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

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

October 30 – November 2, 2023

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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
- Dianne Bull Ezell
- Brett Witherspoon
- Lloyd Clonts
- Tyler McCormick
- Kevin Deng
- Emma Brown

The Ohio State University

- Siddharth Rajan
- Raymond Cao
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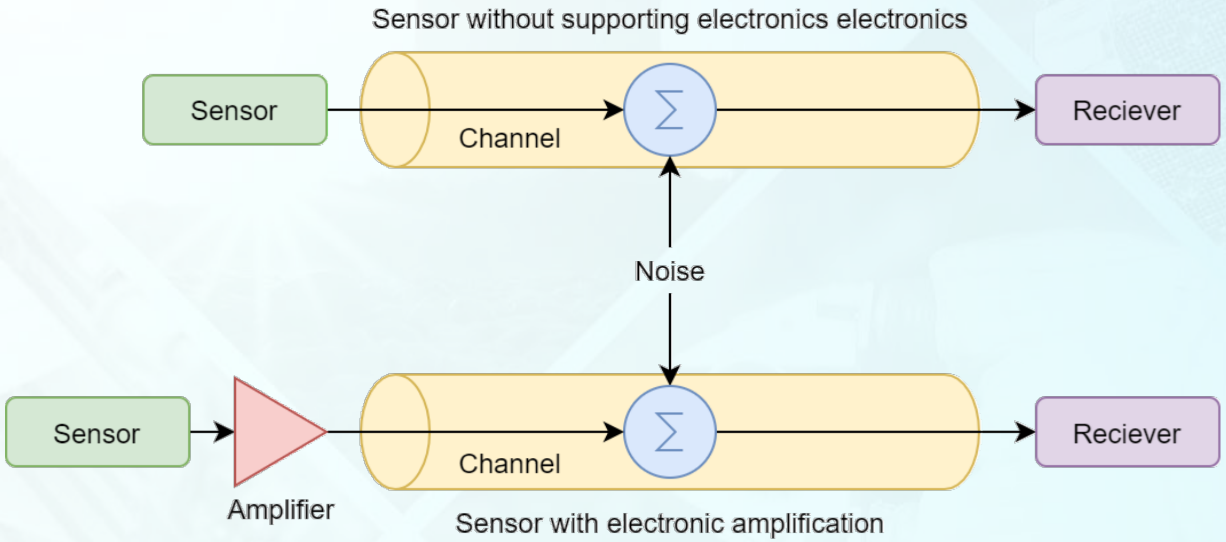
- Hyunsoo Lee
- John Cobbinah
- Adithya Balaji

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



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

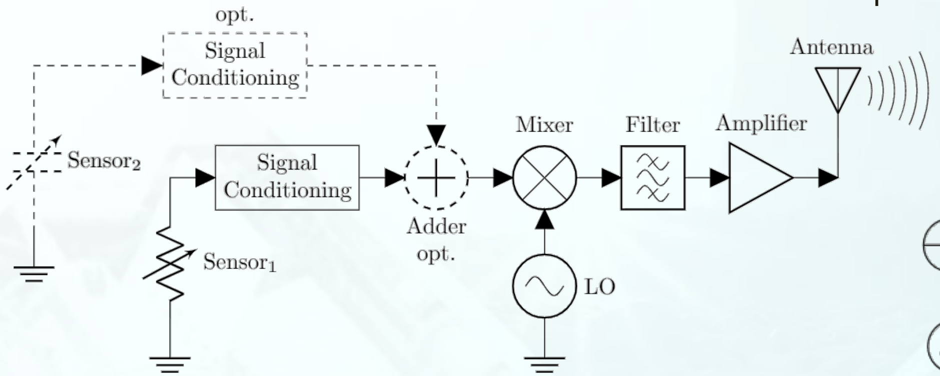
$$SNR = \frac{A \cdot S}{N_{CH} + N_A}$$

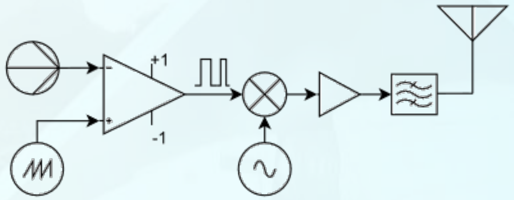
Technology Overview

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

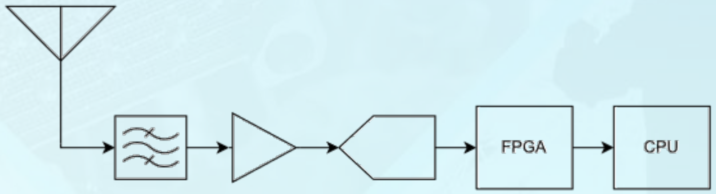
- Designing low complexity, cost effective, and radiation robust sensor signal conditioning and wireless transmission circuitry will increase safety and reliability while reducing maintenance costs associated with nuclear reactors, spent fuel casks, and emergency robotics
- Complex algorithms can be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

