SAND2021-14282PE

Semiconductor Particle Detector based on Work Function Modulation

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November 11, 2021

PhD Dissertation Defense

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Funding Statements

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists, Office of Science Graduate Student Research (SCGSR) program. The SCGSR program is administered by the Oak Ridge Institute for Science and Education for the DOE under contract number DE-SC0014664.

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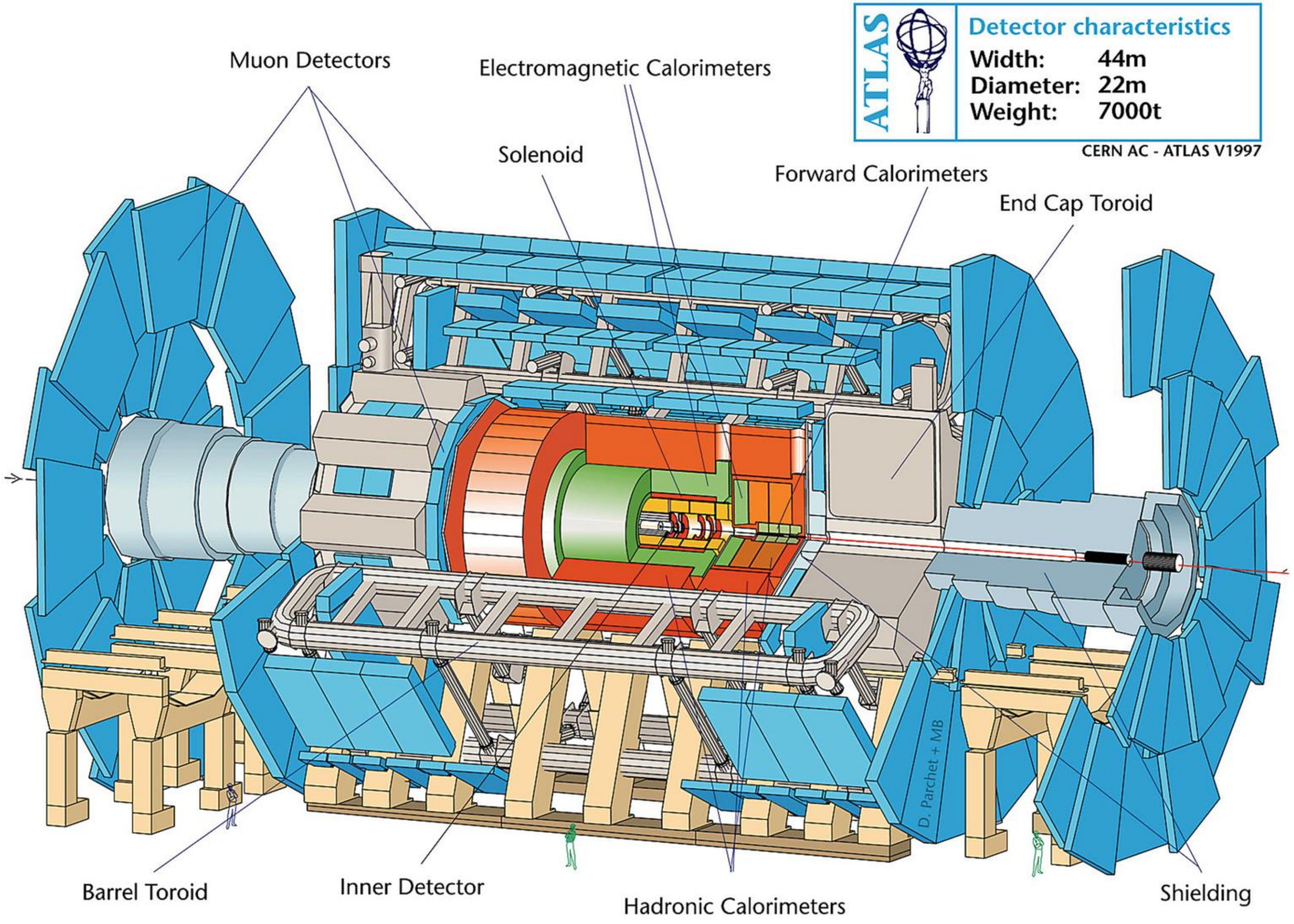
Outline

- Project Background
- Circuit Development
- Work Function Reference Circuit – First Prototype Irradiation at Sandia
- Work Function Reference Circuit – Second Prototype Irradiation at Georgia Tech
- Geant4 Modeling
- Conclusion

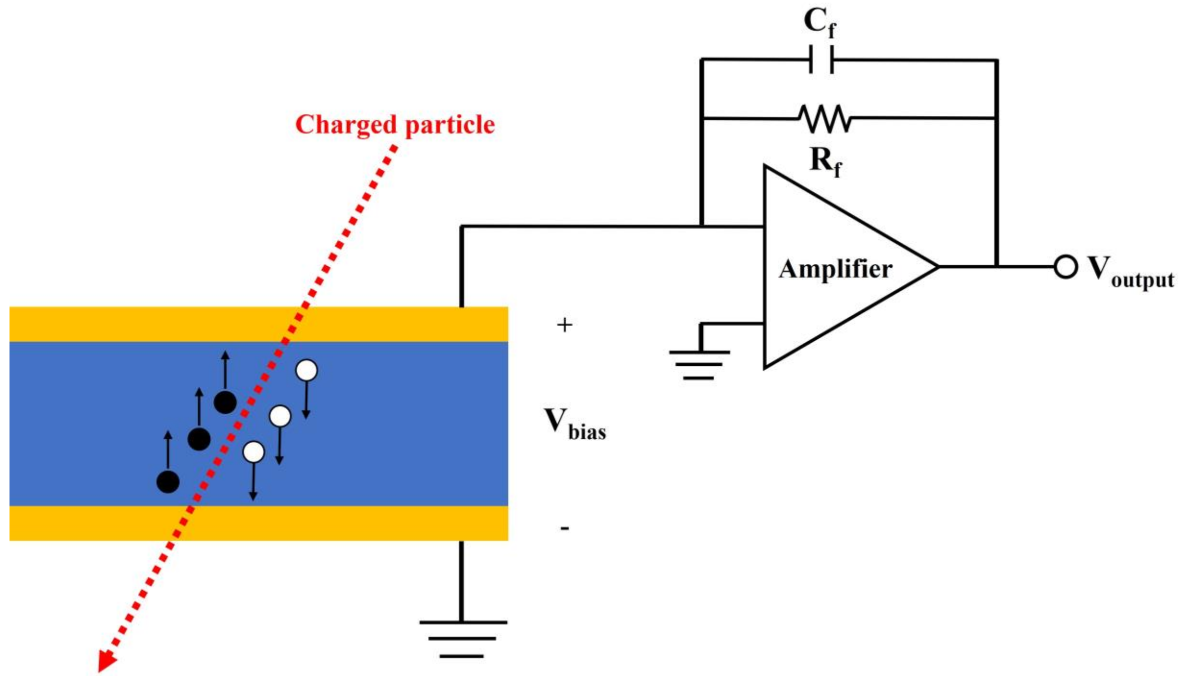
ATLAS at CERN LHC



H.H.J. ten Kate. IEEE Trans. Appl. Supercond. **10** (1), 347 -352. 2000. https://doi.org/10.1109/77.828245
CERN Atlas Collaboration. https://cds.cern.ch/record/39038

Solid-State (Semiconductor) Detectors

- Charged particle passes through detector, creating electron-hole pairs; record current to determine particle energy
- For neutrons
  - Energy transfer to crystal lattice can generate primary knock-on atoms which create electron-hole pairs
  - Detecting reaction products after incident neutrons interact with a neutron reactive material like ^{10}B or LiF



G.L. Miller et al., Annu. Rev. Nucl. Sci. **12** (1), 189-220. 1962. https://doi.org/10.1146/annurev.ns.12.120162.001201.
A.N. Caruso. J. Phys.: Condens. Matter. **22** (44), 443201. 2010. http://dx.doi.org/10.1088/0953-8984/22/44/443201.

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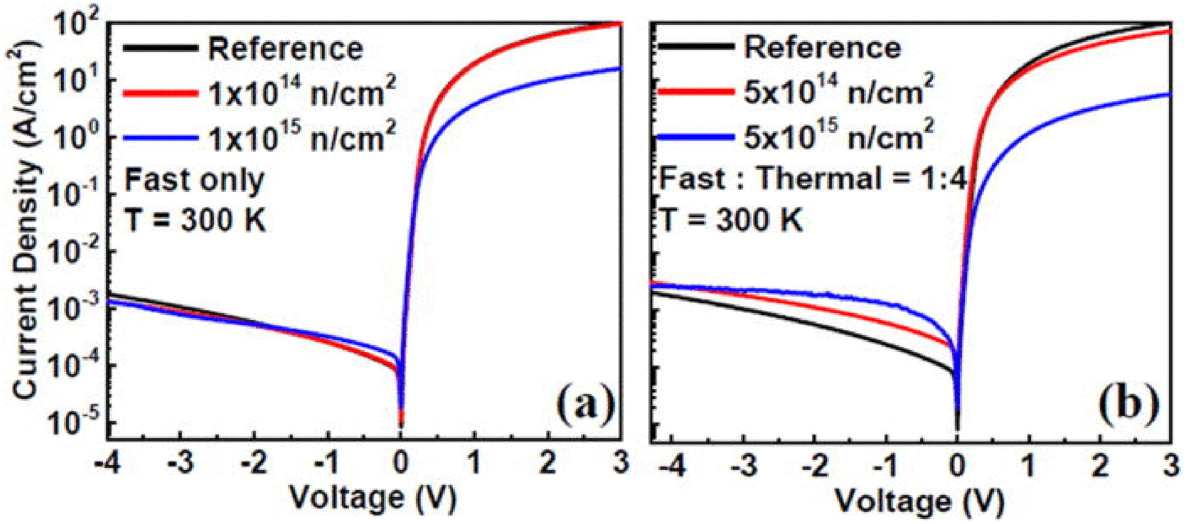
Gallium Nitride and Radiation Hardness

- Some studies looking at GaN devices under neutron exposure
- Typically, the goal is to study radiation hardness
    - Pre- and post-irradiation I/V characteristics
    - Estimations of carrier lifetimes
    - Investigating defects and effects on material properties



C. Lin et al. Appl. Phys. Lett. **103** (16), 162106. 2013. https://doi.org/10.1063/1.4826091
R.X. Wang et al. Appl. Phys. Lett. **87**, 031906. 2005. https://doi.org/10.1063/1.1999011

Project Overview

- Utilize transient signatures in a solid-state detector as a new mechanism of particle detection
- Novel approach: record fluctuations in Schottky barrier height of a gallium nitride (GaN) Schottky diode to identify particle events
  - Circuit design: modified bandgap reference circuit that outputs voltage proportional to work function of GaN
- Hypothesize that the signature of the fluctuations will be different for different types of particles
  - Focus on neutron detection, with comparison to alpha particles

Physical Mechanism Hypothesis

- Neutron enters the detector and transfers momentum to a lattice atom
- As the lattice atom oscillates to its neutral position, internal phonon waves are generated
- These phonon waves induce an in-phase, internal electric field via the piezoelectric effect
- At the metal-semiconductor interface of a Schottky diode, these local changes in the electric field induce fluctuations in the Schottky barrier height
- We hypothesize that the Schottky barrier height fluctuations are the source of the transient signals observed in the circuit output:

$$\Phi_B(t) = \phi_m(t) - \chi_e(t)$$

where ϕ_m is the metal work function and χ_e is the electron affinity

R. Tung. Appl. Phys. Rev. **1**, 011304. 2014. https://doi.org/10.1063/1.4858400.

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Significance and Applications

- New mechanism seeking transient signatures as a method for particle detection
- Combines analog circuit design with piezoelectric/ultra-wide bandgap semiconductor materials
- Small footprint
- Potential applications include
  - More accurate dosimeter for protection of radiation workers
  - Utilization in an urban radiation detection network
  - In parallel with other detection techniques like optical radiation detection
  - In conjunction with other detectors for nuclear nonproliferation treaty verification

A.N. Hollis et al. Int. J. Uncertainty Quantif. **11** (5). 2021. https://doi.org/10.1615/Int.J.UncertaintyQuantification.2021034400
R.C. Runkle et al. J. Appl. Phys. **108** (11), 13. 2010. https://doi.org/10.1063/1.3503495

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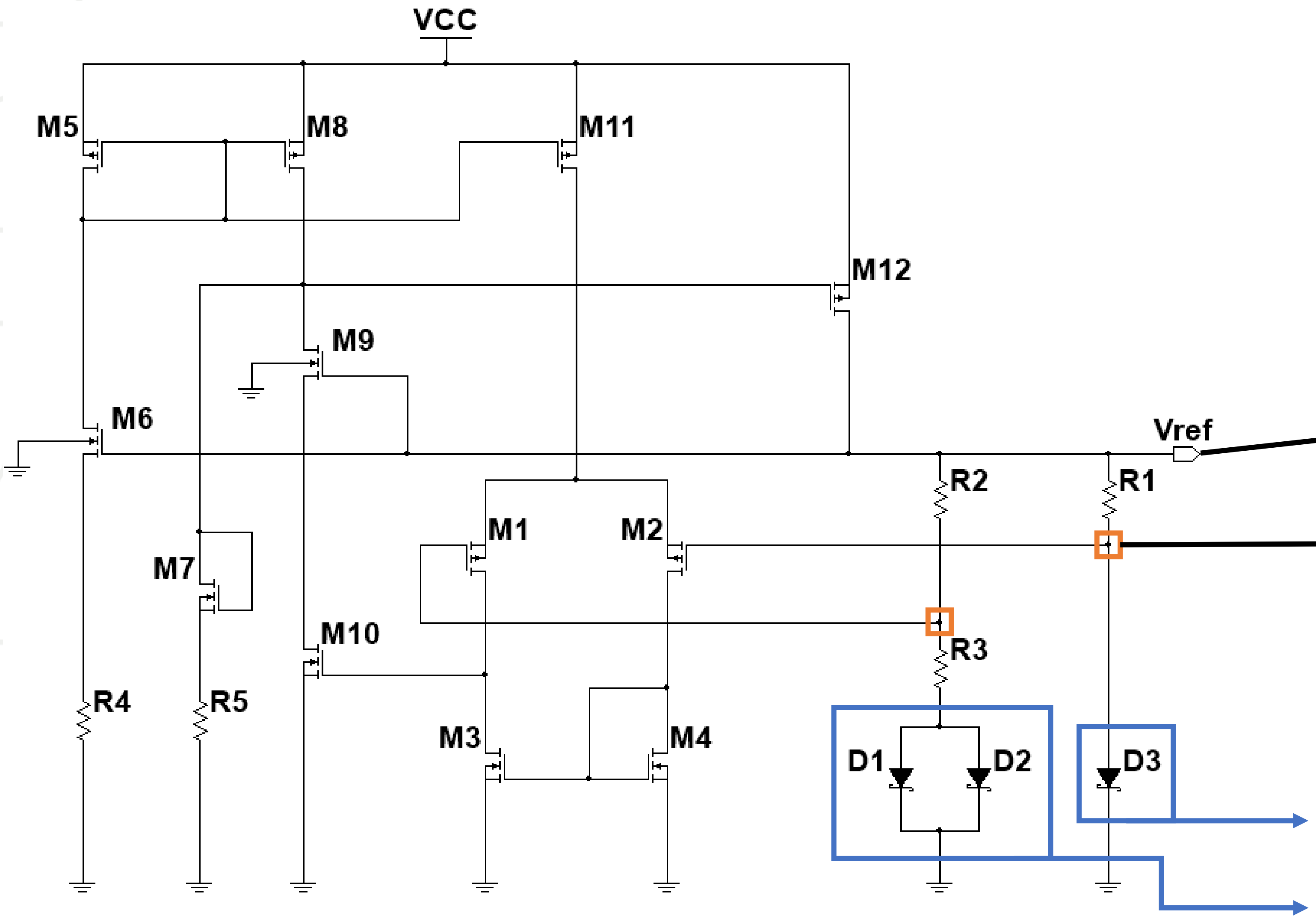
Bandgap Reference (BGR) Circuit

- Goal of bandgap reference circuit: analog circuit whose voltage output equals that of the bandgap energy of the semiconductor being used
- Output of typical semiconductor devices is heavily temperature-dependent
- BGR circuit produces a fixed output voltage independent of temperature variations, supply variations, and loading
- Bandgap reference adds components with equal but opposite temperature coefficients
- Our bandgap reference circuit design provides an output voltage proportional to the work function of GaN, which serves as a fixed baseline for observing output fluctuations due to particle events
    - Temperature independence important to lend confidence that fluctuations observed are *not* due to temperature variations and ensures functionality in different environments

R.J. Widlar. IEEE J. Solid-State Circuits. **6** (1), 2-7. 1971. https://doi.org/10.1109/JSSC.1971.1050151.

Work Function Reference Circuit



Node to measure reference voltage

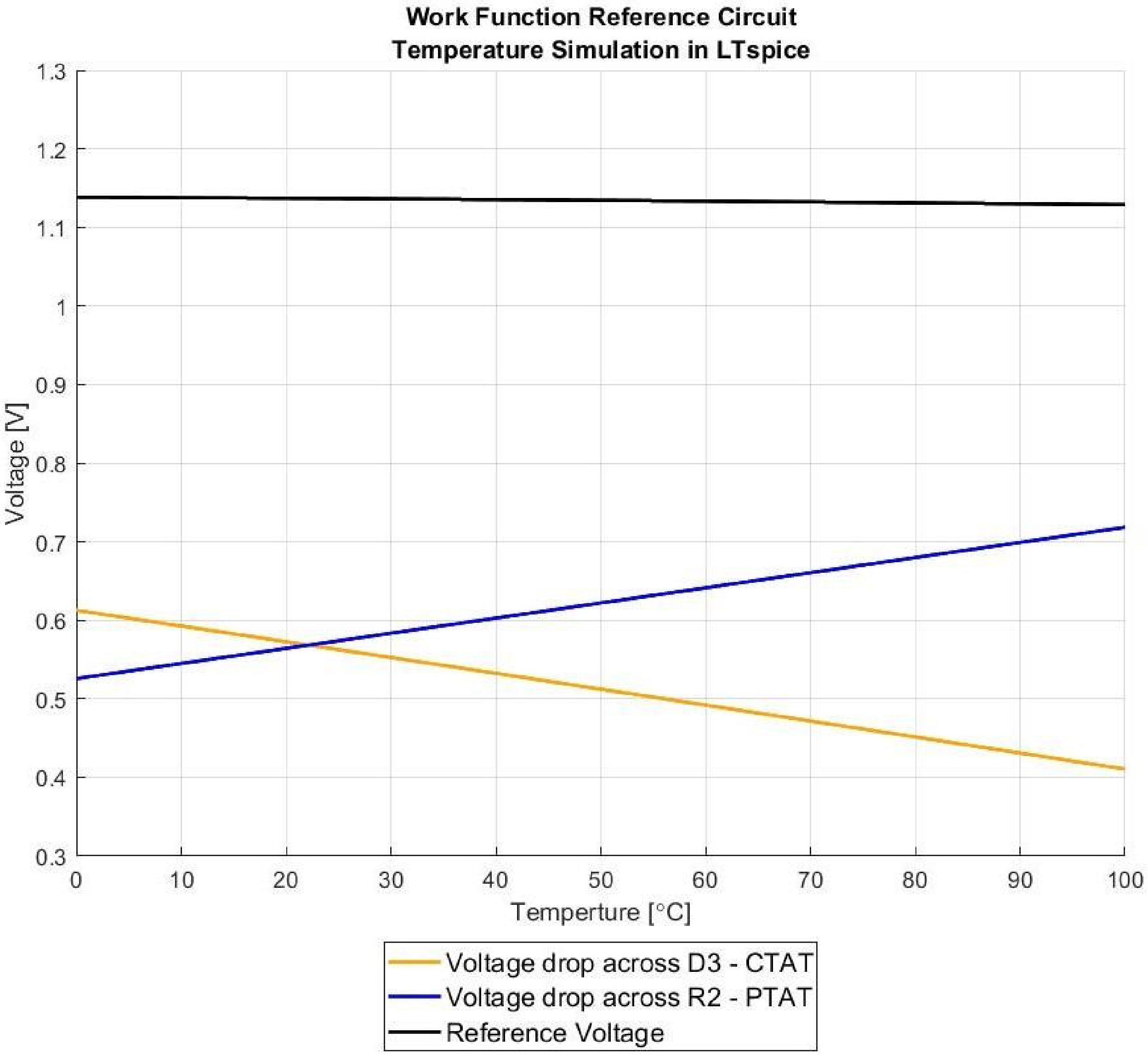
Node to measure voltage drop across D3

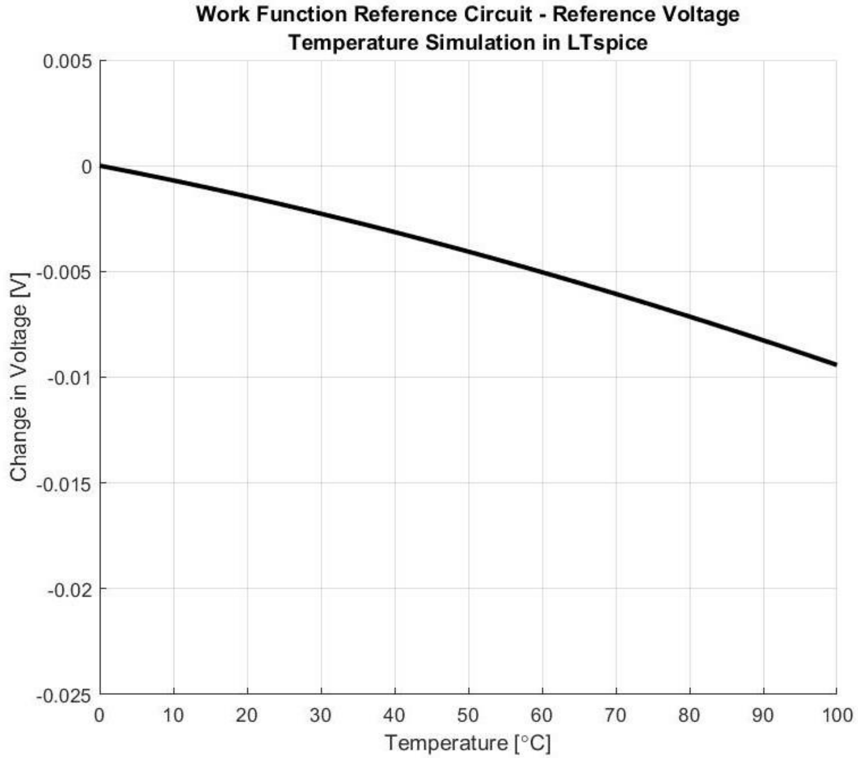
Schottky diode/Schottky-diode-configured HEMT exposed to radiation

Reference Schottky diodes/Schottky-diode-configured HEMTs

Circuit modified from Fig. 7-22, CMOS bandgap reference with substrate diodes. H. Camenzind. Designing Analog Chips. 2005.

