TCAD simulations of the ATLAS ITk-Strip sensors for the HL-LHC

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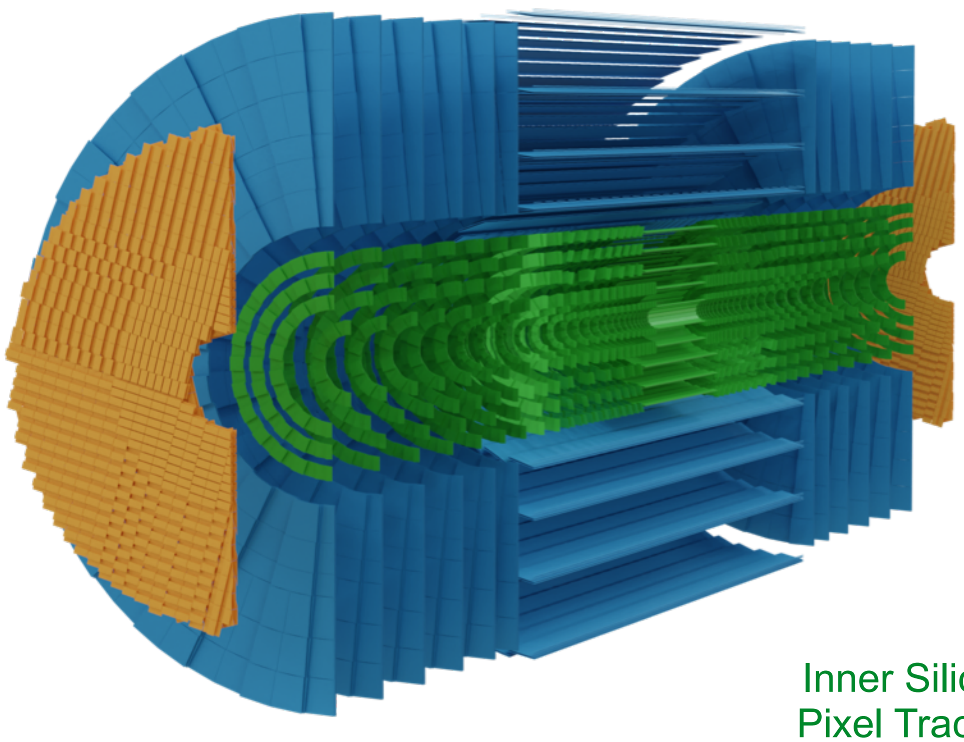
on behalf of ATLAS ITk Strip Sensors community

43rd RD50 Workshop
29 November 2023

ATLAS EXPERIMENT

Carleton University

ATLAS ITk Strip Detector



Inner Silicon
Pixel Tracker

Forward High-Granularity
Timing Detector

Silicon Strip Tracker

165 m^2 of silicon sensors

60 million readout channels

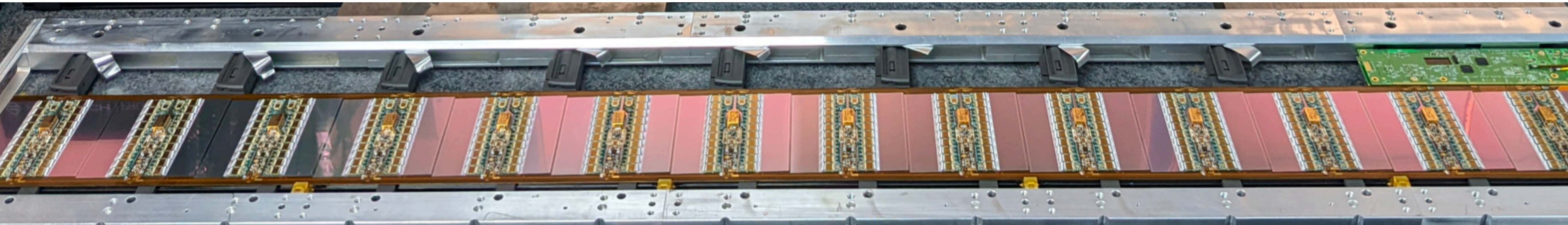
300,000 ASICs

Performance gains of new detectors to expand HL-LHC physics program

- Silicon tracking out to 1 m radius with less detector material
- Forward tracking: $2.4 < |\eta| < 4.0$
- 10x readout rate: 1 MHz
- Robust to radiation: ITk Strip expects fluences ~50 MRad, 1.2×10^{15} n_{eq}/cm^2

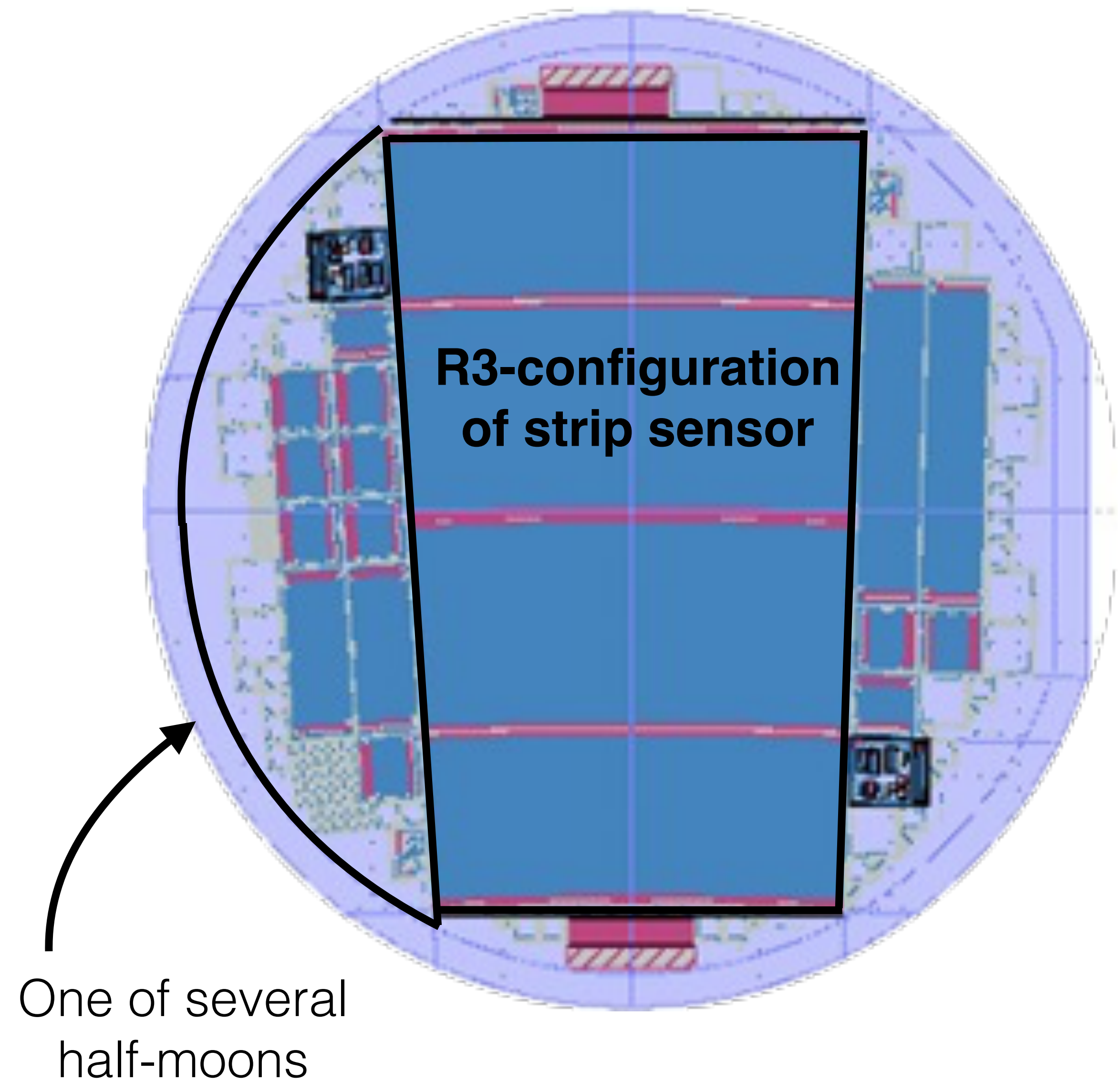
- Sensor and ASIC designs approved and in production
  - Still much to understand about long-term performance, optimal operation / digitization, & simulations
- Today: Comparing TCAD simulations & lab measurements
  - across sensor geometries and test structures
  - with varying radiation fluences

ITk Strip Staves built at BNL



ITk Silicon Strip Sensors

- n^{+}-in-p sensors: 304 μm active depth, varying geometries
- Half-moons on wafer periphery with several sizes of mini strip sensors and square test diodes



ITk Silicon Strip Sensors

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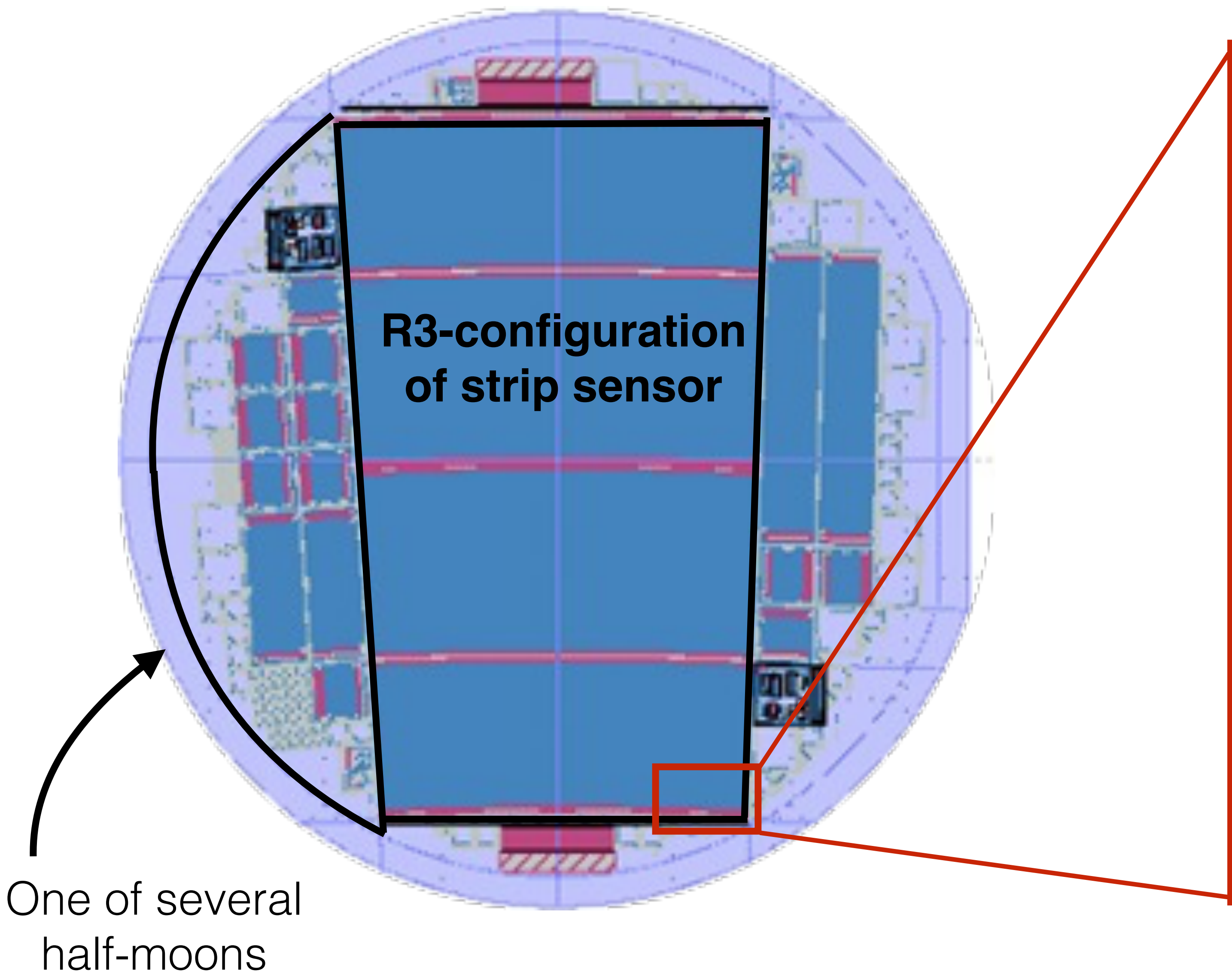
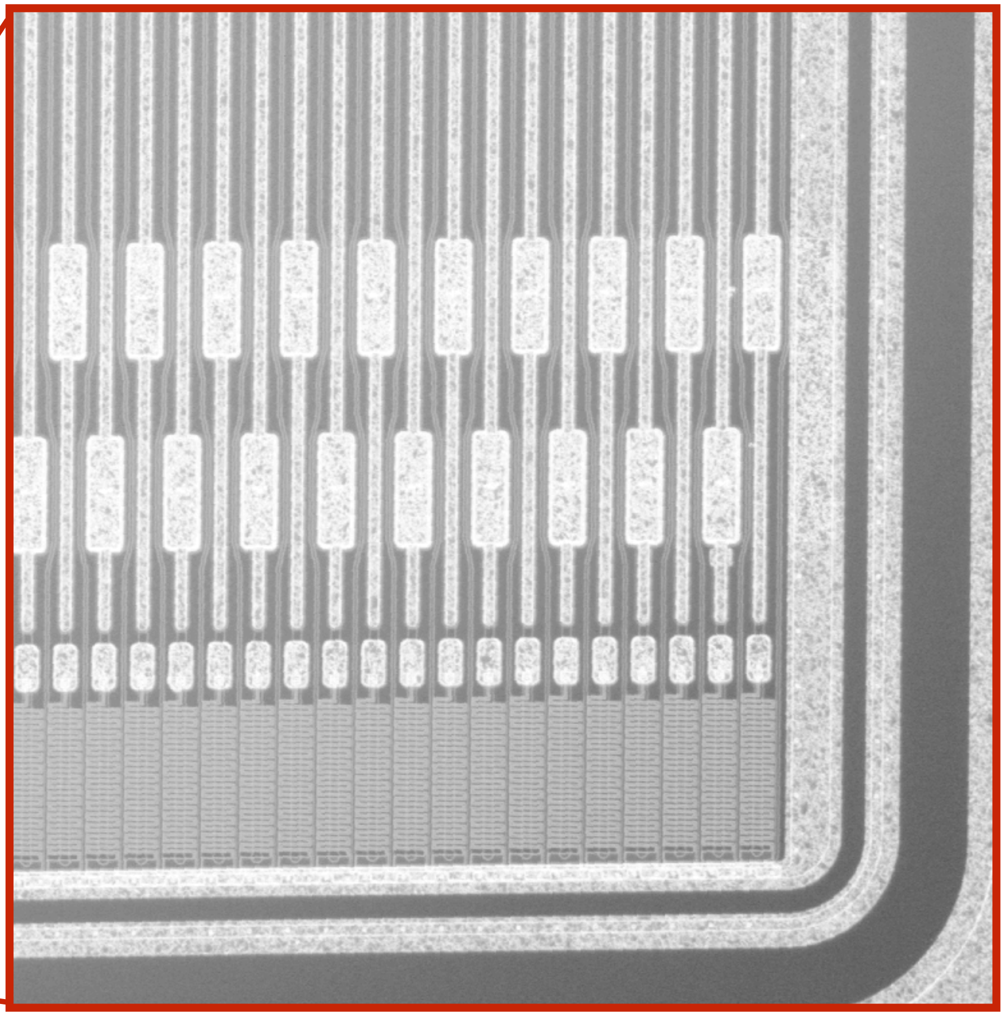
- $\mathcal{O}$(thousand) AC-coupled n^+ strips separated by p-stop implants

