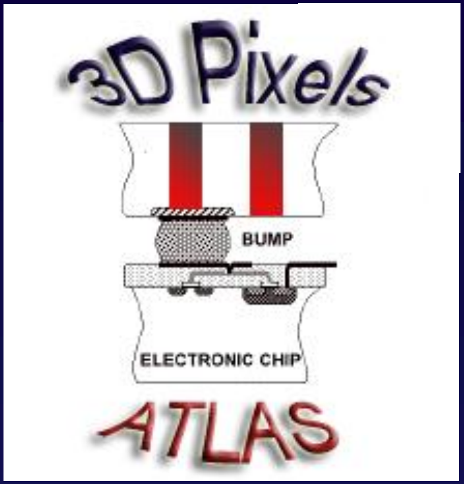
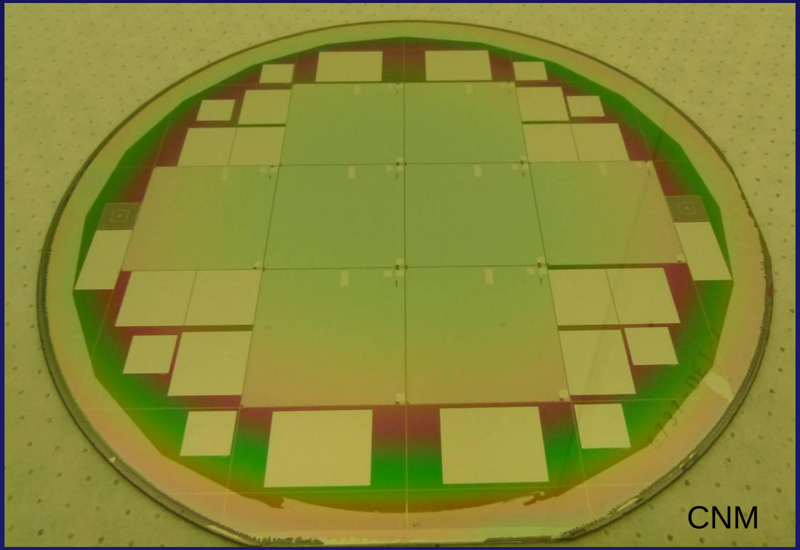
Progress with 3D detectors for the IBL



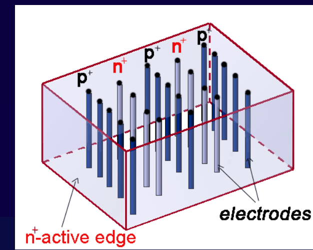
Cinzia Da Vià, The University of Manchester, UK

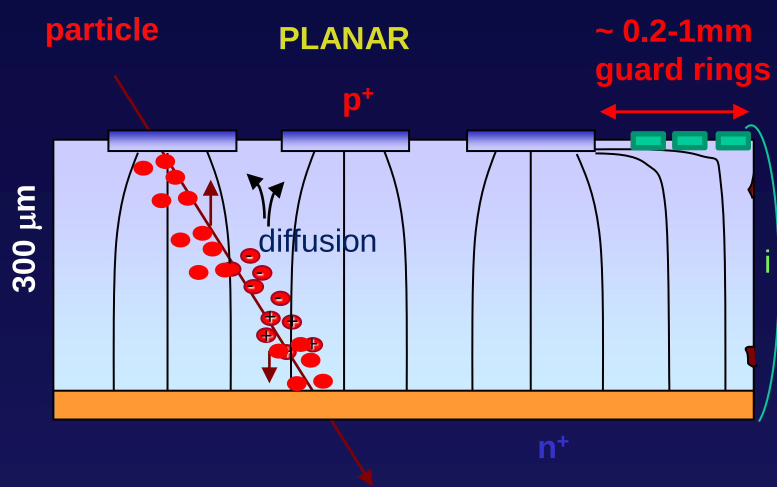
GF Dalla Betta (Trento University), G. Pellegrini, C. Fleta (CNM Barcelona) M. Boscardin , G. Giacomini, N. Zorzi (FBK Trento) A. Kok, T-E Hansen (SINTEF), J. Hasi, C. Kenney (SLAC), S, Parker (Hawaii). S. Grinstein (IFAE), A. Micelli (Udine), C. Gemme, G. Darbo (Genova) D-L Pohl (Bonn).

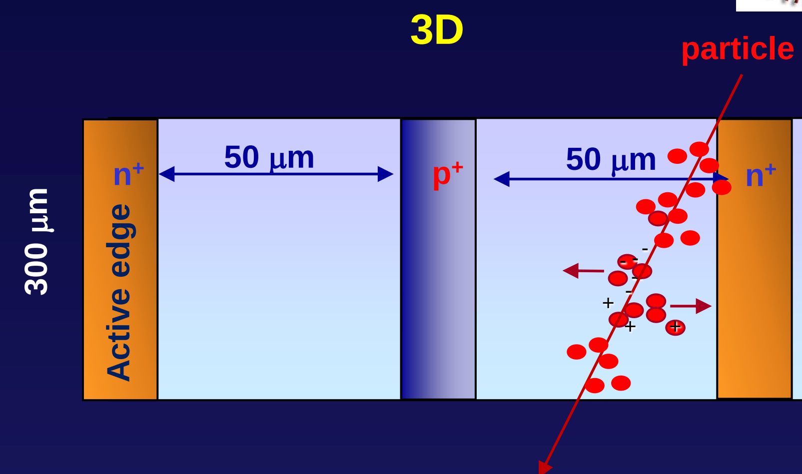
- Introduction
- 3D silicon for the ATLAS IBL
- Performance
- Selection and Production Yield
- Summary and outlook



Introduction

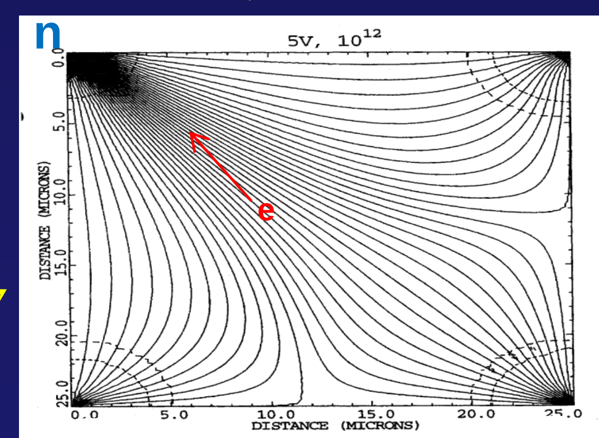






	3D	planar
❖DEPLETION VOLTAGES	< 10 V	70 V
❖After irradiation	180 V	1000V
❖Power dissipation	goes with V	goes with V
❖EDGE SENSITIVITY	< 5 µm	500 µm
❖CHARGE 1 MIP (300 mm)	24000e^-	24000e^-
❖CAPA CITANCE	30-50f	~20fF
❖COLLECTION DISTANCE	50 µm	300 µm
❖SPEED	1-2ns	10-20 ns

MEDICI simulation of a 3D structure

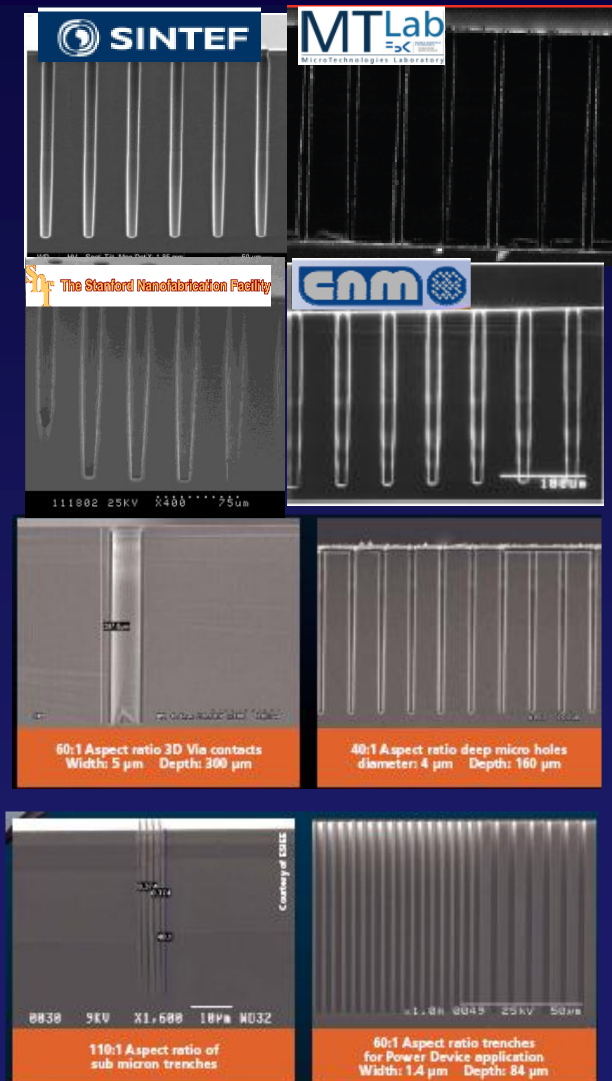


Drift lines parallel to the surface

3D has Lower charge sharing probability

Micromachining

M. Puech. ALCATEL



"SHARP"
SUPER HIGH ASPECT RATIO > 110:1
UNIQUE ALCATEL DRIE PATENTED PROCESS
ALCATEL Micro Machining Systems

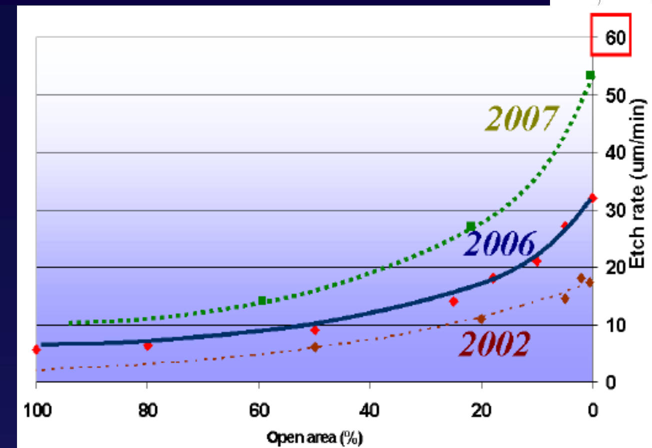
11:1 1997

24:1 2009

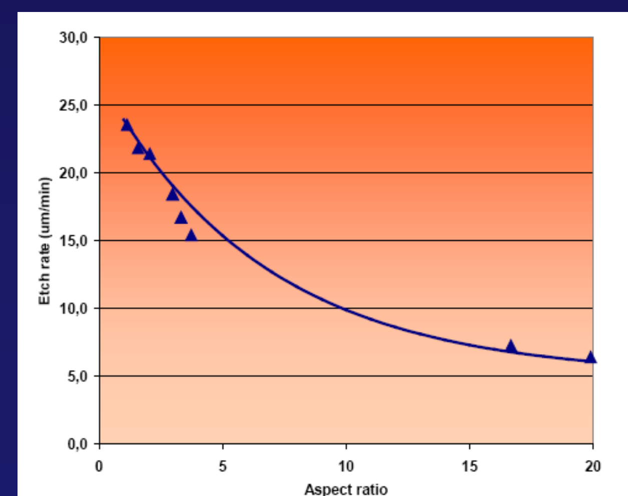
Today

40-60:1

110:1!!!



Etching rate depends on exposed area



etching rate depends on aspect ratio

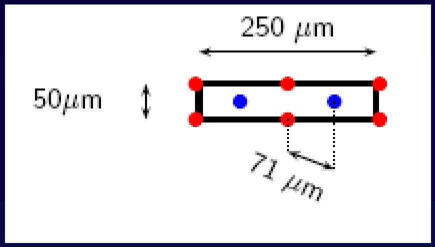
3D sensors for IBL

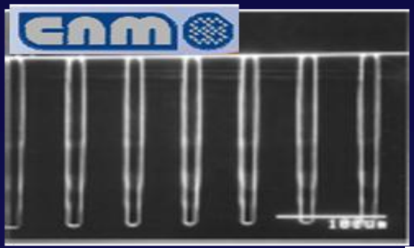
➢3D is a silicon sensor technology designed specifically to be radiation hard can be processed front side (with support wafer) and double sided

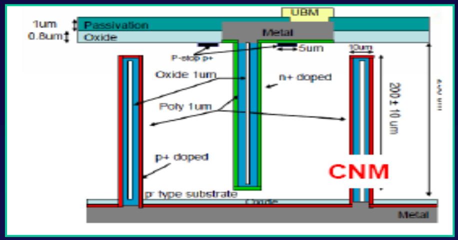
➢First prototypes were available at the end of 1990ties. Few years later more industries started producing 3D sensors

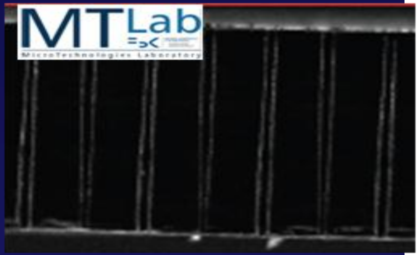
➢The current design parameters have been tuned to optimize the IBL constraints in terms of signal amplitude, noise, bias voltage and consequent system requirements

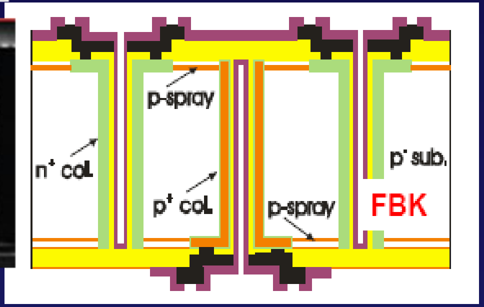
➢In June 2009, four facilities decided to 'join' knowhow and effort for a common goal: optimise the process and speedup a parallel industrialization strategy to guarantee a reliable production of 3D sensors. Two were finally selected for the 'fast track' ATLAS IBL. The remaining two still contribute to the effort and looking into future optimizations of the design