LTspice Circuit Simulations





Temperature dependencies:

- Diode voltage: -2.02 mV/°C
- Reference voltage: -94.5 μV/°C

Environmental Chamber Temperature Experiments

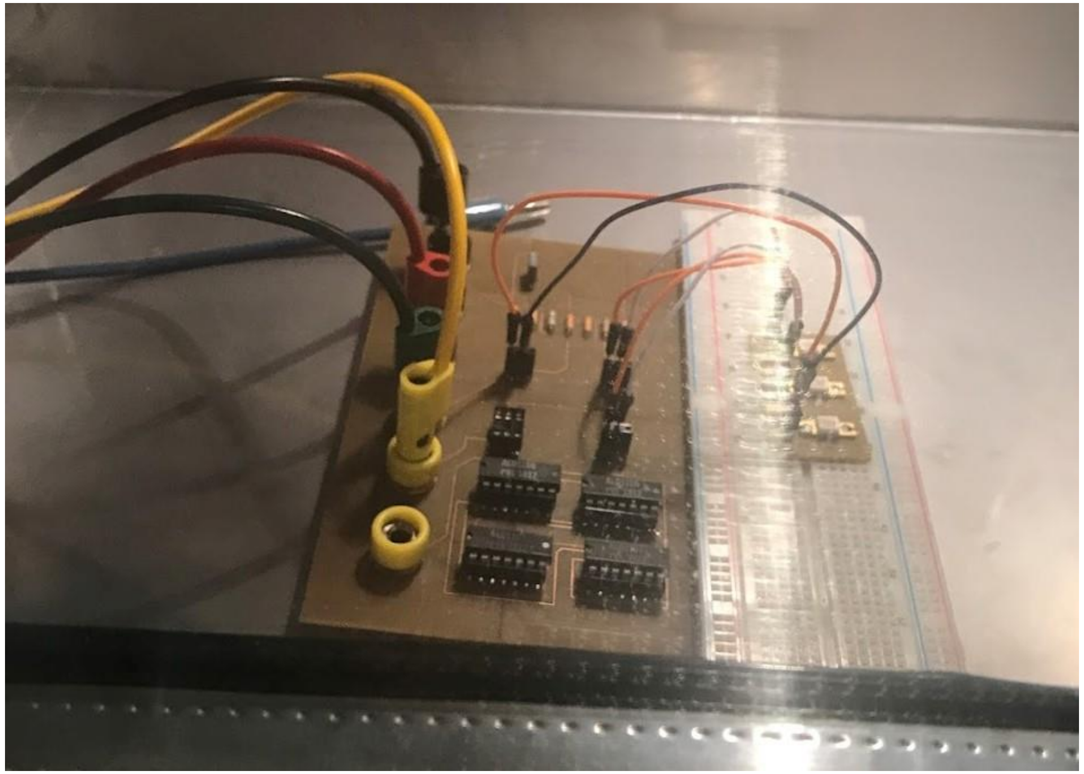
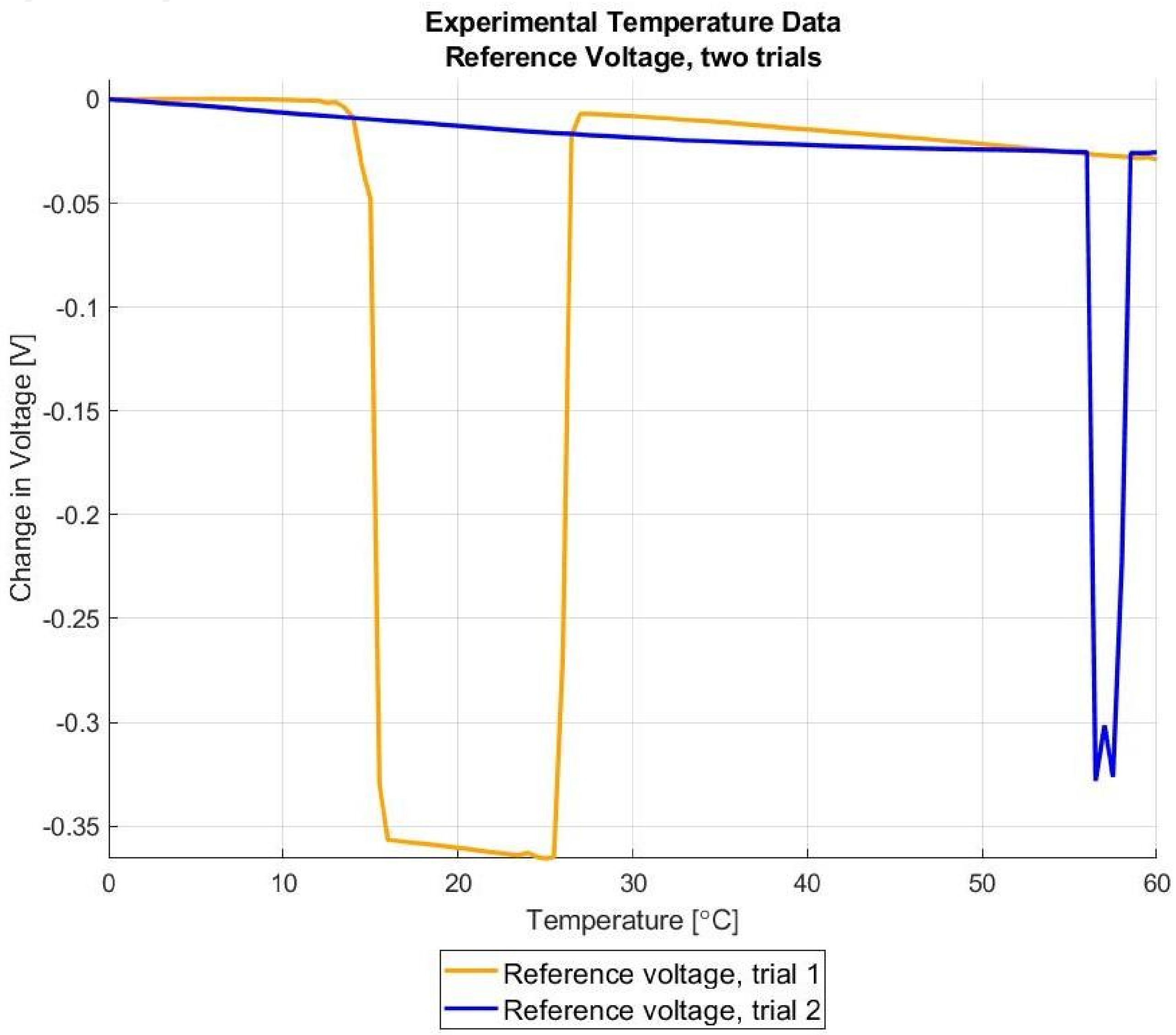
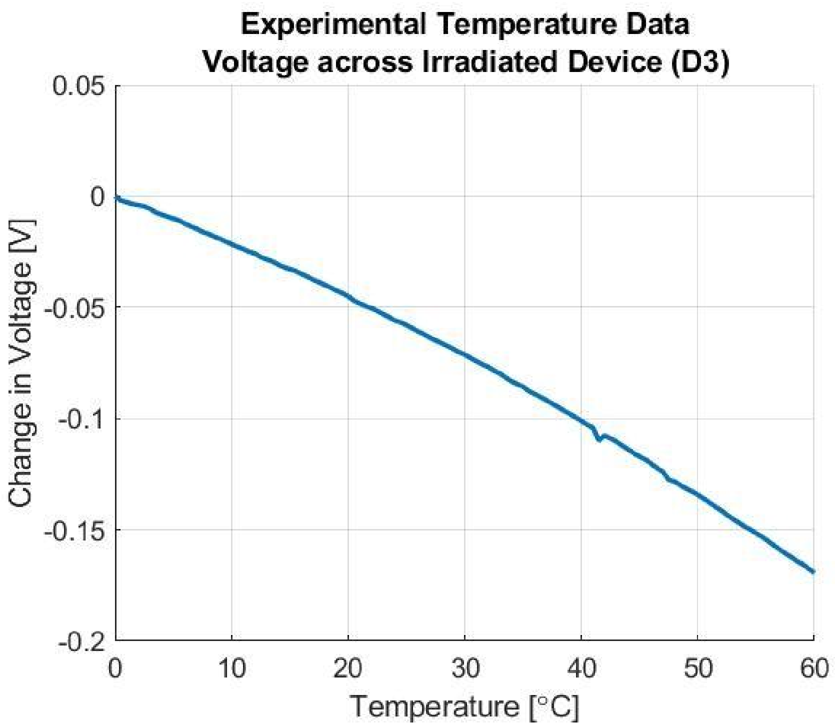


Photo credit: Aaron Green

Environmental Chamber Temperature Experiments





Temperature dependencies:

- Diode voltage: -2.82 mV/°C
- Reference voltage: -0.509 mV/°C

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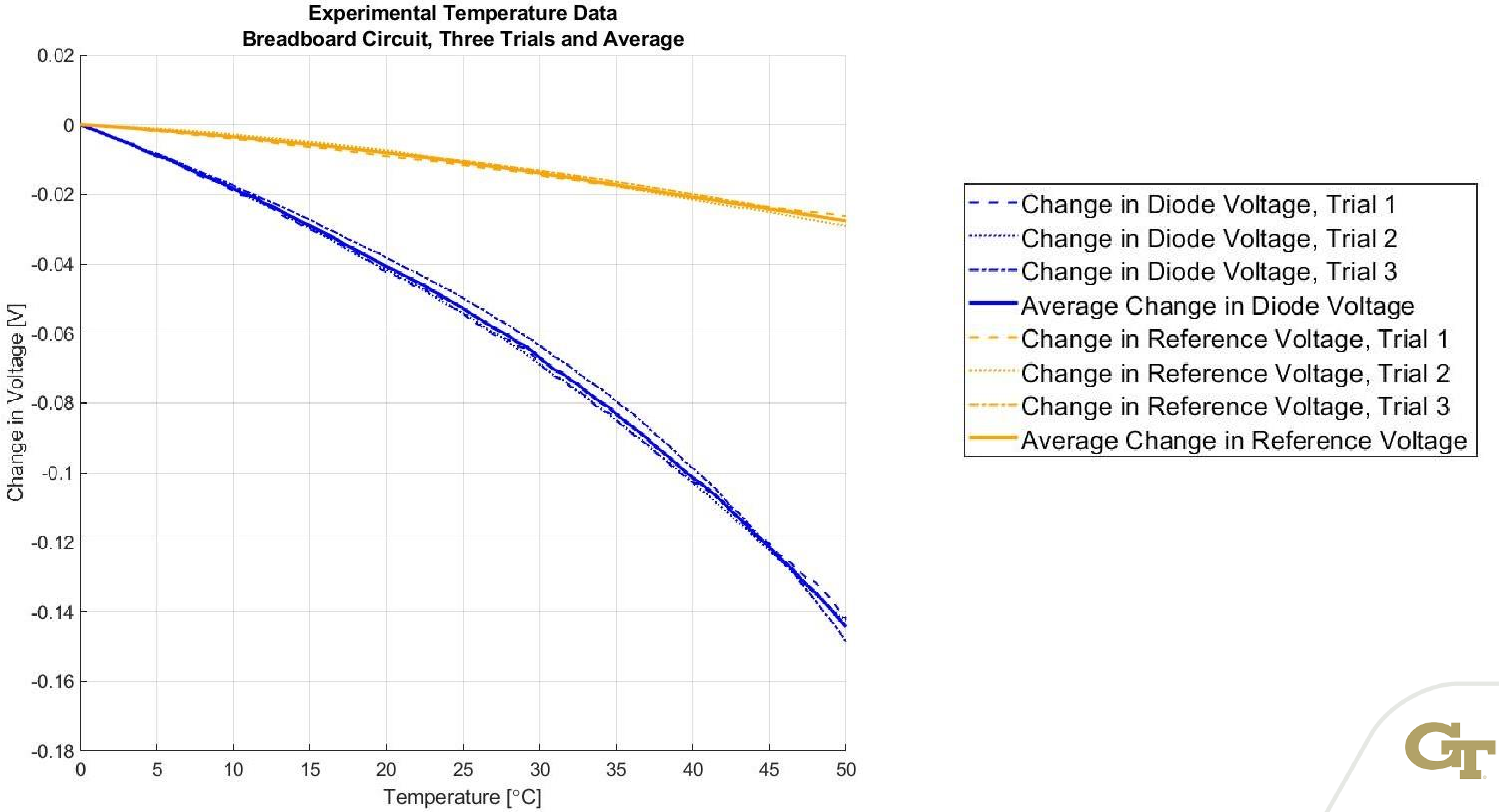
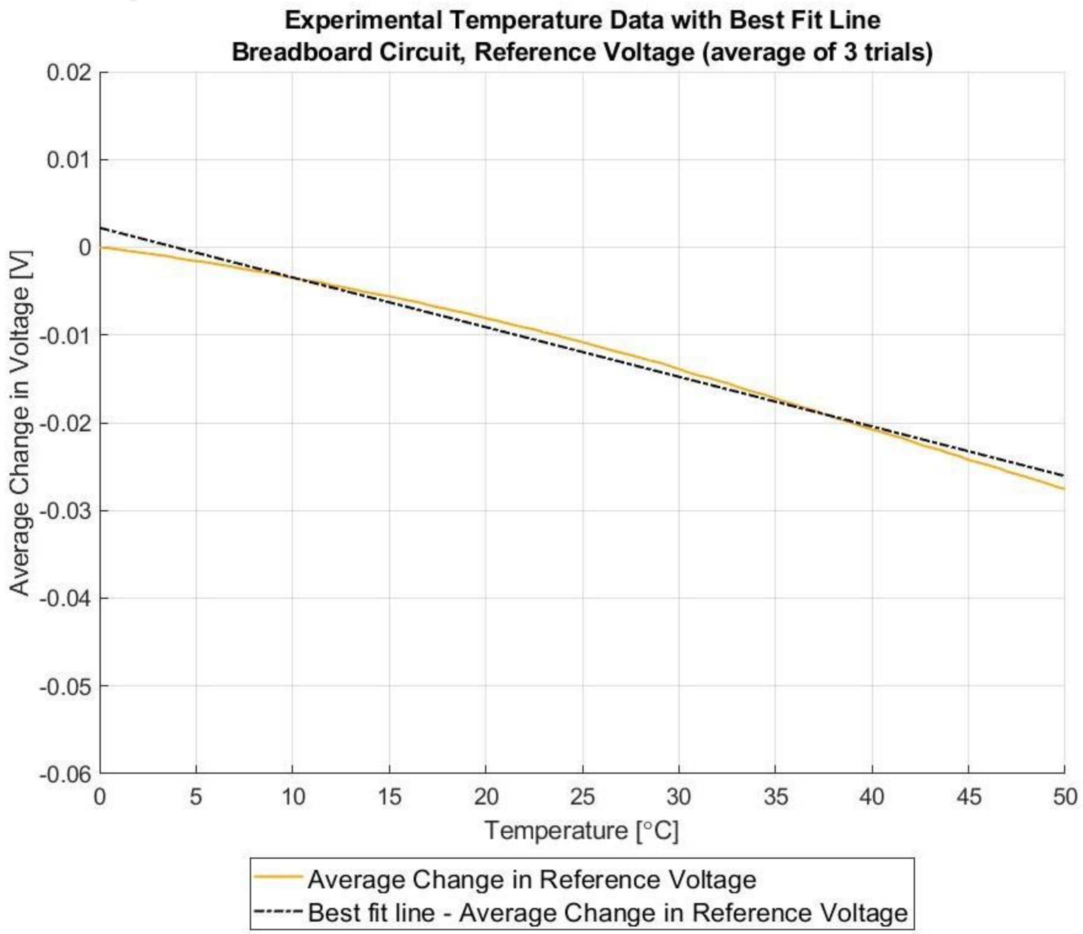
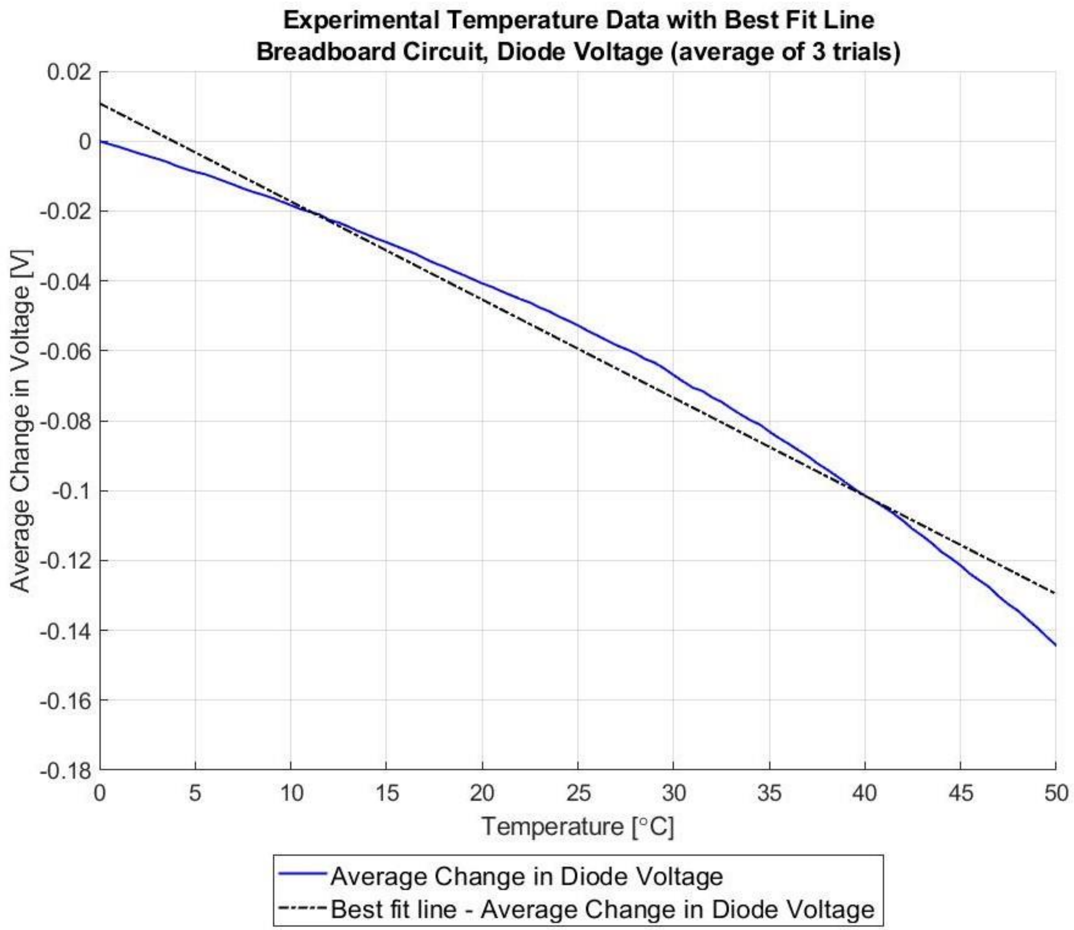
Environmental Chamber Temperature Experiments



Environmental Chamber Temperature Experiments





Temperature dependencies:

- Diode voltage: -2.8 mV/°C
- Reference voltage: -0.566 mV/°C

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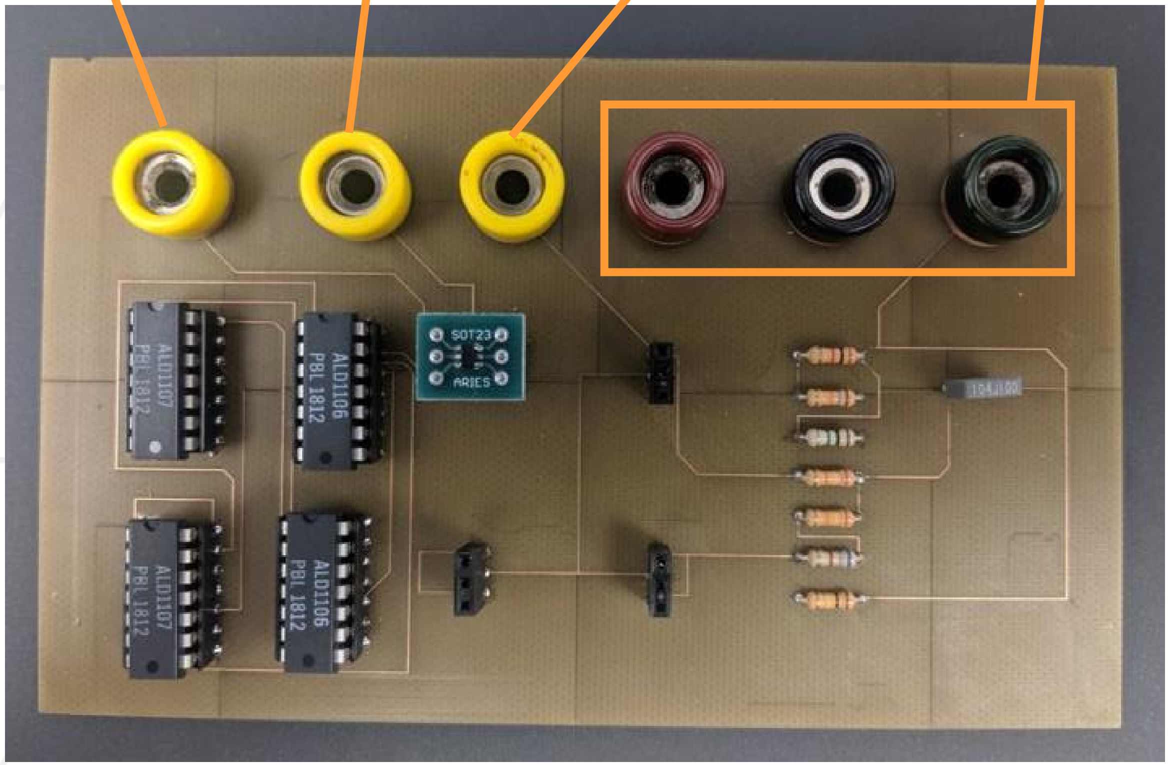
Work Function Reference PCB – First Prototype

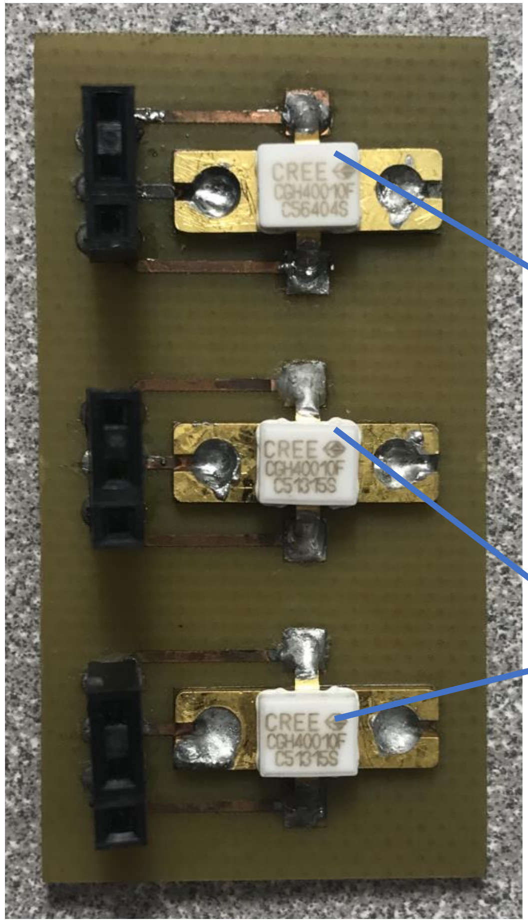
Operational amplifier voltage

Reference voltage

Voltage drop across irradiated diode

Power supply



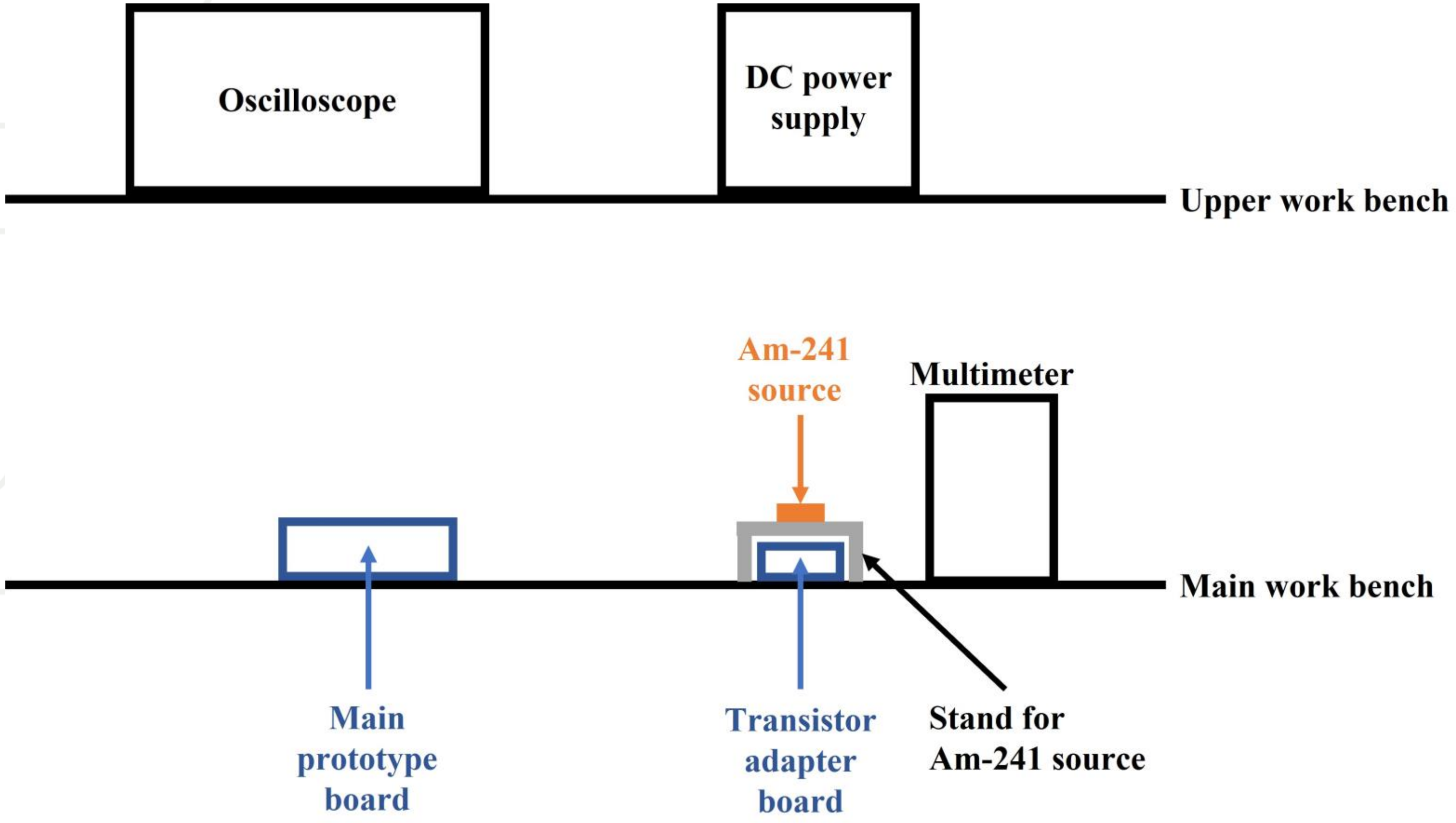


Transistor/Schottky diode exposed to radiation (corresponds to D3 on schematic)

Reference transistors/Schottky diodes (corresponds to D1 and D2 on schematic)

PCB manufactured at Georgia Tech Interdisciplinary Design Commons

Alpha Irradiation Experiment at Sandia



- Am-241 alpha source
- Measured activity $4.62 \times 10^{-2} \mu Ci$
- Approximately 1 decay per 31.3 ms interacting with the irradiated transistor at 1cm

