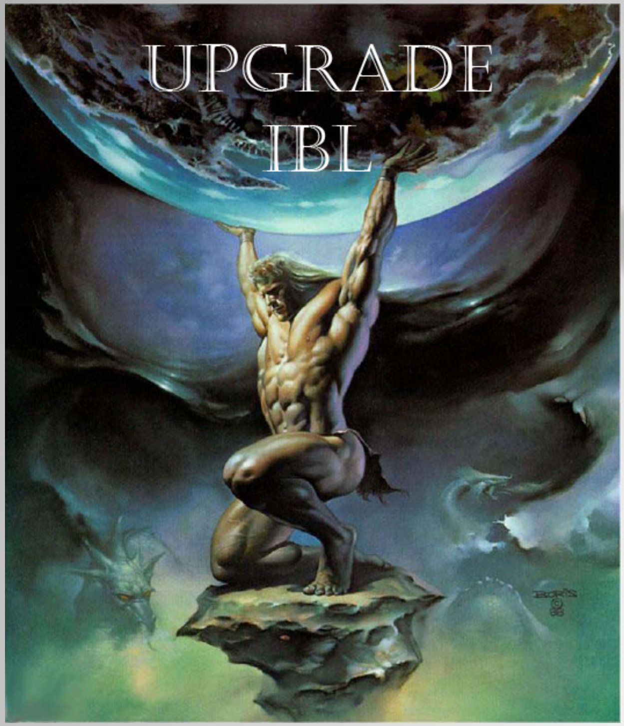


Planar Pixel Sensors

3D Pixel Sensors

Silicon sensor technologies for ATLAS IBL upgrade

TIPP 2011 – Chicago

Philippe Grenier (SLAC National Accelerator Laboratory)

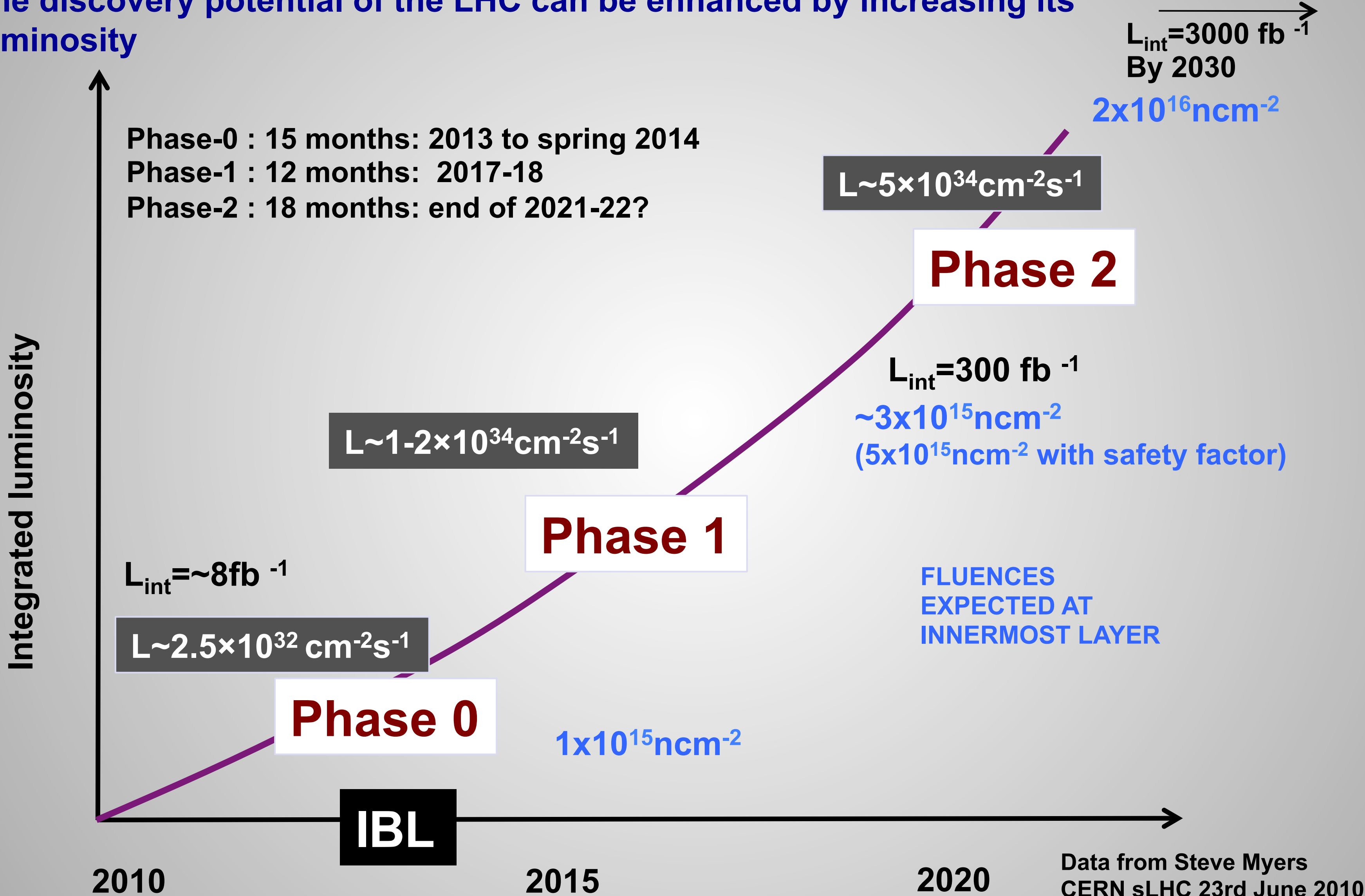
For the ATLAS IBL Collaboration

Outline

- ATLAS Upgrades and Insertable B Layer (IBL)
- Planar Pixel Sensors
- 3D Pixel Sensors
- Lab and Testbeam measurements
- Selection criteria
- Conclusion

Motivation for ATLAS Upgrades

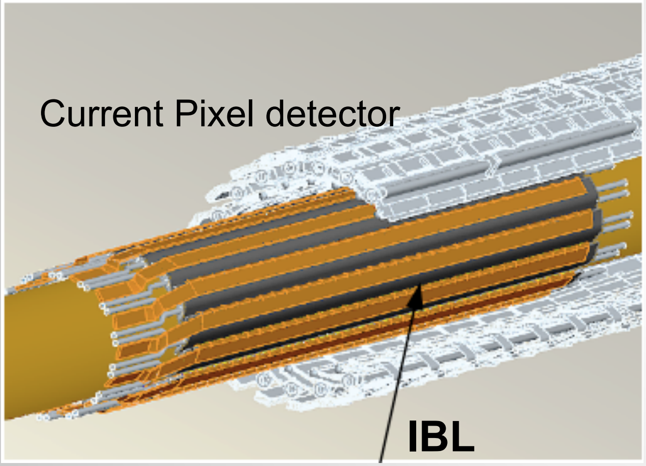
The discovery potential of the LHC can be enhanced by increasing its luminosity

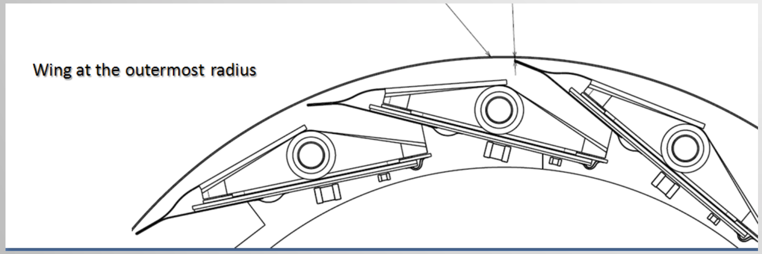


Data from Steve Myers
CERN sLHC 23rd June 2010.

ATLAS Insertable B Layer (IBL)

- Performance of current innermost Pixel Detector layer will degrade before main tracker upgrade.
- To maintain physics performance (b-tagging) and insure against radiation effects:
- Insertion of new pixel inside current pixel detector: Insertable B Layer IBL.
- IBL design: 250 Mrad TID and 5.10^{15} n_{eq}/cm^2 NIEL.
- Installation originally planned for 2015-2016… advanced (in January 2011) to …. 2013!





