U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

ASI Advanced Sensors and Instrumentation

Gallium Nitride-based 100-Mrad Electronics Technology for Advanced Nuclear Reactor Wireless Communications

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

November 4, 6-7, 2024

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Oak Ridge National Laboratory

Project Overview

Research Purpose and Scope:

- Electronics technologies available for present day, in-service nuclear reactor sensing and communications are unsuitable due to high radiation and high temperature environments
- This project will investigate and demonstrate the suitability of gallium nitride (GaN) HEMT-based electronics for reactor sensor interfacing and wireless communications
- Successful completion will advance the state-of-the-art in harsh environment electronics technologies for present and future advanced reactor applications

Participants:

Oak Ridge National Laboratory

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- Nance Ericson
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- Brett Witherspoon
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- Kevin Deng
- Emma Brown
- Adam Buchalter

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The Ohio State University

- Siddharth Rajan
- Raymond Cao
- Chandan Joishi
- Jack Lanza
- Hyunsoo Lee
- John Cobbinah
- Adithya Balaji

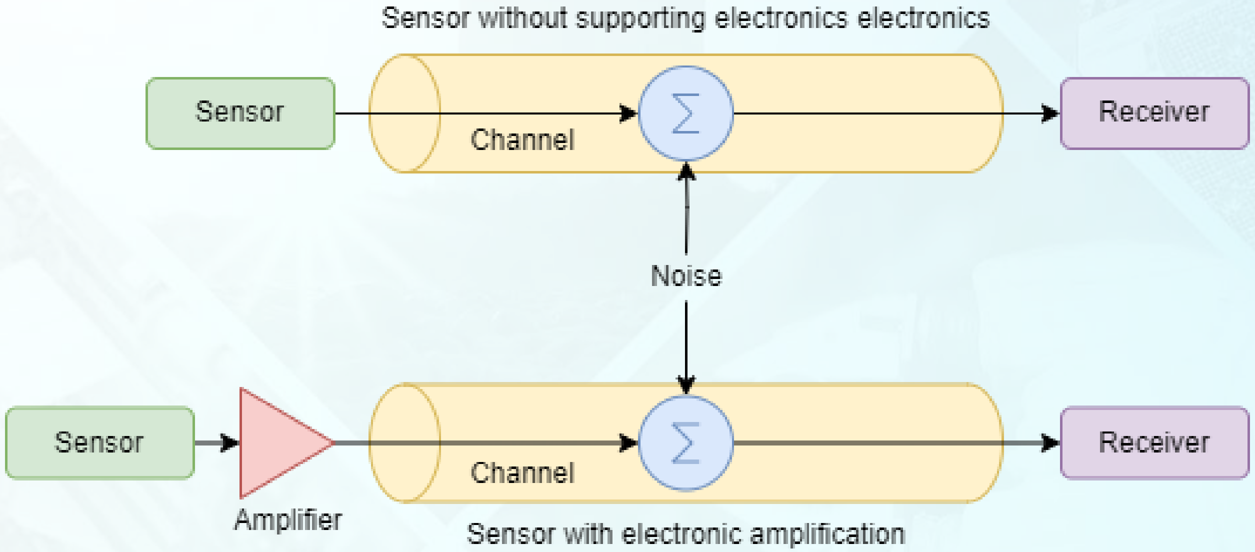
The Ohio State University

Schedule:

- October 2021 – September 2024

Technology Impact: Why Radiation-Hardened Electronics?

- Placing sensors and associated electronics closer to a nuclear reactor core will improve reactor control and operation through increased signal accuracy, precision, and fidelity resulting in safer and more efficient energy production
- Electronics placed closer to sensors can multiplex and/or processes signals, reduce bandwidth for transmission, and reduce cabling and penetration requirements lowering costs and increasing infrastructural integrity



$$SNR = \frac{S}{N_{CH}}$$

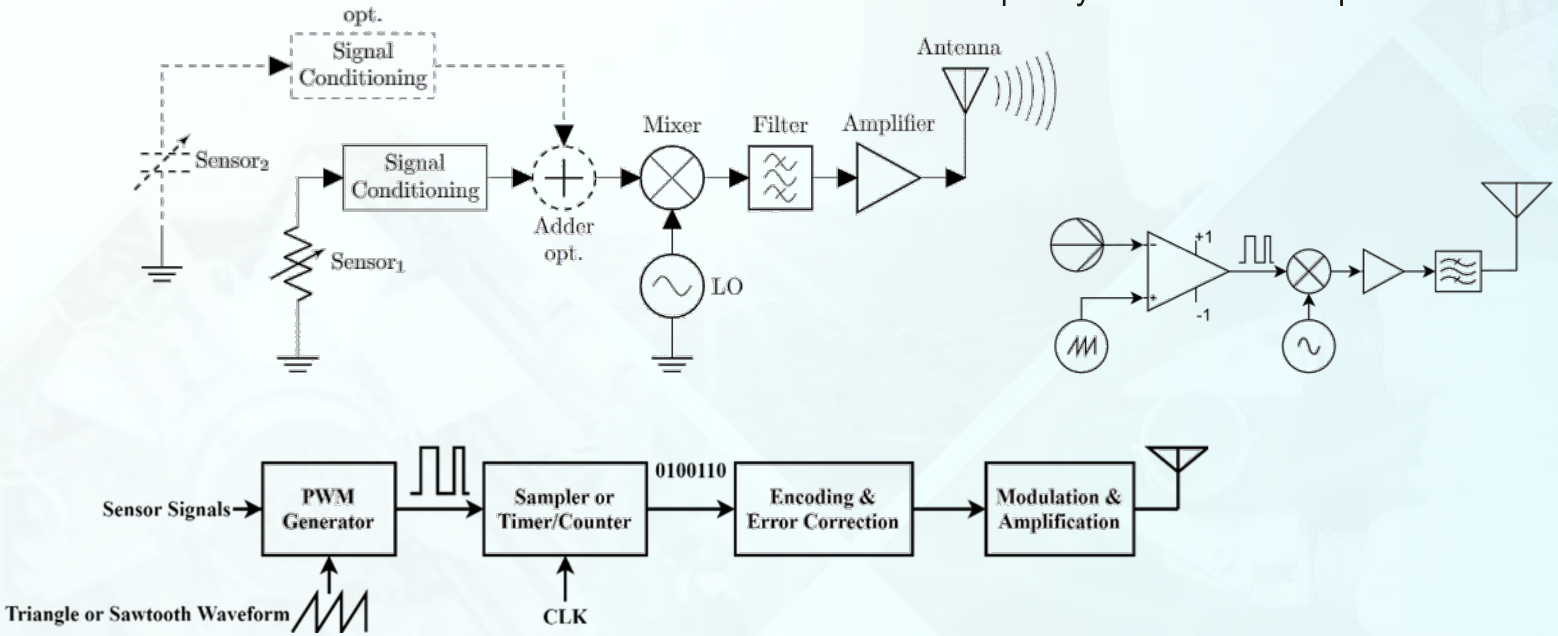
$$SNR = \frac{A \cdot S}{N_{CH} + N_A}$$

Technology Overview

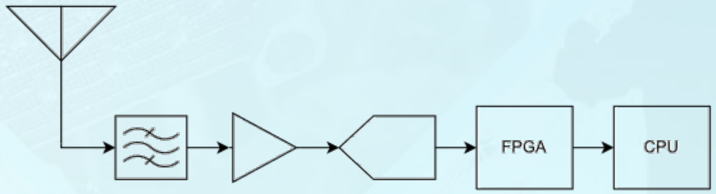
Investigate and demonstrate the suitability of gallium nitride (GaN) HEMT-based electronics for reactor sensor interfacing and wireless communications.