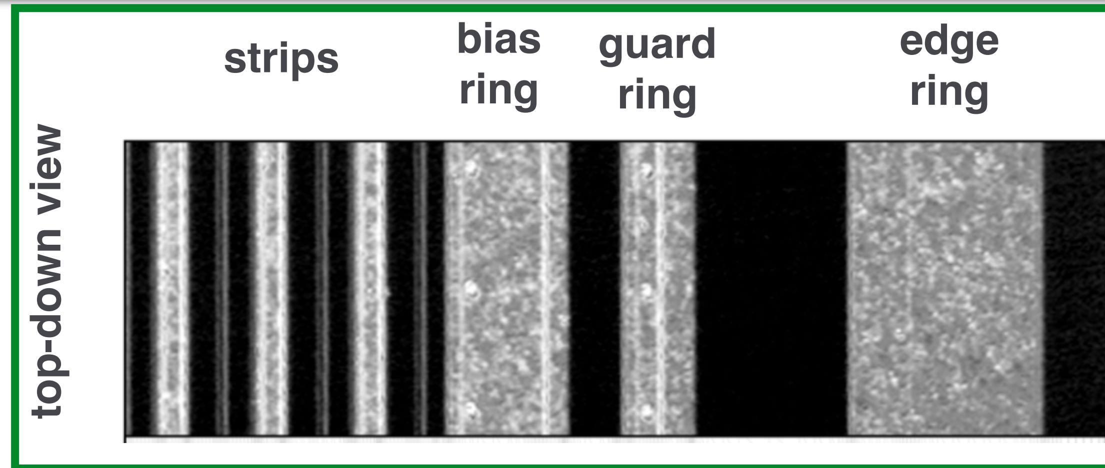




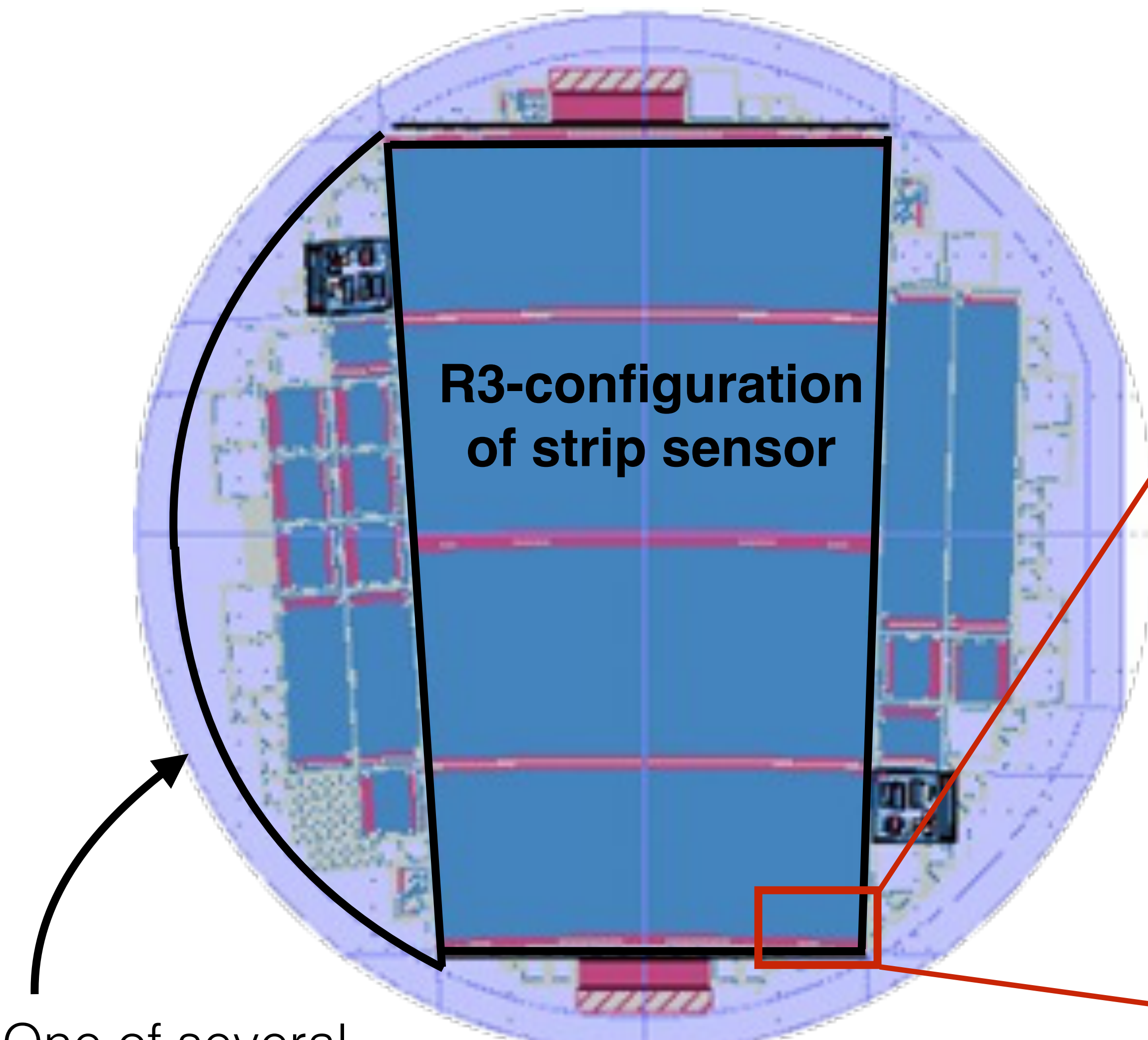
Zoom-in on Strip Sensor Corner

ITk Silicon Strip Sensors

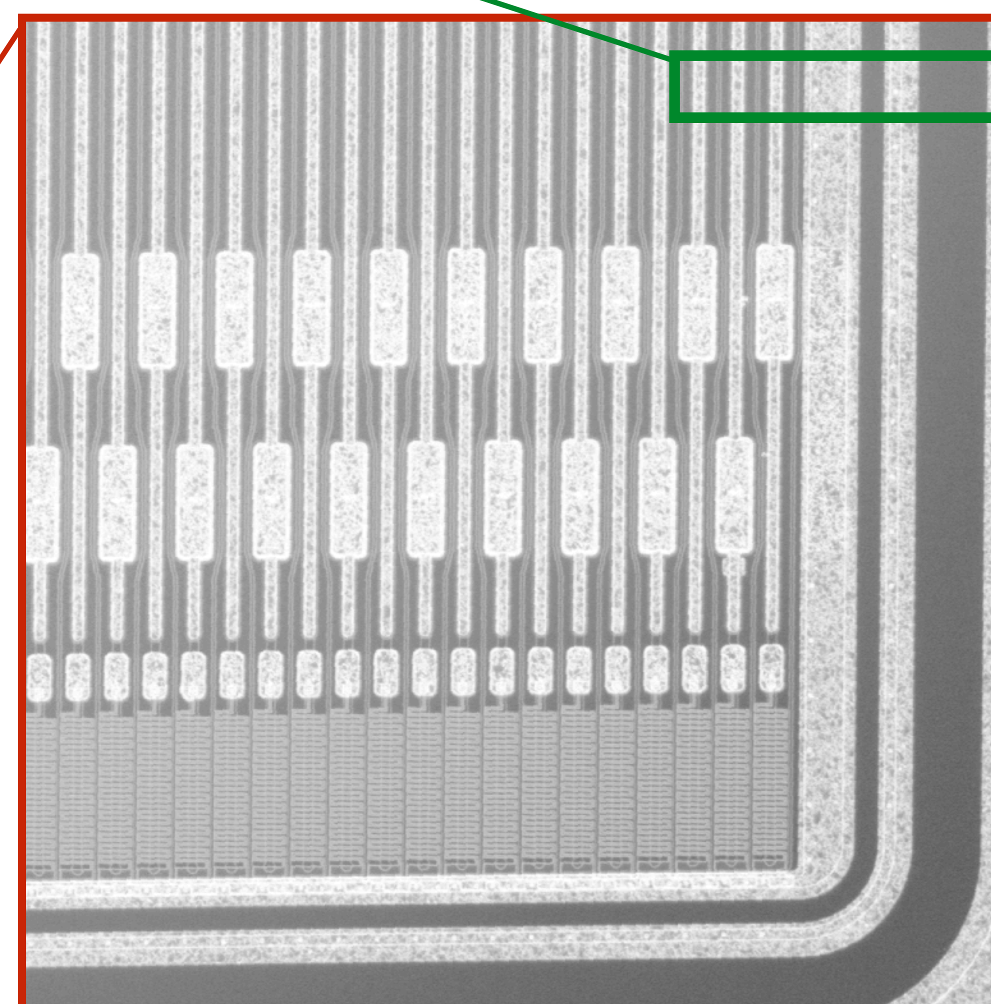
- n+-in-p sensors: 304 μm active depth, varying geometries
- Half-moons on wafer periphery with several sizes of mini strip sensors and square test diodes
- $\mathcal{O}$(thousand) AC-coupled n+ strips separated by p-stop implants
- Surrounded by bias ring, n-doped guard ring, and edge metal



Zoom-in on edge



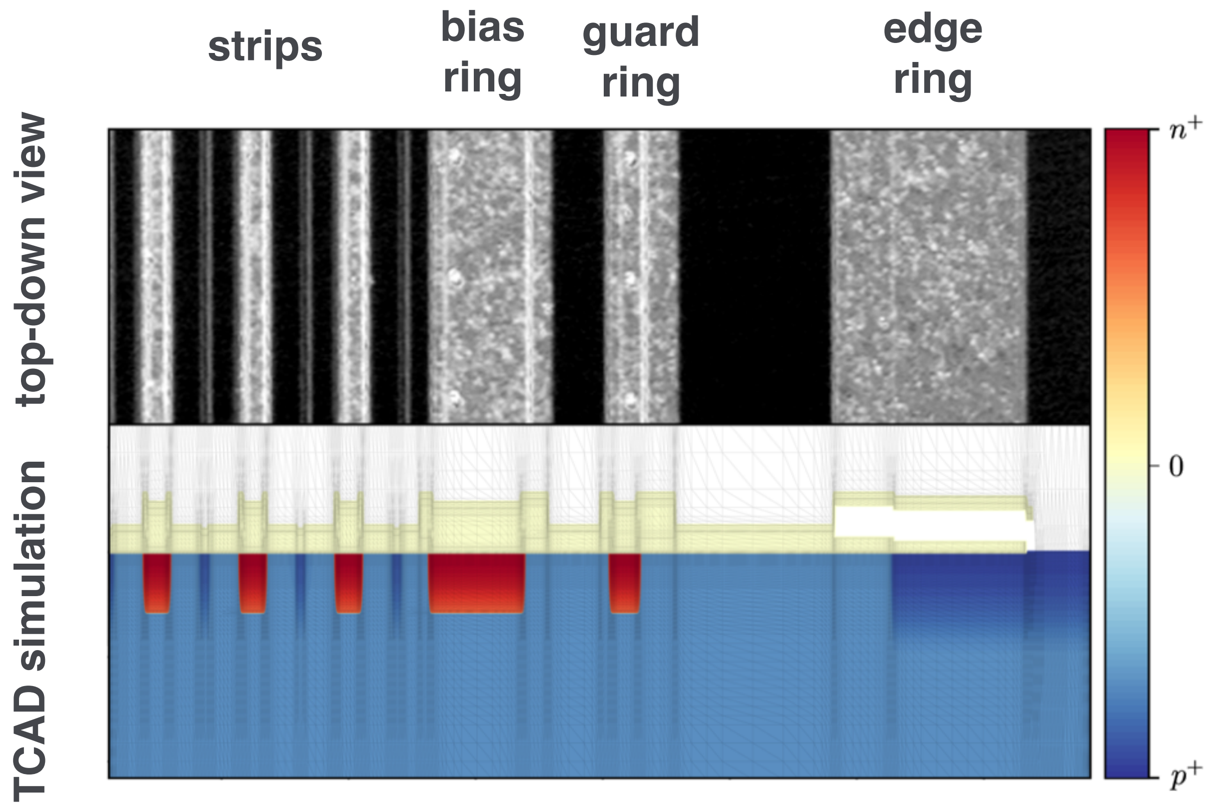
One of several half-moons



Zoom-in on Strip Sensor Corner

TCAD sensor model

- 2D cross-section model for both sensor bulk & edge implemented by Callan Jessiman
  - Will show new results at upcoming 13th Hiroshima Symposium
- Parameters informed by combination of
  - ATLAS technical specs + HPK info
  - Metrology measurements
  - CV measurements & TCAD tuning

