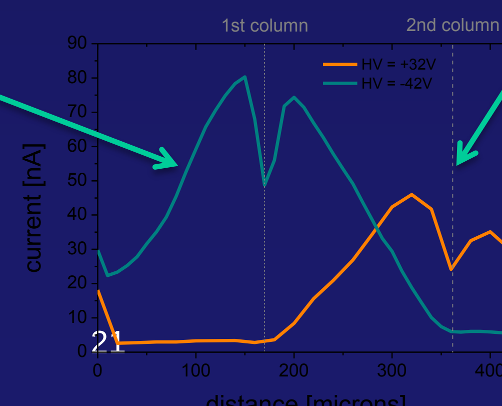


Mapping using at the DIAMOND synchrtron micro-beam
Spot size : 3µm /*/ Beam Energy : 15keV /*/ HV = -40V /*/ Absorber 24



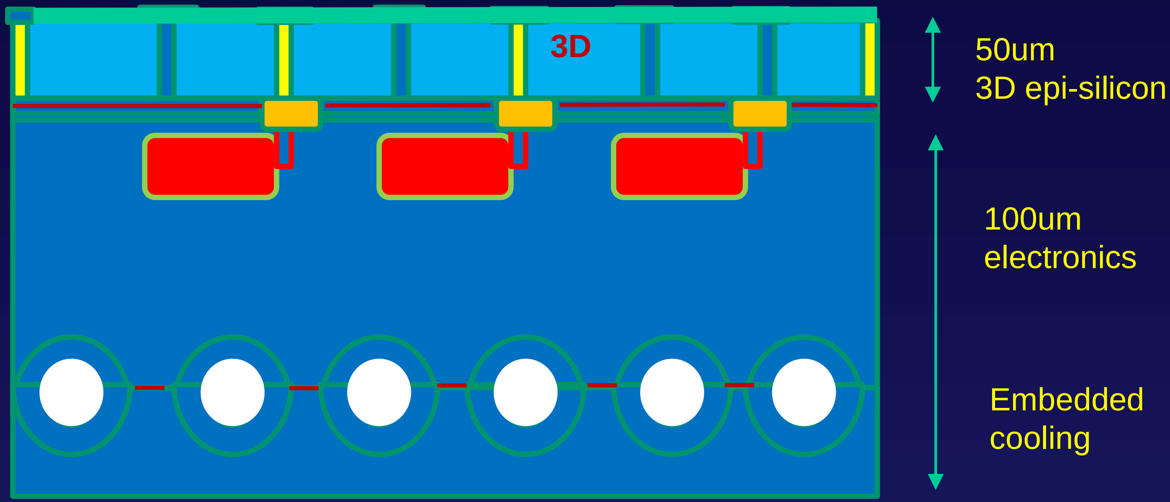




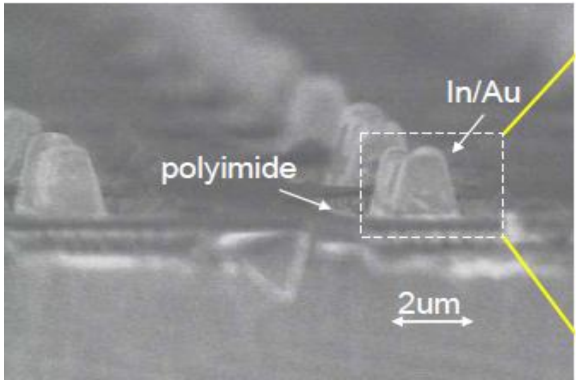


DIAMOND AND RELATED MATERIALS Volume: 20 Issue: 3 Pages: 398-402 DOI: 10.1016/j.diamond.2011.01.042 Published: MAR 2011

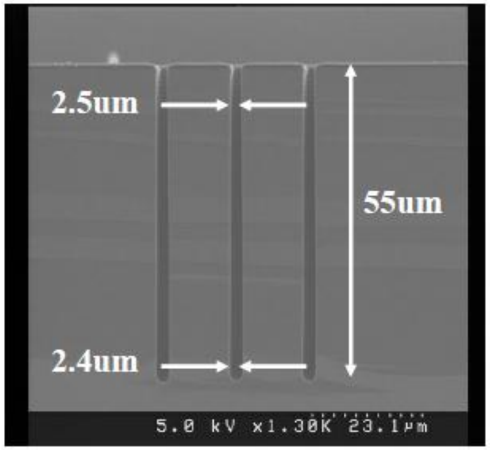
The future: Low mass 3D system



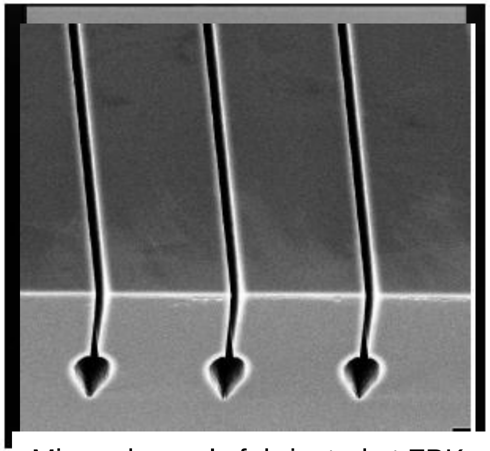
- Processing vias on thin silicon requires a support wafer
- In 3D Capacitance decrease with thickness
- EPI silicon can be grown up to 150um
- The EPI-Cz interface can stop etching
- The support wafer can be removed after bump bonding (or after UBM using reversible wafer bonding)