- Designing low complexity, cost effective, and radiation robust sensor signal conditioning and wireless transmission circuitry will increase safety and reliability while reducing maintenance costs associated with nuclear reactors, spent fuel casks, and emergency robotics
- Complex algorithms can be performed in a low-radiation environment

Low complexity transmitter examples



High complexity receiver



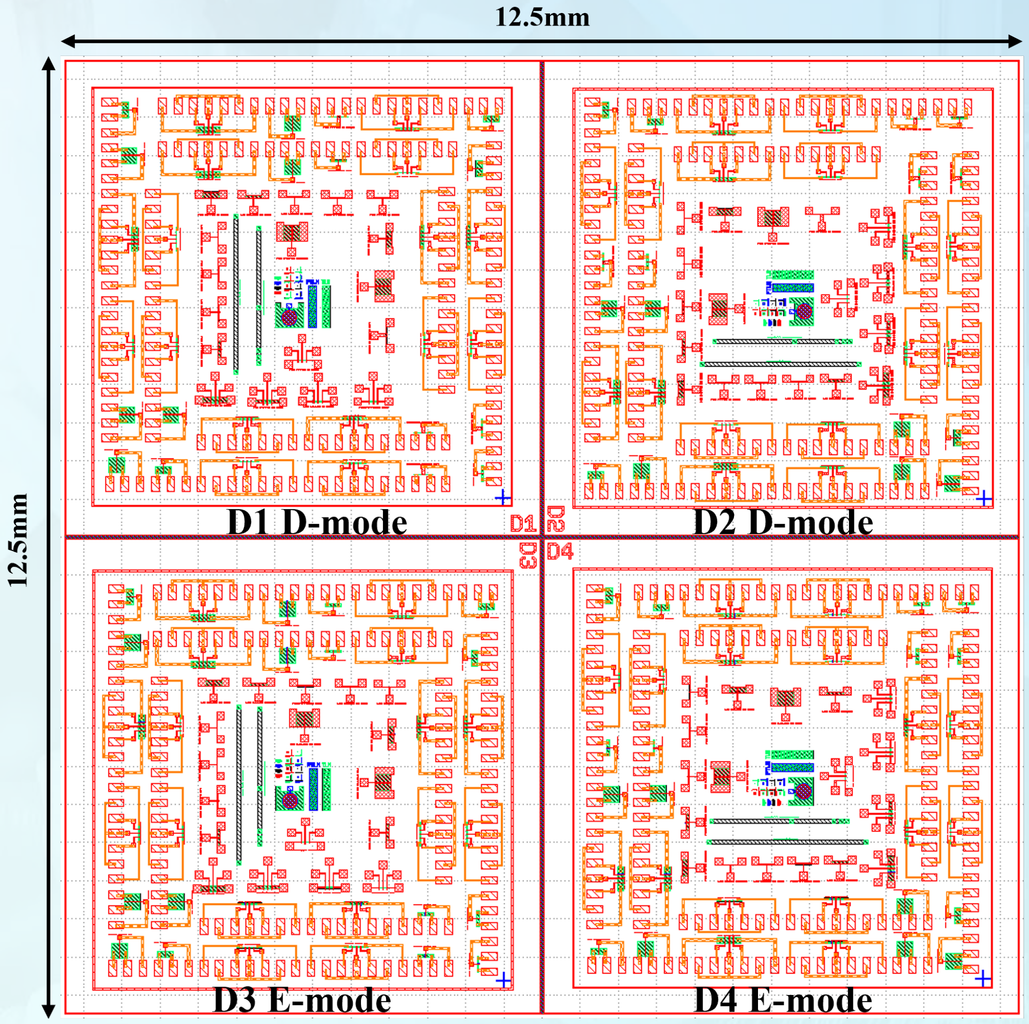
Si-Based Electronics Components Radiation Limits

	Neutron Displacement Damage [1]		**Total Ionization Dose (TID) Damage** [2]	
	Max Fluence (n/cm^2)	Displacement effect	TID (rad)	TID effect
Diodes/ Photodiodes	10^{13}-10^{15}	↑ leakage current; ↑ forward voltage threshold	10^{6}-10^{8}	↑ photocurrents
LEDs	10^{12}-10^{14}	↓ light intensity	10^{7}-10^{8}	0.25 dB attenuation
BJTs	10^{13}	Current gain degradation	10^{5}-10^{7}	Current gain degradation; ↑ leakage current
JFETs	10^{14}	↑ channel resistivity; ↓ carrier mobilities	$>10^{8}$	Minimal effects
SiC JFETs	10^{16}	↑ channel resistivity; ↓ carrier mobilities	$>10^{8}$	Minimal effects
MOSFETs	10^{15}	↑ channel resistivity; ↓ carrier mobilities	10^{6}	↑ threshold voltage; ↑ leakage current
CMOS	10^{15}	↑ channel resistivity; ↓ carrier mobilities	10^{8}	variation in threshold voltage; variations in leakage current

[1] Neamen, Donald A. Semiconductor physics and devices: basic principles. New York, NY: McGraw-Hill,, 2012.
[2] H. Spieler, "Introduction to radiation-resistant semiconductor devices and circuits." AIP Conference Proceedings. Vol. 390. No. 1. American Institute of Physics, 1997.

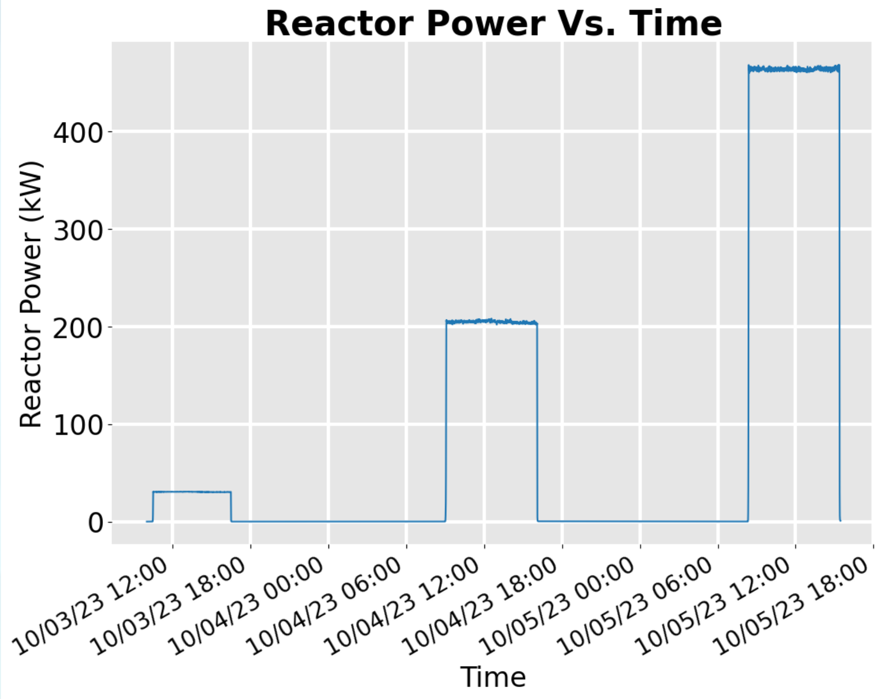
Why GaN?