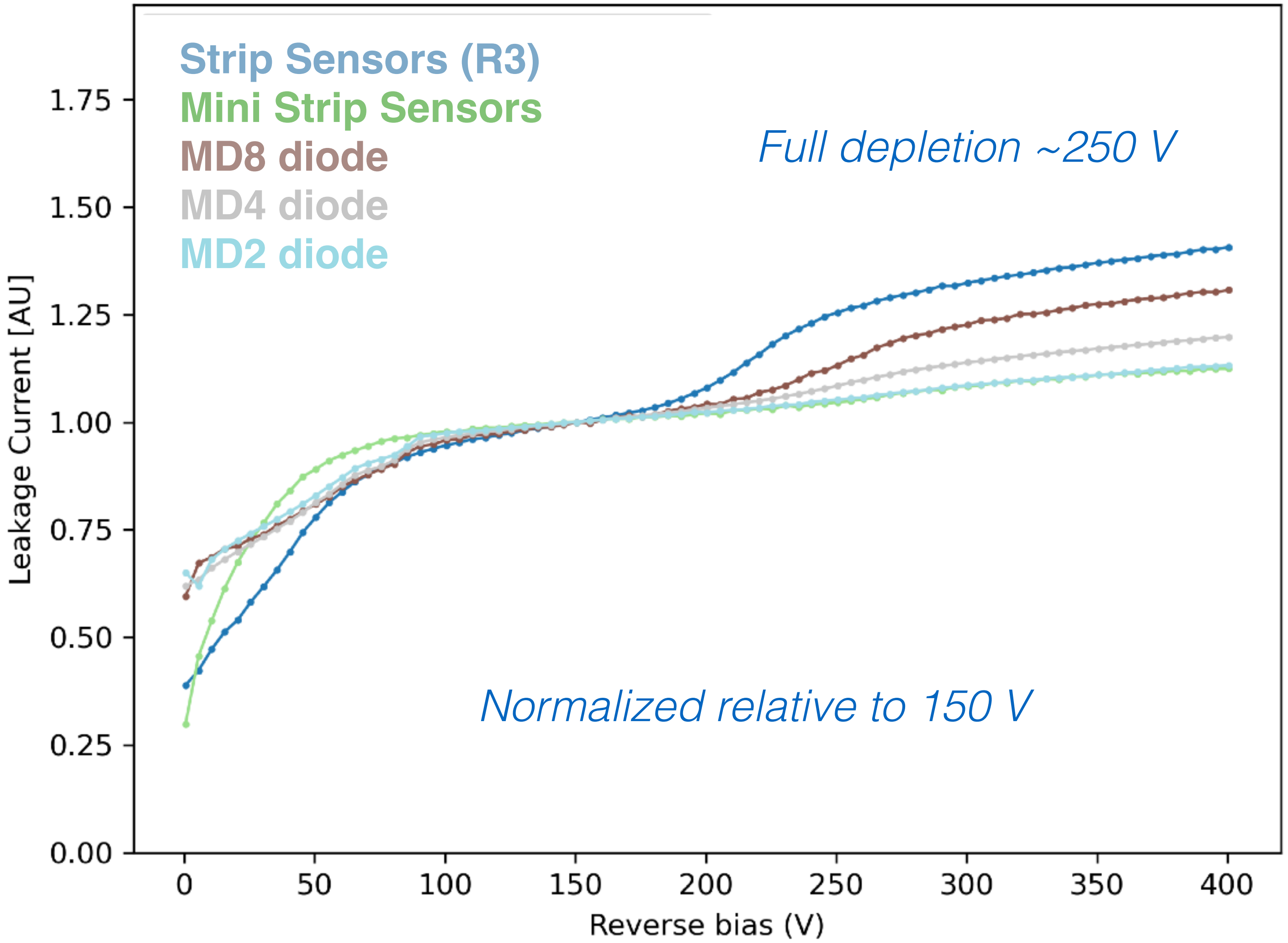


Context	Parameter	Value	Source
Substrate	thickness p-type doping	305 μm 3.2×10^{12} cm^{-3}	tuning TCAD to match CV
Backplane	thickness p-type dose doping depth (σ)	15 μm 10^{14} cm^{-2} 1 μm	total from metrology − rest guess (typical value)
Sensor	horizontal layout		microscope, GDS
Oxide	thickness charge	0.7 μm 10^{11} e/cm^2	calculated from CV
Passivation	thickness structure	0.6 μm half SiO_2, half Si_3N_4	guess (typical structure)
Strips	thickness coupling thickness n-type dose doping depth (σ)	1.25 μm 0.24 μm 2×10^{15} cm^{-2} 0.5 μm	calculated from $C_{coupling}$ calculated from $R_{implant}$ guess (typical value)
Bias rail Guard ring	thickness, doping	same as strips	guess (similar structures)
Edge metal	thickness doping contact to Si	same as strips same as backplane under outer overhang	guess (similar structures) guess (typical value) guess (typical layout)
p-stop	width p-type peak conc. doping depth (σ)	6.5 μm 4.5×10^{15} cm^{-3} 1 μm	microscope, matches spec tuning TCAD to match CV

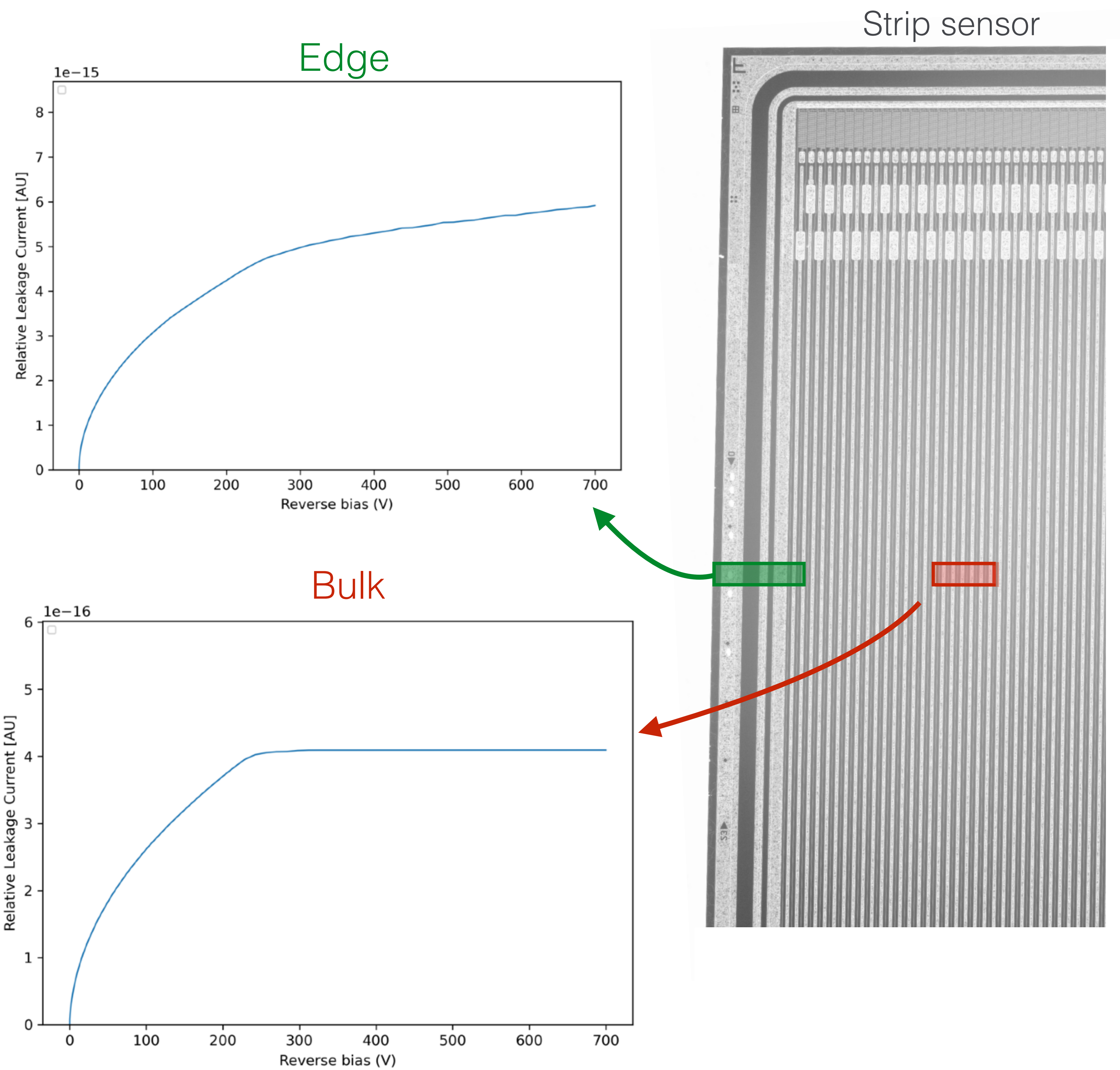
Lab IVs for various test structures

- IVs of sensors and diodes measured at Carleton with Semiprobe system
- Diodes show expected increase in current density with growing circumference-to-area (edge effects)
- **Strip sensors** see 2 plateaus, with second rise between 200-250 V
  - Effect also seen in test diodes, appears to grow with larger area-to-circumference → Suggests bulk effect
  - Effect negligible in **mini strip sensors** & MD2
  - To be understood

Structure	nStrips	Size (cm)	Current @ 150 V [nA/cm²]
R3 Strips	896x4	~7 x 12	0.85
Minis	104	1 x 1	0.78
MD8	-	0.8 x 0.8	0.50
MD4	-	0.4 x 0.4	0.93
MD2	-	0.2 x 0.2	1.95



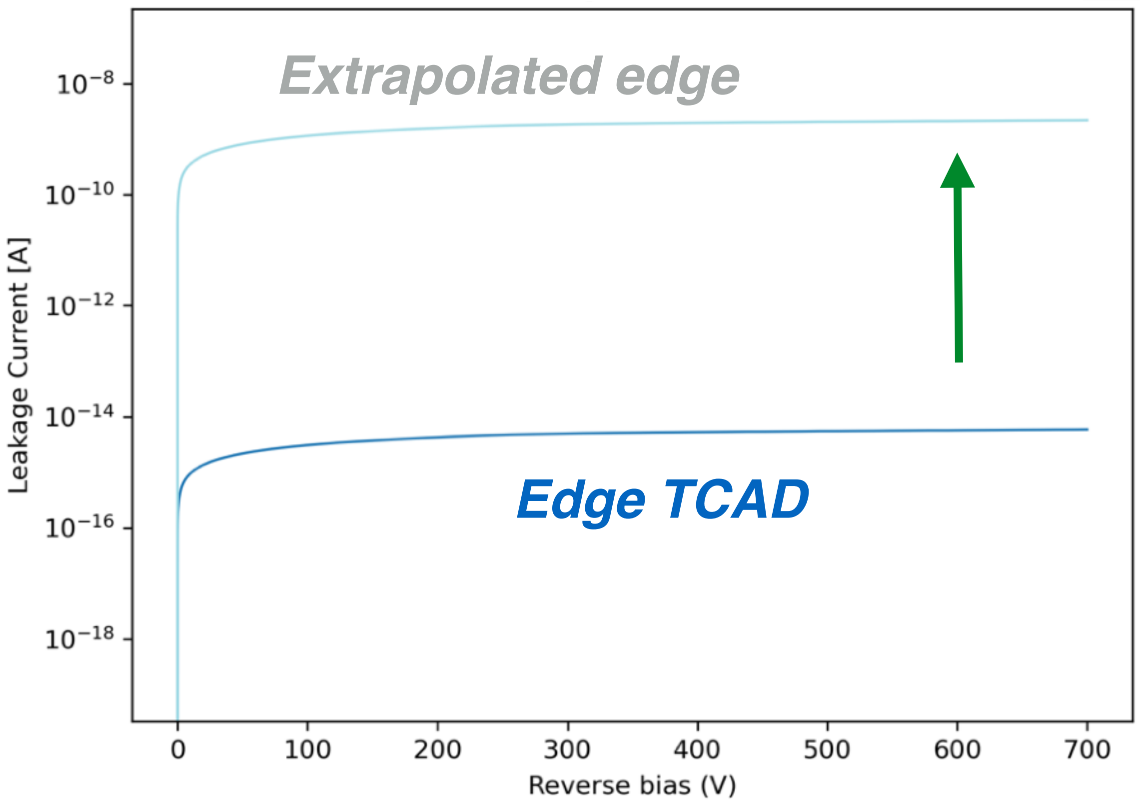
Building full-sensor IV simulations



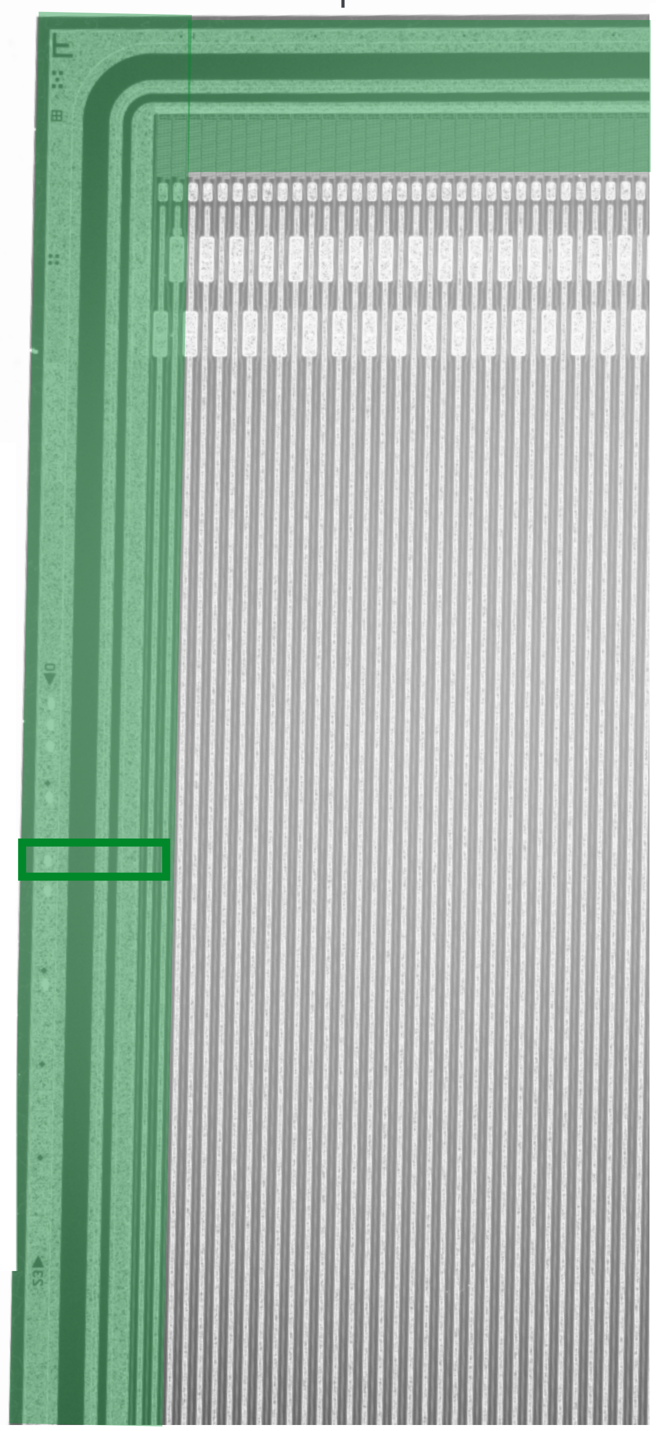
- Simulate small 2D cross-sections at edge and bulk
  - Tuned carrier lifetime by extrapolating bulk prediction to total sensor area

