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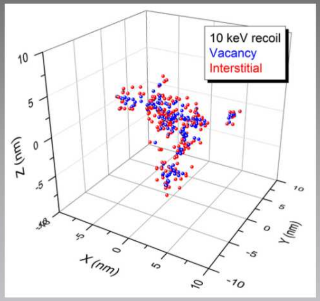

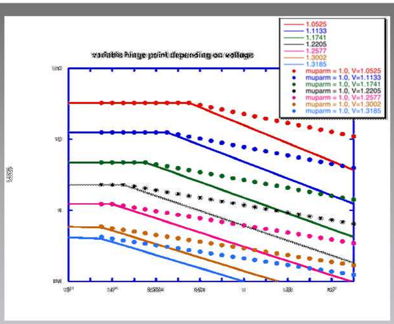

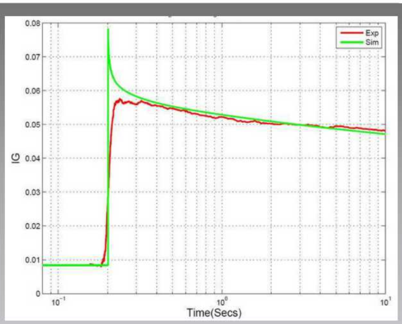

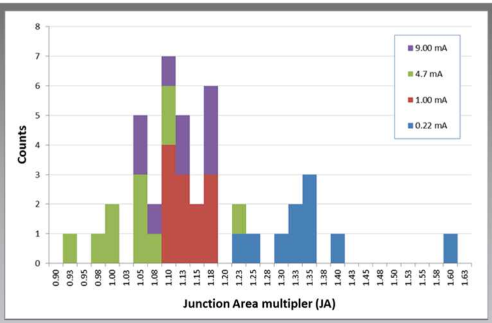

Radiation Hardened Electronics Technology

November 5 - 7, 2018 | Phoenix, AZ

Component & System Analysis in a Harsh Radiation Environment

Steven D Wix

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Sandia National Laboratories

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Sandia National Laboratories

Sandia National Laboratories
Electrical Sciences

Our primary mission is to anticipate and advance the science, engineering, and technology needed to understand the control of electrical energy in complex systems for national security applications.

- ❑ Create and steward major electromagnetic and radiation environment simulators (test capabilities)
- ❑ **Advance simulation and modeling capabilities for design and predictive performance assessments**

ASC™

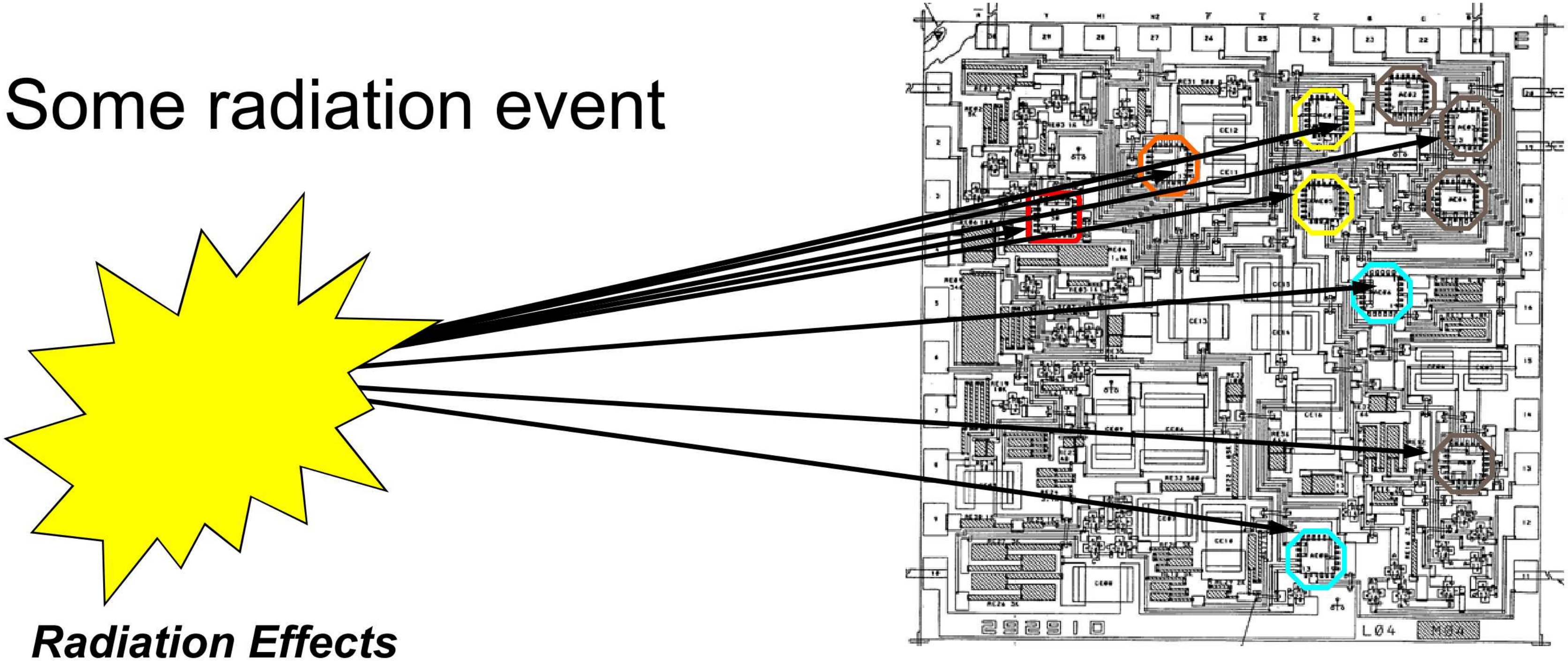
NNSA
National Nuclear Security Administration

Overview

- Radiation Effects in Electronics
- Computational Toolsets
- Analysis

Radiation Effects in Electronics

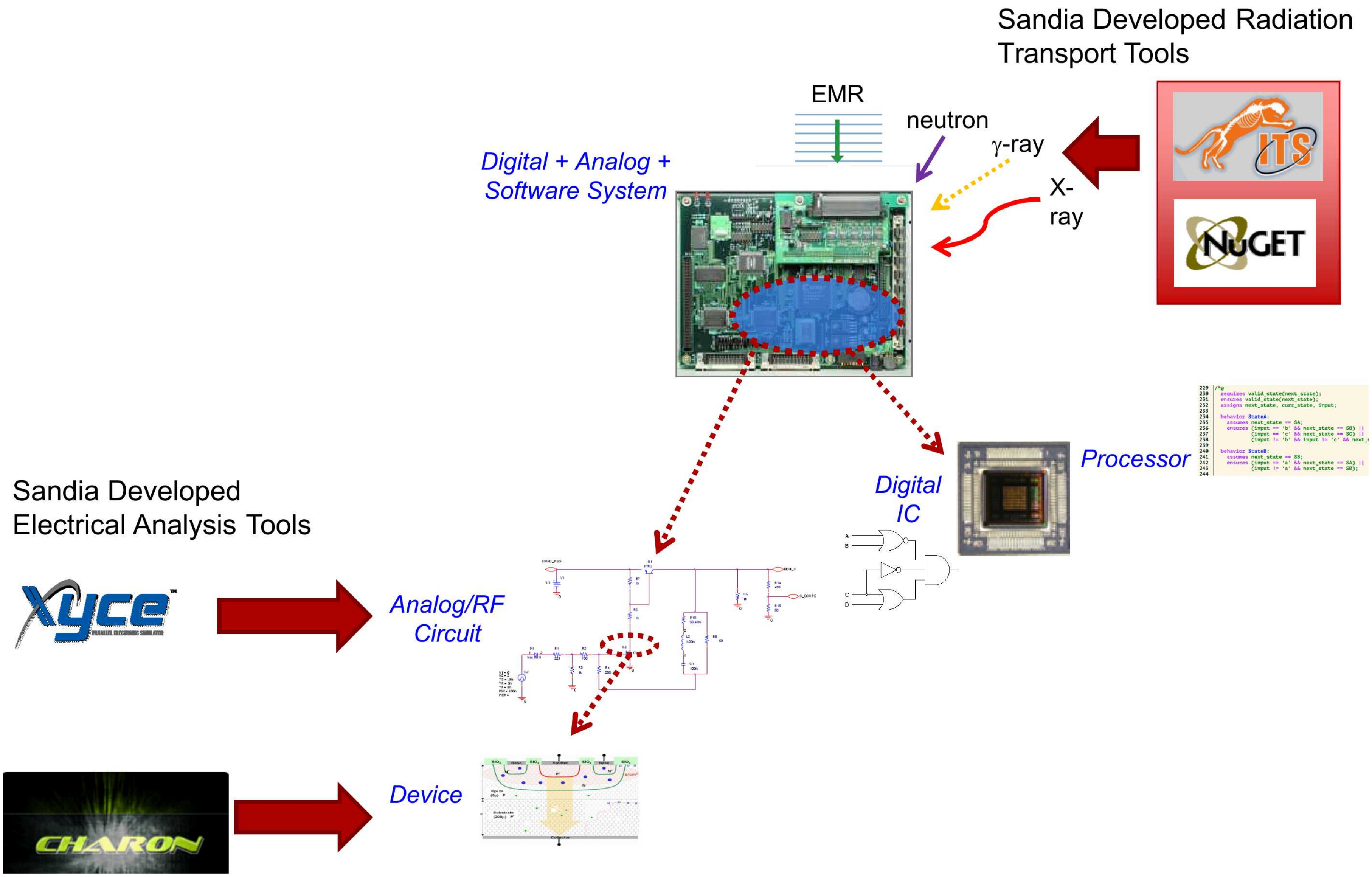
Some radiation event



Radiation Effects
- Dose Rate Transient Photocurrent
- Neutron Damage
- **Total Dose**
- **Single Event**
- Combined Environments

