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

ASI | Advanced Sensors and Instrumentation

Front End Digitizer (FREND)

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

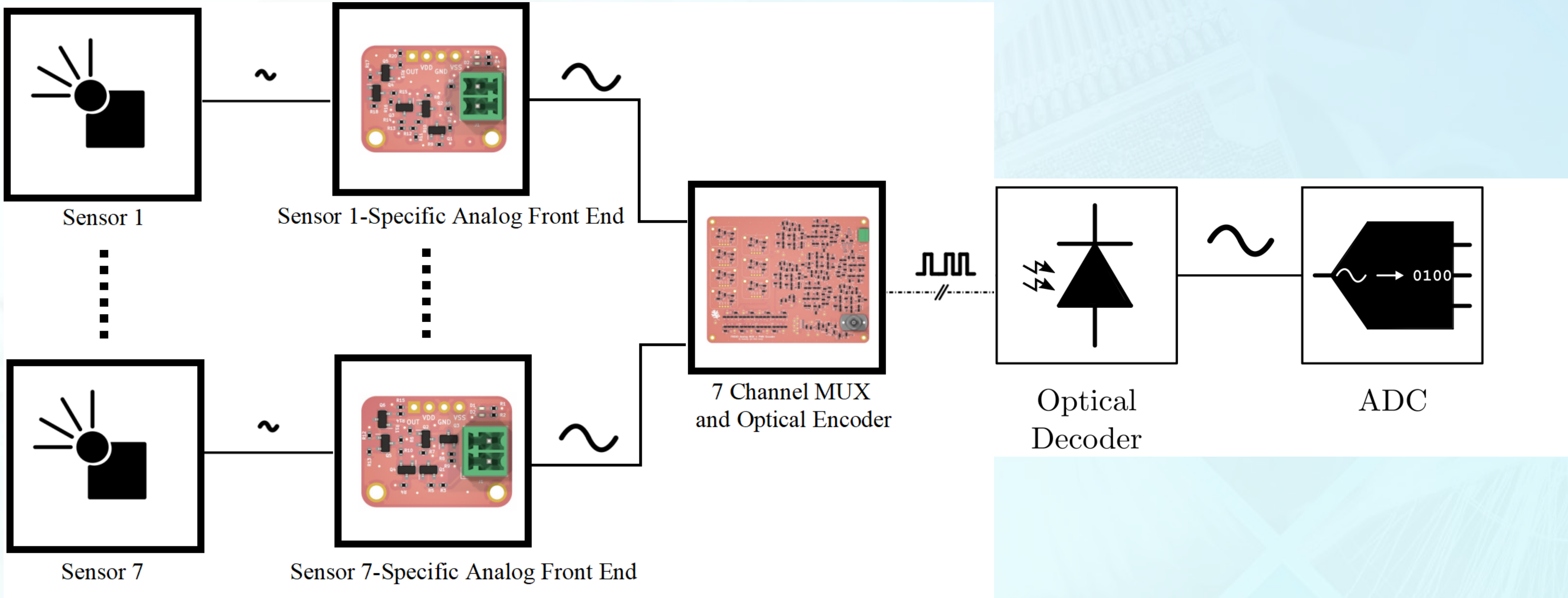
October 30th – November 2nd

Callie Goetz, PhD

Oak Ridge National Laboratory

FREND Overview

- Goal: Read out multiple nuclear instruments at a single experimental location over one fiber optic cable (or cable bundle)
  - Thermocouples, SPNDs, SPGDs, RTDs, fission chamber (stretch goal)

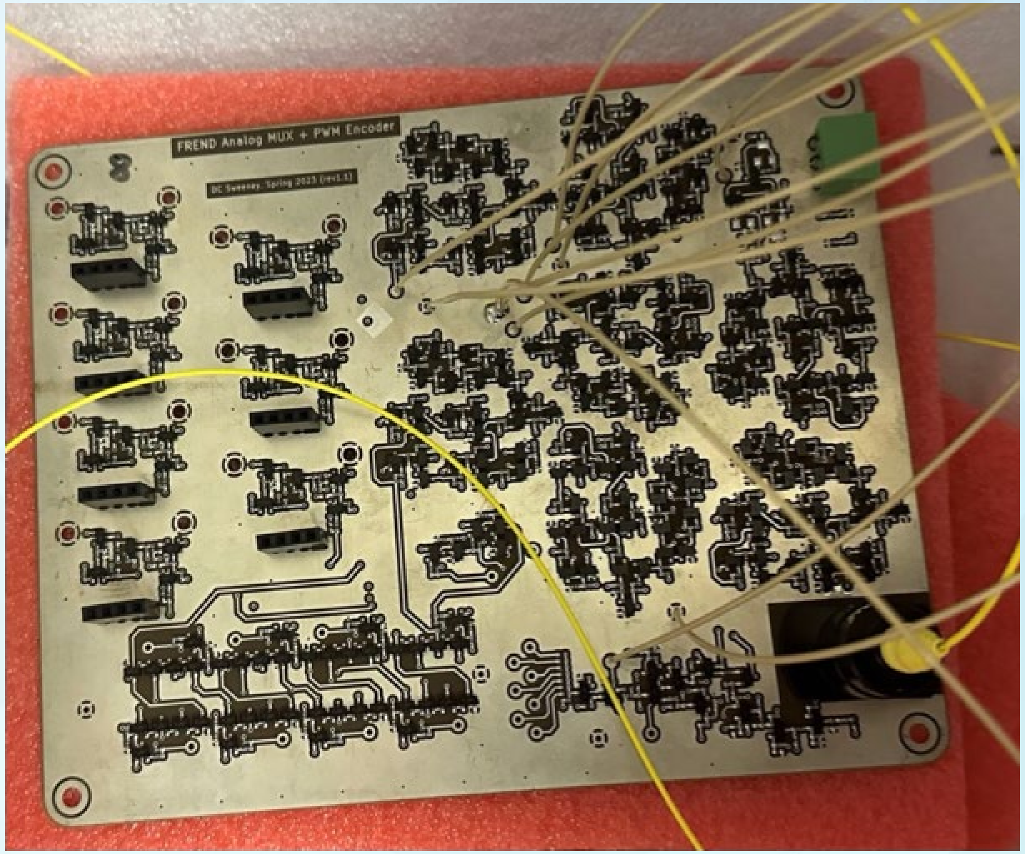


FY23 Effort

- More compact, irradiation-ready redesign
- Preamplifier boards
- Irradiation Goals of FREND System
  - Neutron
  - Neutron/gamma
- Participants:
  - Kyle Reed (electronics design)
  - Dan Sweeney (electronics layout)
  - Callie Goetz (PI)