Building full-sensor IV simulations

Scale to total edge-like area



Strip sensor



- Simulate small 2D cross-sections at edge and bulk
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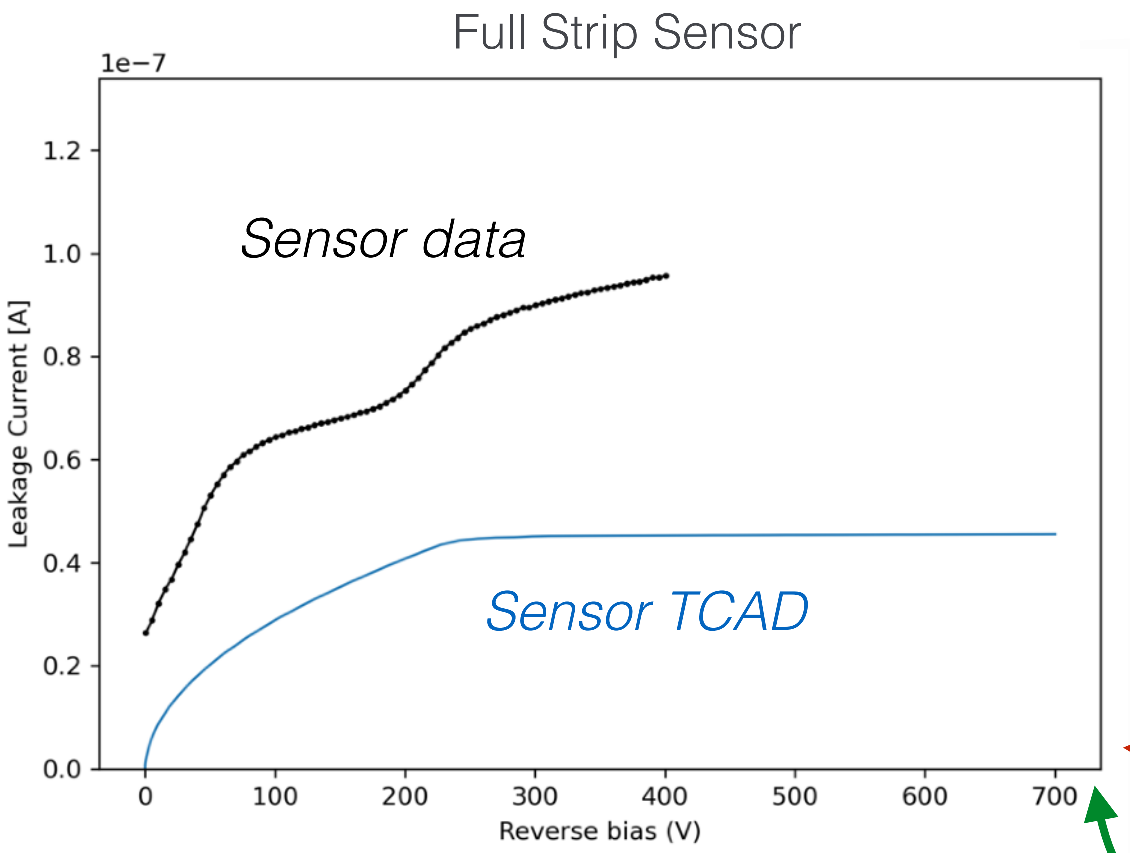
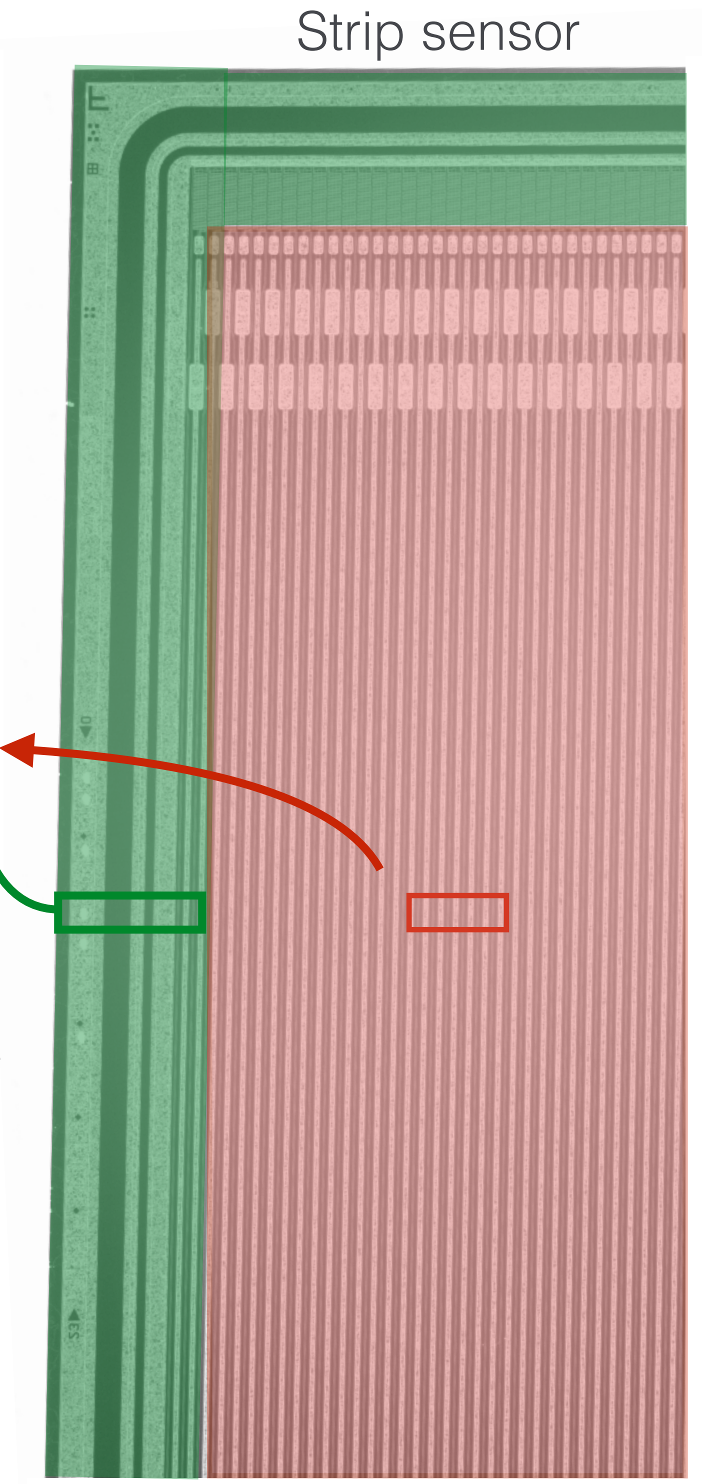
- Extrapolate simulation to match total sensor area of edge or of bulk

Building full-sensor IV simulations



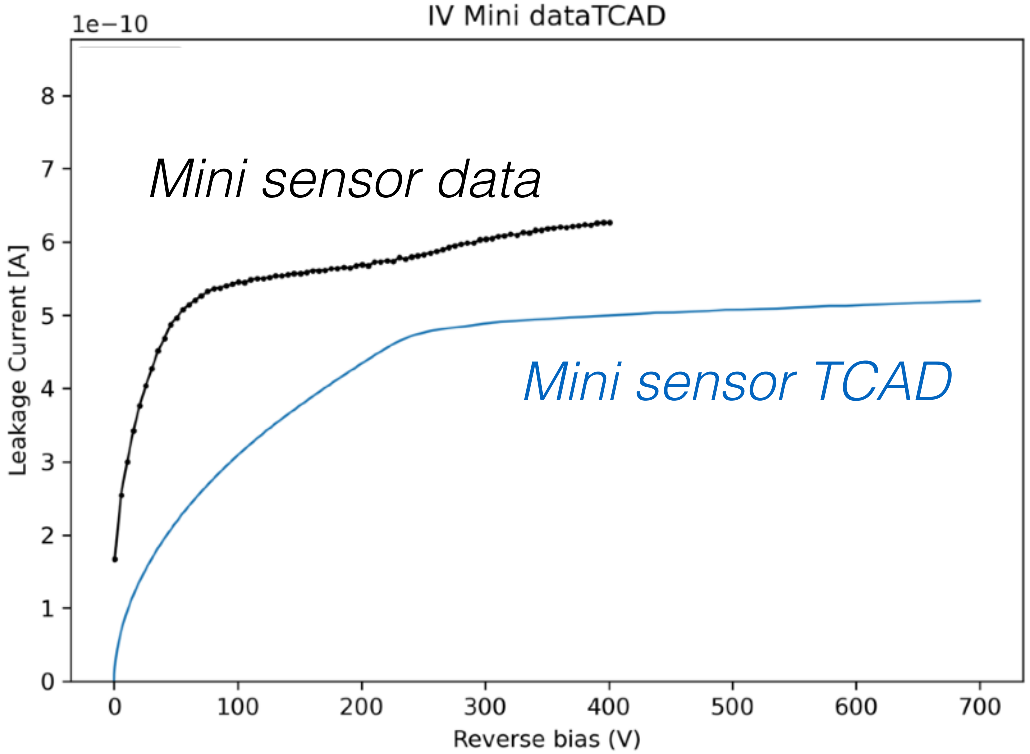


- Simulate small 2D cross-sections at edge and bulk
    - Tuned carrier lifetime by extrapolating bulk prediction to total sensor area
- Extrapolate simulation to match total sensor area of edge or of bulk
- Add extrapolated IVs for edge and bulk simulations into a total sensor estimate

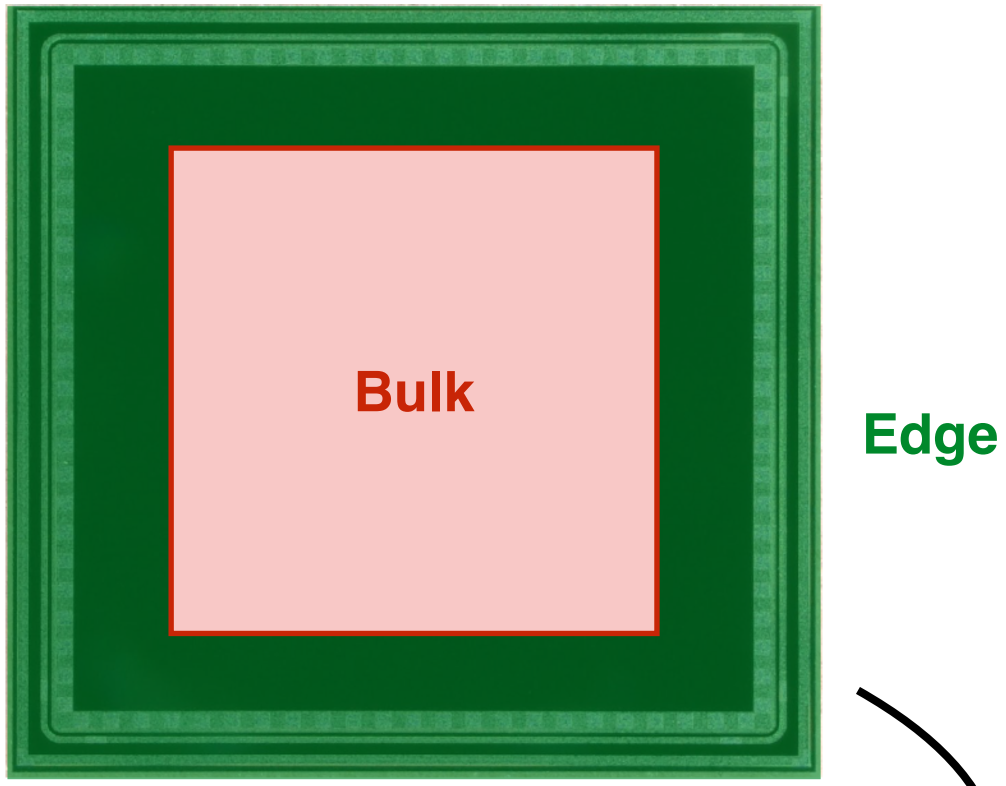
- Combined bulk+edge simulation is within 2x of data
- Differing IV characteristics