IBL mounted on new beam pipe
Length: ~64cm
Envelope: Rin = 31mm, Rout=40mm
14 staves, 32 pixel sensors / stave.
Front-end chip:

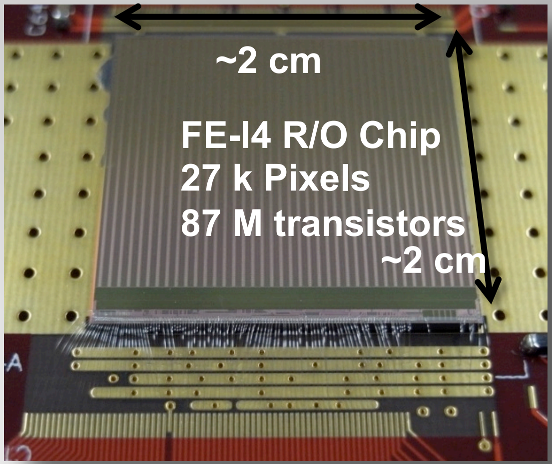
- FE-I4, ATLAS upgrades.
- 50µm x 250µm
- 80(col) x 336 (rows) = 26880 cells.
- 2cm x 2cm!

Two competing sensor technologies: Planar and 3D pixel sensors.
Diamond technology dropped: production time not compatible with IBL in 2013.

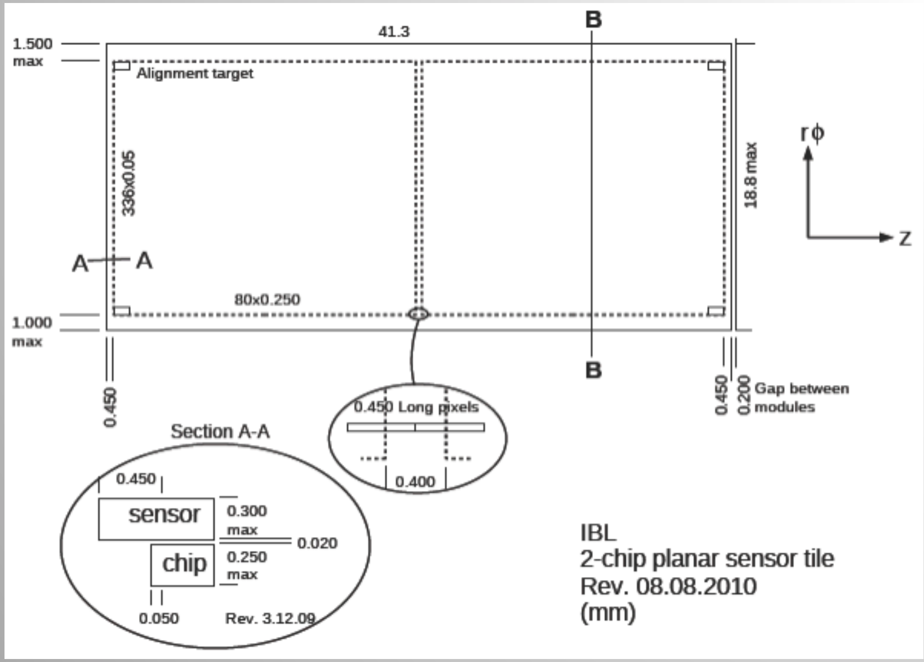
IBL Sensors specifications and module prototyping

Sensor specifications for IBL:

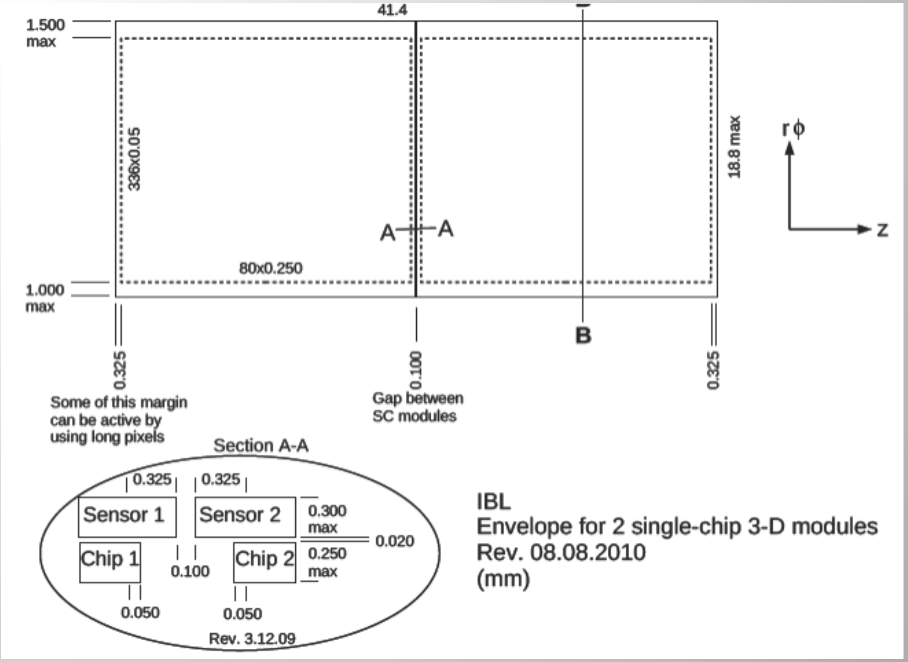
- maximum bias voltage: 1000 V.
- sensor thickness: 225 ± 25 μm
- coolant temperature: -30 C
- sensor temperature: -15 C
- sensor max. power dissipation: 200 mW/cm^2 at -15 C
- edge width: 450 μm
- tracking efficiency > 98%.



Planar 2-chip sensor tile



3D 1-chip sensor tile



IBL sensor fast track qualification and production

<table>
<tr><th>Task</th><th>PLANAR</th><th>3D</th></tr>
<tr><td>Ready for installation</td><td>July 4, 2013</td><td>Aug 1, 2013</td></tr>
<tr><td>Finish loading</td><td>Feb 15, 2013</td><td>Mar 15, 2013</td></tr>
<tr><td>Start stave loading</td><td>Sept 19, 2012</td><td>Oct 15, 2012</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>Sensor production completed</td><td>June 11, 2012</td><td>Aug 27, 2012</td></tr>
<tr><td></td><td>6 batches x 25 wafers</td><td>10 batches x 22 wafers</td></tr>
<tr><td colspan="3">Sensor production has to start asap:

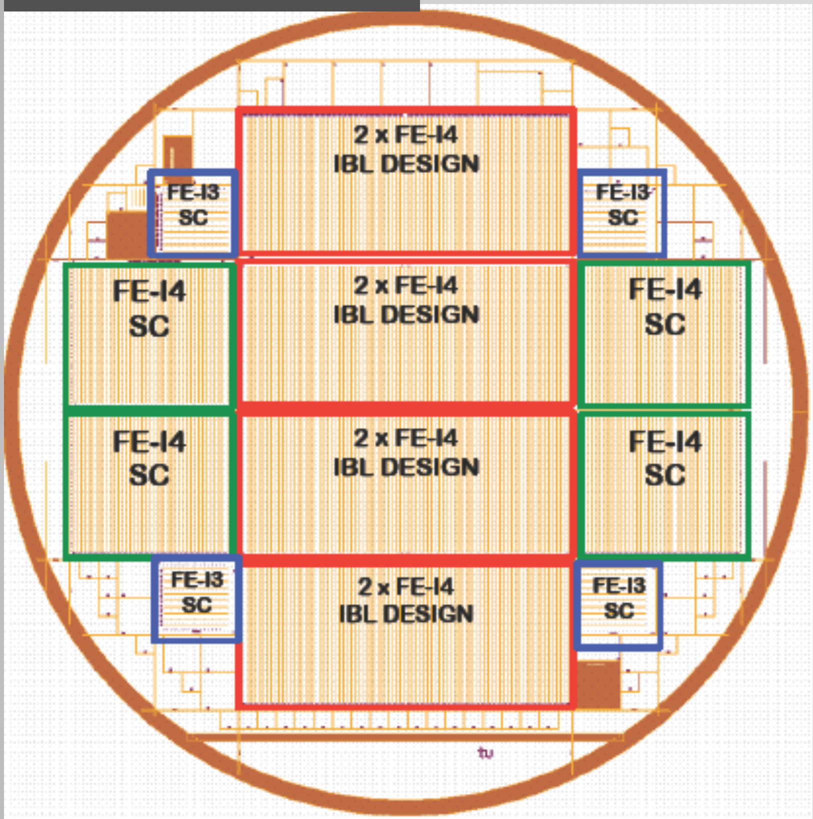
IBL Fast Track Qualification for sensor choice: review July 4-5, choice soon after.