Tohuku University/Zycube
M. Motovoshi



T. Matsumoto and M. Koyanagi et al., SSDM, 1995.



Micro-channels fabricated at FBK
In collaboration with the Pisa group

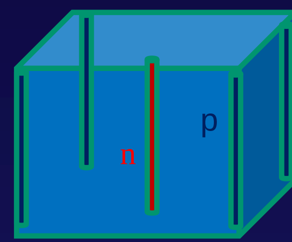
See poster by Boscardin, Bosi et al

Behaviour at reduced cell dimensions

How much signal can we expect?

Expected pixel dimension with 65nm technology

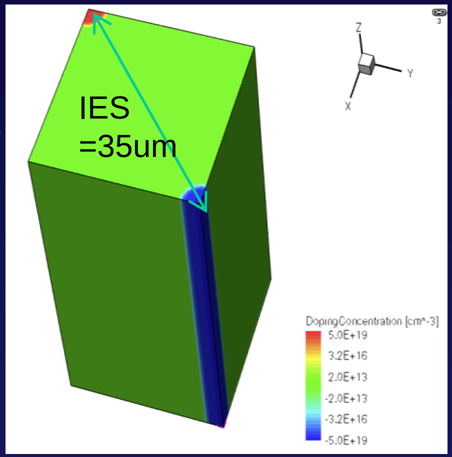
$50x50x50um^3$



Inter-Electrode Spacing=35um

Simulated structure:

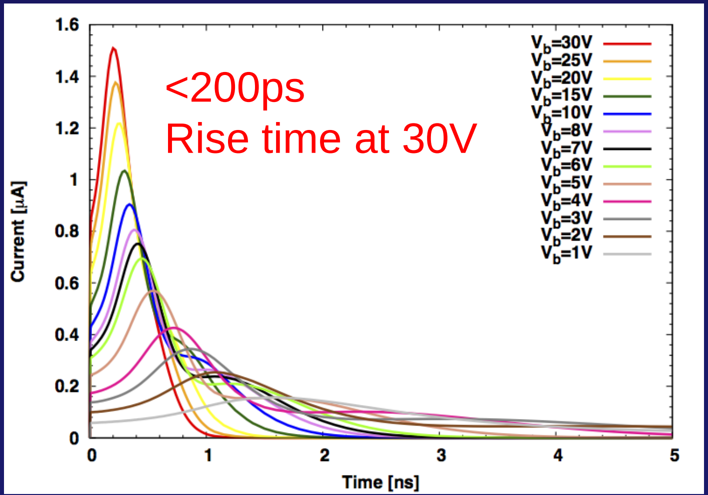
- 25x25x50um
- Electrodes diameter 3um
- MIP in the center

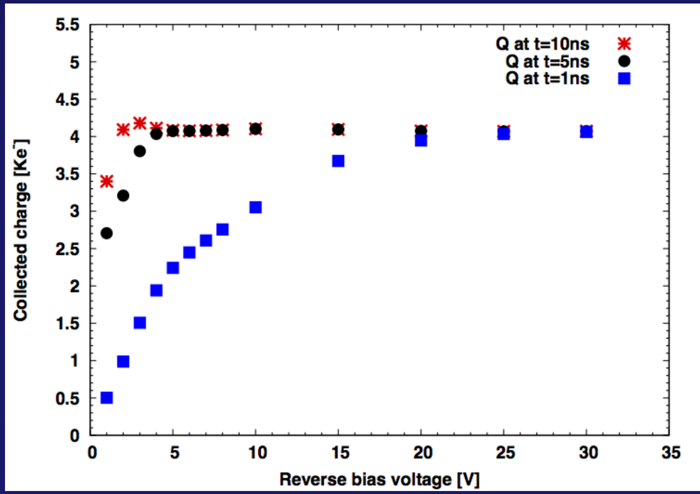


Simulation Marco Povoli, Trento/Manchester

- Expected charge in 50um silicon is equal to 4000 electrons
- Collected charge is reported at different integration times (1,5 and 10 ns)
- At 5 and 10ns integration time full collection is reached well before 5V of bias
- If the proper bias voltage is applied (e.g. 30V) devices can collect full charge in less than 1ns