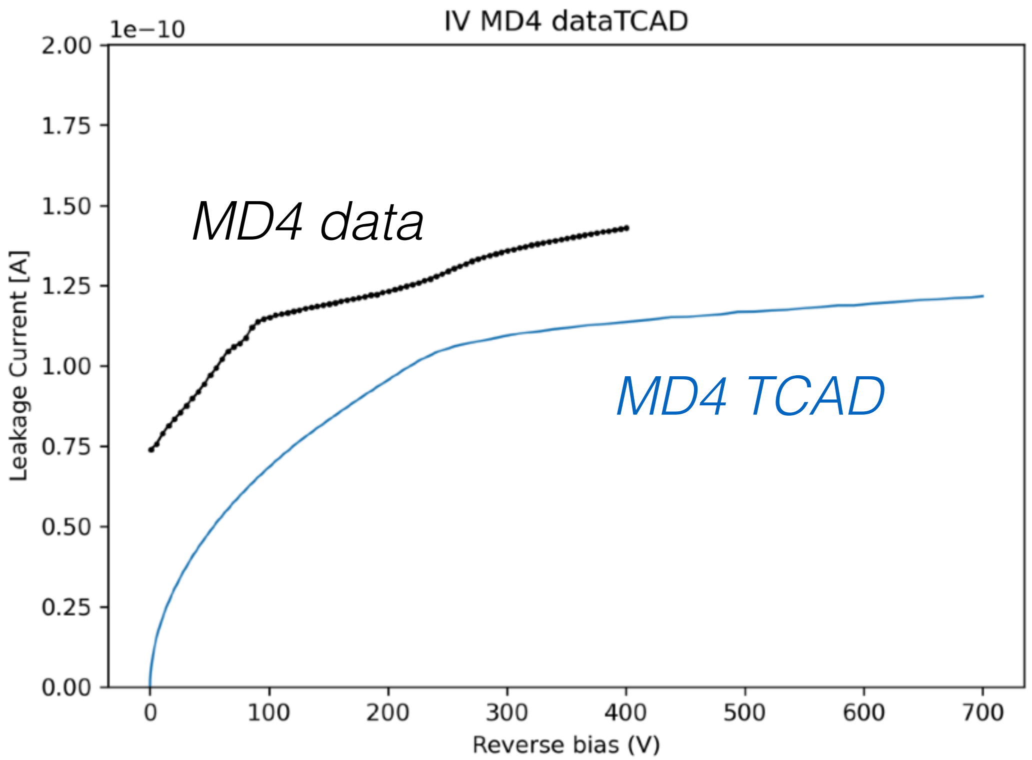
Building per-structure IV simulations

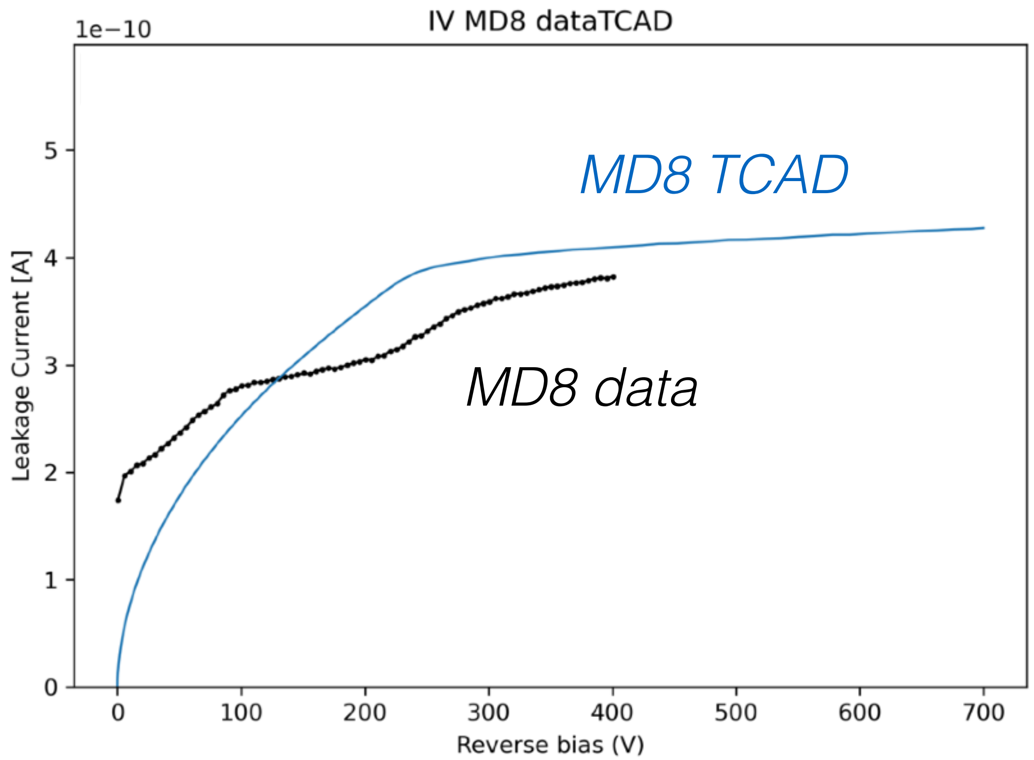
- Can also extrapolate to various test structures
- Diodes are not directly simulated in these results



MD8 diode



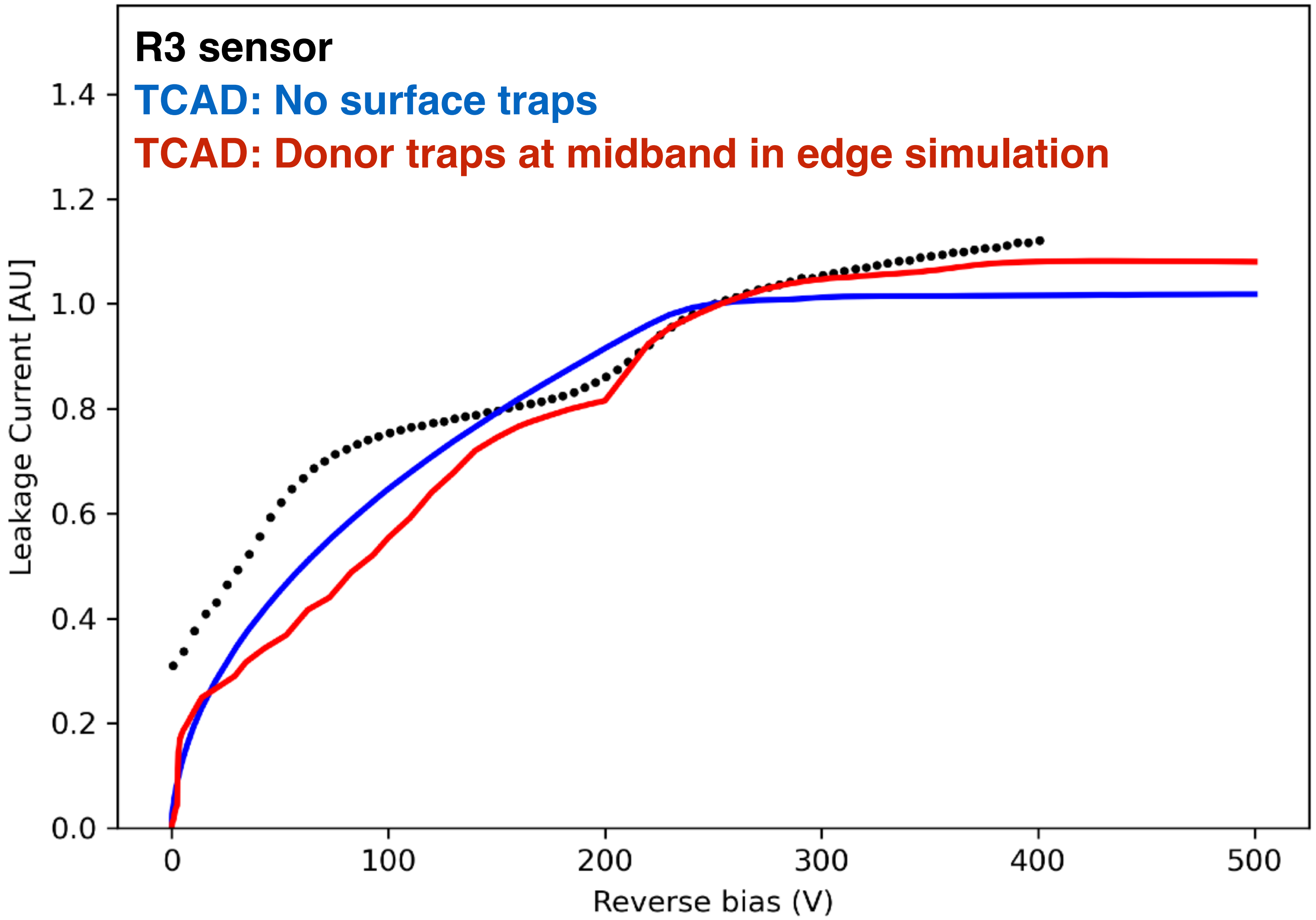




Matching IVs with TCAD traps

- To reproduce IV characteristics, simulate inherent traps from manufacturing
- A surface trap (silicon-oxide boundary) near midband found to produce a second IV rise
  - Primarily in simulations of structure edge

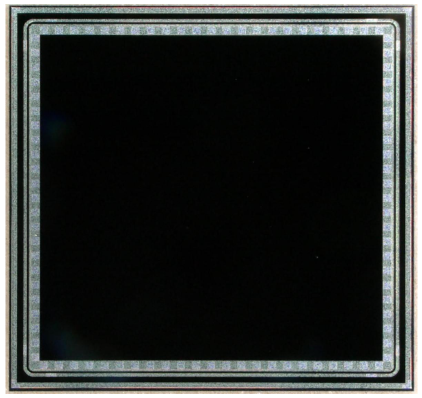
Strip sensor data vs combined bulk+edge simulations



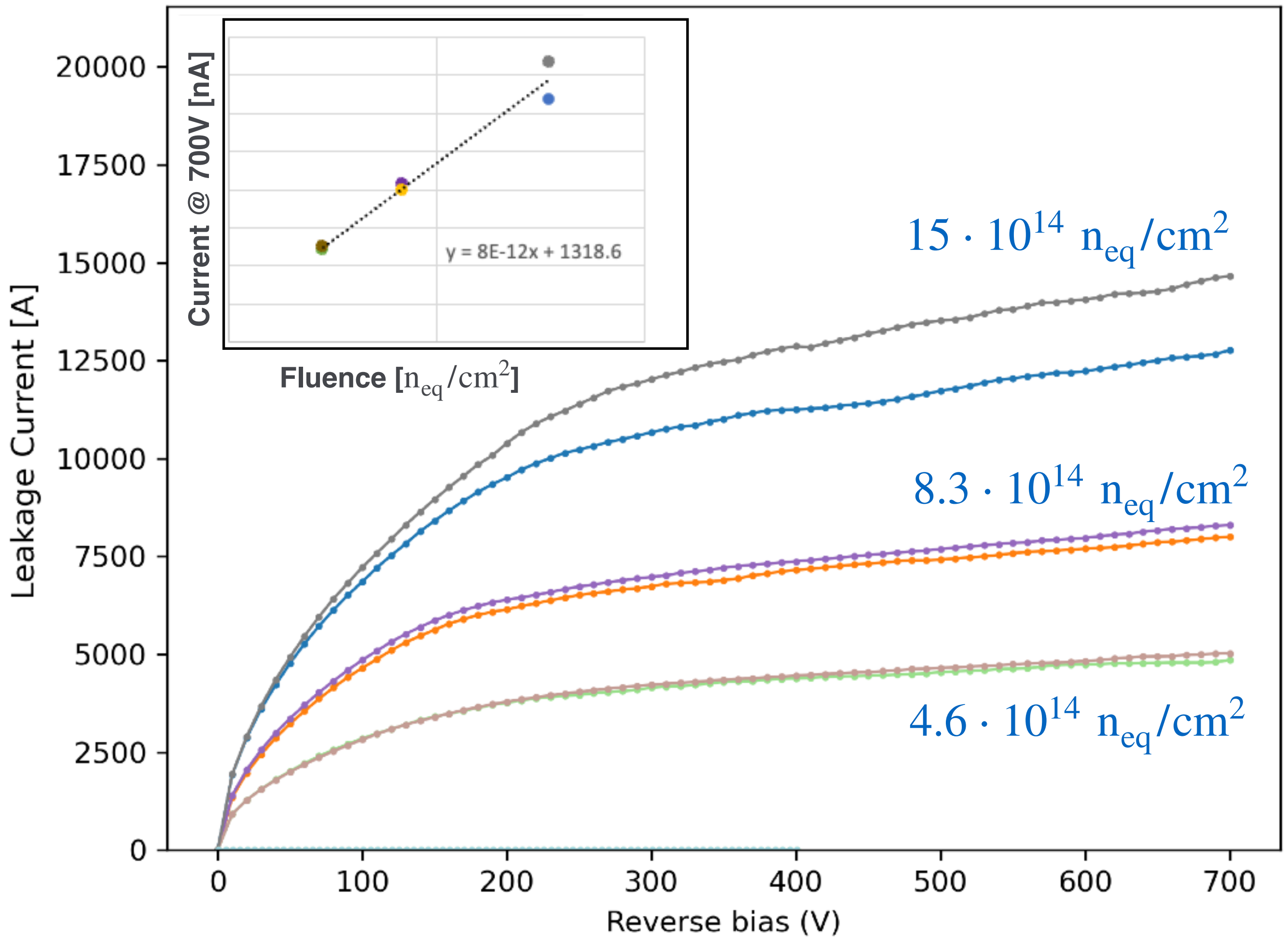
IVs after proton irradiation

- MD8 diodes irradiated with protons to various fluences at CYRIC (Tohoku University, Japan)
    - Annealed at 60°C for 80 minutes, then measured at -20 °C by KEK
- Clear increase in leakage current, nearly linear dependence on fluence $\sim 8 \cdot 10^{-12} \frac{\text{nA}}{\text{n}_{\text{eq}}/\text{cm}^2}$
- Smooth rise in current, fairly linear slope after 200 V