Irradiation-Ready FREND

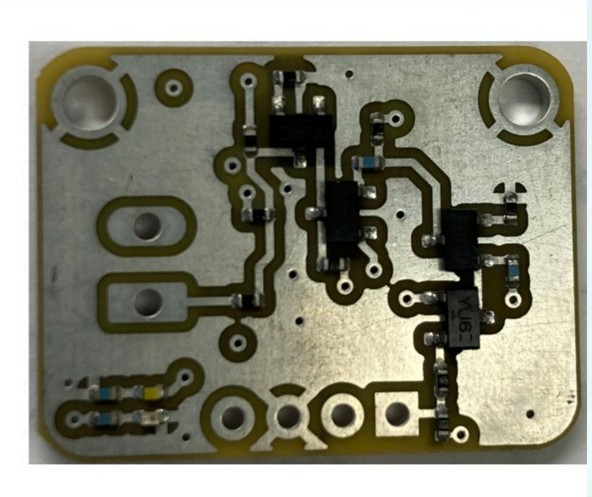
- Combine analog front end/optical encoder onto one board (space saving)
- Increase to 7 channels with 1 index channel, reduce cross talk
- Activation concerns:
  - Lead free solder
  - As little gold as possible (Sn mask)
  - Less copper with larger keep out zones,
- Integrity concerns:
  - Through hole
  - Minimize plastic components
  - No silk screen



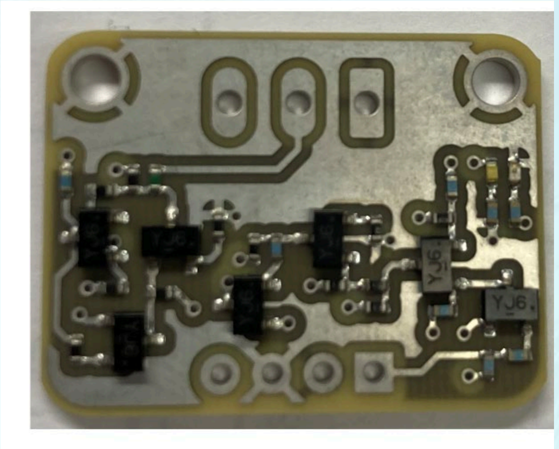
Preamplifier Boards

- Cold junction compensated thermocouple
  - Compensated with thermistor
  - Output: -1 V – +1 V
- Current preamplifier – SPND, SPGD, fission chamber, ion chamber
  - Input: 4-20 mA current source
  - Output: -1 V – +1 V
  - Settable gain

Thermocouple Preamp

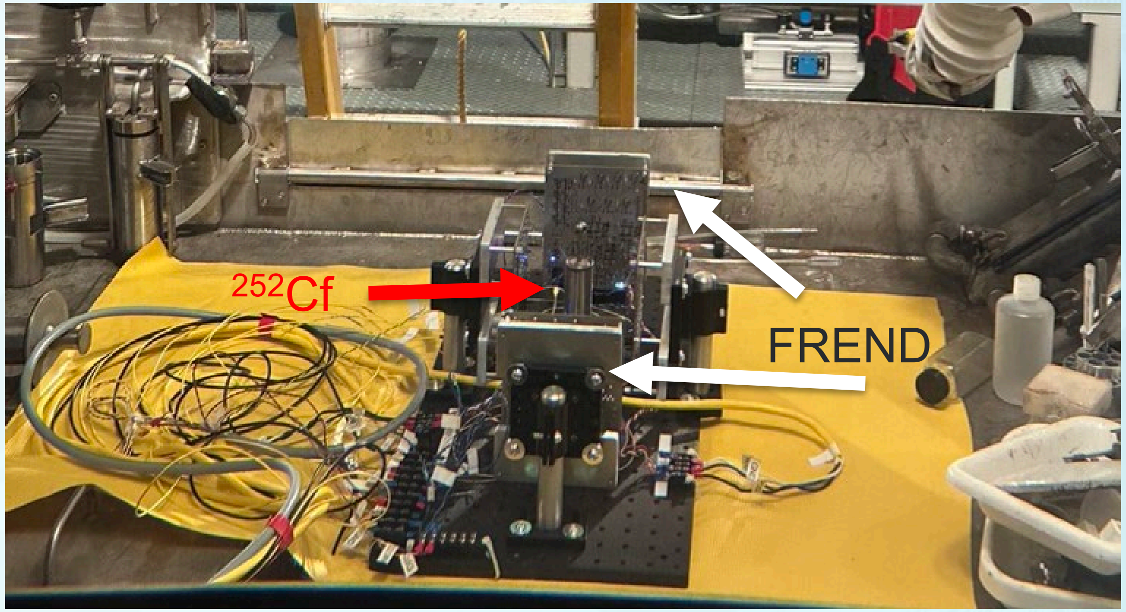


Current to Voltage Preamp



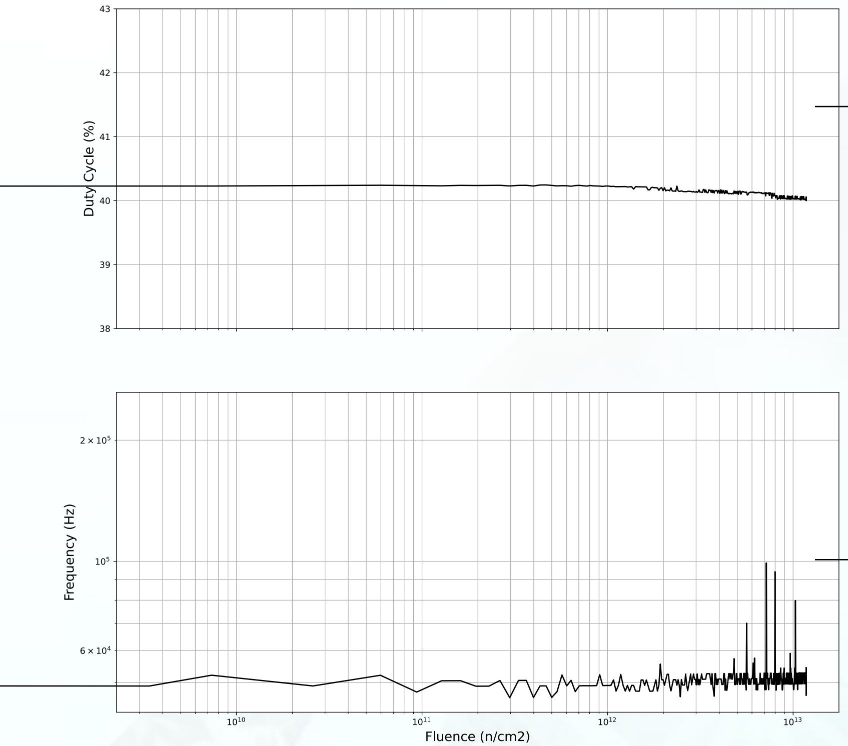
Cf252 Room Temperature Irradiation

- 1.85 mg 252Cf source - fast neutrons
- Boards 1, 2 (6 cm) , and 3 (19 cm)
- Resistive dividers on all 7 channels holding each to a constant voltage
- Automated monitoring (Saleae):
  - Clock
  - Summer
  - FREND output via photodetectors
- 2.8-week irradiation, fluence:
  - Board 1&2: 1.6×10^{13} n/cm^2
  - Board 3: 0.5×10^{13} n/cm^2
- Survivability test