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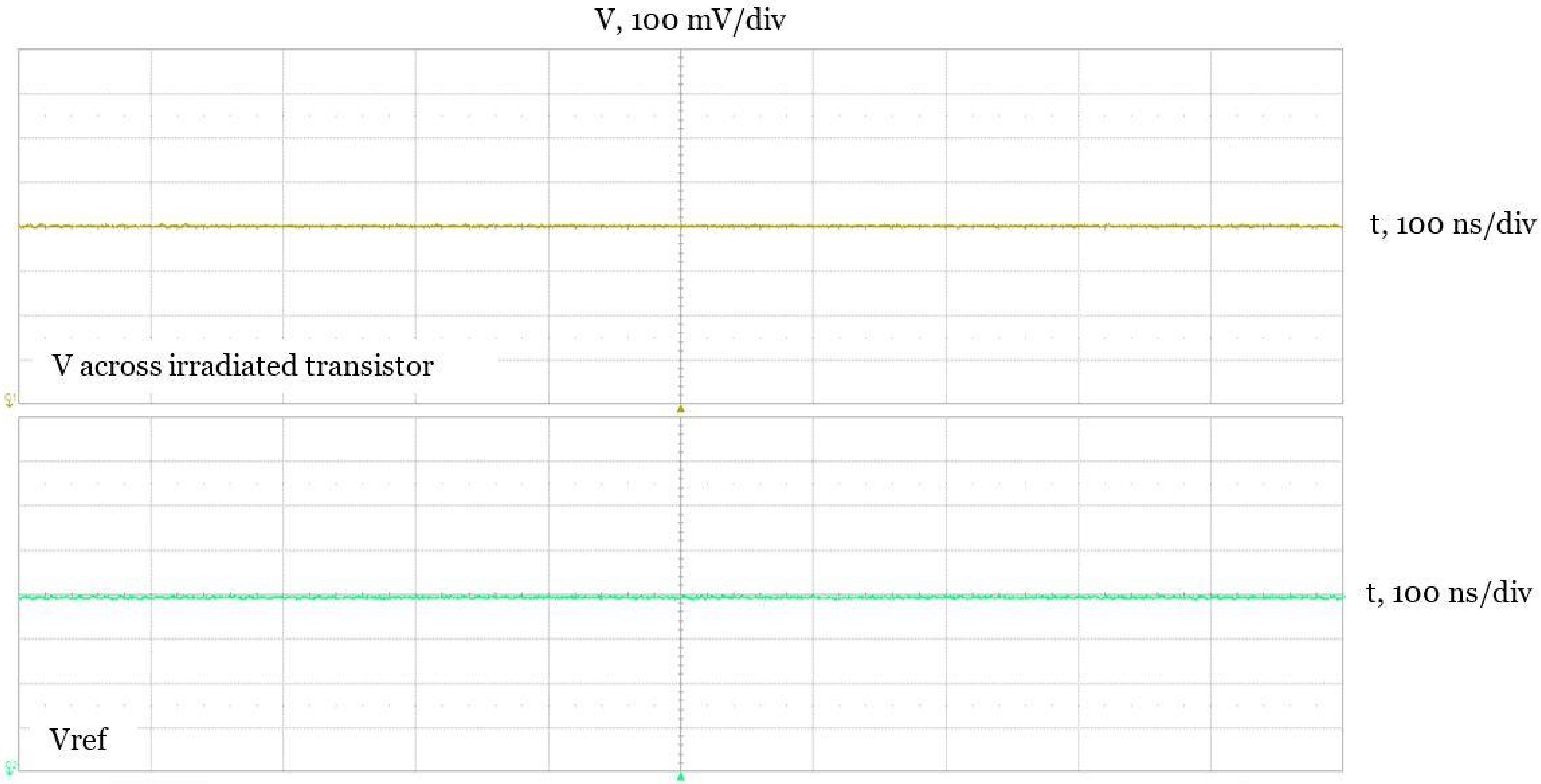
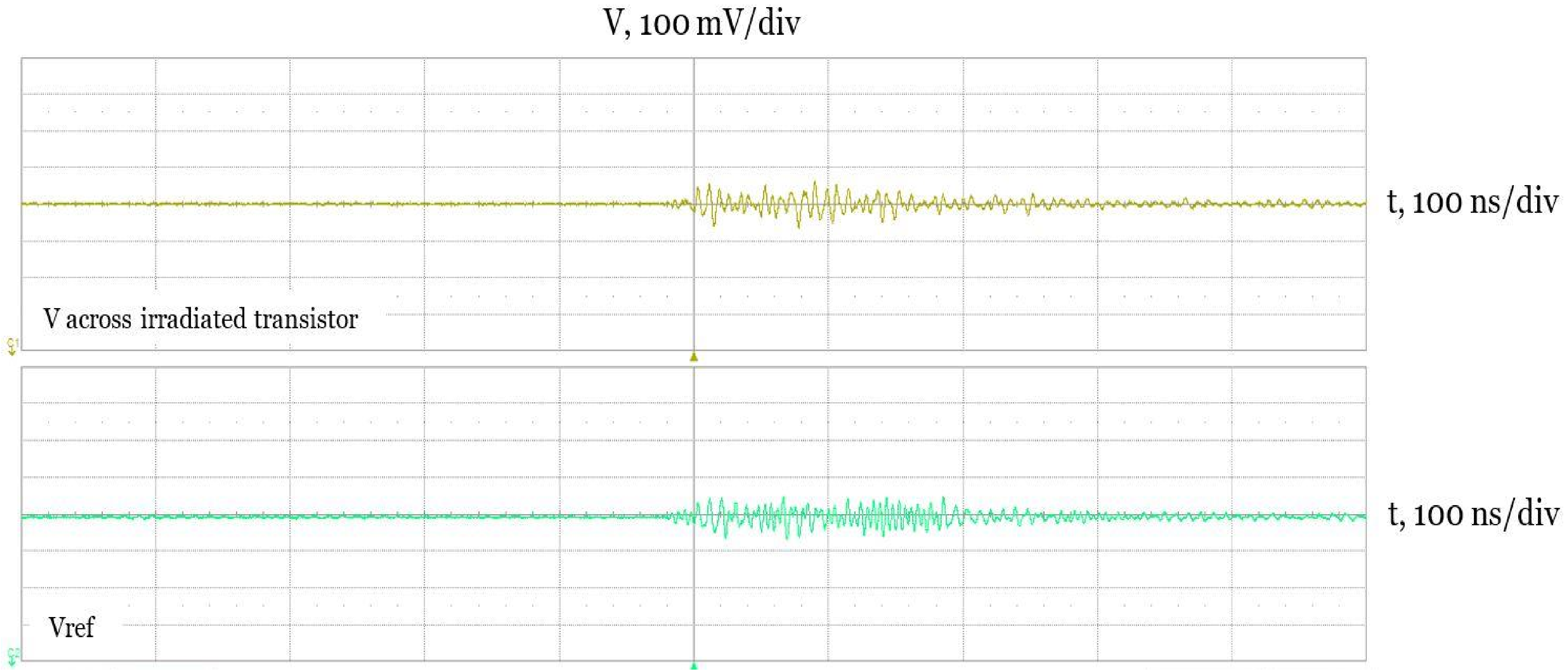
Alpha Irradiation Experiment at Sandia
Oscilloscope Output – No Source



Alpha Irradiation Experiment at Sandia
Oscilloscope Output – Am-241 Alpha Source



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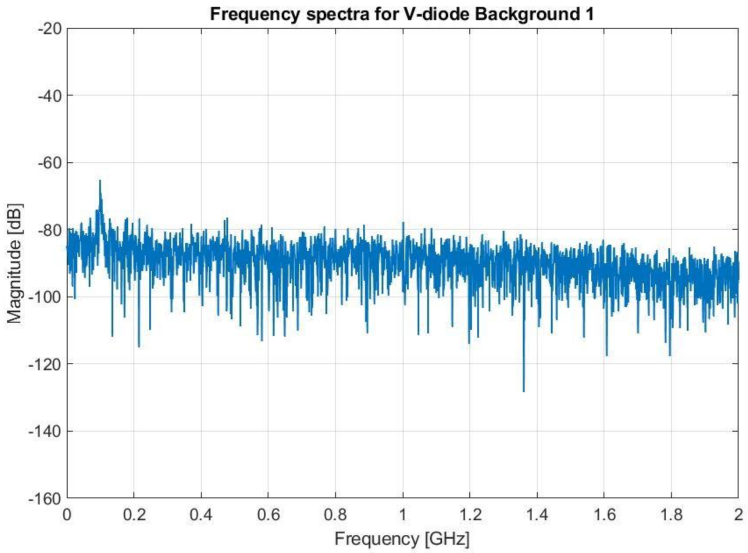
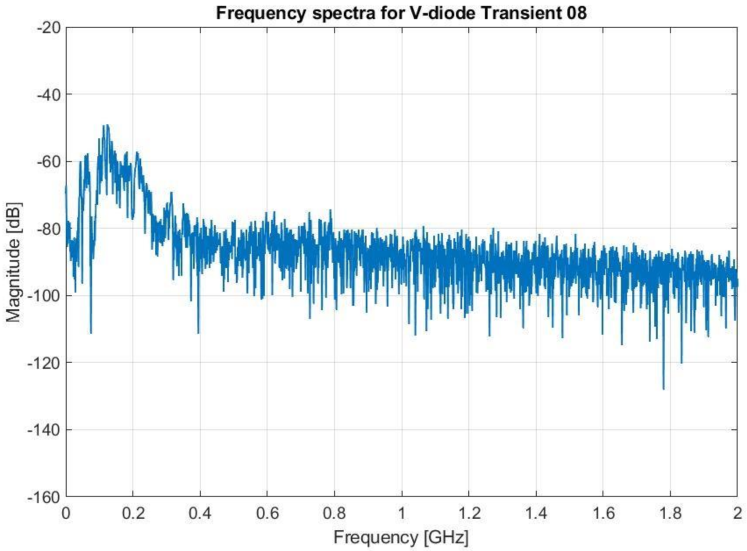
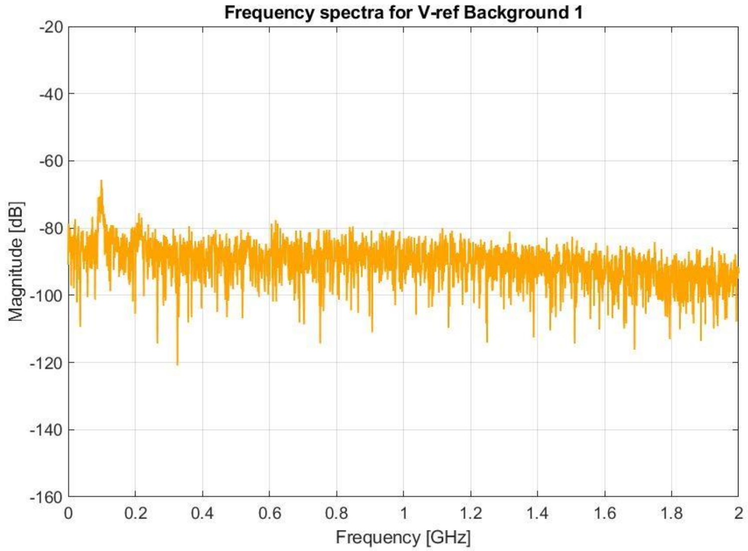
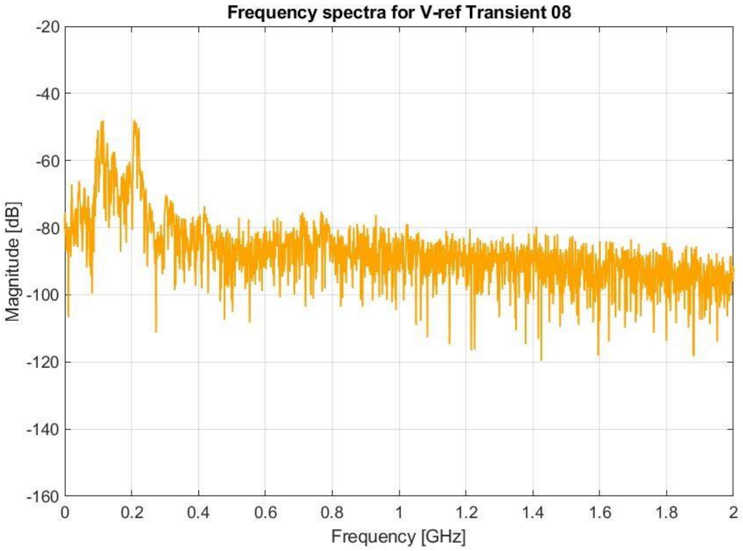
Alpha Irradiation Experiment at Sandia
Frequency Spectra









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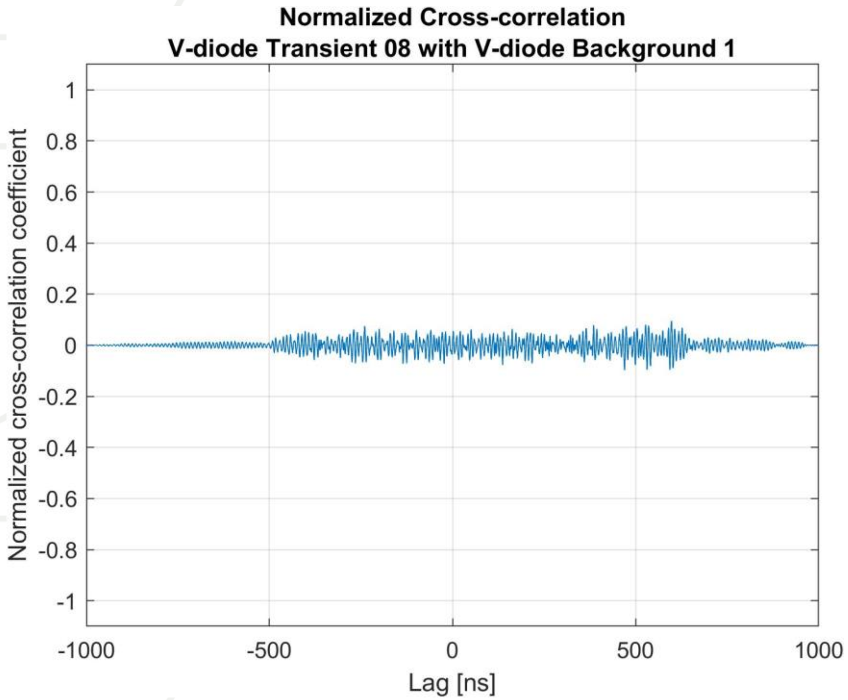
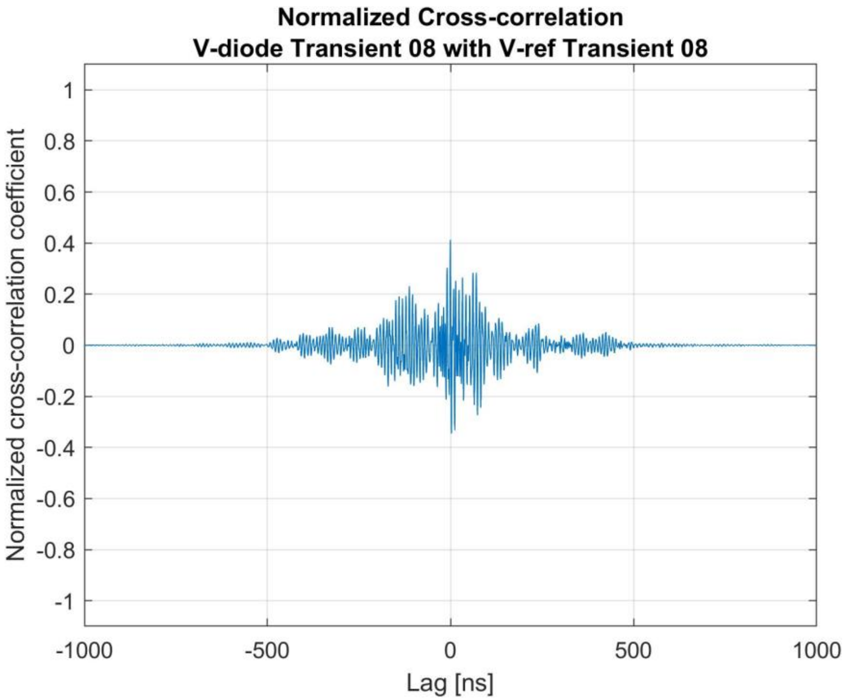
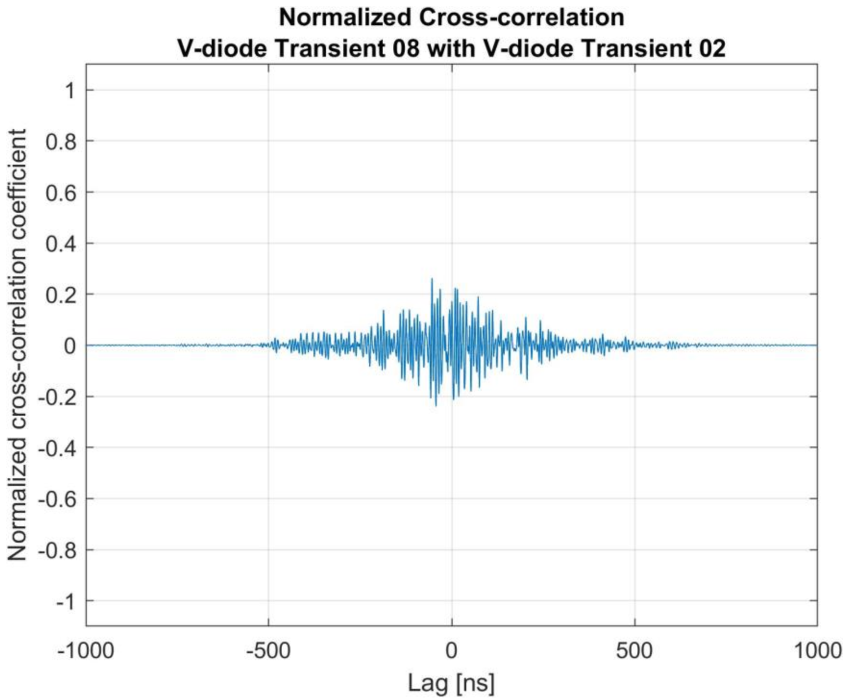
Alpha Irradiation Experiment at Sandia Cross-Correlation







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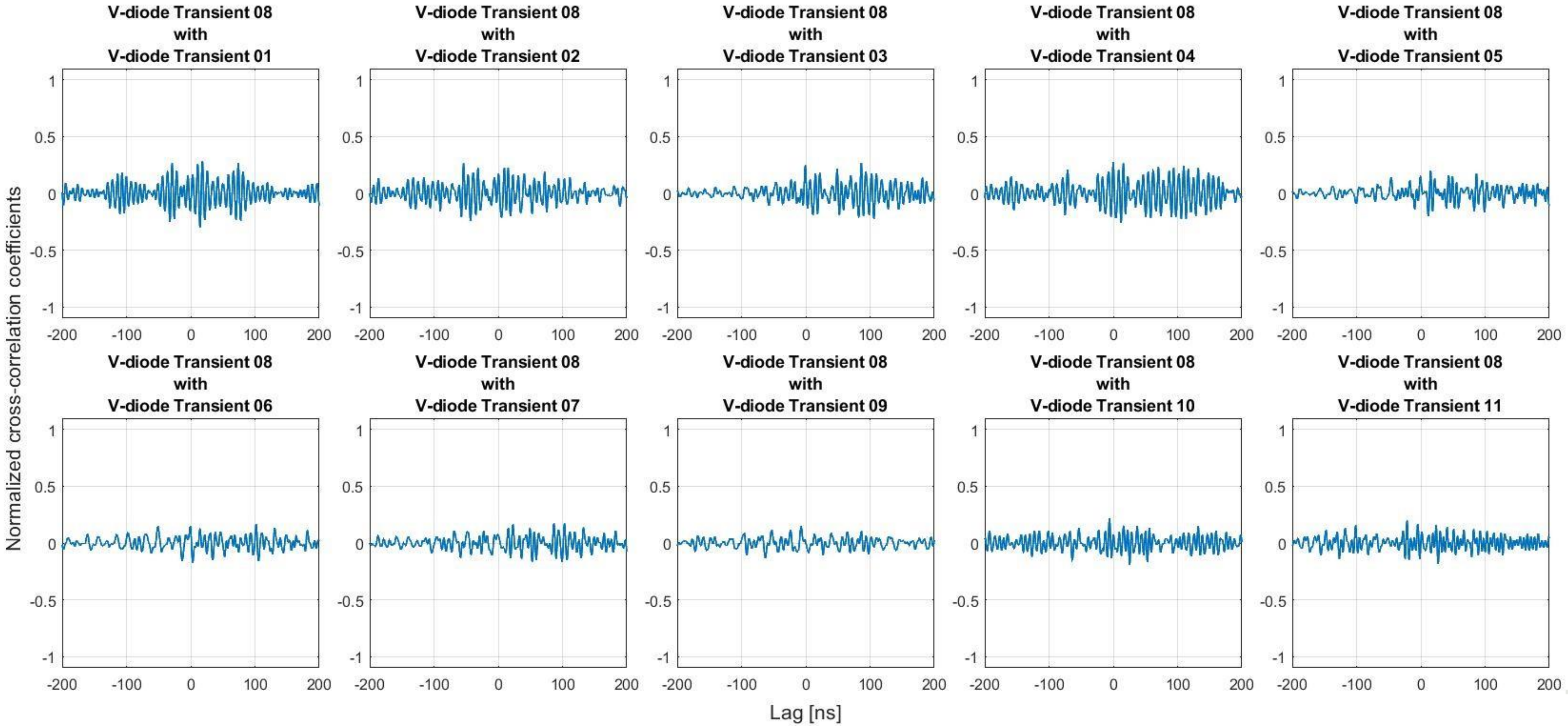
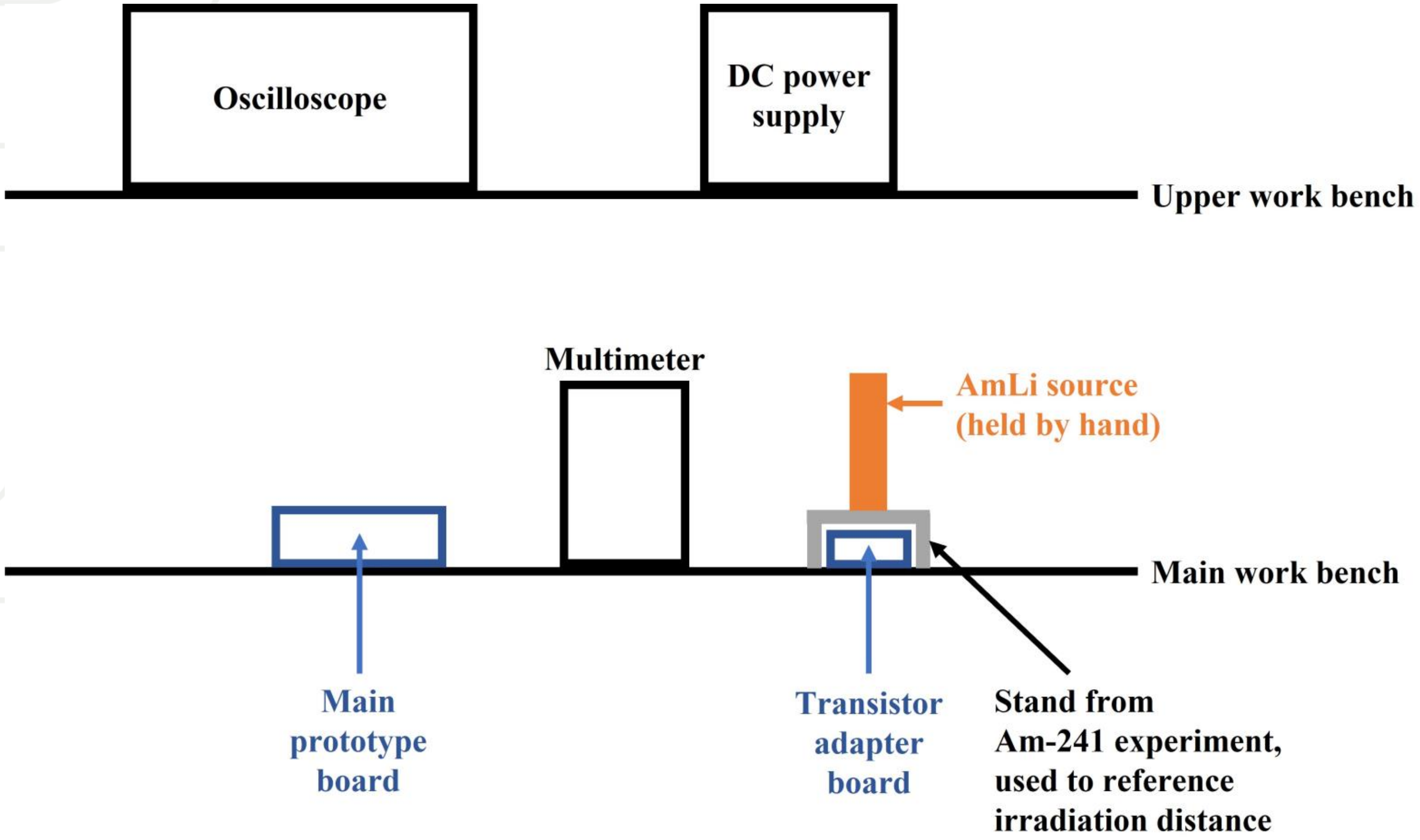
Alpha Irradiation Experiment at Sandia Cross-Correlation



Neutron Irradiation Experiment at Sandia



- AmLi neutron source
- Measured activity $8.18 \times 10^4 \mu\text{Ci}$
- Approximately 1 decay per 20.4 ns interacting with the irradiated transistor at 1cm