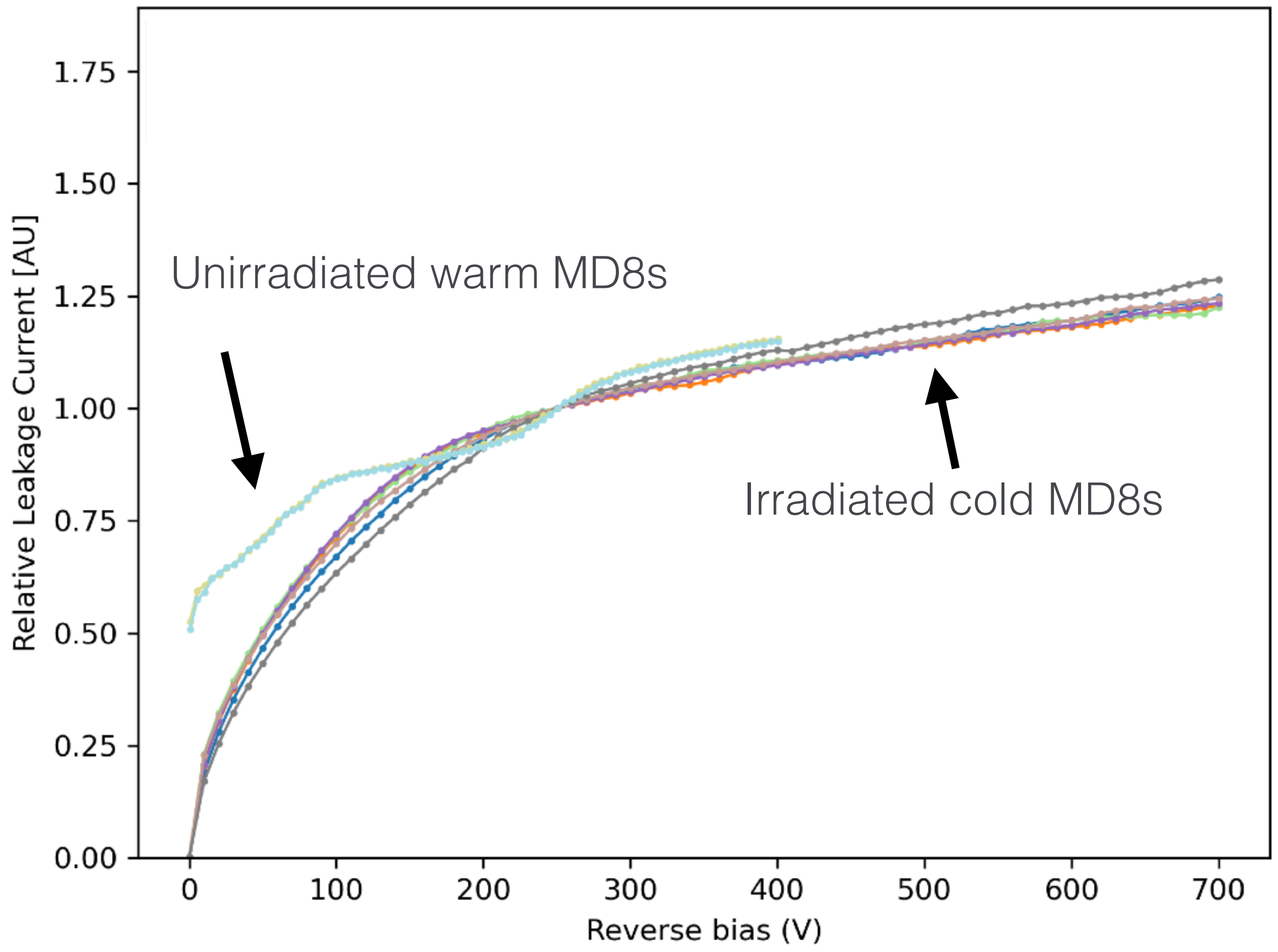
MD8 diode



Irradiated MD8s: Absolute IV curves

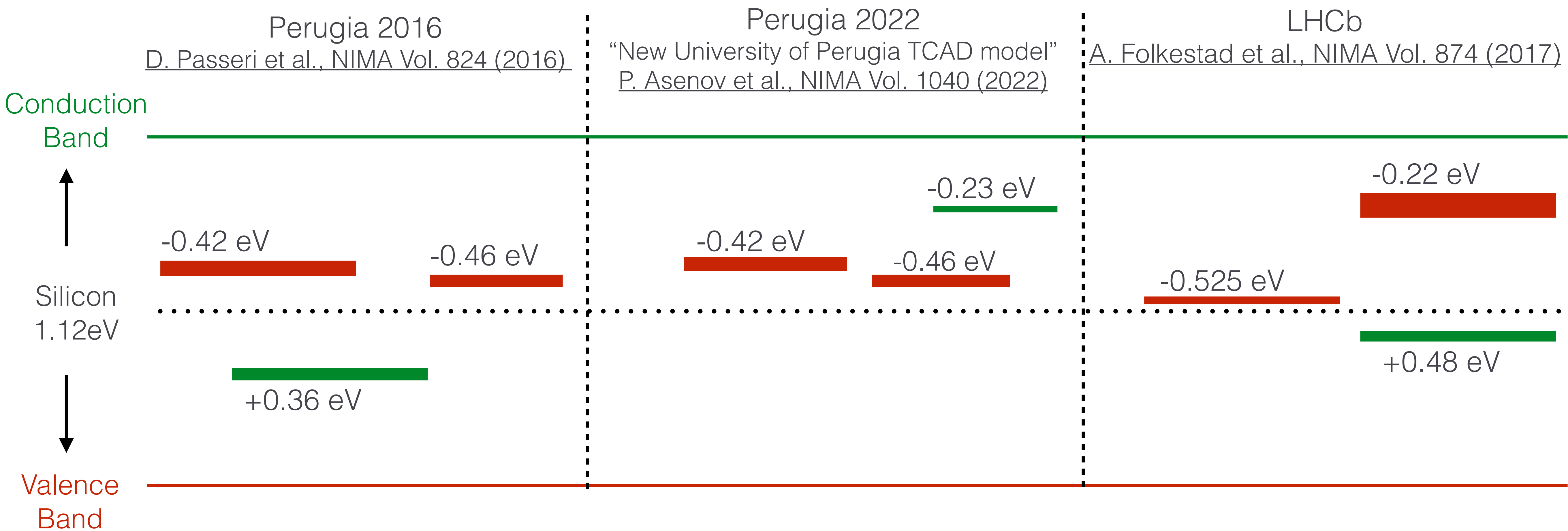


Normalized relative to 250 V



Parameterizing trap effects

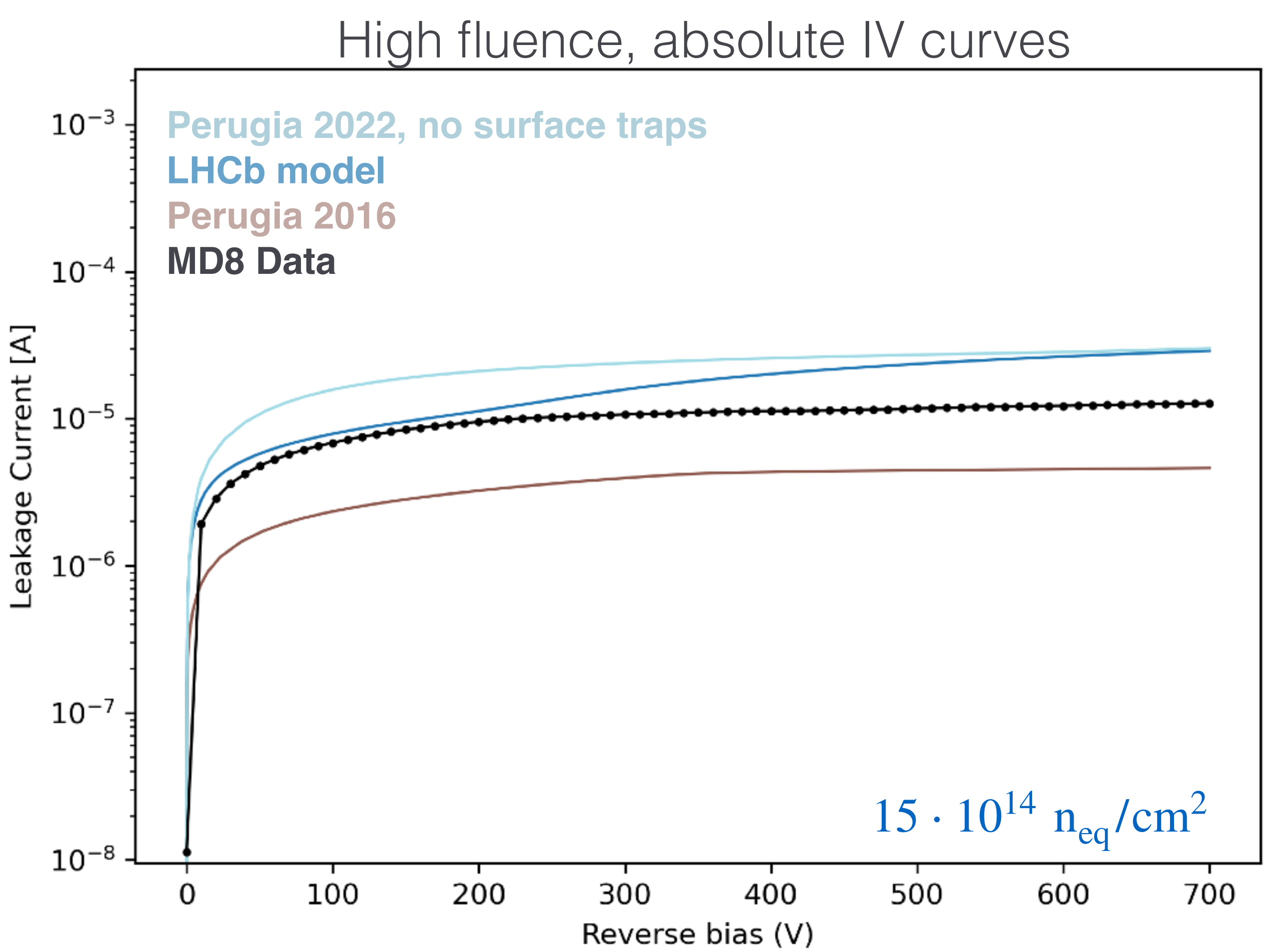
- Models exist to parameterize radiation effects using a small number of effective traps implemented in TCAD
  - 3 models, visualize below the Donor and Acceptor traps
  - Perugia 2022 model also includes a parameterization of surface traps at Silicon/Oxide boundary

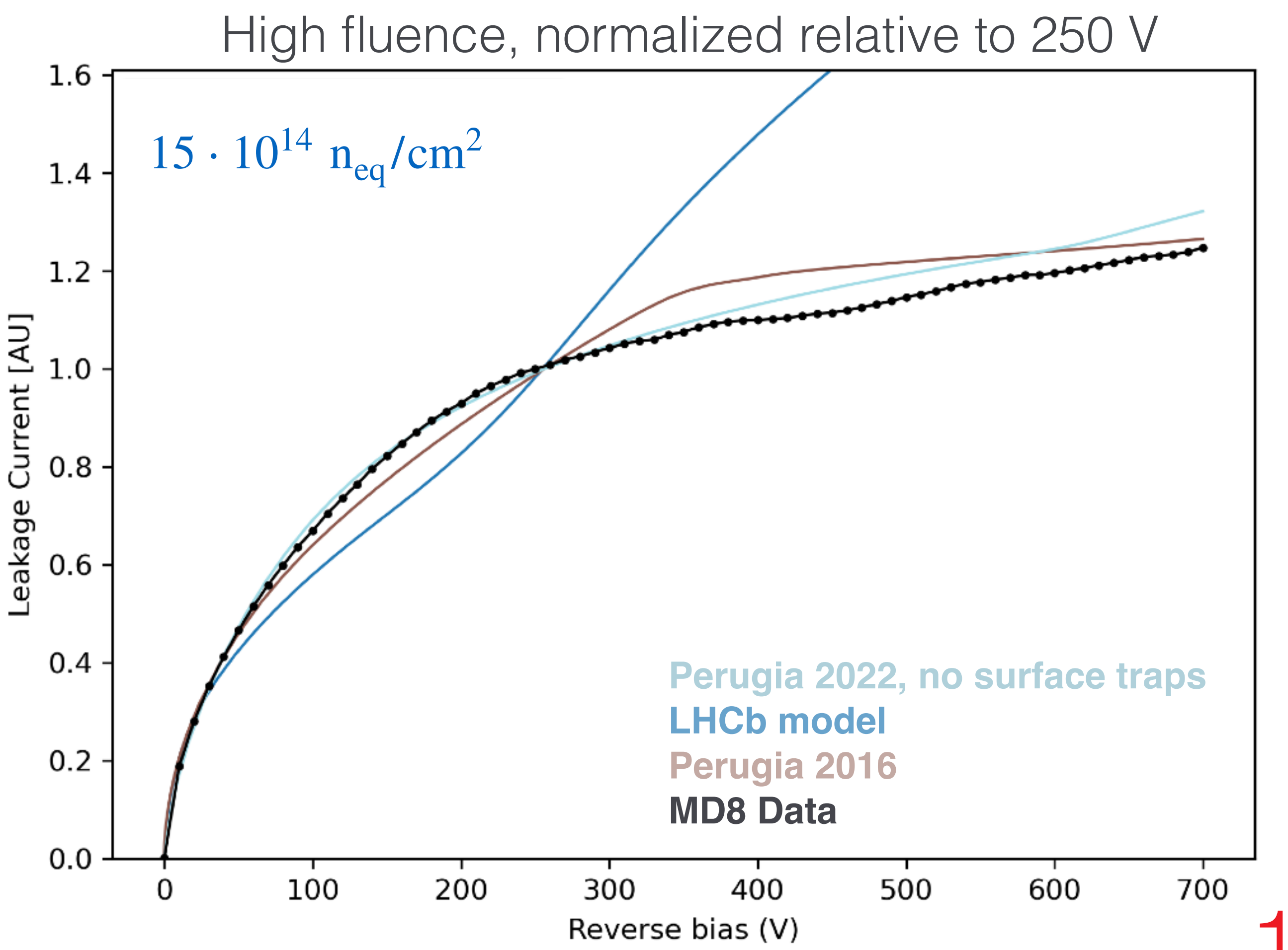


- How do these models perform for ITk Strip sensors? Implemented in TCAD to compare with MD8 diodes
- Using default physics models of carrier mobility and trap generation-recombination processes
  - Shockley–Read–Hall Recombination - models lifetime of free carriers

Comparing models to MD8s

- Direct implementation of low-temp models give ballpark agreement of magnitude with irradiated+annealed MD8s
  - Great out-of-the-box shape agreement