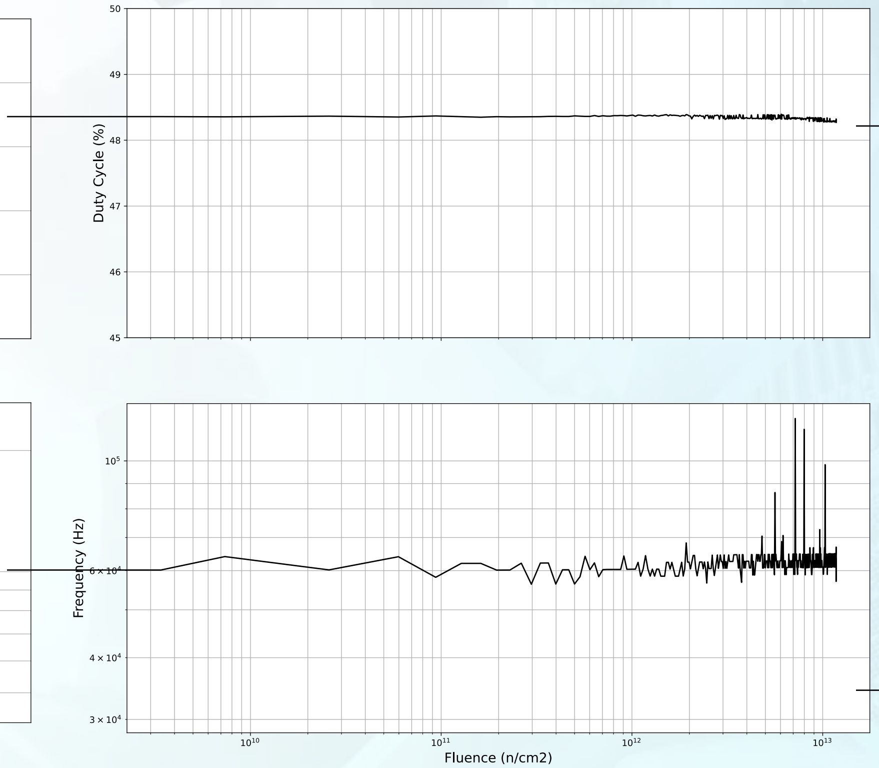


Cf252 Irradiation Results – Clock

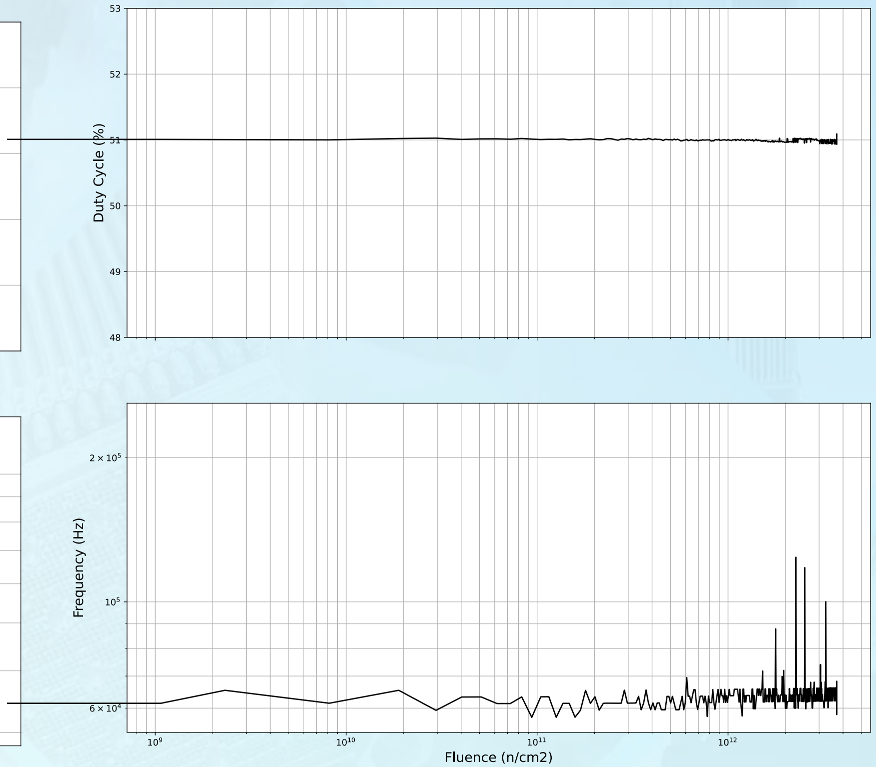
Board 1



Board 2

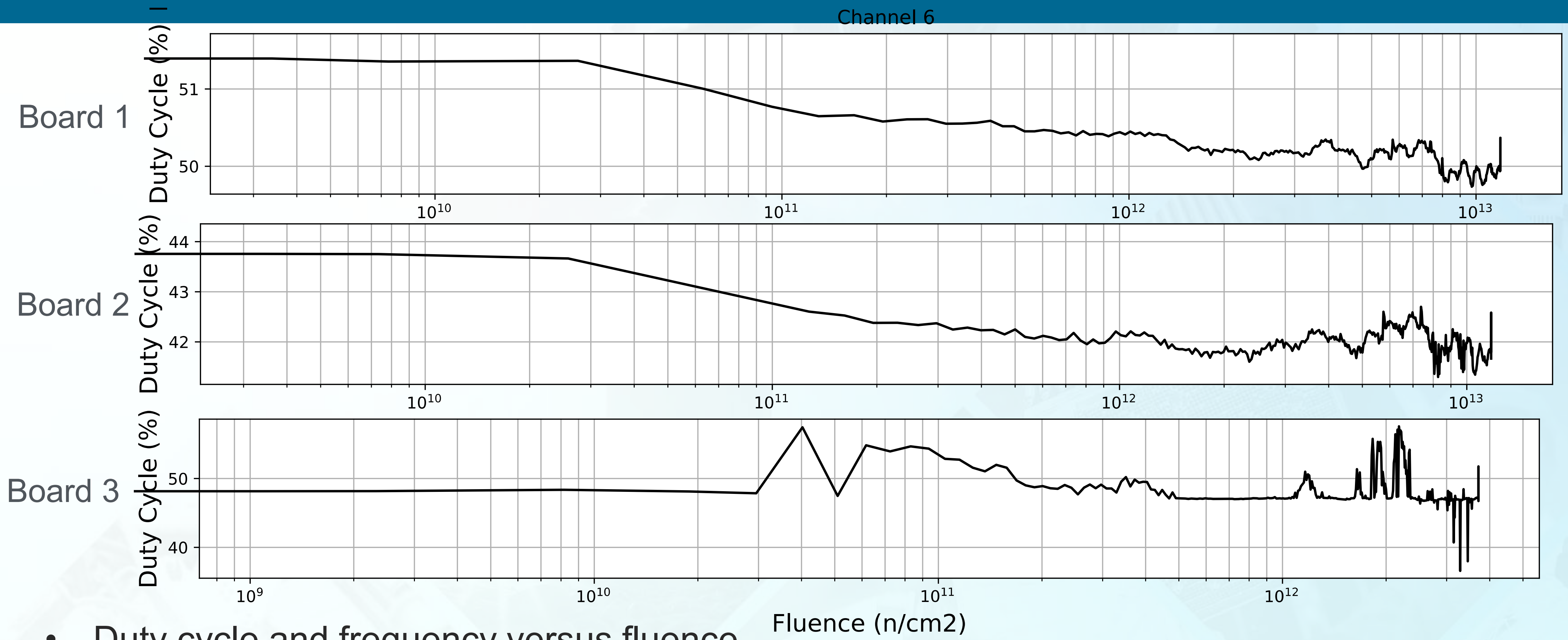


Board 3



- Duty cycle and frequency versus fluence
- Fluence: 10^{13} n/cm^2
- No failures observed
- Minimal changes to duty cycle (< 0.1 %)

