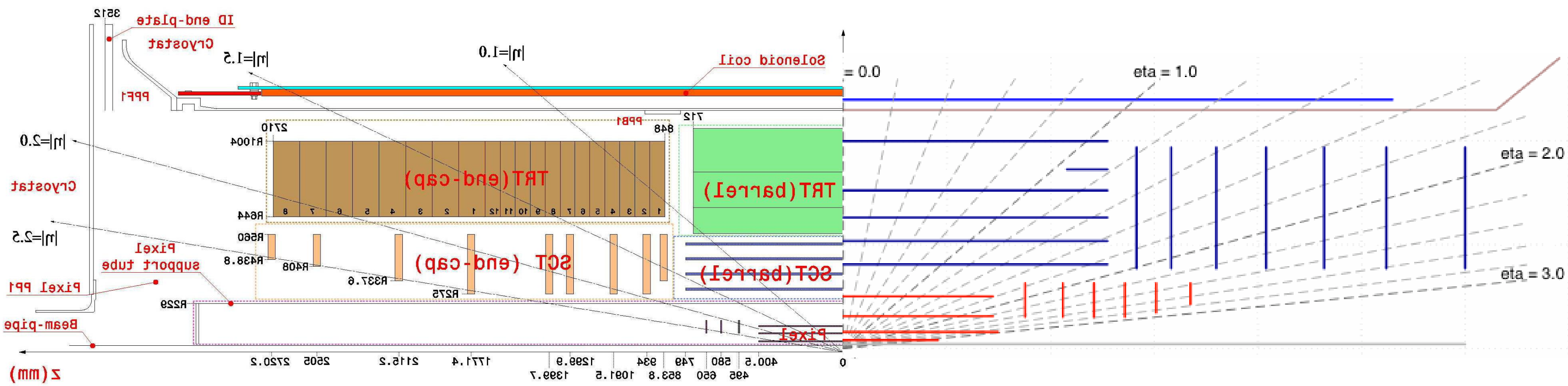
Development of n-in-p large-area silicon microstrip sensors for very high radiation environments

Y. Unno
for
the ATLAS12 sensor community and
Hamamatsu Photonics K.K.

ATLAS Tracker Layouts

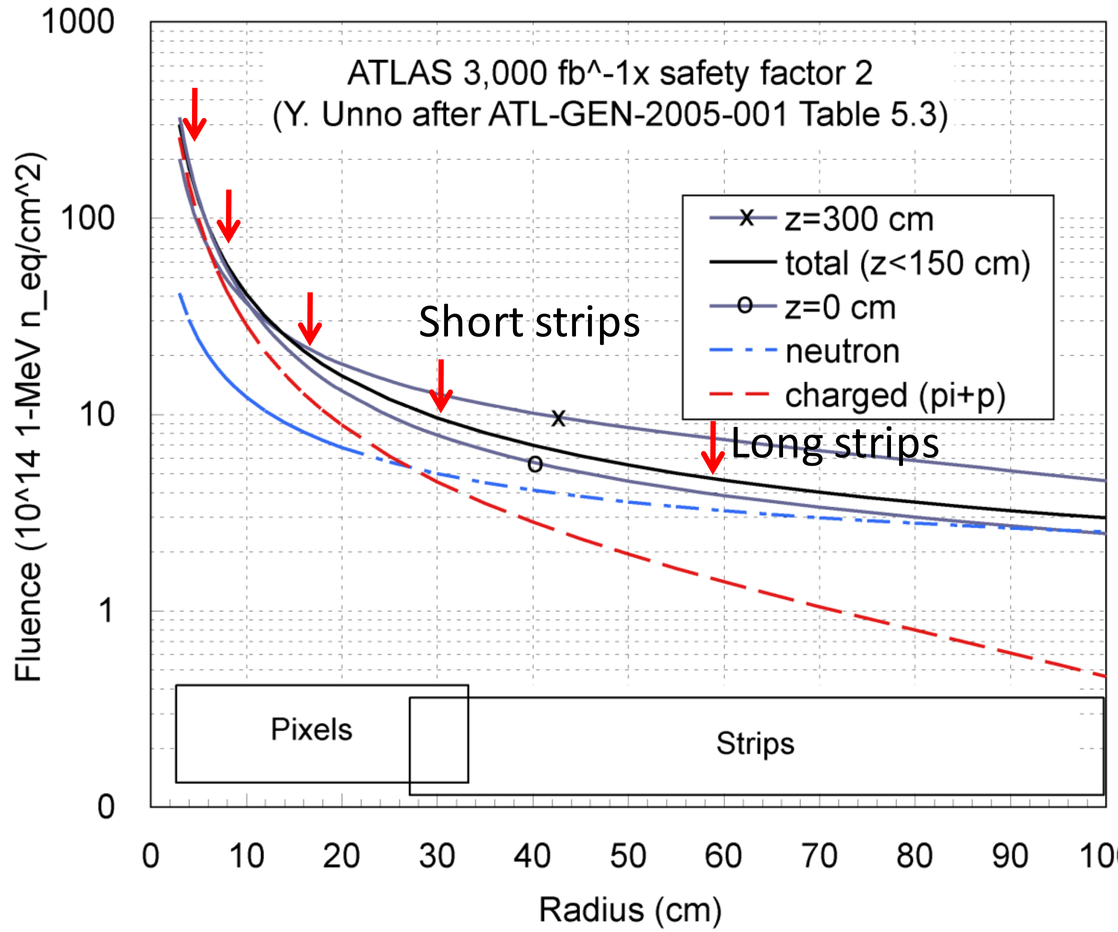


- Current inner tracker
  - Pixels: 5-12 cm
    - Si area: 2.7 m^2
    - IBL(2015): 3.3 cm
  - Strips: 30-51 (B)/28-56 (EC) cm
    - Si area: 62 m^2
  - Transition Radiation Tracker (TRT): 56-107 cm
    - Occupancy is acceptable for <3x10^{34} cm^{-2}s^{-1}
    - Phase-II at HL-LHC: 5x10^{34} cm^{-2}s^{-1}

- Phase-II upgrade (LOI)
  - Pixels: 4-25 cm
    - Si area: 8.2 m^2
  - Strips: 40.-100 (B) cm
    - Si area: 122 (B)+71(EC)=193 m^2
- Major changes from LHC
  - All silicon tracker
  - Large increase of Si area
    - both in Pixels and Strips
    - ~ 3 × LHC ATLAS

Particle fluences in ATLAS

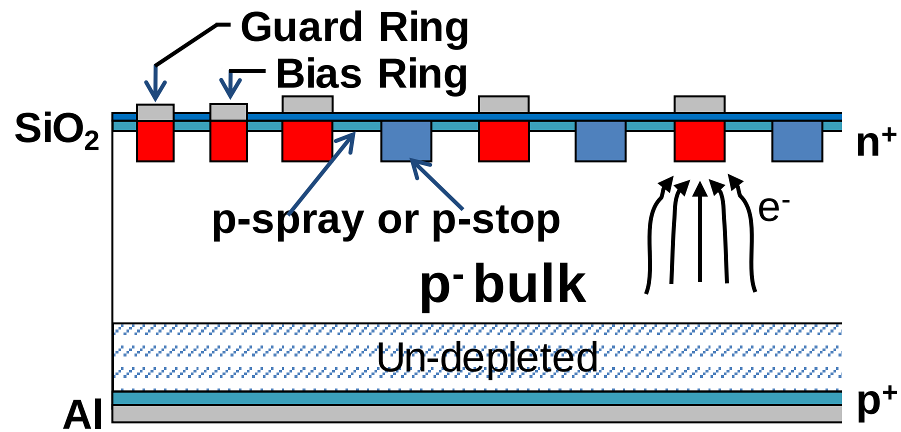
- ATLAS detector to design for
  - Instantaneous lum.: 7×10^{34} cm^{-2}s^{-1}
  - Integrated lum.: 6000 fb^{-1} (including safety factor 2 in dose rate)
  - Pileup: 200 events/crossing
- IBL (LHC)
  - Insertable B-layer pixel
  - r = 3.3 cm
    - Flunece ~3×10^{15} neq/cm^2
    - at Int.L~300 fb^{-1}
- **PIXELs (HL-LHC)**
  - **Inner: r=3.7 cm ~2.2×10^{16}**
  - **Medium: r = 7.5 cm, ~6×10^{15}**
  - **Med/Out: r=15.5 cm ~2×10^{15}**
  - **Outer: r = 31 cm (?) ~1×10^{15}**
  - **Charged:Neutrons ≥ 1**
- **STRIPs (HL-LHC)**
  - **Replacing Strip and TRT**
  - **Short strip: r = 30 cm, e.g.**
    - **~1×10^{15}**
  - **Long strips: r = 60 cm,**
    - **~5×10^{14}**
  - **Neutrons:Charged ≥ 1**