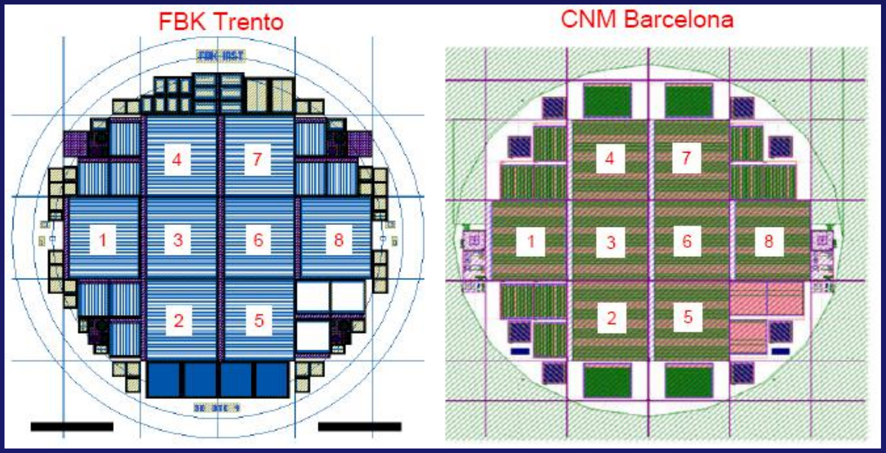








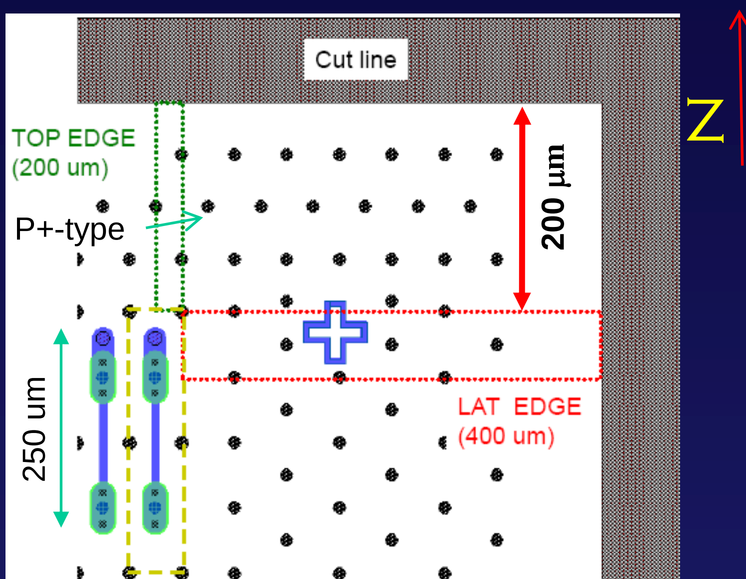


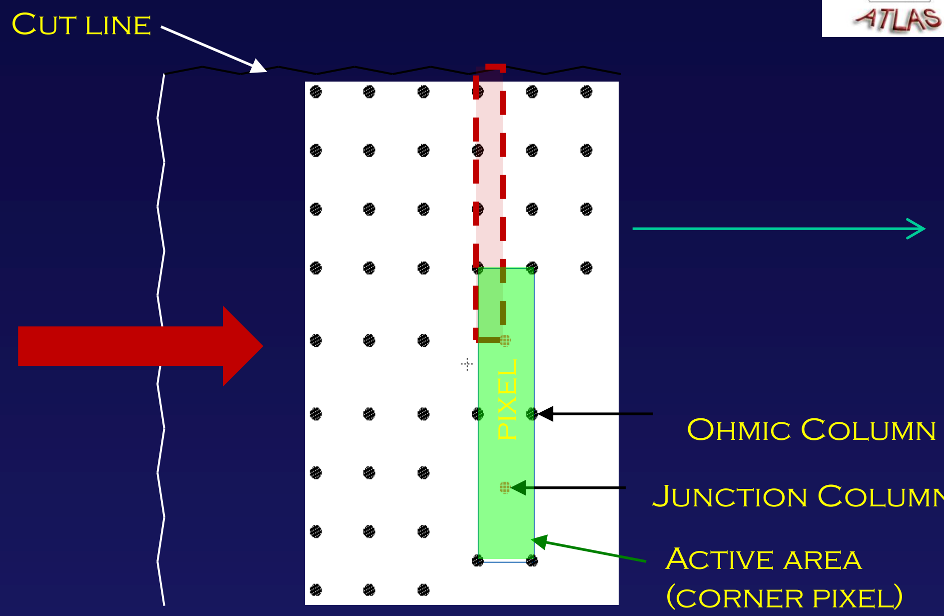


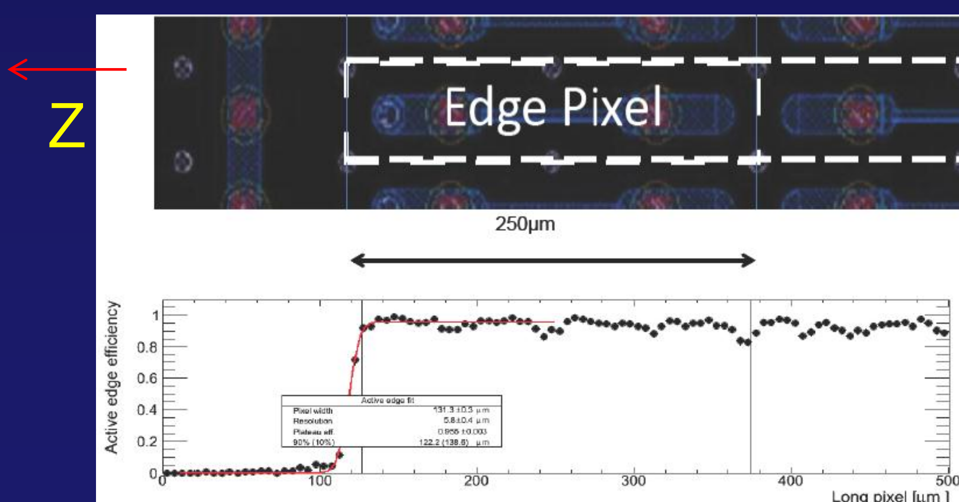
Common floor-plan wafer layout

200 μm guard fences

Design and simulation
GF Dalla Betta, M. Povoli Trento







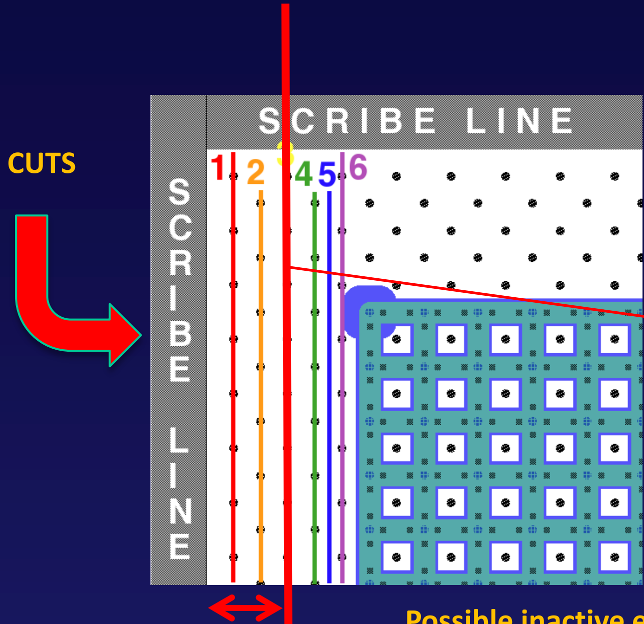
3D-CNM34, irradiated with protons at 5E15neq/cm2: 1D hit efficiency in the long pixel direction for edge pixels. All edge pixels have been added together. Operation conditions are: FE-I4 threshold = 1300e, bias voltage = -140V, magnetic field = 1.6T, tilt angle = 0 degrees.

Edge pixel: regular length 250 mm

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

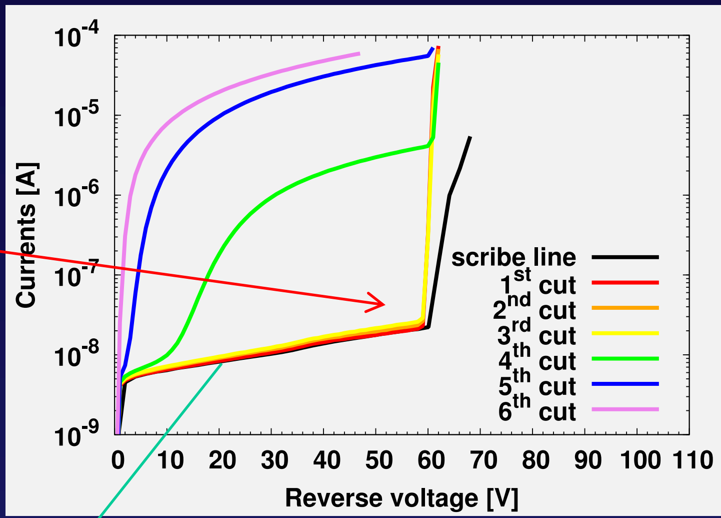
Analysis
IFAE Barcelona
More from
A. Micelli IBL
Test beam data

Incidentally Slim edge can be slimmer (performed on 3D diodes, pitch 80um)

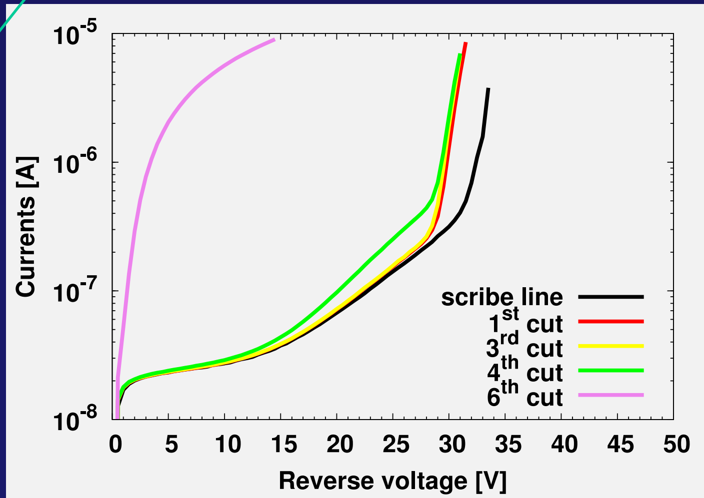


Possible inactive edge Reduction!!!!

ATLAS09, Lower p-spray, Higher Breakdown



ATLAS07, High p-spray, Low Breakdown

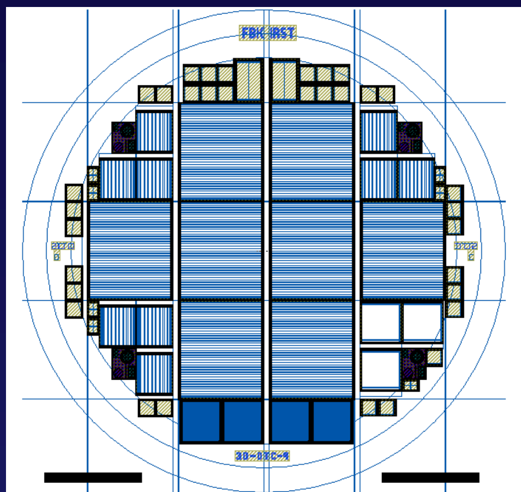


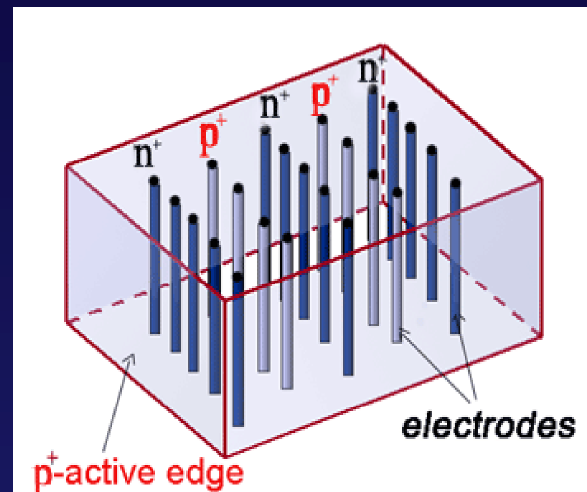
- **Firs test with ATLAS07 devices:**
  - High p-spray dose, low breakdown (30V)
  - No signs of early breakdown up to the 5th cut
- **Second test with ATLAS09 devices:**
  - Lower p-spray, higher breakdown (>50V)
  - Same results
  - Edge area can be reduced by ~100-150um

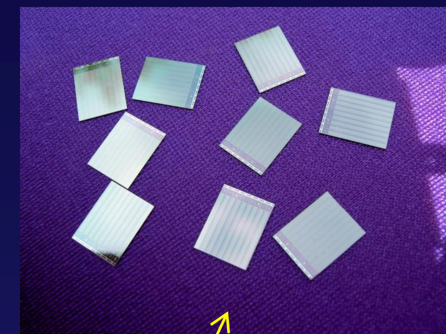
[M. Povoli iWoRID2011, Zurich, 3-7 July 2011]

full3D have been fabricated with the same floorplan

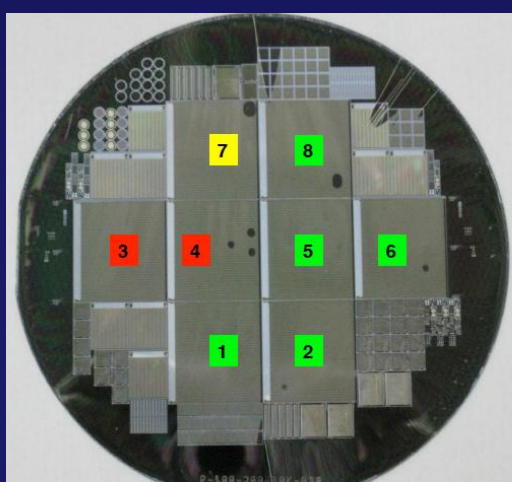
Design by GF Dalla Betta, C. Kenney, A. Kok, G Pellegrini

