Silicon sensor technologies for ATLAS IBL upgrade

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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
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?

- **Phase 0**: $L \sim 1 \times 2 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$
- **Phase 1**: $L \sim 2.5 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$
- **Phase 2**: $L \sim 5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$

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**Integrated luminosity**

- **Phase 0**: $L_{int} \approx 8 \text{ fb}^{-1}$
- **Phase 1**: $L_{int} \approx 300 \text{ fb}^{-1}$
- **Phase 2**: $L_{int} \approx 3000 \text{ fb}^{-1}$

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**FLUENCES EXPECTED AT INNERMOST LAYER**

- **Phase 0**: $1 \times 10^{15} \text{ncm}^{-2}$
- **Phase 1**: $2 \times 10^{16} \text{ncm}^{-2}$
- **Phase 2**: $3 \times 10^{15} \text{ncm}^{-2}$ (with safety factor)

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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 $5 \times 10^{15} \text{n}_\text{eq}/\text{cm}^2 \text{ NIEL}$.
- Installation originally planned for 2015-2016... advanced (in January 2011) to ... 2013!

IBL mounted on new beam pipe
Length: ~64cm
Envelope: $R_\text{in} = 31\text{mm}$, $R_\text{out}=40\text{mm}$
14 staves, 32 pixel sensors / stave.
Front-end chip:
- FE-I4, ATLAS upgrades.
- $50\mu\text{m} \times 250\mu\text{m}$
- $80(\text{col}) \times 336(\text{rows}) = 26880$ cells.
- $2\text{cm} \times 2\text{cm}$!

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/cm² 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

| Task                                | PLANAR         | 3D             |
|-------------------------------------|----------------|----------------|
| Ready for installation             | July 4, 2013   | Aug 1, 2013    |
| Finish loading                      | Feb 15, 2013   | Mar 15, 2013   |
| Start stave loading                 | Sept 19, 2012  | Oct 15, 2012   |
| Sensor production completed         | June 11, 2012  | Aug 27, 2012   |
| 6 batches x 25 wafers               | 10 batches x 22 wafers |

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

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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**

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

Partial 3D:
- Processing from both sides of wafer.
- No active edge.

Different Electrodes/cell: 2E, 3E, 4E
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:**                               | Low charge collection after irradiation:            |
| Standard processing                                  | o Increase high voltage                             |
| Many qualified vendors                               | o Need small-signal readout electronics              |
| High yield                                           |                                                       |
| Relatively low cost                                  | Increasing leakage current with fluence:            |
| Experience with sensor design and optimization       | o Need efficiency cooling                           |
| Radiation hardness models                            | o Annealing reduces leakage current                  |
|                                                       |                                                       |
|                                                       | Sensor edge usually conductive:                     |
|                                                       | o Need guard rings                                   |
|                                                       | o 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. | ✓ minimize inactive edge by shifting guard rings underneath active pixel region.  
| ✓ 13 (out of 16) guard rings, to stay within 450 mm \[\rightarrow\] proven to be sufficient. | \[\rightarrow\] 200 µm inactive edge achievable. |
| ✓ 450 µm Inactive edge | ✓ First IV curves show standard behavior. |
| ✓ 250 µm pixel | ✓ Simulation shows uniform depletion of edge pixels |
| ✓ 500 µm long pixel | ✓ |

![Conservative Design Diagram](image1)

![Slim Edge Design Diagram](image2)
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 ($4 \times 10^{15} \text{n}_{eq}/\text{cm}^2$)
- 1 PPS Conservative (250 µm thick) irradiated at Ljubljana ($4 \times 10^{15} \text{n}_{eq}/\text{cm}^2$)

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

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

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%.

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

Preliminary

Irradiated to $4 \times 10^{15}$ neq/cm².
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)
- $V_{bd} > 25 \text{ V}$
- $I_{op} < 2 \mu\text{A}$

**Good sensor**
- All pixels/columns working fine
- $I_{\text{pixel}} = 5 \text{ pA}$
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….