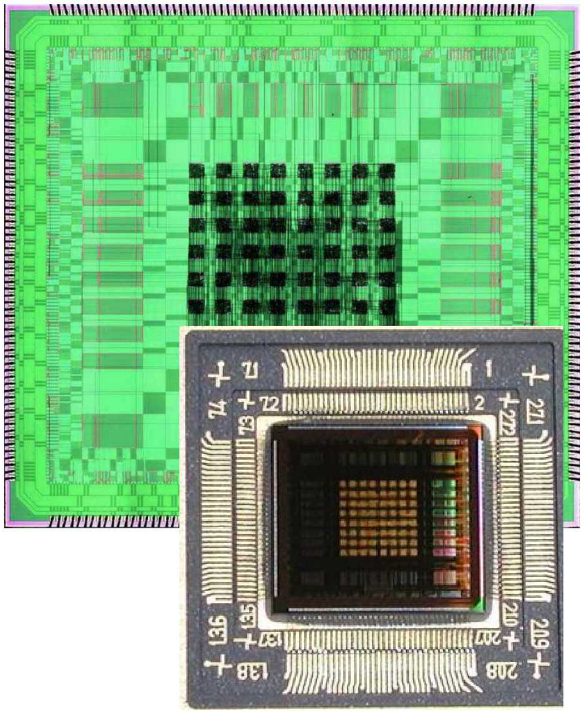
Circuit level response
- Device Response
- Circuit effects
- Signal Integrity/PCB effects

Modeling Radiation Effects in Electronics



Xyce Parallel Circuit Simulator

- Xyce: Massively Parallel circuit simulator:
  - Distributed Memory Parallel (MPI-based)
  - Unique solver algorithms
  - SPICE “Compatible”
  - Industry standard models (BSIM, PSP, EKV, VBIC, etc)
  - ADMS model compiler
- Analysis types
  - DC, TRAN, AC
  - Harmonic Balance (HB)
  - Multi-time PDE (MPDE)
  - Model order reduction (MOR)
  - Direct and Adjoint sensitivity analysis
- Sandia-specific models
  - Prompt Photocurrent
  - Prompt Neutron
  - Thermal
- Other, non-traditional models
  - Neuron/synapse
  - Reaction network
  - TCAD (PDE-based)
- Xyce Release 6.10 pending
  - Open Source!
  - GPL v3 license



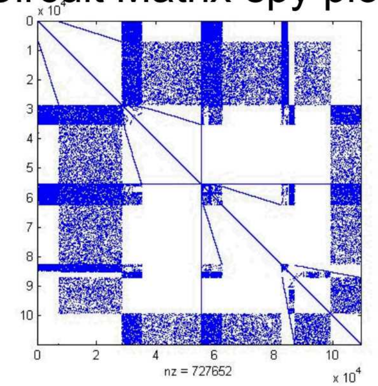
http://xyce.sandia.gov

Open Source Releases (starting in 2013):
Versions 6.0 - 6.10
>1000 unique external downloads since 6.0.
Next release (v6.10) ~November 2018

What Xyce Is, and Is Not

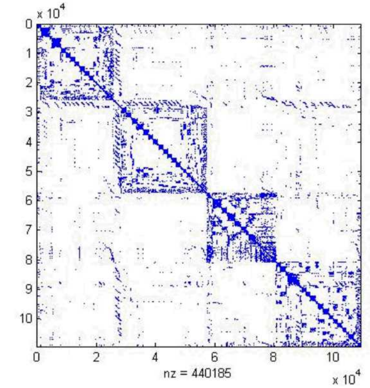
- **Xyce is: "True Spice"**
  - Large, monolithic, single Jacobian matrix.
  - Accurate.
  - Known parallel linear solvers don't scale perfectly.

Circuit Matrix spy plot



- **Xyce is not (currently): "Fast Spice"**
  - Loosely coupled separate blocks
    - Implicit solver methods within blocks
    - Explicit methods used to couple blocks
  - Table models
  - Model order reduction
  - Exploits circuit hierarchy
  - Effective primarily for digital circuits
  - less accurate than "true spice"

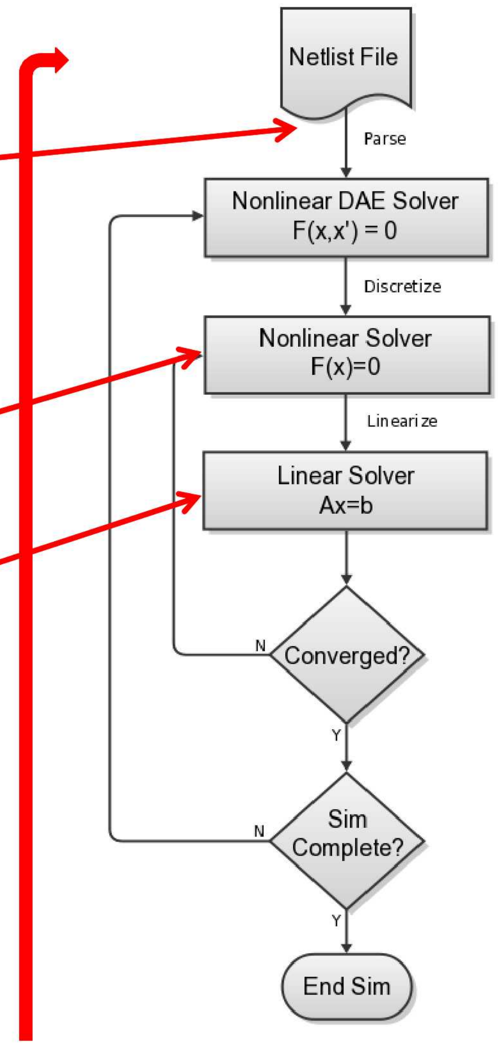
BTF+Hypergraph



4 processors

Xyce Simulation Flow

- Parsing
  - Convert netlist file syntax to equivalent devices and network/circuit connectivity
  - Distribute devices over multiple processors
  - Determine global ordering and communication
- Device Evaluation
  - Loop through all devices for state evaluation and matrix loading
- Linear Solve
  - Sparse linear algebra and solvers used to solve linearized system
- Advanced Analysis Methods
  - Sampling: Monte Carlo, LHS (DAKOTA)



What is Charon?