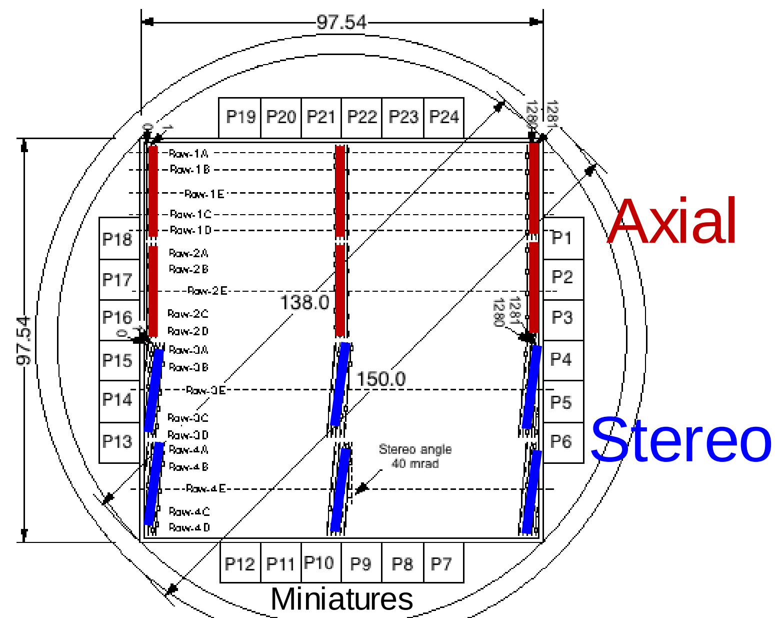


Radiation Hard n-in-p Silicon Sensors

- n^+-strip in p-type substrate (n-in-p)
  - Collects electrons
    - like current n-in-n pixels
    - Faster signal, reduced charge trapping
  - Depletes from the segmented side
    - Good signal even under-depleted
  - Single-sided process
    - 30-40% cheaper than n-in-n
    - More foundries and available capacity world-wide
  - Easier handling/testing
    - due to lack of patterned back-side implant
- Collaboration of ATLAS with Hamamatsu Photonics (HPK)
  - ATLAS07
  - 9.75x9.75 cm^2 sensors (6 inch wafers)
  - 4 segments (2 axial, 2 stereo), 1280 strip each, 74.5 mm pitch
  - FZ <100>, 320 µm thick material
  - Miniature sensors (1x1 cm^2) for irradiation studies

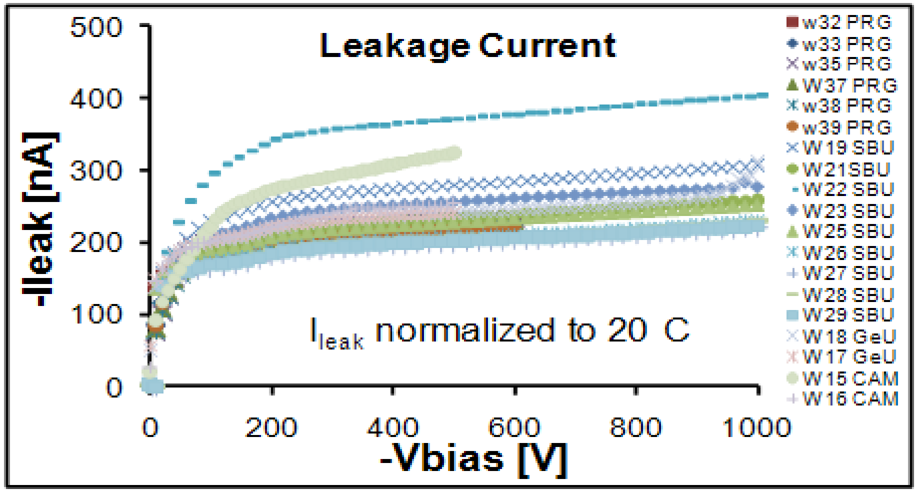
Last symposium (HSTD8),
Y. Unno, et. al., Nucl. Inst. Meth. A, Vol. 636 (2011) S24-S30

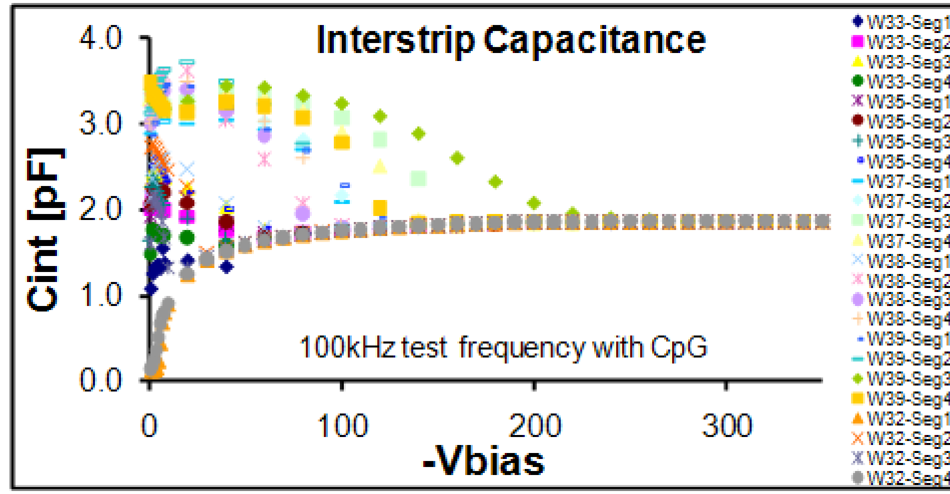


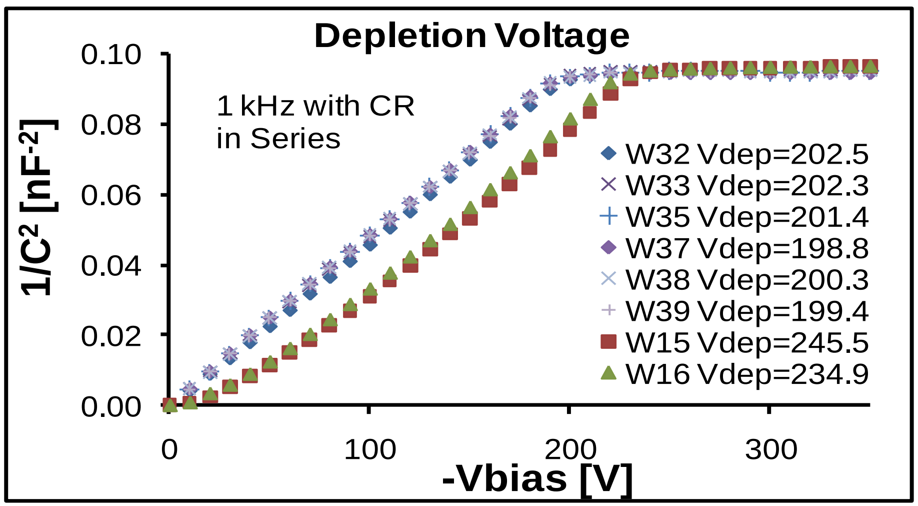


ATLAS07 sensor to study axial and stereo layouts

Evaluation of ATLAS07 Sensors





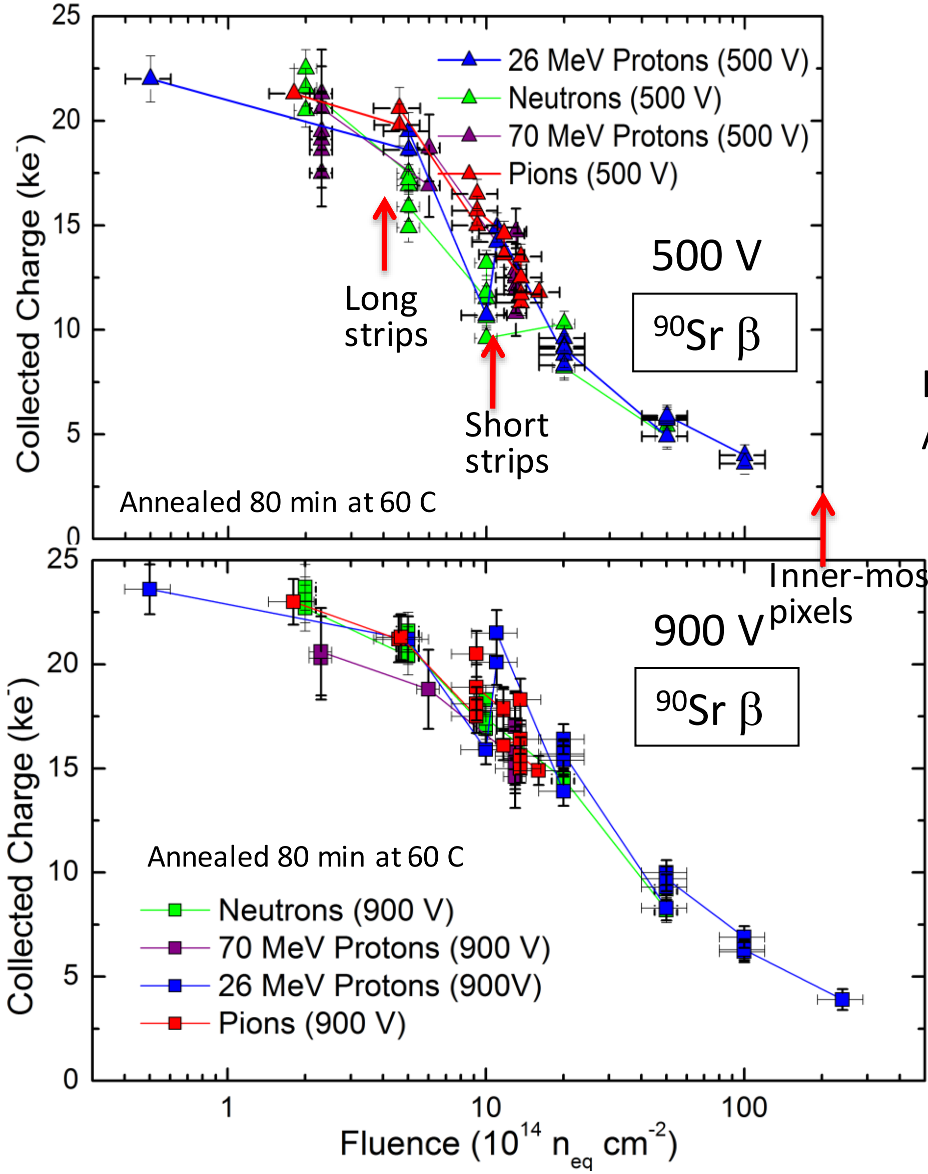


	Specification	Measurement
Leakage Current	<200 µA at 600 V	200– 370nA
Full Depletion Voltage	<500 V	190 – 245V
Coupling Capacitance (1kHz)	>20 pF/cm	24 – 30pF
Polysilicon Resistance	1.5+/-0.5MΩ	1.3 -1.6MΩ
Current through dielectric	I_{diel} < 10 nA	< 5nA
Strip Current	No explicit limit	< 2nA
Interstrip Capacitance (100kHz)	<1.1pF/cm (3 probe)	0.7 – 0.8pF
Interstrip Resistance	> 10x R_{bias}~15 MΩ	>19 GΩ