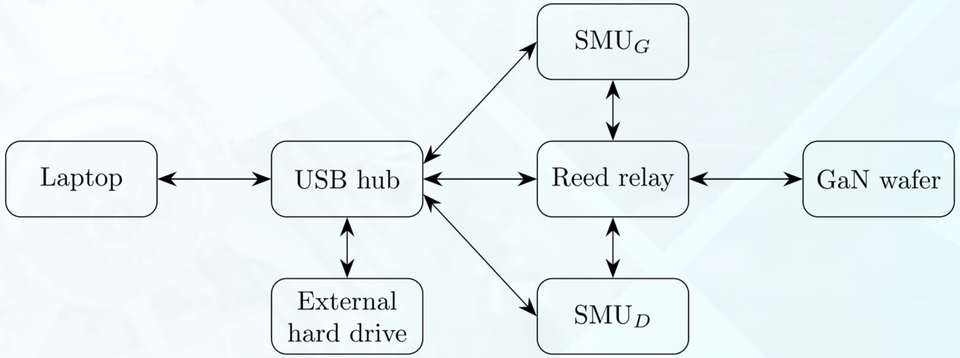
- High bonding in binary and ternary nitrides makes GaN devices intrinsically resistant to displacements
- Enhancement-mode (E-mode) and depletion-mode (D-mode) device fabrication and operation is possible without requiring gate insulation for the field effect devices
- The 2D electron gas (2DEG) allows for channel charges as high as 3×10^{13} cm^{-2} without introducing dopants, which allows for high channel mobilities by reducing impurities
- GaN HEMTs have been shown to withstand 600 Mrad ionizing dose (neutron limits are under investigation by this team)

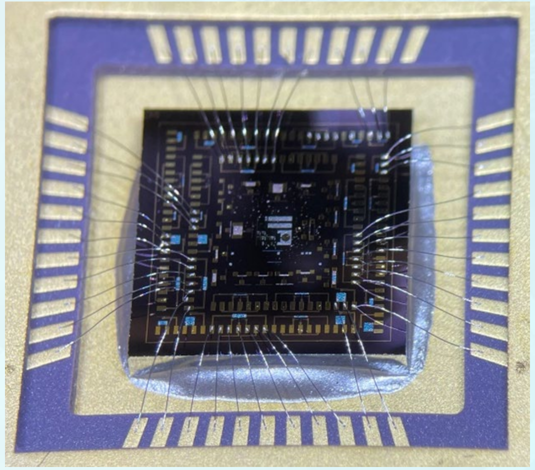


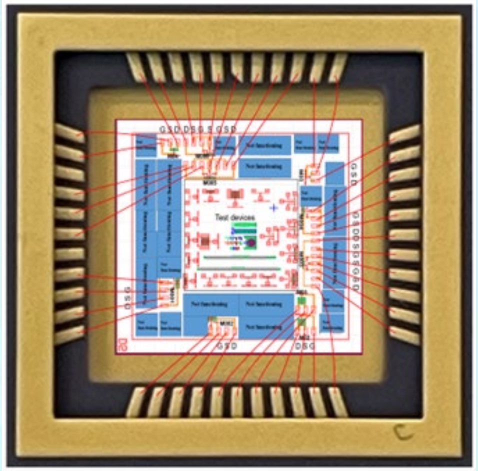
October 2023 Heated Irradiation Overview

- Two die (1 E-mode and 1 D-mode) were irradiated in the OSU Dry Well Facility (DWF) while heated to understand the temperature and irradiation effects
- The irradiation was performed over three days
- The first two days the samples were heated
- The third day the samples were only irradiated
- Transistor characteristic curves (I-V curves) were taken before, during, and after irradiation
- To date, the saturation current, threshold voltage, cut-off current, and transconductance variations to the reactor radiation spectrum have been investigated