PRE-IRRADIATED RESPONSE





3D ATLAS R&D Collaboration Processing Meeting at SINTEF

3D sensors in numbers:

15 years R&D
5 years 3DATLAS R&D Collaboration with
18 institutions and 5 processing facilities
3 years Cooperation for industrialization
~120000 electrodes/FE-I4
~36Millions 'class A' holes etched for the IBL
80 years is the age of Sherwood Parker in 2012

ATLAS 3D Silicon Sensors R&D Collaboration

VTT

B. Stugu, H. Sandaker, K. Helle, (Bergen University), M. Barbero, F. Hügging, M. Karagounis, V. Kostyukhin, H. Krüger,, D-L Paul, N. Wermes (Bonn University), M. Capua, A. Mastroberardino; G. Susinno (Calabria University), C. Gallrapp, B. Di Girolamo; D. Dobos, A. La Rosa, H. Pernegger, S. Roe (CERN), T. Slavicek, S. Pospisil (Czech Technical University), K. Jakobs, M. Köhler, U. Parzefall (Freiburg University), N. Darbo, G. Gariano, C. Gemme, A. Rovani, E. Ruscino (University and INFN of Genova), C. Butter, R. Bates, V. Oshea (Glasgow University), S. Parker (The University of Hawaii), M. Cavalli-Sforza, S. Grinstein, I. Korokolov, C. Padilla (IFAE Barcelona), K. Einsweiler, M. Garcia-Sciveres (Lawrence Berkeley National Laboratory), M. Borri, C. Da Vià*, I. Haughton, C. Lai, C. Nellist, S.J. Watts (The University of Manchester), M. Hoeferkamp, S. Seidel (The University of New Mexico), H. Gjersdal, K-N Sjoebaek, S. Stapnes, O. Rohne, (Oslo University) D. Su, C. Young, P. Hansson, P. Grenier, J. Hasi, C. Kenney, M. Kocian, P. Jackson, D. Silverstein (SLAC), H. Davetak, B. DeWilde, D. Tsybychev (Stony Brook University). G-F Dalla Betta, P. Gabos, M. Povoli (University and INFN of Trento) , M. Cobal, M-P Giordani, Luca Selmi, Andrea Cristofoli, David Esseni, Andrea Micelli, Pierpaolo Palestri (University of Udine)

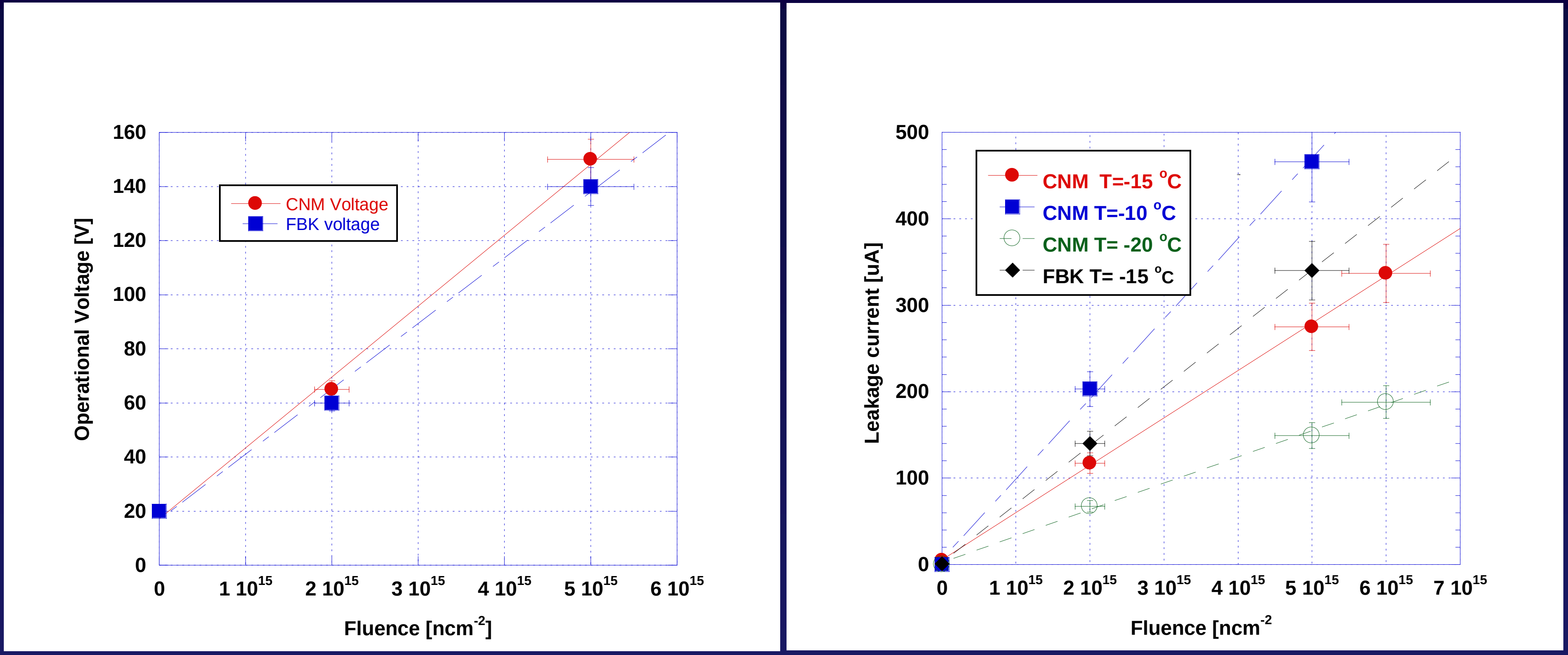
Processing Facilities: C. Fleta, M. Lozano G. Pellegrini, (CNM Barcelona, Spain); (M. Boscardin, A. Bagolini, P. Conci, G. Giacomini, C. Piemonte, S. Ronchin, E. Vianello, N. Zorzi (FBK-Trento, Italy) , T-E. Hansen, T. Hansen, A. Kok, N. Lietaer (SINTEF Norway), J. Hasi, C. Kenney (Stanford). J. Kalliopuska, A. Oja (VTT , Finland)*