- <u>All specifications already met!!</u>

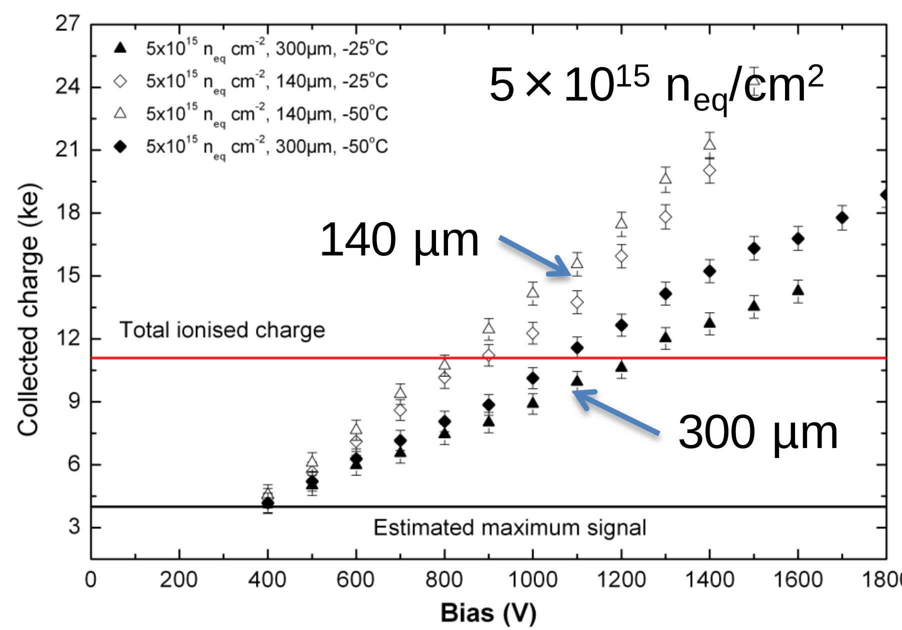
J. Bohm, et. al., Nucl. Inst. Meth. A, Vol. 636 (2011) S104-S110

Charge Collection after Irradiation



- Partly with ATLAS07 mini's
- Silicon thickness ~300 μm
  - CC ~13000-18000 e at 1×10^{15} n_{eq}/cm^2 at 500-900 V bias voltage.
- And, "Charge multiplication"
  - in thin sensors?

H.F.-W.Sadrozinski, et al., Nucl. Instr. and Meth. A(2011), doi:10.1016 / j.nima.2011.04.06



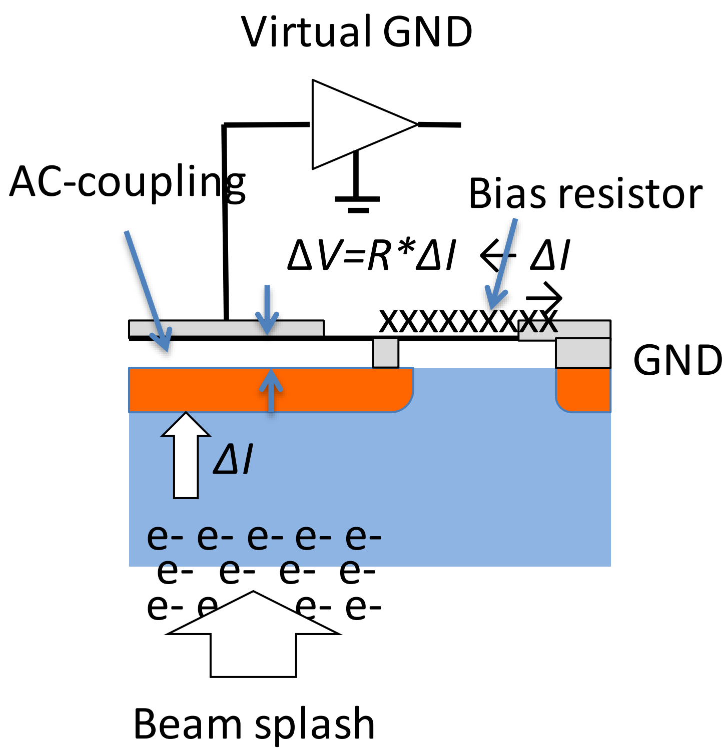
R&D's in Other Wafers

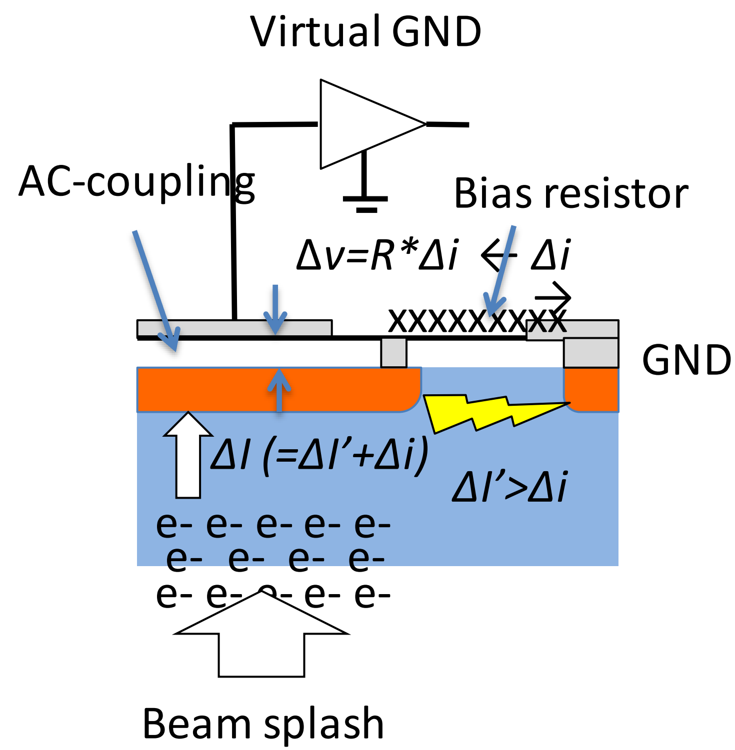
- In the meantime, other R&D's were:

(1) Punchthrough protection (PTP) structures
(2) Least-wide edge region ("slim edge")
  - HSTD8, PIXEL2012
  - S. Mitsui et al., Nucl. Instr. Meth. A699 (2013) 36-40
  - Y. Unno et al., Nucl. Instr. Meth. A699 (2013) 72-77
  - Y. Unno et al., Nucl. Instr. Meth. (2013) http://dx.doi.org/10.1016/j. nima.2013.04.075i

(1) Mitigation of "Stereo" dead area
  - This ATLAS12 sensors

PTP Function – Extra path

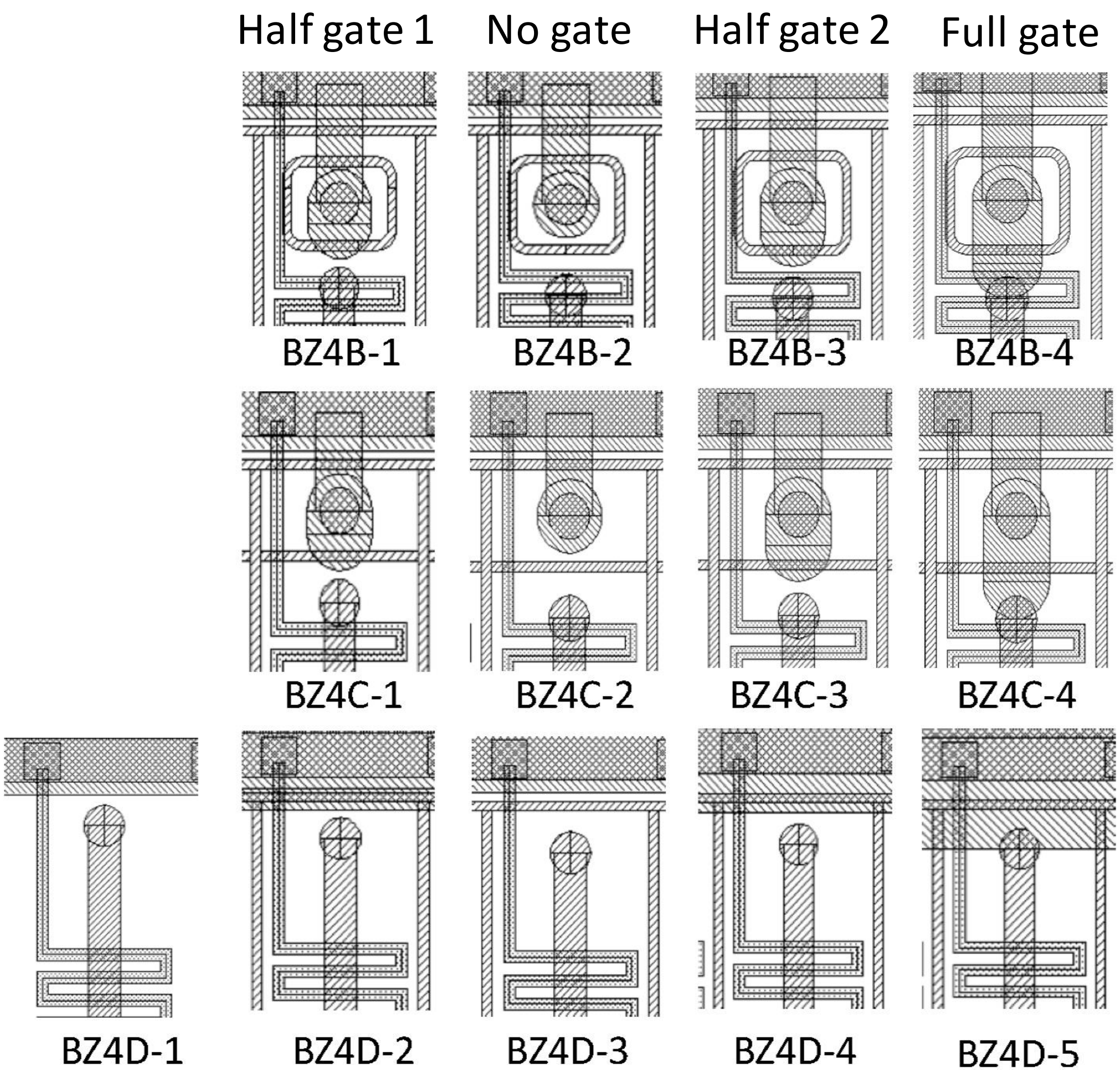




- Without extra path
  - Charges created by beam splash
  - run through bias resistor and
  - generate voltage difference over AC coupling

- With Extra path
  - which turns on when the voltage difference between the implant and bias rail is > onset.
  - Voltage difference over AC-coupling can be limited to the voltage drop that generates the turn-on.