Heavy program of sensor irradiations and beam tests in 2011:
• 4 protons irradiation campaigns at Karlsruhe (26 MeV protons).
• 3 neutrons irradiation campaigns at Ljubljana (reactor neutrons).
• 2 beam tests (Feb. and April) at DESY (4 GeV positrons).
• 1 beam test (June) at CERN (180 GeV pions): Irradiated PPS/3D under IBL Operating conditions (temp, field).

Pre-production to check yield (see next), to be completed by mid-June.</td></tr>
<tr><td>Other critical items:</td><td colspan="2">FE-I4 submission, bump bonding, stave, flex…</td></tr>
</table>

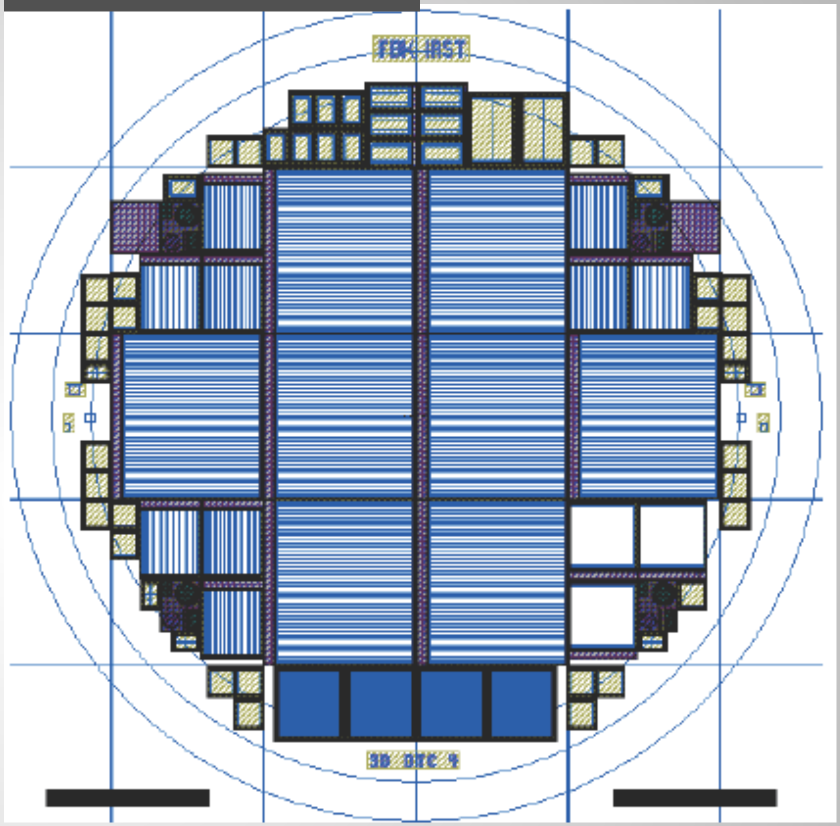
IBL sensor pre-production floor-plan

Planar Floor-Plan

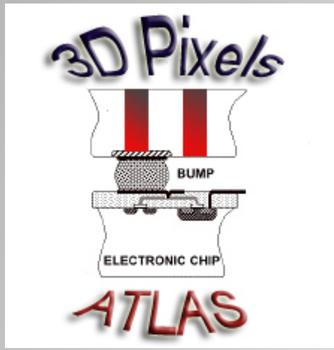


- 4 IBL tiles, 4 single-chip modules.
- (IBL-type design).
- Test structures
- At CiS, Germany.

3D Floor-Plan



- 8 IBL single-chip modules.
- (IBL-type design).
- Test structures
- At CNM (Spain) and FBK (Italy).



ATLAS 3D Silicon Sensors R&D Collaboration

VTT

The Stanford Nanofabrication Facility

SINTEF

ITC irst FONDAZIONE BRUNO KESSLER

cnm Centre Nacional de Microelectrònica

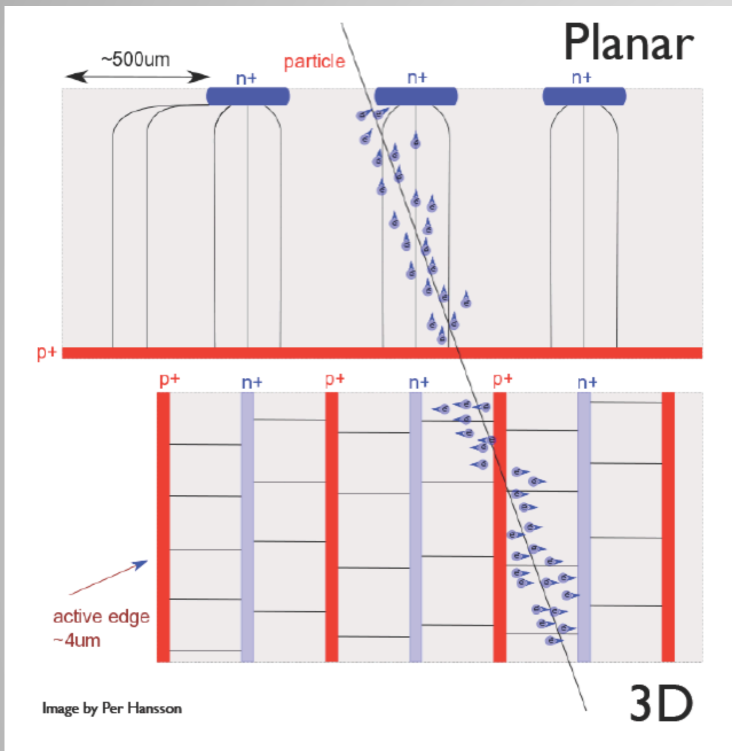
B. Stugu, H. Sandaker, K. Helle, (Bergen University), M. Barbero, F. Hügging, M. Karagounis, V. Kostyukhin, H. Krüger, J-W Tsung, N. Wermes (Bonn University), M. Capua; S. Fazio, A. Mastroberardino; G. Susinno (Calabria University), C. Gallrapp, B. Di Girolamo; D. Dobos, A. La Rosa, H. Pernegger, S. 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, J. Freestone, S. Kolya, C. Li, 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, 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, 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

3D Principle and Designs

- Proposed by S. Parker, J. Segal and C. Kenney in 1997: NIM A 395 (1997) 328.
- Electrodes penetrate through silicon bulk: short collection distance.



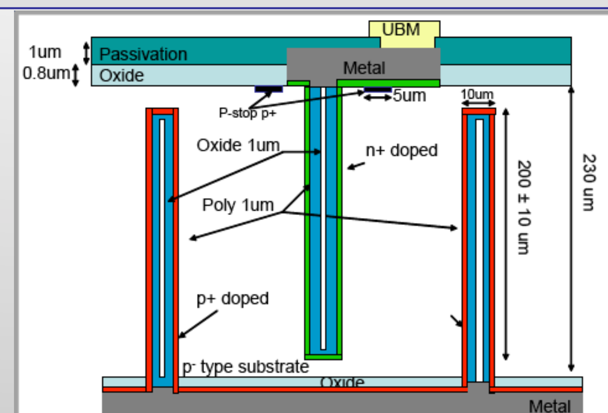
3D Advantages
Low depletion voltage and low power
Fast charge collection
Active edge: sensor edge is an electrode
No charge shift from Lorentz angle
Smaller trapping probability: Radiation Hard

3D Complications
Higher capacitance: more noise ? (but more signal)
Partially inactive columns: loss of efficiency at normal incidence
Production Yield/cost

Different Electrodes/cell: 2E, 3E, 4E

Two designs:

- Full 3D: SINTEF, Stanford.
- Partial 3D: CNM, FBK: IBL type.



Partial 3D:

Processing from both sides of wafer.

No active edge.

Planar Pixel Sensor (PPS) Collaboration

R&D within the planar pixel proposal:

- slim edge sensors to reduce inactive area
- radiation damage in planar sensors
- bulk materials
- simulation of sensor design and detector layout
- low threshold operation of FE readout
- low cost, large scale pixel production

Participating institutes:

- CERN
- AS, Prague
- LAL Orsay
- LPNHE Paris
- Bonn University
- HU Berlin
- DESY
- TU Dortmund
- Goettingen University
- MPP and HLL Munich
- Udine University and INFN
- KEK
- IFAE-CNM Barcelona
- Liverpool University
- UC Berkeley and LBNL
- UNM Albuquerque
- UC Santa Cruz

Industrial partners: CiS, HLL Munich, HPK, Micron.