18 institutions and 5 processing facilities

**spokesperson*

Leakage currents and operational voltages after irradiation at different T

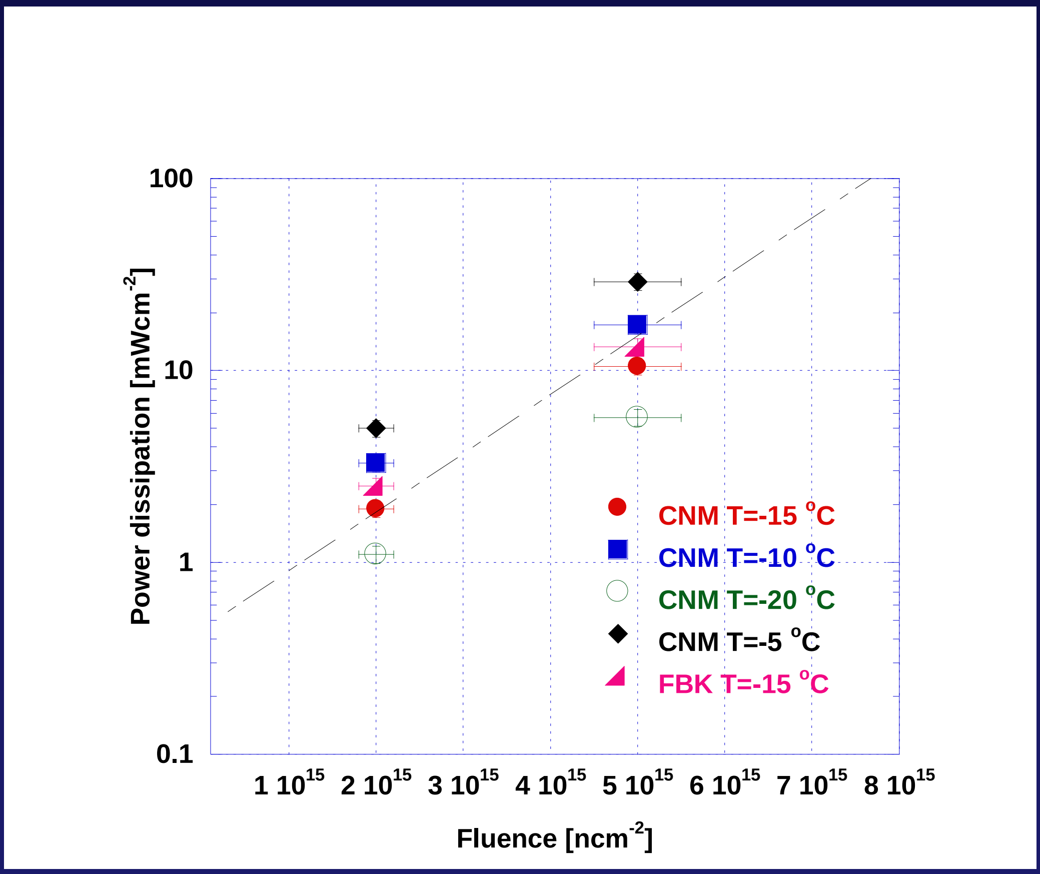
A. Micelli, C. Gemme, S. Grinstein



T [°C] FEC-off	Fluence x 10 15 [ncm-2]			Vop [V]			Current [uA] Per chip		
-20 CNM	2	5	6	63	151	151	67	149	188
-15 CNM	2	5	6	63	152		117	275	326
-15 FBK	2	5		60	140		137	340	
-10 CNM	2	5		64	158		203	466	
-5 CNM	2	5		63	145		569	795	