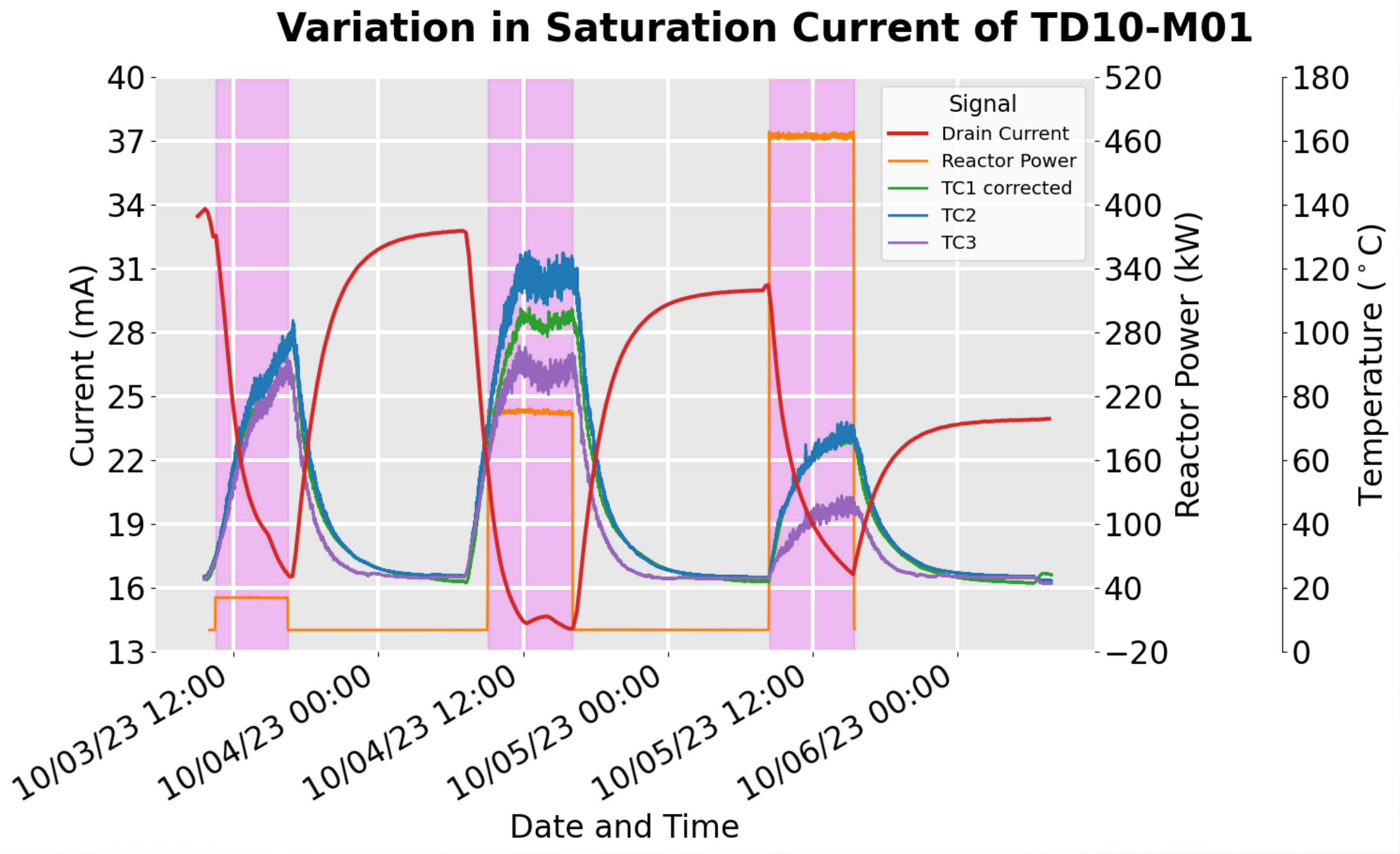




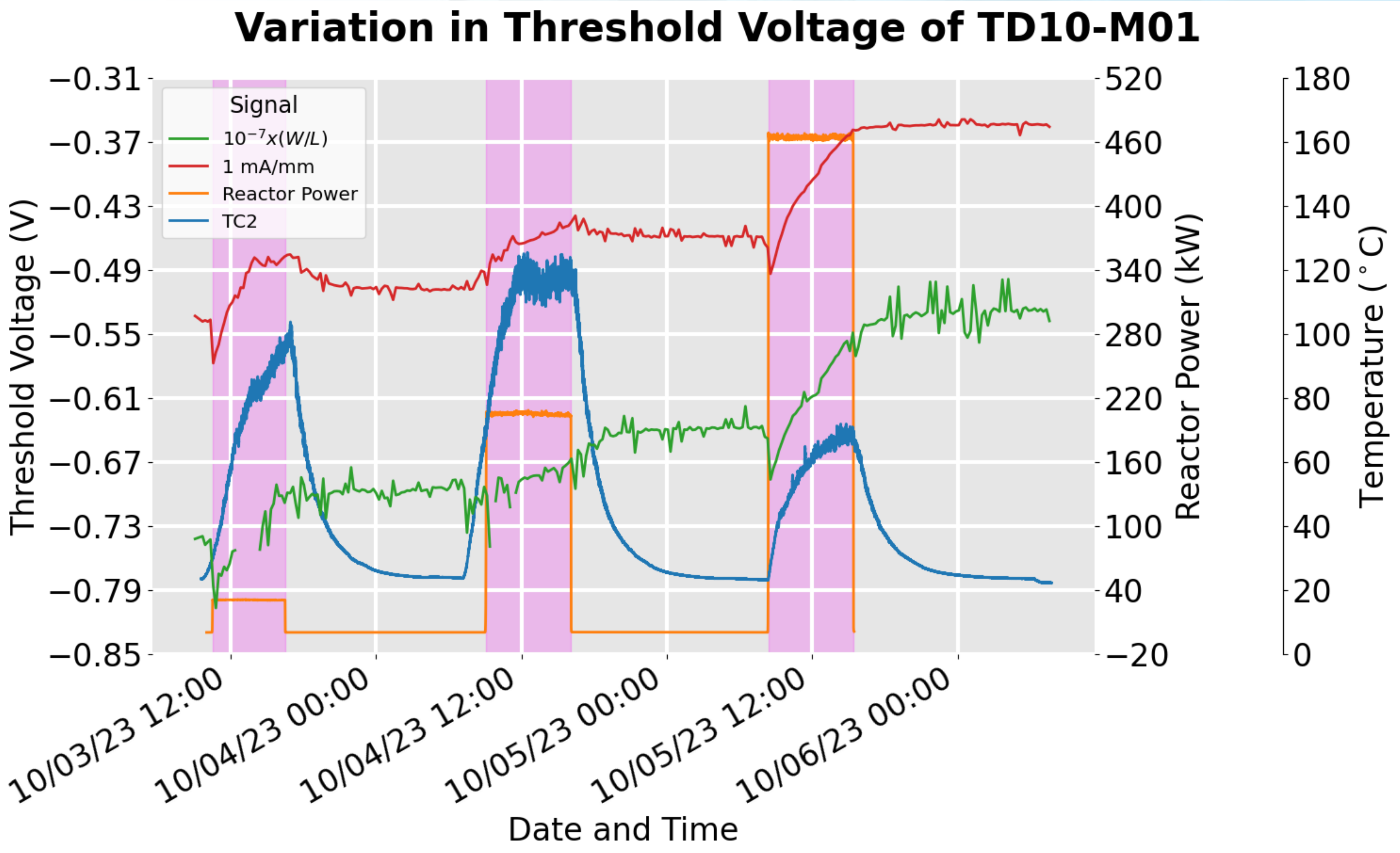




October 2023 Heated Irradiation: Saturation Current Example

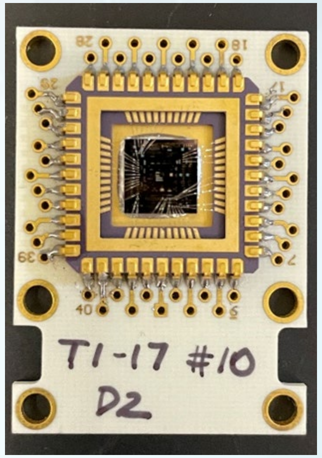


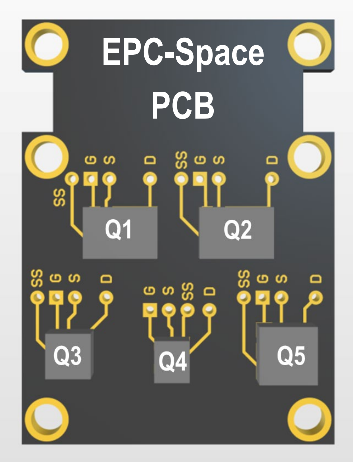
October 2023 Heated Irradiation: Threshold Voltage Example

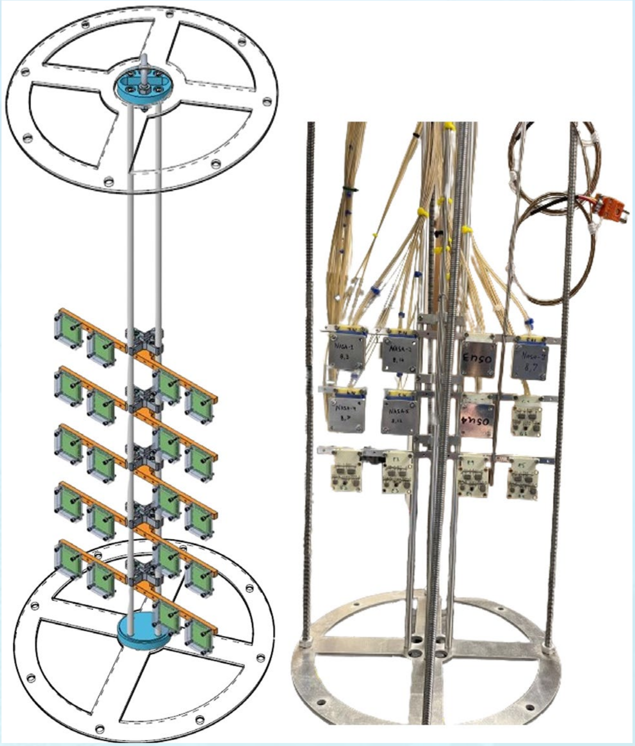


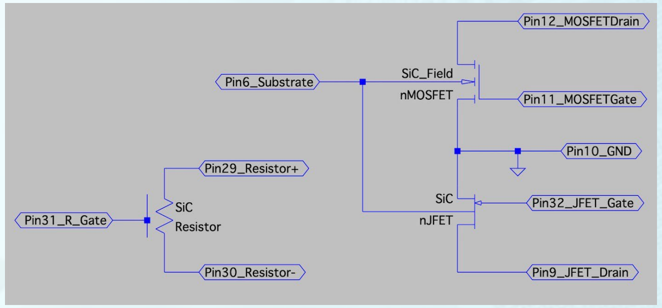
June 2024 Simultaneous Irradiation Experiment

