The Radiation Hardness of the ATLAS Pixel Sensor

- Requirements
- Design
- Surface Damage
- Bulk Damage
- Performance

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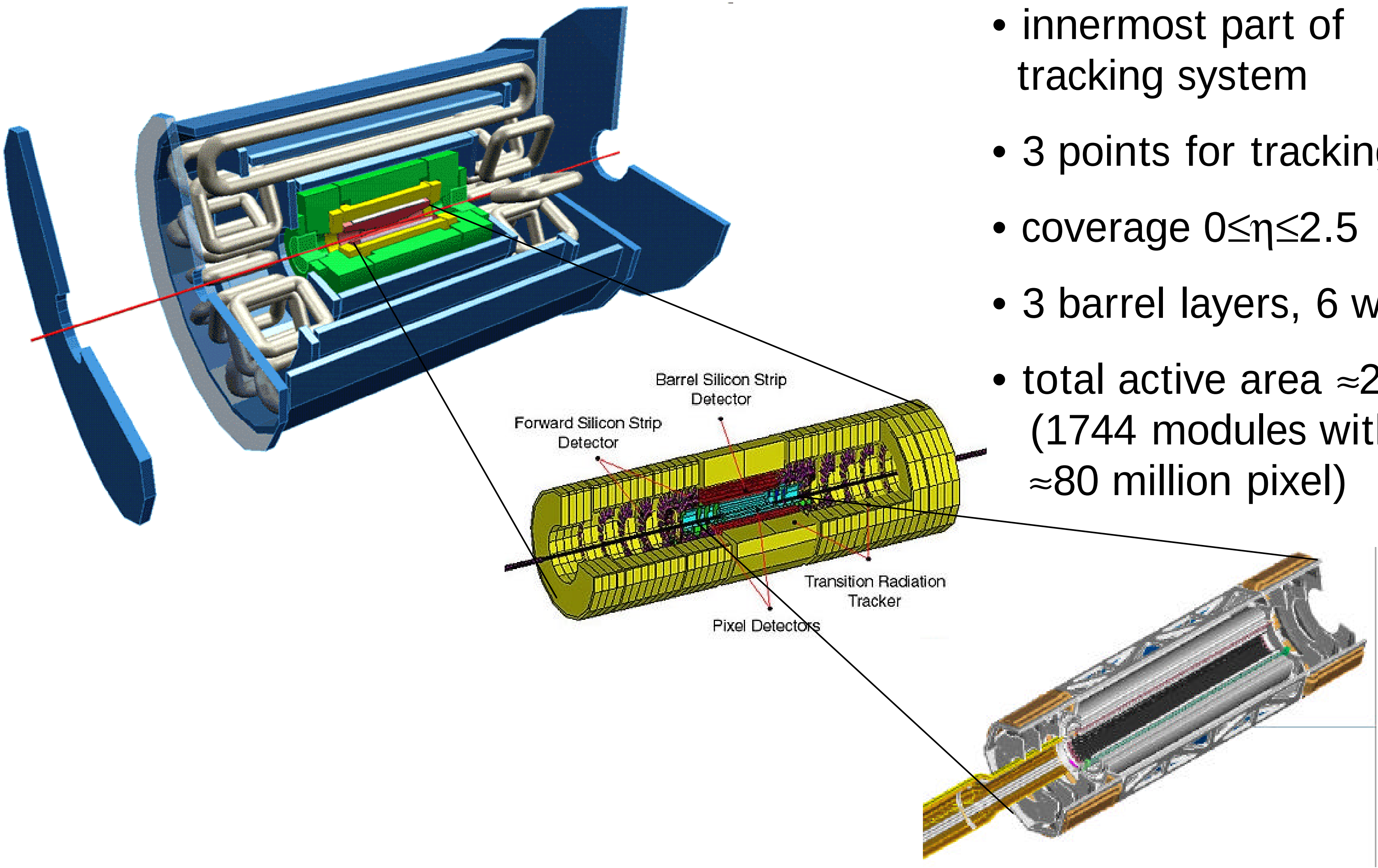
for the ATLAS Pixel Collaboration

1st Workshop on Radiation Hard Semiconductor Devices
for Very High Luminosity Colliders,

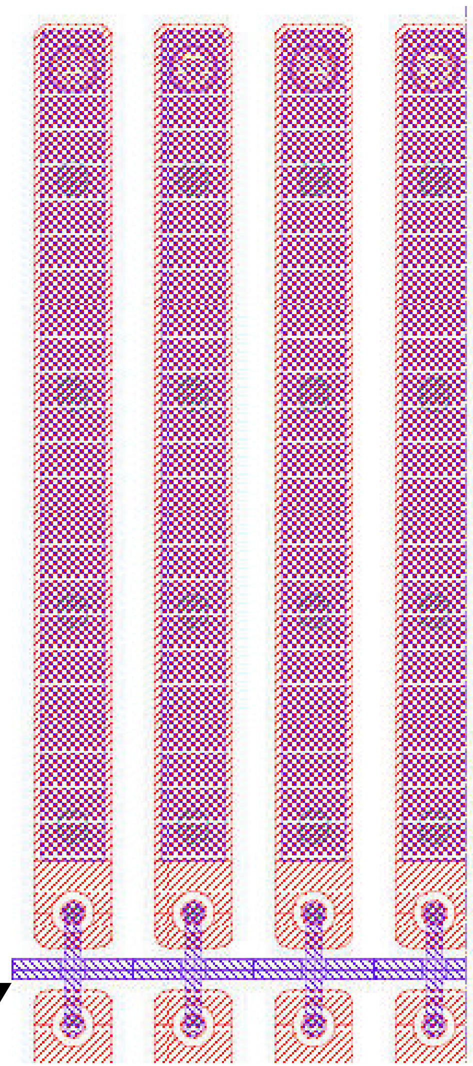
The ATLAS-Pixel-Detector



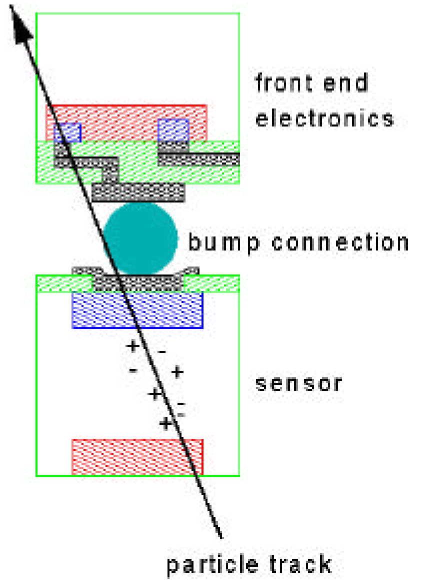
- innermost part of tracking system
- 3 points for tracking
- coverage $0 \leq \eta \leq 2.5$
- 3 barrel layers, 6 wheels
- total active area $\approx 2 m^2$ (1744 modules with $\approx$80 million pixel)