Power dissipation at different Temperatures after irradiation

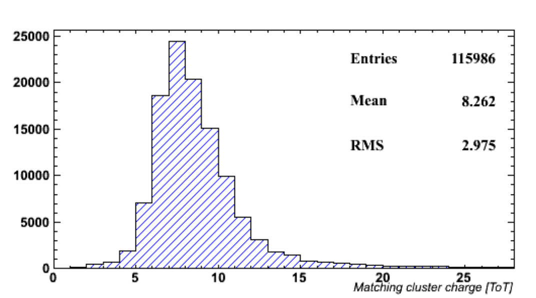
C. Gemme, A. Micelli, S. Grinstein

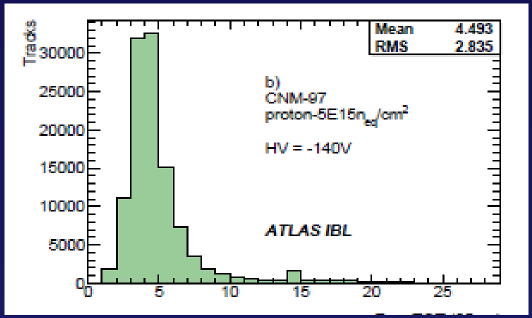


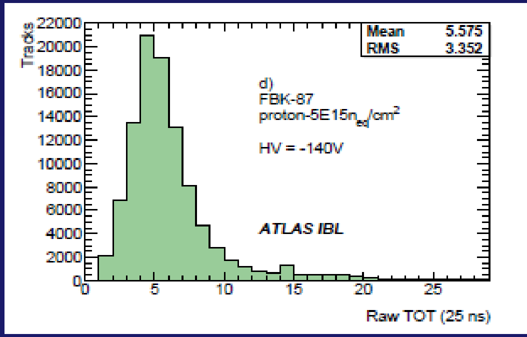
IBL requirement on sensor Power dissipation
< 200 mW/cm^2 at 5 x 10^{15} n_{eq}/cm^2 and -15 ° C (after annealing)

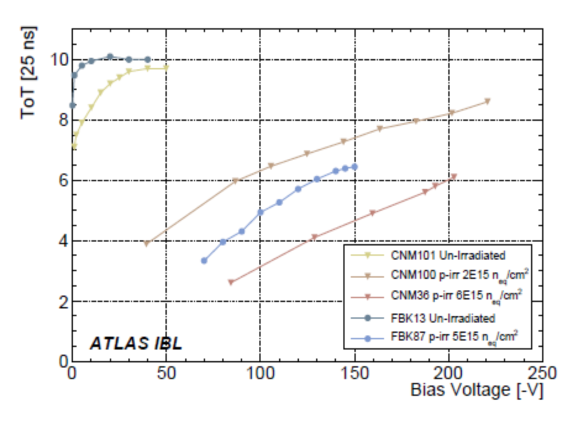
Temp. [ºC]	Fluence x10^{15} [ncm^{-2}]		W CNM [mWcm^{-2}]		W FBK mWcm^{-2}]	
-20	2	5 6	1.1	5.7 7.1		
-15	2	5 6	1.9	10.5 12.7	2.5	13
-10	2	5	3.3	17.3		
-5	2	5	5	29		