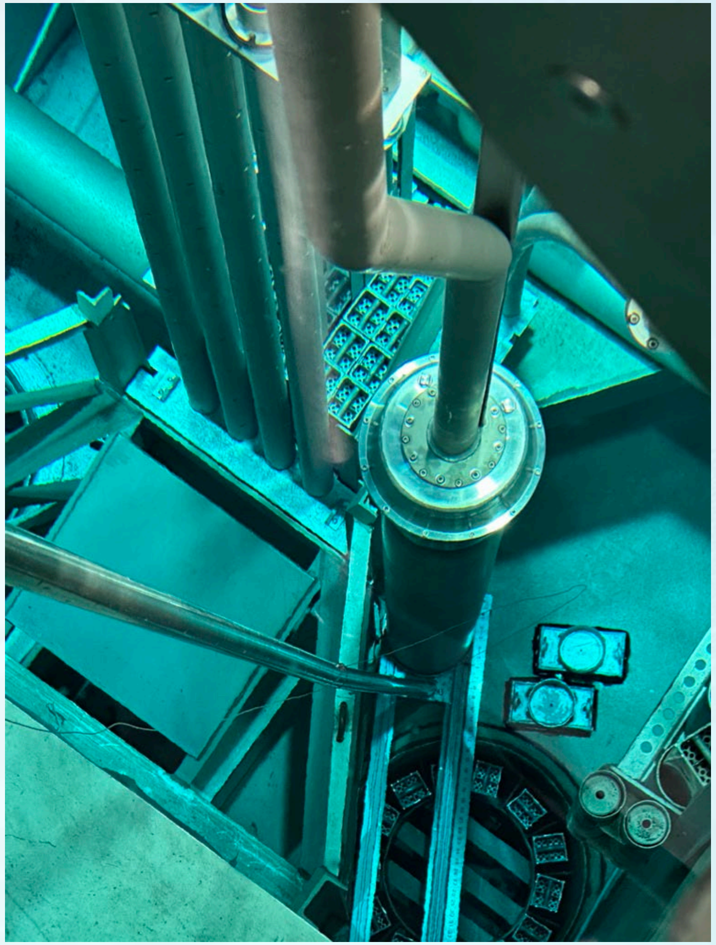
Cf252 Irradiation Results – FREND Output

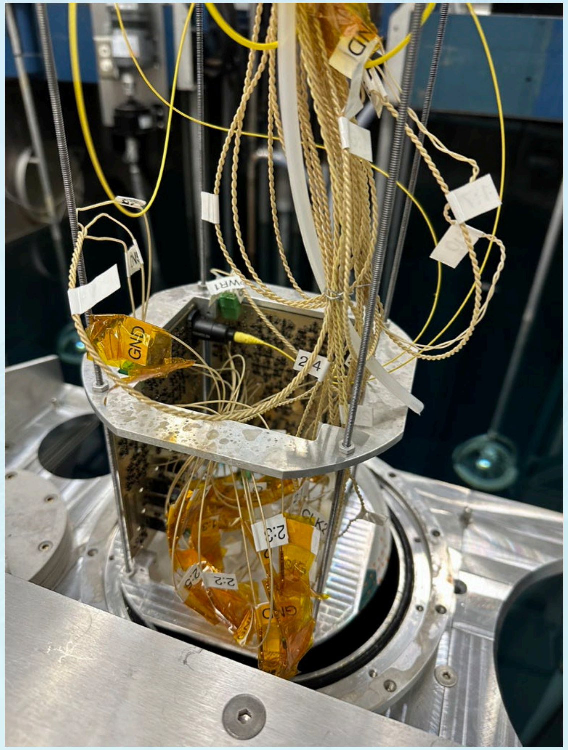


- Duty cycle and frequency versus fluence
- Fluence: 10^{13} n/cm^2
- No failures observed
- Minimal changes to duty cycle (~1%)

PULSTAR Irradiation

- Boards 5 & 6: water leak
- Boards 8 & 9: 10^{16} n/cm^2
- Automated monitoring (Saleae):
  - Flip Flops (DFF)
  - Summer
  - Clock
  - FREND output via photodetectors
- Thermocouple preamplifier boards with SMU input
- Irradiated 8 hr each day, dry tube backed away from core at night to minimize extra gamma-only exposure