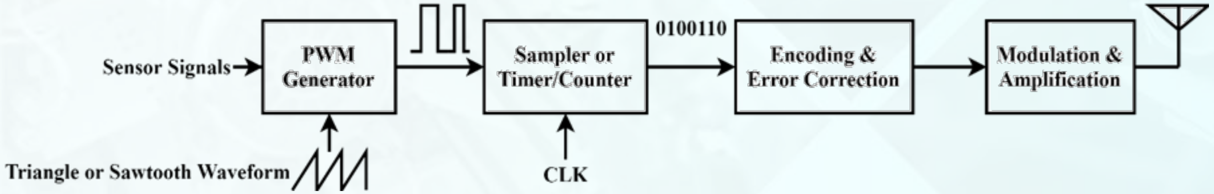
Low complexity transmitter examples



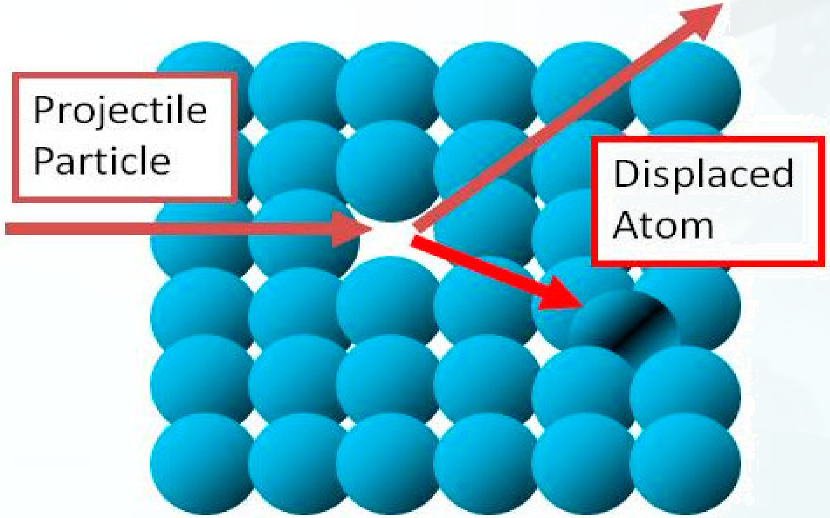


High complexity receiver

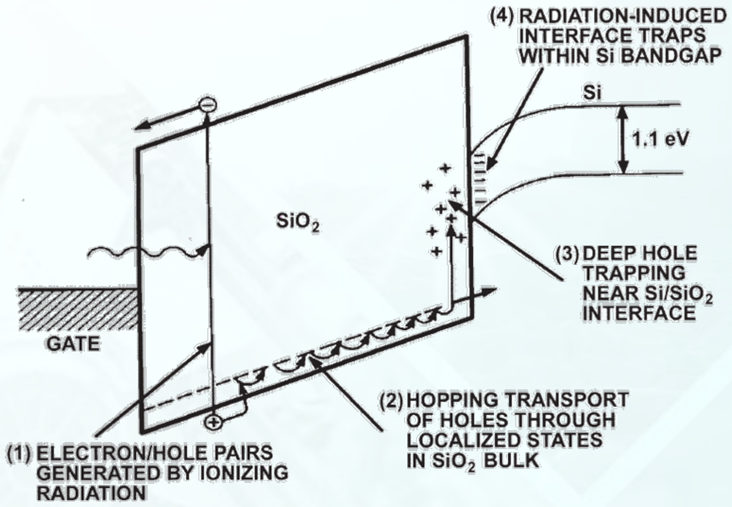




Radiation Effects on Semiconductor Devices



https://wpo-altertechnology.com/displacement-damage-testing/



A. Dawiec, Development of an ultra-fast X-ray camera using hybrid pixel detectors, HumanComputer Interaction [cs.HC], Universite de la Mediterranee — Aix-Marseille II, Marseille France (2011)

- Neutrons
  - Neutrons will transfer energy to interstitial atoms displacing atoms which may recombine with dopant or impure atoms producing stable defects
  - Minority carrier removal and increased material resistivity are associated with neutron displacement damage
- Ionizing Radiation
  - Compton effect and pair creation from high energy photons create ions in the incident materials
  - Charges are trapped in electrical insulators that generate electric fields and induce currents
  - Dose rates contribute to single event errors such as single event upsets or latch ups

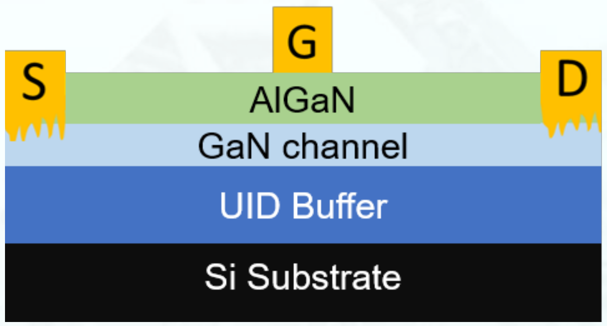
Si-Based Electronics Components Radiation Limits

	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

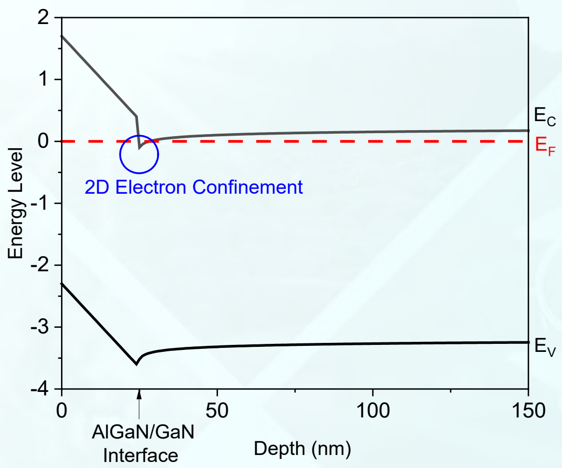
[1] Neamen, Donald A. Semiconductor physics and devices: basic principles. New York, NY: McGraw-Hill,, 2012.
[2] H. Spieler, "Introduction to radiation-resistant semiconductor devices and circuits." AIP Conference Proceedings. Vol. 390. No. 1. American Institute of Physics, 1997.

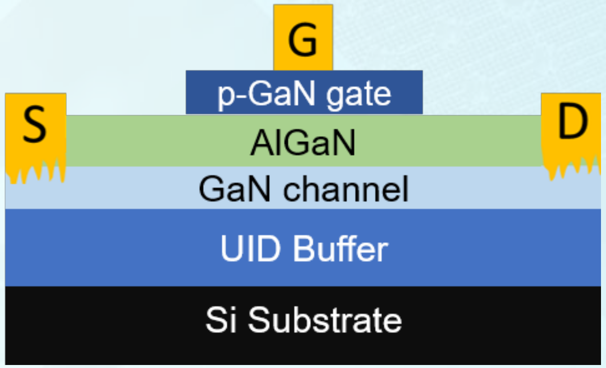
Why GaN?

- 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)