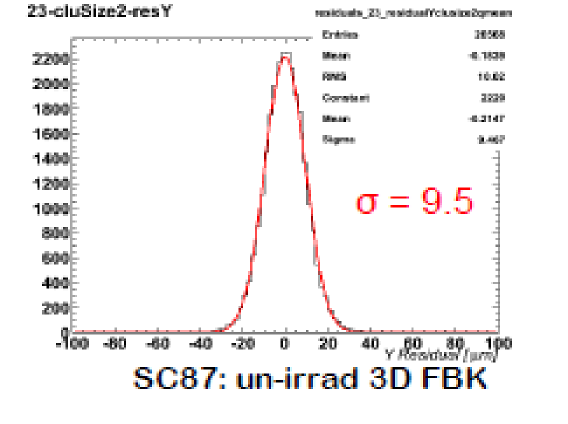
Test beam at the CERN SpS

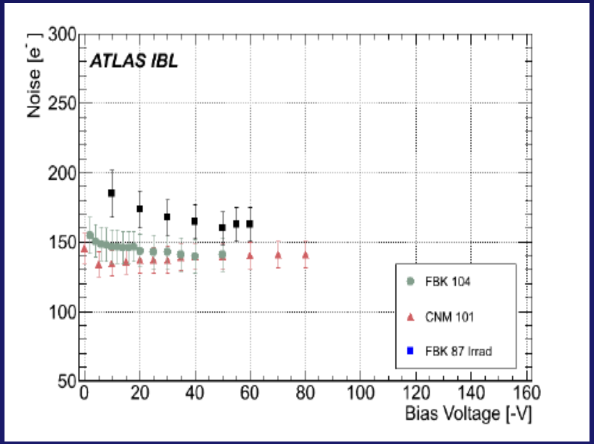


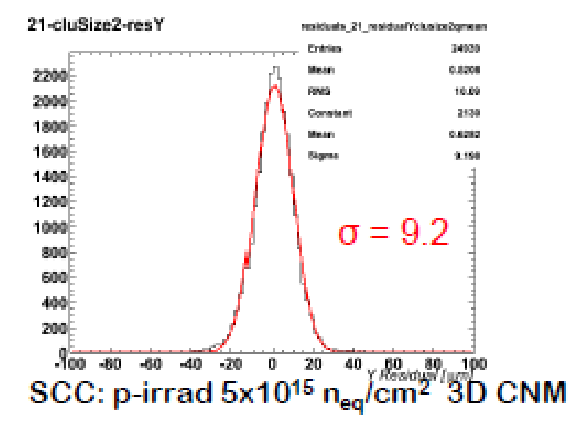








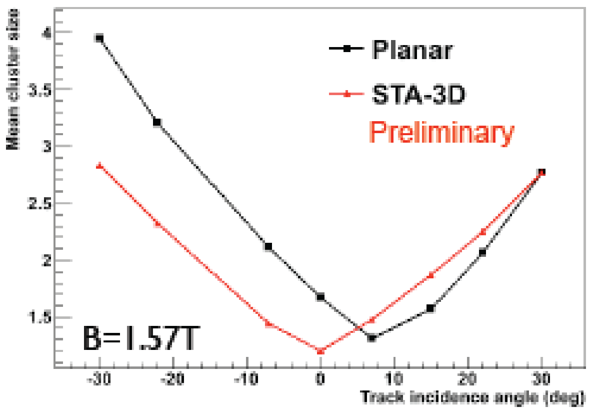


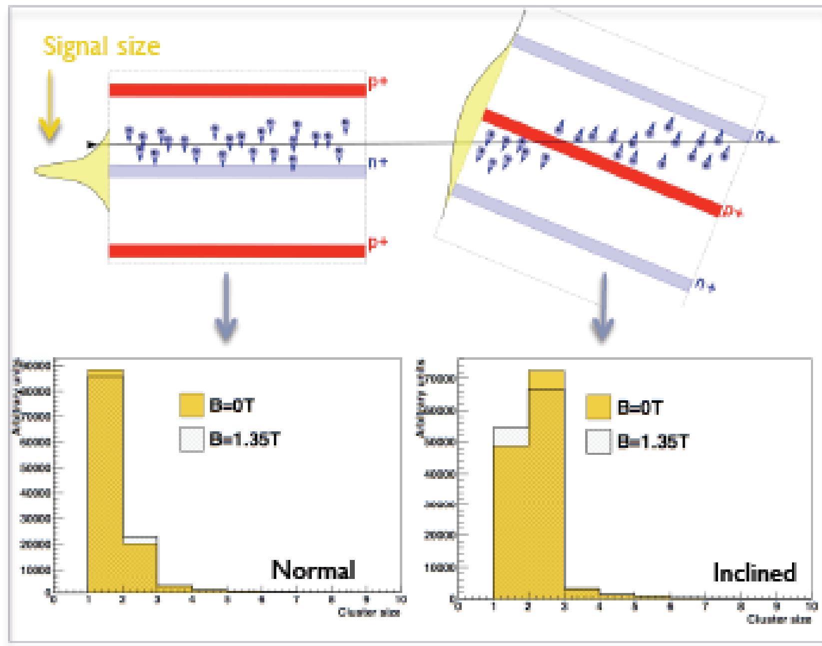


Charge sharing, tracking resolution and Lorentz effect

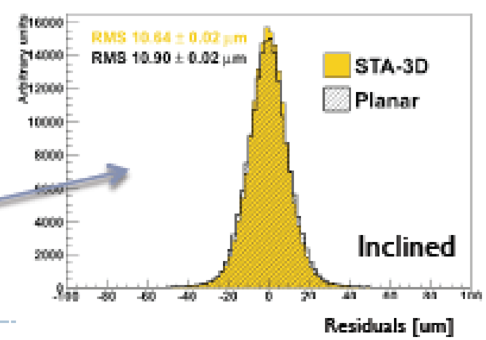
P. Hansson et al. Nuclear Instruments and Methods in Physics Research A 628 (2011) 216–220