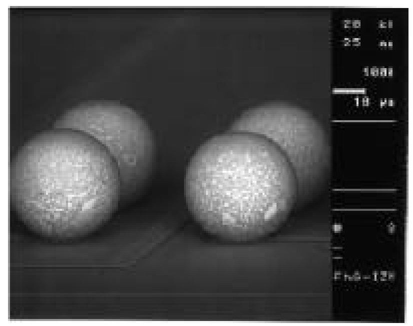
Requirements for Sensor

- pixel size 50 µm × 400 µm
- 10 years operation in harsh radiation environment:
  - up to 10^{15} n_{eq}/cm^2
  - and 500 kGy
- difficult access conditions require high reliability
- testability of sensor before module assembly



bias grid





Development Strategy

Design Studies

performed within ATLAS

- isolation technique
- design of pixel cell

Silicon Studies

performed within ROSE

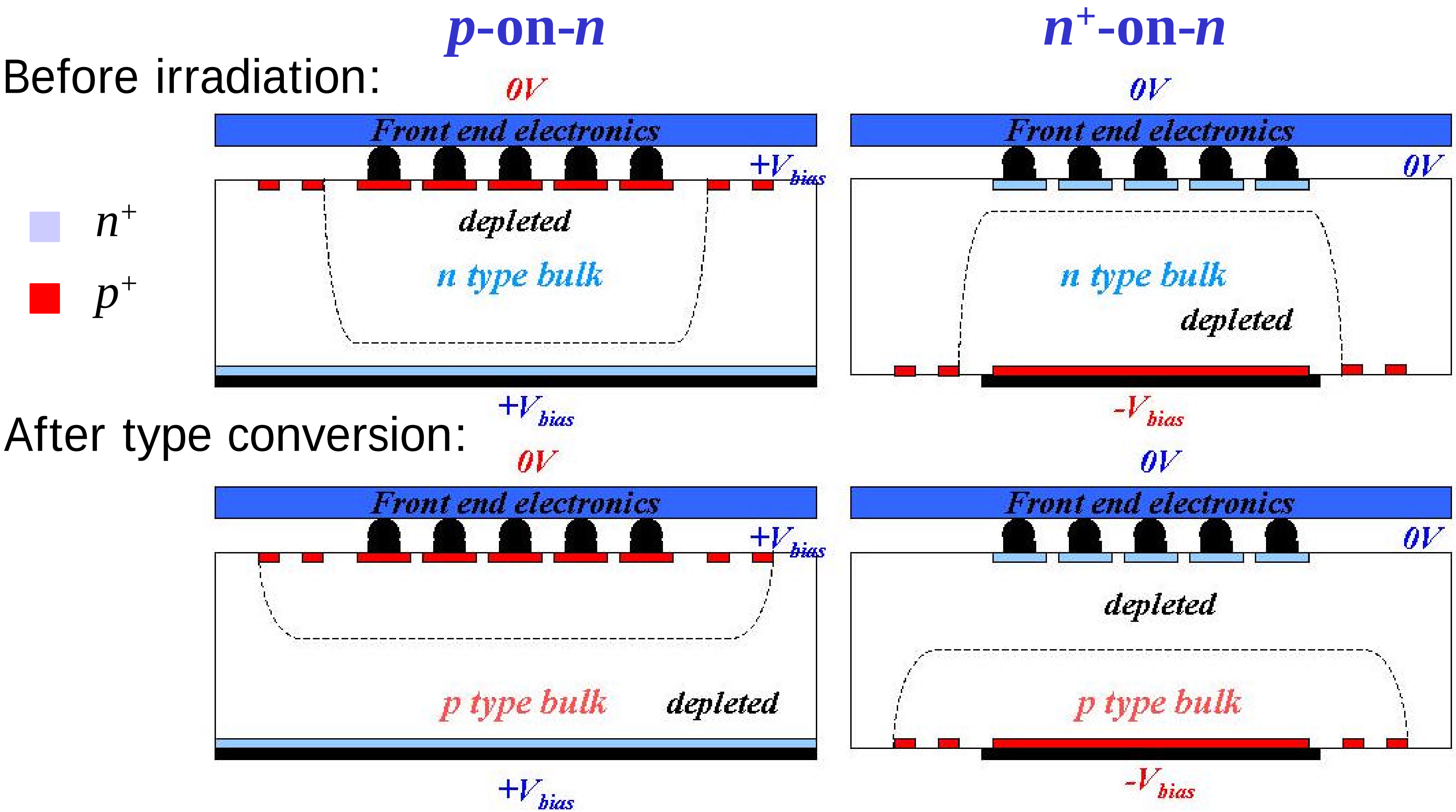
- various Si impurities
- damage parameters
- fabrication process

Radiation Hard Sensors

Detector Concept: p^+-on-n vs. n^+-on-n

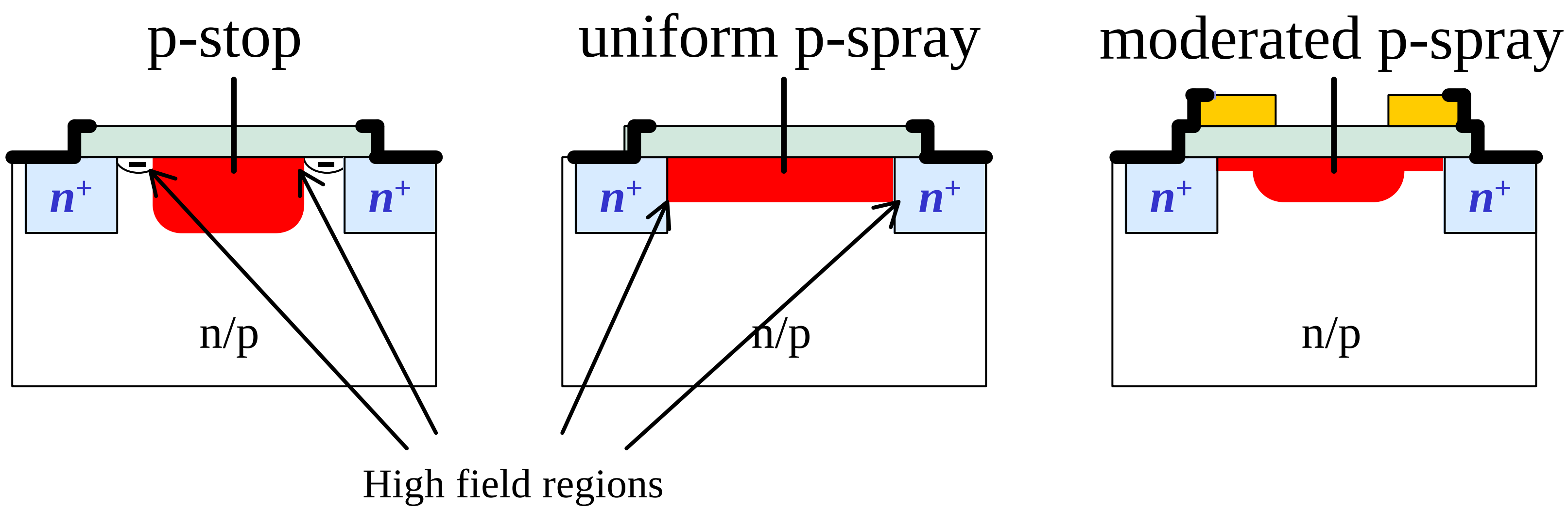
Before irradiation:

After type conversion:



– have to be (almost) fully depleted	– can be operated partially depleted
– potential drop on the read out side	– potential drop on the back side
– only single sided processing necessary	– double sided processing needed

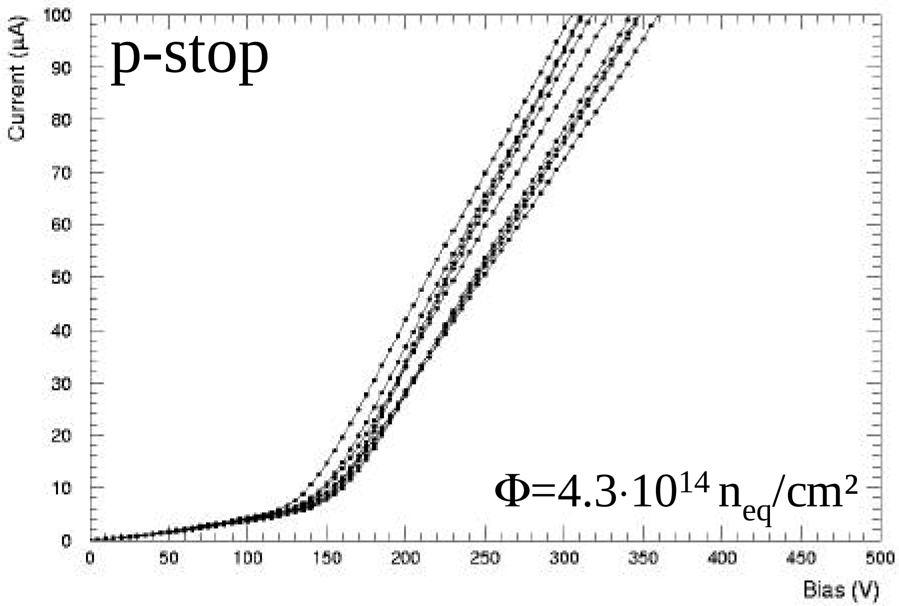
Pixel Isolation: Design Options

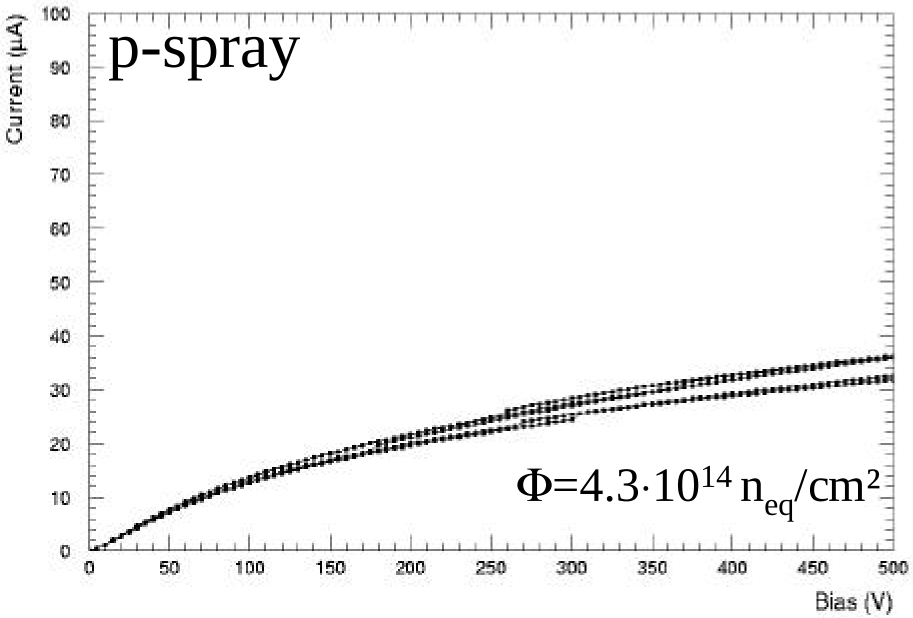


Before irrad.:	low E-field ⇒ high breakdown voltage	high E-field ⇒ low breakdown voltage	low E-field ⇒ high breakdown voltage
After irrad.:	high E-field ⇒ low breakdown voltage	low E-field ⇒ high breakdown voltage	low E-field ⇒ high breakdown voltage
under irradiation:	degrades	improves	improves

Pixel Isolation: Breakdown Voltage

IV-Characterisics:



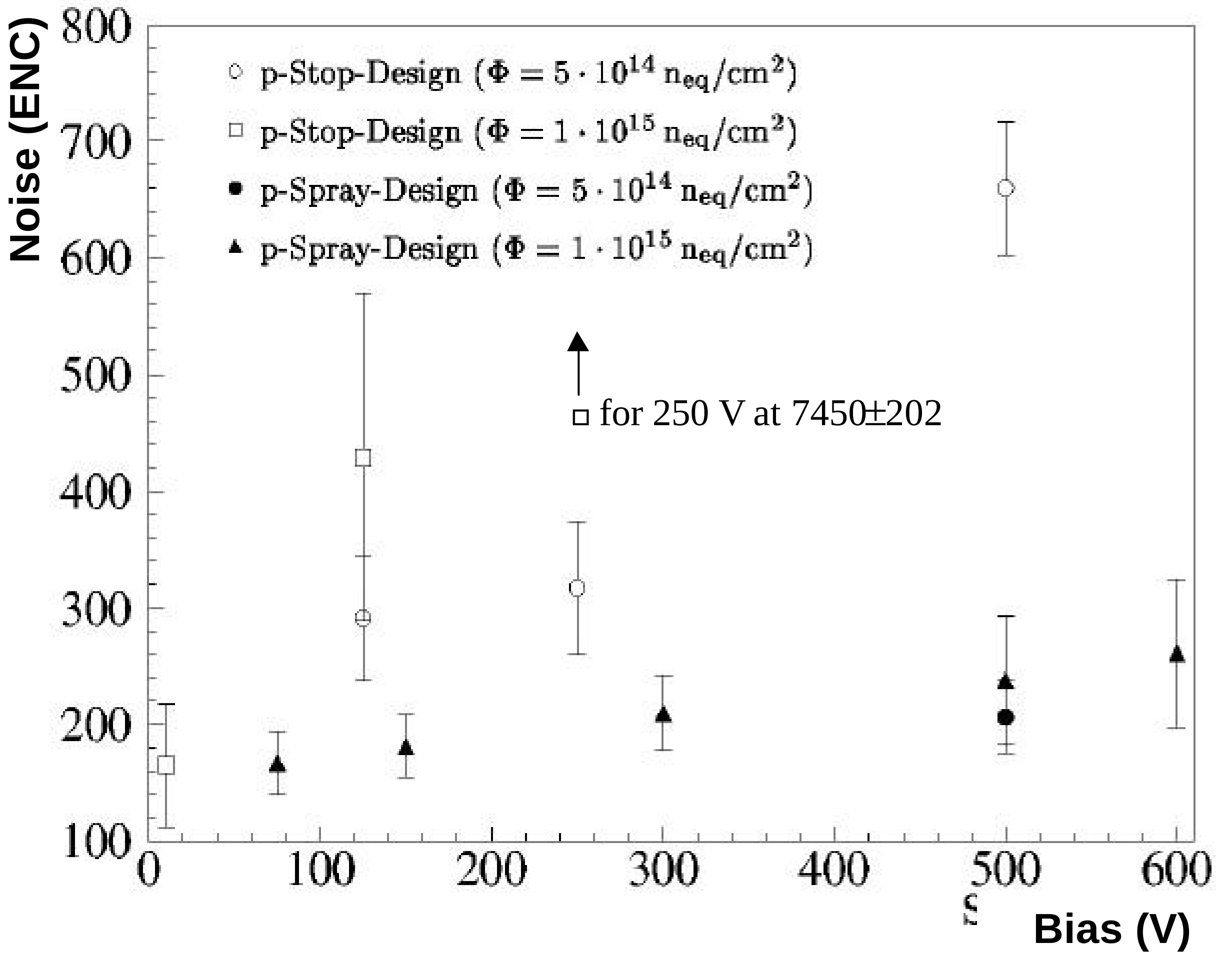


- higher breakdown voltage for p-spray
- IV-curve is flatter

Pixel Isolation: Noise

- with p-spray less noise

further advantages:
- no additional mask step
- possibility of bias grid

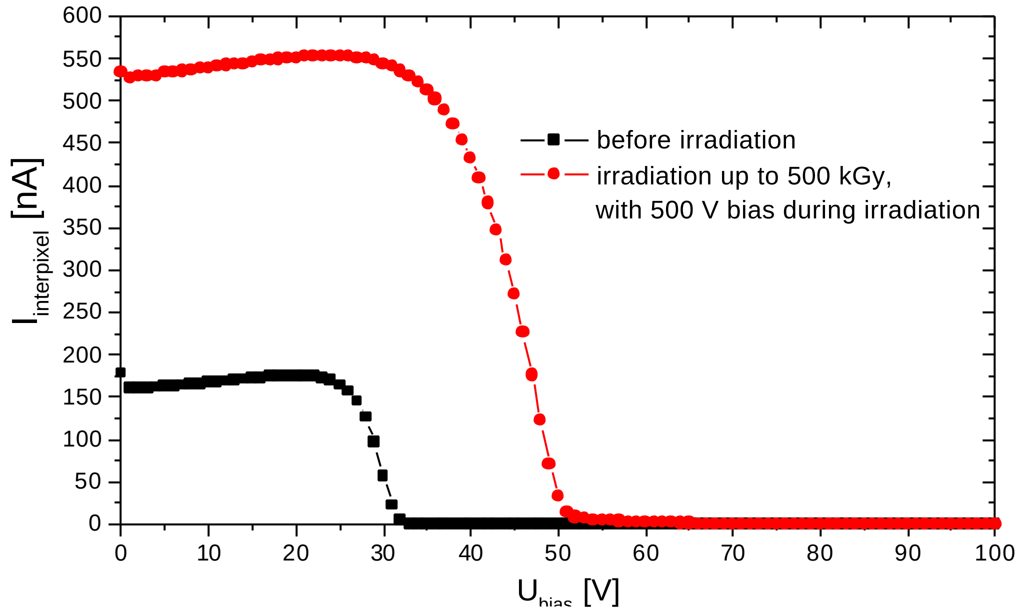


Pixel Isolation: Surface Damage

Direct test of interpixel isolation on real sensors by measuring pinch-off voltages

Worst case test:

- irradiation with 20 keV electrons
- no bulk damage
- no type conversion
- 500 V bias during irradiation



Pinch-off at higher voltages, but pixels still isolated

- effect of p-spray isolation
- ≈100 MΩ at 100 V bias
- saturation at about 50 kGy
- no contribution to leakage current

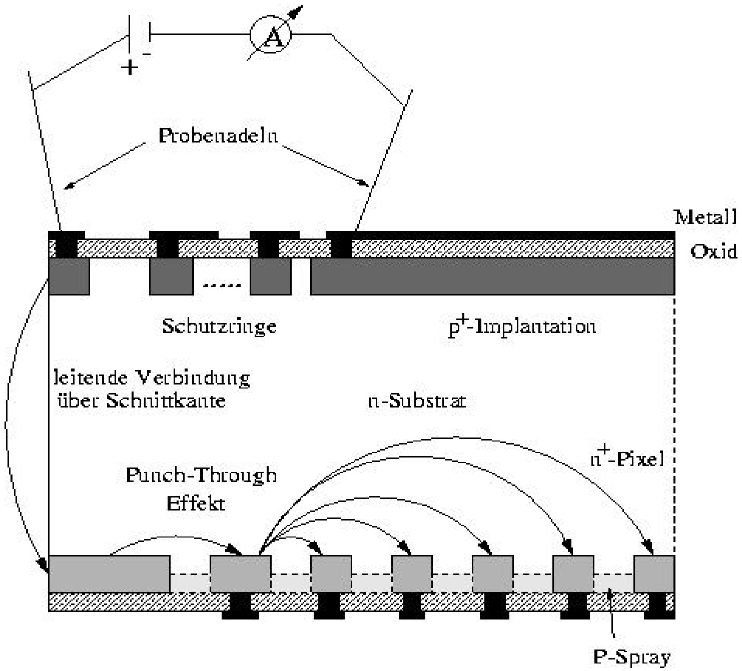
⇒ p-spray intrinsically radiation hard

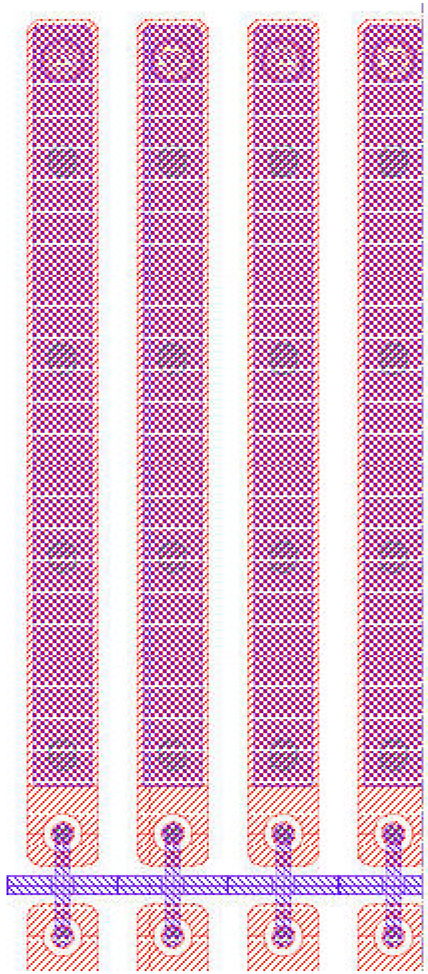
Biasgrid

punch-through contact to pixels

⇒ testability before module assembly (quality assurance)