Planar Pixel Sensors: technology and designs

PPS Advantages	Challenges
Mature technology: Standard processing Many qualified vendors High yield Relatively low cost Experience with sensor design and optimization Radiation hardness models	Low charge collection after irradiation: ○ Increase high voltage ○ Need small-signal readout electronics Increasing leakage current with fluence: ○ Need efficiency cooling ○ Annealing reduces leakage current Sensor edge usually conductive: ○ Need guard rings ○ Significant inactive area

Three designs have been envisaged for IBL:

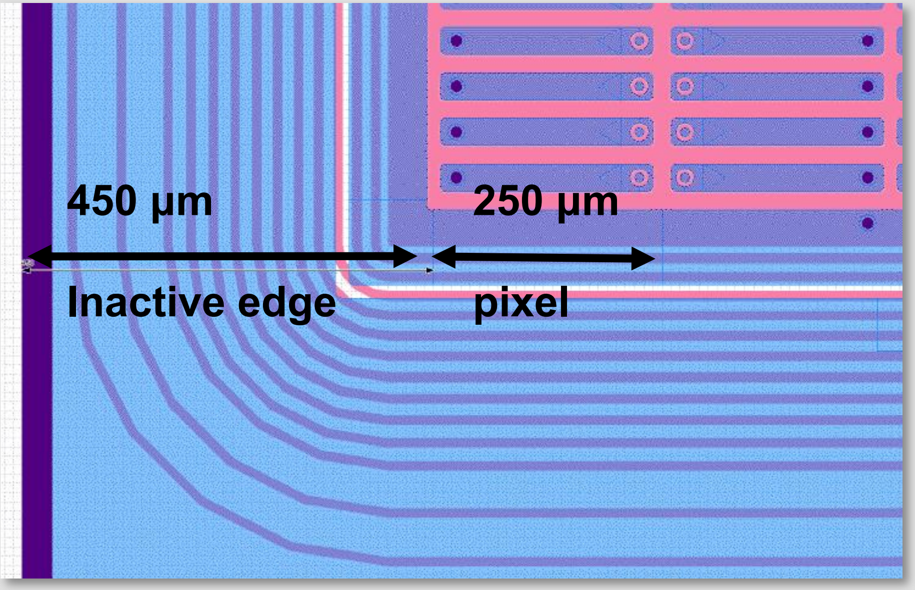
- Conservative design (ATLAS-like), n-in-n (CiS)
- Slim edge design (~200 μm inactive edge), n-in-n: CiS 🡸 chosen for IBL.
- Thin sensors (~150 μm thickness), n-in-p: HLL Munich

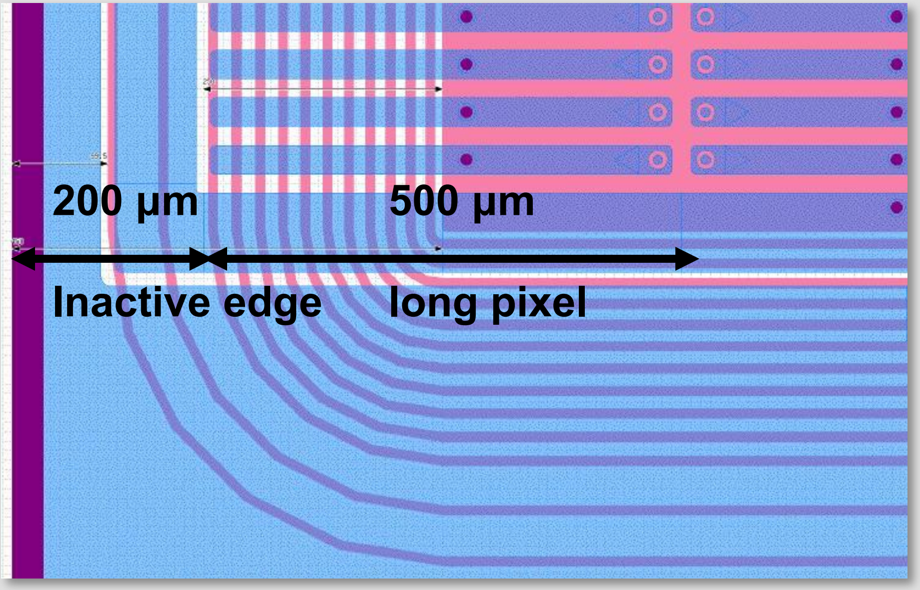
Additional R&D for future upgrades:

- Thin (~150 μm) n-in-p sensors: HPK
- Thin (~200 μm) n-in-p sensors: Micron

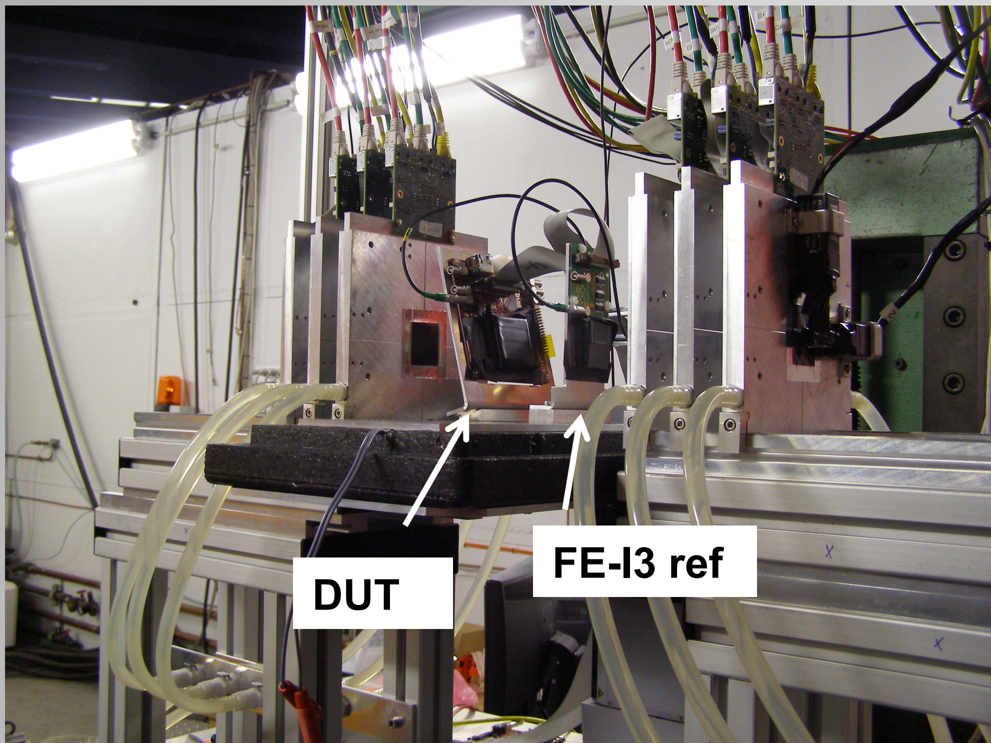
Planar Pixel Sensors: Designs

Conservative Design	Slim Edge Design
○ goal is to resemble current ATLAS design as far as possible. ○ 13 (out of 16) guard rings, to stay within 450 mm ➔ proven to be sufficient.	○ minimize inactive edge by shifting guard rings underneath active pixel region . ➔ 200 µm inactive edge achievable ○ simulation shows uniform depletion of edge pixels ○ first IV curves show standard behavior.