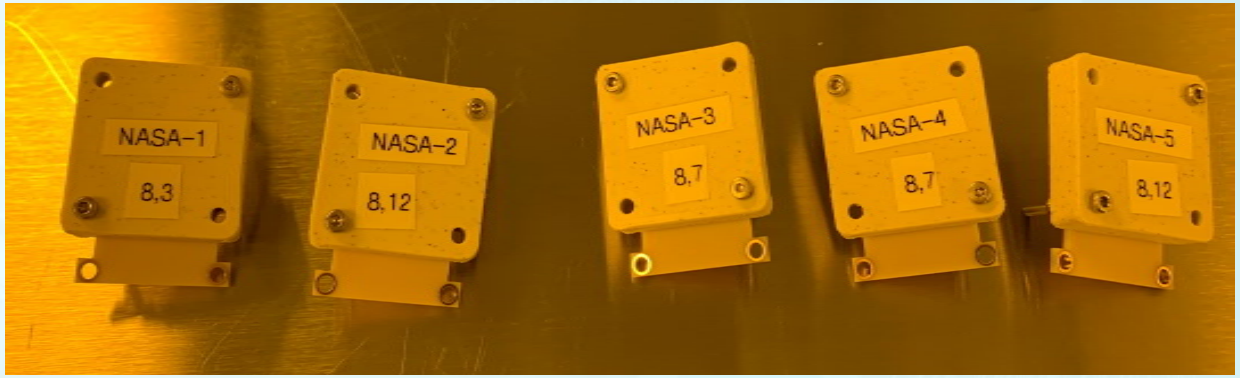
- A dual irradiation experiment was performed in June 2024 in two of OSU's reactor facilities -- the Auxiliary Irradiation Facility (AIF) and the Dry Well Facility (DWF)
- The AIF has a particle flux that is an order of magnitude greater than the DWF
- OSU GaN HEMT samples were measured in situ in the AIF
- OSU GaN HEMTs, EPC-Space eGaN® HEMTs, and NASA-Glenn SiC JFETs were measured in situ in the DWF for a technology comparison irradiation