Novel PTP structures – Gated

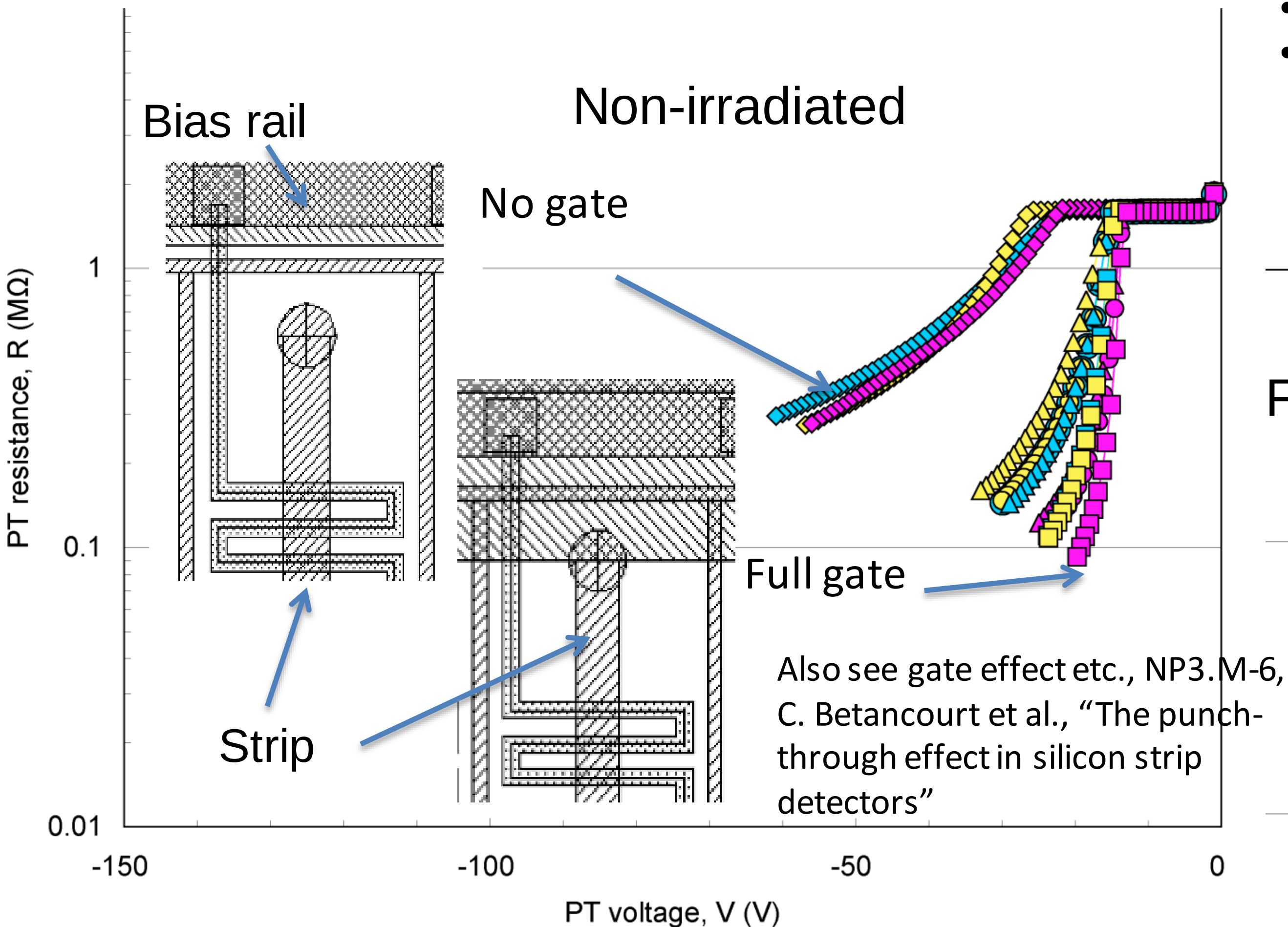


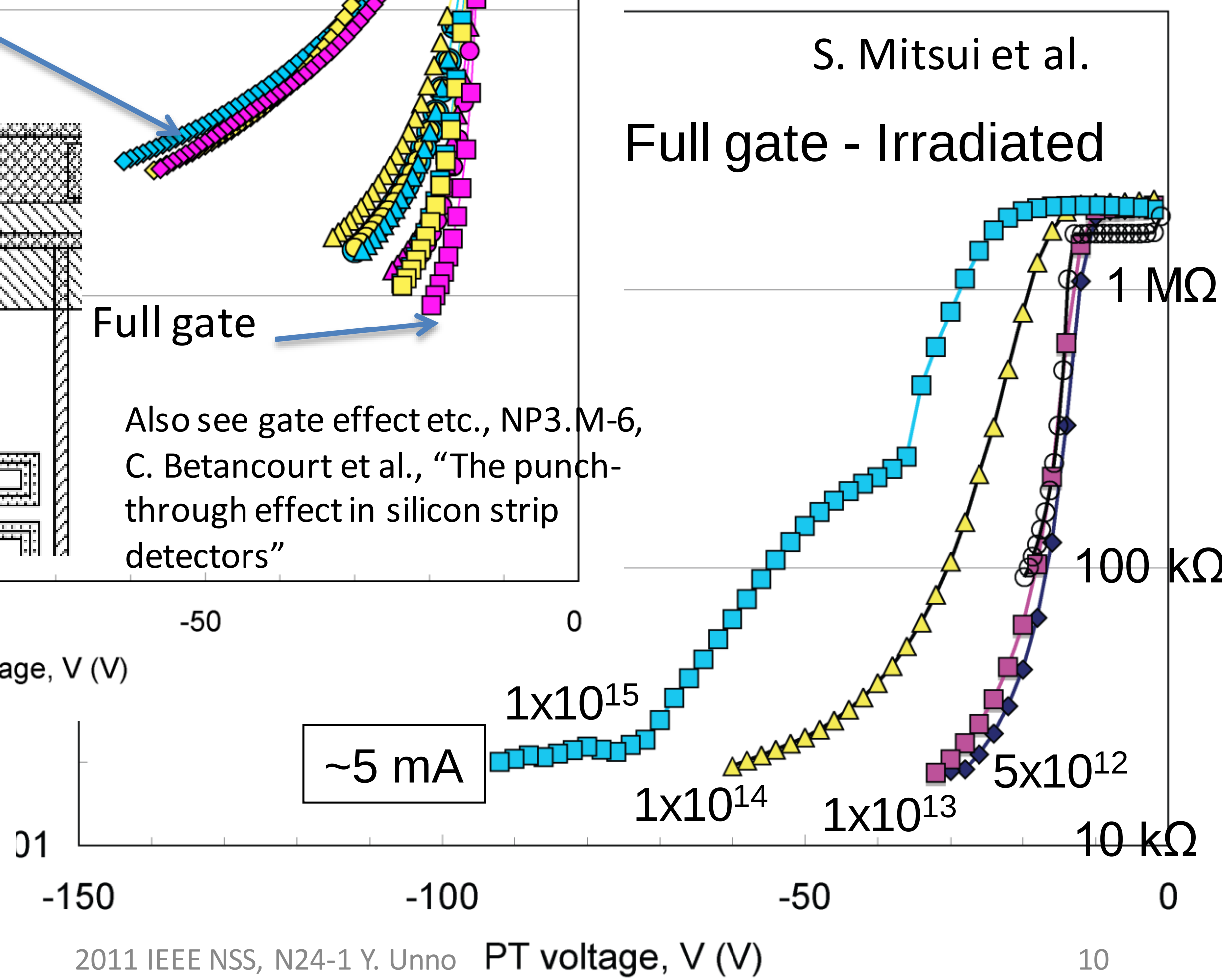
- Protection of AC coupling insulator
  - ΔV < 100 V
- KEK's internal study with a new mask

- BZ4B - ATLAS07 variations
- BZ4C – "Compartment" type variations
- BZ4D – "Simple" type variations