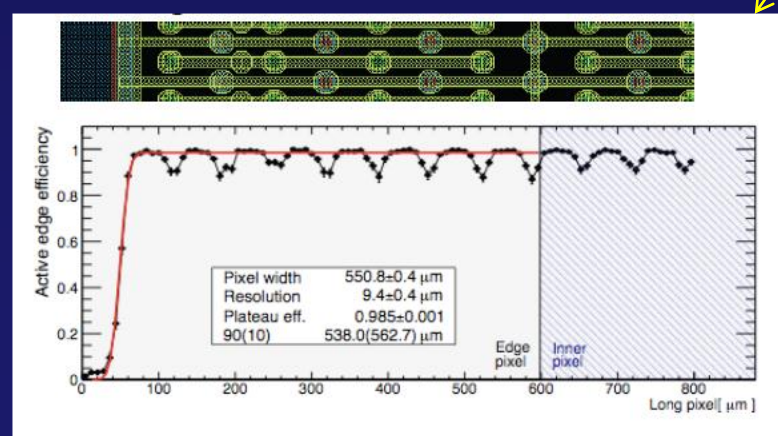






FE-I3

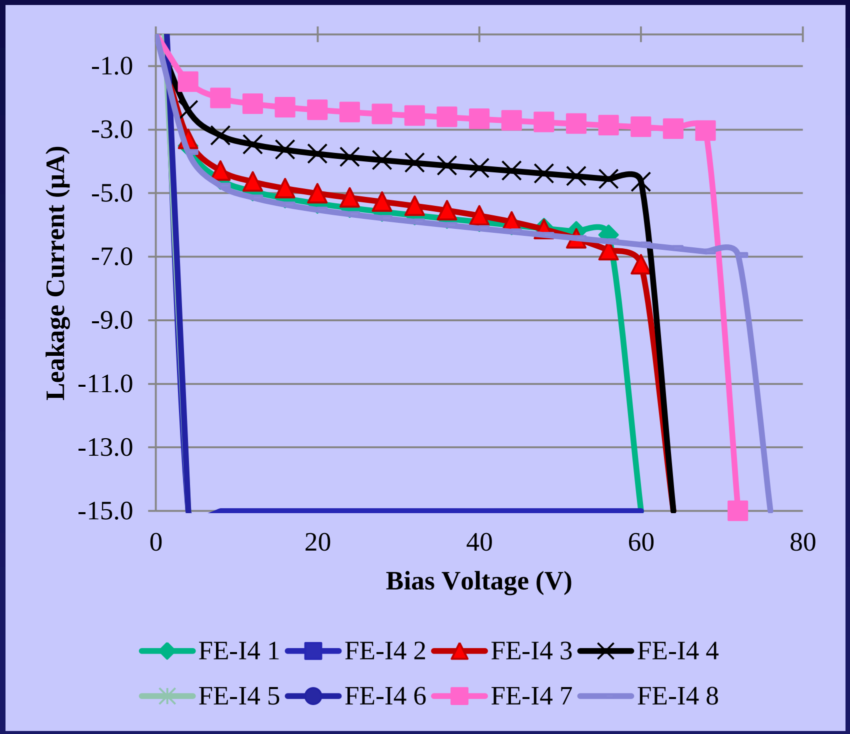


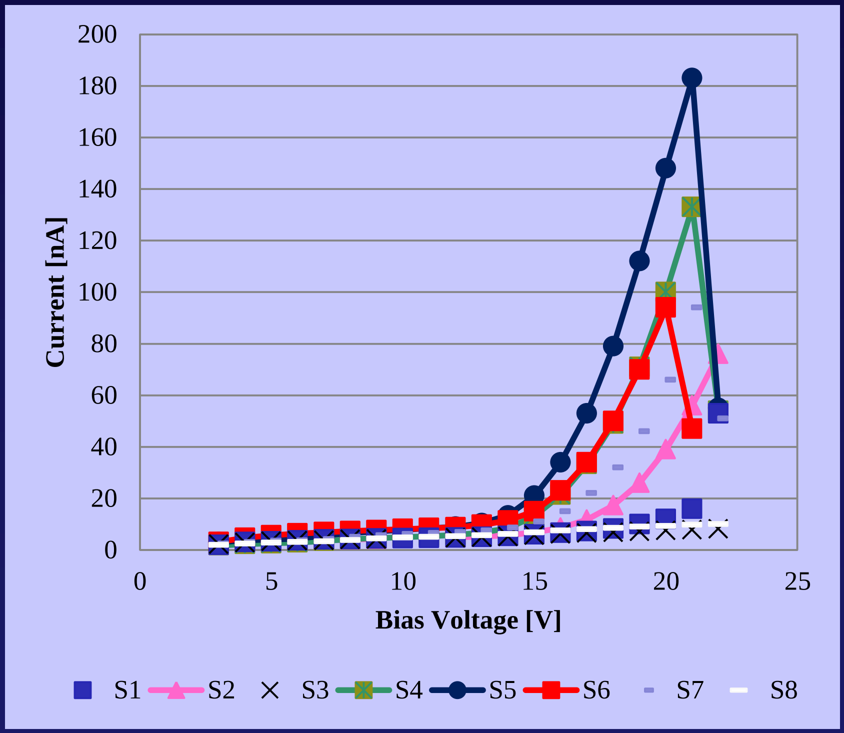


Active Edge
= 543-537= 6±9.8 μm

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

Full 3D with active edges FE-I4 sensors IV on wafer





SINTEF/Stanford

SLAC/Stanford

A. Kok, T-E Hansen, J Hasi, C. Kenney.

Consistent 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 μm from the surface
Before and after irradiation

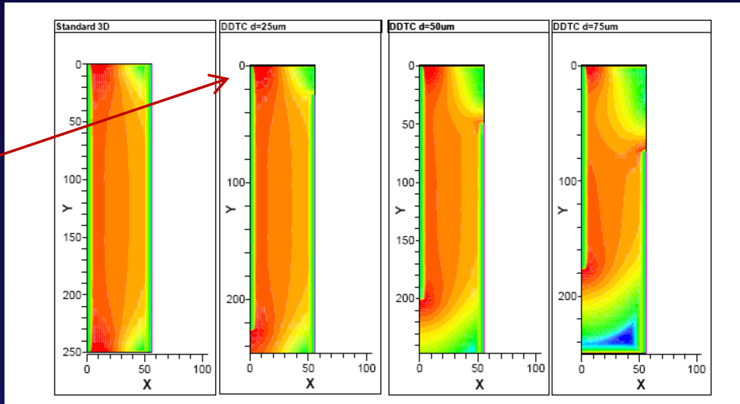


Figure 6.2: Electric field distribution taken from a 2-D cross section of the 3-D structure along the diagonal that connects two columns of opposite doping types. Four cases are here represented: one standard 3D detector and three 3D-DDTC detectors with d spacing of 25, 50 and 75 μm.

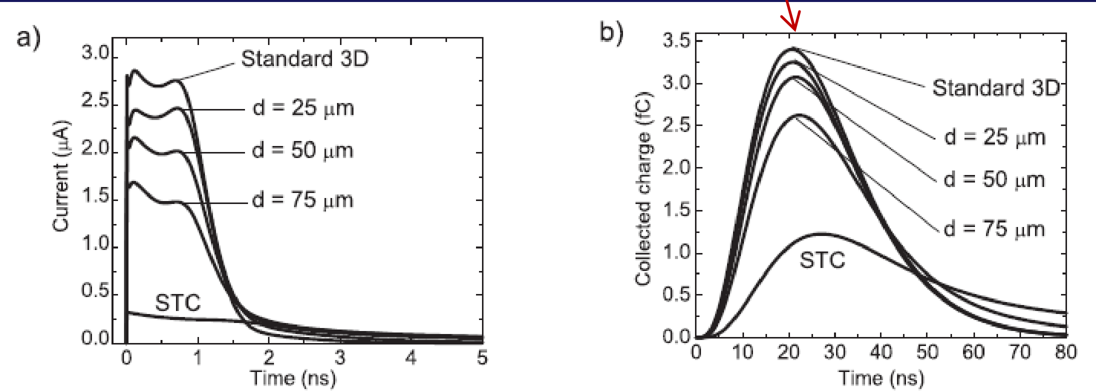
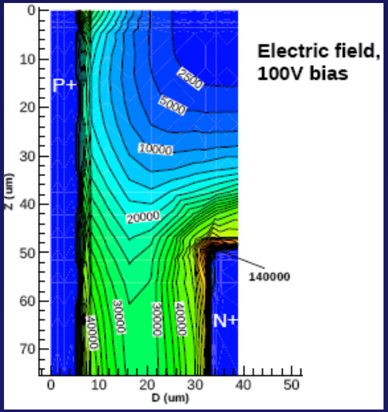
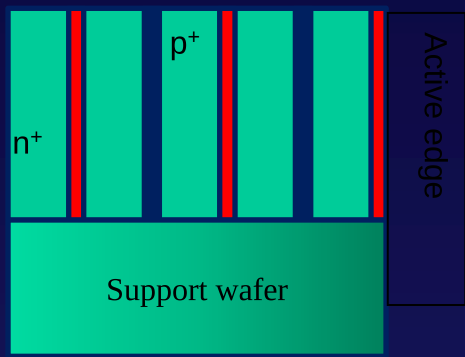


Figure 6.3: Simulated transient signals in 3D detectors of different geometries, biased at 16V, in response to a MIP particle: a) current signal; b) equivalent charge signal at the output of a semi-gaussian shaper with 20ns peaking time.

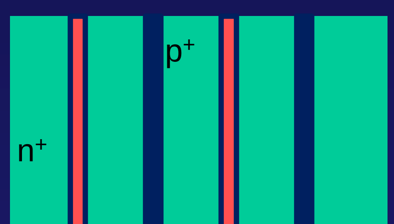


Simulations (from A. Zoboli
PhD thesis, Trento, March 2009)
D. Pennicard, Glasgow IEEE/NSS 08

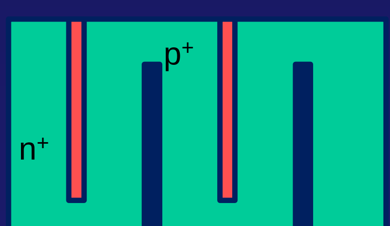
3D sensors behaviour after irradiation



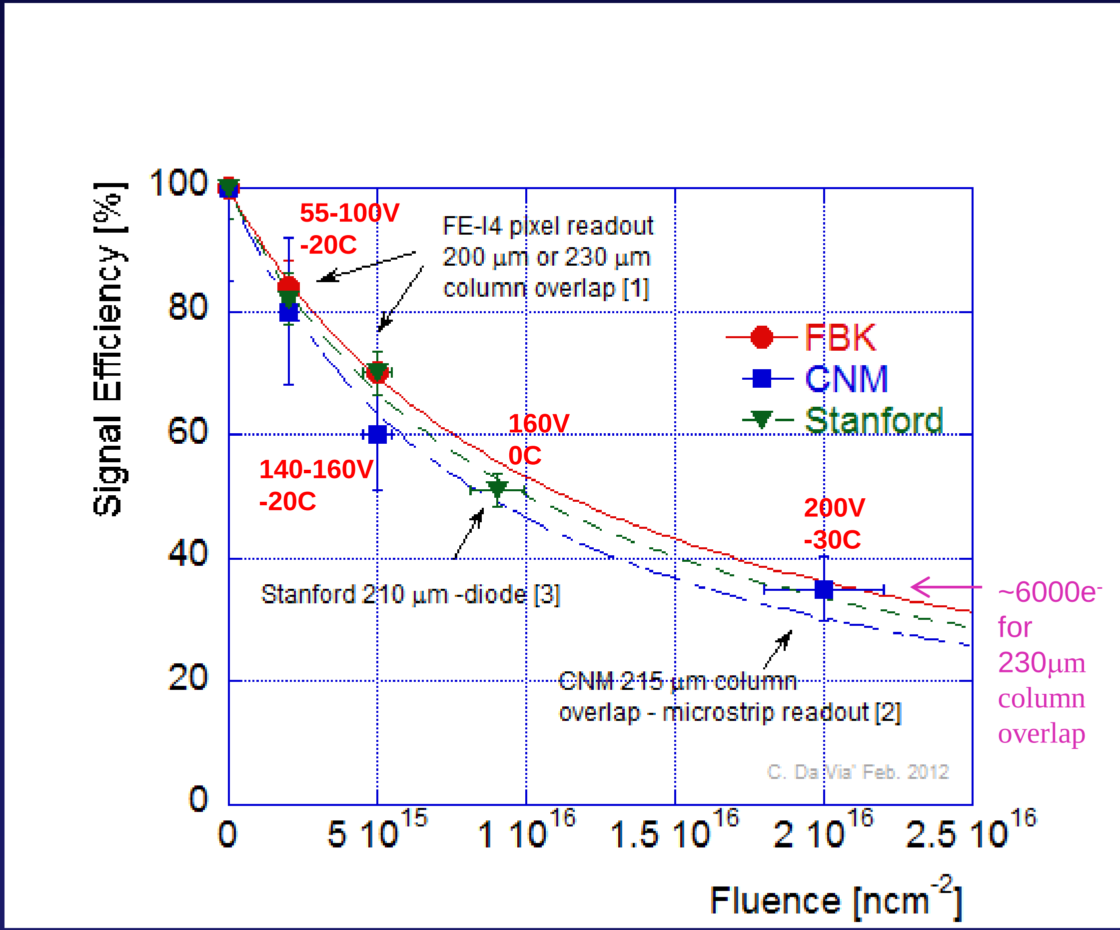
SINTEF/STANFORD



FBK



CNM



~6000e- for 230µm column overlap

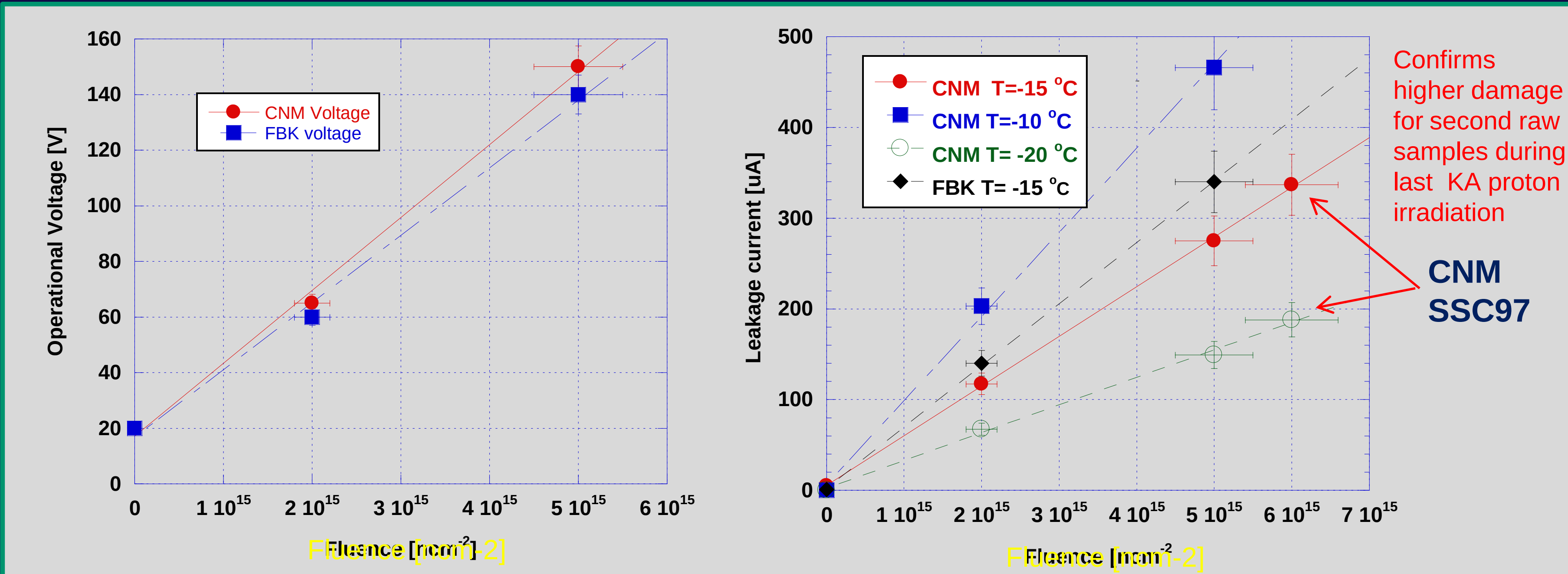
[1] 2011 CNM-FBK IBL Modules. (C. Gemme, A. Micelli, S. Grinstein, lab tests) (test beam coordinated by P. Grenier, J. Wingarted, A. La Rosa) , unpublished.