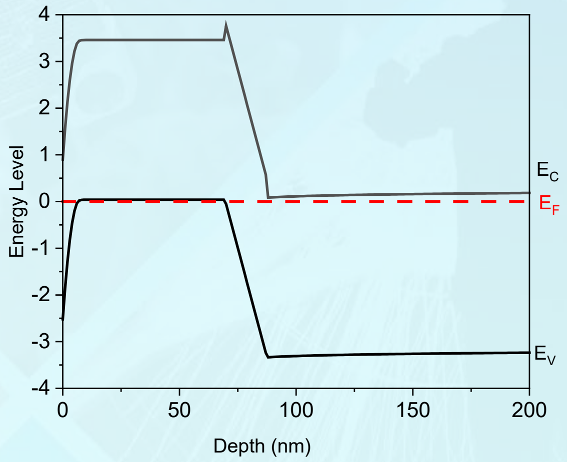


GaN HEMT Depletion Mode Device



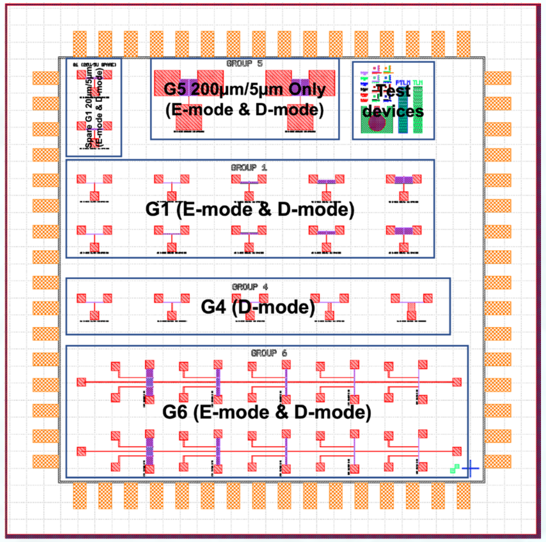


GaN HEMT Enhancement Mode Device

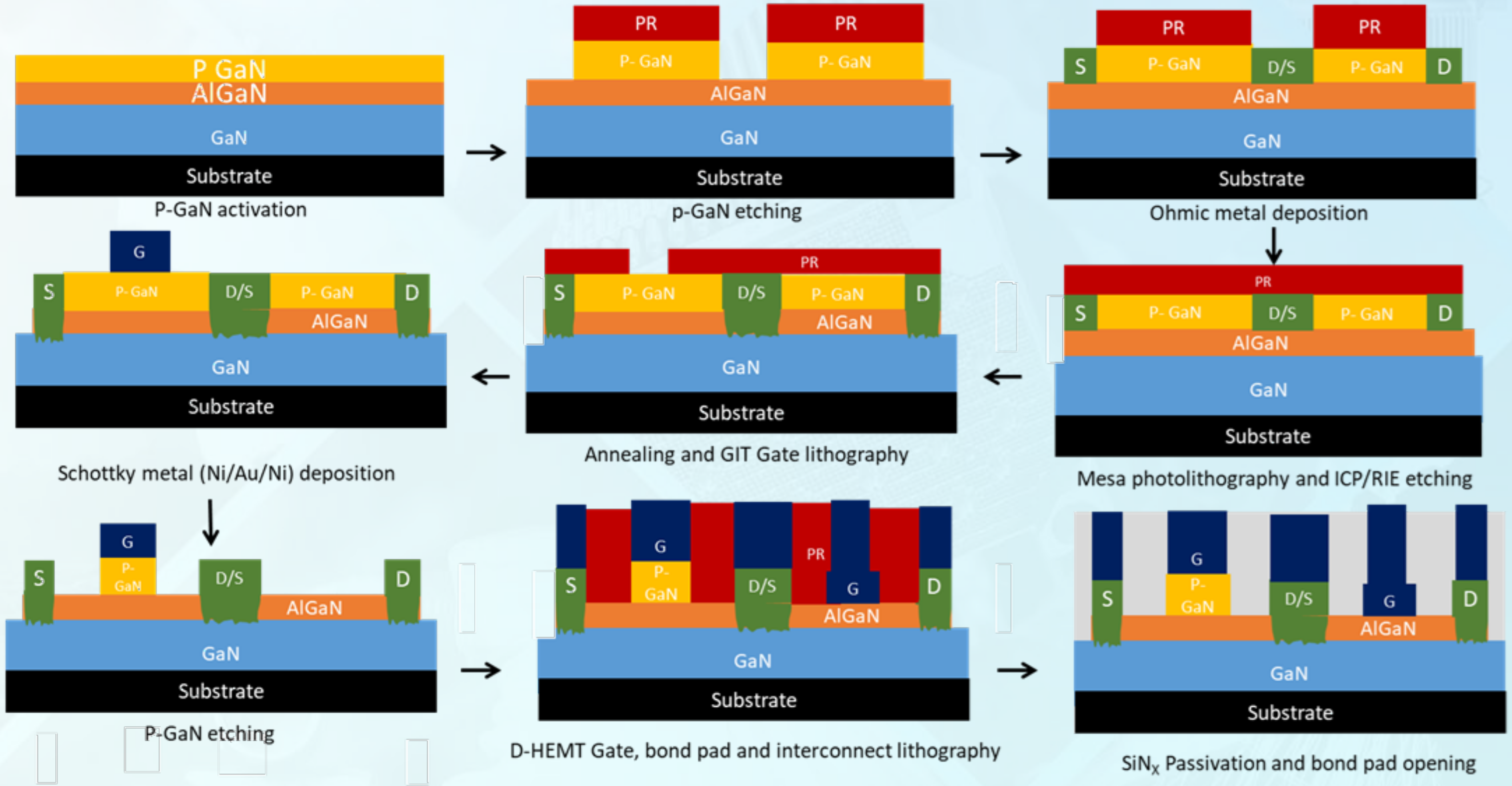


GaN HEMT Fabrication Process

- Process flow for monolithic enhancement-depletion mode circuits is being developed on commercially obtained epitaxial wafers (p-GaN/AlGaN/GaN/sapphire)
- Process parameter optimization for etch, contacts is underway
- Epitaxial wafers from vendors are being qualified for device fabrication