- Semiconductor parallel *TCAD* code with support for modeling displacement damage due to neutron radiation as well as effects from other sources of radiation (e.g. ionization)
- Finite-volume and finite-element discretizations of governing PDEs
  - Drift-Diffusion
  - Drift-Diffusion + Energy (Lattice Heating)

Electric Potential

$$\begin{cases} \nabla \cdot \left(\epsilon \vec{\mathbf{E}}\right) = q\,(p - n + C) \\ \vec{\mathbf{E}} = -\nabla V \end{cases}$$

Constitutive Relations

$$\left.\begin{aligned} \vec{\mathbf{J}}_n &= q\left(n\mu_n \vec{\mathbf{E}} + D_n \nabla n\right) \\ \vec{\mathbf{J}}_p &= q\left(p\mu_p \vec{\mathbf{E}} - D_p \nabla p\right) \end{aligned}\right\}$$

Conservation

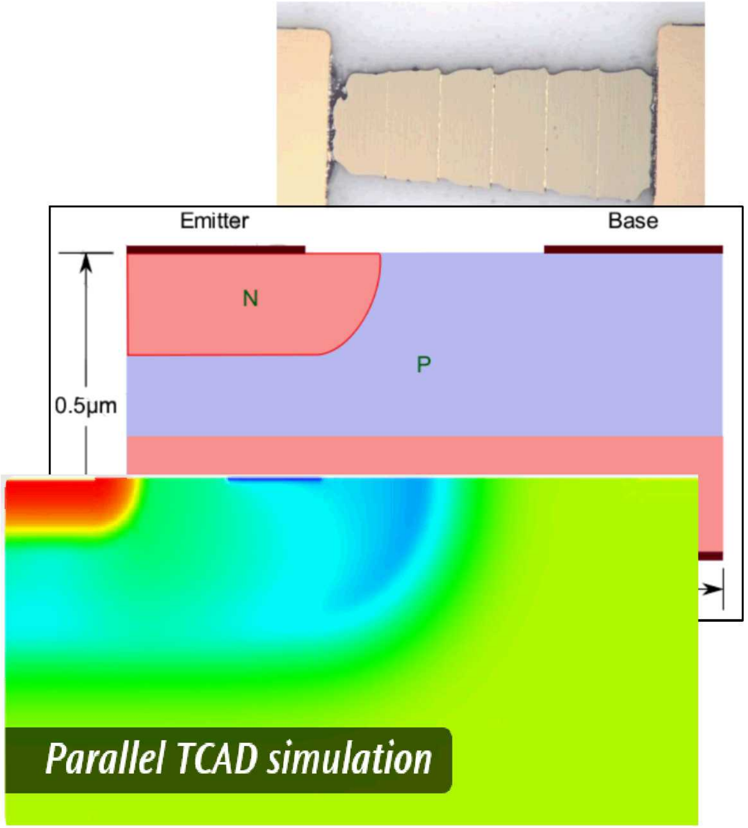
$$\left.\begin{aligned} \nabla \cdot \vec{\mathbf{J}}_n - qR &= q\frac{\partial n}{\partial t} \\ -\nabla \cdot \vec{\mathbf{J}}_p - qR &= q\frac{\partial p}{\partial t} \end{aligned}\right\}$$

Lattice Heating

$$\nabla \cdot (\kappa \nabla T_L) + H = \rho c \frac{\partial T_L}{\partial T}$$

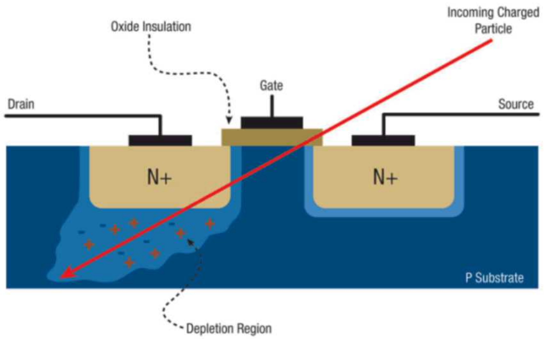
Charon Environments & Device Modeling Capability

- Environments
  - Normal
  - Dose Rate – reactor environments
  - *SEE* –Active Research Area
  - Total Dose – future
- Devices
  - Diodes
  - BJT (Si)
  - HBT (III-V)
  - FETs
  - Memristor
  - Ultra-Wide Band Gap Diodes (new models)



Ongoing/Future Charon Development

- Expanding Physics Capability
  - SEE/SEU
  - Si HVD Analysis
  - GaN development
    - High Voltage Diodes
    - HEMTs
  - Frequency Domain Modeling (HB)
  - Improved coupled electrical & thermal
  - Dose Rate/Total Dose model development
- Next Generation Development
  - In preparation of next gen computational hardware



Single-Event Effects

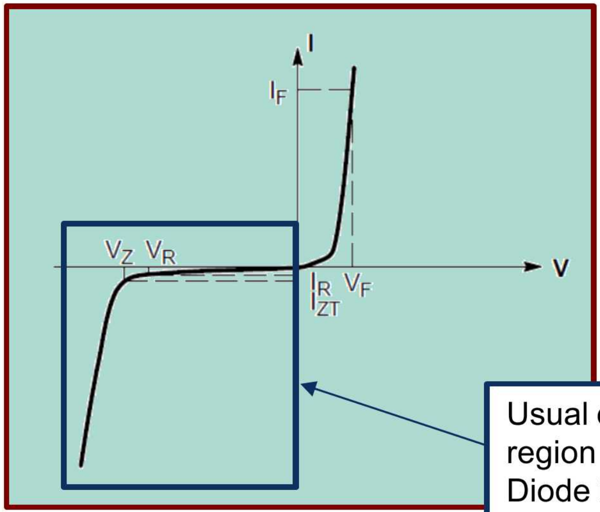
Selecting a Nominal Device: Zener Diode Example

Zener Diode

MMSZ5239BT1G
Zener Diode
9.1V 500 mW,
SOD123,
Cu wire bond

- A diode is an electronic component that only allows current to flow in one direction.
- A Zener diode is a special diode which is used to supply a constant voltage.

Current Voltage Characteristic of a Zener Diode



Usual operational region of a Zener Diode in an electrical circuit

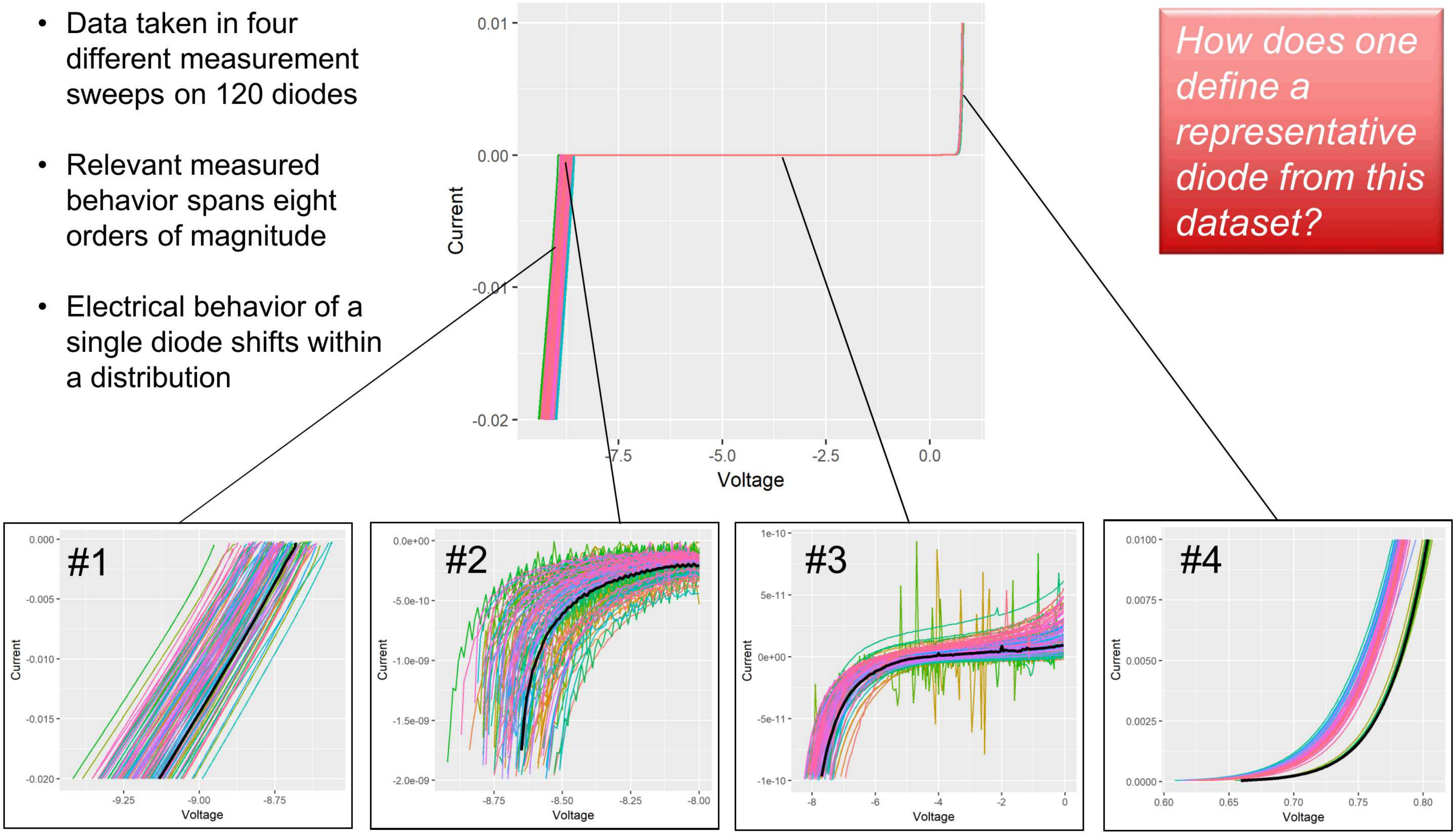
Electrical parameters defining the diode electrical behavior