[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

Leakage currents and operational voltages After irradiation

A. Micelli, C. Gemme, S. Grinstein

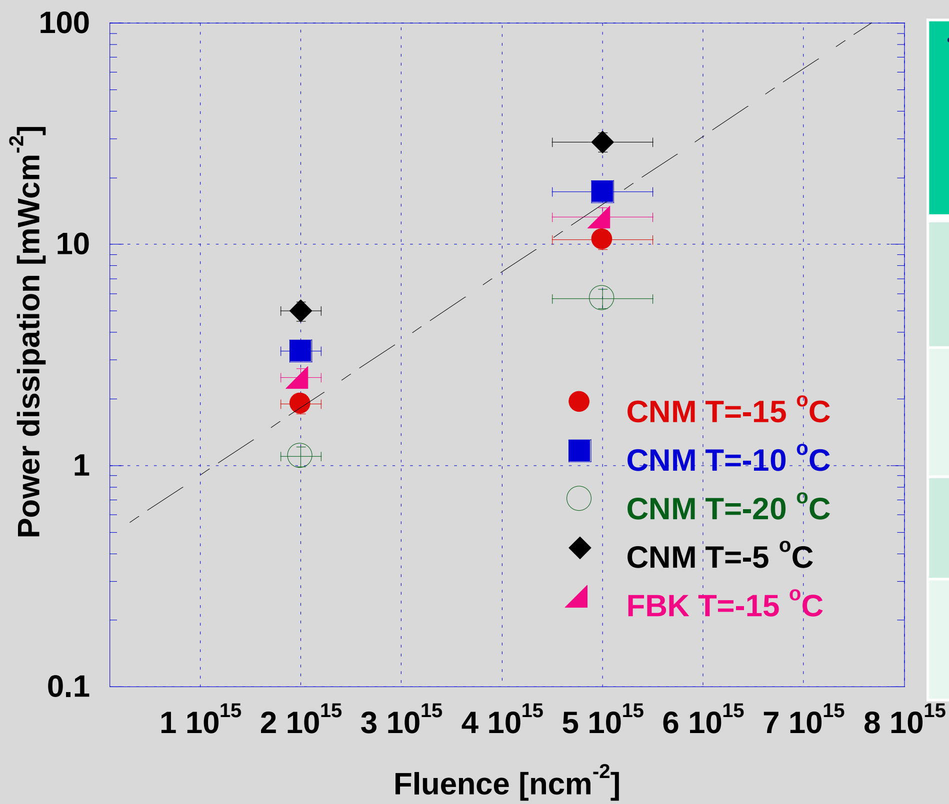


T [°C] FEC-off	Fluence x 10 ^{15} [ncm^{-2}]			Vop [V]			Current [uA] Per chip		
-20 CNM	2	5	6	63	151	151	67	149	188
-15 CNM	2	5	6	63	152		117	275	326
-15 FBK	2	5		60	140		137	340	
-10 CNM	2	5		64	158		203	466	
-5 CNM	2	5		63	145		569	795	

Power dissipation at different Temperatures after irradiation

C. Gemme, A. Micelli, S. Grinstein

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



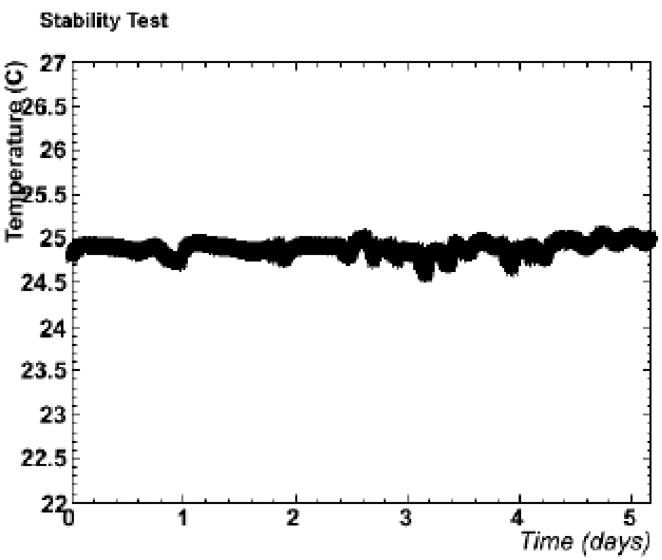
Temp. [°C]	Fluence $x10^{15}$ [ncm^{-2}]		W CNM [$mWcm^{-2}$]		W FBK $mWcm^{-2}$]	
-20	2	5 6	1.1	5.7 7.1		
-15	2	5 6	1.9	10.5 12.7	2.5	13
-10	2	5	3.3	17.3		
-5	2	5	5	29		

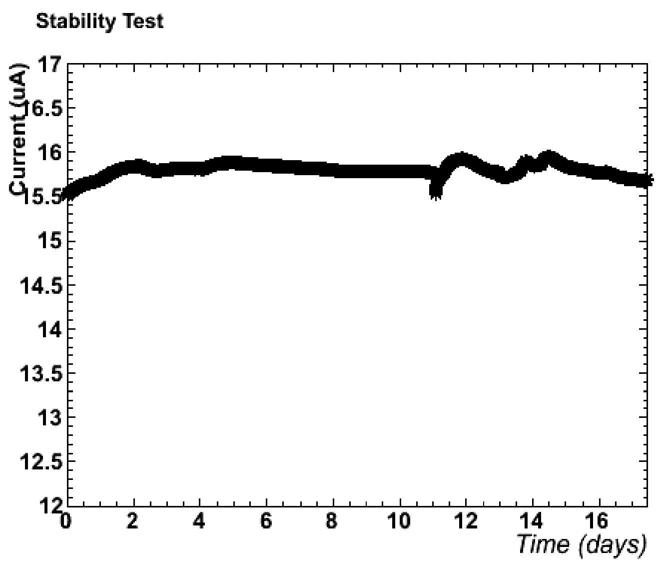
Reliability:
long term stability tests at enhanced bias
Non irradiated at +25°C

3D ATLAS, Review Meeting CERN 07-06--11

Long term current monitoring @ RT

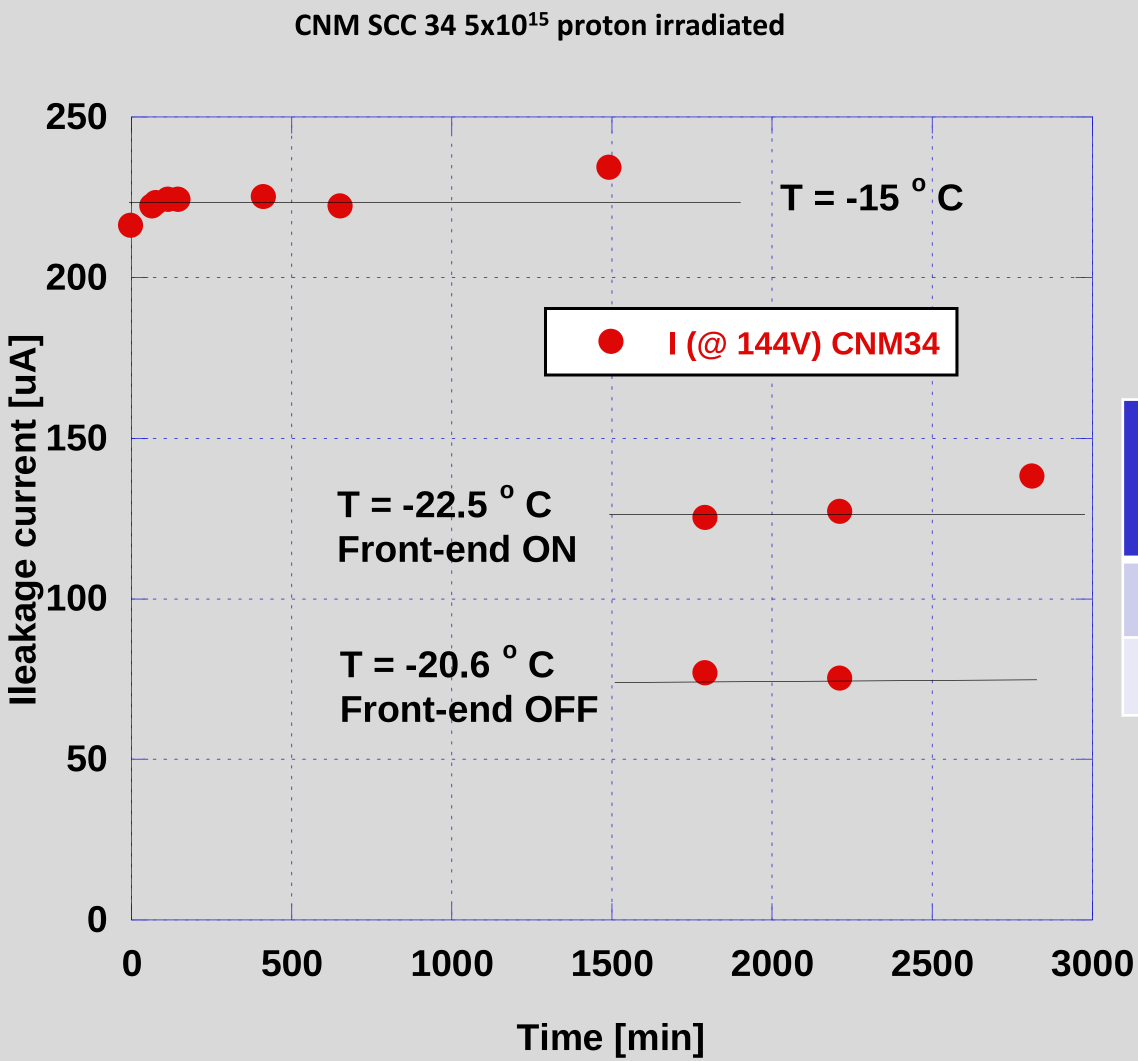
CNM sensor "BON_CN4_3D_38"
No FE communication, no FE power
HV = 50V (~5x depletion voltage !)





No significant variation observed over 17 days of continuous monitoring

Reliability: long term stability tests at operational V_{bias} Irradiated at $5x10^{15} ncm^{-2}$ during June test beam



T is measured by a PT1000 Resistor glued on the Aluminium plate on the back of the PCB.

Temp. [ºC]	Current Test beam FEon [uA]	Current Climate Ch. Feoff [uA]
-15	225	275
-15	235	340

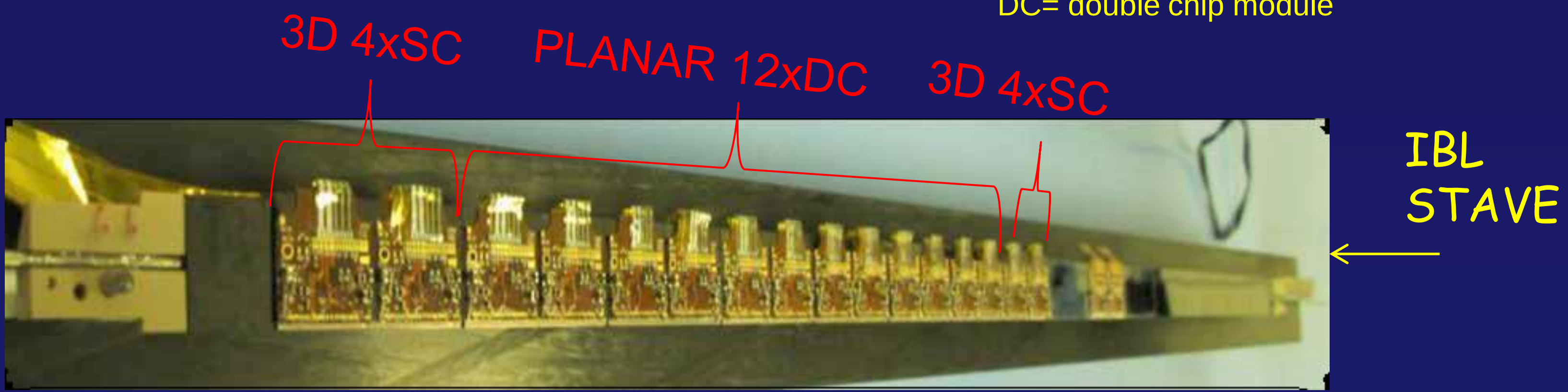
Number of required sensors/modules for the IBL agreed scenario after the sensors review: 75% 25% (risk due to 3D yield uncertainty in July 2011)

FLIP-CHIP QUANTITIES (ASSEMBLIES)	PLANAR SC (DC)	3D SC
Modules as installed target (75%, 25%)	336 (168 mod.)	112 SC
Modules to be prepared for 100% planar	448 (224 mod.)	112 SC
Modules to build (2x as installed)	896 (448 mod.)	**224 SC**

For bump-bonding we have been allocated 2 batches of 25 wafers (originally 75 wafers)