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





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

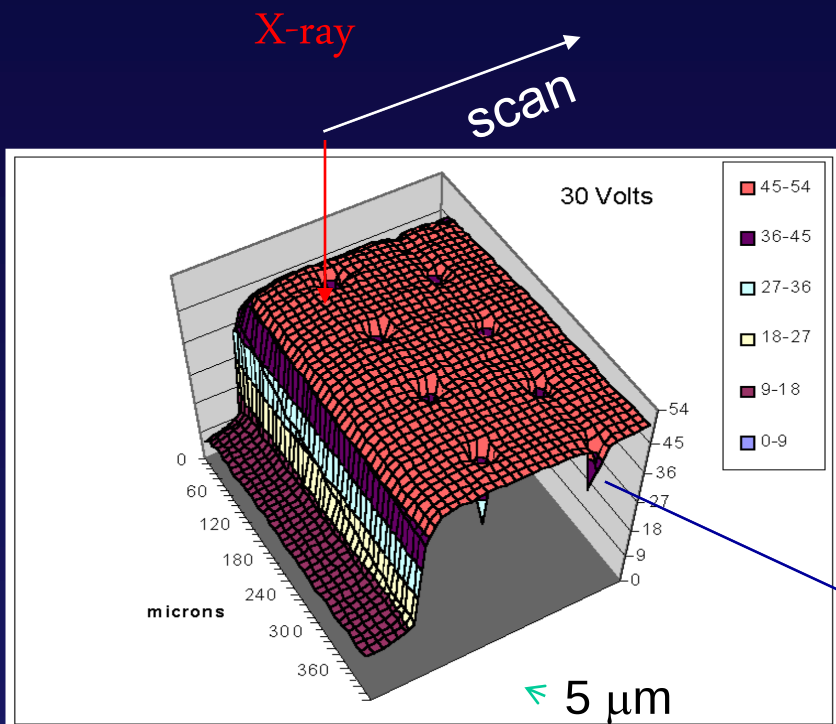


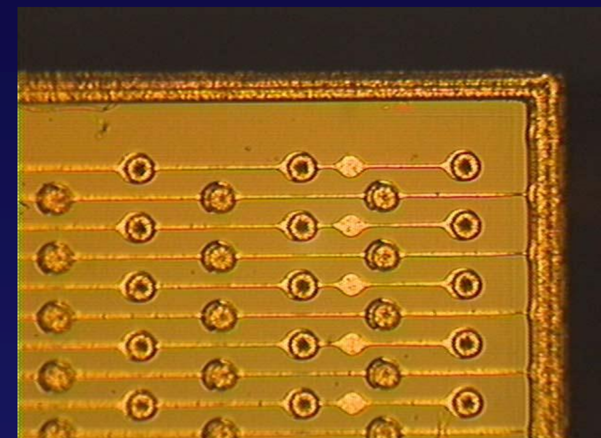
σ= 10.9 μm

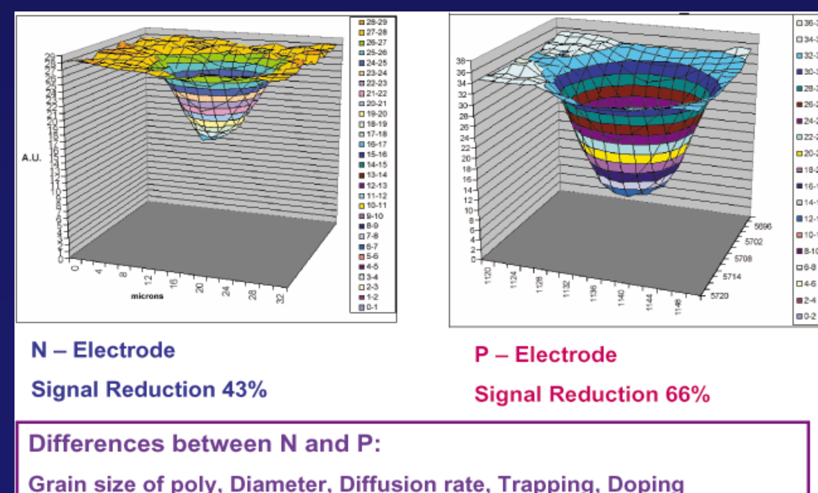
Track resolution not de-convoluted

Active edge and electrode response of 3D sensors

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





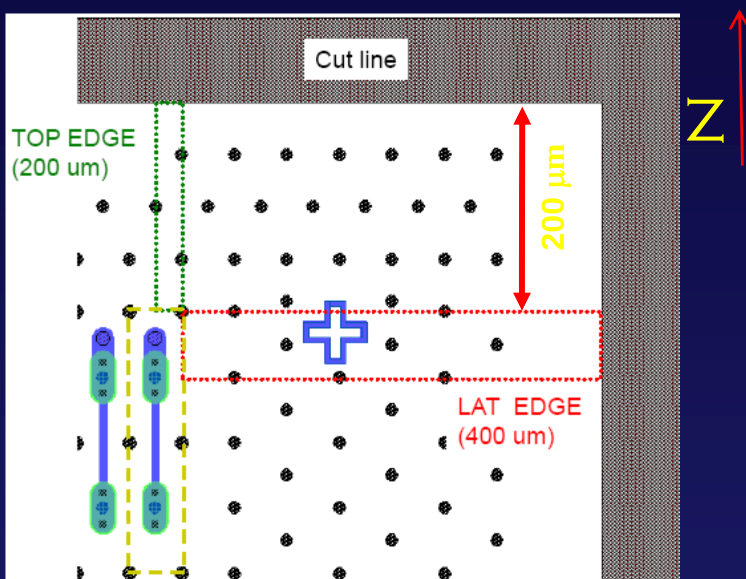


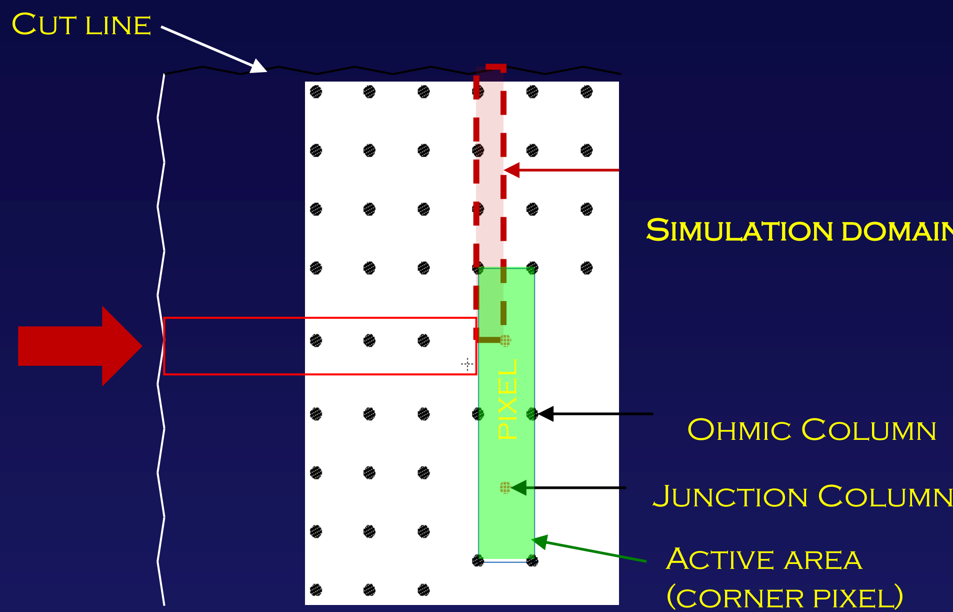
12 KeV X-ray scan at ALS, Berkeley, in 2 μm steps, of a 3D, n bulk and edges, 181 μm thick sensor.