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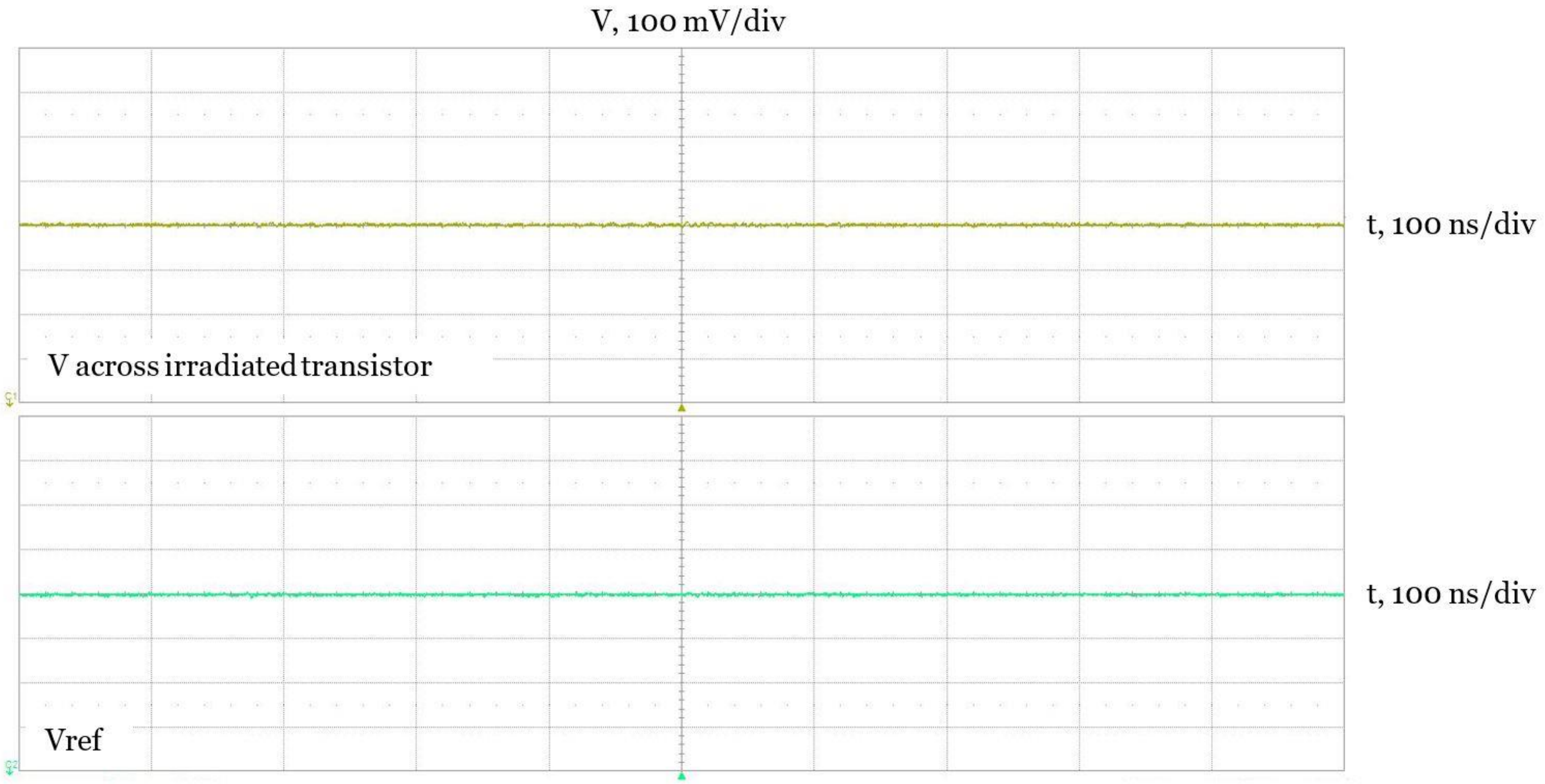
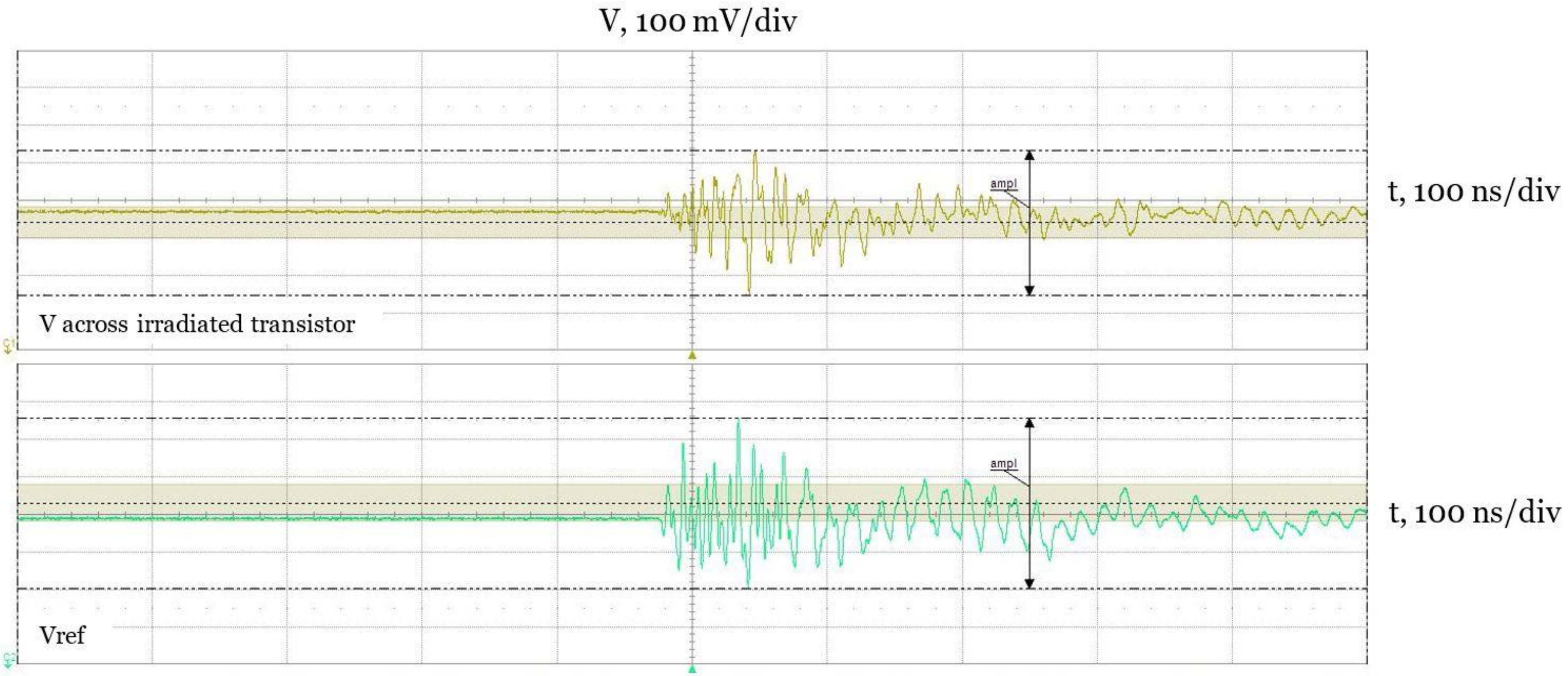
Neutron Irradiation Experiment at Sandia Oscilloscope Output – No Source



Neutron Irradiation Experiment at Sandia
Oscilloscope Output – AmLi Neutron Source



Irradiation Experiments at Sandia
Comparing Alpha and Neutron Experiments

	Alpha Irradiation	Neutron Irradiation
Peak-to-peak amplitude Diode voltage	71.1 ± 42.1 mV	302 ± 63.2 mV
Peak-to-peak amplitude Reference voltage	62.4 ± 39.0 mV	370.2 ± 97.7 mV
Decay time	Less than 400 ns	Greater than 500 ns

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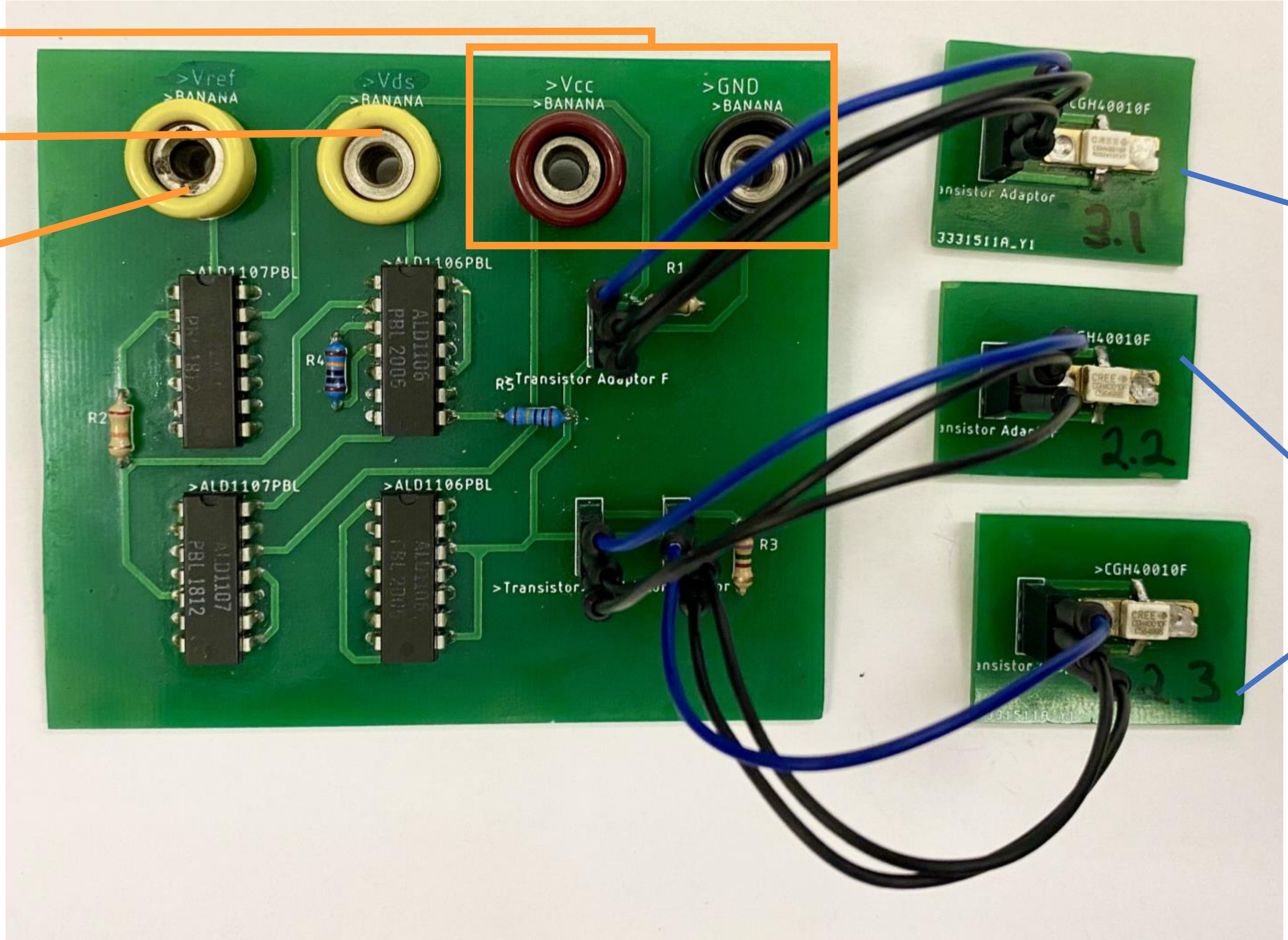
- **Work Function Reference Circuit – Second Prototype Irradiation at Georgia Tech**
- Geant4 Modeling
- Conclusion

Work Function Reference PCB – Second Prototype

Power supply

Reference voltage

Voltage drop across irradiated diode

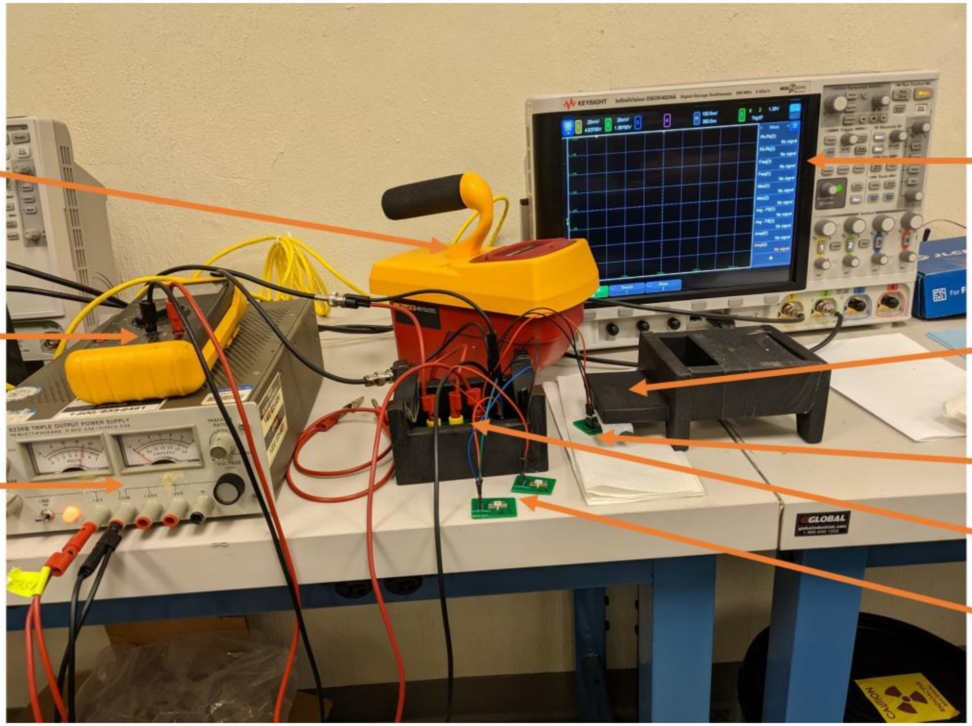


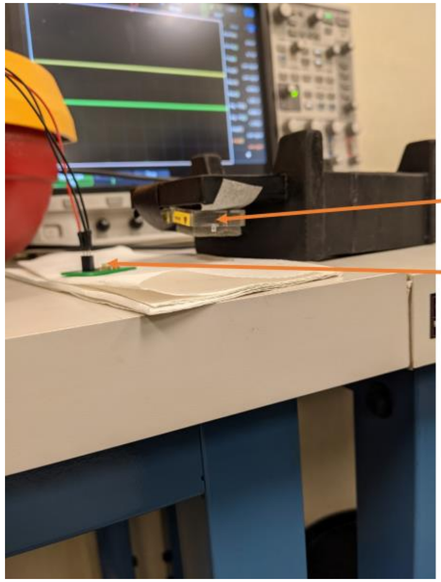
Transistor/Schottky diode exposed to radiation (corresponds to D3 on schematic)

Reference transistors/Schottky diodes (corresponds to D1 and D2 on schematic)

PCB manufactured by JLC PCB

Alpha Irradiation Experiment at Georgia Tech





- Am-241 alpha source
- Measured activity 0.103 mCi
- Approximately 1 decay per 16.2 μs interacting with the irradiated transistor at 1cm

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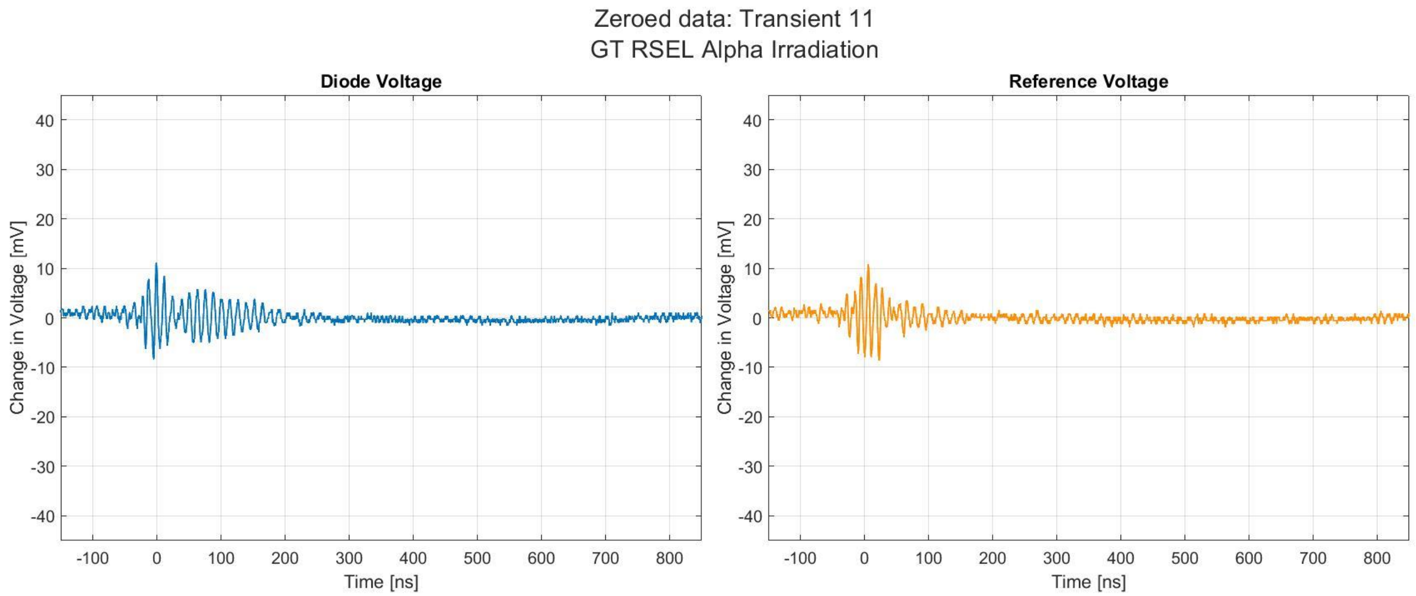
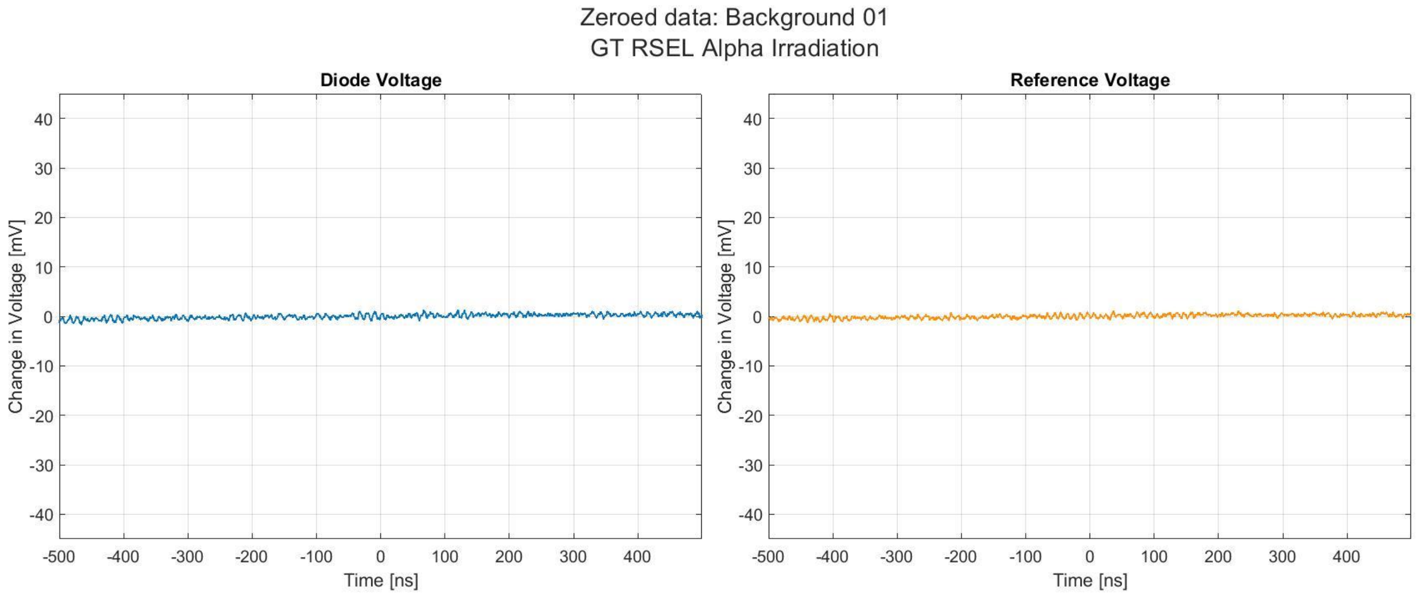
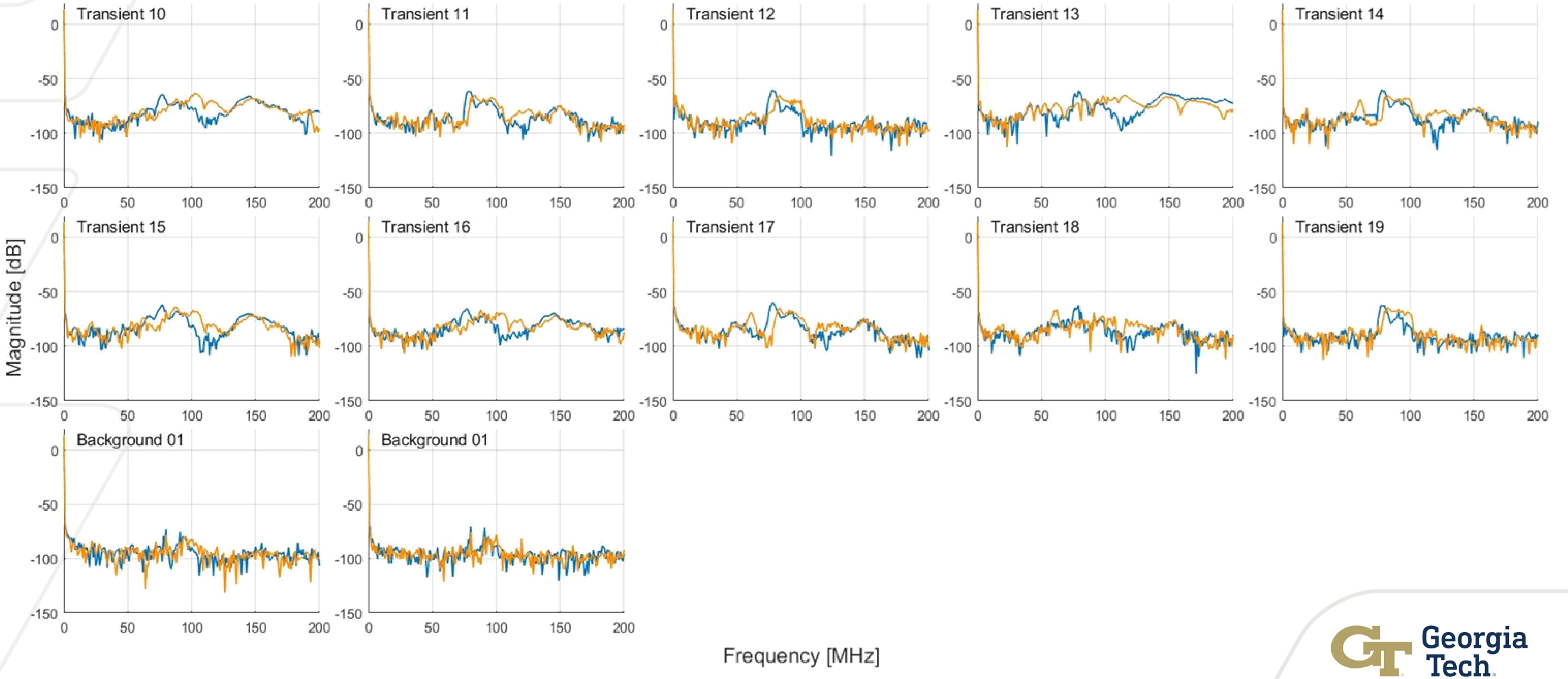
Alpha Irradiation Experiment at Georgia Tech