Completion agreed at review in July 2011 was February 2012

SC= single chip module
DC= double chip module

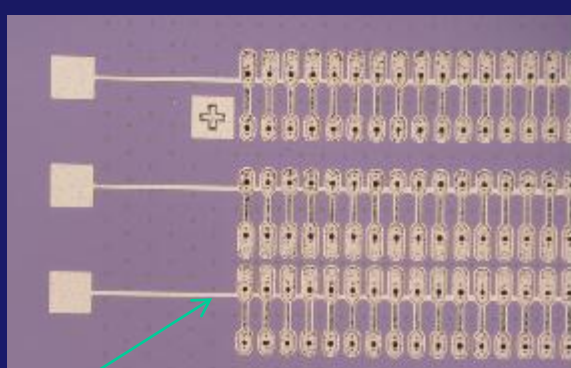


IBL 3D sensors Selection Parameters

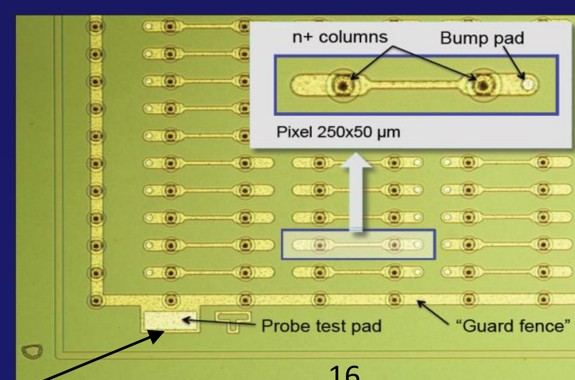
The following specifications are required to qualify a 3D device as functioning correctly before bump-bonding:

- Operation at room temperature (20–24 ^{o}C)
- Vdepl ≤ 15V
- Vop ≥ Vdepl +10V where Vdepl is the full depletion voltage.
- Current at 20 – 24 ^{o}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



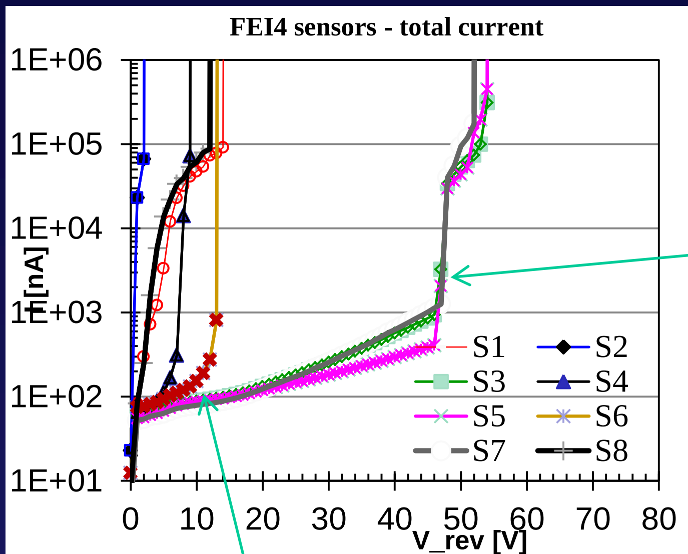
FBK temporary metal

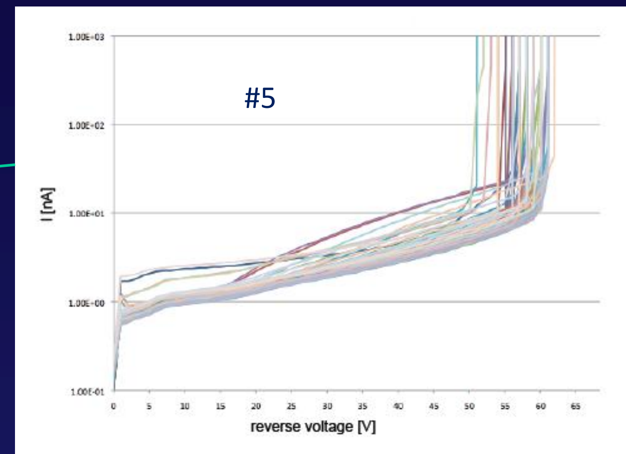


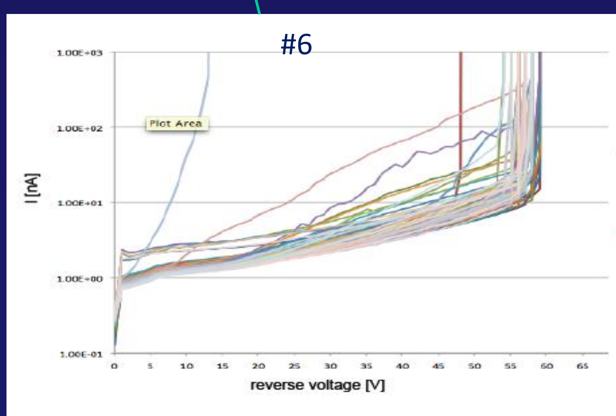
CNM guard ring current

FBK ATLAS09 Wafer 14 : selected for bump-bonding

N. Zorzi, G. Giacomini



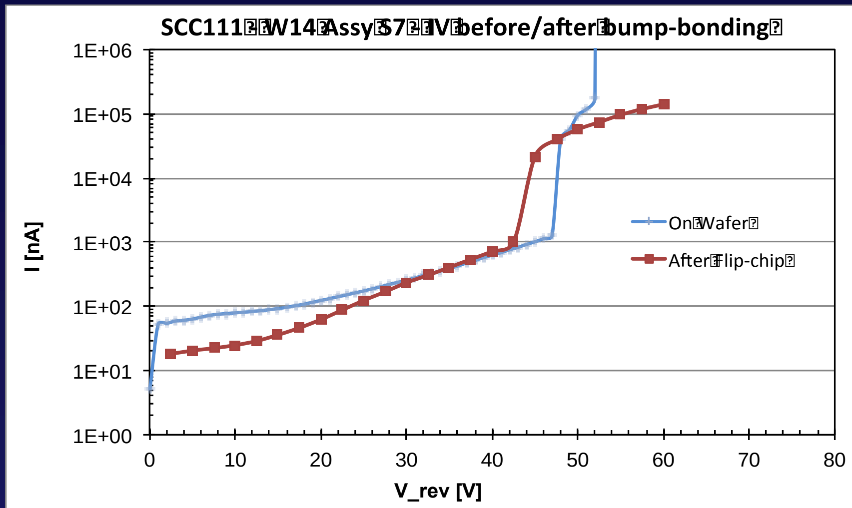


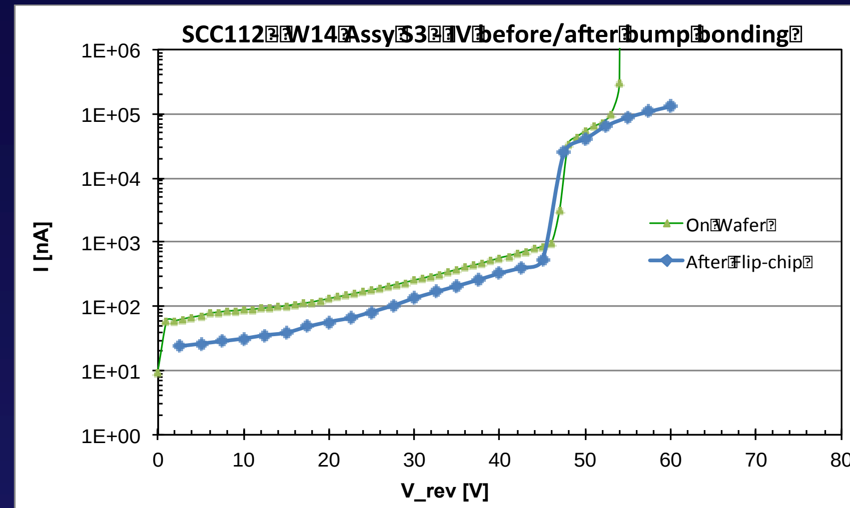


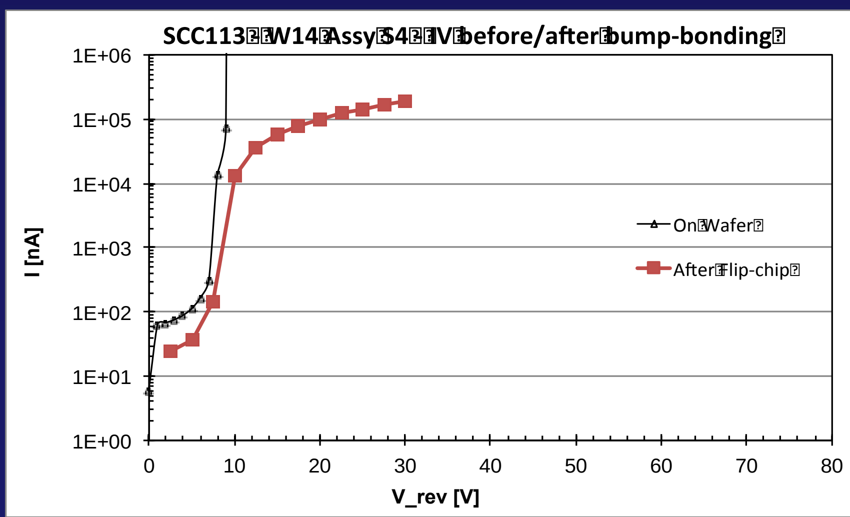
- Temporary metal shorts together a full column of pixel.
- All columns IV measured separately and summed up together.
- Metal etched off before being sent for bump-bonding

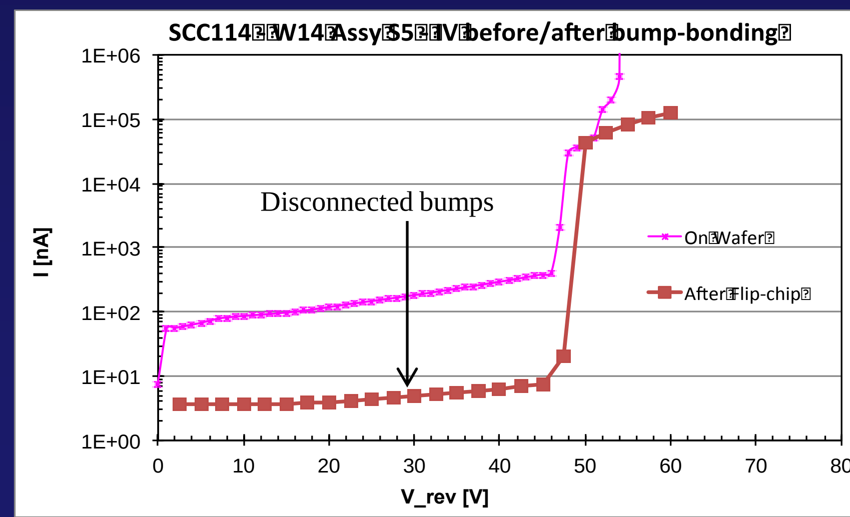
ATLAS09 Wafer 14 before and after bump-bonding

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







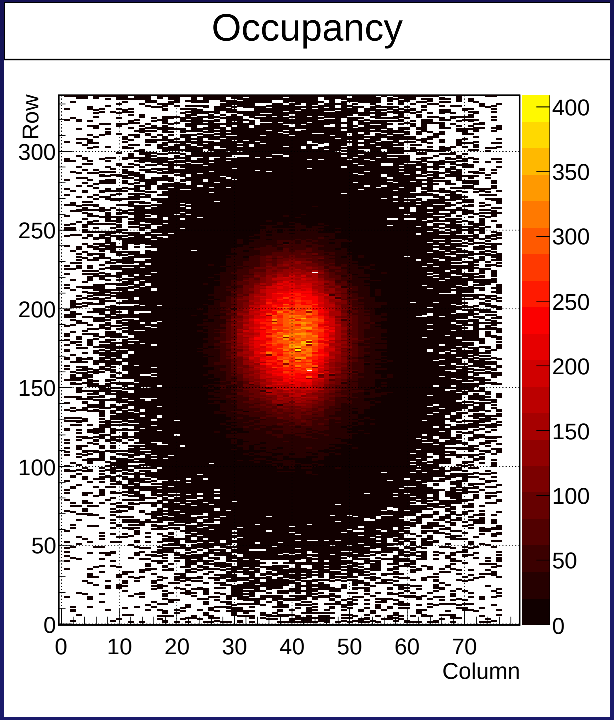


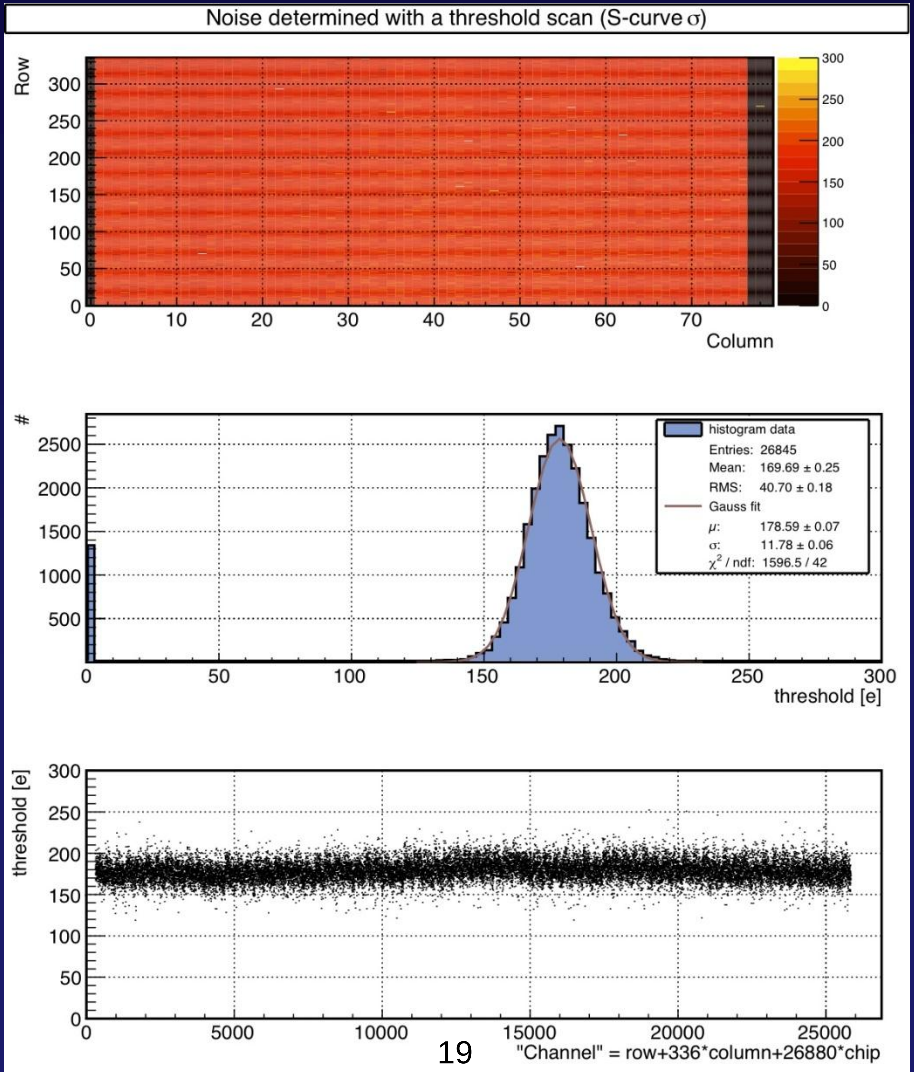
Cinzia Da Viá , Uni. Manchester. "trento" Workshop, Ljubljana 29th February 2012