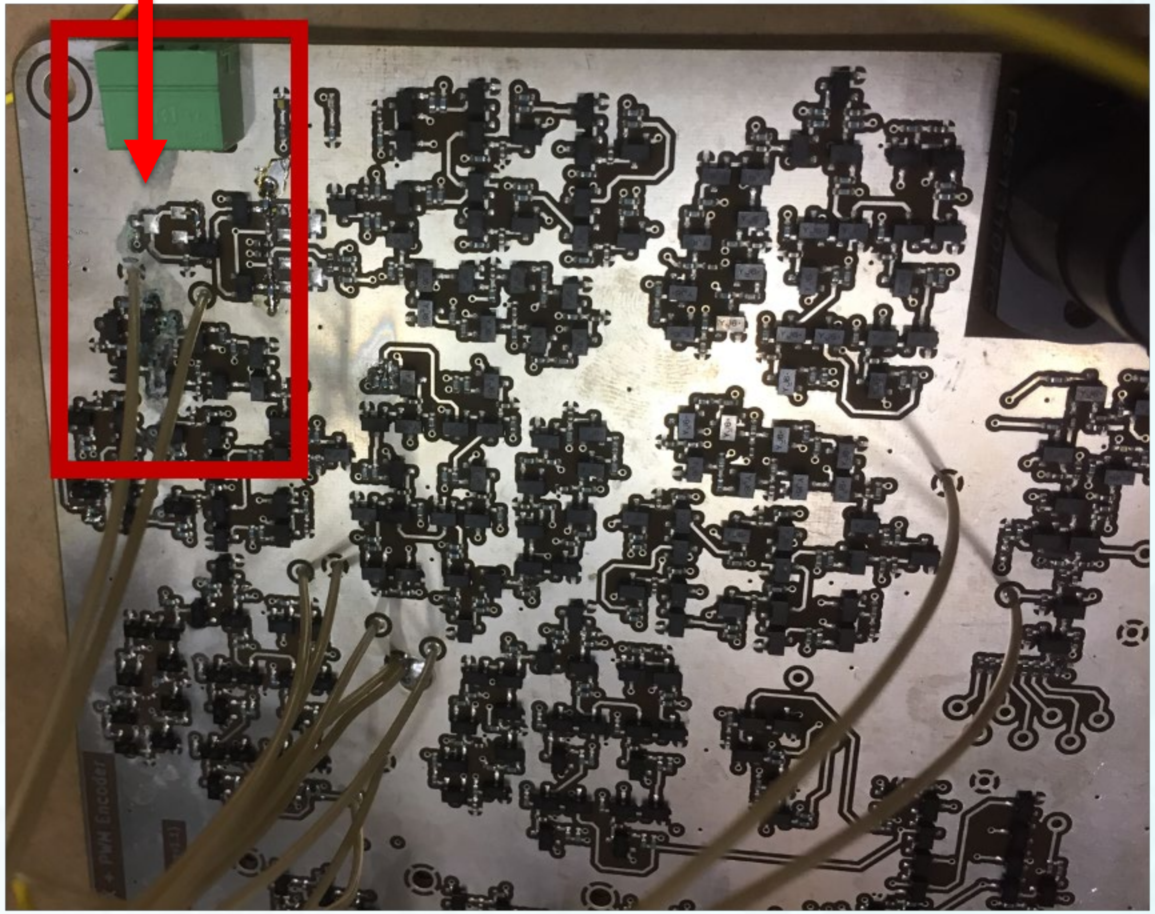




PULSTAR Irradiation – Water leak

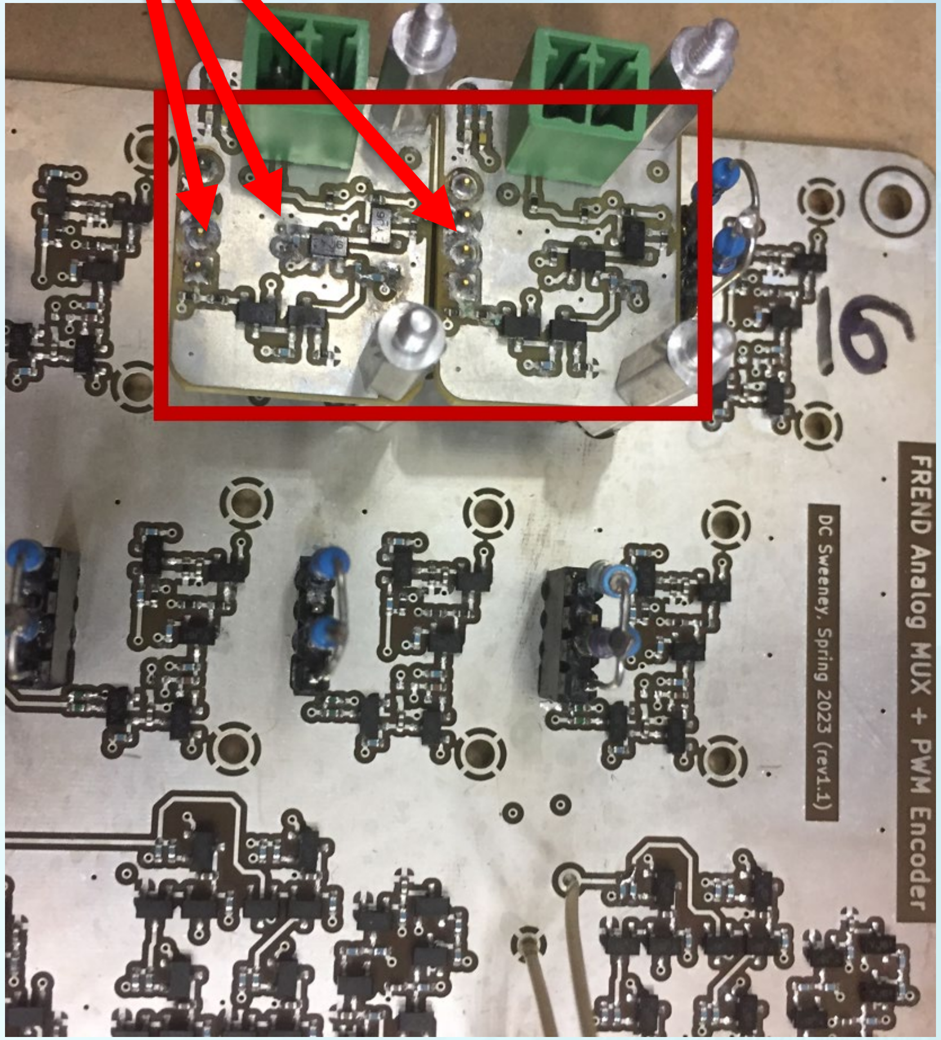
Water Damage

Board 5



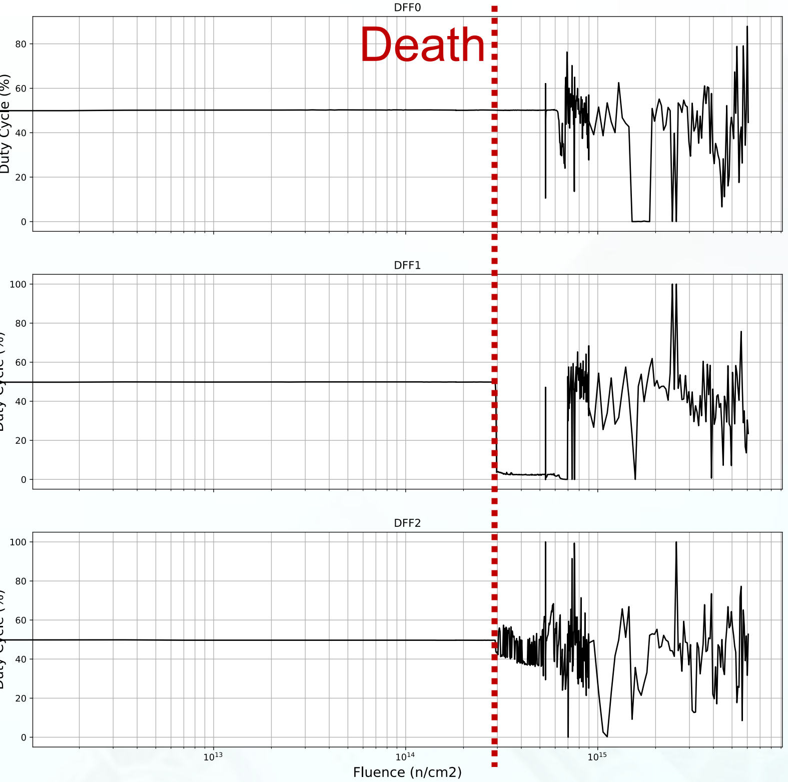
Water Damage

Board 6

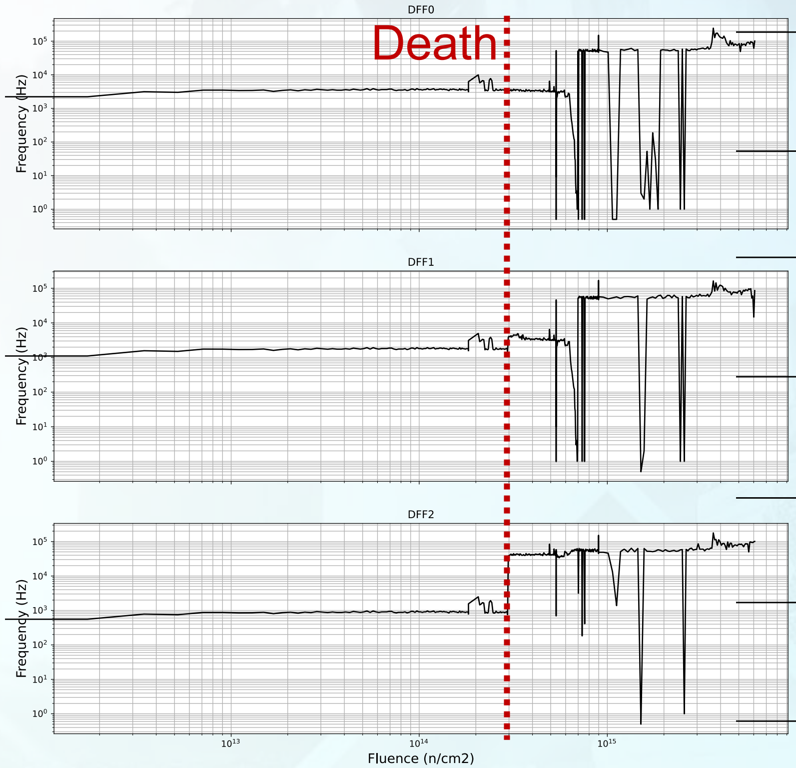


PULSTAR Irradiation Results – Board 8

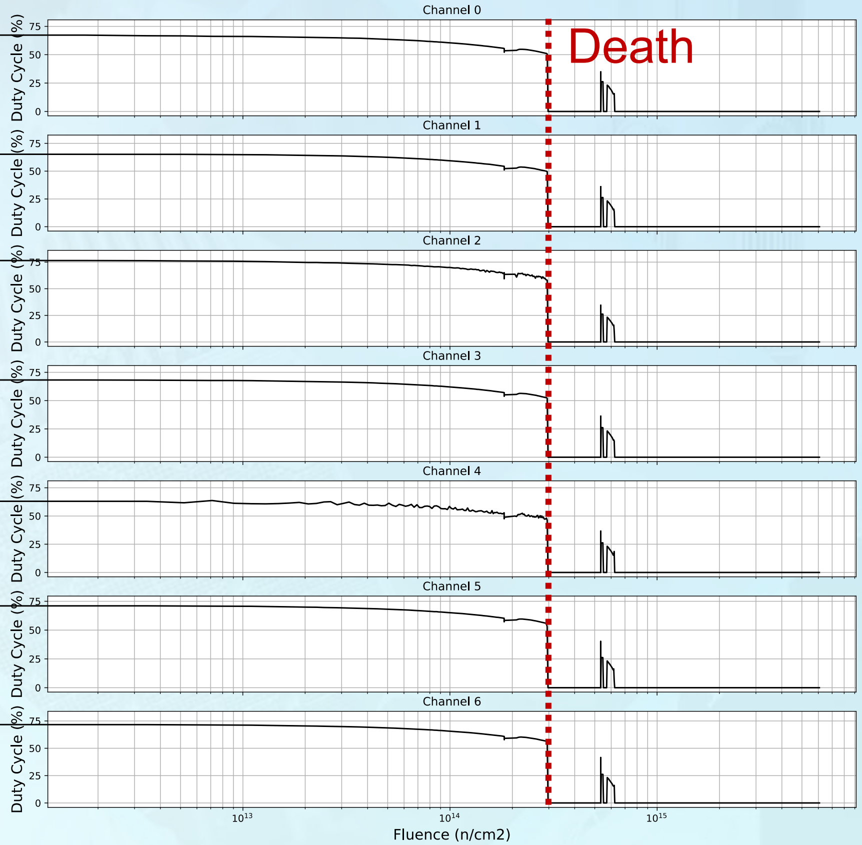