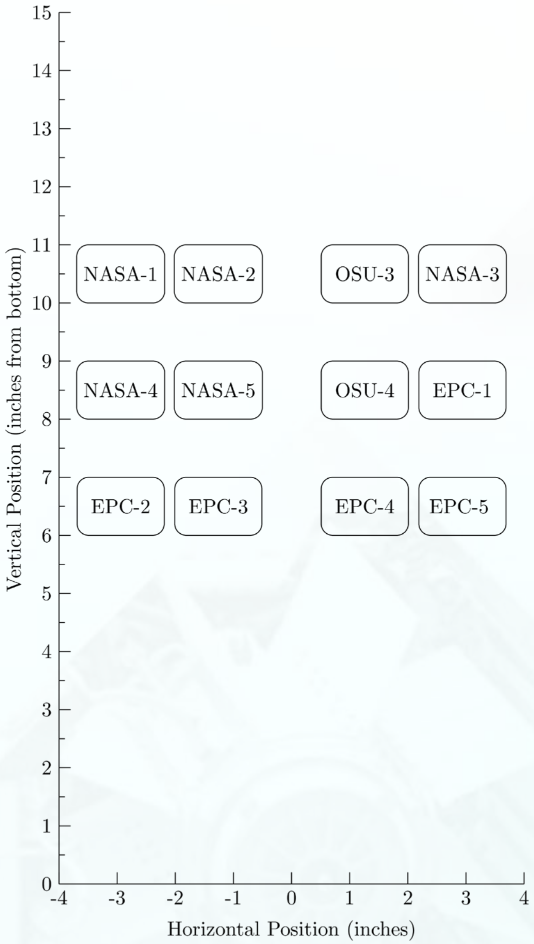


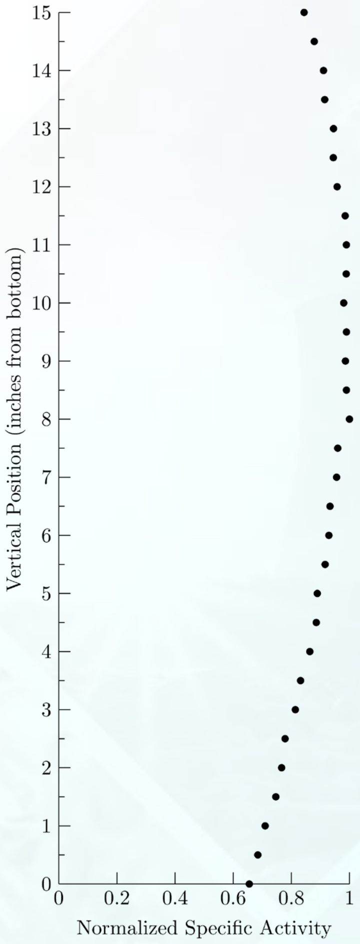


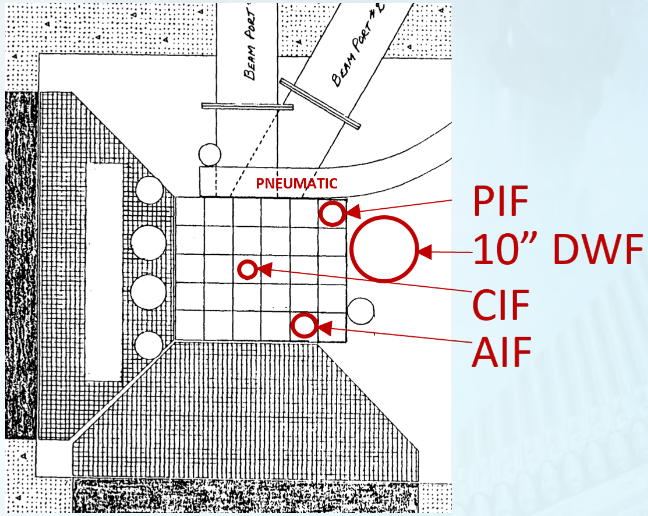


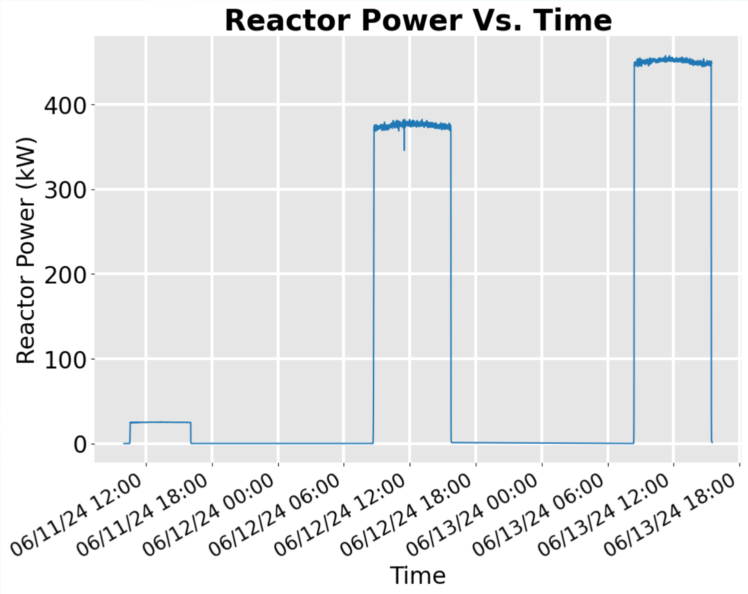


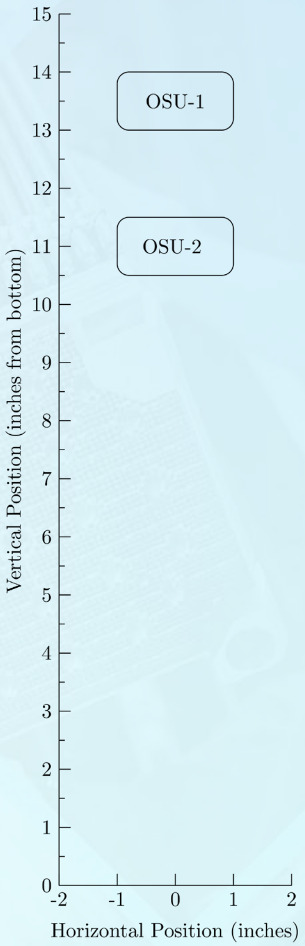
June 2024 Irradiation Profiles