Symbol	Parameter
V_Z	Reverse Zener Voltage @ I_{ZT}
I_{ZT}	Reverse Current
Z_{ZT}	Maximum Zener Impedance @ I_{ZT}
I_{ZK}	Reverse Current
Z_{ZK}	Maximum Zener Impedance @ I_{ZK}
I_R	Reverse Leakage Current @ V_R
V_R	Reverse Voltage
I_F	Forward Current
V_F	Forward Voltage @ I_F

Voltage at which diode allows current to pass

Zener Diode Characterization Data

- Data taken in four different measurement sweeps on 120 diodes
- Relevant measured behavior spans eight orders of magnitude
- Electrical behavior of a single diode shifts within a distribution

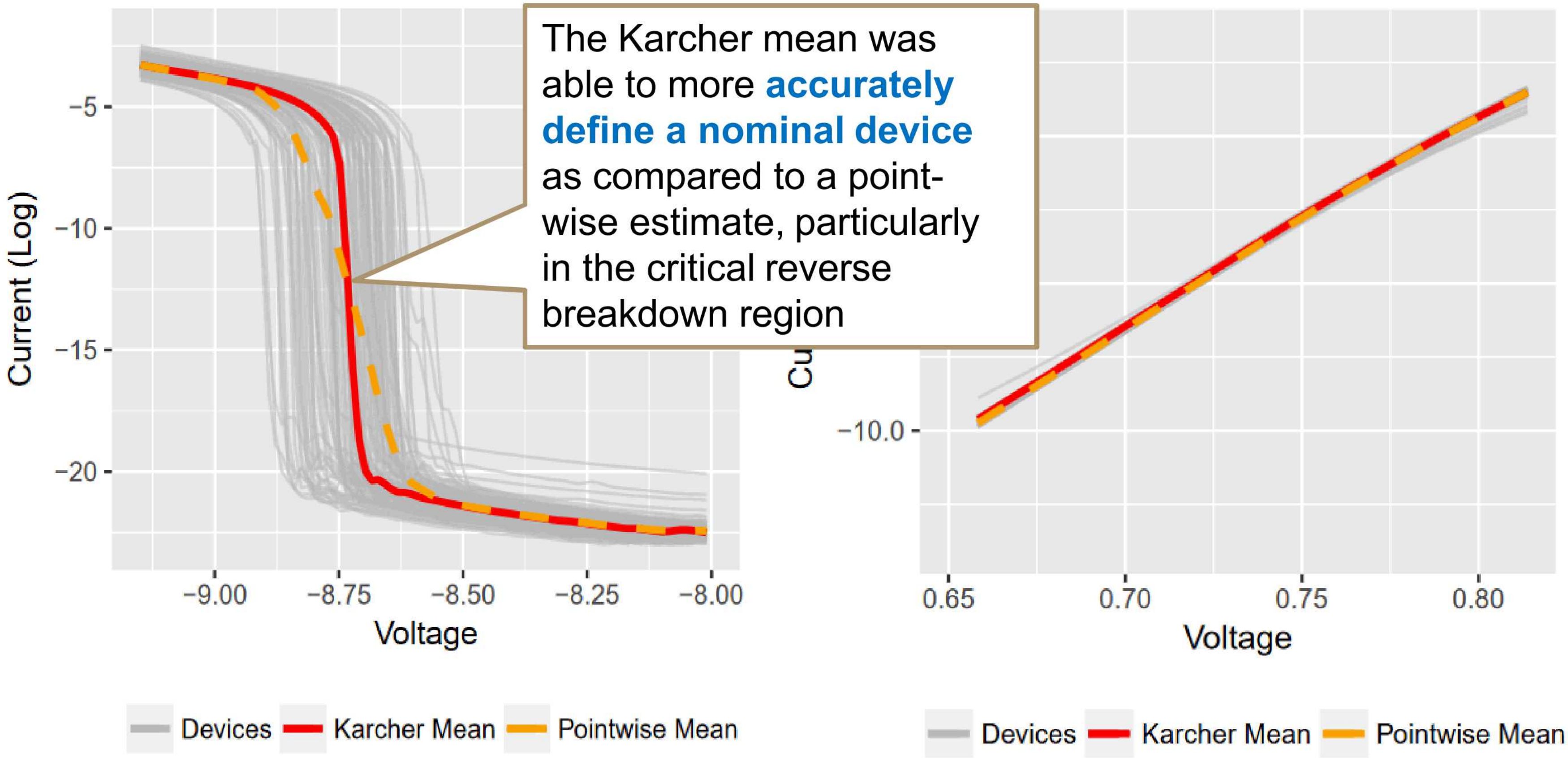


How does one define a representative diode from this dataset?

Karcher/Pointwise Mean Comparison

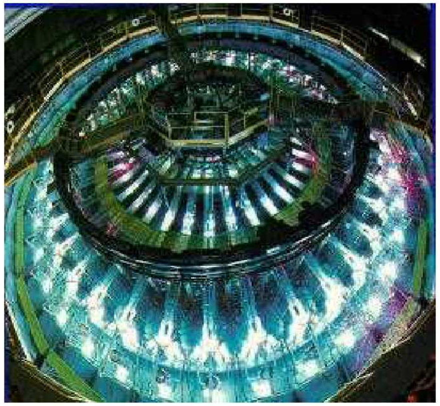
Reverse Breakdown

Forward

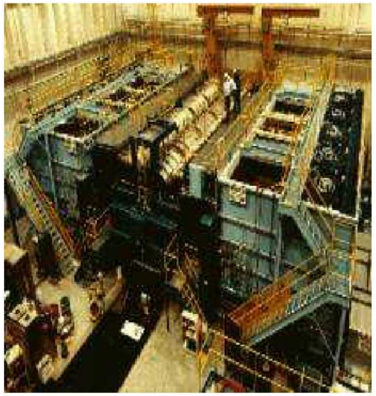


From N. Martin, T. Buchheit, S. Reza, *Selection of a Nominal Device Using Functional Data Analysis*, IEEE International Conference on Data Science and Advanced Analytics, 2018.

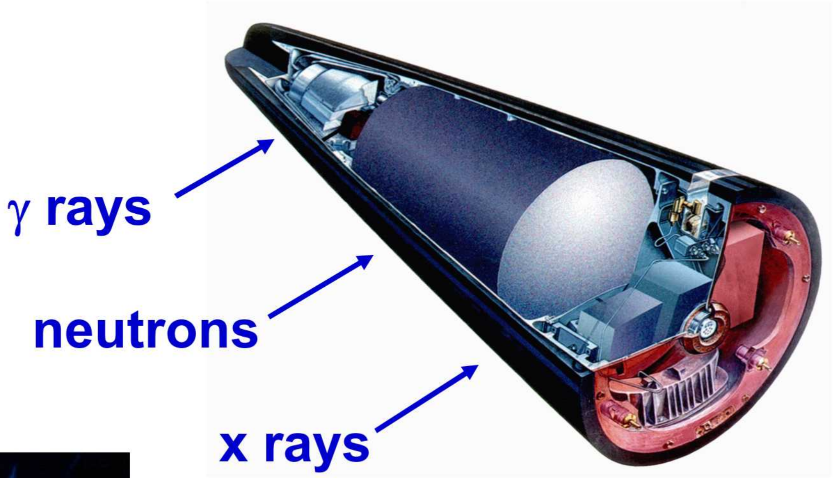
Sandia facilities provide an essential set of environments to support radiation qualification

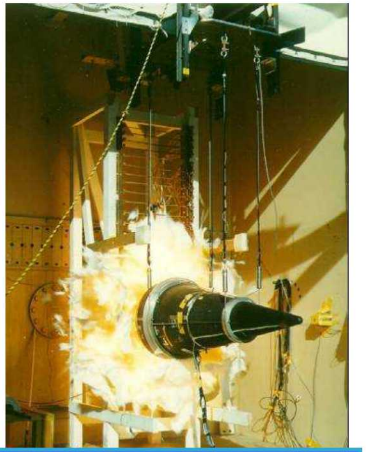


SATURN: Hot X-rays



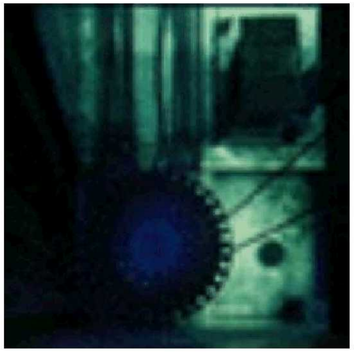
HERMES III: pulsed γ





LIHE:

Impulse Surrogate



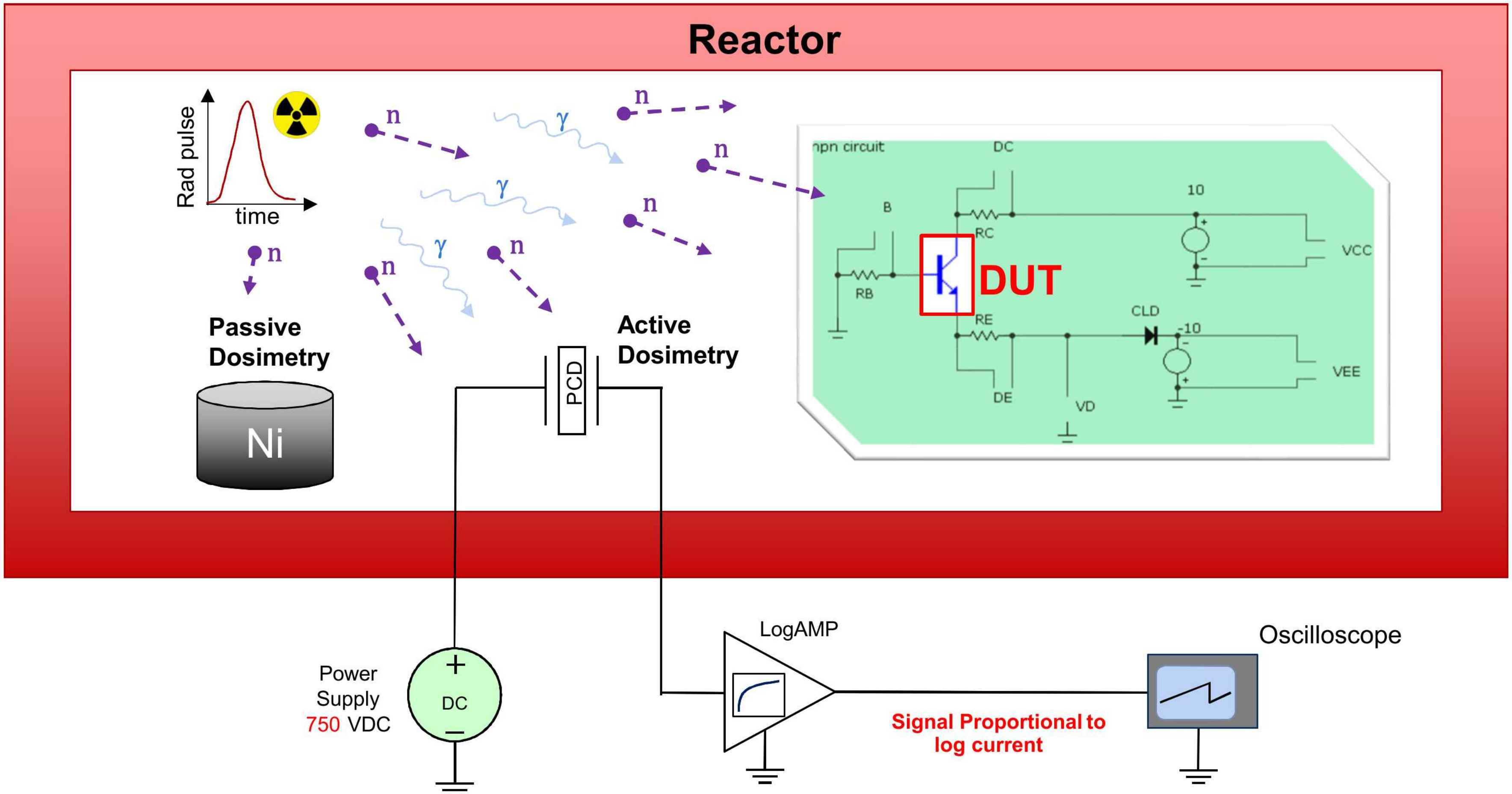
GIF: Steady-state γ

ACRR: n-γ

Z: Cold X-rays

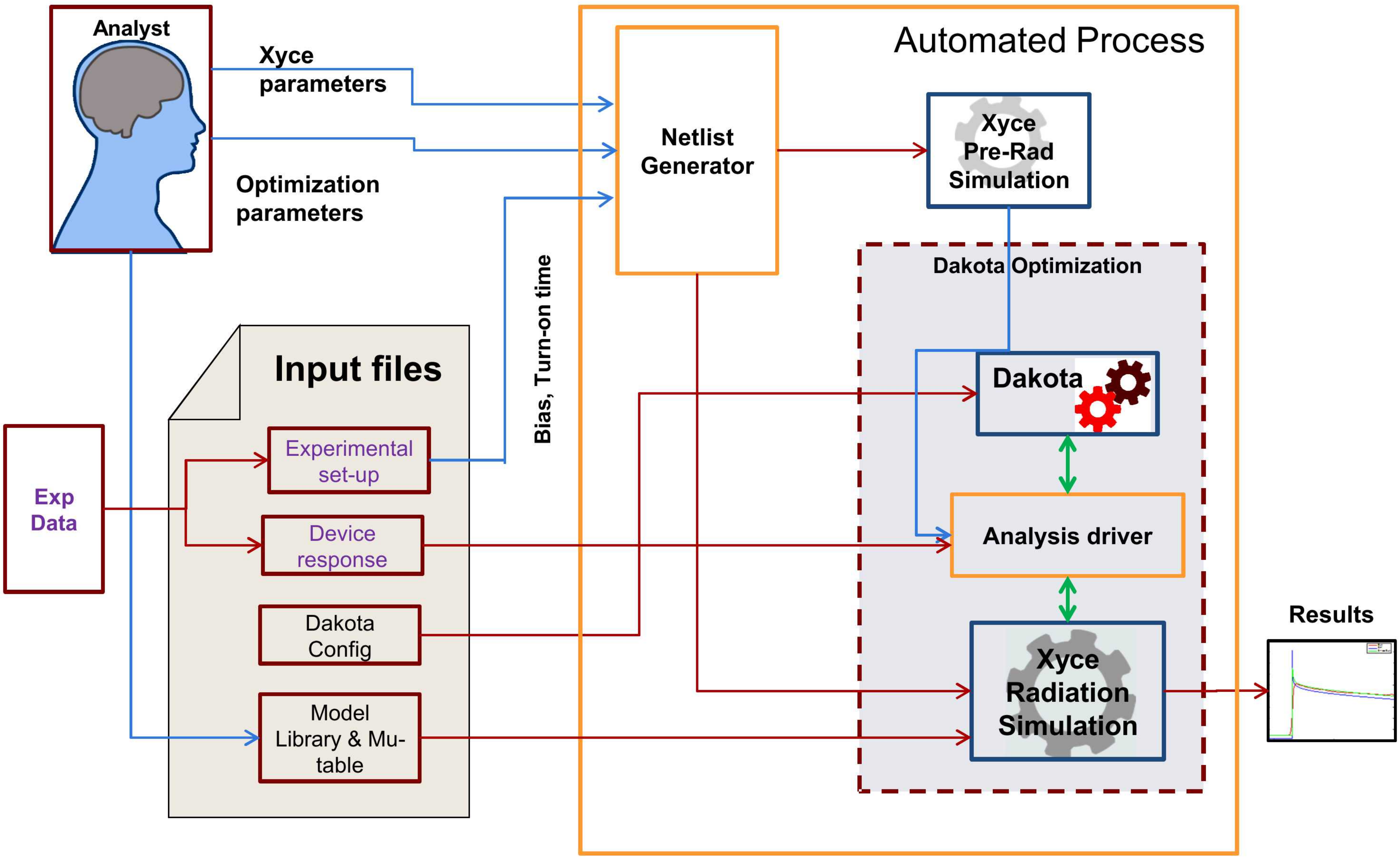
IBL: Neutron Surrogate

Radiation Testing

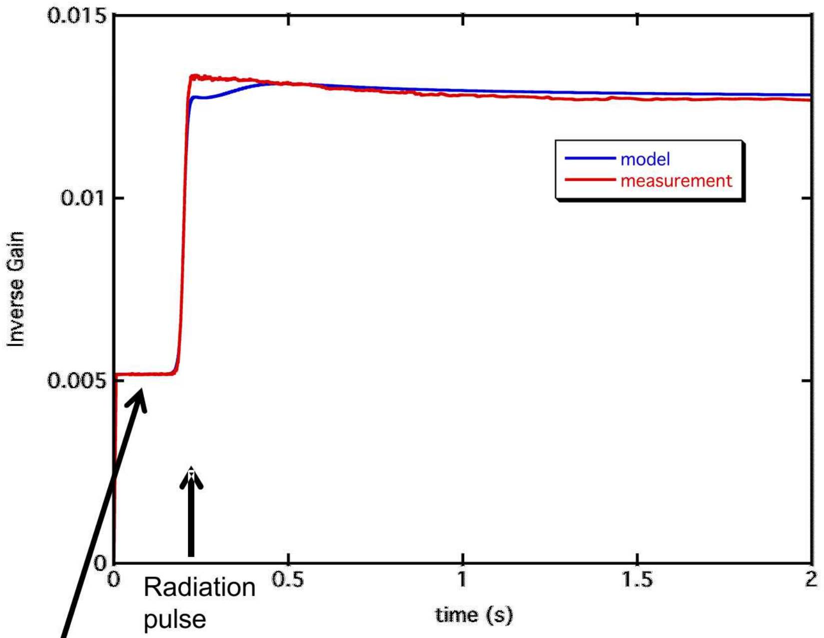


The device (DUT) can be biased (active, delayed-on) or unbiased (candy-bag)