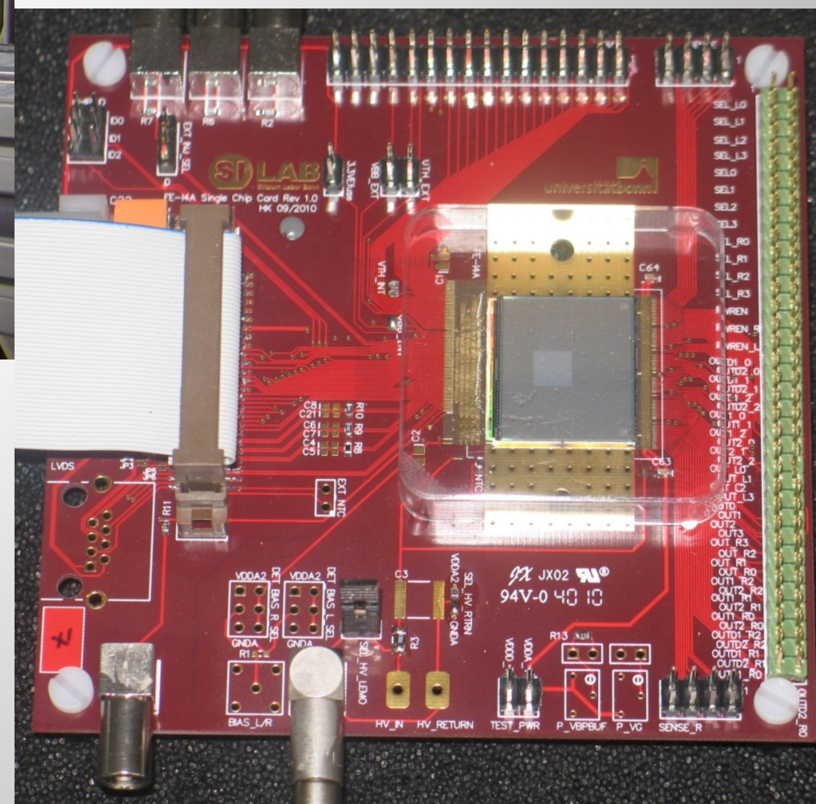




First FE-I4 TestBeam: DESY, February 2011

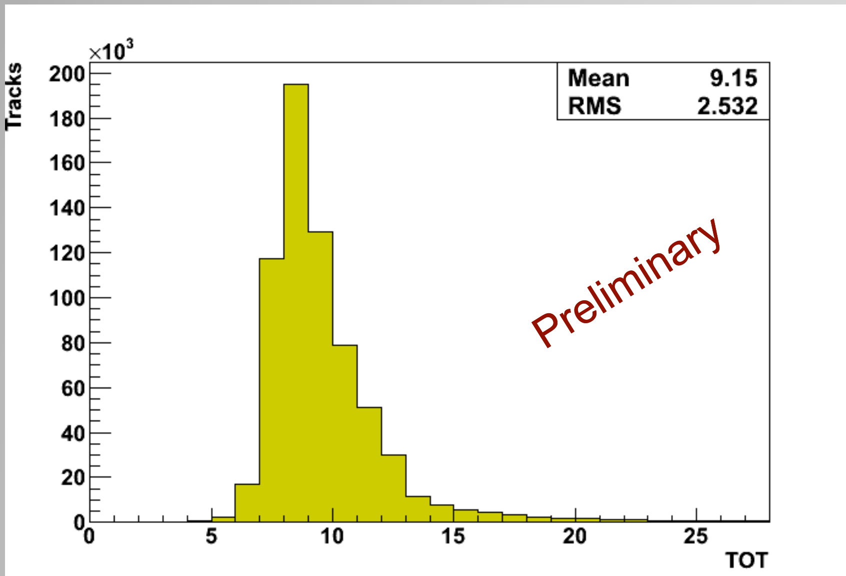


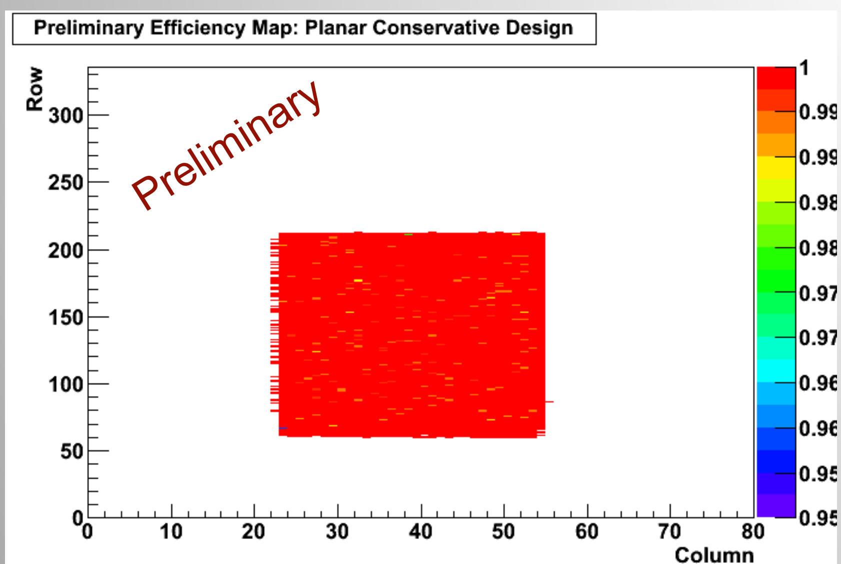
EUTelescope at DESY, 4 GeV positron beams
(6 planes of Mimosa26 sensors)
1 FE-I3 reference planar sensor
1 Device Under Test at a time
(Multiple scattering)
First FE-I4 sensor (PPS) tested!
3 Slim Edge + 2 Conservative



FE-I4 chip + sensor on pcb

DESY February testbeam results:





PPS, Slim Edge Design sensor (250 µm thick)

Un-irradiated device.

Charge collection measured in units on 25ns of Time Over Threshold (TOT).

Calibration: 10TOT at 30ke-: larger than expected, under investigation.

Tracking efficiency, over all sensor.

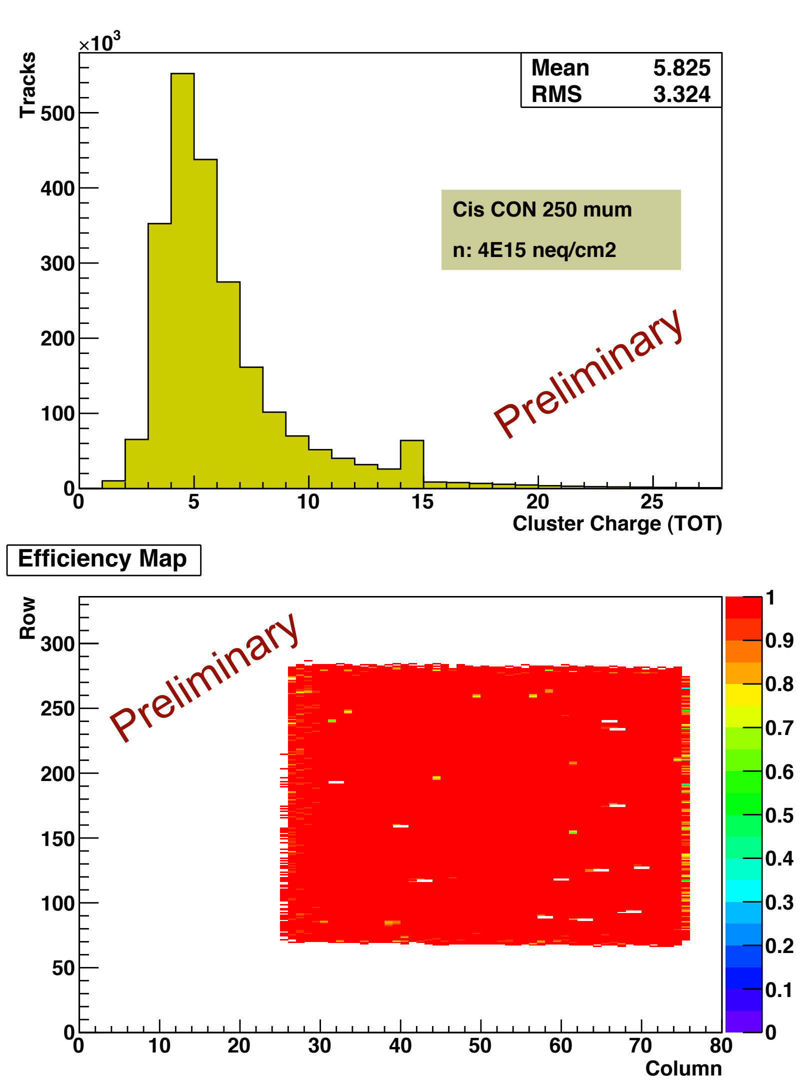
Require a hit in other device (FE-I3 reference) to avoid fake tracks.

A few noisy/dead pixels.

Over tracking efficiency: 99.95 %, excellent!