⇒ biasing of uncontacted pixels

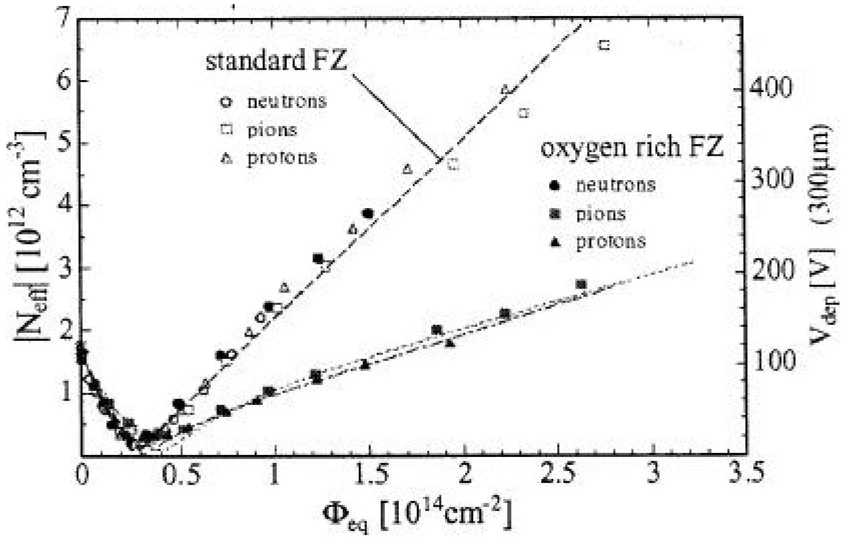




Bulk Damage: oxygenated vs. standard material

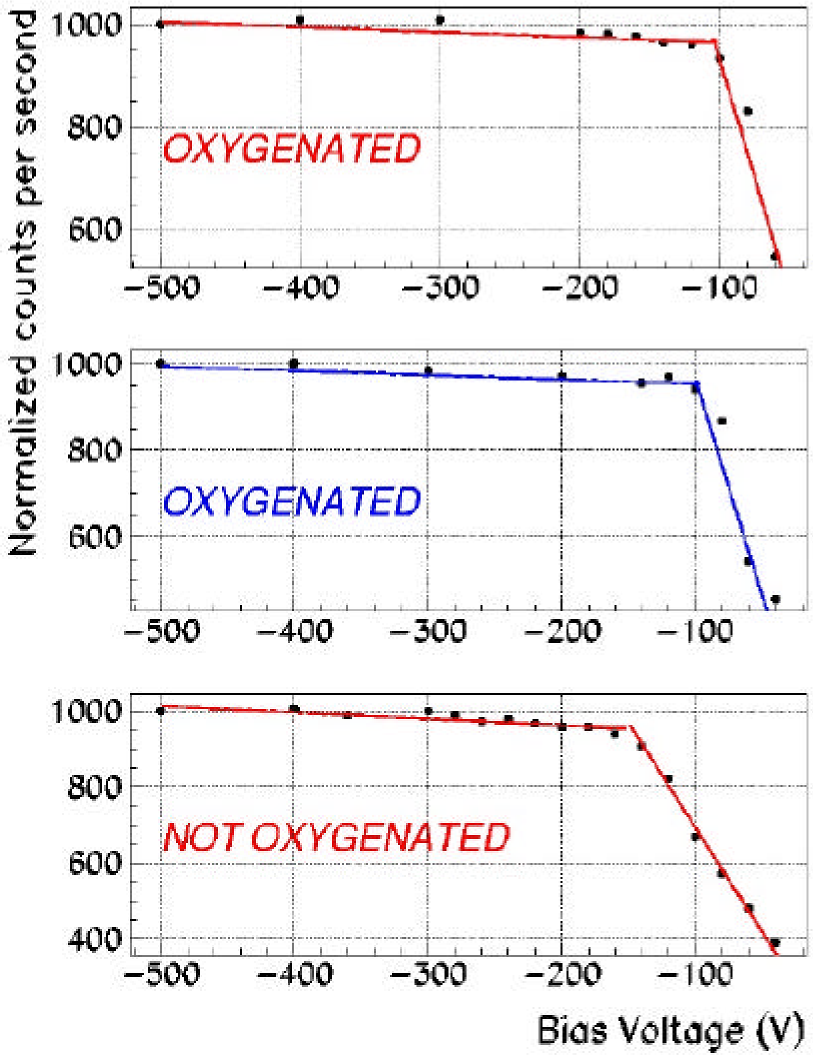
ROSE-Results:

- oxygenation improves radiation hardness w.r.t charged hadrons:



Measurement with Am-source:

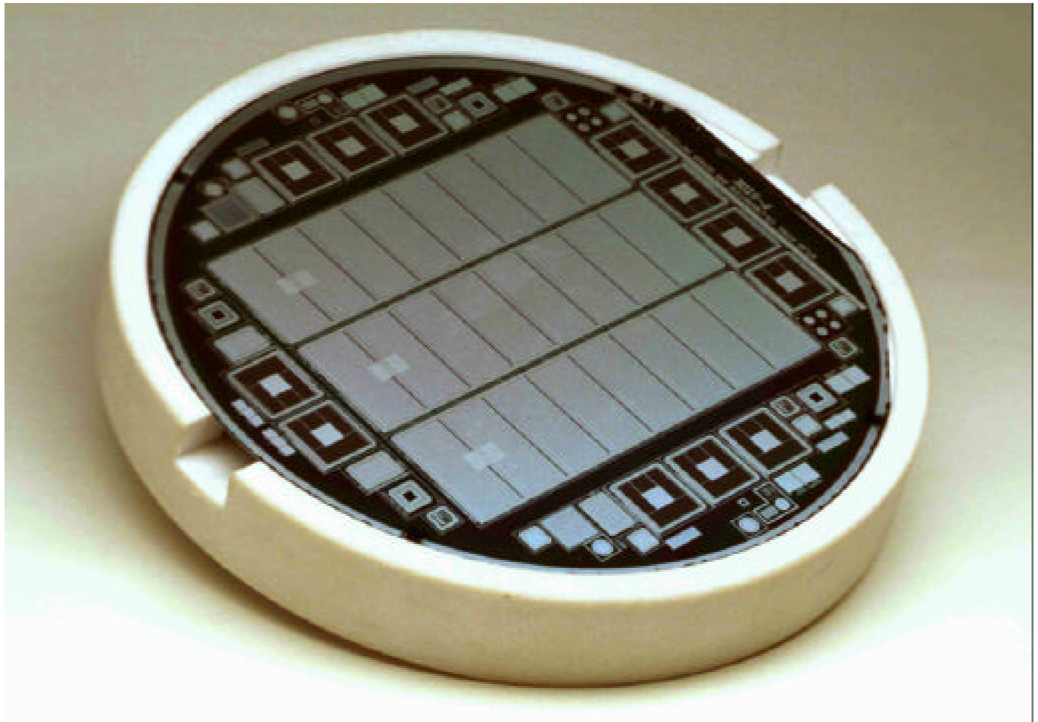
- measurement of hit bus frequency with varied bias voltages
- oxy and not-oxy sensors irradiated with $4.3{\cdot}10^{14}$ n_{eq}/cm^2