Radiation Model Calibration Workflow



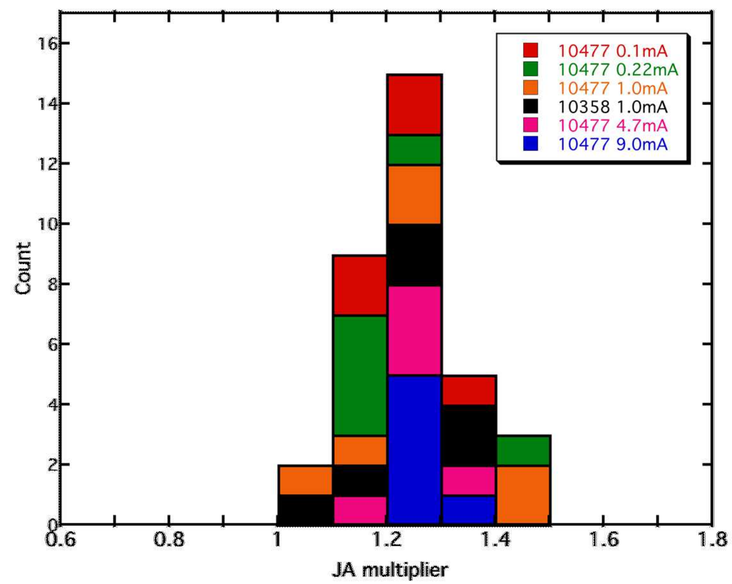
Device Responses from Calibration



JA calibration parameter optimized to calibrate InvG change

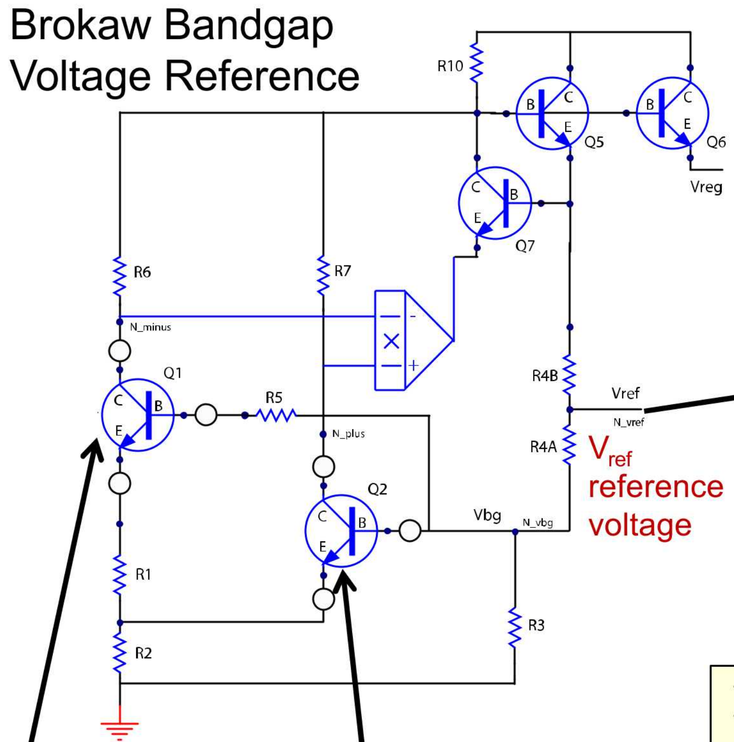
Pre-rad is matched through the VBIC model

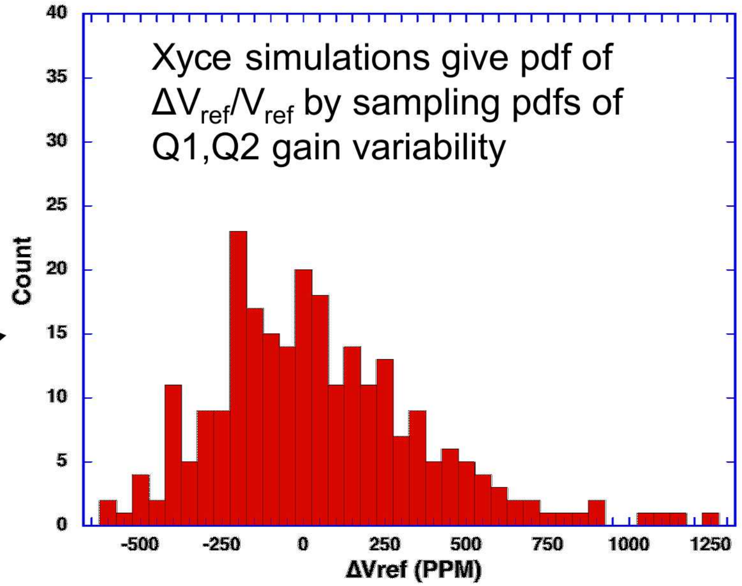
JA distribution captures device-to-device variability in the radiation response

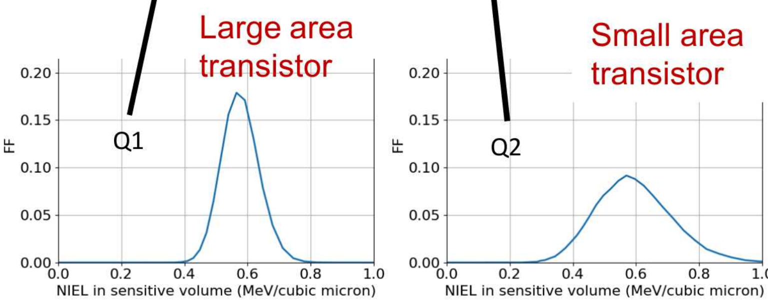


MatLAB used to plot all individual experimental vs. simulated device response waveforms (IG vs. time)

Precision Voltage Reference (PVR) Variability Analysis







Gain variability of Q1,Q2

- Gain variability in transistors (Q1,Q2) causes offsetting shifts in Voltage Regulator output V_{ref}.
- Circuit response is simulated using Xyce and DAKOTA to sample experimentally calibrated gain variabilities in Q1 and Q2.
- Resulting variability distributions in circuit response used for PVR UQ / QMU analyses