DESY April: irradiated sensors with neutrons

- 2 PPS Slim Edge (250 µm thick) irradiated at Ljubljana (4.10^{15} n_{eq}/cm^2)
- 1 PPS Conservative (250 µm thick) irradiated at Ljubljana (4.10^{15} n_{eq}/cm^2)



PPS, Conservative Design sensor (250 µm thick)

Irradiated to 4.10^{15} n_{eq}/cm^2.

Bias voltage: -1000 V.

Cold box temperature: -50C (dry ice).

Beam at normal incidence.

Charge Collection Efficiency from TOT: hard to estimate due to TOT calibration issue, but >50%.

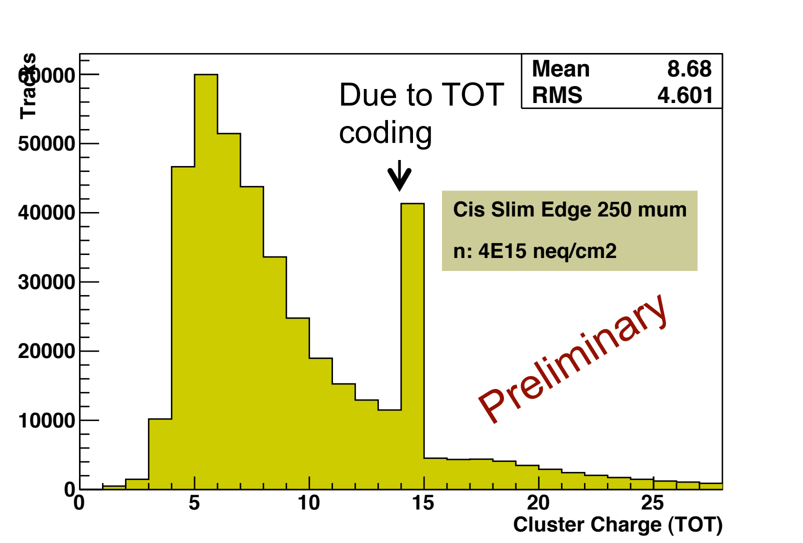
Very few dead or noisy pixels!

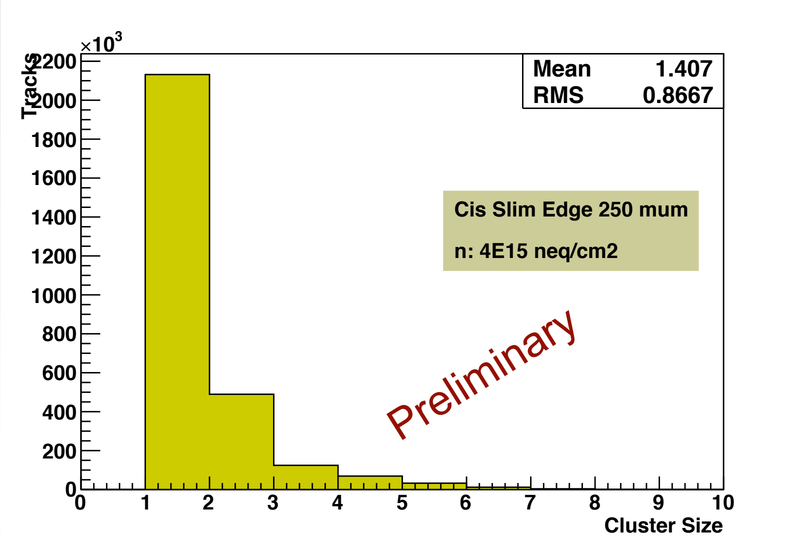
Overall tracking efficiency: 98.4%.

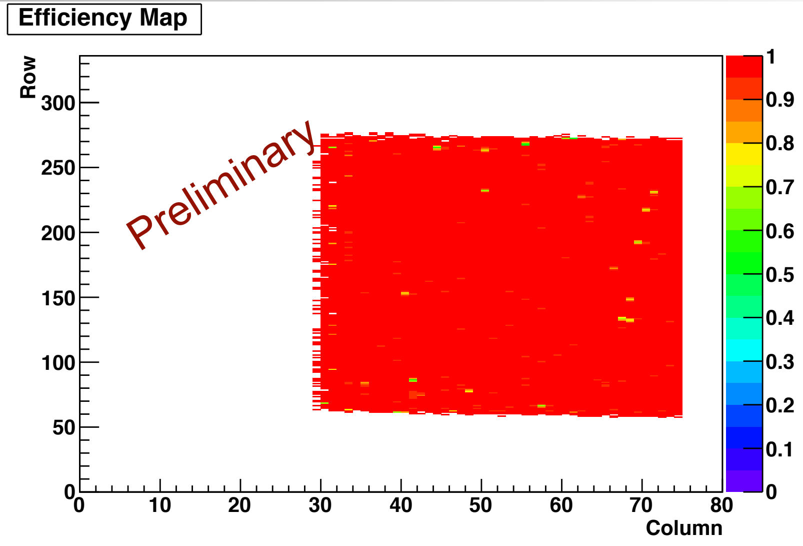
Sensor is working well!

DESY April: irradiated sensors with neutrons

PPS, Slim Edge Design sensor (250 µm thick)



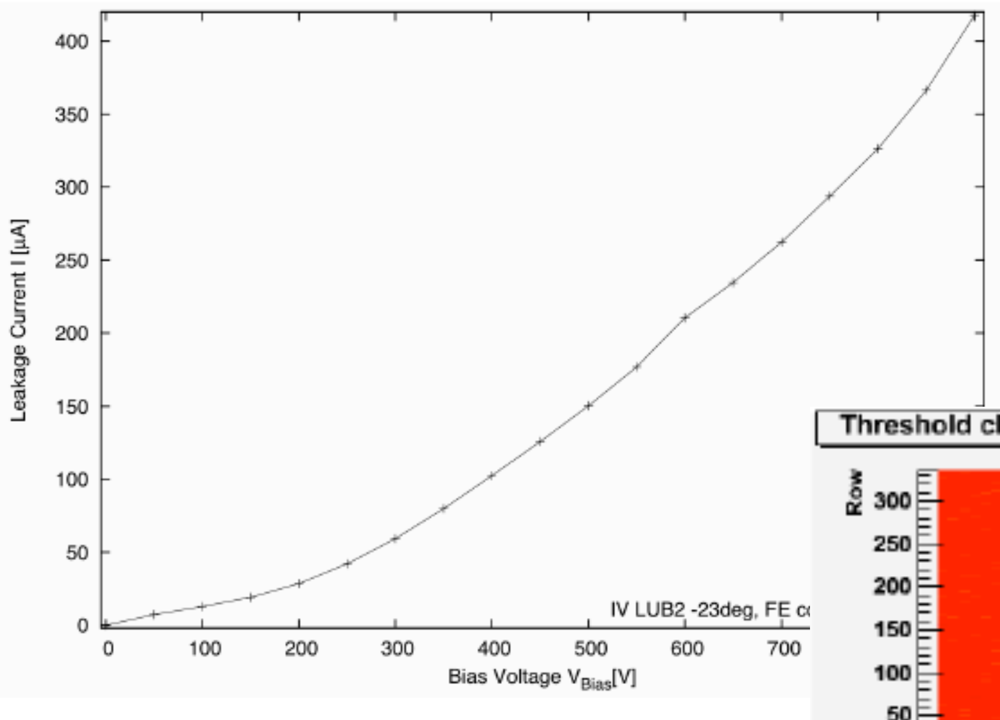




Irradiated to 4.10^{15} n_{eq}/cm^2.
Bias voltage: -1000 V.
Cold box temperature: -50C (dry ice).
Beam at normal incidence.
Charge Collection Efficiency from TOT: hard to estimate due to TOT calibration issue, but >50%.