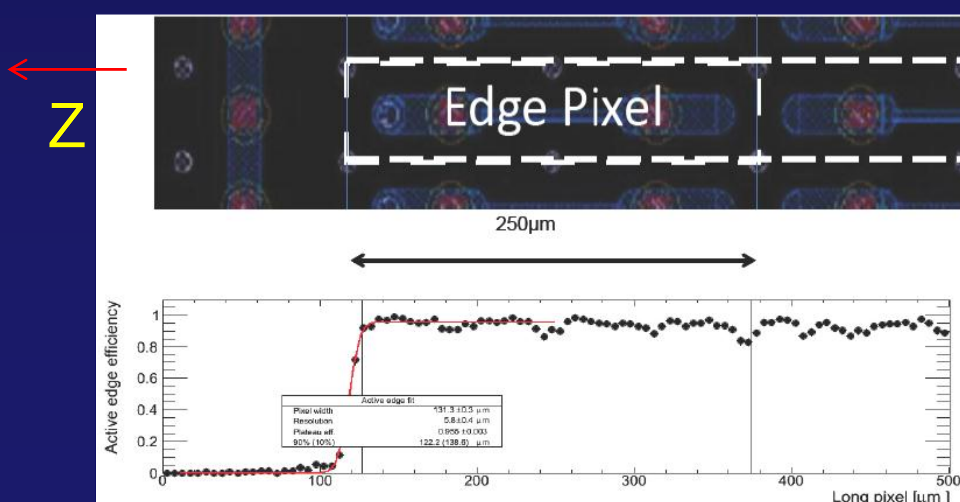
Electrodes ~ 1.8% of total area

CNM and FBK use 200 μm guard fences

Design and simulation
GF Dalla Betta, Trento







3D-CNM34, irradiated with protons at 5E15neq/cm2: 1D hit efficiency in the long pixel direction for edge pixels. All edge pixels have added together. Operation conditions are: FE-I4 threshold = 1300e, bias voltage = -140V, magnetic field = 1.6T, tilt angle = 0 degrees.

Edge pixel: regular length 250 μm
- Inactive area: 200μm
- Actual efficiency extends:
- 50%: 20-30μm
- Effective inactive area from dicing: ~200μm.
- Same for all 3D samples.