Acknowledgements

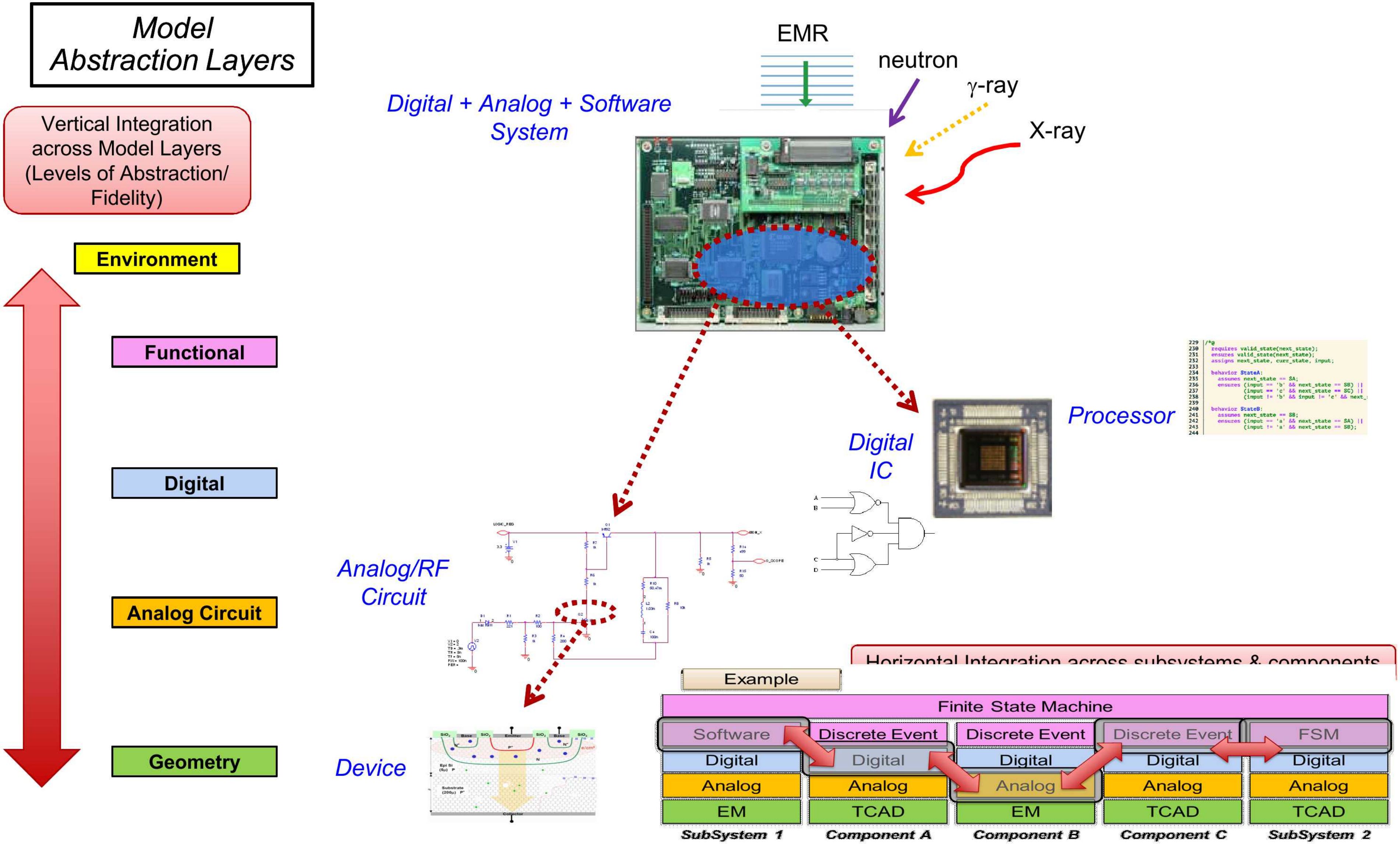
- The Simulation Tool development teams
  - Eric Keiter, Jason Verley and the rest of the Xyce Team
  - Larry Musson, Gary Hennigan and the rest of the Charon team
- The Physical Simulation team for all the dosimetry processing and radiation testing:
  - Billy Martin, Charles Morrow, Don King, and the rest of the DRT
- The analyst team for their contributions to calibration, simulation and validation :
  - Biliana Paskaleva, Alan Mar, Perry Robertson, Brian Fox, Chuck Hembree, Rachelle Thompson and Shahed Reza
- Special thanks to Cheryl Lam and Joe Castro for their contributions

Questions?

- Steven Wix
- Sandia National Laboratories
- sdwix@sandia.gov

Backup Slides

Integrated Multi-Scale Electrical Simulation



Xyce Model Support with ADMS

ADMS = *Automatic Device Model Synthesizer*

Verilog-A: industry standard format for new models:e.g. VBIC, Mextram, EKV, HiCUM, etc

ADMS translates Verilog-A to Xyce-compliant C/C++ code;

API automatically handles data structures, matrices, tedious details.

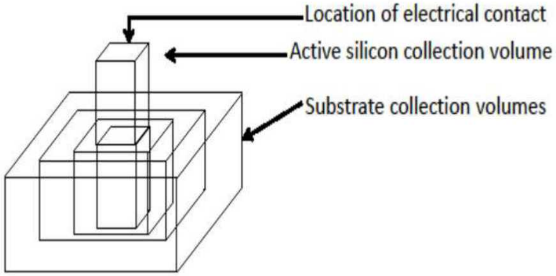
…itivities via Sacado automatic differentiation

…d to include Stocahstic Expansions via Stokhos.

C++ code snippet
(actual Xyce file is 1500 lines)

SEE High Altitude View

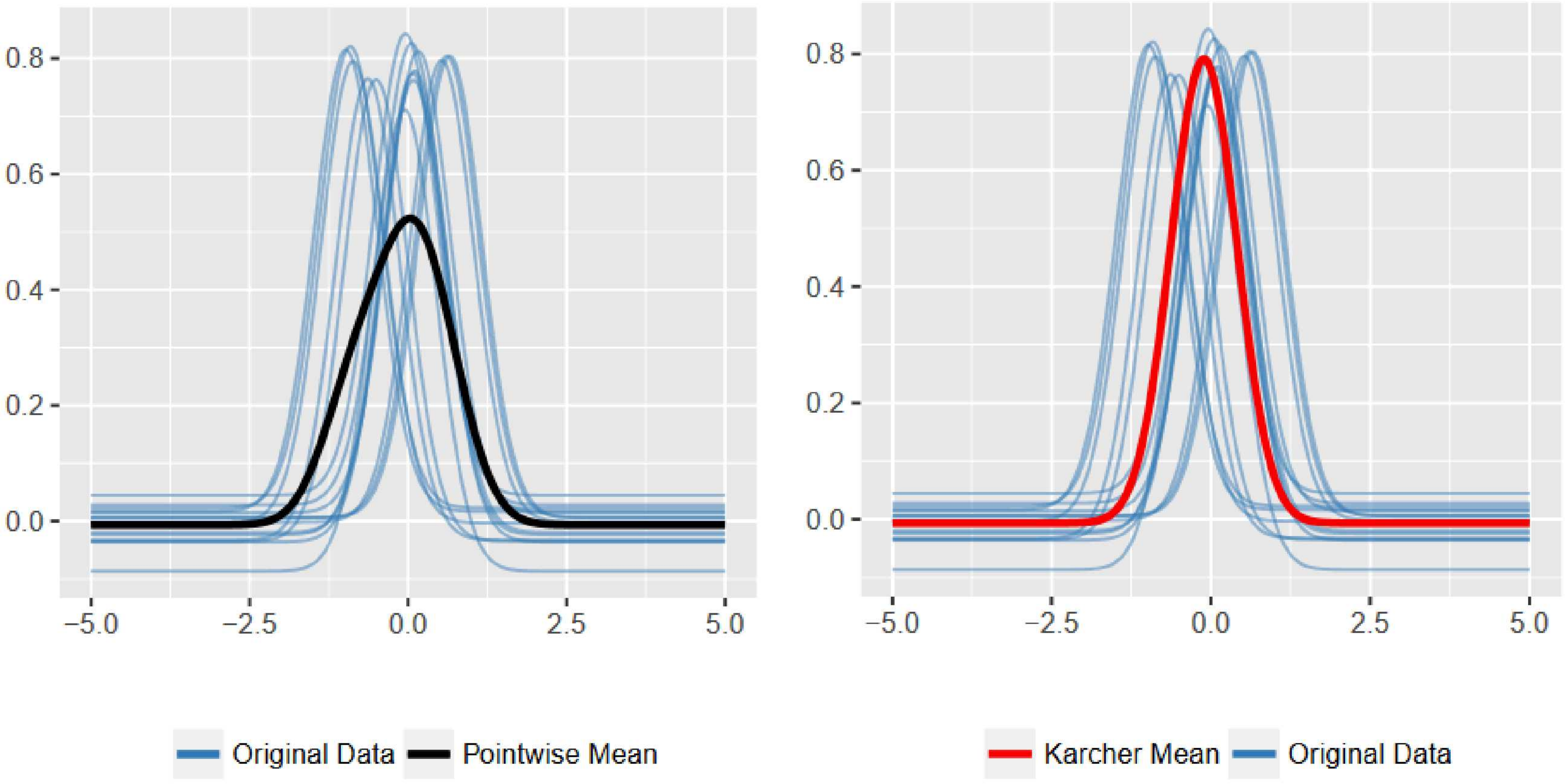
- We anticipate a union of tools & activities
- **Charon**
  - Device physics
    - Drift-Diffusion Model
    - Finite Element / Finite Volume
    - Recombination / Charge generation
  - *How to inform secondary effects due to parasitic bipolar enhancement
- **Monte-Carlo Radiative Energy Deposition (MRED)**
  - Particle physics (Geant 4)
  - Nested Sensitive Volumes
    - Provides approximation for device physics at reduced cost
  - *How are nested sensitive volumes defined for silicon-on-insulator (SOI) devices
- **Xyce**
  - Circuit simulation
    - Charon/ MRED SEE informed netlists
  - *Explain current anomalies in existing data
- **Experiments**
  - Design of experiments
  - *Validation data for research and publication