W14 Good Device – S7

D-L. Pohl

- Source and noise scan demonstrate that most of the pixel are connected:
  - IV curve is representative of the all pixels
  - Bump-bonding is feasible after provisional metal removal





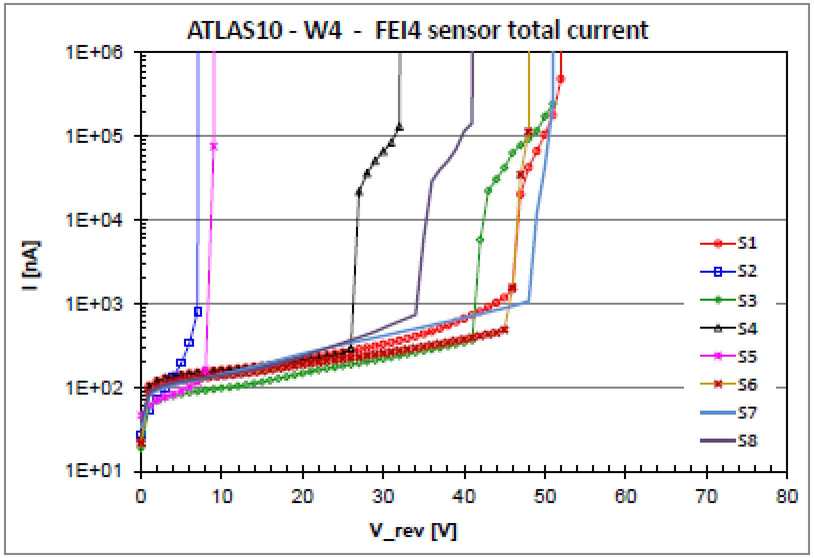
Production: technical sheet/wafer A10 FBK

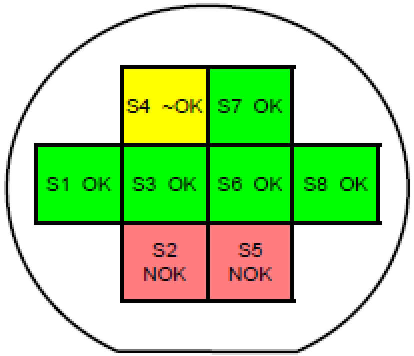
Batch: ATLAS10
Wafer: 4

Wafer thickness [µm]	230	(nominal value/~~measured value~~)
Wafer bow [µm]	value	(~~measured value~~/not available)

# of good detectors	5
# of ~ good detectors	1
# of bad detectors	2

	Class	Current @ 20V [nA]	"slope" (15÷20)V [#]	Breakdown Voltage [V]
S1	OK	2.13E+02	1.186	47
S2	NOK	2.00E+06	1.000	8
S3	OK	1.46E+02	1.270	43
S4	~OK	2.10E+02	1.178	27
S5	NOK	2.00E+06	3.000	9
S6	OK	1.86E+02	1.195	47
S7	OK	2.51E+02	1.345	49
S8	OK	2.34E+02	1.375	36
sorting thresholds		2000	2	25
		5000	2.5	30

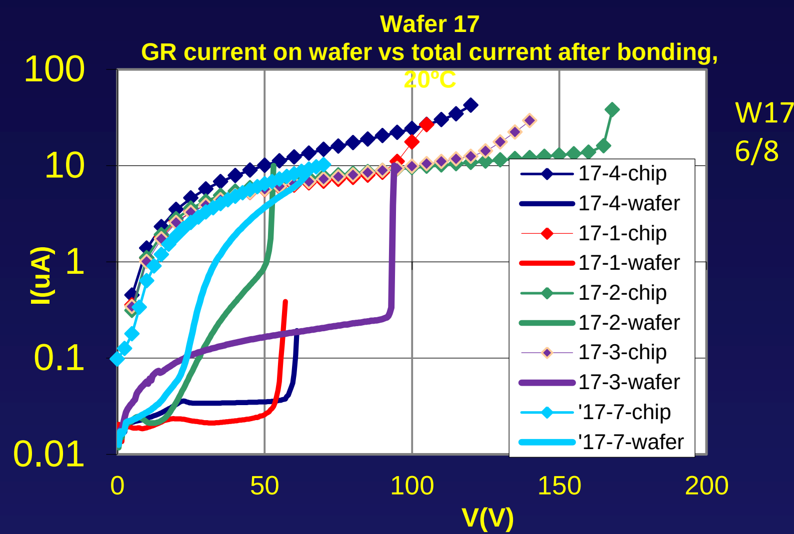


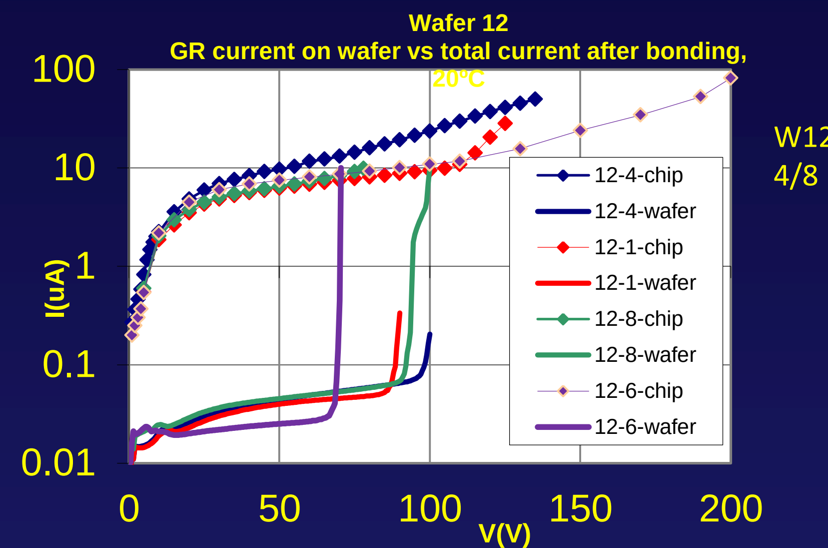


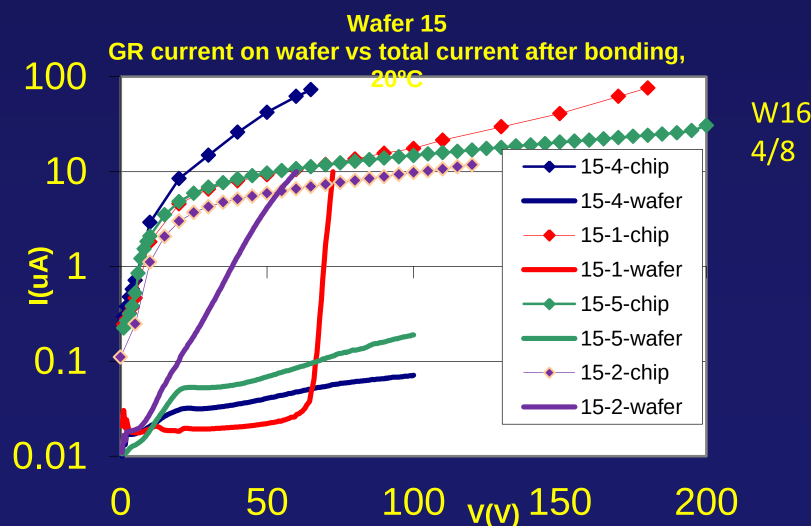
Notes

CNM IBL Qualification wafers before and after bump-bonding

C. Fleta. S. Grinstein, G. Pellegrini







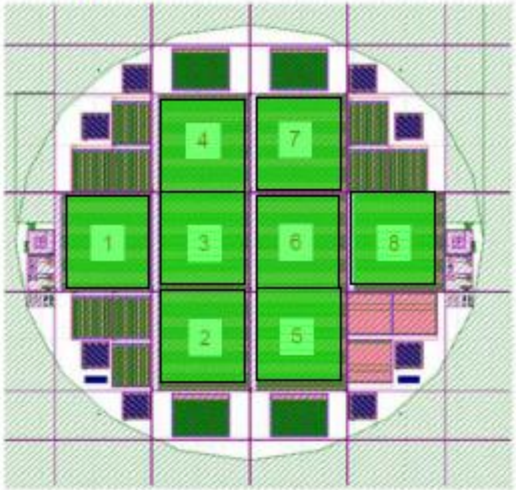
GR current identifies potential defects

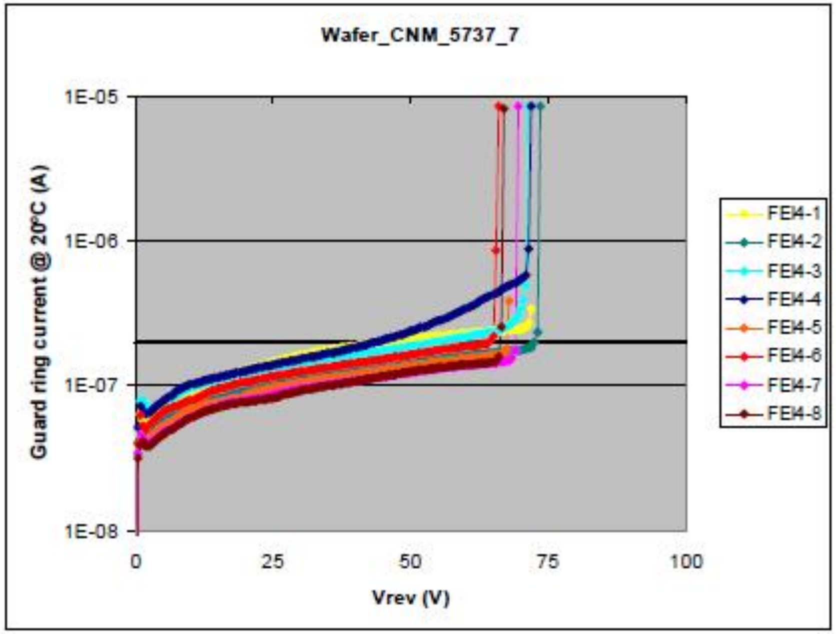
Also could be enhanced by stress and neighbour sensors

100% Reproduced behaviour before and after BB

3D IBL production: technical sheet for each of the selected wafers: ex. CNM

Batch: 5737
Wafer: 7





bowing

Wafer curvature: 60.8µm

	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

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

MANCHESTER 1824

3D Pixels ATLAS

IBL 3D Processing status Summary

Cinzia Da Viá , Uni. Manchester. "trento" Workshop, Ljubljana 29th February 2012

19 CLASS B sensors – can be used for testing

Batch	Status	Compl. Date	tested	Selected wafers	Yield on selected	Number of good sensors
A10	Completed	July/sept11	20	12	60%	58
A11	Completed	18-31Oct	11	4	44%	14
A12	On-going	March12	-	-	-	-
A13	On-going	April 12	-	-	-	-
CNM1	Completed	10-31Oct	19	18	60%	86
CNM2	Completed	06-fEB12	17	15	71%	85
CNM3	On-going	March12	-	-	-	-
TOTAL= Today			**67**	**49**	**62%**	**243**
TO IZM				**43**	**65%**	**225**

Summary

The 3DATLAS collaboration committed to produce 224 3D sensors compatible with the ~4cm ^{2} FE-I4 at CNM and FBK by IBL loading time in spring 2012

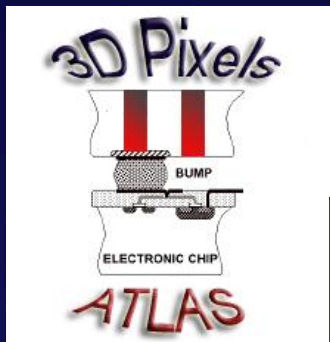
- 67 production wafers have been completed and tested,
- 49 selected and 43 sent to IZM with a total yield of ~62%
- = 225 class A sensors are ready and waiting to be bump-bonded at IZM

Further batches are in an advanced processing state both at CNM and FBK To be completed by March-April 2012

Outlook:

- Full3D and Double sided-3D behaving as expected after irradiation
- Efficiency of CNM assemblies irradiated at 5x10^15 n/cm2 measured after bias (160V) and lowered threshold (1200-1500e) at 15degrees=98.9% and resolution 9.2um for cluster size2 (more on A. Micelli's talk)
- Reliable operation after 5×10^{15}ncm^{-2} at -5^{o}C during test beam (low power dissipation)
- Edge efficiency for slim fences double sided 3D measured at ~170 um from physical edge in test beams before and after irradiation
- Full3D with active edges processed and will be tested in 2012
- Dense work-plan for PH1 (AFP) and PH2 pixels being prepared to fully exploit micromachining

3D ATLAS R&D Collaboration



Formed in 2007 to industrialise 3D technology
for ATLAS pixel upgrades

B. Stugu, H. Sandaker, K. Helle, (Bergen University), M. Backhaus, M. Barbero, J. Janssen, F. Hügging, M. Karagounis, V. Kostyukhin, H. Krüger, D-L Pohl, J-W Tsung, N. Wermes (Bonn University), M. Capua; S. Fazio, A. Mastroberardino; R. Mendicino, 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), G. 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, K. Shota Tsiskaridze C. Padilla (IFAE Barcelona), K. Einsweiler, M. Garcia-Sciveres (Lawrence Berkeley National Laboratory), M. Borri, C. Da Vià, J. Freestone, C. Lai, C. Nellist, J. Pater, R. Thompson, S.J. Watts (The University of Manchester), M. Hoeferkamp, S. Seidel (The University of New Mexico), E. Bolle, 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, M. Povoli (University and INFN of Trento), M. Cobal, M-P Giordani, L. Selmi, A. Cristofoli, D. Esseni, A. Micelli, P. Palestri (University of Udine)