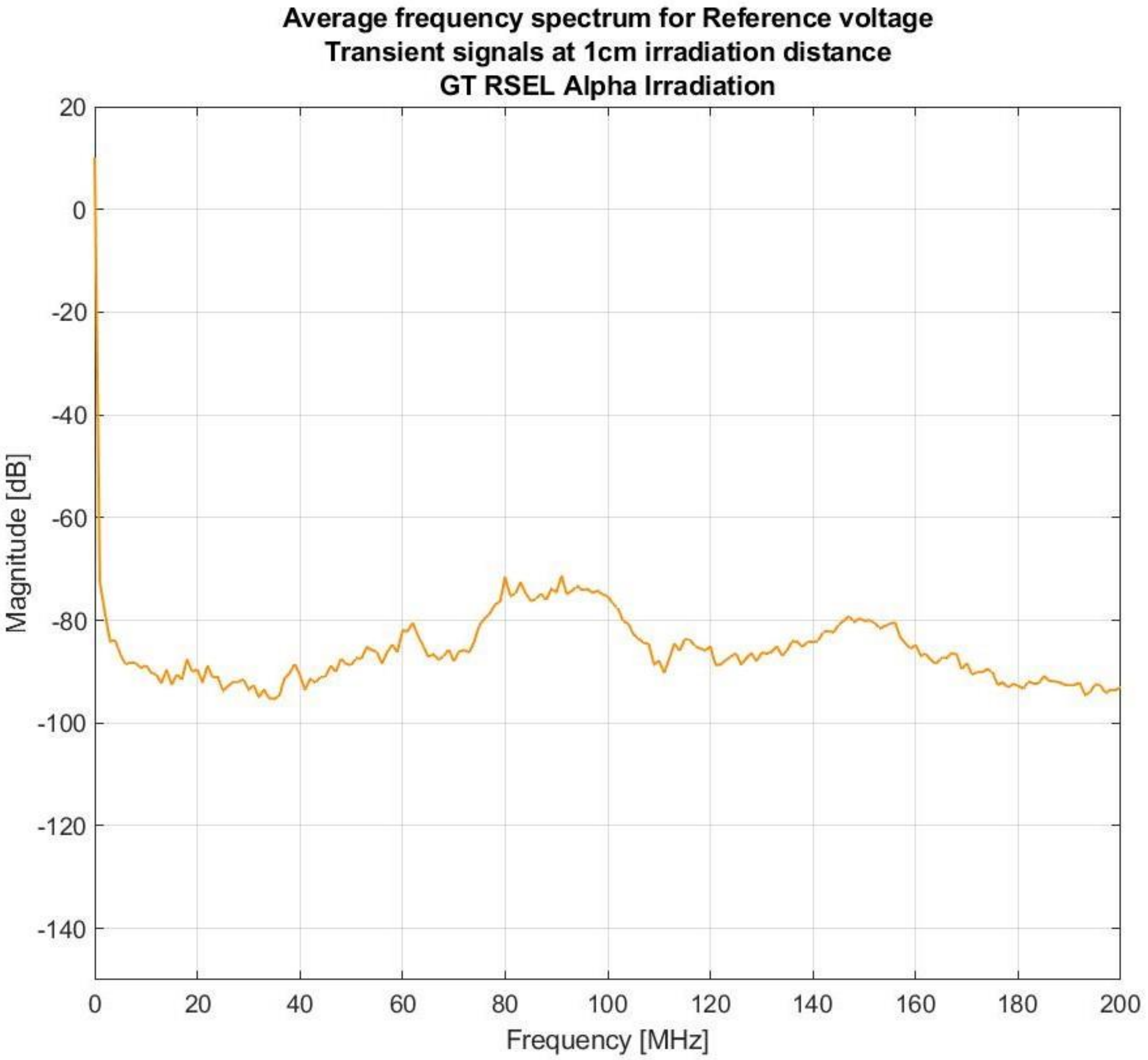


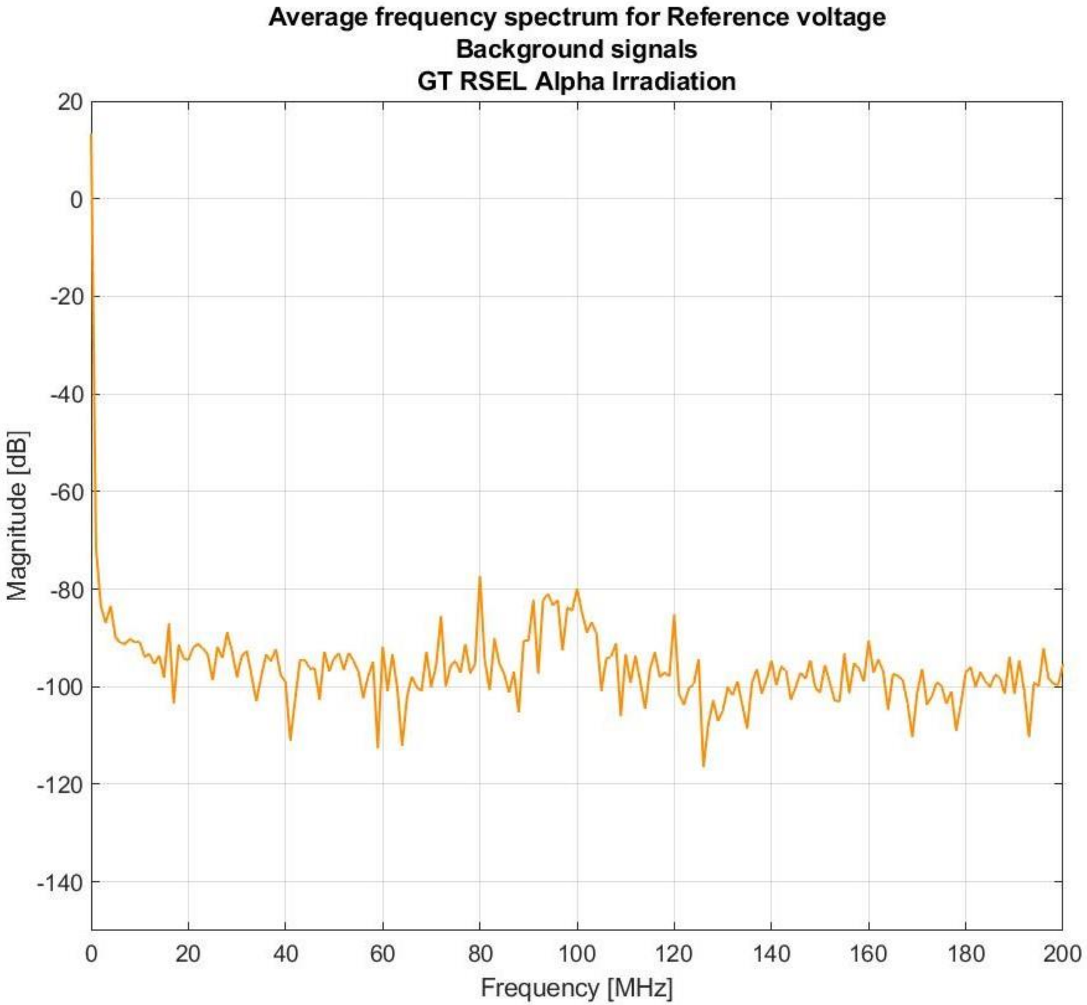


Alpha Irradiation at Georgia Tech Frequency Spectra

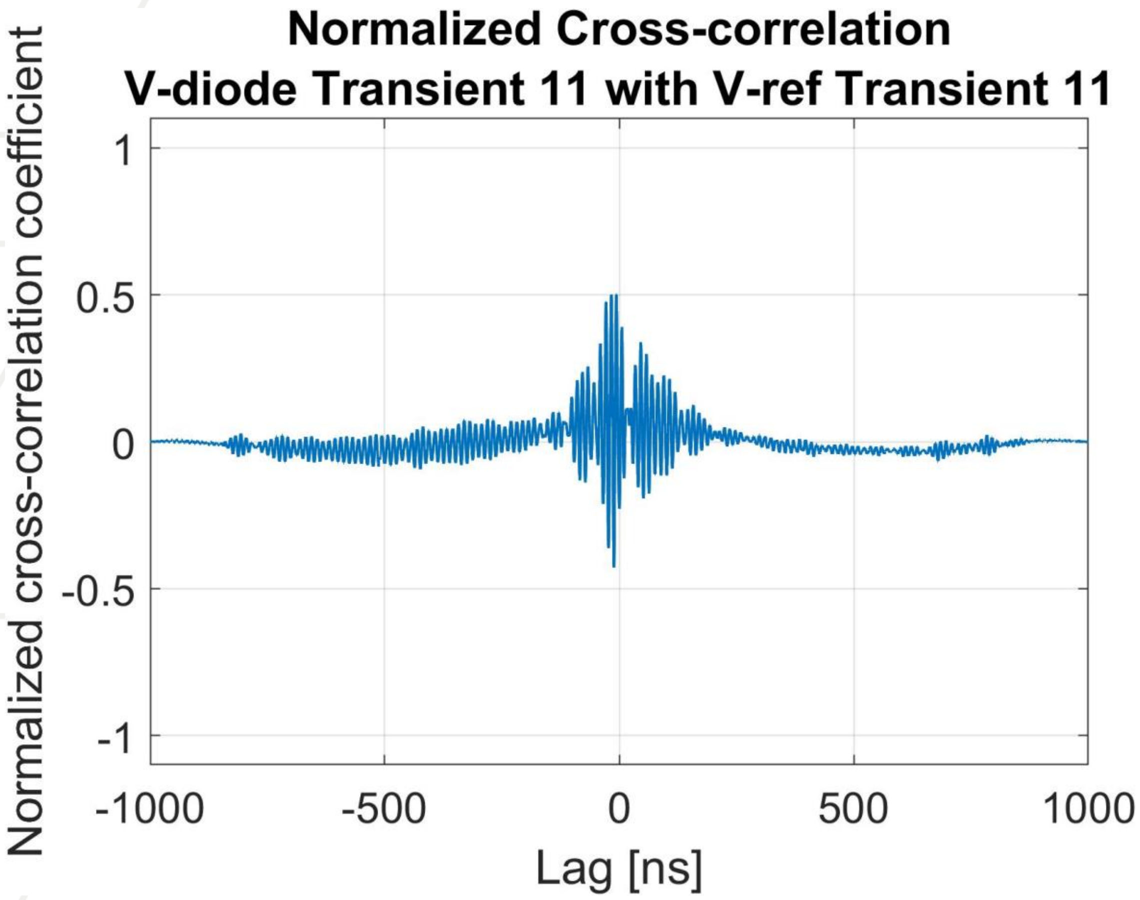


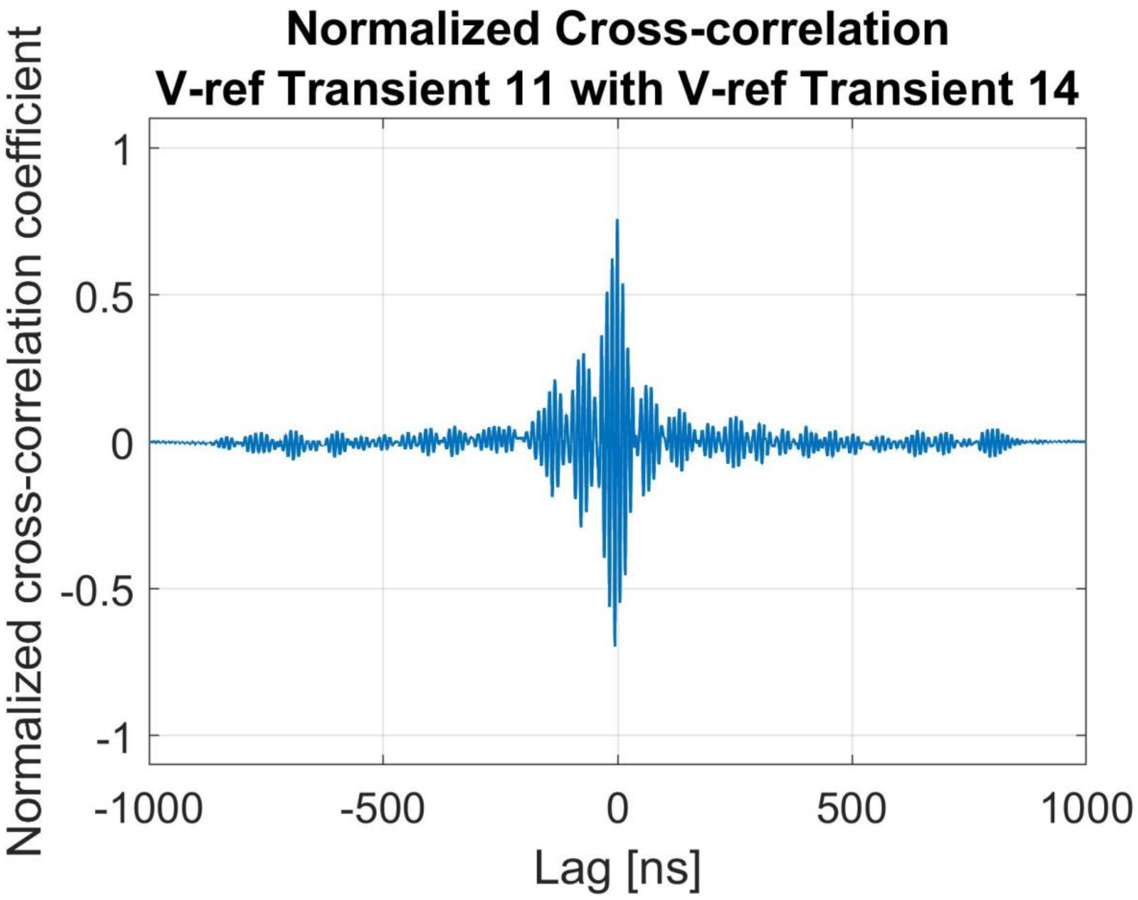
Alpha Irradiation at Georgia Tech
Average Frequency Spectra



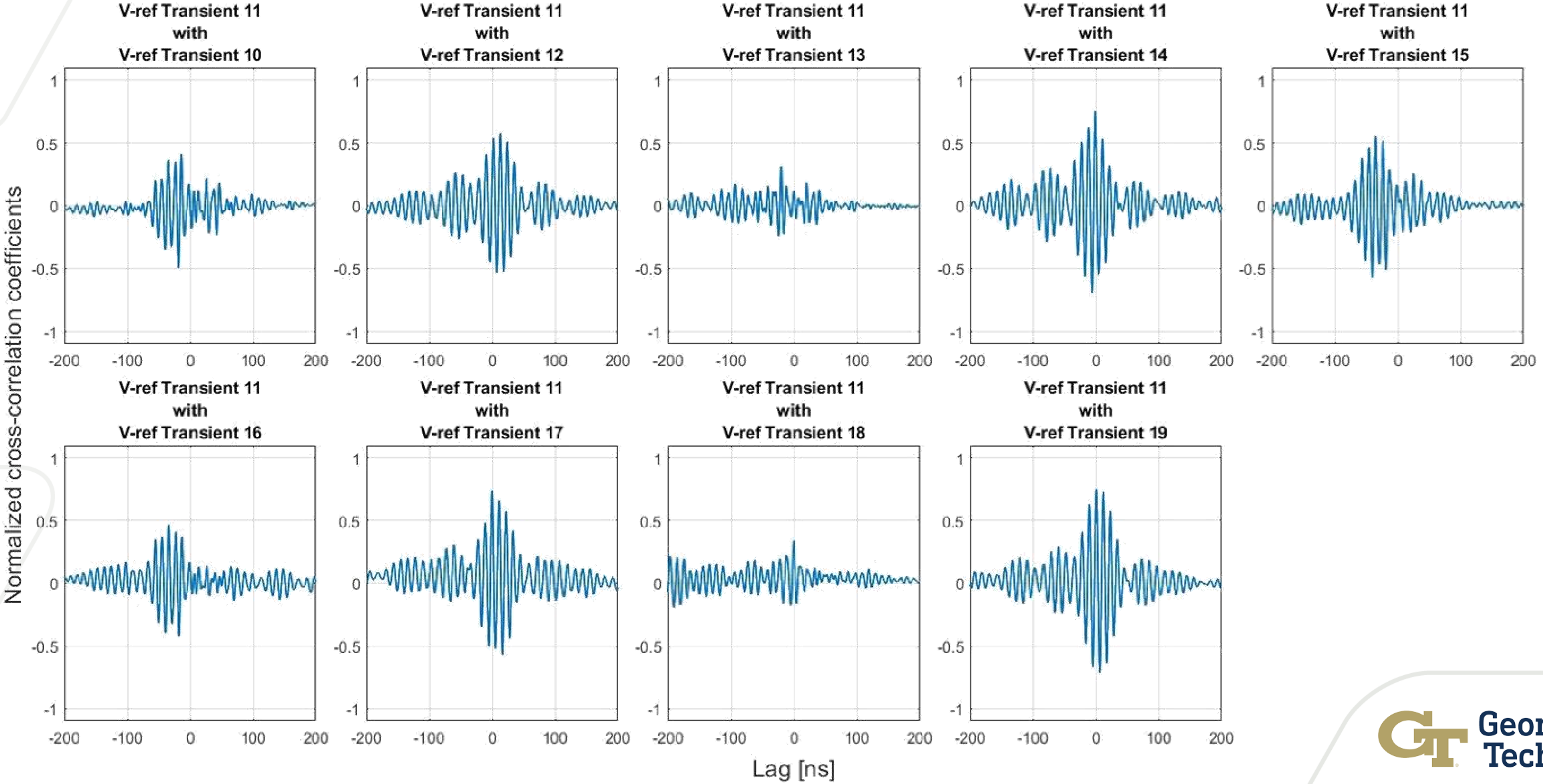


Alpha Irradiation at Georgia Tech
Cross-Correlation

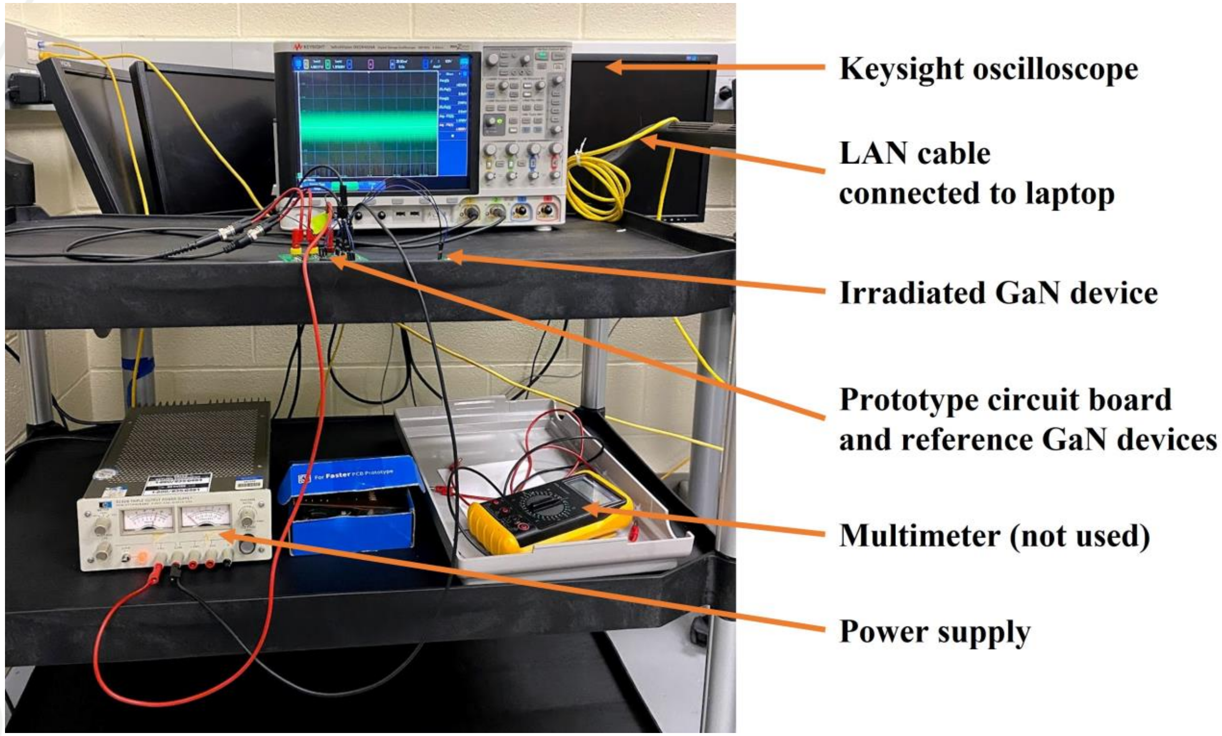


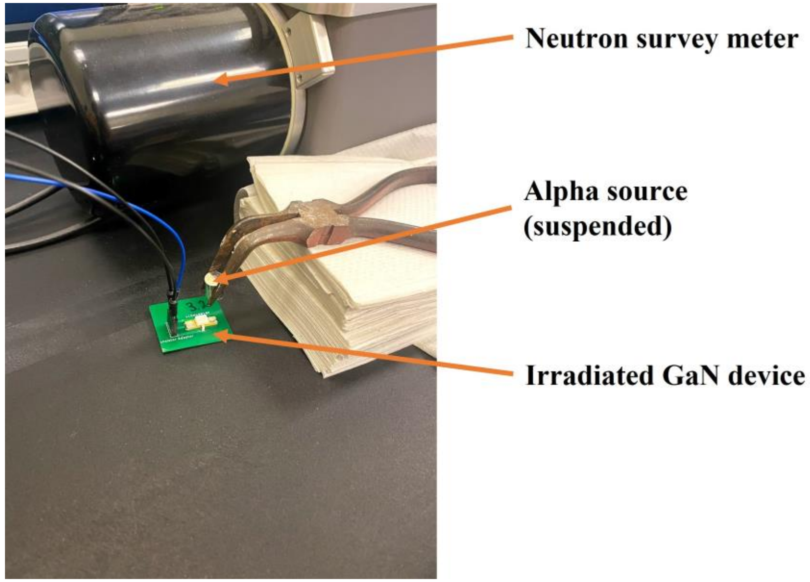


Alpha Irradiation at Georgia Tech
Cross-Correlation



Neutron Irradiation Experiment at Georgia Tech





- Weak Cf-252 neutron source
- Neutron production rate 9.2×10^3 neutrons/second
- Approximately 1 decay per 6.7 ms interacting with the irradiated transistor at 1cm

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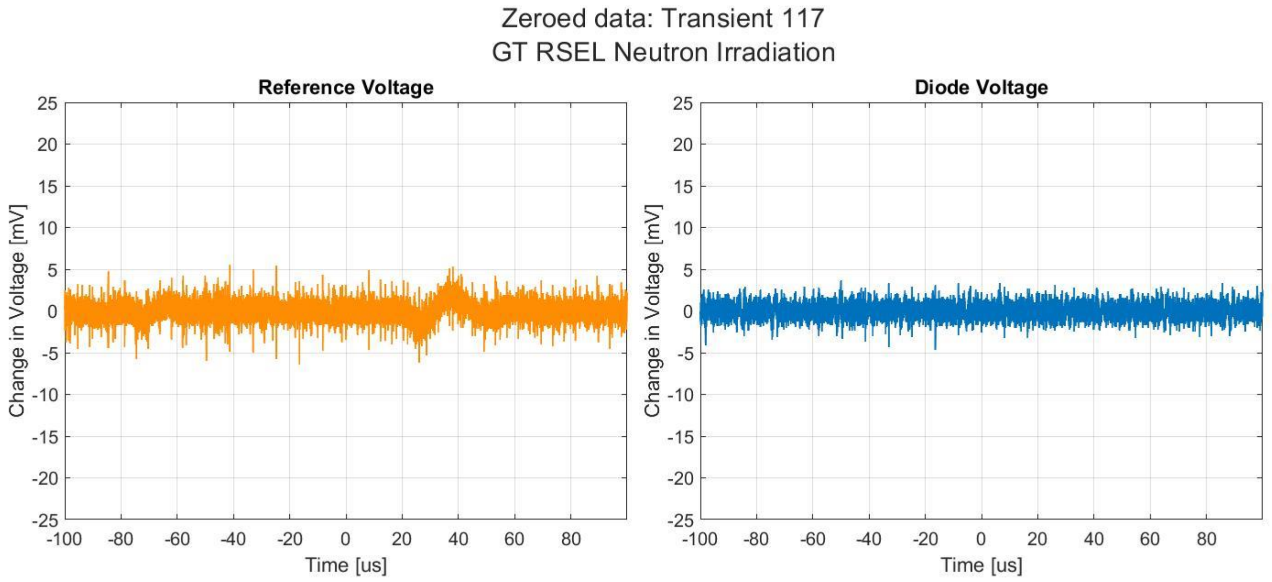
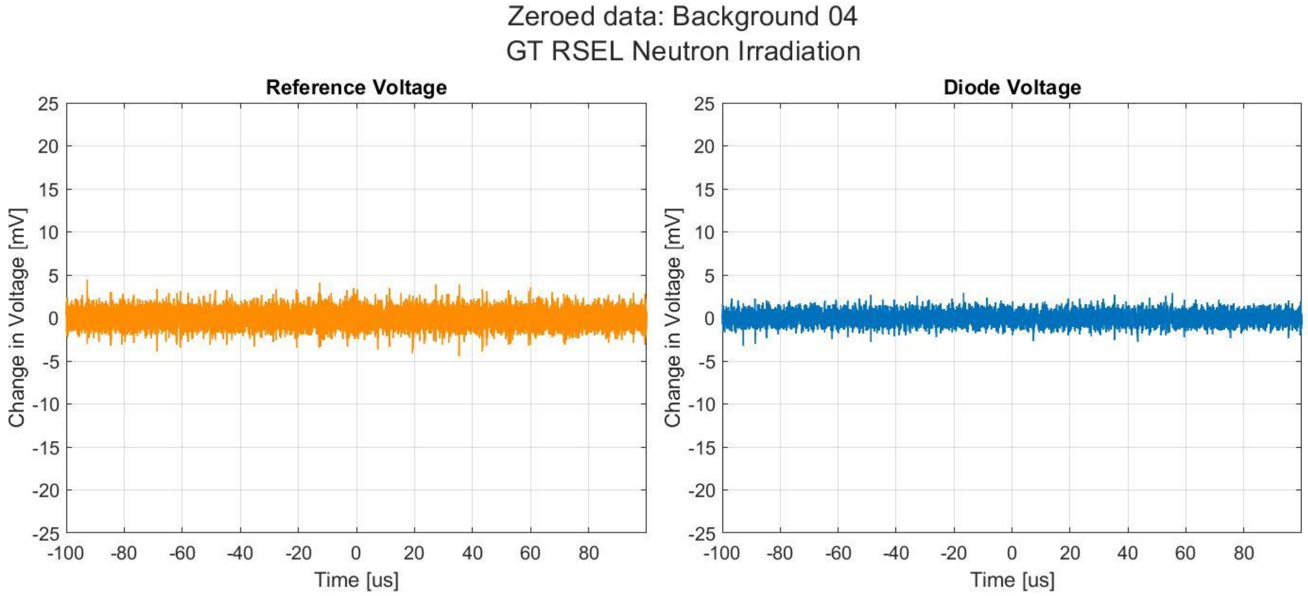
Neutron Irradiation Experiment at Georgia Tech