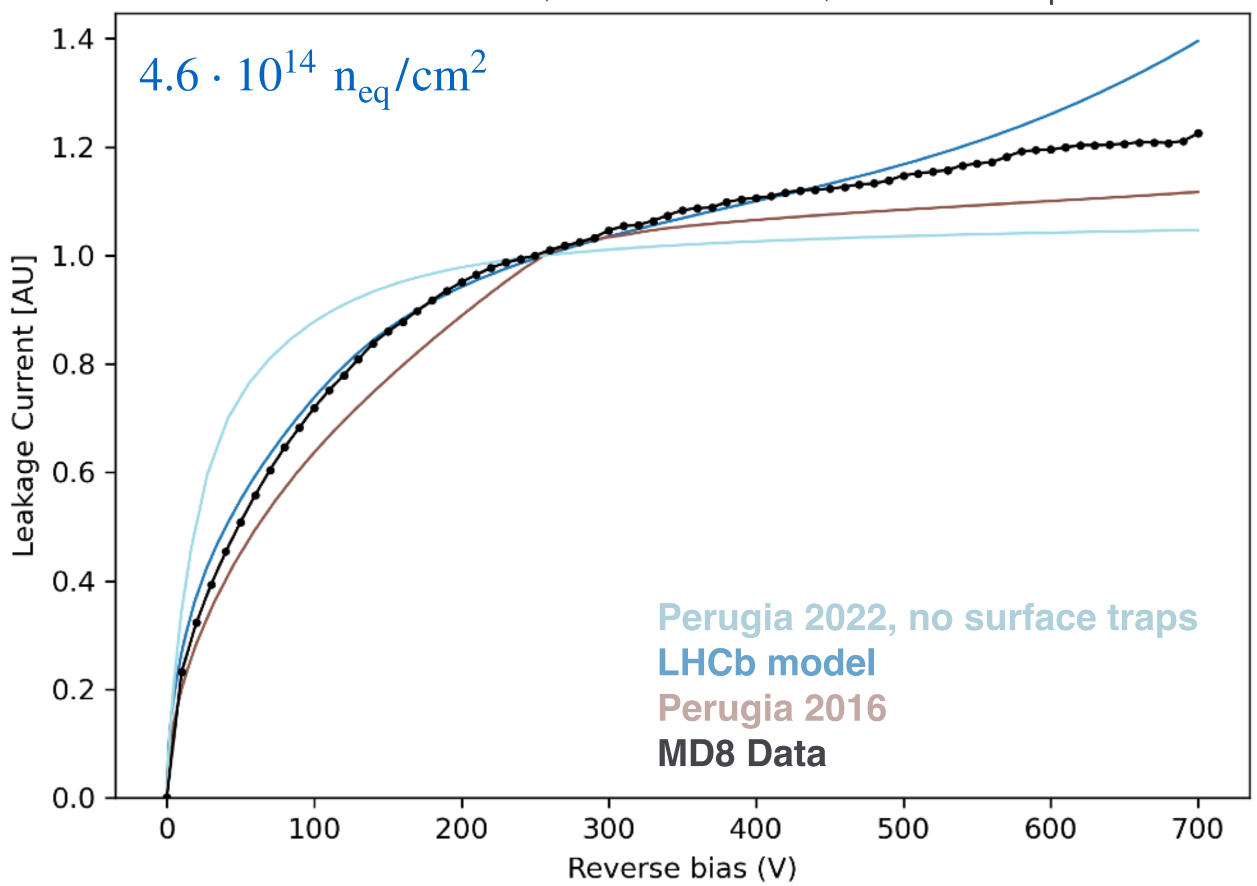




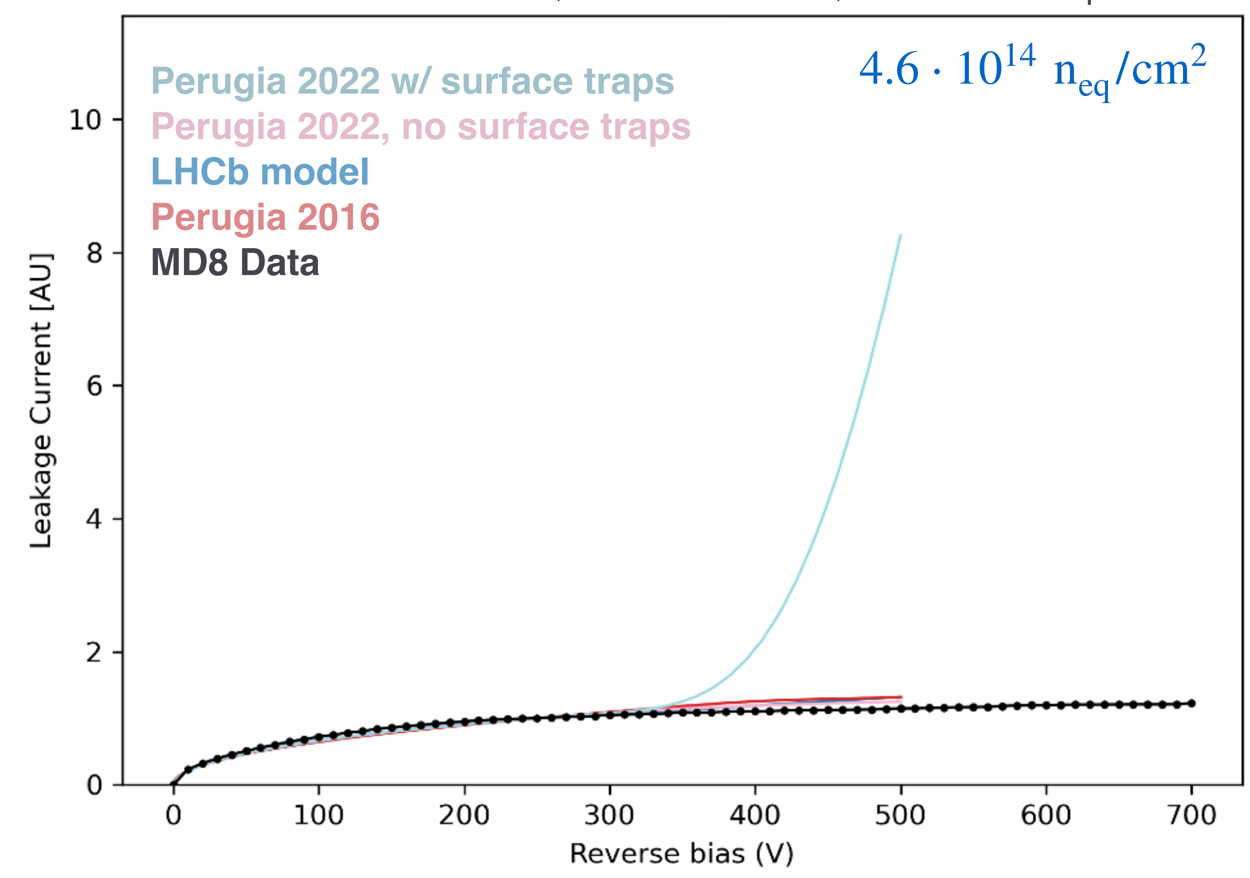
Comparing models to MD8s

- Direct implementation of low-temp models give ballpark agreement of magnitude with irradiated+annealed MD8s
  - Great out-of-the-box shape agreement
- For cold temperatures, model with best agreement varies with fluence
- Perugia 2022 + surface charges implemented w/ naive linear dependence on fluence until saturation
  - Fails cold simulations, give early soft breakdown in warm simulations

Low fluence, normalized, cold temp.

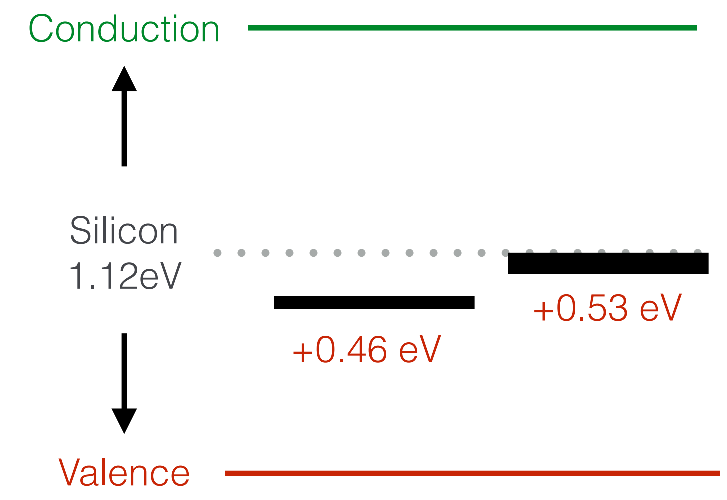


Low fluence, normalized, warm temp.

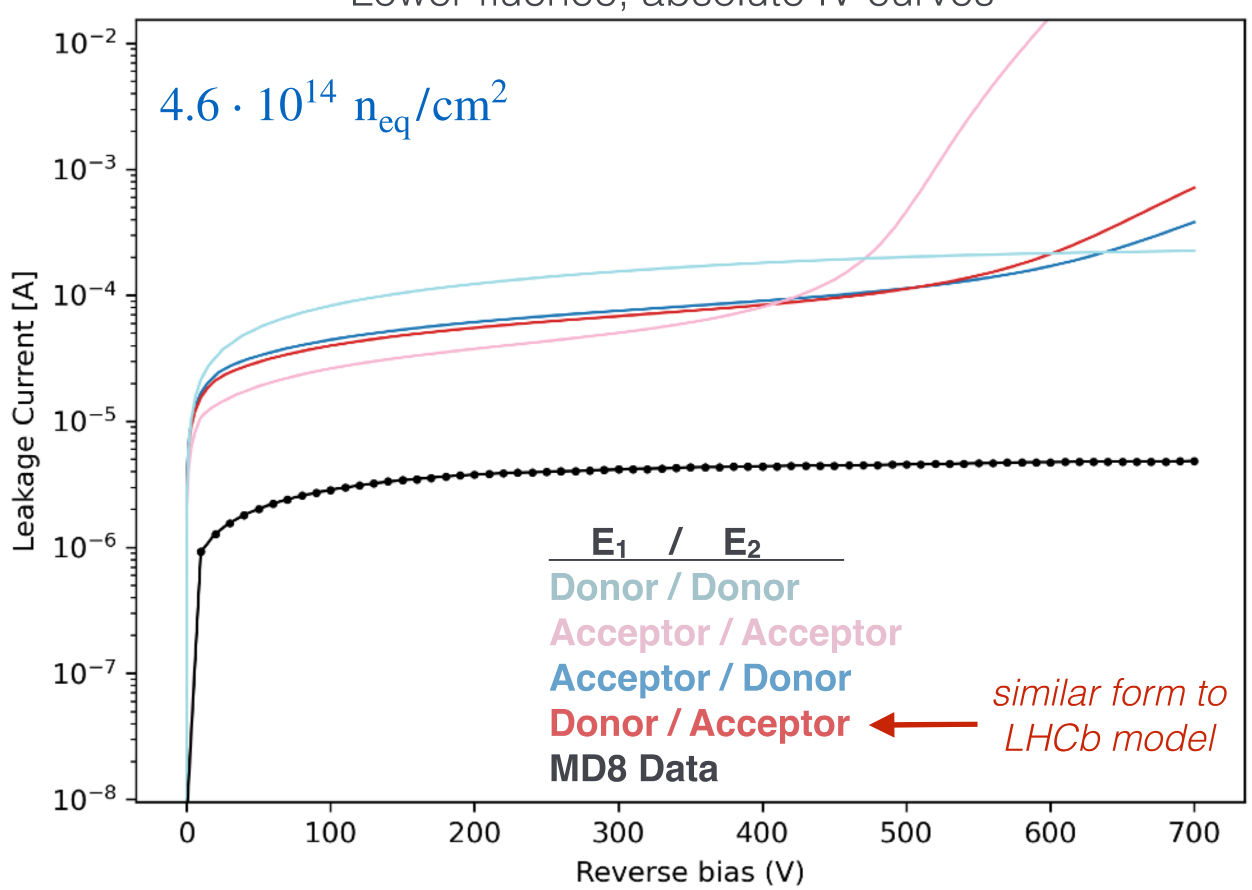


Deep-Level Transient Spectroscopy

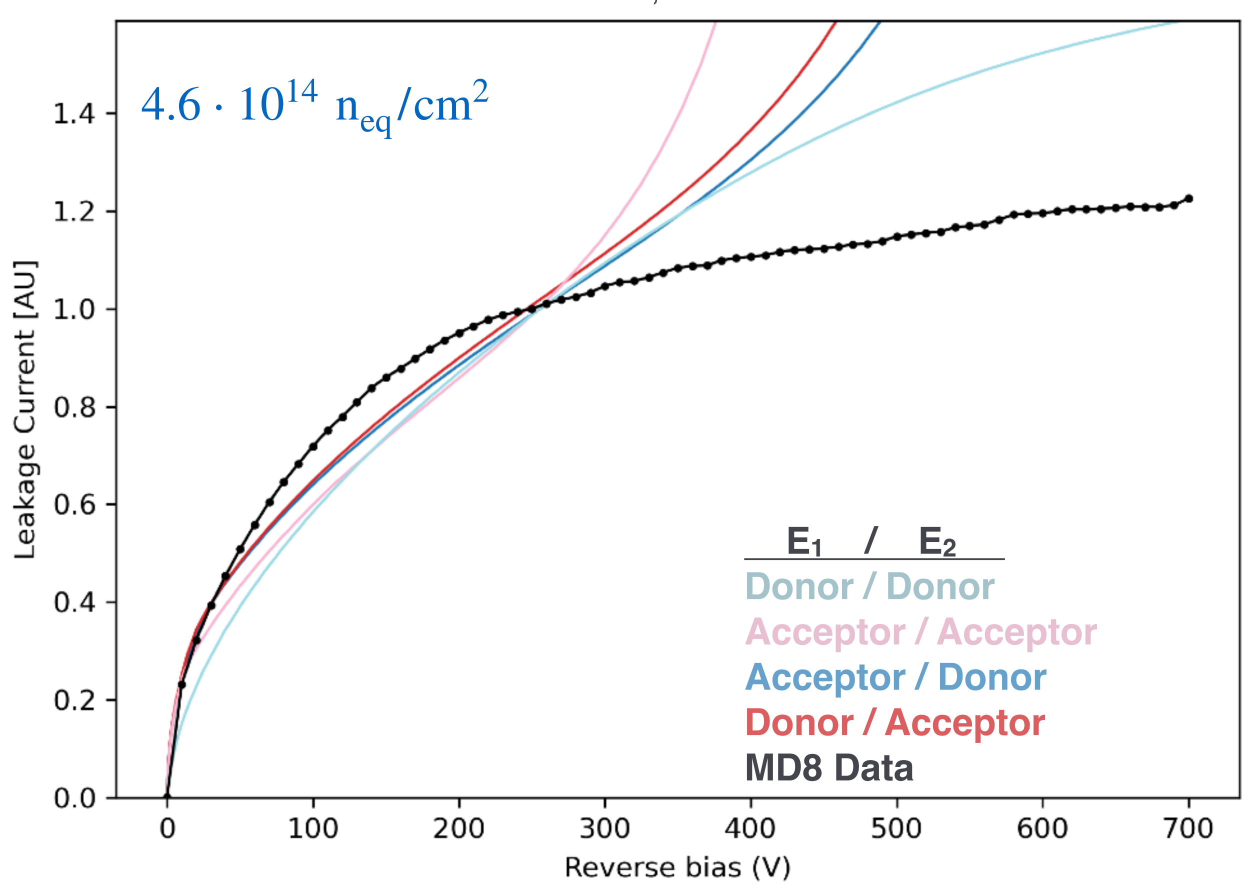
- DLTS scan fills traps to measure their energy levels & concentrations
  - See talks by Christoph Klein on method and results (earlier today & upcoming at 13th Hiroshima Symposium)
- DLTS on irradiated (+ annealed) MD8s have identified 2 hole trap candidates in the sensor bulk from proton irradiations
  - E_1 = **0.46 eV,** capture XS = 1.7e-14, prod. rate = 0.07 (per n_{eq}/cm^2)
  - E_2 = **0.53 eV**, capture XS = 7.7e-13, prod. rate = 0.08 (per n_{eq}/cm^2)
- Low-temp simulation under different Donor or Acceptor assumptions
  - Current is ~10x larger than MD8s, with soft breakdown (earlier at high fluence)
  - Larger IV slope beyond 150 V