Processing Facilities: C. Fleta, M. Lozano G. Pellegrini, D.Quirion (CNM Barcelona, Spain); (M. Boscardin, A. Bagolini, G. Giacomini, F. Mattedi, 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)*

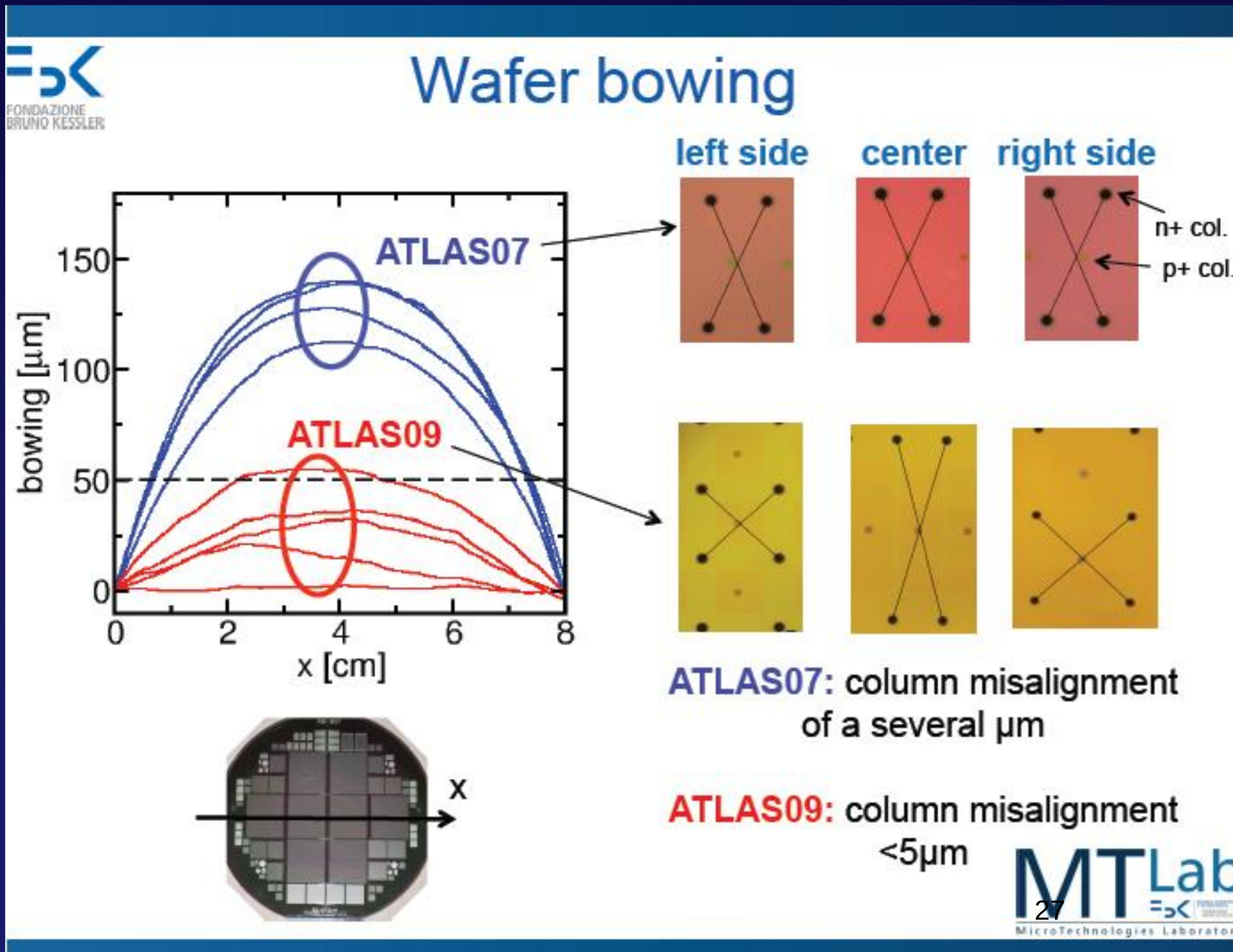
18 institutions and 5 processing facilities

25

spares

QA for wafer bowing is < 60 microns with an alignment <5 microns This is valid for both FBK (this slide) and CNM

from E. Vianello, FBK,
3D processing meeting 19-5-11

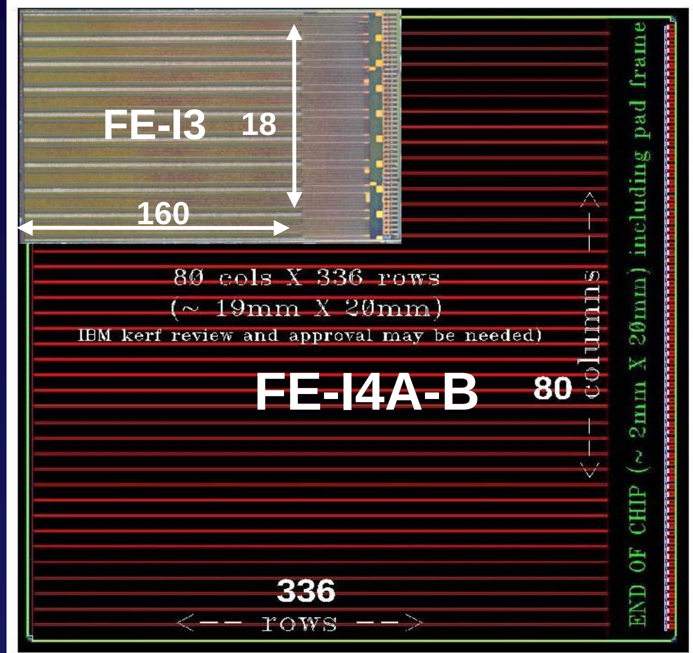


IBL sensors specifications

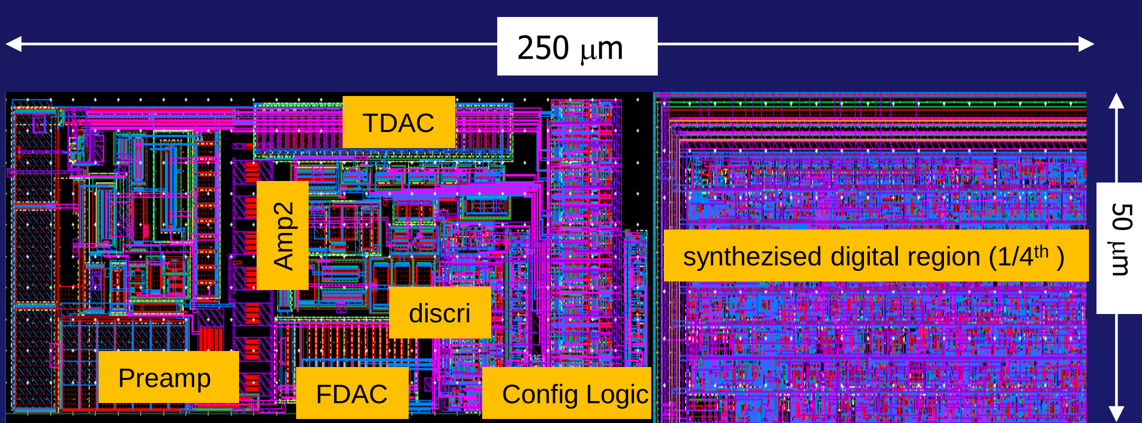
Sensor specifications for IBL:

- Qualify to 5×10^{15} n_{eq}
- max. power dissipation: 200 mW/cm² at -15 C
- tracking efficiency > 98%.

	3D n-in-p sensor	planar n-in-n sensor
active size W x L [mm²]	16.8 x 20.0	16.8 x 40.9
total size W x L [mm²]	18.8 x 20.5	18.54 x 41.27 (?)
thickness [mm]	0.23	0.20
Typical depletion voltage [V]	≤ 15	≤ 35
Typical inital operation voltage [V]	25	60 (V_{dep}+30V)
at of at end of lifetime [V]	180	1000



	FE-I3	FE-I4
Pixel Size [μm²]	50×400	50×250
Pixel Array	18×160	80×336
Chip Size [mm²]	7.6×10.8	20.2×19.0
Active Fraction	74 %	89 %
Analog Current [μA/pix]	26	10
Digital Current [μA/pix]	17	10
Analog Voltage [V]	1.6	1.4
Digital Voltage [V]	2	1.2
pseudo-LVDS out [Mb/s]	40	160

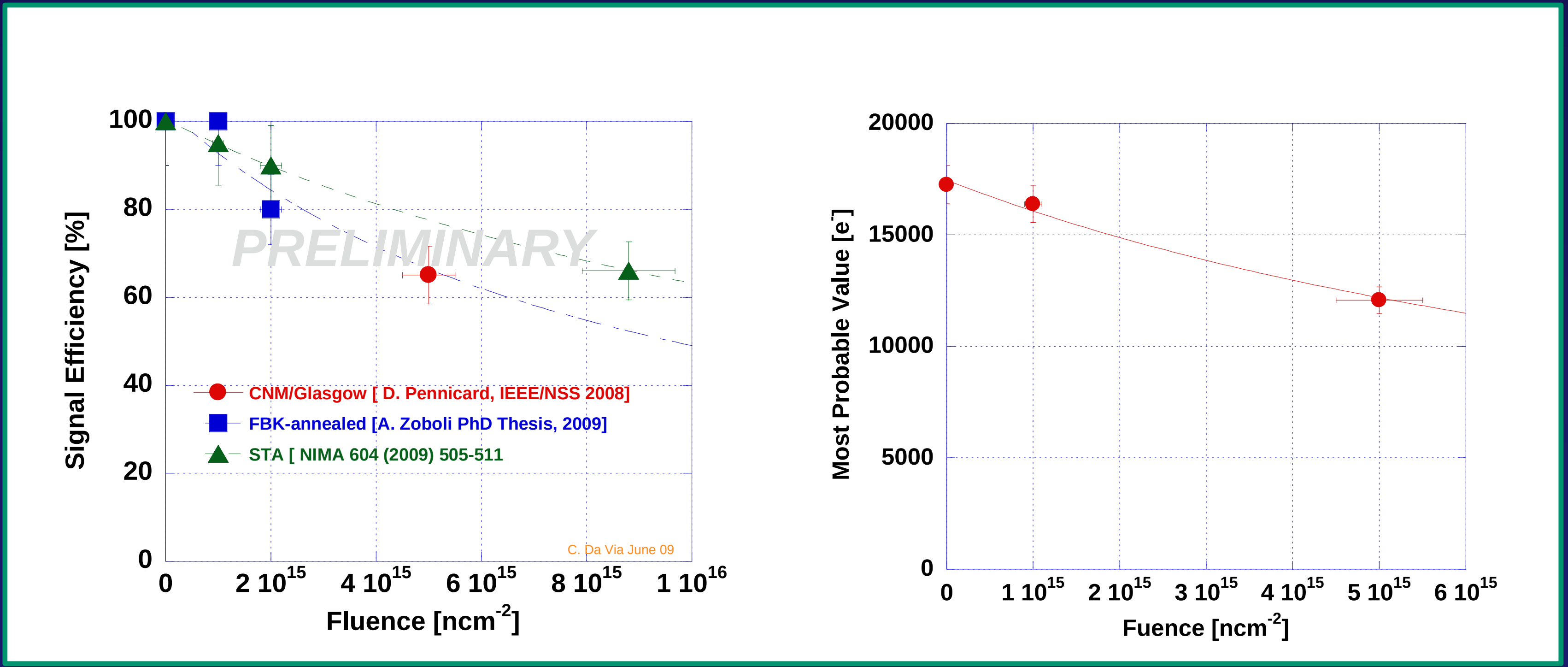


Most probable signal after IBL fluence

Compilation of Stanford, CNM,FBK

MPS predicted=230μm x 75e$^-$ = 17 250 e$^-$

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



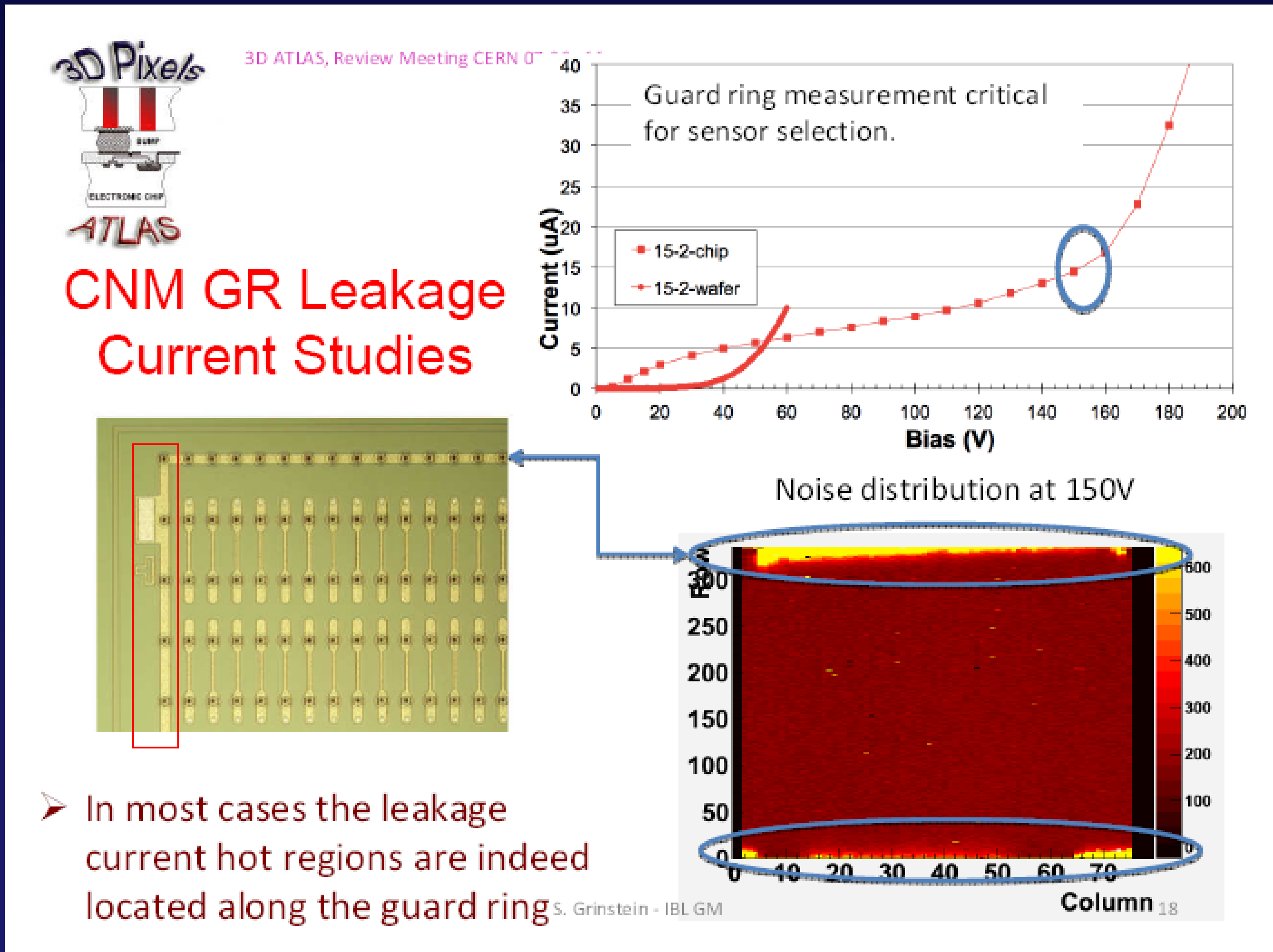
QA and Sensor selection criteria

Each wafer should have at least 3 good FE-I4 3D sensors to be selected.

