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.

- **Phase 0**: 15 months: 2013 to spring 2014
- **Phase 1**: 12 months: 2017-18
- **Phase 2**: 18 months: end of 2021-22?

**Integrated luminosity**

- $L_{int}=8 \text{ fb}^{-1}$
- $L_{int}=300 \text{ fb}^{-1}$
- $L_{int}=3000 \text{ fb}^{-1}$

**Expected fluences at innermost layer**

- $L \approx 2.5 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}$
- $L \approx 1-2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$
- $L \approx 5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$

By 2030:

- $2 \times 10^{16} \text{ ncm}^{-2}$
- $\sim 3 \times 10^{15} \text{ ncm}^{-2}$
- $(5 \times 10^{15} \text{ ncm}^{-2} \text{ with safety factor})$
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 $5 \times 10^{15}$ 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>
<thead>
<tr>
<th>Task</th>
<th>PLANAR</th>
<th>3D</th>
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<tbody>
<tr>
<td>Ready for installation</td>
<td>July 4, 2013</td>
<td>Aug 1, 2013</td>
</tr>
<tr>
<td></td>
<td>6 batches x 25 wafers</td>
<td>10 batches x 22 wafers</td>
</tr>
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</table>

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.

Other critical items: | FE-I4 submission, bump bonding, stave, flex…
IBL sensor pre-production floor-plan

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

- 8 IBL single-chip modules.
- (IBL-type design).
- Test structures
- At CNM (Spain) and FBK (Italy).
ATLAS 3D Collaboration

ATLAS 3D Silicon Sensors R&D Collaboration

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)


18 institutions and 5 processing facilities
3D Principle and Designs

- 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**

**Two designs:**

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

<table>
<thead>
<tr>
<th>PPS Advantages</th>
<th>Challenges</th>
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<tbody>
<tr>
<td>Mature technology: Standard processing Many qualified vendors High yield Relatively low cost Experience with sensor design and optimization Radiation hardness models</td>
<td>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</td>
</tr>
</tbody>
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#### 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**

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

<table>
<thead>
<tr>
<th><img src="image1" alt="Conservative Design Diagram" /></th>
<th><img src="image2" alt="Slim Edge Design Diagram" /></th>
</tr>
</thead>
<tbody>
<tr>
<td>Inactive edge</td>
<td>Inactive edge</td>
</tr>
<tr>
<td>pixel</td>
<td>long pixel</td>
</tr>
</tbody>
</table>

| 450 µm                                | 200 µm                              |
| 250 µm                                | 500 µm                              |

* Philippe Grenier  TIPP 2011 – Pixel Sensors for ATLAS IBL  12
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
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 ($4 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$)
- 1 PPS Conservative (250 µm thick) irradiated at Ljubljana ($4 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$)

**PPS, Conservative Design sensor (250 µm thick)**

Irradiated to $4 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$.

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)

Due to TOT coding

Cis Slim Edge 250 mum  
n: 4E15 neq/cm²

Irradiated to $4 \times 10^{15}$ \( \text{n}_{\text{eq}/\text{cm}^2}\).
Bias voltage: -1000 V.
Cold box temperature: -50°C (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
- $I_{\text{pixel}} = 5 \text{ pA}$

$V_{bd} > 25 \text{ V}$ and $I_{op} < 2\mu\text{A}$
**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).

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**Graphs**

- **W12 before bump-bonding**
  - Measured at Barcelona, CERN, Bonn
- **W12-after bump-bonding**
  - C. Da Via IBL Module WG 19-05-11
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…. 