New Challenge – PTP Structures

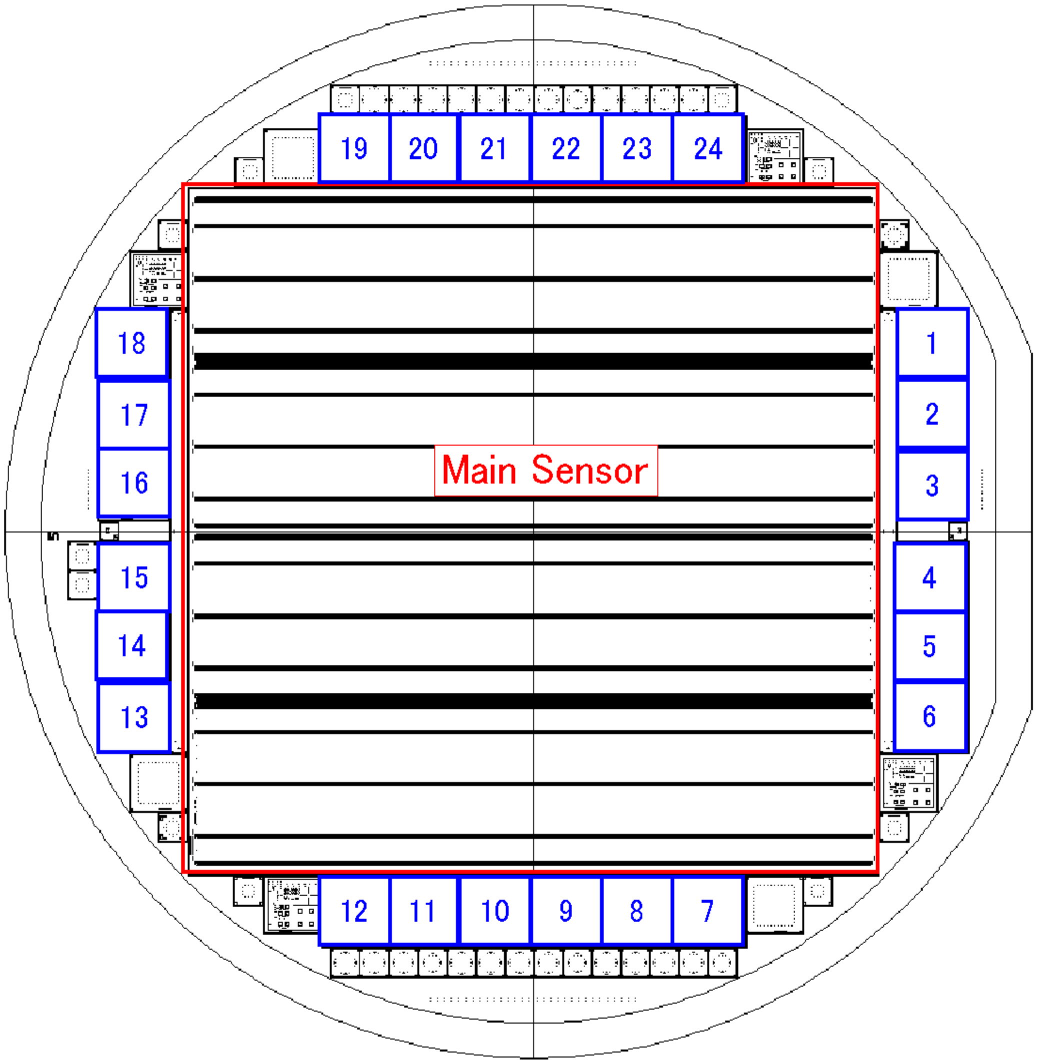
- P-stop is a barrier
- Full gate - Reducing onset voltage, cut-off rate, saturation resistance





- PTP - Insurance for protecting integrated AC coupling capacitors from beam splash
- ΔV (Implant-Metal) ≤100 V

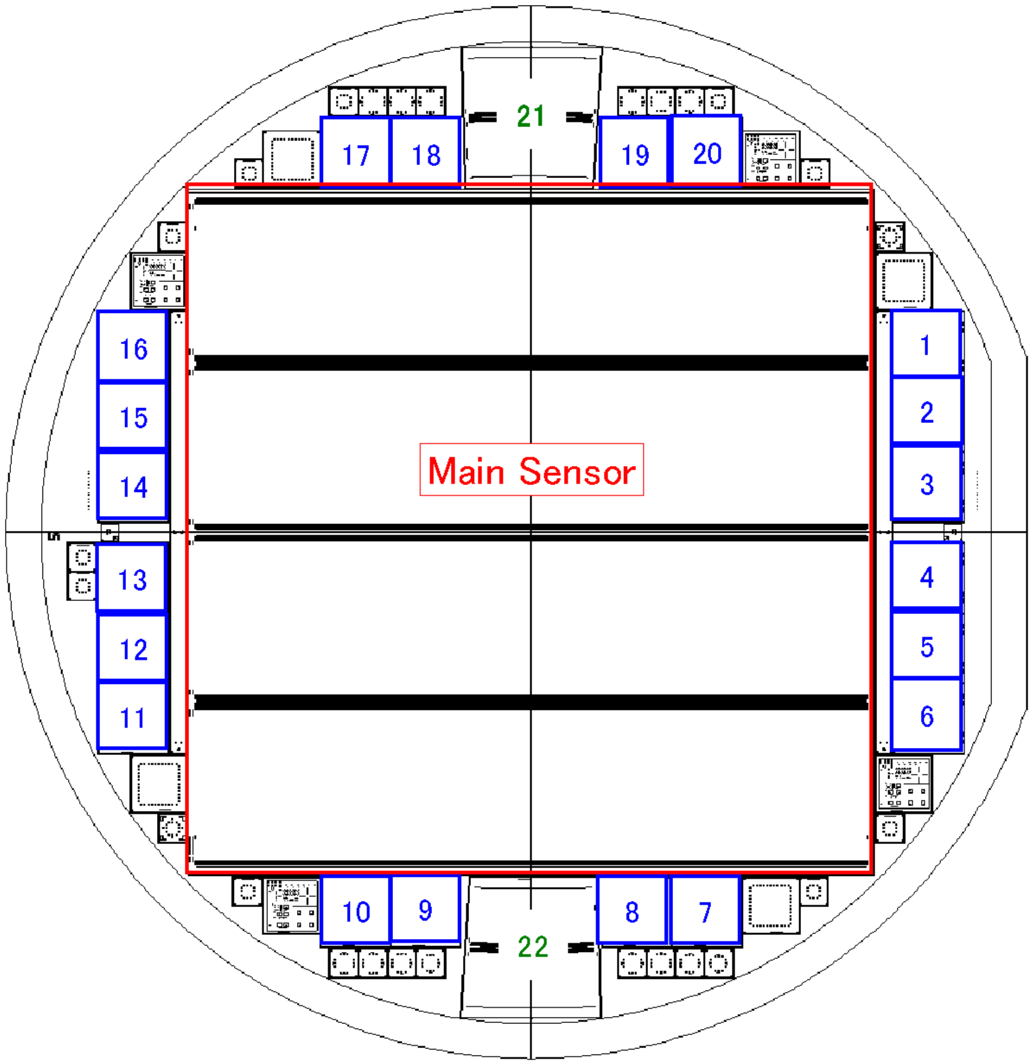
ATLAS12M wafer layout



1	BZ3-A
2	BZ2-C
3	BZ3-B
4	BZ4-B2
5	BZ6-C
6	BZ3-C
7	BZ1 (PTP10um)
8	BZ6-E
9	BZ3-D
10	BZ3-E
11	BZ3-F
12	BZ6-C
13	BZ3-A
14	BZ2-C
15	BZ3-B
16	BZ4-B2
17	BZ6-E
18	BZ3-C
19	BZ1 (PTP10um)
20	BZ3-D
21	End Cap Small Pitch -C
22	End Cap Small Pitch -E
23	End Cap Small Pitch -C
24	End Cap Small Pitch -E

- Main sensor at the center of the wafer
- 1-24 Baby sensors in the peripheral of the main sensor