QA action	Level	Description/Comments
Visual inspection	Each fabrication step	Check for shorts, discoloration or anomalies on the sensor surface, front –back misalignment
Wafer bow	completed wafer	Measurement of wafer bow, no problem for bump-bonding but potential risk of higher leakage and electrodes misalignment
Critical steps analysis with test wafers	DRIE Poly-doping	Optical inspection, test of resistance, presence of voids or anomalies
IV on test structures	Completed wafer	Gives a global indication of wafer quality. Test structures are distributed all around the wafer perimeter where IV would indicate worst case.
IV on FE-I4 sensors Used by CNM	On wafer and after UBM	Useful to select good sensors after process completion and after UBM deposition. Requires a guard ring
Use of temporary metal Used by FBK	On wafer	Gives a reliable measurement of the sensor quality at pixel level, performed before final metal deposition.
X-Ray inspection at IZM	After UBM After bump-bonding	Performed at IZM

Guard Ring studies at CNM

S. Grinstein IFAE

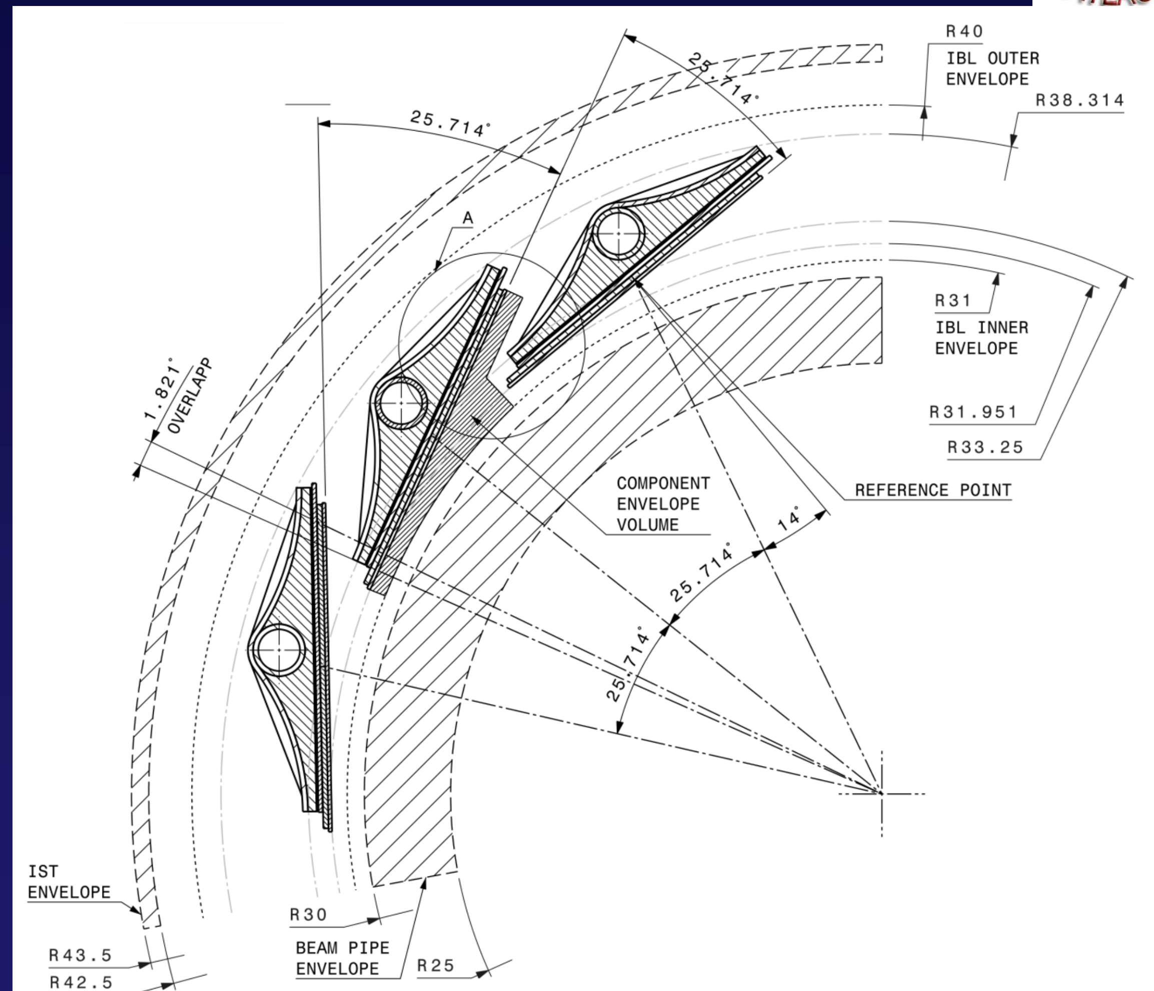


ATLAS IBL Layout and parameters

Layout

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

These numbers have a redundancy of 100% to account for loading yield



Requirements

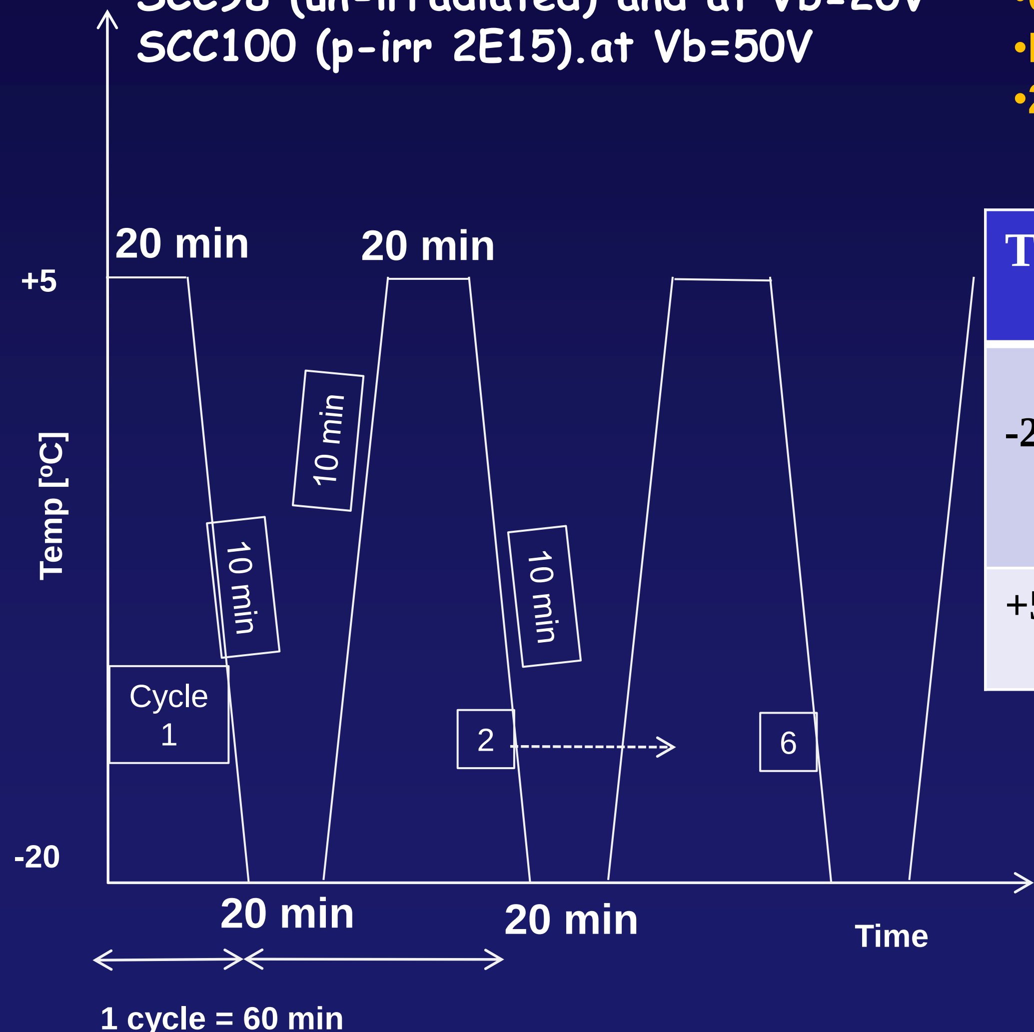
- "Hermetic" to straight tracks in Φ (1.8° overlap)
- No overlap in Z: minimize gap between sensor active area.

Parameters

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

Stability test:
Rapid thermal cycling

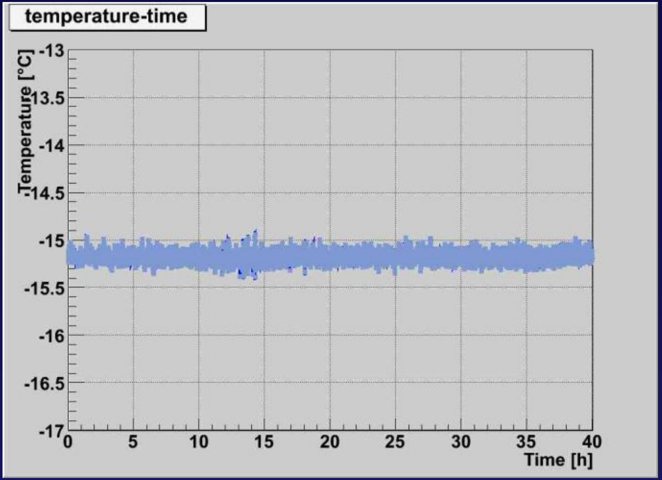
SCC98 (un-irradiated) and at Vb=20V
SCC100 (p-irr 2E15).at Vb=50V

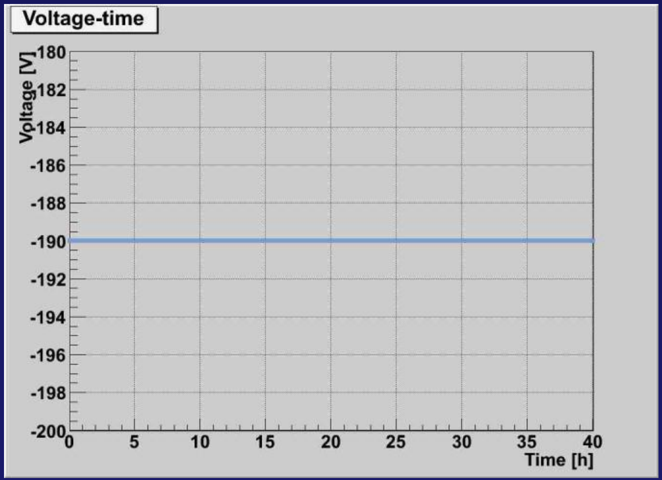


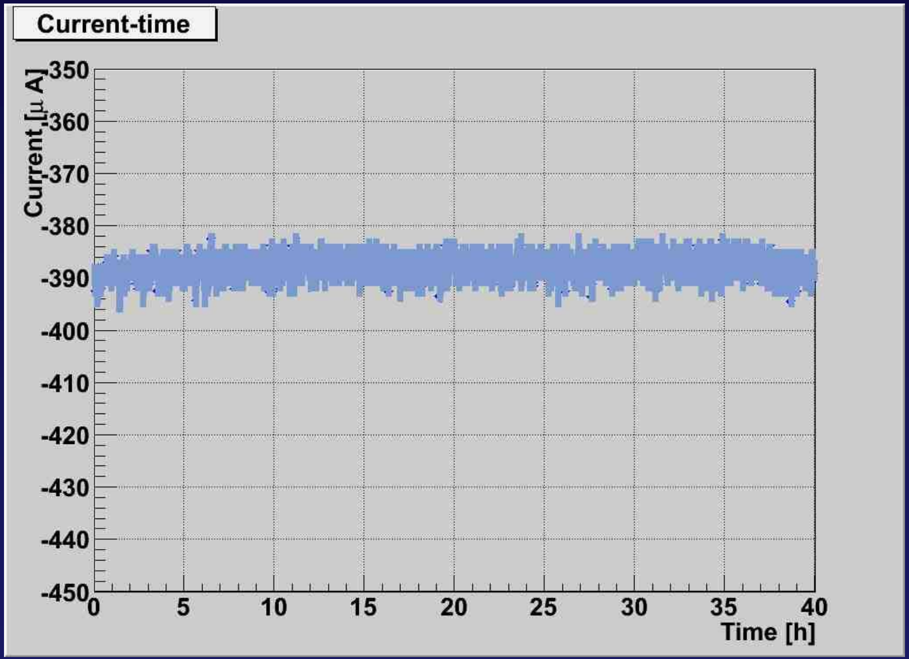
- 6 cycles (x 60 min)
- Rapid (10 min) T ramp-up and down
- 20 min stability and I measurement

T	Current SSC98		Current SCC100	
-20C	Cycle 1 22nA	Cycle 6 23nA	Cycle 1 55uA	Cycle 6 53uA
+5C		180nA		867uA

Long term stability tests at operational IBL conditions CNM neutron Irrad. at 5×10^{15}ncm^{-2} (R. Medicino, C. Gallrapp)







•T is measured using a PT 1000 resistor glued on the Aluminium plate
•The FrontEnd chip ON all time
HV on sensor is 190 V – voltage drop on 100kohm bias resistor