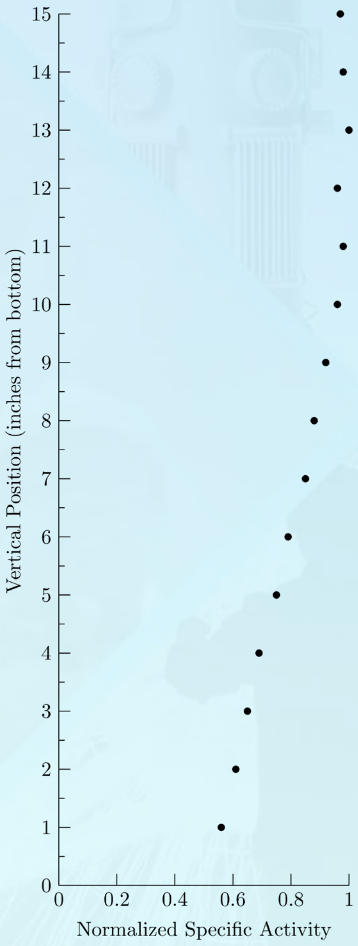




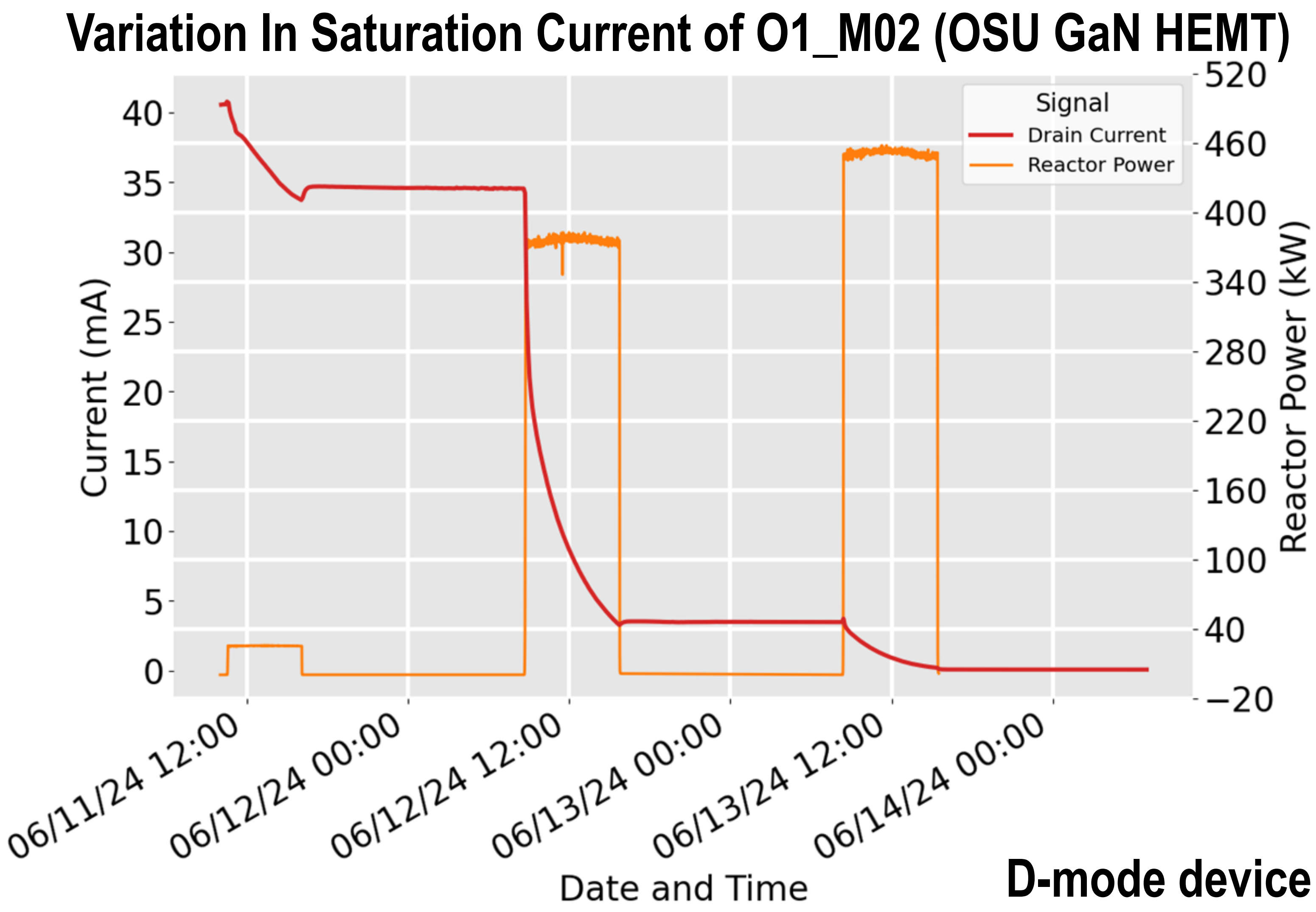






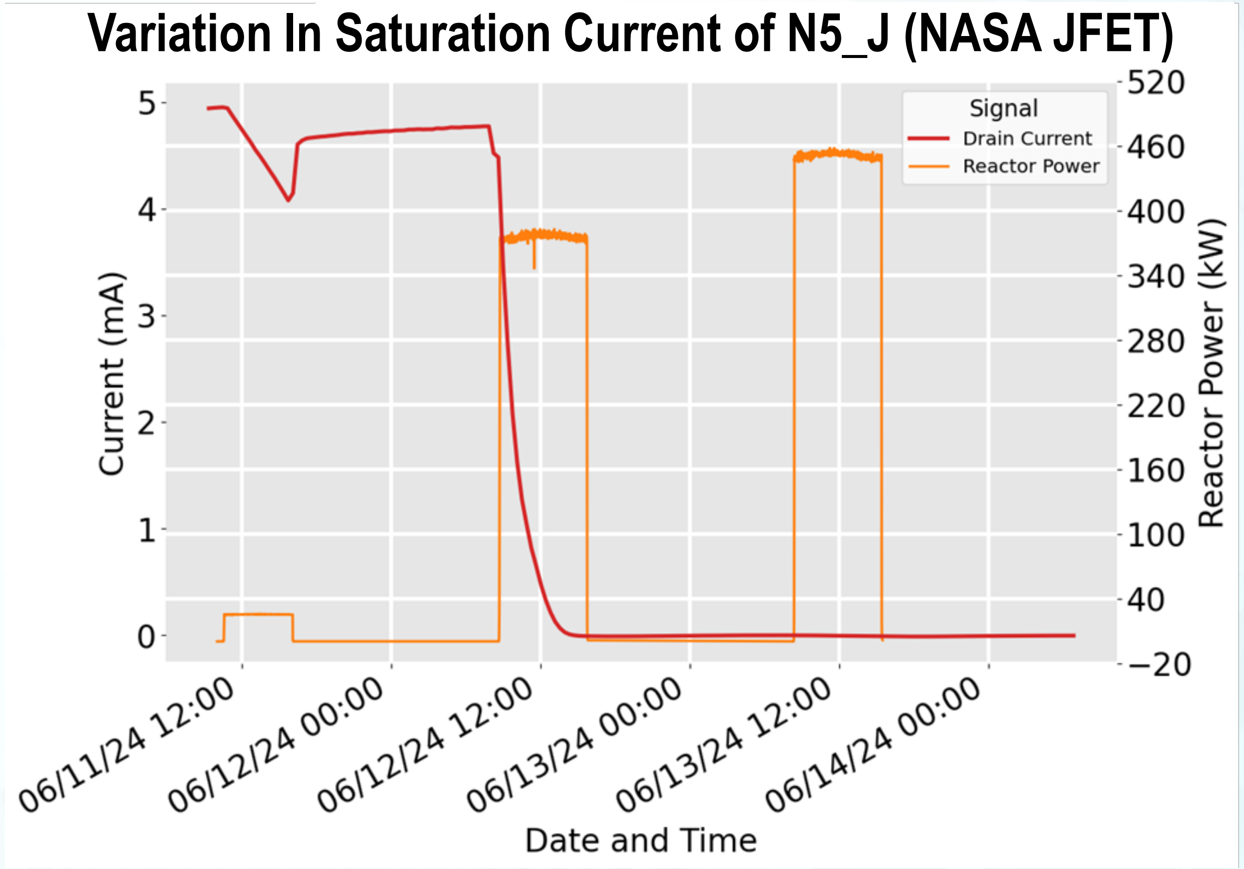


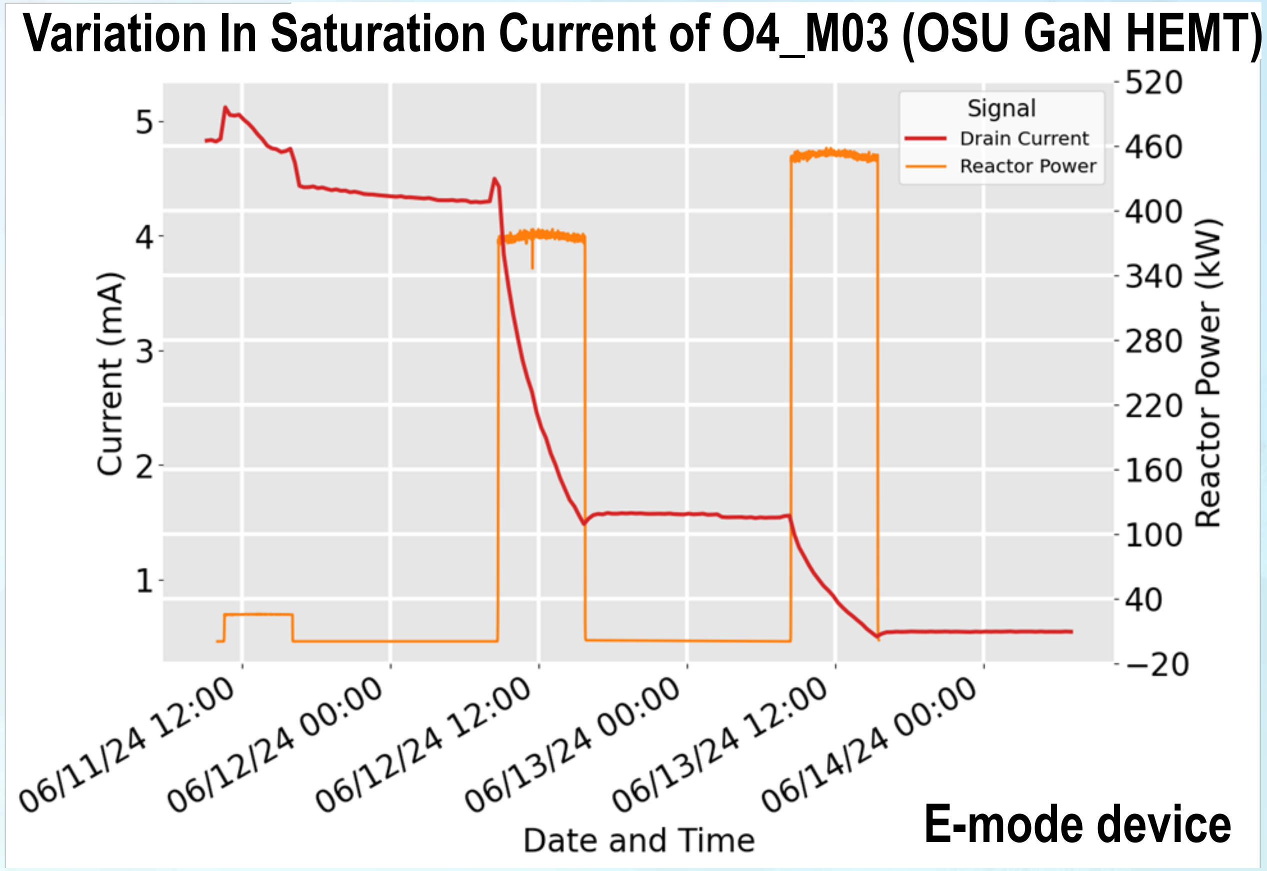
June 2024 Irradiation AIF Saturation Current Example