$\Phi = 4.3{\cdot}10^{14}\ n_{eq}/cm^2$

Overall Design

- oxygenated Si substrate
- *n*⁺-on-*n*-pixel
- moderated p-spray isolation
- bias grid for testability
- 3 sensor tiles per wafer
- various test and monitor structures



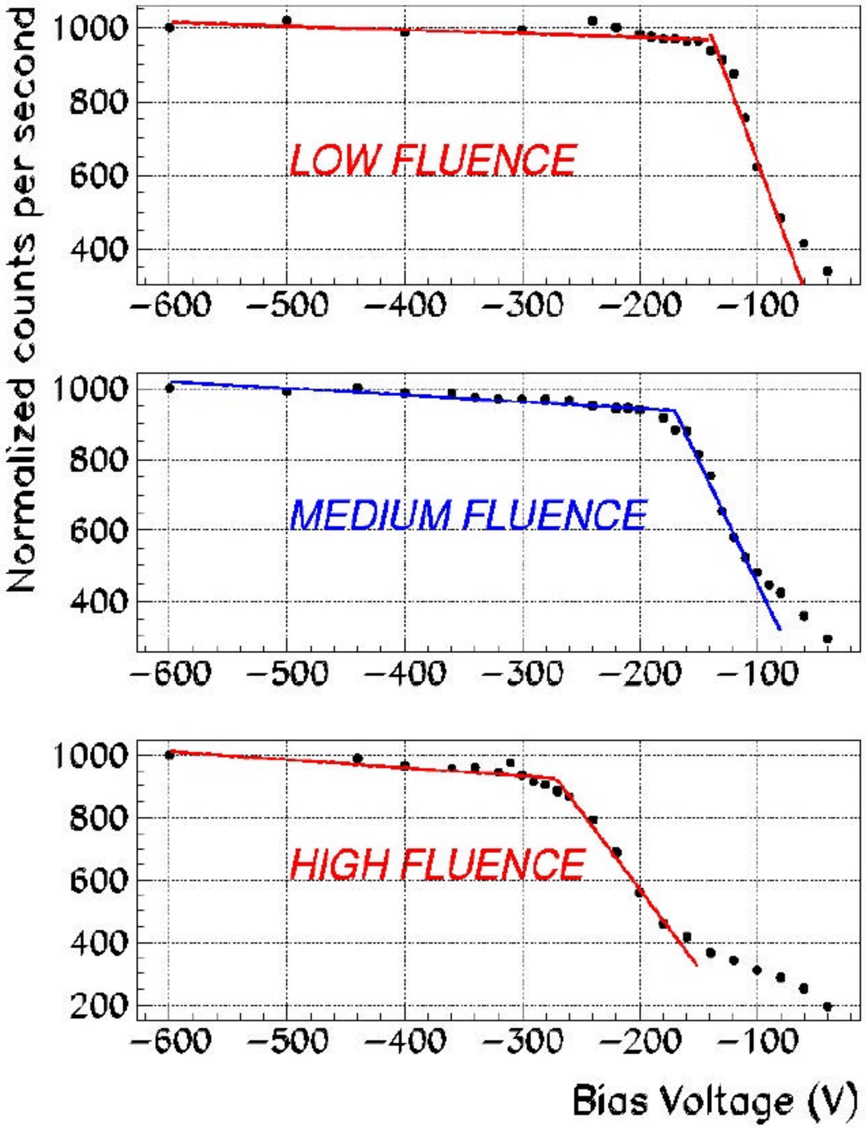
Photograph of pixel sensor wafer

Performance: Depletion Voltage

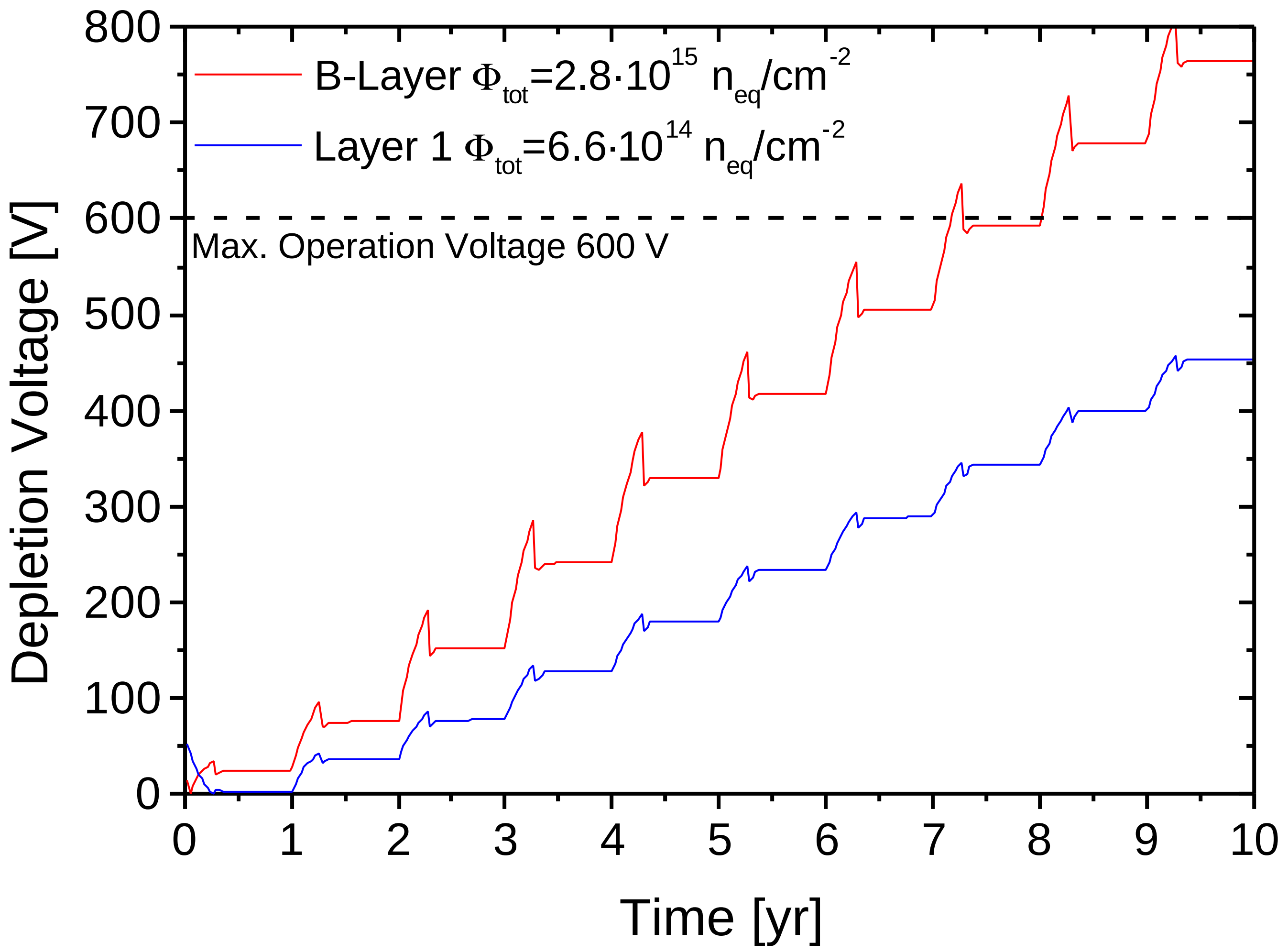
Measurement with Am-source:

- sensors irradiated with
  $3.0 \cdot 10^{14}\ n_{eq}/cm^2$,
  $5.0 \cdot 10^{14}\ n_{eq}/cm^2$,
  and $11 \cdot 10^{14}\ n_{eq}/cm^2$

- devices can be fully depleted
- results for depletion voltages are consistent with Hamburg model



Prediction for Depletion Voltage



Scenario:

100 d Beam/a at 0°C

20 d warm-up at 20°C

rest of year at -10°C

sensor thickness

B-layer 200 µm

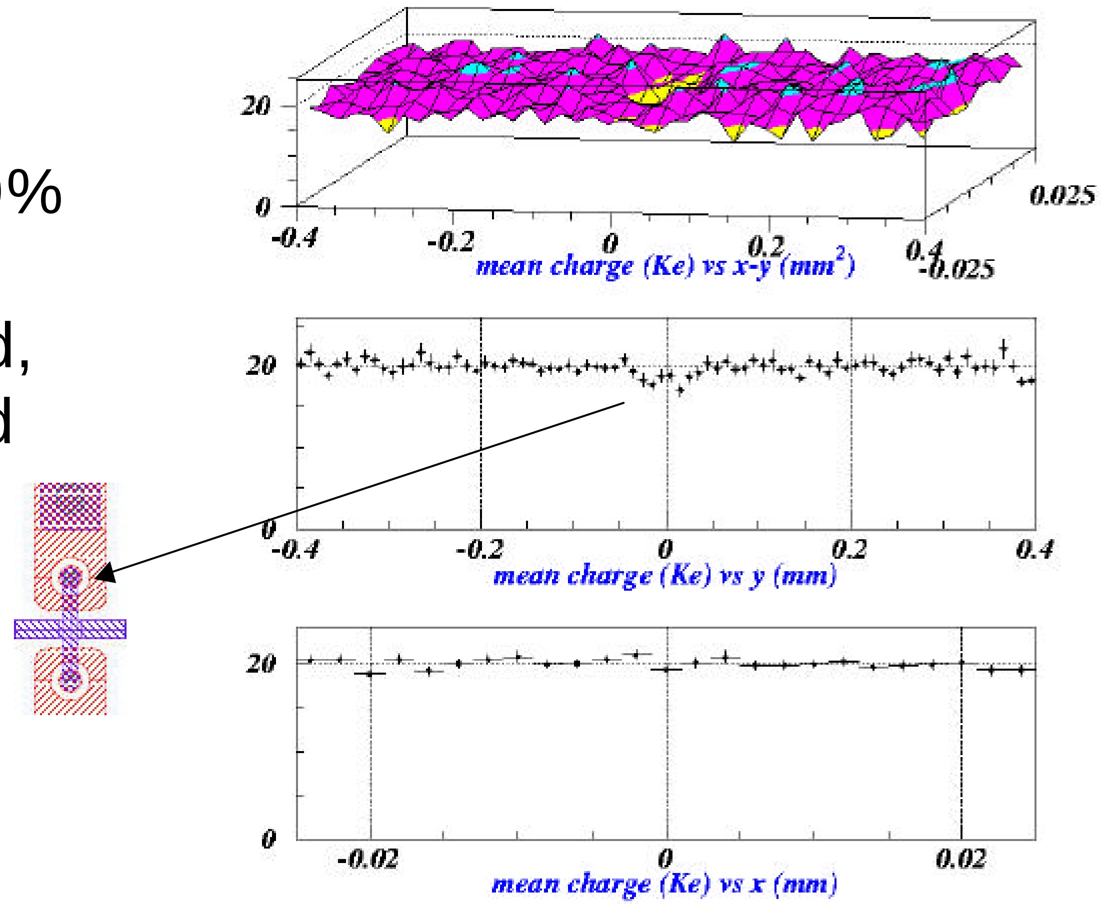
Layer 1 250 µm

oxygenated material

calculated with Hamburg model

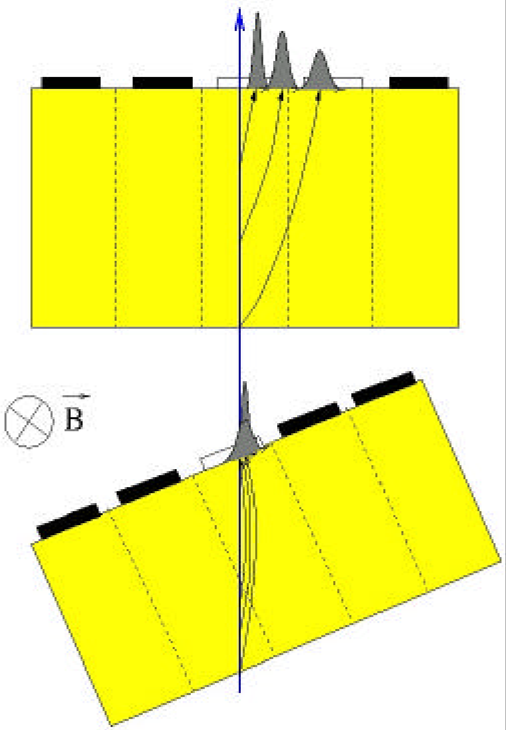
Performance: Charge Collection

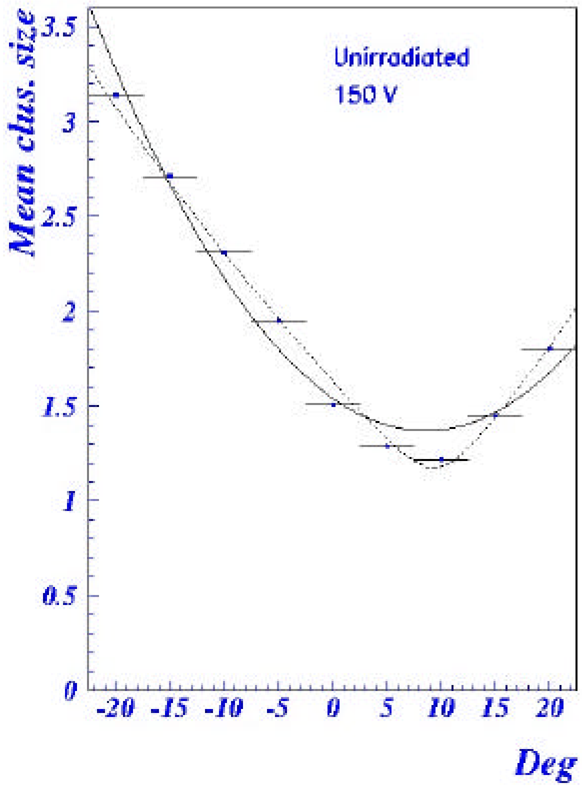
- homogenous charge collection over pixel
- charge loss of about 10% at bias dots,
  but still above threshold,
  only small area affected