*Research Aspects

*Overall integrated, validated workflow from TCAD to IC evaluation

Mean Estimation Using Karcher Mean



$$\mu_q = argmin_{f \in F} \sum_{i=1}^{n} d_a(f, f_i)^2$$

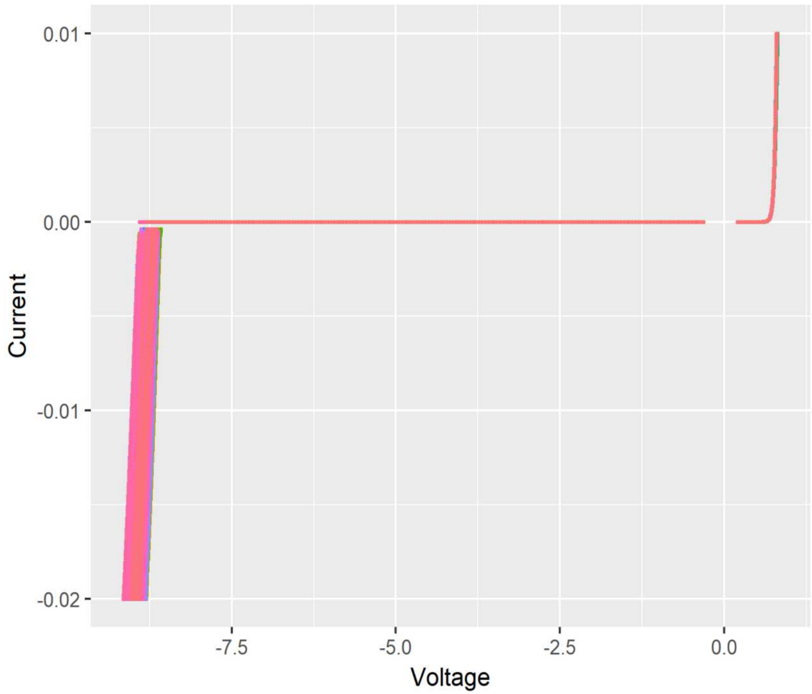
d_a is a distance metric

Applying FDA to Zener Diode Data

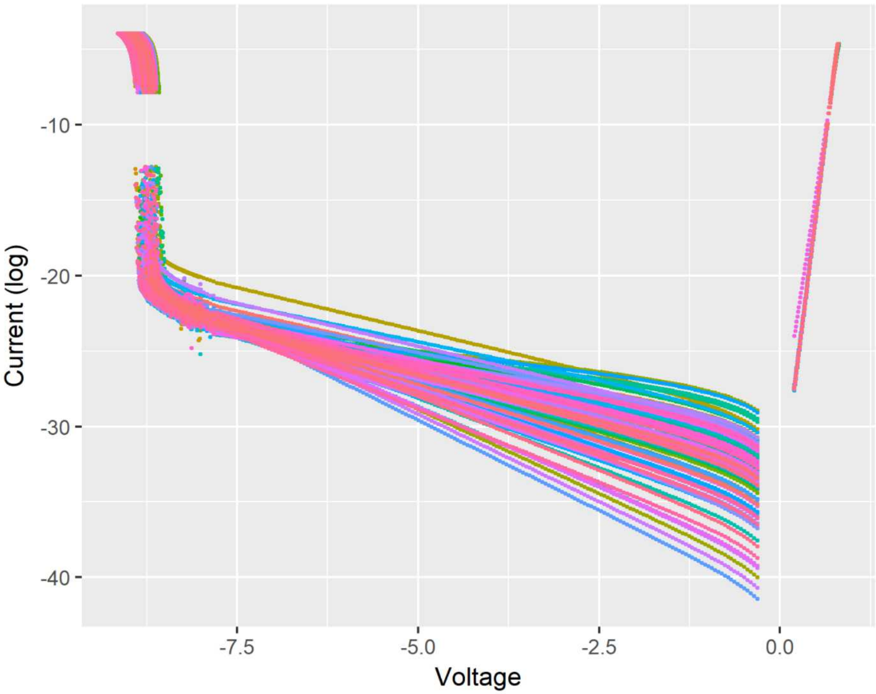
Experimental Data

120 Zener Diodes

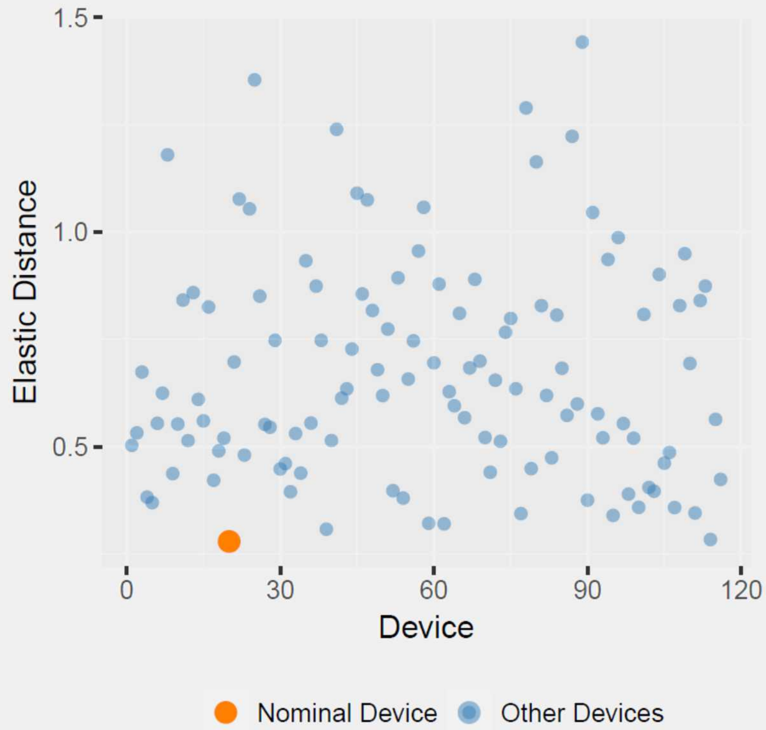
Original Scale

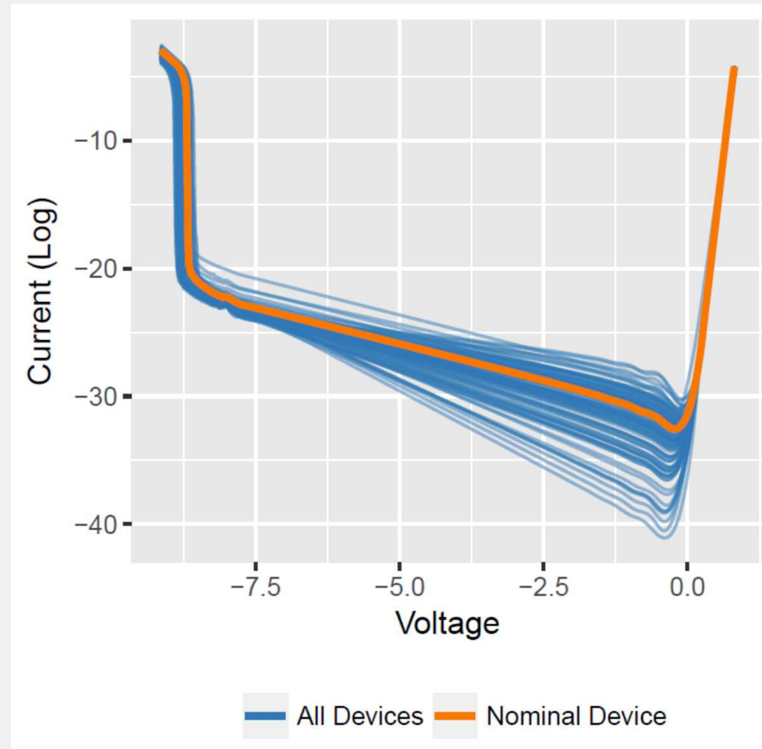


Log Scale



Characterization of Variability & Selection of Nominal Device





Summary & Future Work

- **FDA approach** was used to warp data, calculate a Karcher mean, and assess elastic distances to identify a nominal device.

- This approach was able to more **accurately define a mean function** compared to a point-wise estimate, particularly in the critical reverse breakdown region.

- This provides an **objective method** to chose a representative device from a sample of devices, which is extremely useful in the first phase of parameter calibration for compact models in electronic circuit design.

Next steps include:

- Incorporating tolerance bounds for functional data.
- Propagating uncertainty in the devices to the calibration parameters.