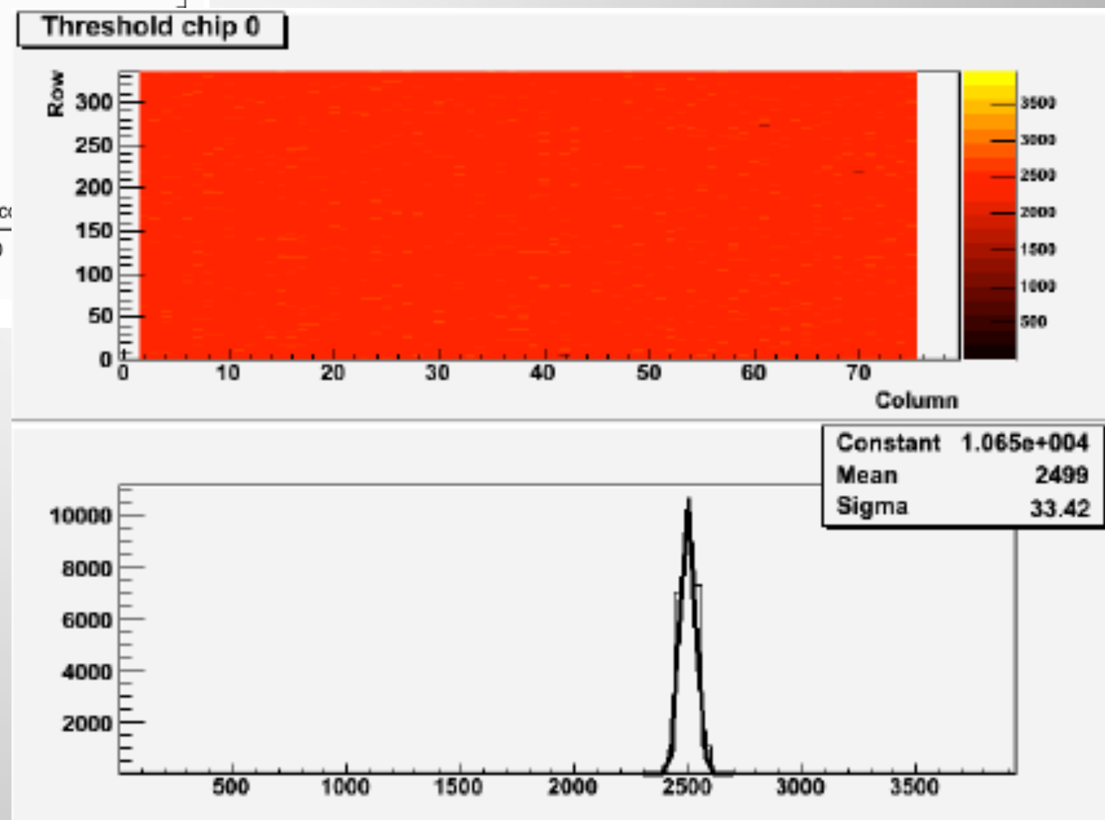
Overall tracking efficiency: 99.4%.
Sensor is working well!

Lab test and characterization of neutron irradiated sensors



I-V curve:

- as expected, high leakage current.
- no plateau visible.
- Operation voltage was set at -1000V
- Temp: -23C.

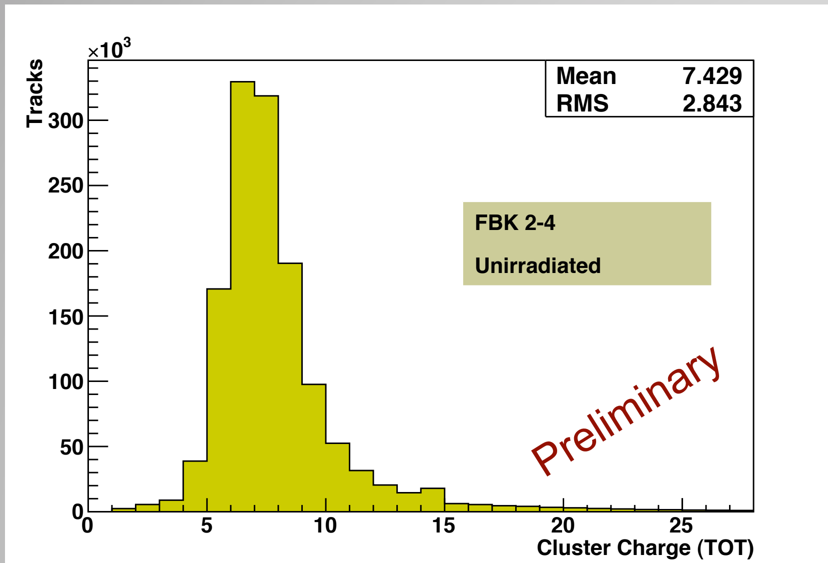


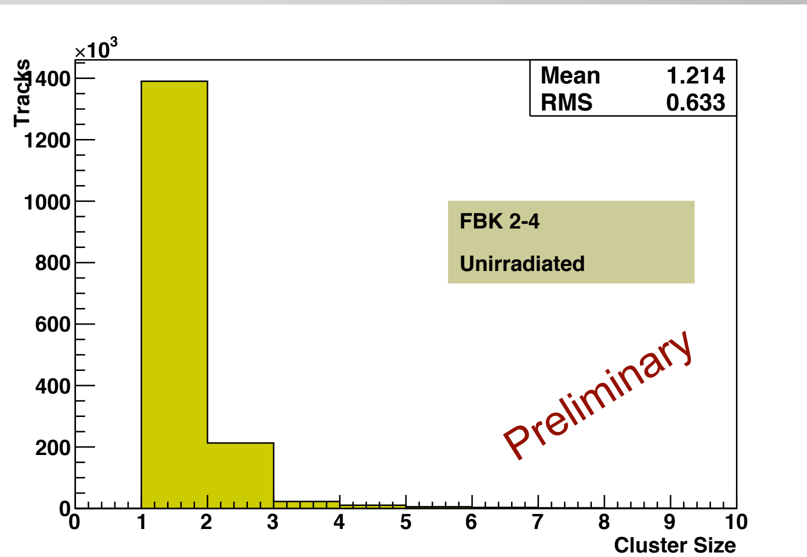
Key point: tuning of front-end chip

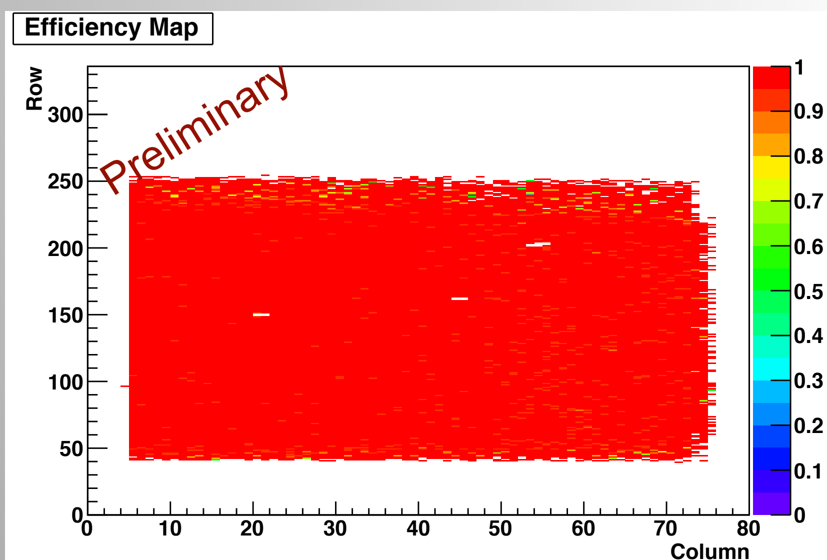
- Threshold: 2500 e-.
- TOT: 8 at 20ke-.

Aim at as low Threshold as possible (reduced charge with fluence), and low noise.

DESY April: FBK testbeam results







FBK un-irradiated, from early batch:

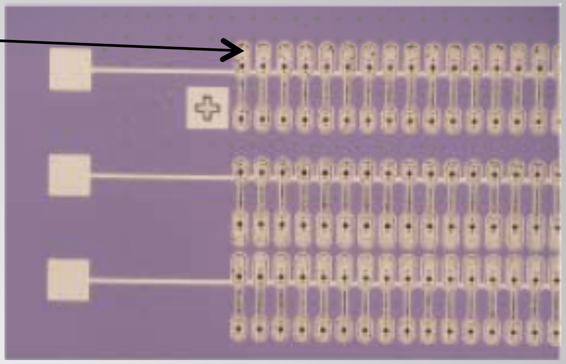
Normal beam incidence. Works very well.

TOT and cluster size distributions as expected.

Overall tracking efficiency: 98%: loss of efficiency for tracks going through electrodes (electrodes not filled). Recover full efficiency tilted tracks.