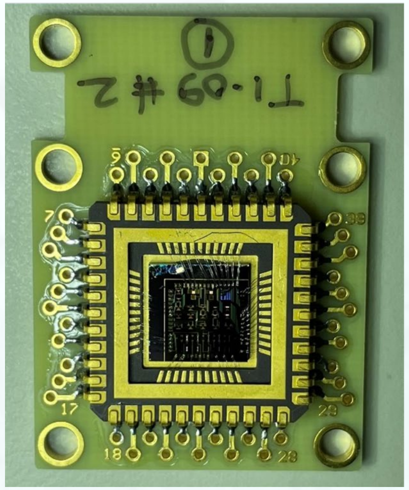


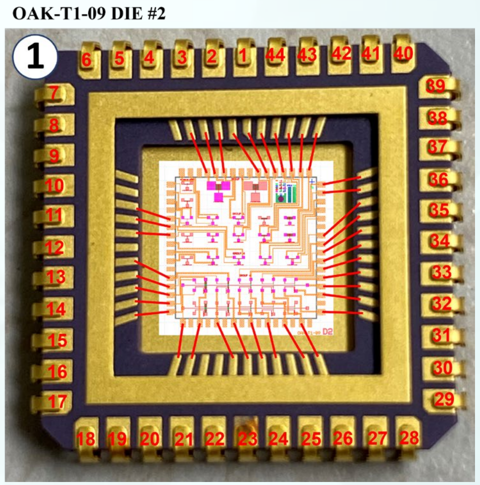
OSU GaN Inverter Fabrication Process



Device Packaging and Selection

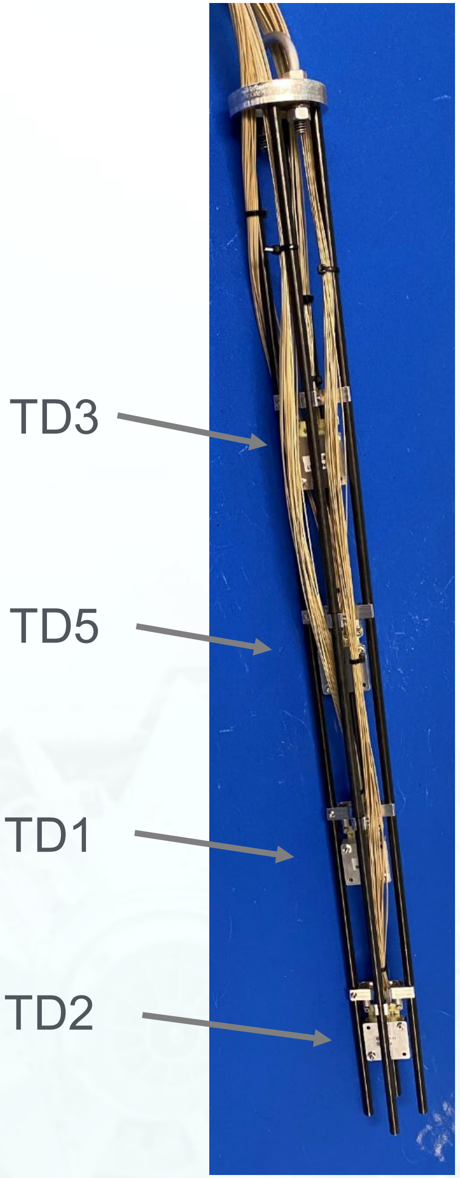
- Dies were mounted and wire bonded to a chip carrier soldered to a printed circuit board
- PEEK insulated cables were soldered to the board for signal conduction
- The 8’ PEEK cables were transitioned to Cat5e cable to the DAQ system
- Transistors were selected across 3 die (TD1, TD2, and TD5) which would receive the largest neutron fluence



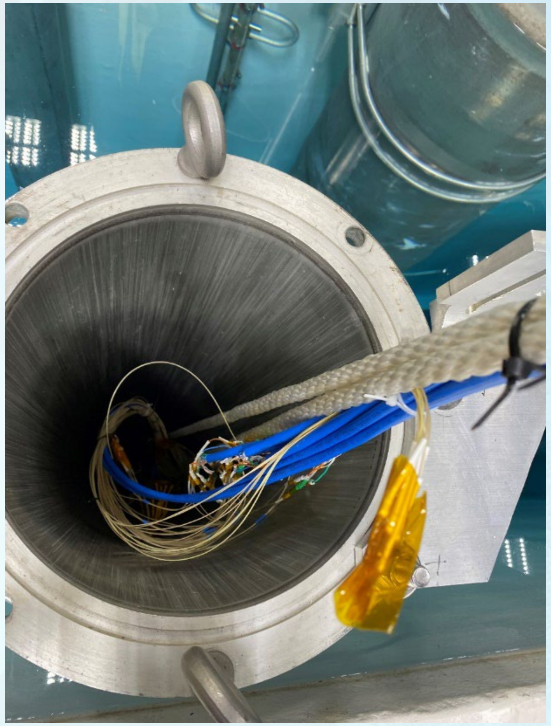


Die #	Device	Mode	Size, W/L (μm)
OAK-T1-09 Die #1	TD1-2	D-mode	20/5
OAK-T1-09 Die #1	TD1-6	E-mode	80/5
OAK-T1-09 Die #1	TD1-10	E-mode	20/5
OAK-T1-09 Die #1	TD1-11	E-mode	5/5
OAK-T1-09 Die #1	TD1-13	E-mode	10/5
OAK-T1-09 Die #1	TD1-14	E-mode	20/5
OAK-T1-11 Die #2	TD2-2	D-mode	20/5
OAK-T1-11 Die #2	TD2-6	D-mode	80/5
OAK-T1-11 Die #2	TD2-7	D-mode	80/5
OAK-T1-11 Die #2	TD2-8	D-mode	20/5
OAK-T1-11 Die #2	TD2-11	D-mode	20/5
OAK-T1-11 Die #2	TD2-14	D-mode	20/5
OAK-T1-11 Die #1	TD5-3	E-mode	200/5
OAK-T1-11 Die #1	TD5-4	E-mode	10/5
OAK-T1-11 Die #1	TD5-12	D-mode	80/5
OAK-T1-11 Die #1	TD5-13	D-mode	40/5