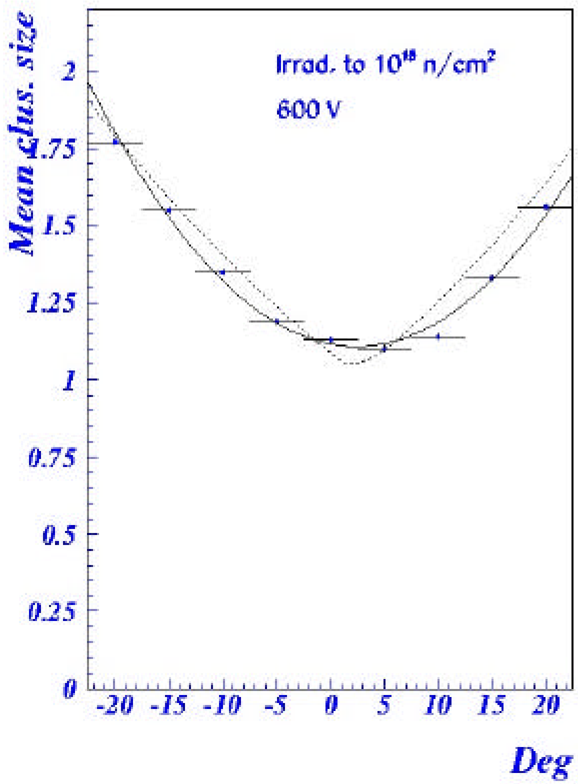


Performance: Lorentz Angle

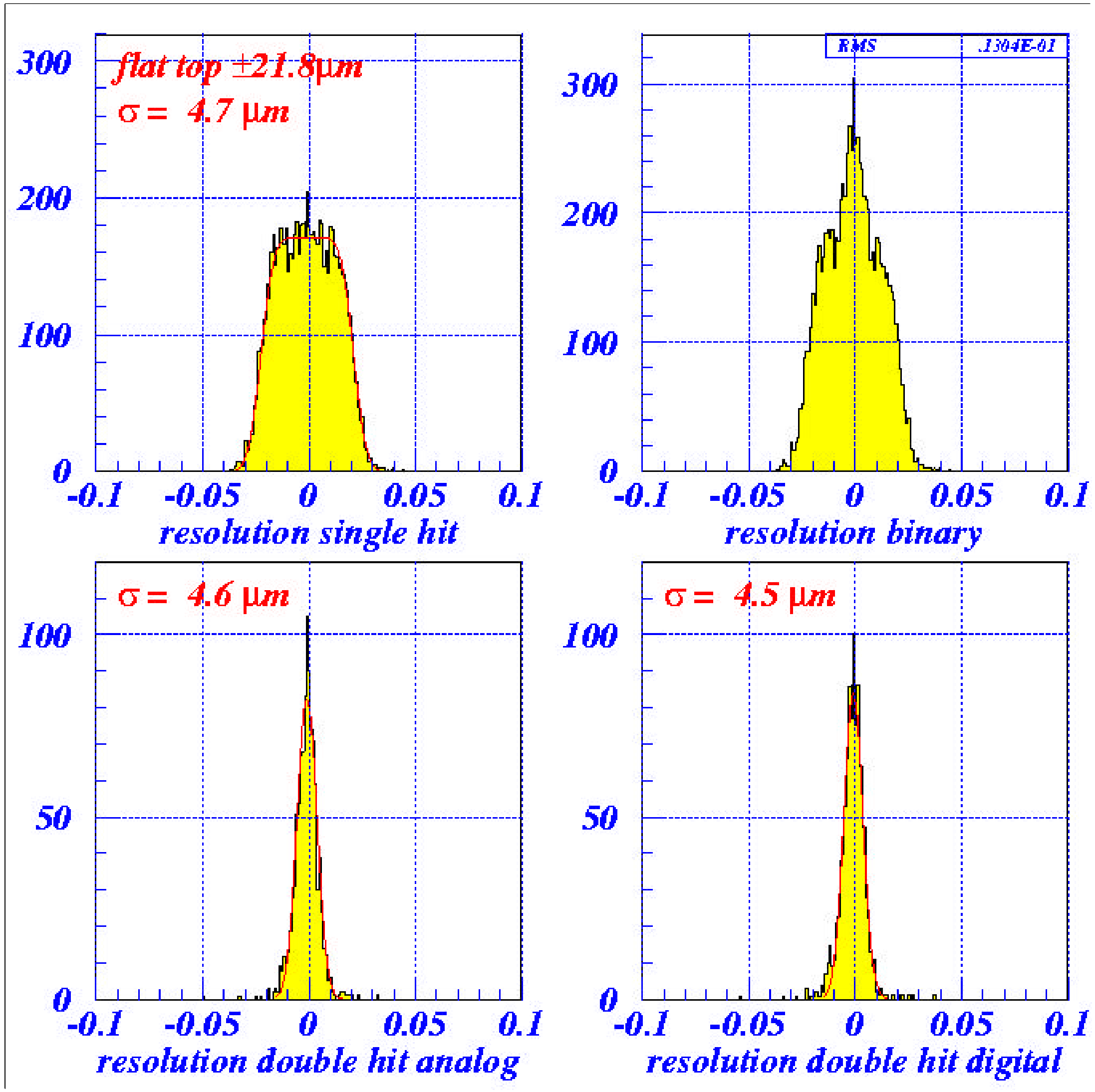
- knowledge of Lorentz angle important for achieving best resolution
- measurements were done in testbeam







Performance: Spatial Resolution



- charge sharing confined to ±5 μm between adjacent pixels
- fraction of 2 pixel clusters
  - 15% at 0° unirradiated
  - 7.5% after 10^{15} n_{eq}/cm^2
- space resolution:
  - flat top: 22 μm -> 23 μm
  - double hit: 5 μm -> 6 μm

after irrad.

Conclusions

- 10 years operation in ATLAS no problem
- a radiation hard design has been achieved:
  - operable up to fluences of $1 \cdot 10^{15}$ 1-MeV n/cm²
  - tolerance for surface damage tested up to 500 kGy
- design enables testing prior to module building (quality assurance)
- production of sensor has started
- high potential for Super-LHC, to be tested