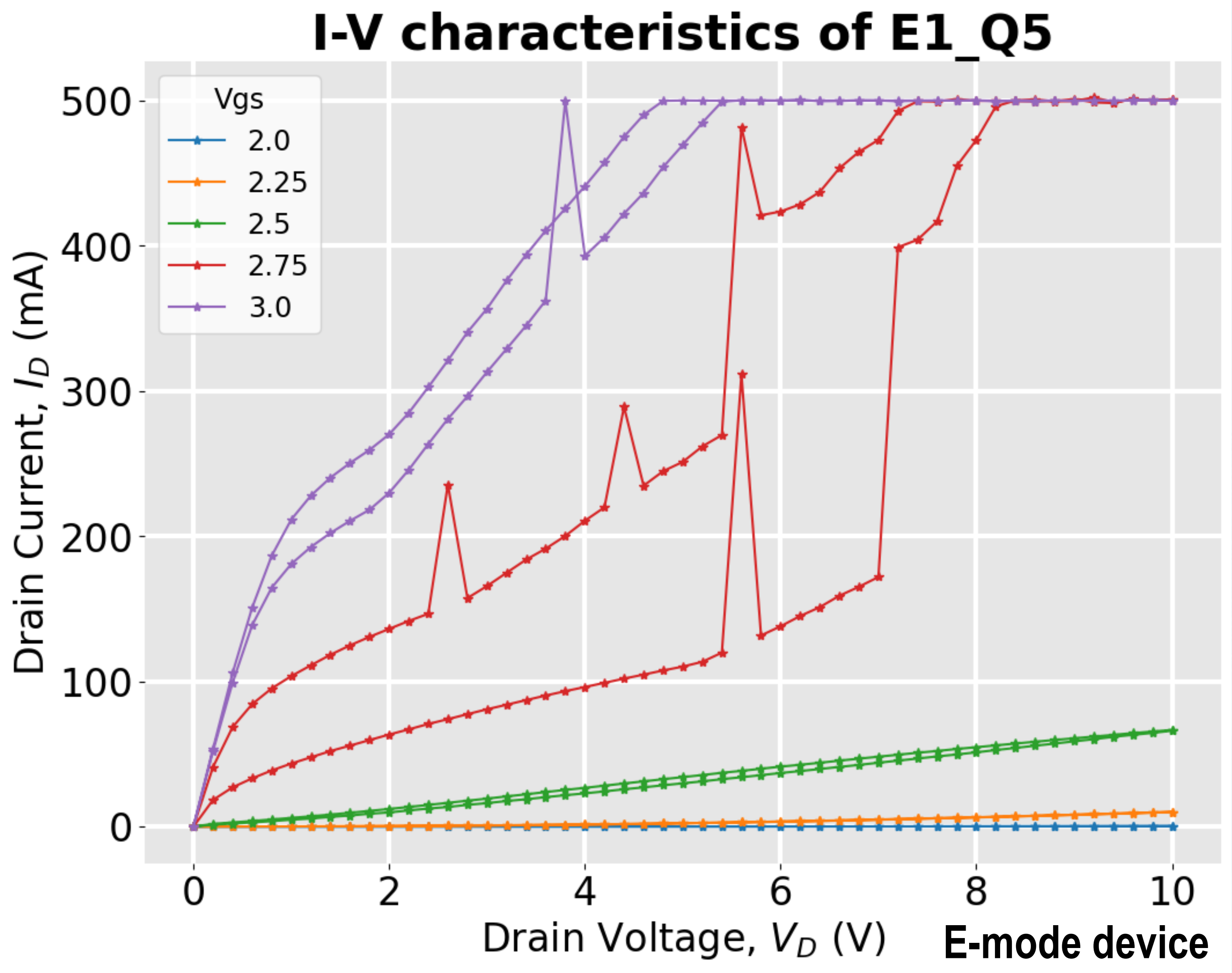
D-mode device

June 2024 Irradiation DWF Saturation Current Comparison





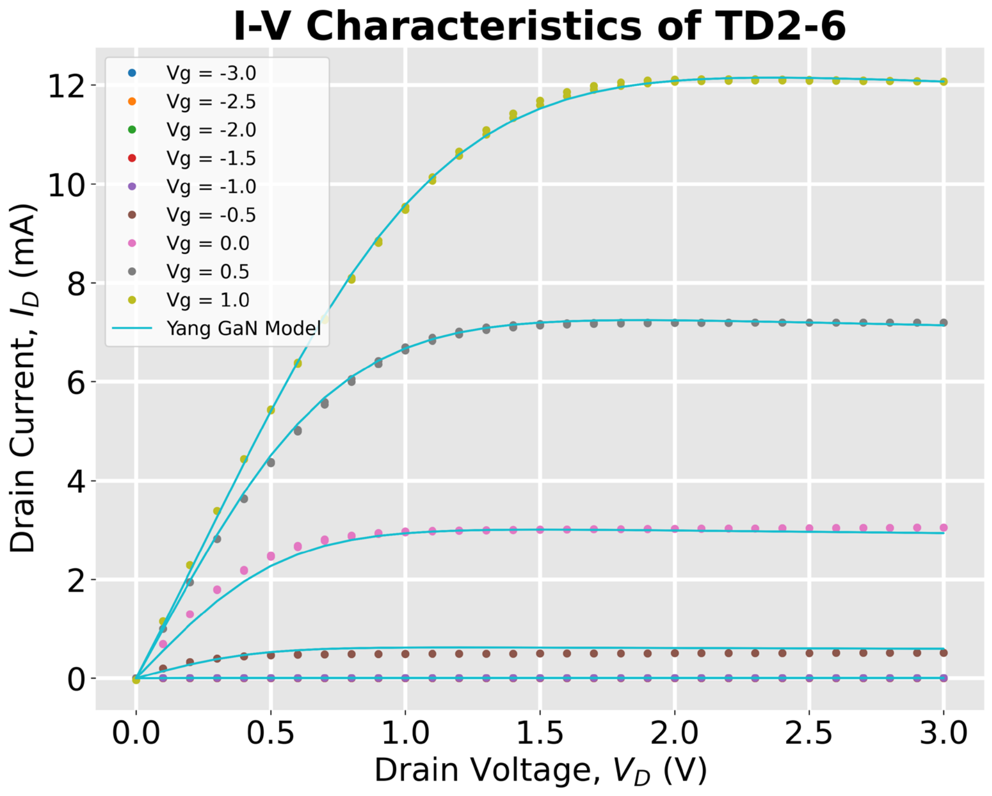
June 2024 Irradiation: EPC-Space Oscillations



E-mode device

Compact Modeling of GaN HEMTs

- Compact modeling of the OSU irradiated GaN HEMTs was performed to analyze how radiation-induced device variations influence circuit behaviors
- Modeling efforts began by investigating various compact model equations developed for GaN HEMTs



Model Method	Mathematical Description
Curtice model	$I_{DS} = \beta(V_{GS} - V_T)^2 \times \tanh(\alpha V_{DS})(1 + \lambda V_{DS})$
Dobes-Pospisil model	$I_{DS} = \beta(V_{GS} - V_T - \gamma V_{DS})^n \times \tanh(\alpha V_{DS})(1 + \lambda V_{DS})$
Balaji Model	$I_{DS} = K_1 \times \tanh(K_2 V_{DS})(1 + K_3 V_{DS})$
Yang Model	$\sinh(\gamma(V_{GS} - V_T - \delta V_{DS})^n) \times \tanh((\alpha_0 + \alpha_1 V_{GS} + \alpha_2 V_{DS})V_{DS})(1 + \lambda V_{DS} + \mu V_{GS})$

Concluding Remarks

- There is a need for improved rad-hard electronics for nuclear reactor applications
- This work demonstrated that GaN HEMTs and SiC JFETs are two strong technologies to meet this need
- GaN HEMT technology is promising for high neutron fluence, high total ionizing dose, and moderate temperature environments
- OSU fabricated GaN HEMTs were irradiated alongside commercial EPC-Space eGaN® HEMTs and NASA-Glenn SiC JFETs
- Despite oscillations in the EPC-Space devices, OSU GaN HEMTs withstood greater particle fluences than the SiC JFETs
- Both EPC-Space and OSU devices had observable characteristic curves for the duration of the irradiation
  - This includes the AIF irradiation of OSU GaN HEMTs

Concluding Remarks

- SiC JFETs are hard for gamma irradiation and better than Si for neutrons, but they are worse than GaN HEMTs for neutrons
- SiC JFETs have the best temperature performance (>400 °C)
- SiC JFETs have greater maturity and have been used in more complex circuits
- Compact modeling of the OSU devices will provide early insights into circuit performance and designs to overcome radiation induced variations in GaN-based instrumentation and control systems

The authors would like to thank NSUF for their support of the irradiations under RTE #4530 (Irradiation of Radiation-Hard GaN Transistors for Mixed Gamma and Neutron Fields under High Temperature) and #4881 (Irradiation of GaN HEMTs and SiC JFETs for Near Core Rad-Hard Electronics).

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Thank You

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