June Irradiation

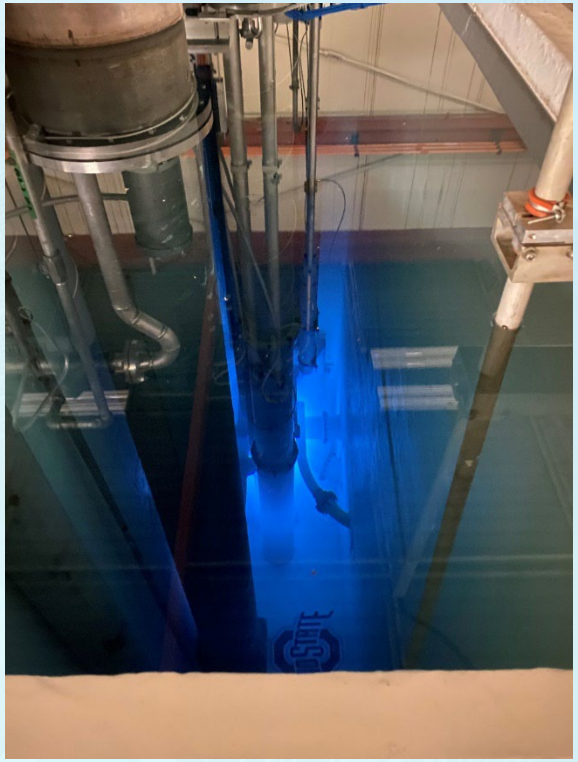


Loading basket into furnace



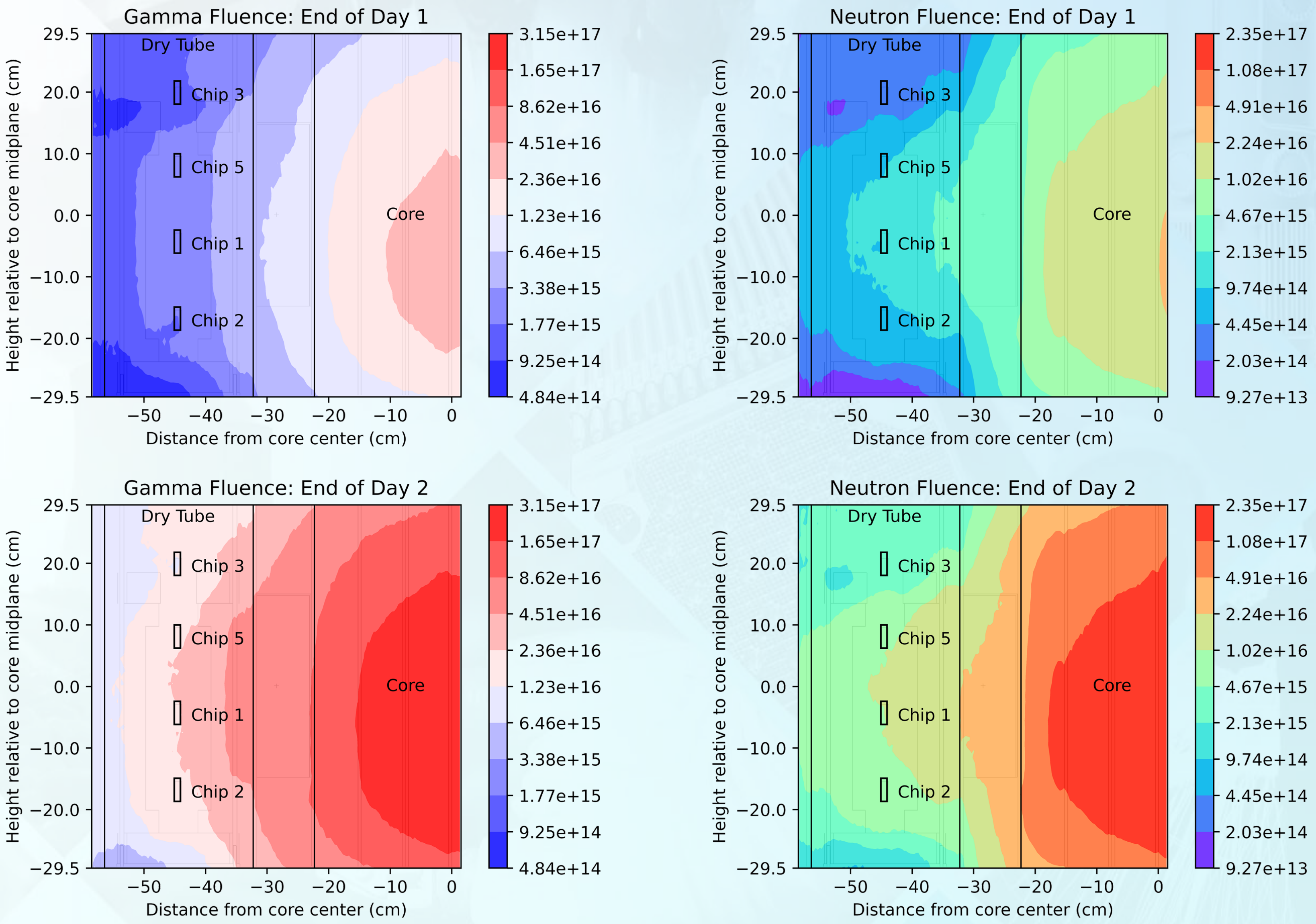
Loading furnace and basket in dry tube

Furnace and basket in dry tube during irradiation on day 1



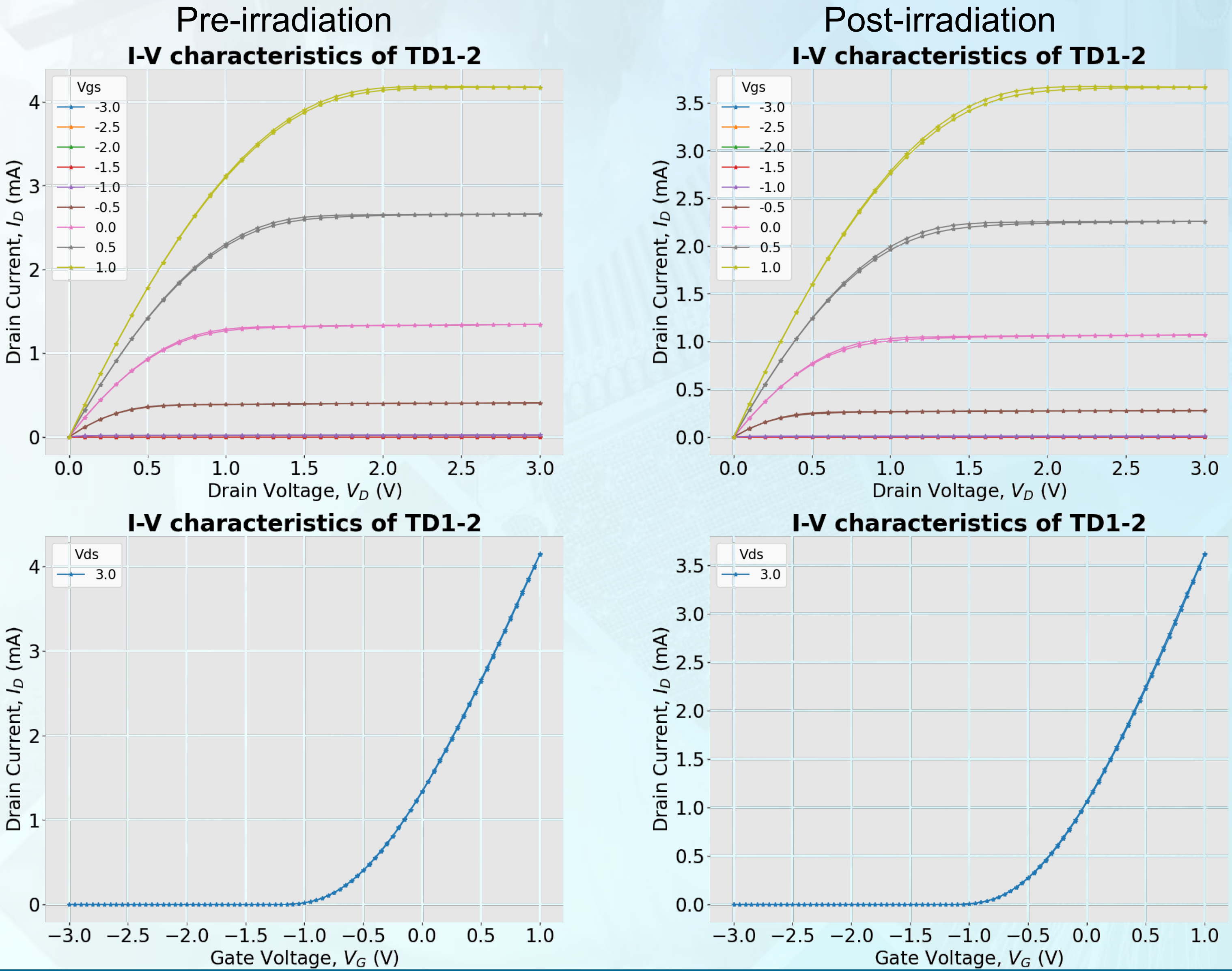
June OSURR Radiation Profile

- Irradiation took place over two 7-hour days
- Day 1 the reactor was operated at 4% power to achieve a neutron fluence of 10^{15} n/cm^2
- Day 2 the reactor was operated at 34% power to achieve a total neutron fluence of 10^{16} n/cm^2
- TD1 received the most gamma and neutron fluences followed by TD5 and TD2.