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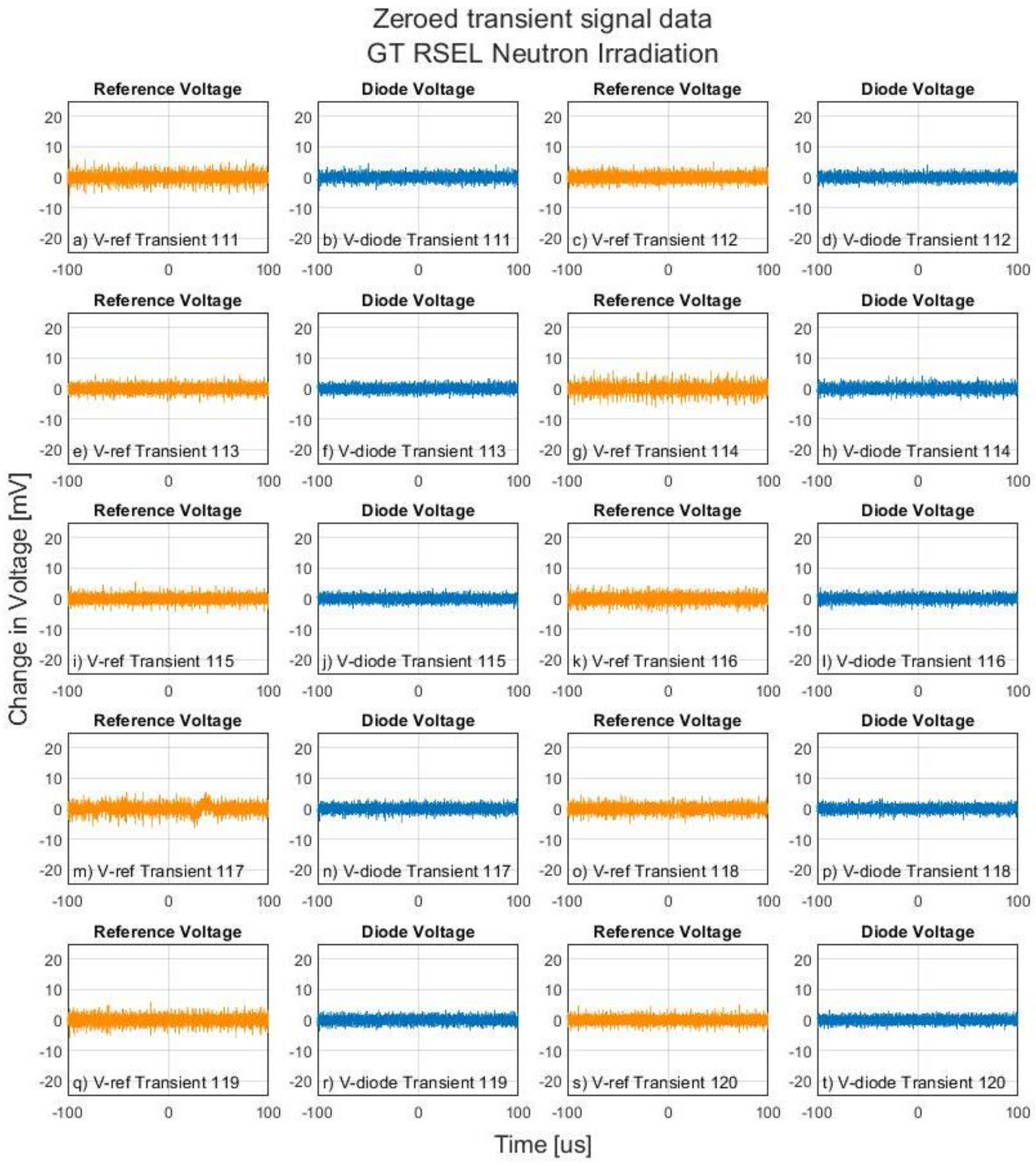
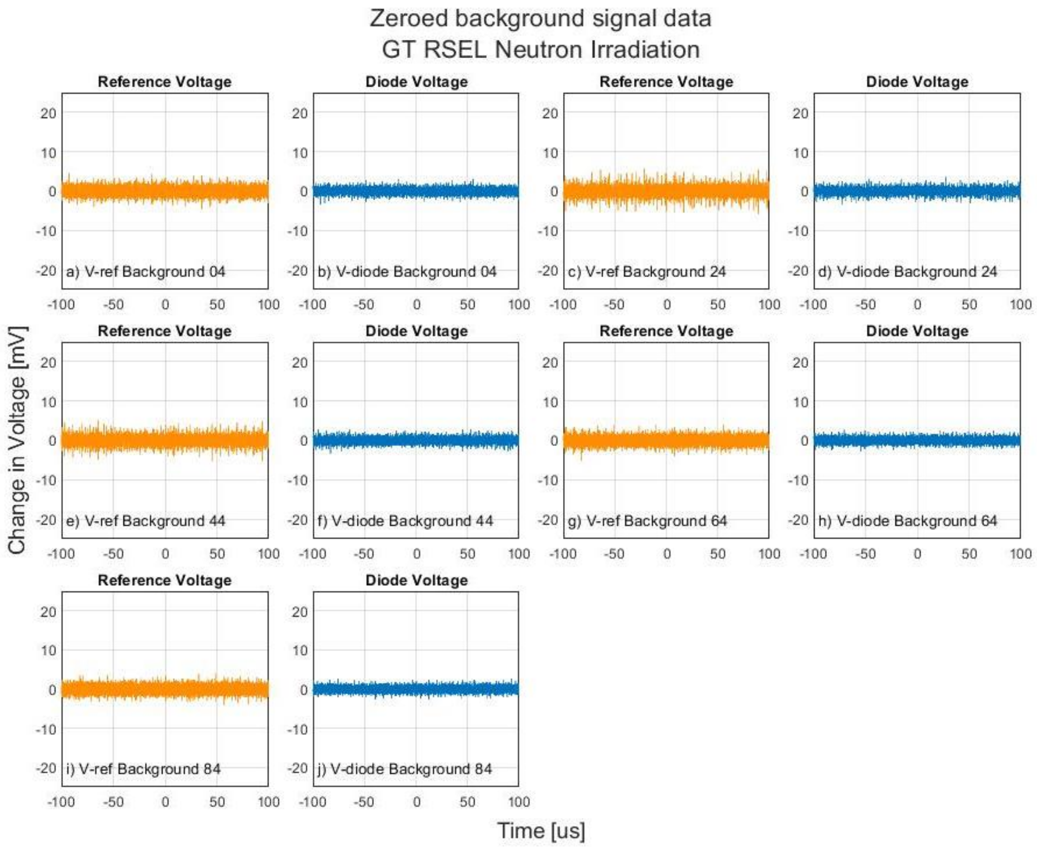
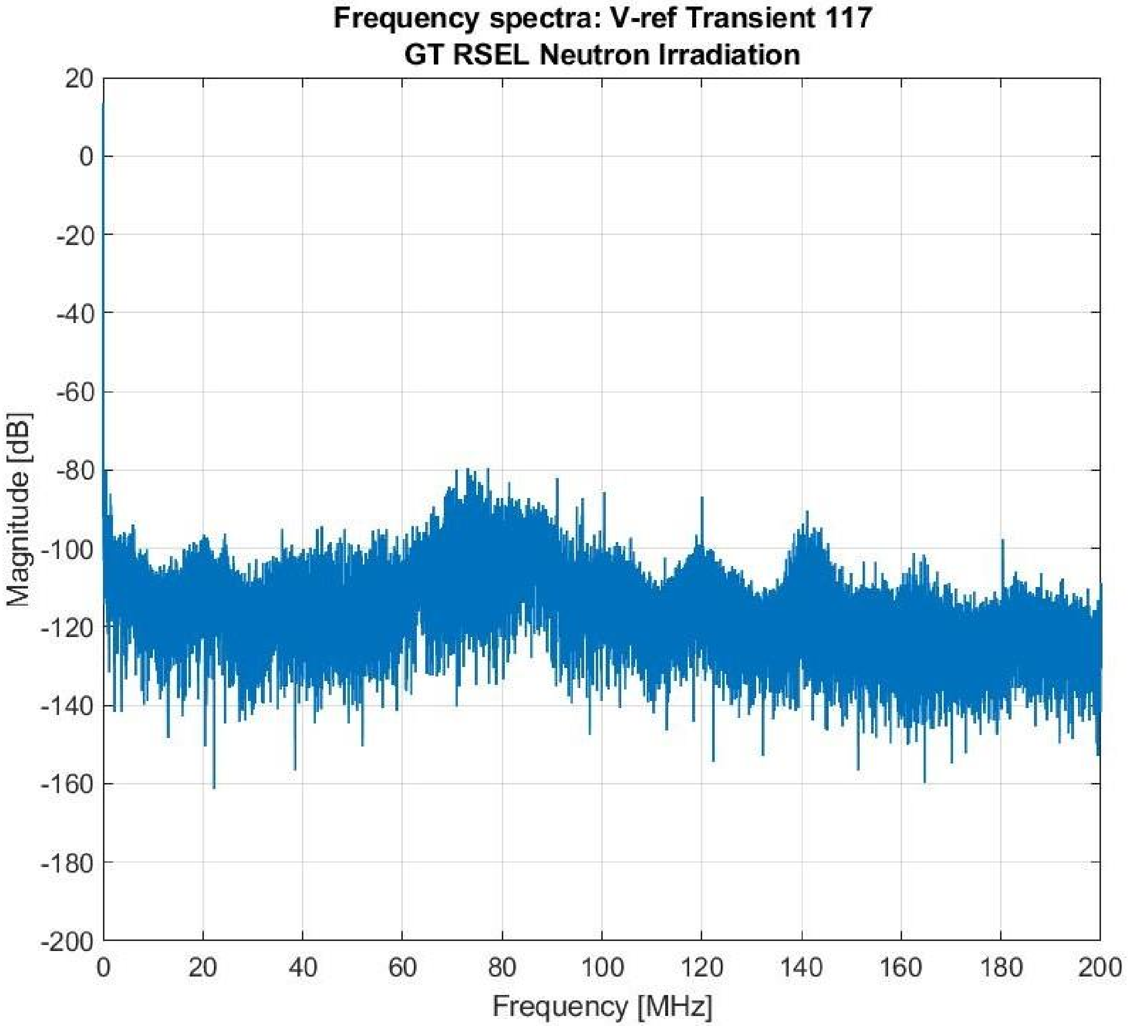
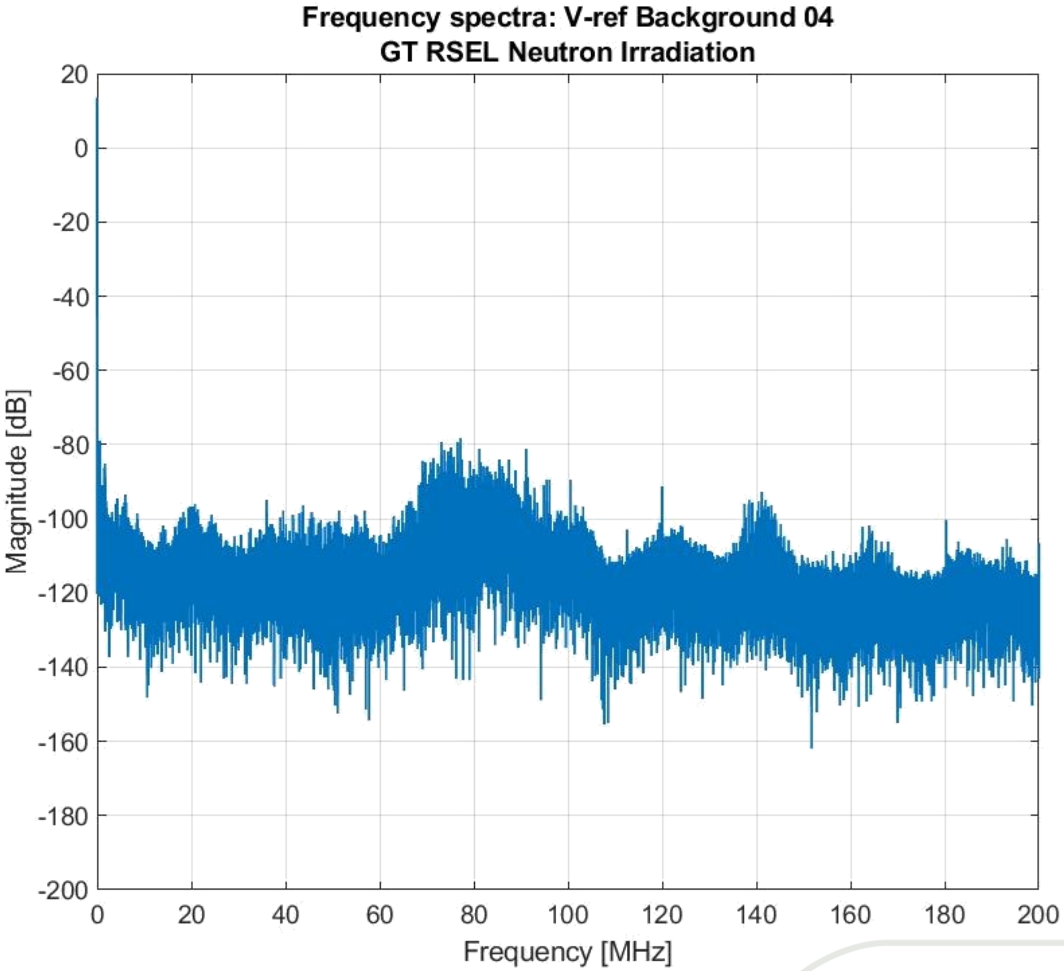
Neutron Irradiation Experiment at Georgia Tech



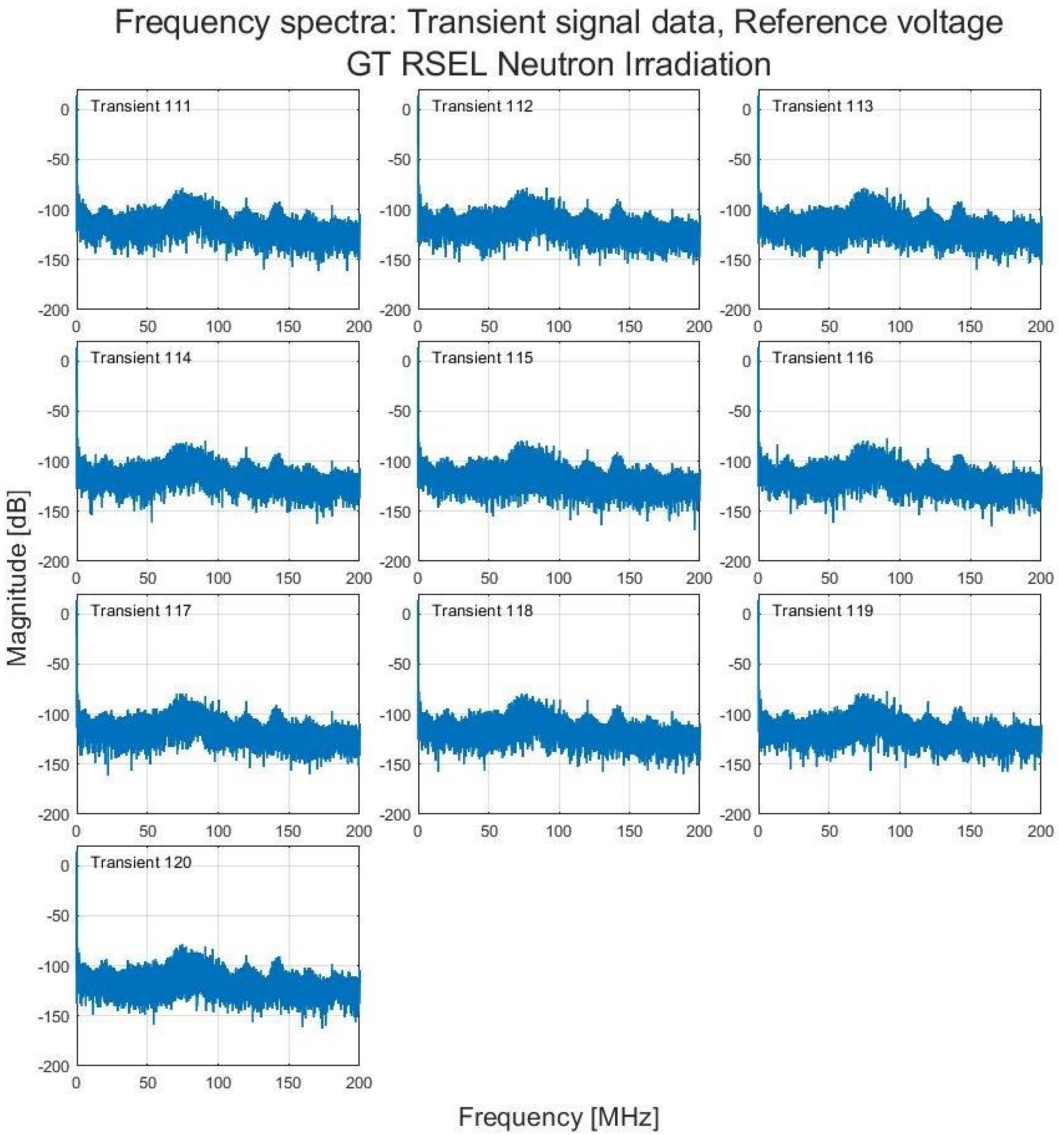


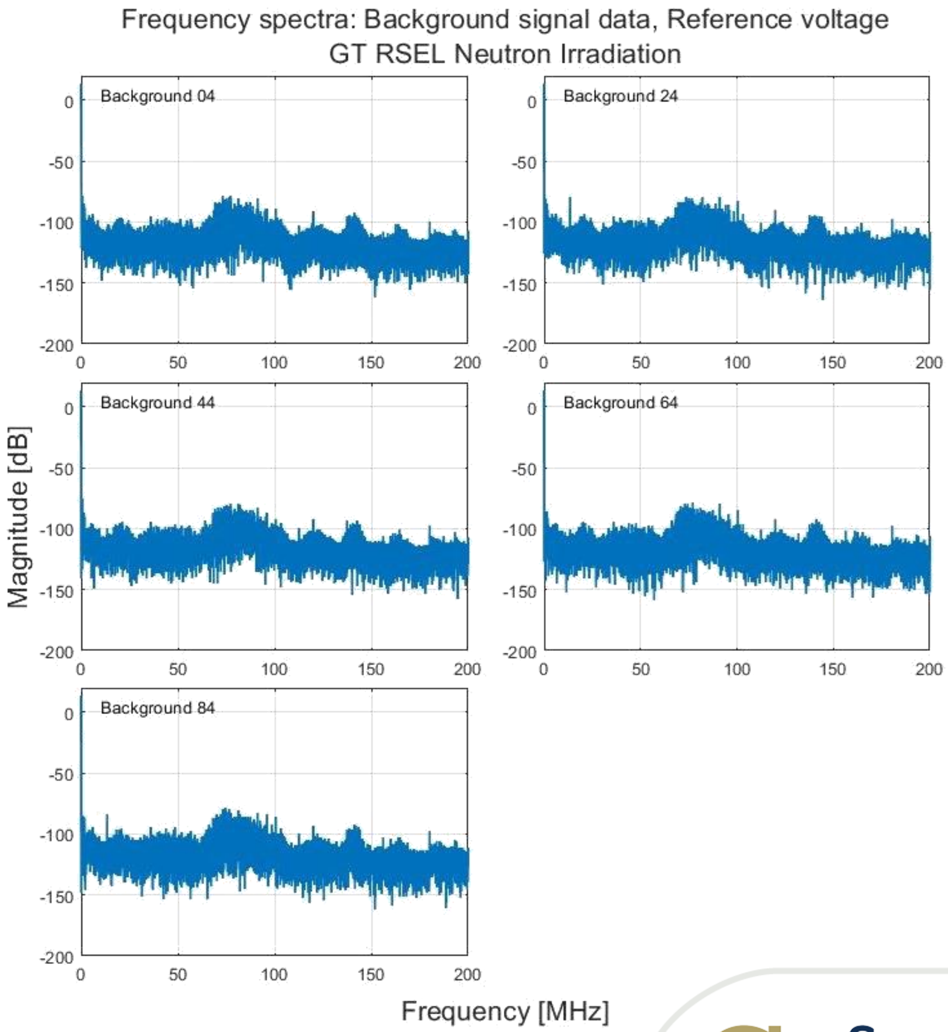
Neutron Irradiation at Georgia Tech
Frequency Spectra



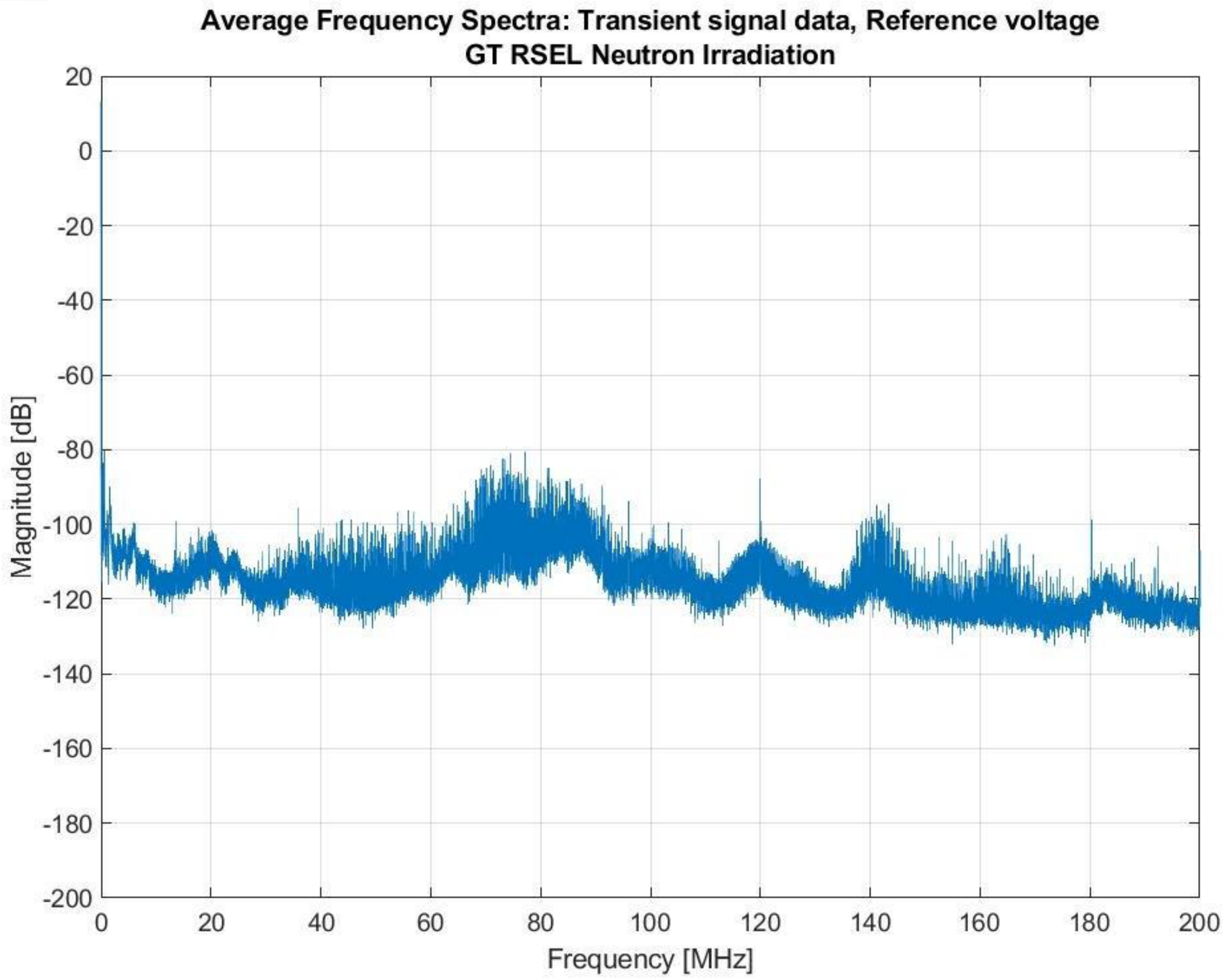


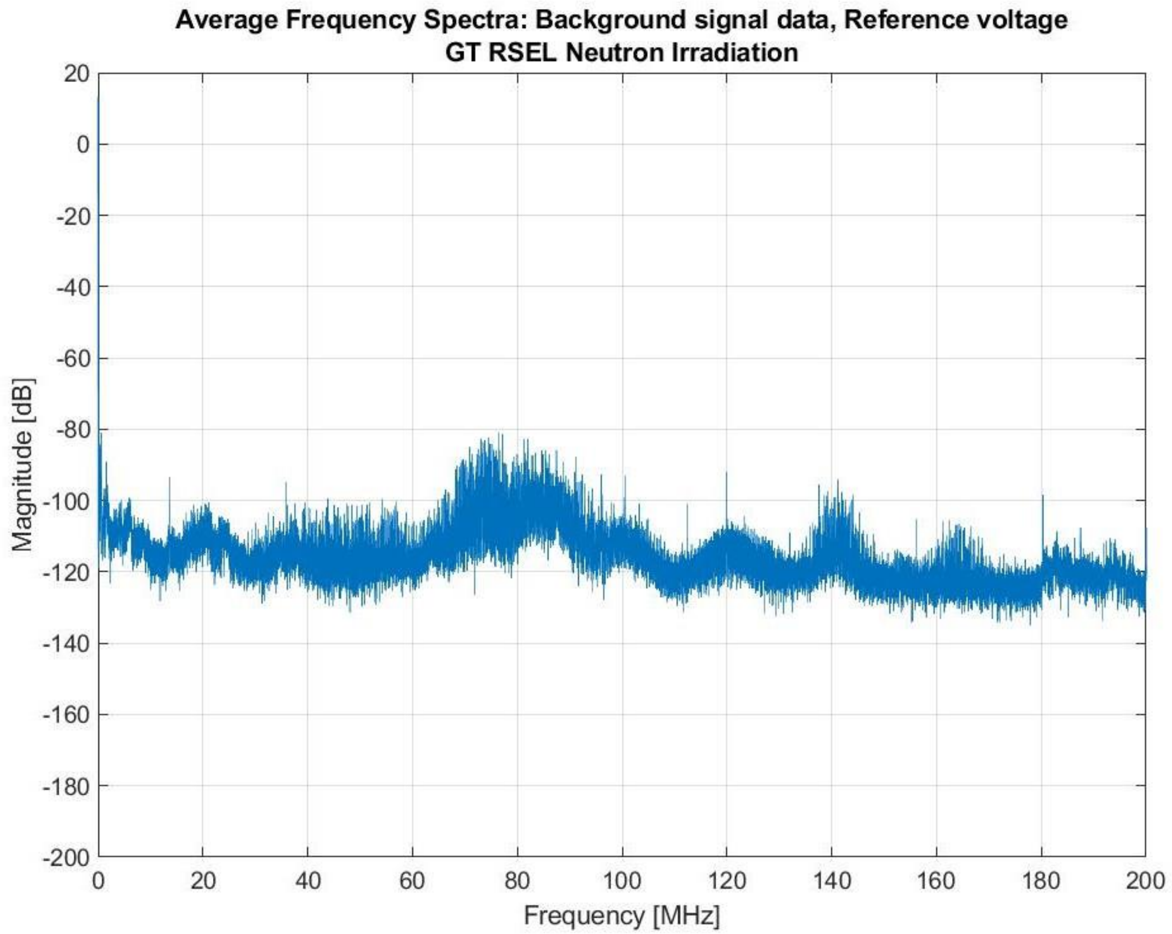
Neutron Irradiation at Georgia Tech
Frequency Spectra