FBK: sensor selection criteria

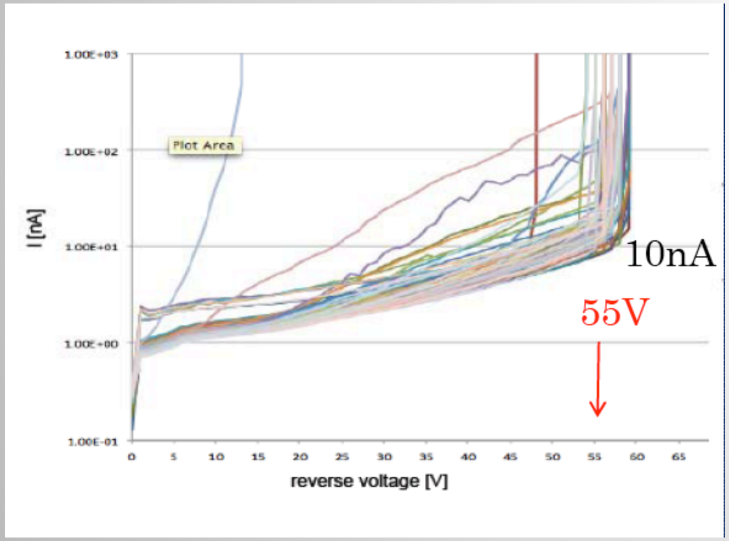
Temporary metal:



- Allows to perform electrical tests prior to bump bonding.
- The temporary metal shorts the 336 pixels of each 80 columns.
- Check the I-V of each 80 strips.

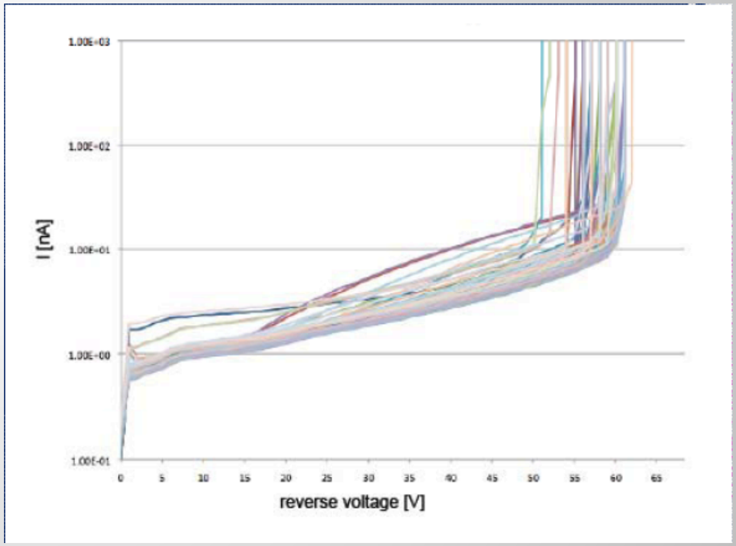
Selection criteria definition

Bad sensor



Plot of current in all 80 “strips”.
Each has 336 pixel (need just one bad pixel)

Good sensor



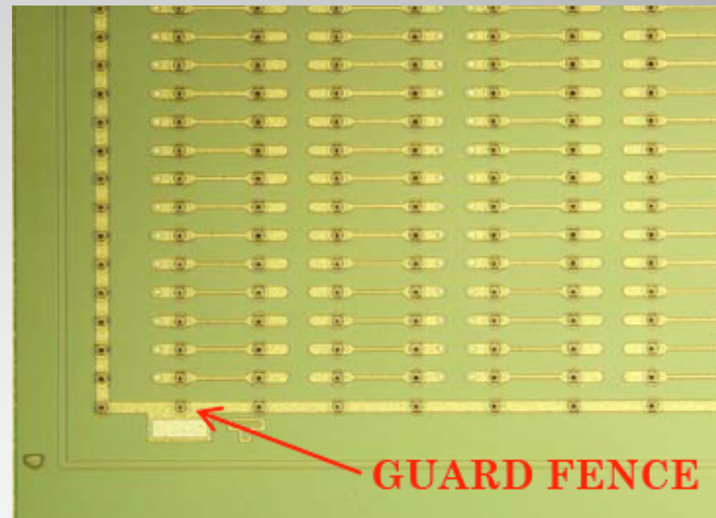
All pixels/columns working fine
I_{pixel} = 5 pA

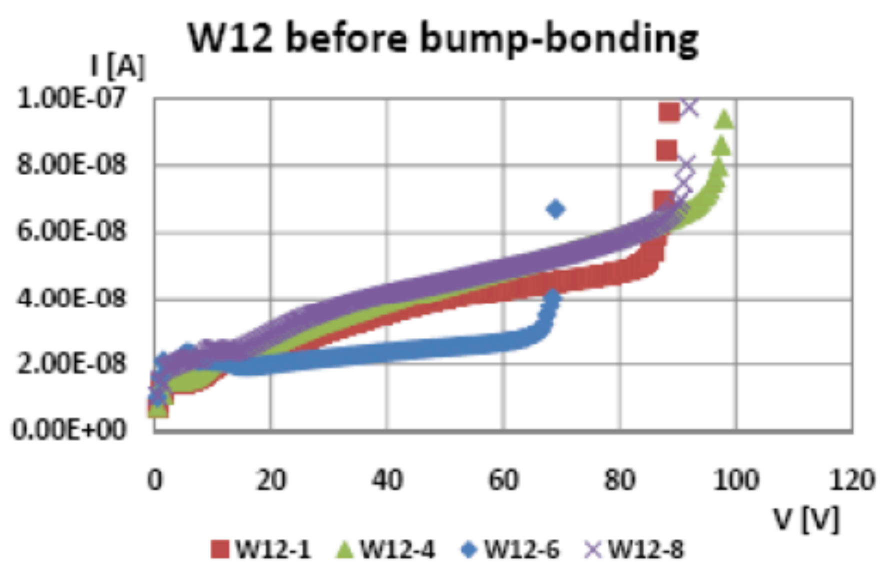
V_{bd} > 25 V and I_{op} < 2μA

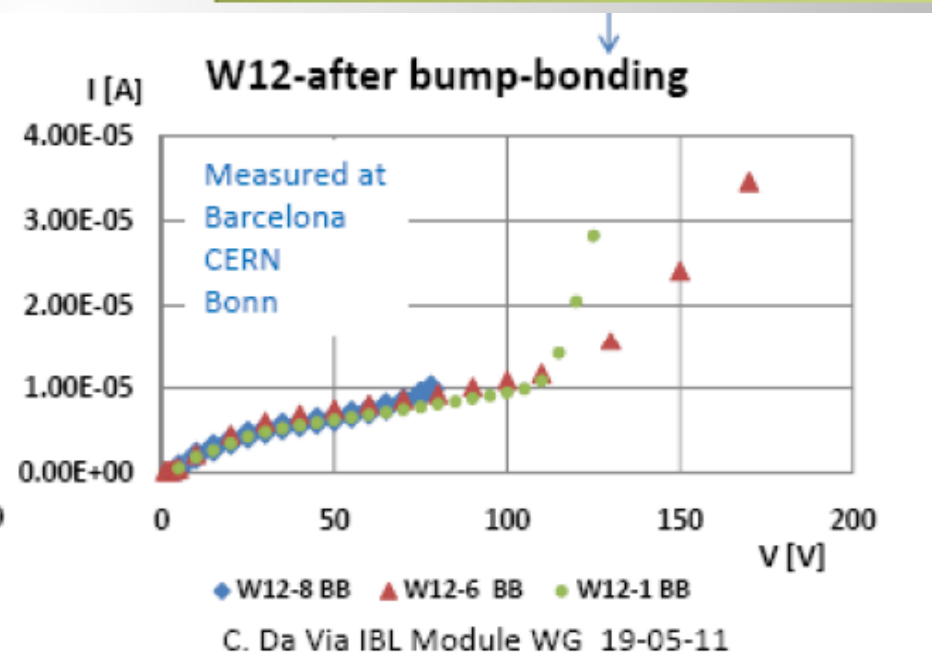
CNM: sensor selection criteria

I-V curve on guard fence

- Not total current of full sensor but gives good indication of the presence of defects.
- Test of full wafers without under-bump-metallization.
- $V_{bd} > 25V$
- Guard fence IV so far is a good criteria for sensor selection
- After bump-bonding: higher current (full sensor).







Conclusions

- IBL installation in 2013: very tight schedule…
- Two competing technologies for pixel sensors Planar and 3D.
- Heavy qualification process: pre-production, irradiation, lab and beam tests. Challenging, given that first IBL-type sensors available since February….
- Main test in June: beam test at CERN with IBL-type sensor.
- Sensor choice in July….