Pre- and Post-Irradiation I-V Characteristic Sweeps of TD1-2

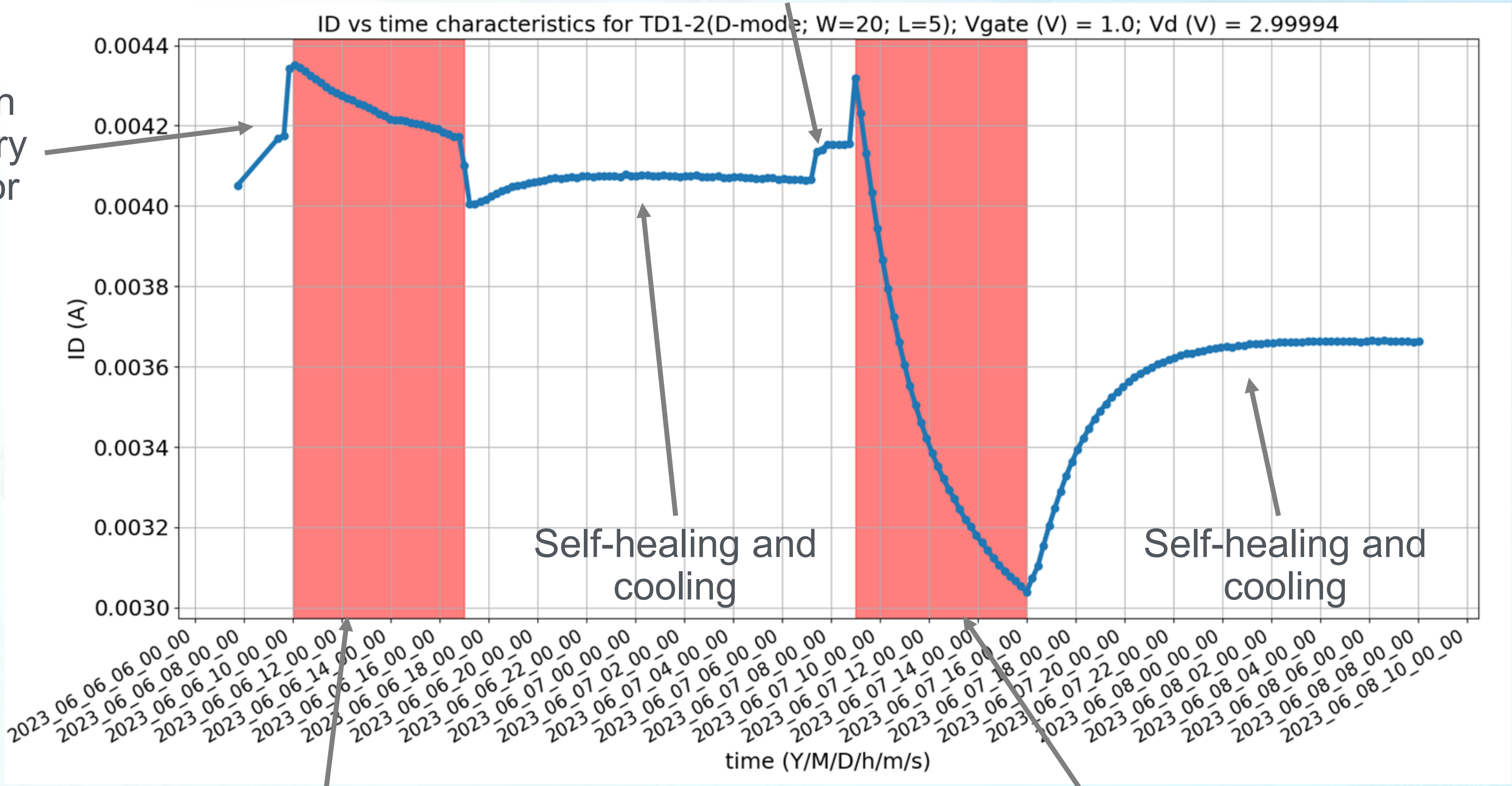
- Current-voltage (I-V) characteristic curves were measured during irradiation
- The plots of the IV characteristics taken of TD1-2 a D-mode device are shown
- The upper plots show the drain current vs drain voltage plots for varying gate voltage
- The lower plots show the drain current vs the gate voltage for a 3 V drain voltage
- The drain current in both sets of plots reduced after irradiation