Neutron Irradiation at Georgia Tech
Average Frequency Spectra





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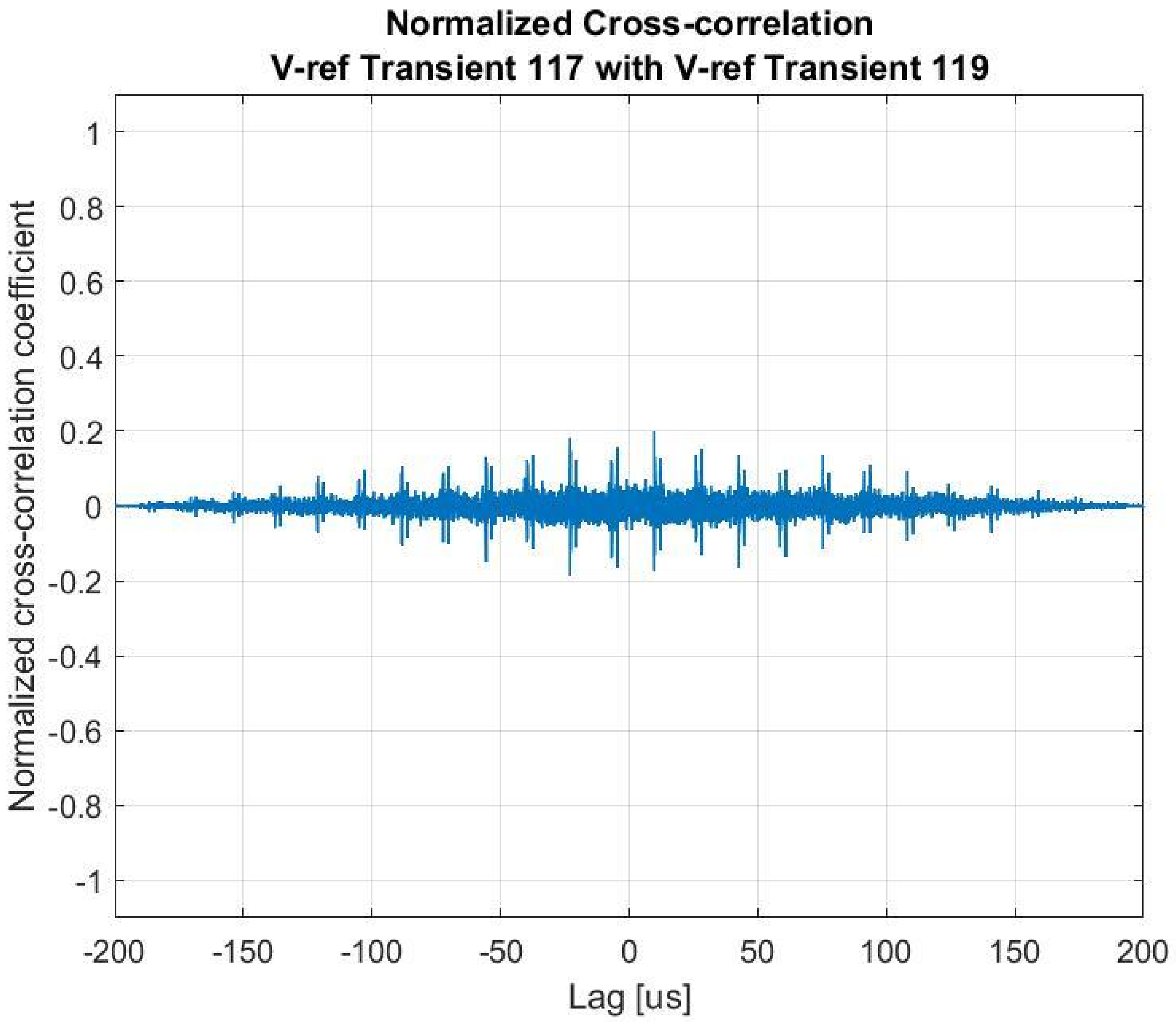
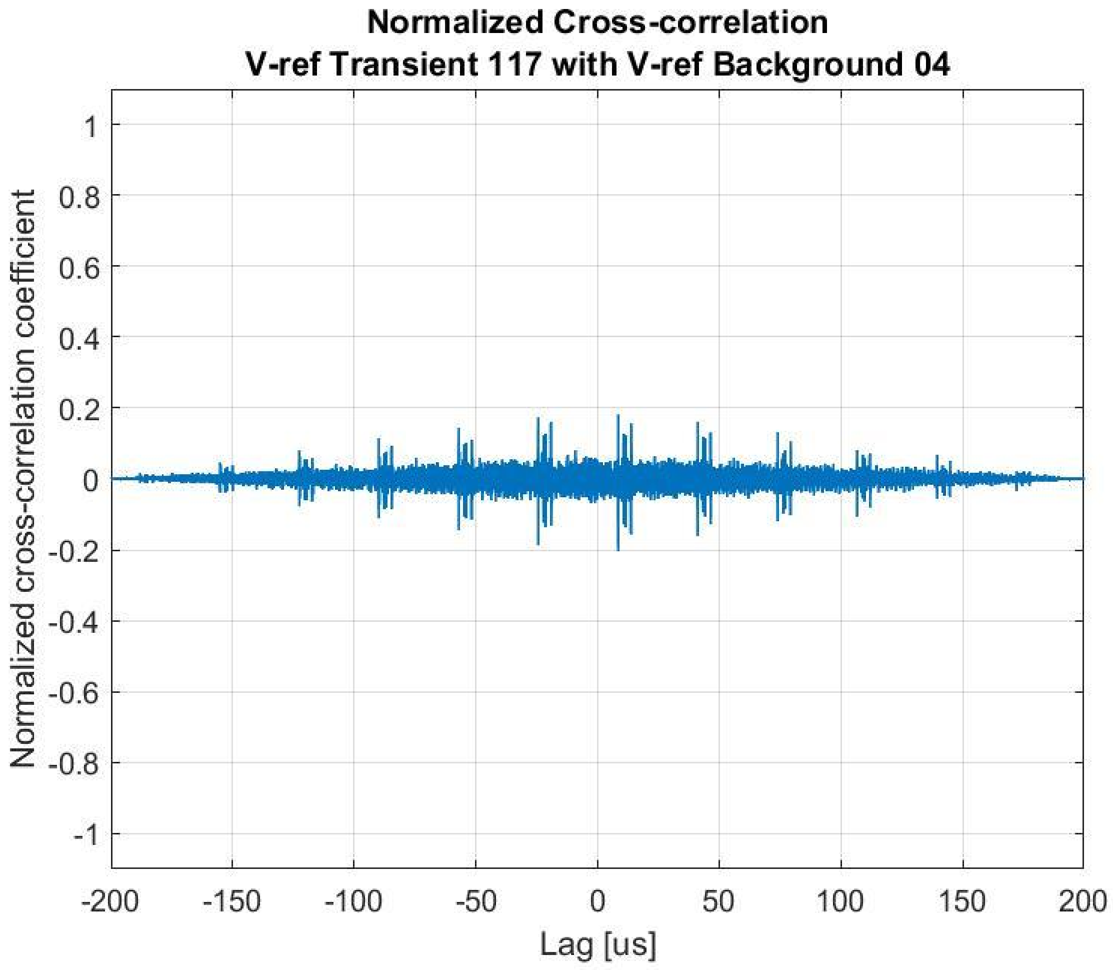
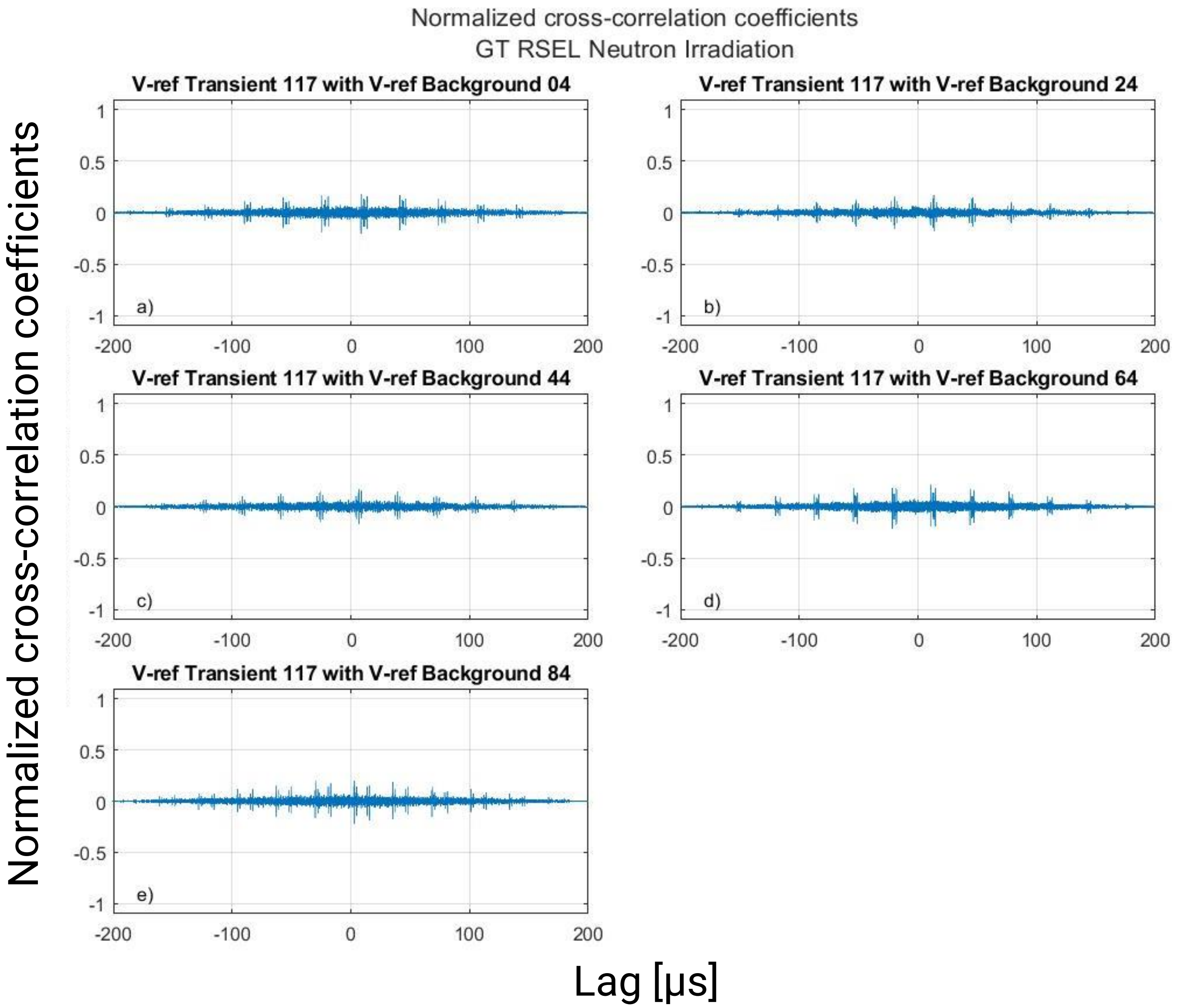
Neutron Irradiation at Georgia Tech
Cross-Correlation

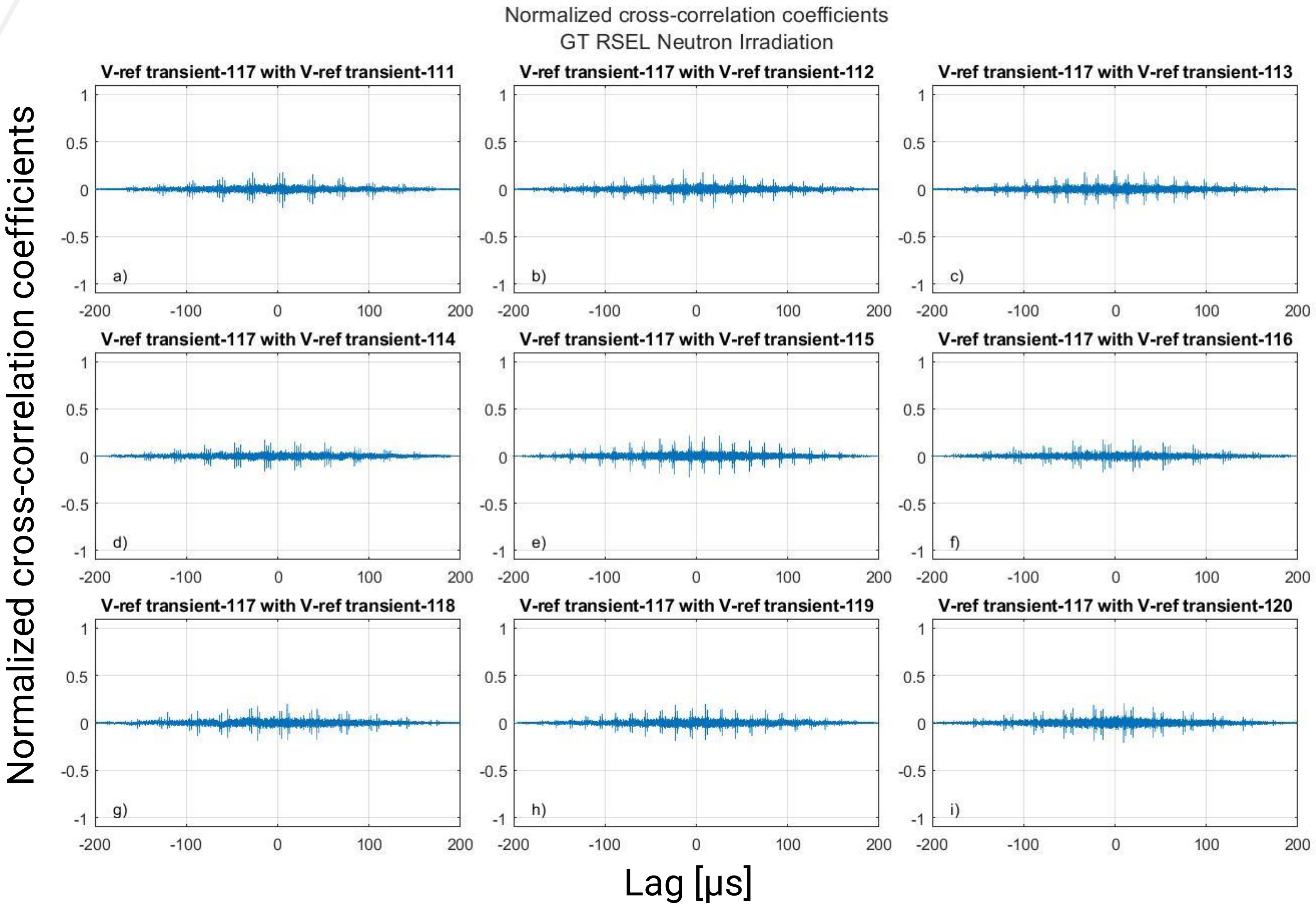




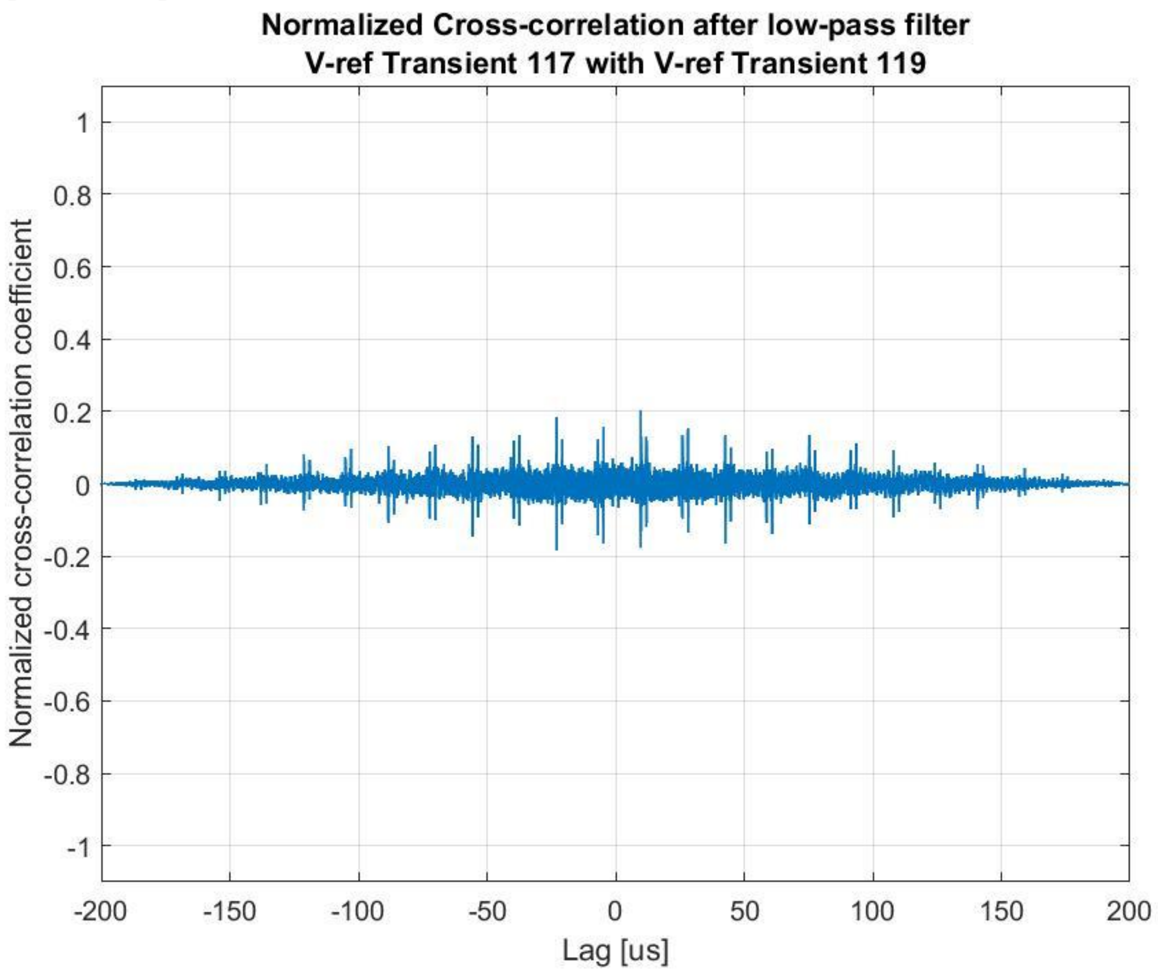
Neutron Irradiation at Georgia Tech
Cross-Correlation

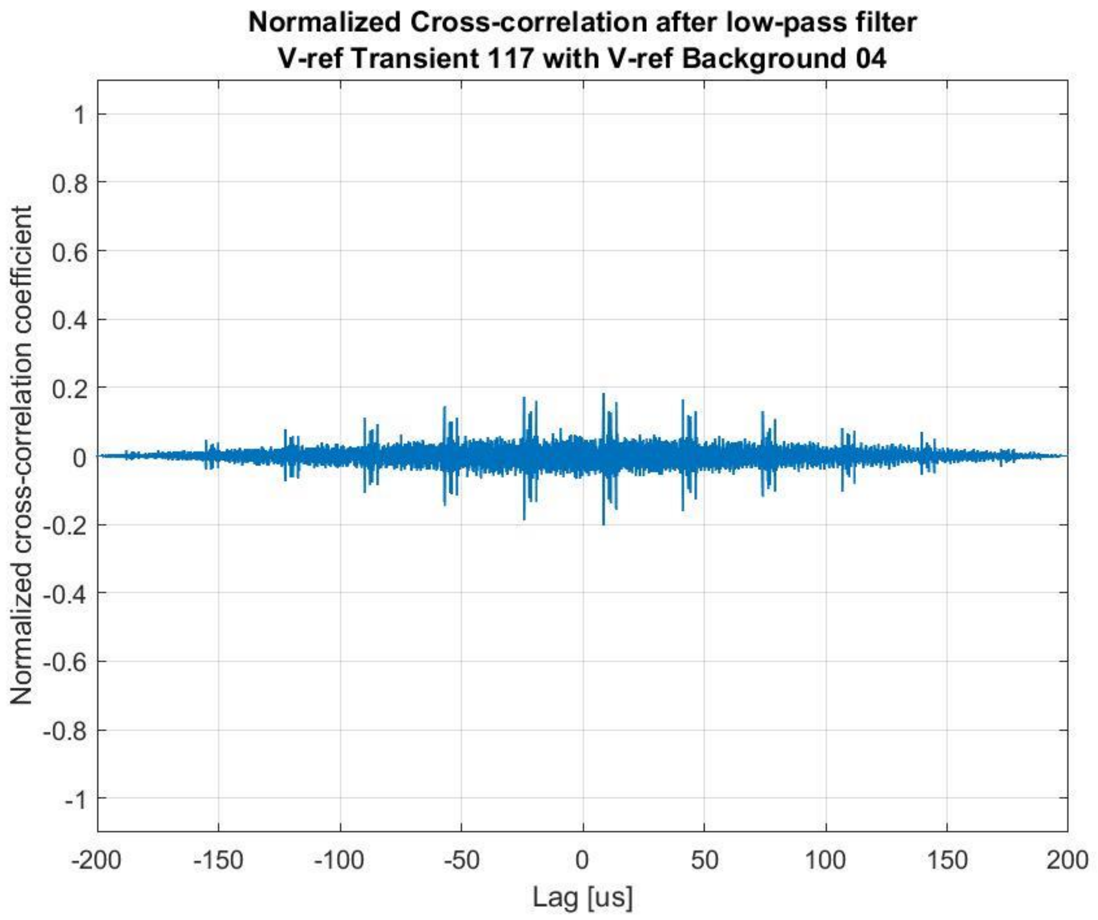


Neutron Irradiation at Georgia Tech
Cross-Correlation



Neutron Irradiation at Georgia Tech
Cross-Correlation after Low Pass Filtering





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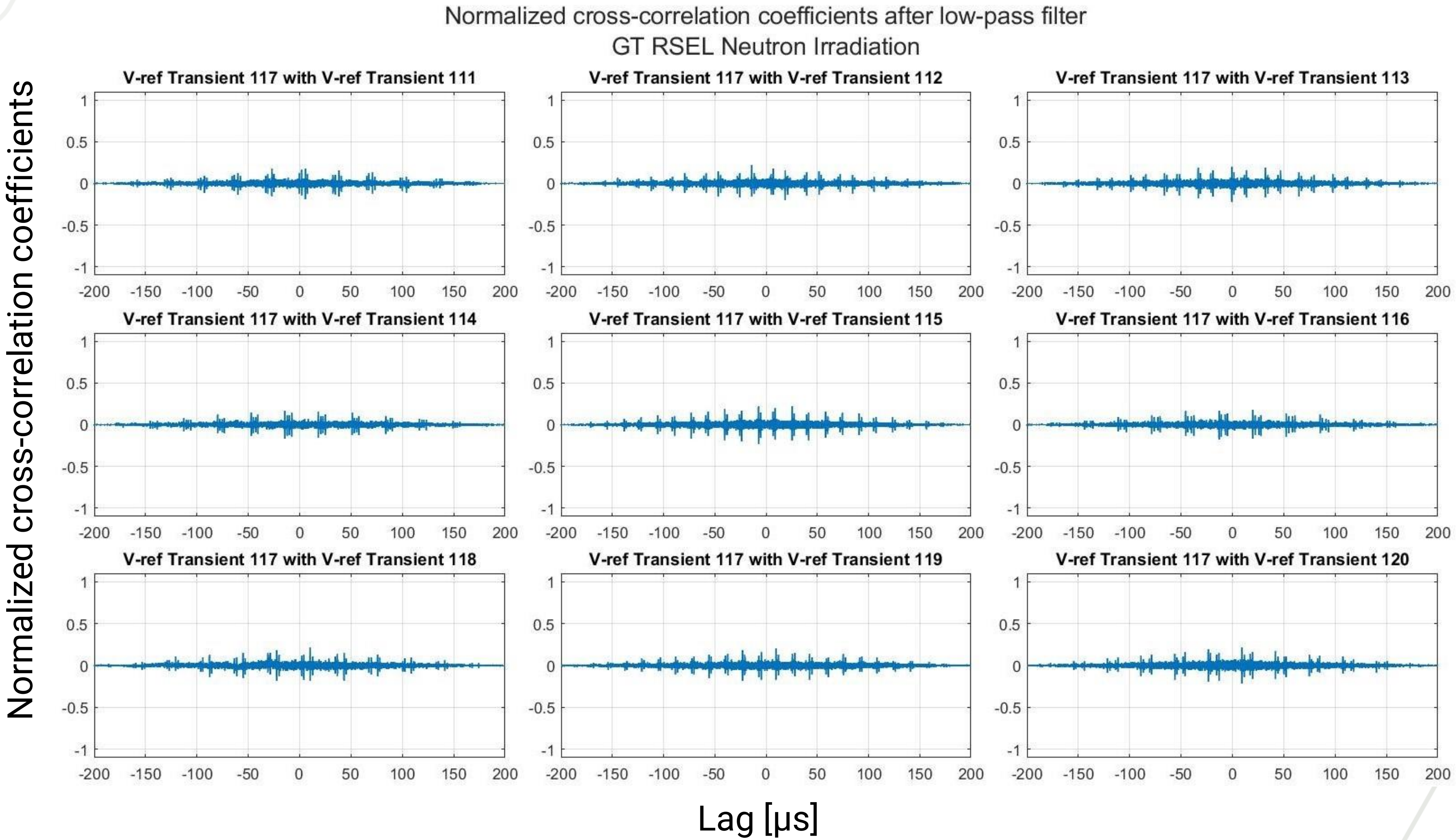
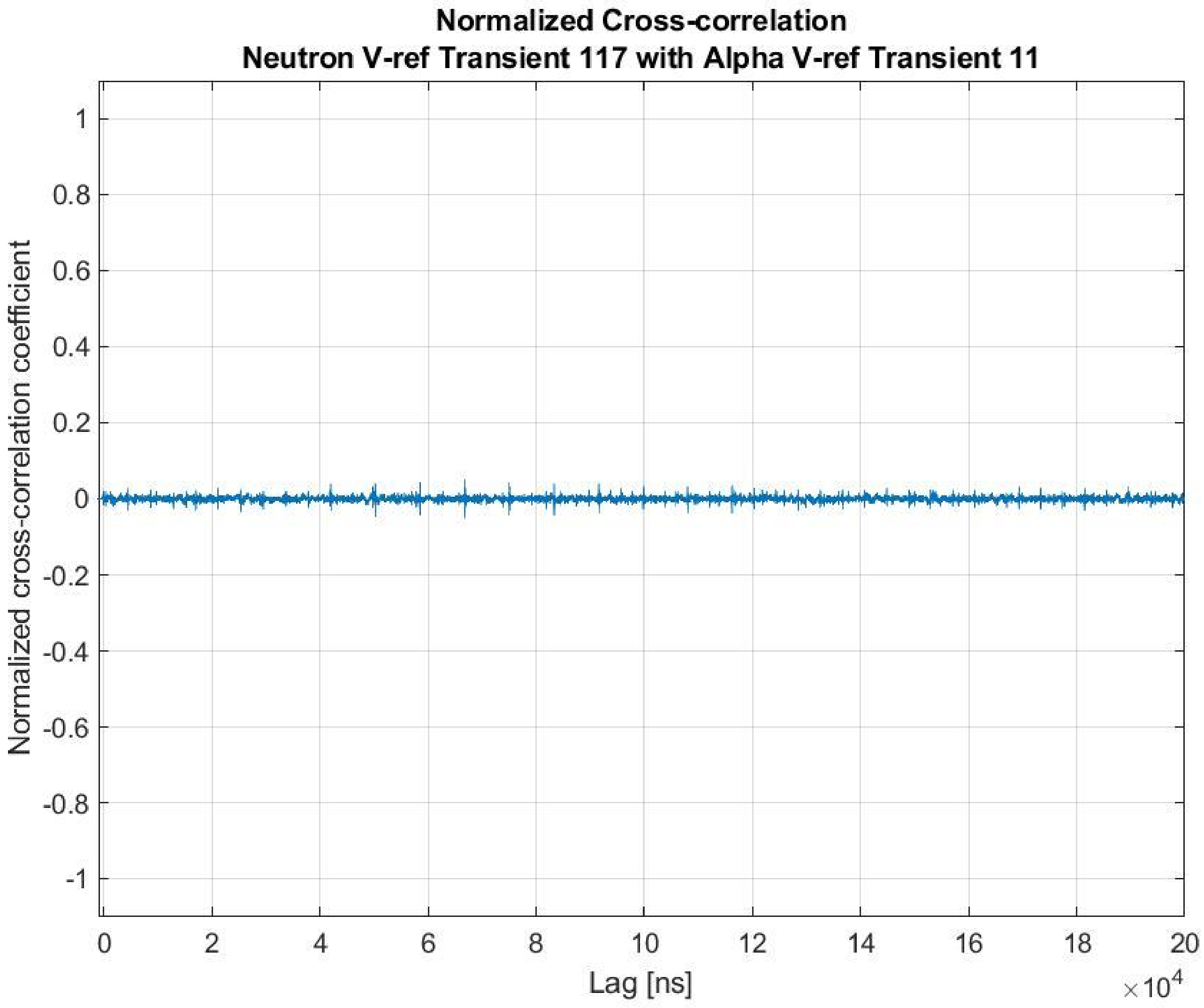
Neutron Irradiation at Georgia Tech
Cross-Correlation after Low Pass Filtering