DFFs – Duty Cycle



DFFs - Frequency



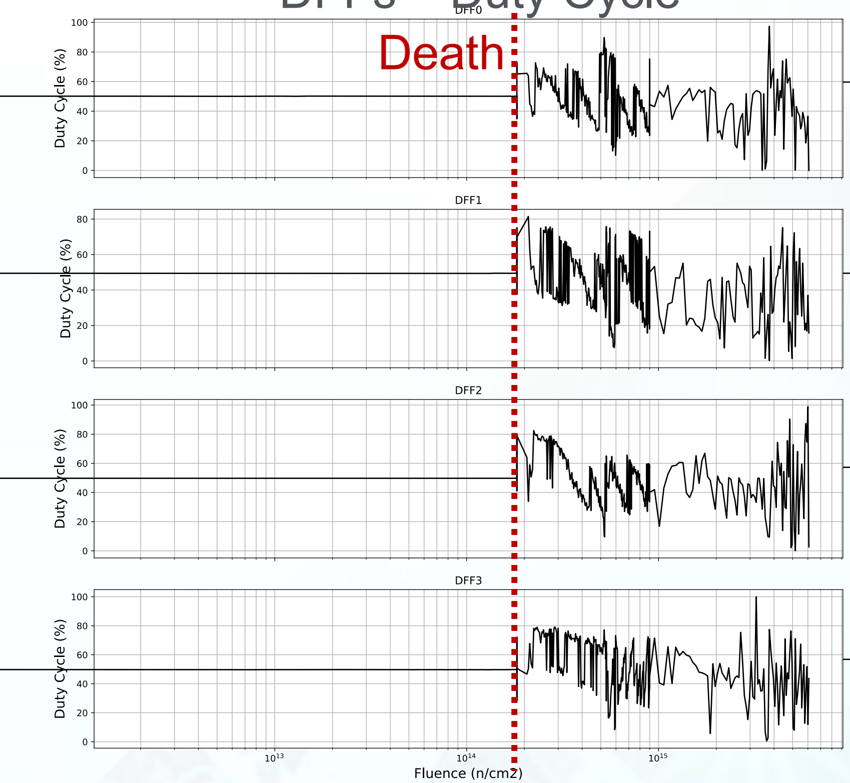
Output



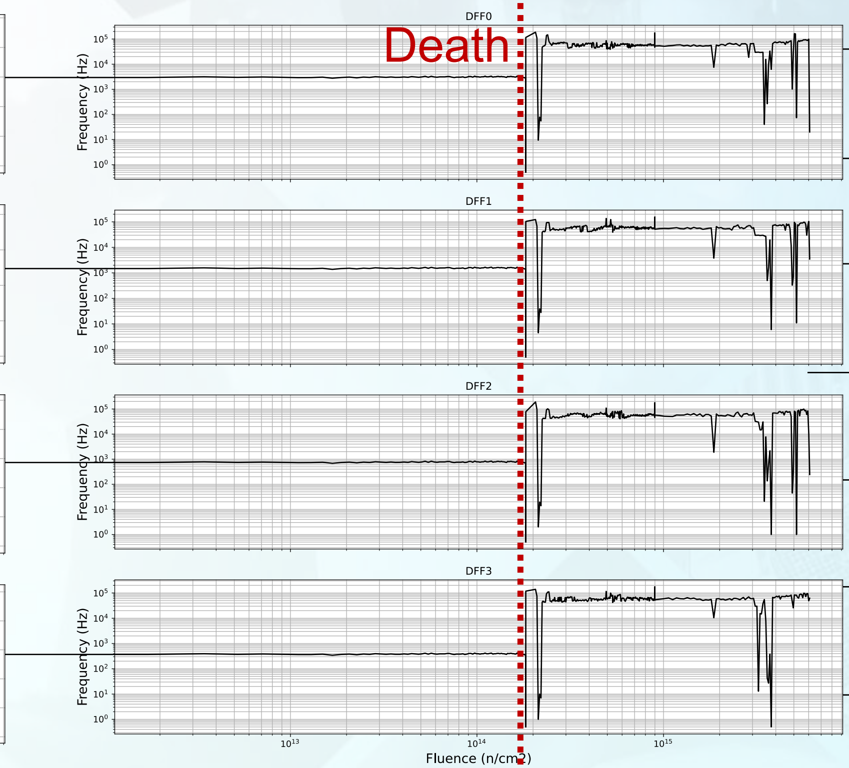
- Failure on DFF1 at $2x10^{14}$ n/cm^2, causing cascading failure
- Frequency change, suggests change to transistor characteristics (threshold voltage) not complete failure