Drain current of TD1-2 in Saturation Over Time in Reactor Pool

Moving dry tube to reactor core

Pre-irradiation and moving dry tube to reactor core



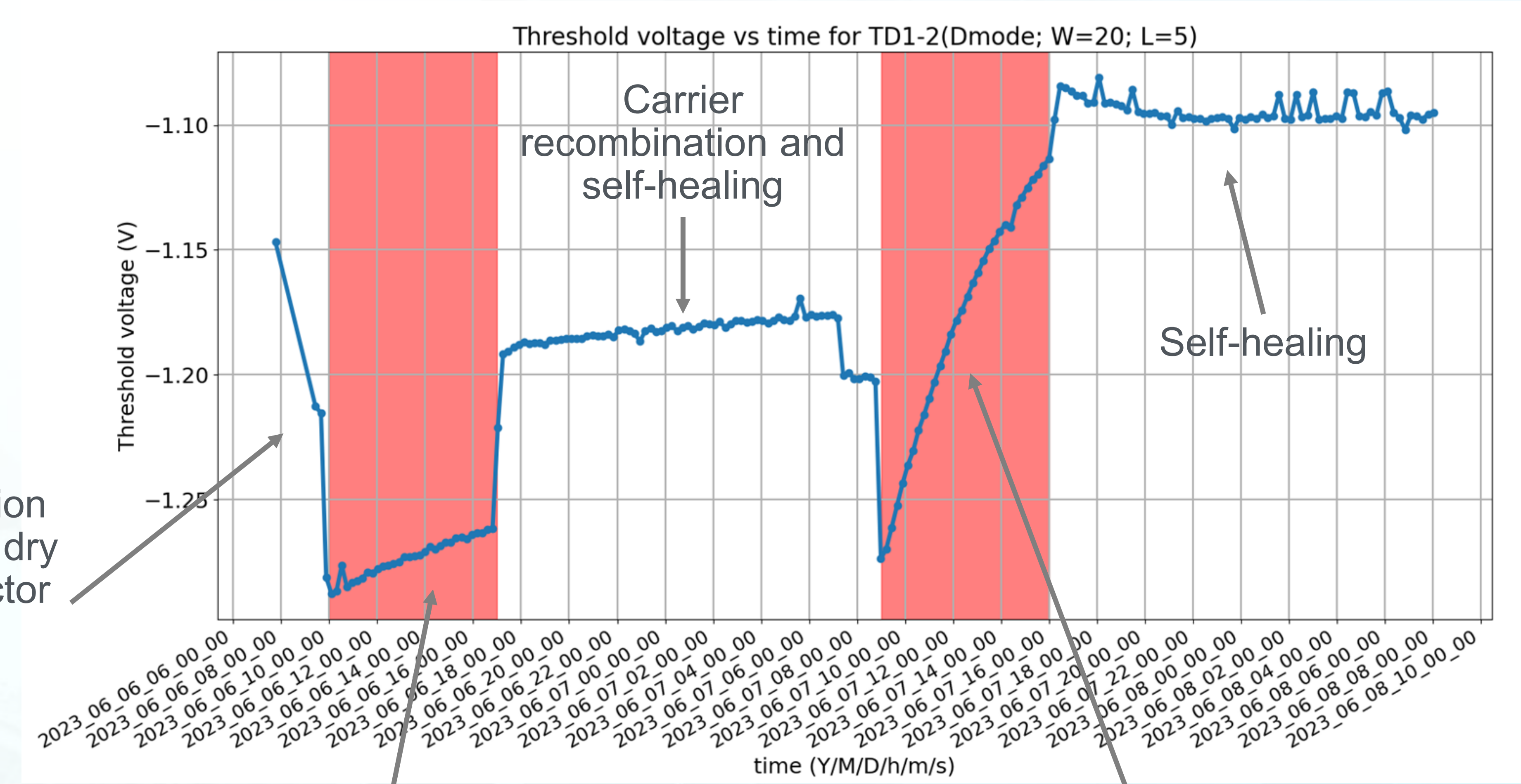
Self-healing and cooling

Self-healing and cooling

Irradiation to 10^{15} n/cm^2

Irradiation to 10^{16} n/cm^2

Threshold Voltage of TD1-2 in Over Time in Reactor Pool



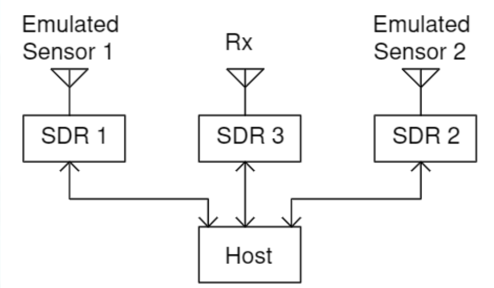
Pre-irradiation and moving dry tube to reactor core

Irradiation to 10^{15} n/cm^2

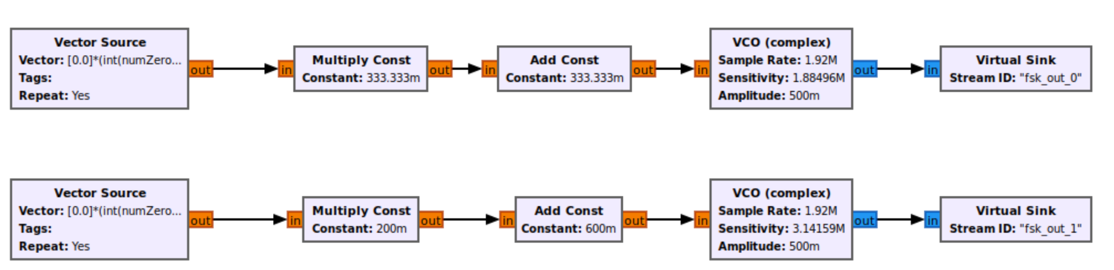
Irradiation to 10^{16} n/cm^2

Wireless System and Testbed Design

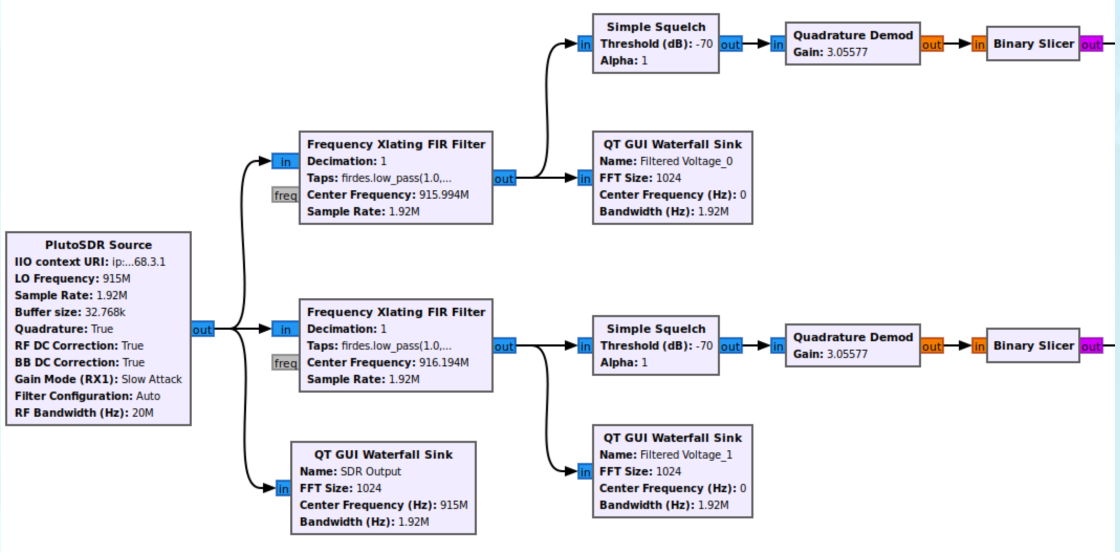
- A wireless system was devised and tested emphasizing transmitter simplicity
- Sensor signals were binary encoded with pulse-width modulation (PWM)
- Frequency-shift keying (FSK) is used to modulate and continuously transmit the sensor data
- Demodulation with frequency-translating finite impulse response (FIR) filter to shift the emulated sensor signal back to baseband with optimal decimation minimizing noise and processing time
- Frequency orthogonality is exploited for multiple sensor channels
- A testbed was constructed to evaluate the devised communication scheme using three software defined radios (SDRs)
- Two sensor transmitters were emulated with ADALM-PLUTO software SDRs with center frequency of 915 MHz
- The receiver was implemented on a third SDR