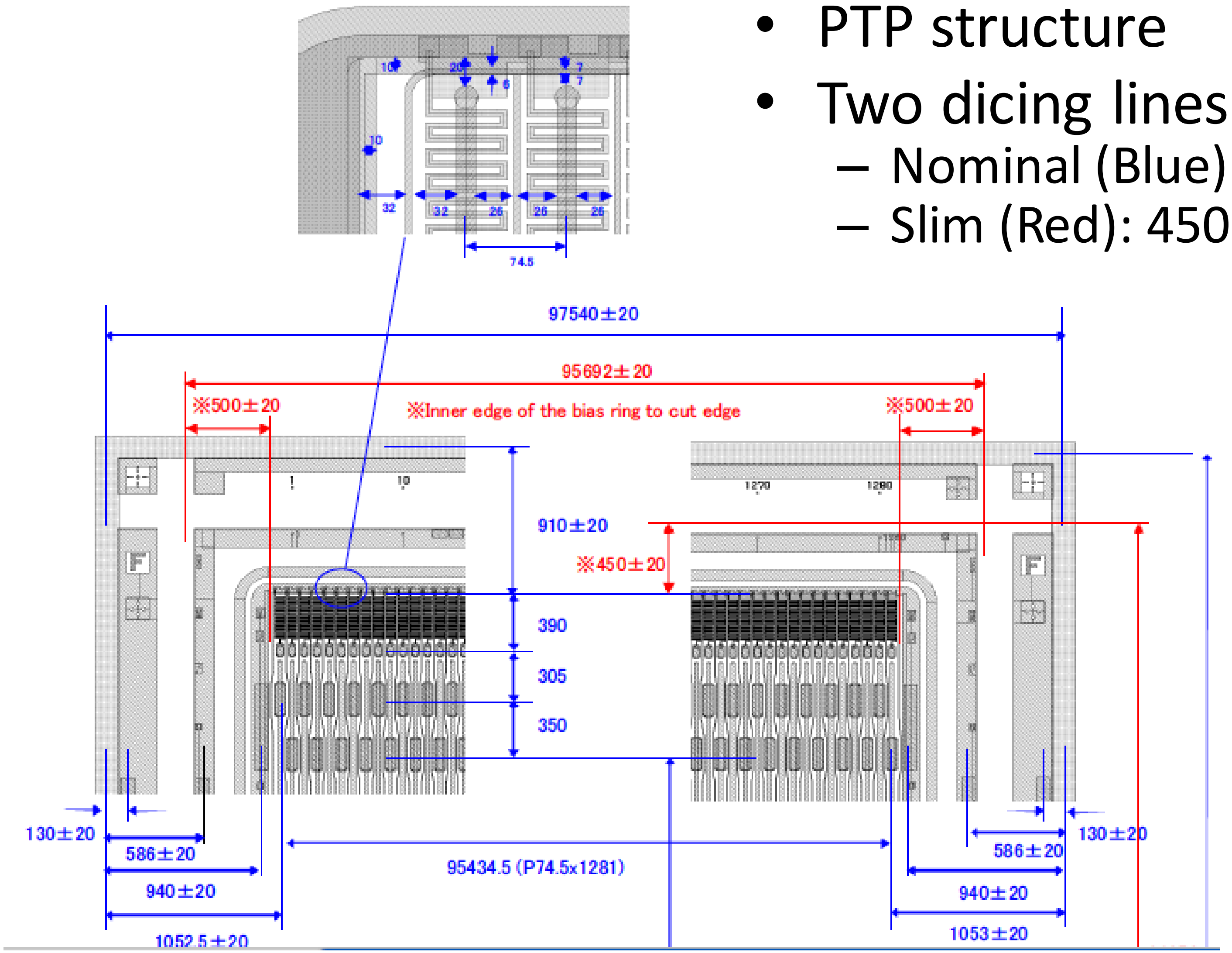
ATLAS12A Wafer Layout



1	BZ1 (PTP 10um)
2	BZ3C
3	BZ3F
4	BZ3C
5	BZ3F
6	BZ3C-unpassivation
7	EC-small pitch-C (AC gang)
8	EC-small pitch-E (AC gang)
9	EC-large pitch-C (AC gang)
10	EC-large pitch-E (AC gang)
11	BZ1 (PTP 10um)
12	BZ3C
13	BZ3F
14	BZ3C
15	BZ3C
16	BZ3C-unpassivation
17	EC-small pitch-C (DC gang)
18	EC-small pitch-E (DC gang)
19	EC-large pitch-C (DC gang)
20	EC-large pitch-E (DC gang)
21	EC-skewed-C
22	EC-skewed-E

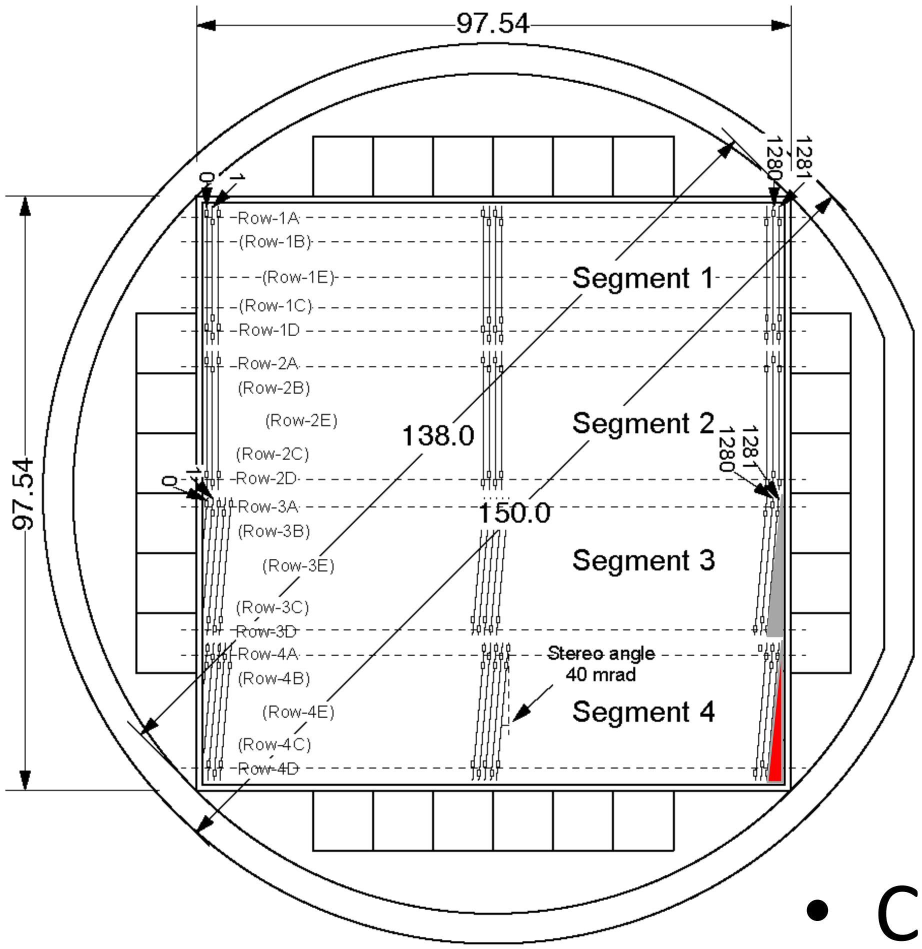
- Main sensor at the center of the wafer
- 1-24 Baby sensors in the peripheral of the main sensor

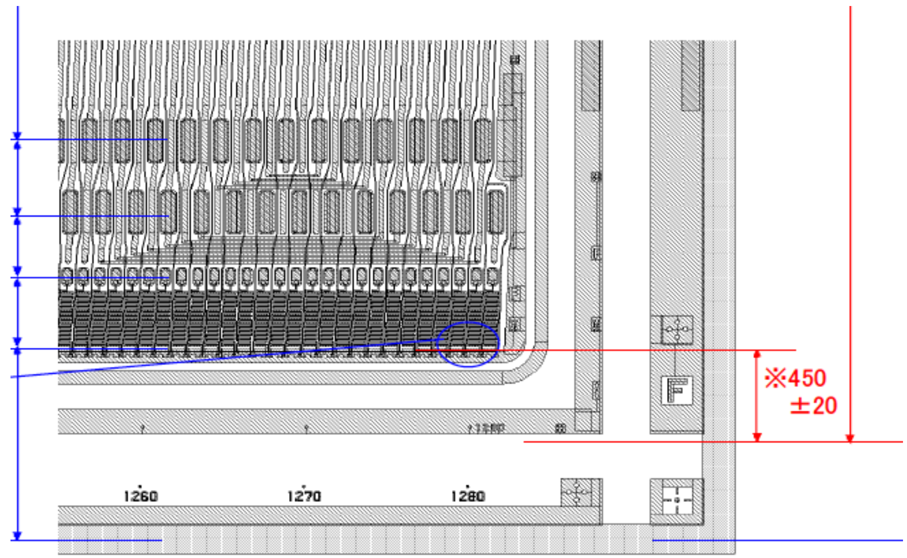
ATLAS12 Main Sensors



- PTP structure
- Two dicing lines:
  - Nominal (Blue): 910-950 µm
  - Slim (Red): 450-500 µm