Lower fluence, absolute IV curves



Lower fluence, relative to 250 V



Outlook

- TCAD model of unirradiated ATLAS ITk Strip sensors and test structures show ballpark agreement in IVs, tuning ongoing to match all characteristics
- Several (out-of-box) models of irradiation defects checked, with good first-pass agreement
- Future work:
  - Study alternative physics models for traps
  - Scan trap energy levels & concentrations → parameterize effect on sensors & diodes
  - Directly simulate test diodes and humidity effects (a la studies by Ilona-Stefana Ninca, see 13th Hiroshima Symposium)
  - Integrate TCAD fields into ATLAS digitization models for use in future tracking simulations at HL-LHC
- See more results by Callan Jessiman at 13th Hiroshima Symposium

Backup

Sensor details

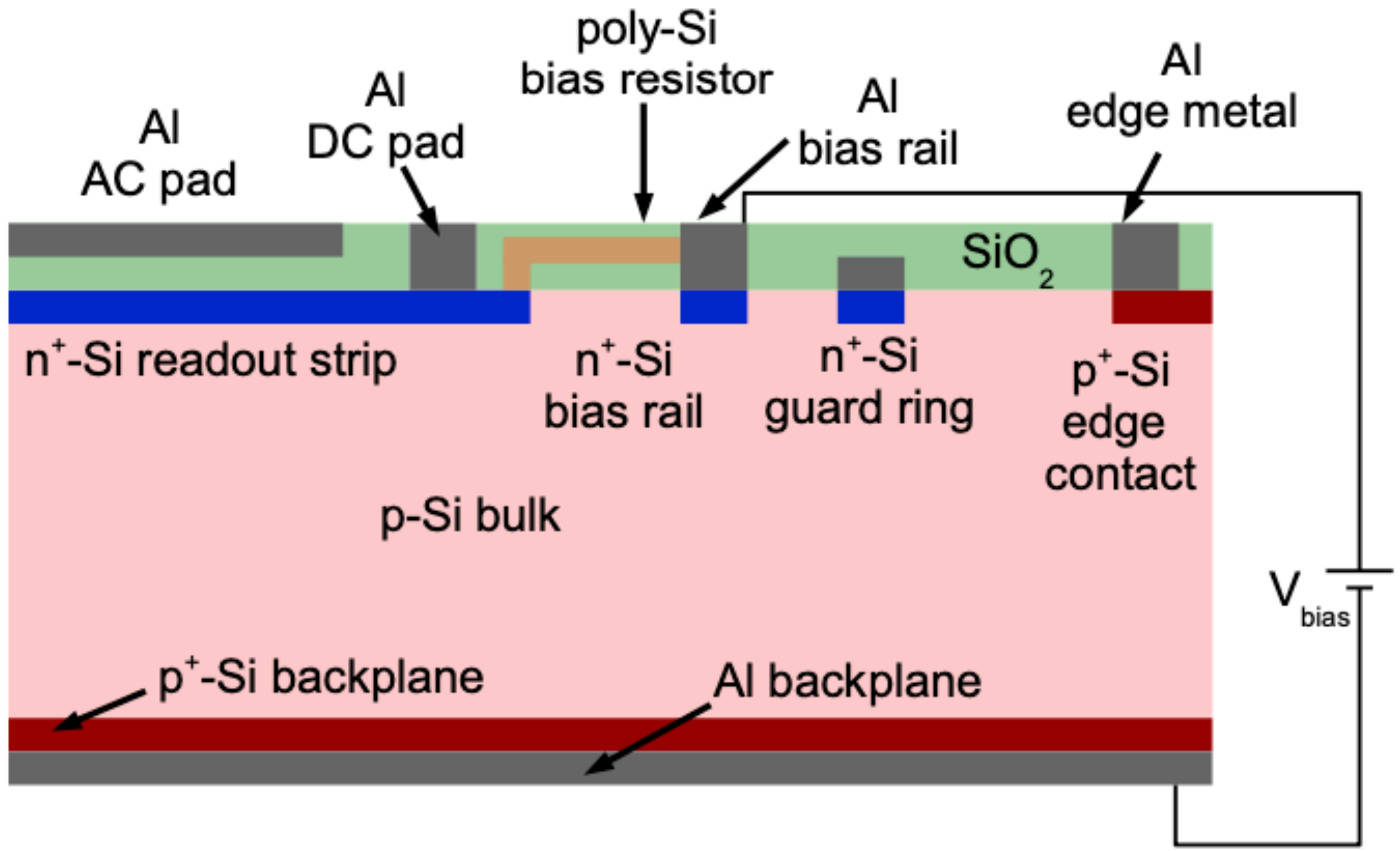
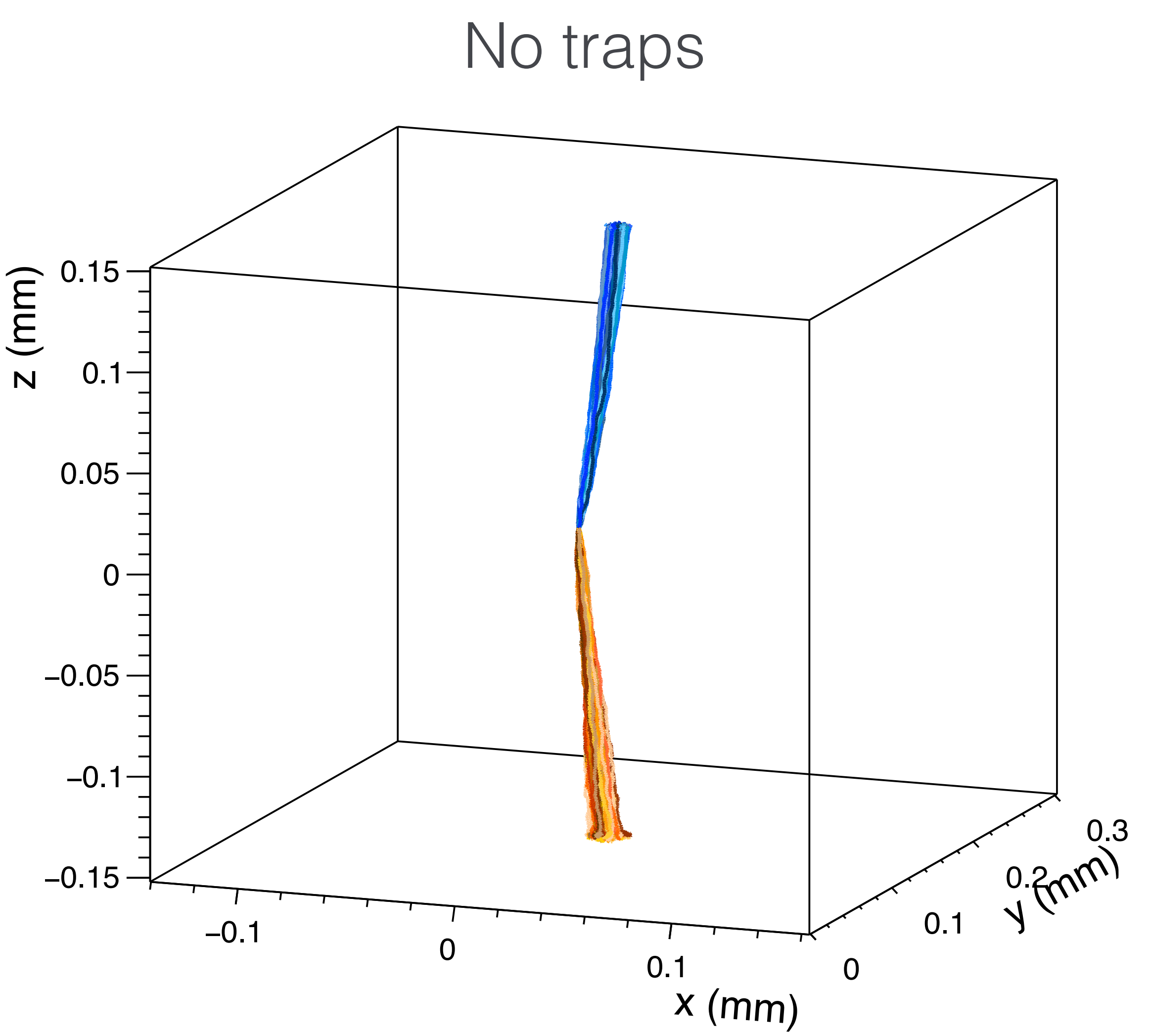
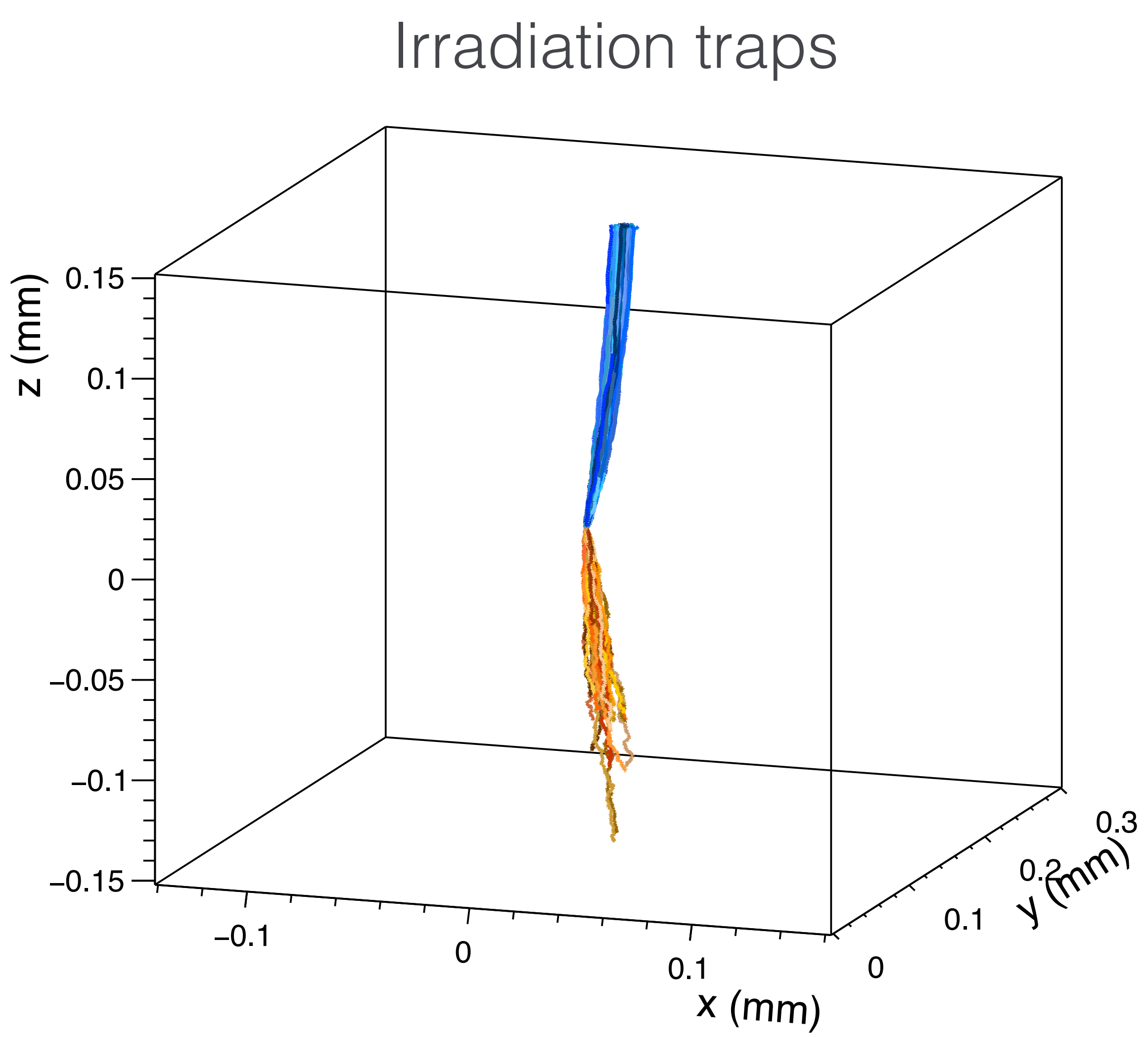


Fig. 4.1: Schematic cross-section of a sensor along the strip direction (not to scale).

Interfacing with AllPix²

- ATLAS charge propagation models for signal digitization are accurate but slow
  - Perform simulations using AllPix² to derive templates (e.g. charge collection efficiency) for quicker digitization
  - Utilize electric field and Ramo potential maps ported from TCAD simulations
- AllPix2 charge propagation shows significant disruptions to charge transport when TCAD + AllPix² traps are used





AllPix² implementation by Damir Duvnjak