Irradiation Experiments at Georgia Tech
Cross-Correlation of Alpha and Neutron Transient Signals



Outline

- Project Background
- Circuit Development
- Work Function Reference Circuit – First Prototype Irradiation at Sandia
- Work Function Reference Circuit – Second Prototype Irradiation at Georgia Tech
- Geant4 Modeling
- Conclusion

Theoretical Modeling with Geant4

- CERN hosts a toolkit that simulates the passage of particles through matter
- C++ based program with source code available
- Support is available, including guides to create custom simulations
- Experimentally validated across a range of disciplines and applications

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T. Kittelmann and M. Boin. Comput. Phys. Commun. **189**, 114-118. 2015. https://doi.org/10.1016/j.cpc.2014.11.009
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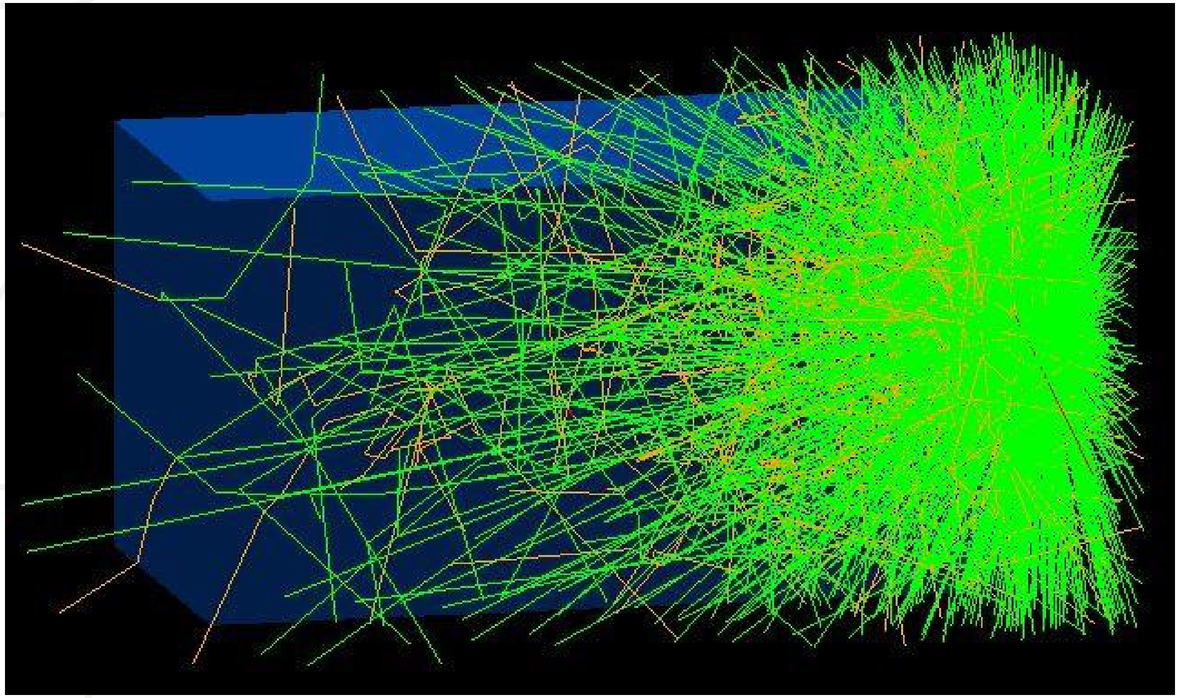
Customizability of Geant4

- Geometry of the system
- Materials involved
- Fundamental particles of interest
- Generation of primary particles of events
- Tracking of particles through materials and external electromagnetic fields
- Physics processes governing particle interactions
- Response of sensitive detector components
- Generation of event data
- Storage of events and tracks
- Visualization of detector and particle trajectories
- Capture for subsequent analysis of simulation data

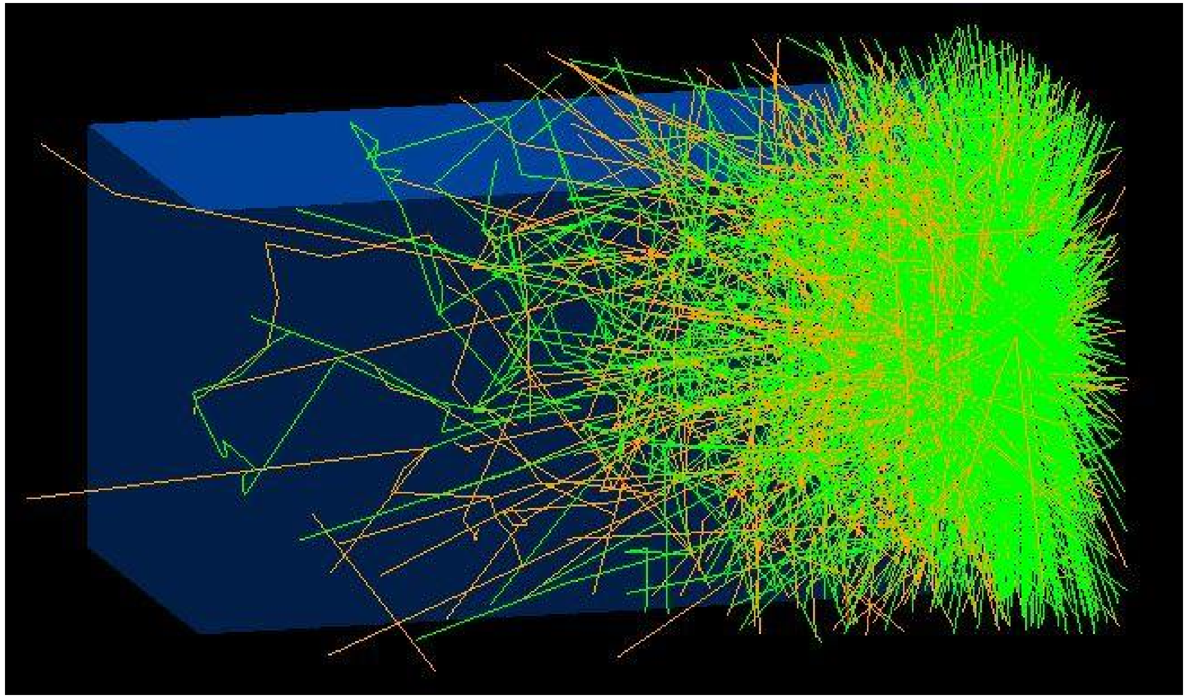
Geant4 Collaboration. Geant4 user's guide for application developers.

Geant4 Simulations – Bulk GaN

2000 neutrons, 2.1 MeV energy

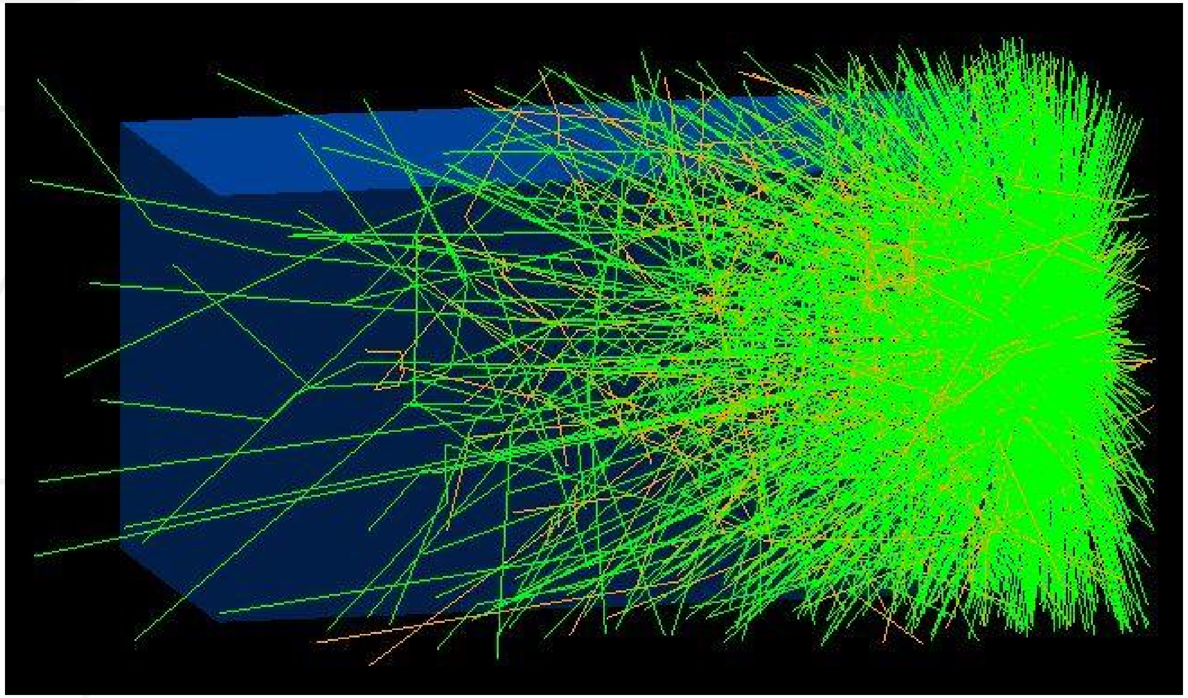


2000 neutrons, 1 eV energy

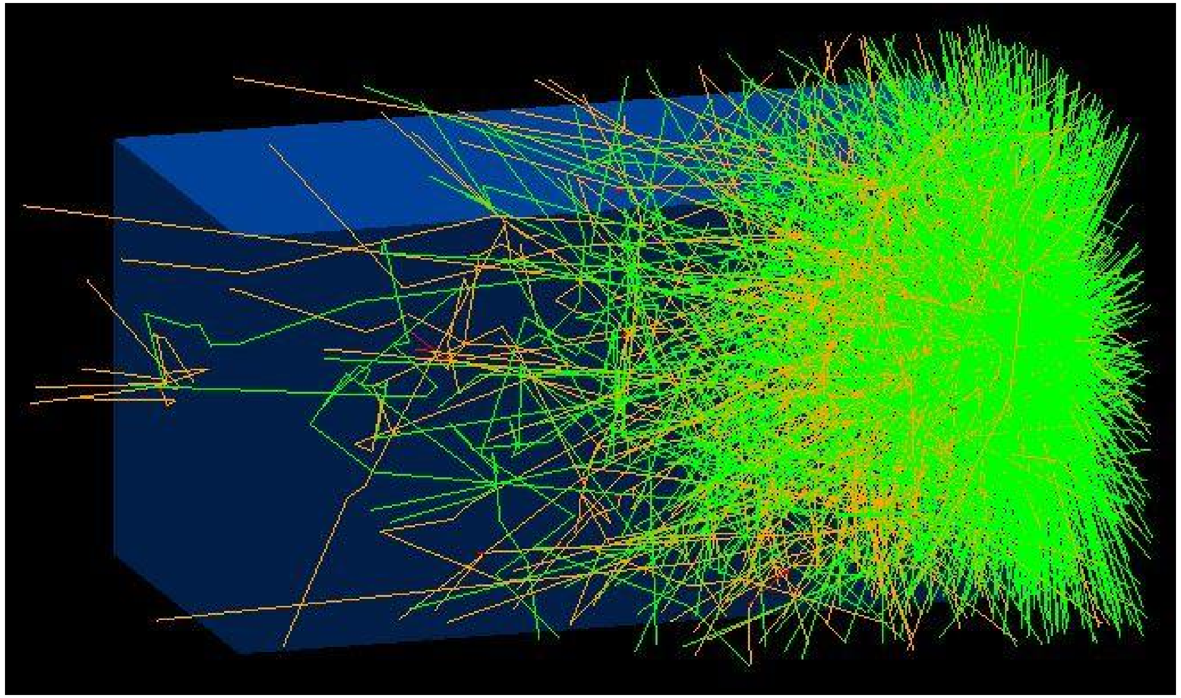


Geant4 Simulations – Bulk AlGaN

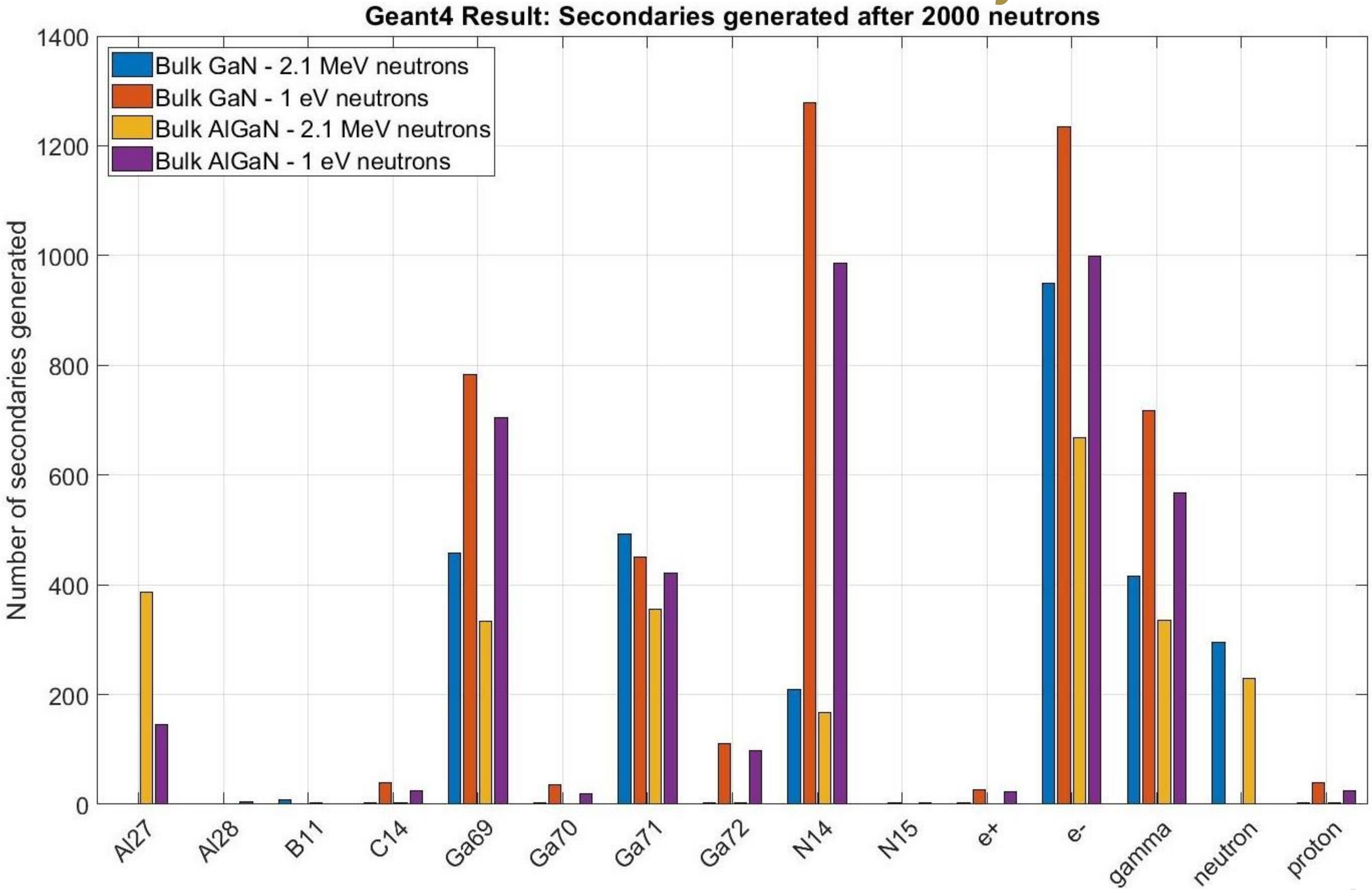
2000 neutrons, 2.1 MeV energy



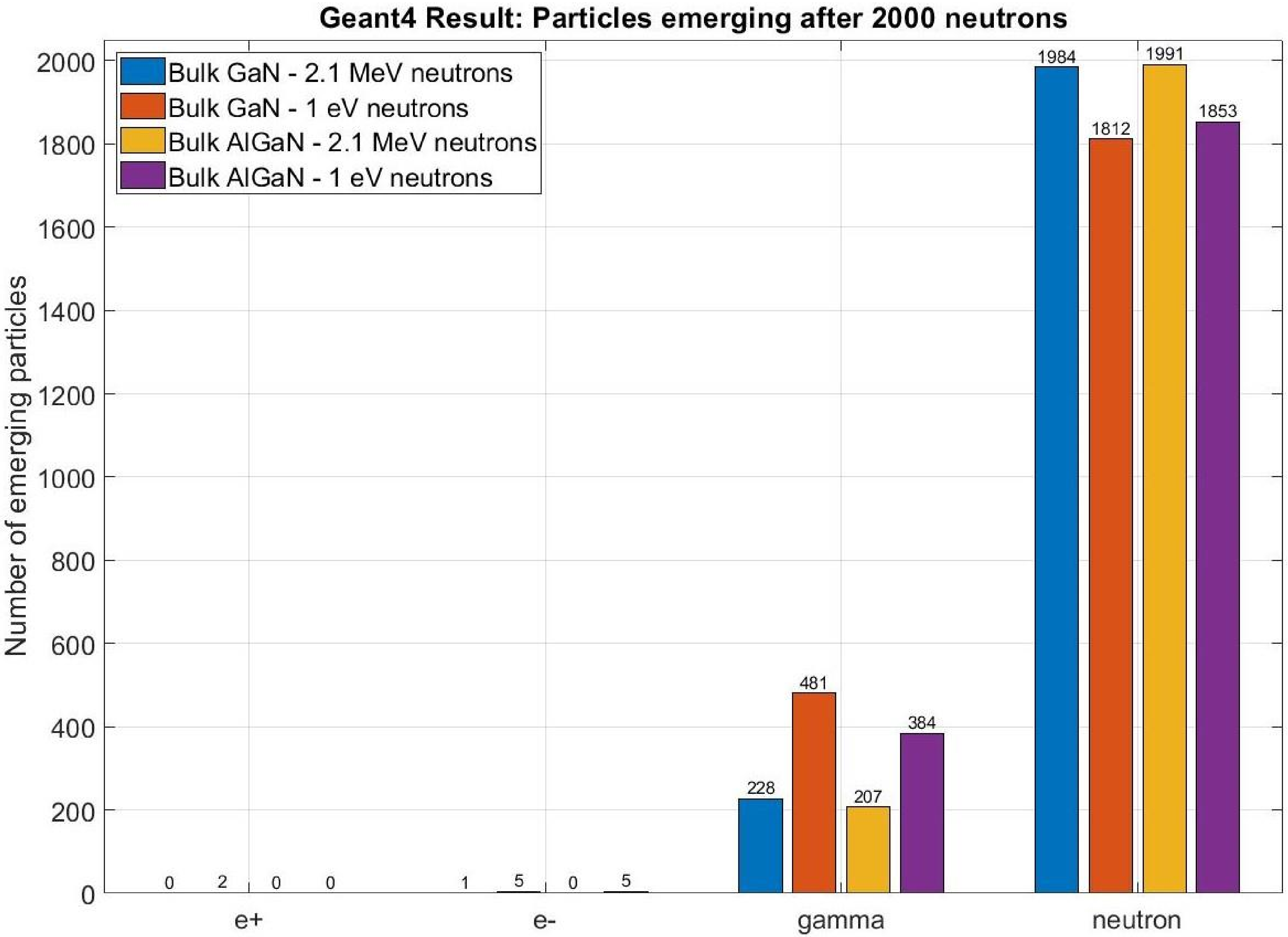
2000 neutrons, 1 eV energy



Geant4 Simulations – Secondary Particles

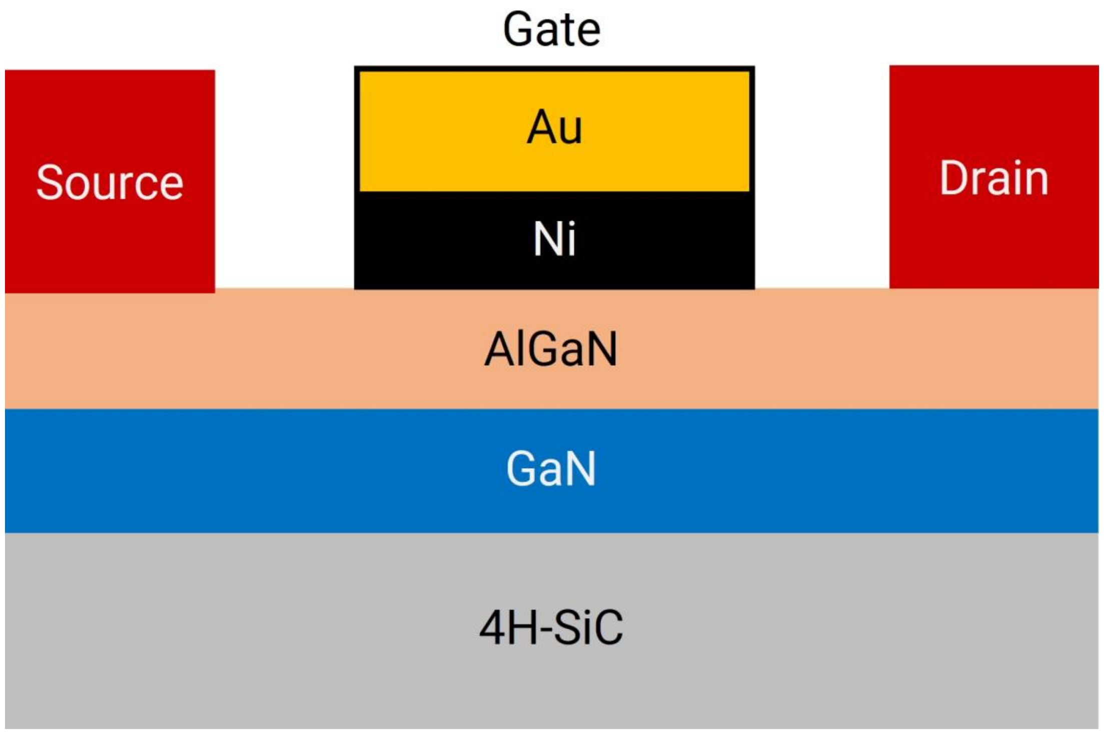


Geant4 Simulations – Emerging Particles



Geant4 Future Work Methodology

- Identify inaccuracies with sensitive detector scoring for bulk GaN and AlGaN
- Scale simulation for micron dimensions
- Build the Cree CGH40010F device in Geant4, with all GaN/AlGaN sections as physical and logical volumes to enable tracking in those areas
- Create generalized particle sources matching those used in the experiments
- Install G4CMP and incorporate phonon and electron-hole pair tracking



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Outline

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Summary

- Designed a work function reference circuit that uses GaN semiconductor devices based on modified analog bandgap reference circuit designs
- Simulation of the circuit design in LTspice indicates improved temperature stability
  - GaN Schottky-diode-connected HEMT voltage temperature dependence: -2.02 mV/°C
  - Reference voltage temperature dependence: -94.5 µV/°C
- Experimental temperature data using a breadboard version of the circuit
  - GaN Schottky-diode-connected HEMT voltage temperature dependence: -2.8 mV/°C
  - Reference voltage temperature dependence: -0.566 mV/°C

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Summary

- Irradiation testing of the first prototype indicated…
  - Output is low-noise under non-irradiative conditions
  - Transient signals are observable
  - Qualitative difference in transients observed for neutron and alpha irradiation
- Irradiation testing of the second prototype indicated…
  - Transient signals are observed under alpha irradiation
  - Quantitative differences in frequency spectra and high normalized cross-correlation values (≥0.7) demonstrate high degree of similarity between signals
  - Transient signals may have been observed under neutron irradiation, though quantitative analysis of frequency spectra and normalized cross-correlation do not conclusively confirm neutron observation occurred
  - External noise sources present during the neutron experiment are confounding the neutron data and ongoing efforts seek to filter out these external sources

Summary

- Geant4 simulations
  - Extremely customizable simulation space
  - Examining bulk GaN and AlGaN materials bombarded with 2000 neutrons of two energies (2.1 MeV and 1 eV) reveals creation of secondary particles that need to be accounted for when analyzing experimental data
  - Primarily neutrons and gammas have sufficient energy to emerge from the bulk materials

Future Work

- Circuit simulation
  - Measure the temperature dependence of GaN Schottky-diode-connected HEMTs independent of the circuit
  - Implement measured temperature dependence in simulation
- Irradiation experiments
  - Redesign prototype board layout to minimize errors
  - Fabricate a new prototype with new discrete components
  - Repeat irradiation tests, utilizing triggering in parallel with BenchVue software for streamlined data collection
  - Implement shielding for the non-irradiated components of the prototype
- Geant4 simulation following planned methodology

Acknowledgements

- Prof. William Hunt, Prof. Laura Cadonati, Prof. Phillip First, Prof. JC Gumbart, Prof. Nepomuk Otte
- Aaron Green
- Other students in the Hunt group, current and former: Amy Wilson, Daniel Canales, Christian Ford, Dave Thompson, Kevin Liow, Ben Barger, Mikias Balkew, Phillip Yamin, Hannah Phillips, Hanna Etelalahti, Daniel Hudadoff
- Dr. Thierry Leichle, Christopher Howard
- Sharmistha Mukhopadhyay, Dr. Hertel
- James Black, Anant Girdhar, and all of the Group Leaders from GT6000
- DOE Office of Science Graduate Student Research program

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- Bob Kaplar and other Sandia colleagues, including Trevor Smith, Andrew Binder, Jeramy Dickerson, Tony Rice, Paul Sharps, Jeffrey Steinfeldt, Eduardo Padilla, Jesus Valencia, Diane Gaylord
- Family and friends, including: Mom and Dad, Heather and Casey, Rachel and Ben, David, Andrea, Emily, Kira, Alex, Kevin, David and Ashley, Sasha, Heather, Meredith, Zephia, Crystal, Aspen, Assia, Christy, Jennifer, Alana, Corisa, Megan, Esther, Dale, Laura

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