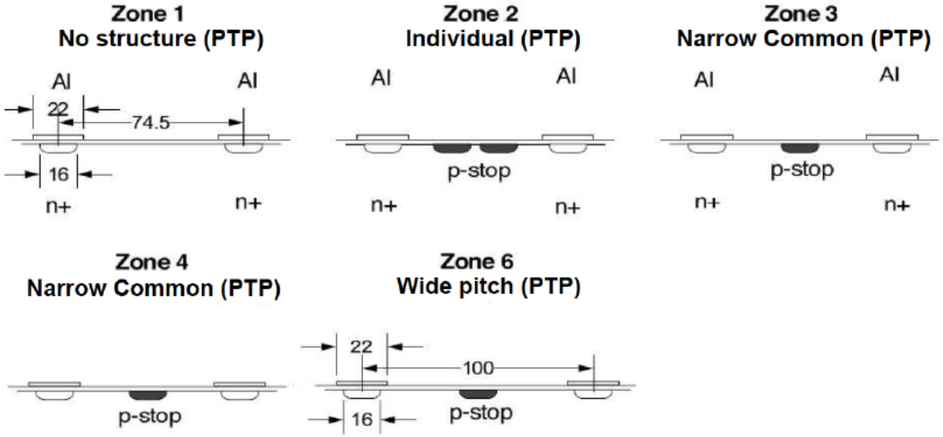
Mitigating “Stereo dead” Area

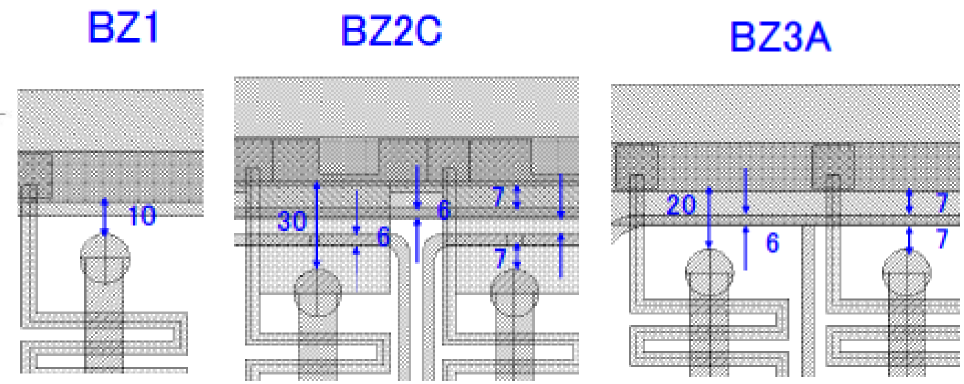


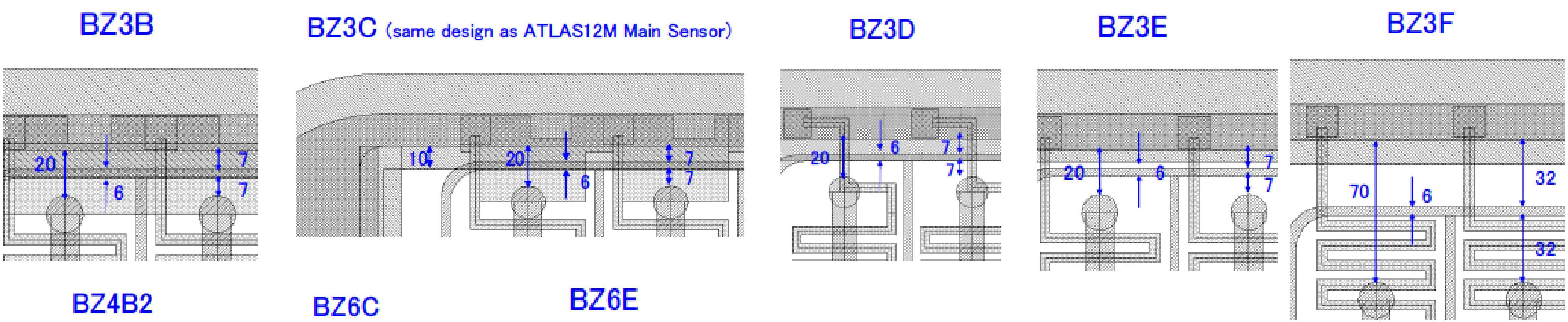


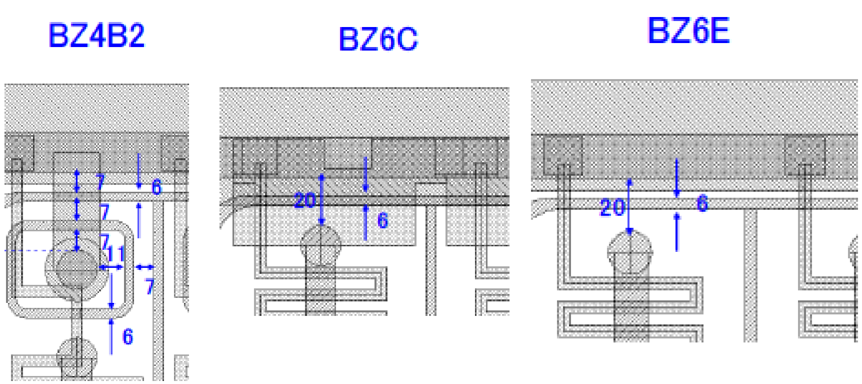
- Corner of Segment4 is made “AC” ganged

Miniature's Structures





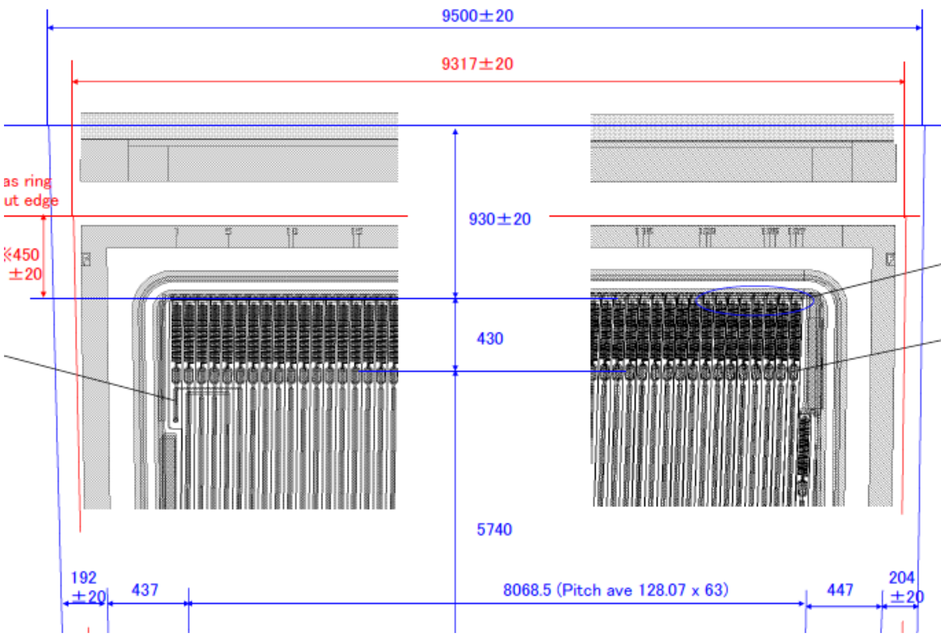




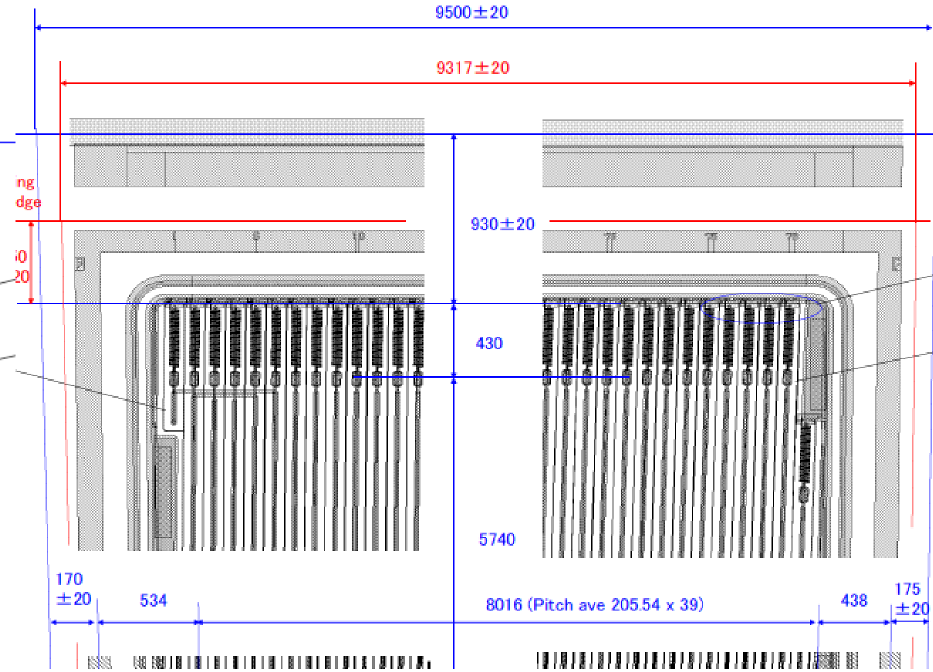
- Zone
  - Pitch, p-stops
- PTP gate
  - A: Half, B: Continuous-Full
  - C: Comb-Full, D: Half+Bias
  - E: No gate, F: Wide gap

Endcap (EC) Mini's

Small Pitch ATLAS12A

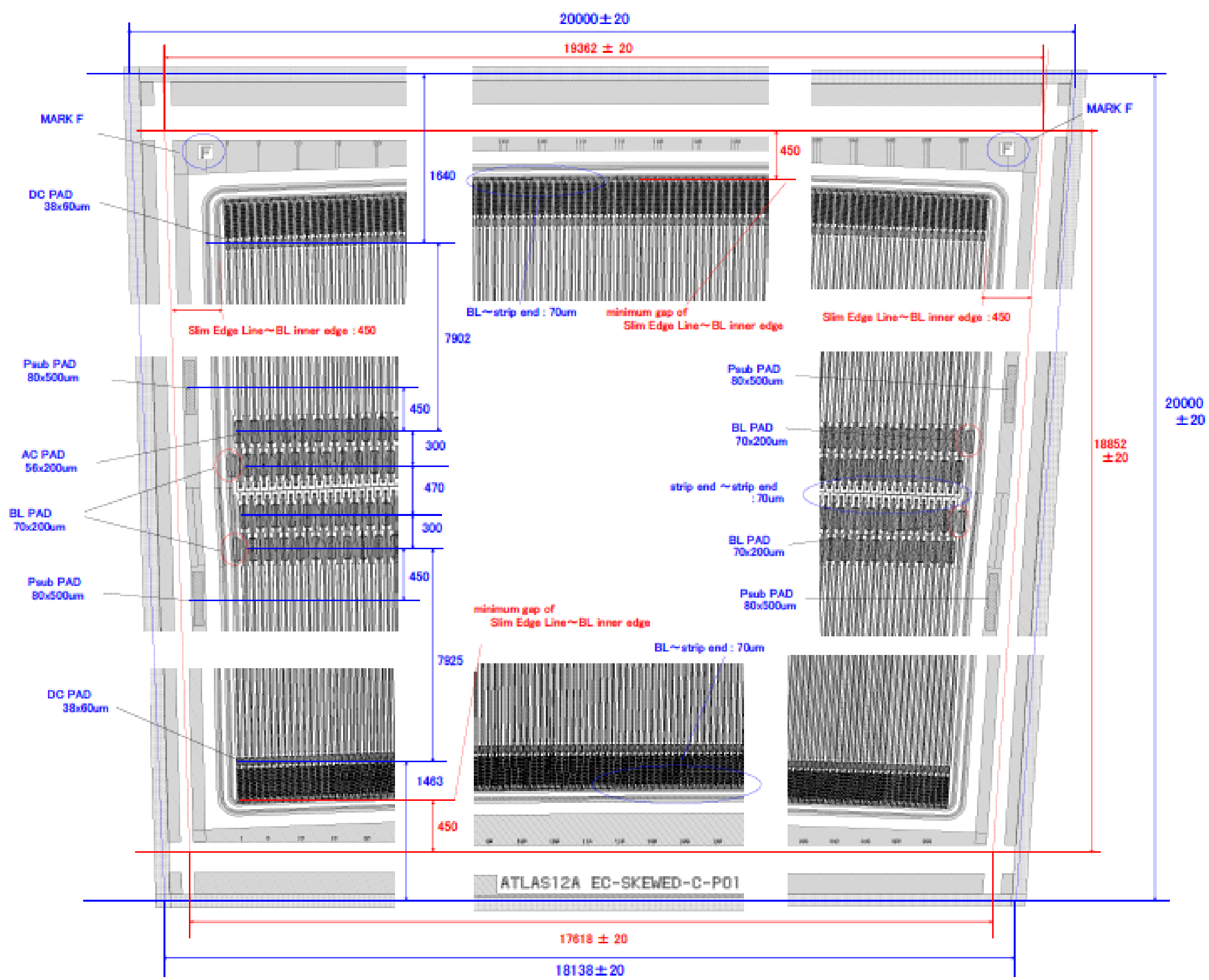


Large Pitch



- Small and Large pitch mini's
  - Average pitch: 128 µm, 205.5 µm
  - Dicing line
    - Side: Slim only (limited by available 1cm x 1cm)
    - End: Slim and STD
  - Stray strip gang
    - 12M: no gang
    - 12A: DC and AC gang