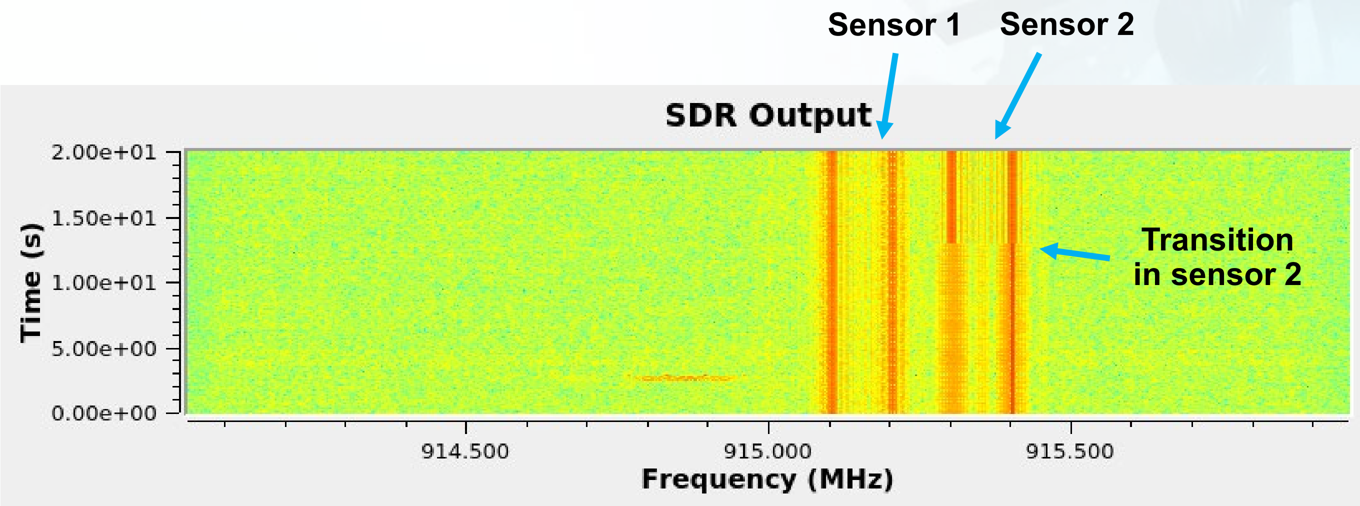
Transmitter chain



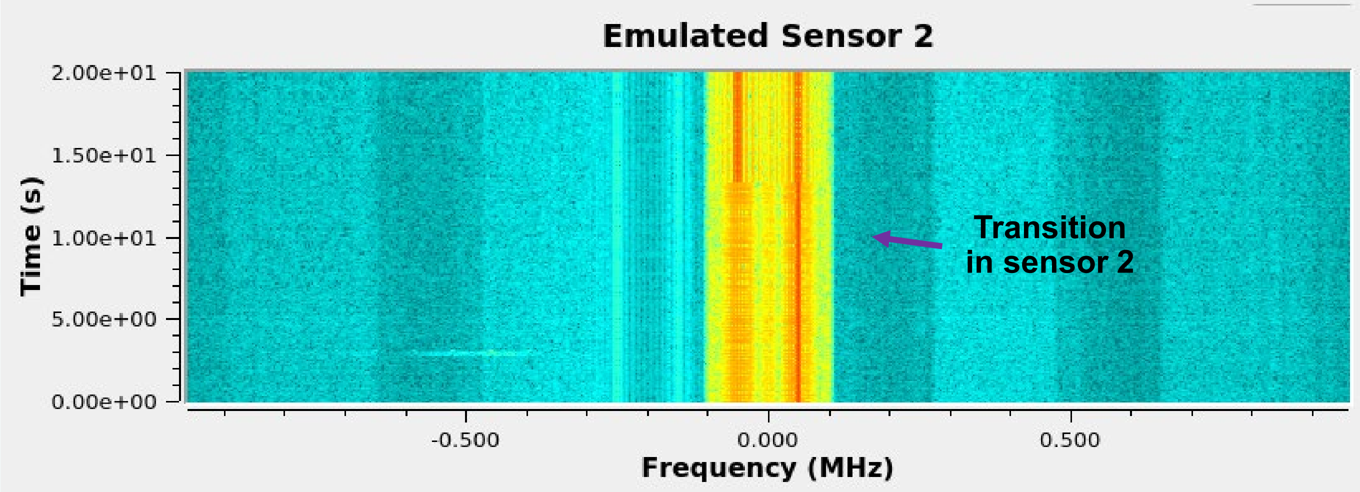
Receiver chain



Wireless Testing Results

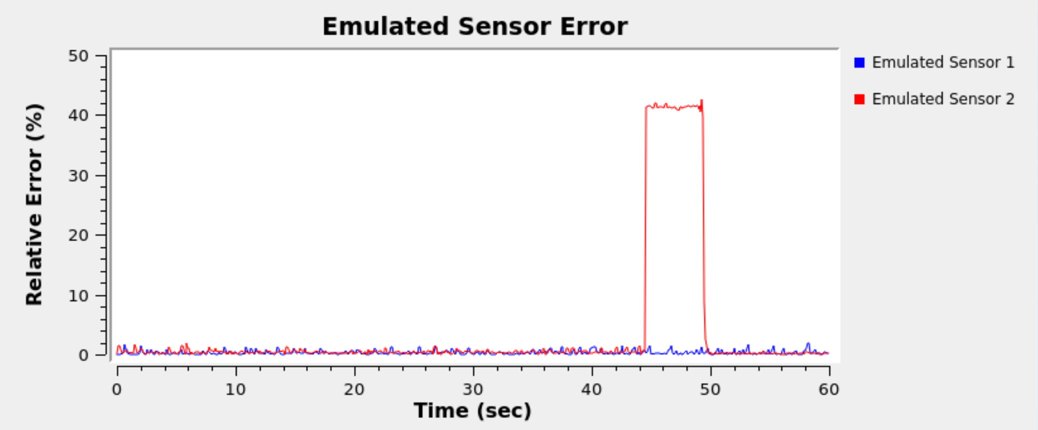


Received signal



Sensor 2 after filter shift to baseband

- Data from two sensors were successfully received
- Nominally the sensors had error due to noise of 1-2%
- To emulate a sensor, the input voltage of sensor 2 was changed from 0.5 V to an 0.85 V (~41% change)
- The emulated sensor voltage corresponds to the duty cycle of the sensor transmitter (0.5 V maps to a 50% duty cycle, 0.85 V maps to an 85 % duty cycle)
- Upon transition the error appears to have spiked due to a delay in the GNU-radio software to adjust the output pulse density



Concluding Remarks

- State-of-the-art silicon-based electronics are not suitable for high temperature radiation environments associated with nuclear reactors and spent fuel storage
- Three sets of E-mode and D-mode GaN HEMTs were fabricated and tested in rad-soft conditions
- E-mode and D-mode GaN HEMTs were irradiated to 10^{16}n/cm^2 in the OSU reactor with little effects
- The devised binary encoded, frequency shift keying modulated communication scheme was successfully simulated
- Two journal publications are nearing completion and will be submitted before the end of the calendar year, a few more are anticipated.

Future work (FY24):

- Irradiation planned to find upper bound of neutron limitation of the OSU fabricated GaN HEMTs
- Irradiation planned to compare the OSU fabricated GaN HEMTs with commercial GaN HEMTs and SiC JFETs
- Compact device models will be generated which include radiation and temperature effects
- GaN-based circuits supporting wireless communications will be designed and simulated with neutron effects

Thank You

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