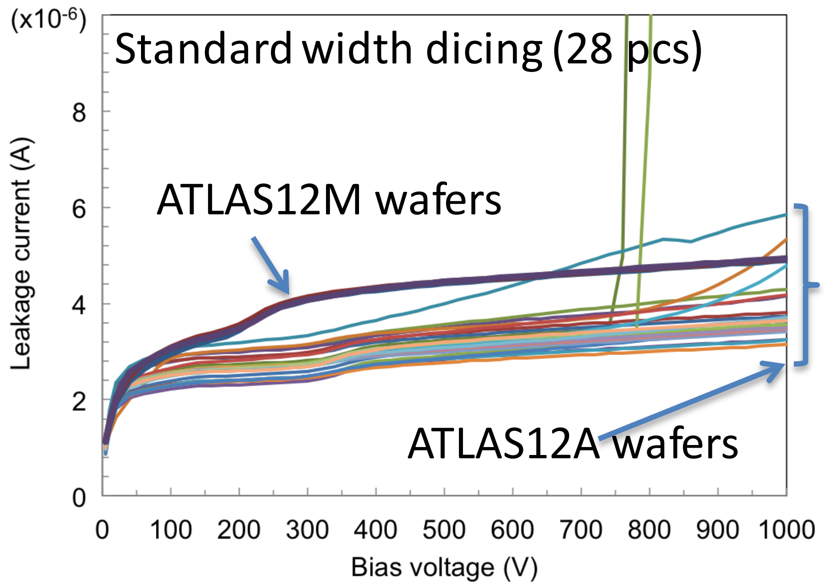
EC Skewed mini

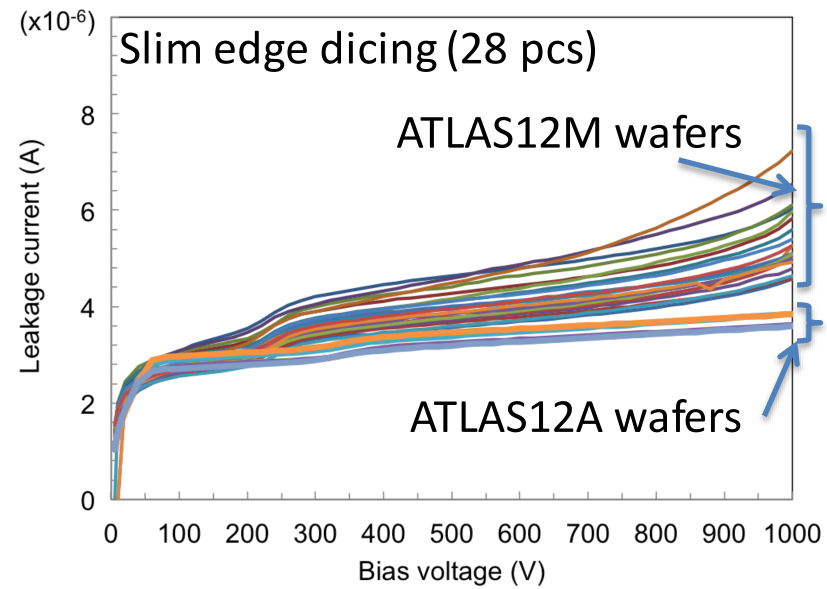


- Basically, 2 cm × 2 cm
- No “short/stray” stereo strips

ATLAS12 I-V after Dicing

- Process finished for ATLAS12A 120 pcs and 12M 45 pcs
- ATLAS12-A 30 and –M 20 wafers were diced to
  - 25 “Standard” width (950 µm) and 25 “Slim” (450 µm)

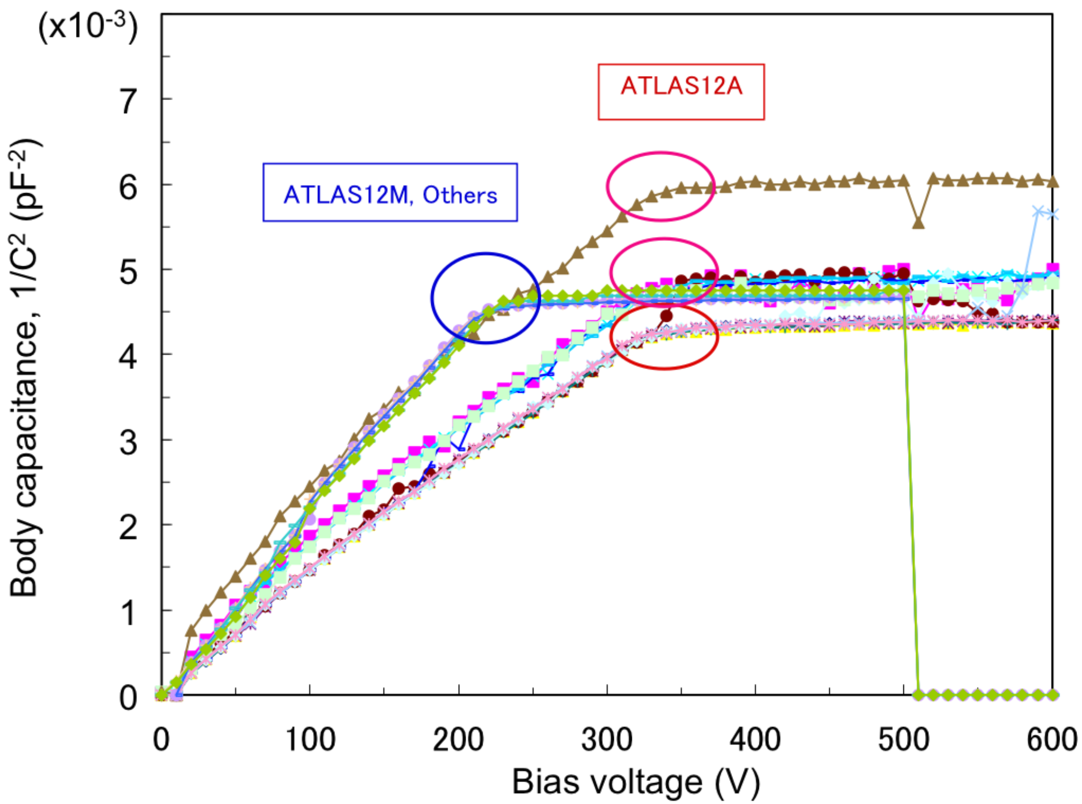




- “Standard” edge dicing
  - Those delivered are in “spec”.
    - I <20µA, MD>600 V
  - Most are flat up to 1000 V
  - MD (~750V) 2pcs (7(±5)% of 30)
- 12A: I-V “wiggle” at 300-400 V

- “Slim” edge dicing
  - Those in “spec”,
  - but not a whole story yet, !2M …
    - Some tendency to increase current, overall and over 800 V
- 12M: I-V “wiggle” at 200-300 V

ATLAS12 Wafer Depletion Voltage



- V_{FDV}: ATLAS12A ~ 350 V, ATLAS12M and others ~230 V
  - Resistivity: ATLAS12A ~ 3 kΩcm, ATLAS12M ~4 kΩcm
  - Different wafer lot may have affected the characteristics in subtle ways.
- Measurement campaign is on-going in the collaboration, including irradiations

Summary

- ATLAS12 prototype sensors
  - Close to the final design for the ATLAS upgrade strip sensor
  - PTP, Slim edge, Stereo ganging, … implemented
- ATLAS12A and 12M
  - Process finished for wafers for 120 sensors ordered
  - Dicing on-going
    - Those “in spec” have been delivered
    - 12A: 5 Slim, 25 Std
    - 12M: 23 Slim, 3 Std
  - I-V after dicing
    - Most are good up to 1000 V
    - Slim has a tendency of “turning up” over 800V, but…
  - Wafer lots are different for ATLAS12A and 12M
    - Full depletion voltages: 12A ~350 V, 12M ~230 V
- More to be reported in the next symposium.

Backups

Abstract

- We have developed a novel and radiation-tolerant n-in-p silicon microstrip sensors for very high radiation environments such as high-luminosity LHC.
- The sensors are designed to be operable to the end-of-life fluence of ≥1 × 10^15 1-MeV neutron-equivalent/cm^2.
- The sensors are fabricated in p-type, float-zone, 6 in. wafers where we lay out two designs of large-area, 9.75 cm × 9.75 cm, strip sensors, together with a number of miniature sensors.
- The large-area sensors have four blocks of short strips, 2.4 cm long each. One design is made with all "axial" segments (ATLAS12A) and the other with two "axial" and two "stereo" strip segments (ATLAS12M).
- Each design has (1) two edge-widths: standard (~900 μm) and slim (~450 μm), and (2) punch-through protection (PTP) structures at the end of each strips.
- The miniature sensors are implemented with variations of the PTP structure, and the "wedge" designs for the endcap sensors with stereo strips or the "skewed" layout.
- A "ganging" of stray stereo strips to the readout strips is designed in a stereo-strip segment of the ATLAS12M sensor and in the "wedge" miniature sensors.
- We report the design and the initial performance of the large area and the miniature sensors with the standard or the slim edge dicing.

ATLAS LHC Tracker Layout