PULSTAR Irradiation Results – Board 9

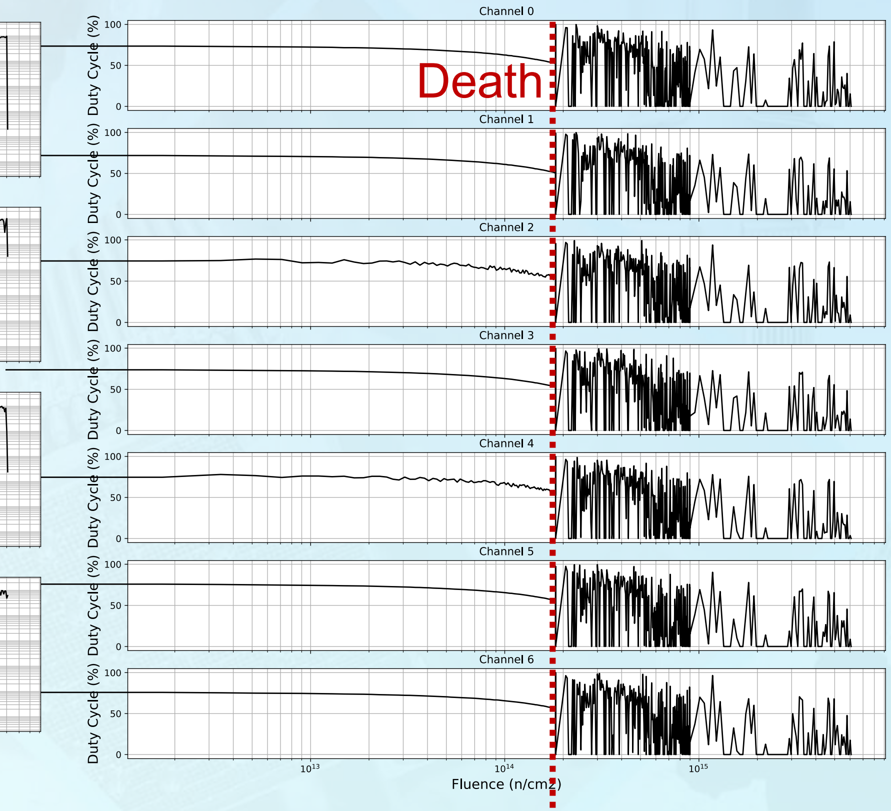
DFFs – Duty Cycle



DFFs - Frequency



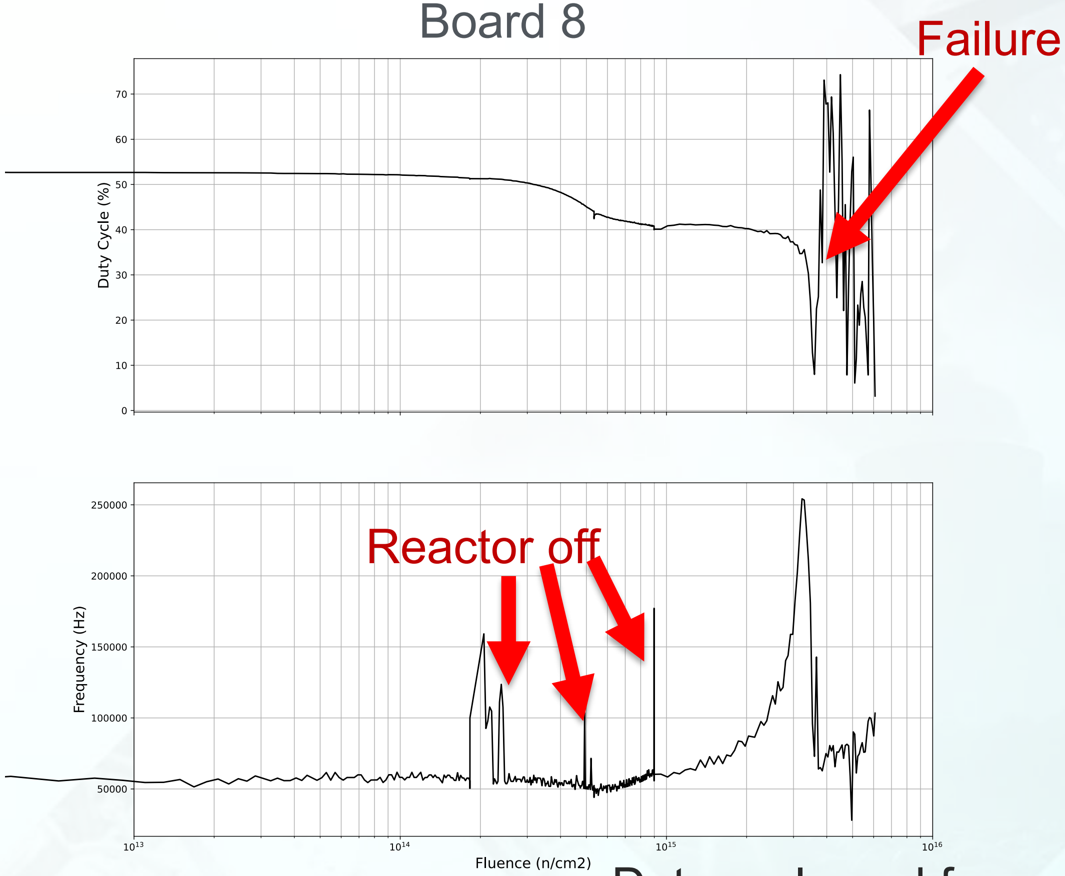
Output



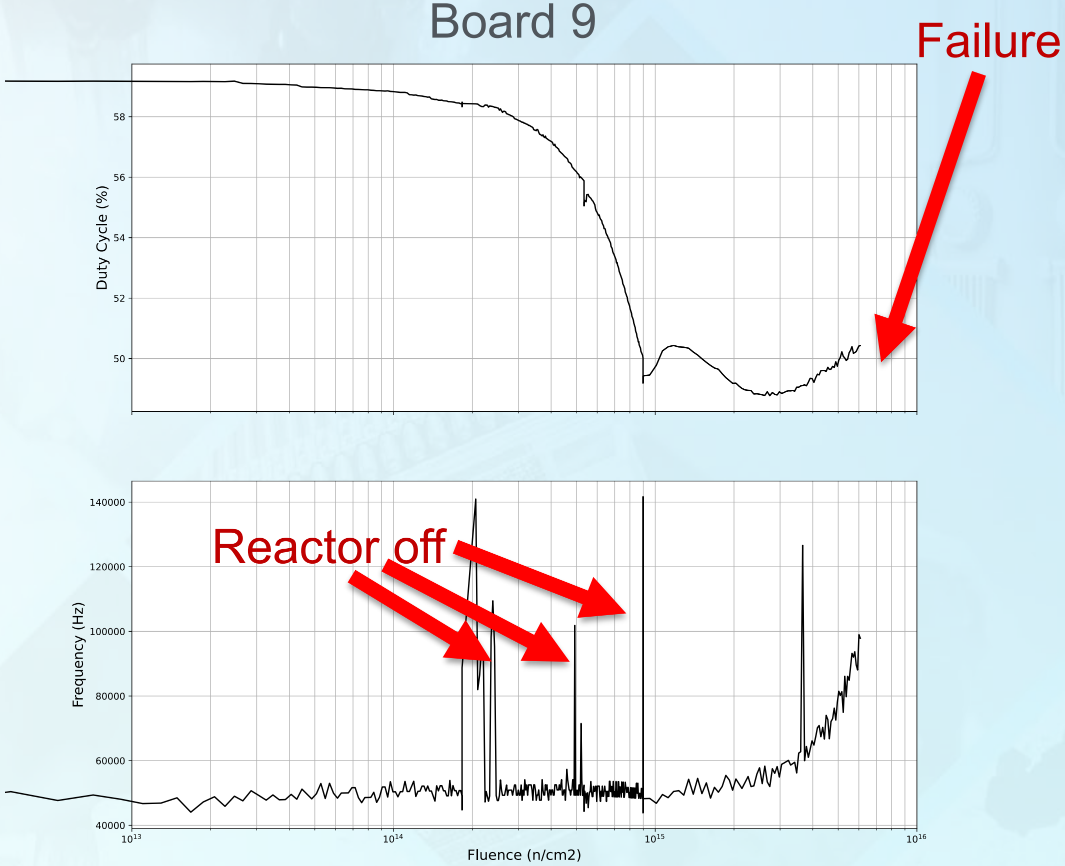
- Power instabilities observed at 1.8×10^{14} n/cm^2 (wild input current variations)
- DFF0 became asymmetric, frequency jumps, suggests failure ahead of DFF0, likely divider after clock
- Reactor turned off, standpipe backed away

PULSTAR Irradiation Results – Clocks

Board 8



Board 9

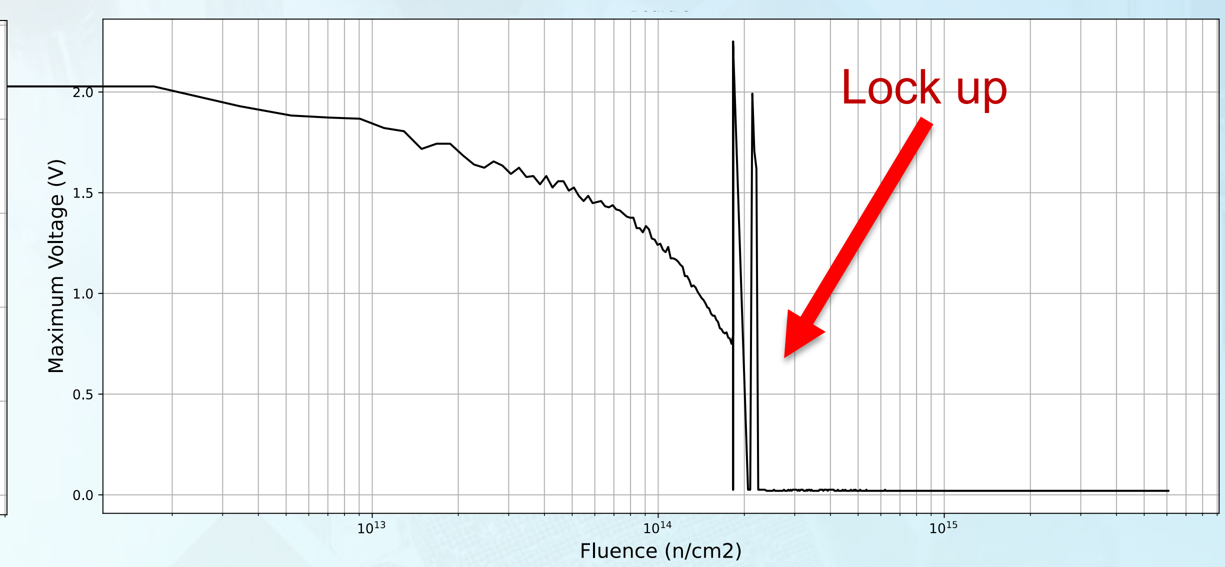


- Duty cycle and frequency versus fluence
- Clocks most radiation-hard portion of circuit
- Board 8 failed at 2.5×10^{15} n/cm^2
- Board 9 failed between $7 \times 10^{15} – 1 \times 10^{16}$ n/cm^2
- Offer lessons for radiation-hardness of FREND

PULSTAR Irradiation Results – Laser Diode

Board 8

Board 9



- Maximum voltage of laser diode versus fluence – indicative of health
- Exponential decline of signals suggests drift in sawtooth wave or comparator due to irradiation
- Board 9: locks due to failure in synchronization stage, pulled low

Irradiation Summary

Board number	Irradiation facility	Cause of death	Max fluence (n/cm^2)	Death fluence (n/cm^2)
1	^{252}Cf	NA	2.5×10^{13}	Survived
2	^{252}Cf	NA	2.5×10^{13}	Survived
3	^{252}Cf	NA	2.5×10^{13}	Survived
5	PULSTAR	Water damage	1.3×10^{13}	Survived
6	PULSTAR	Water damage	1.3×10^{13}	Survived
8	PULSTAR	Radiation	1×10^{16}	2×10^{14}
9	PULSTAR	Radiation	1×10^{16}	1.8×10^{14}

Interesting note: no single event effects observed (common in other radiation fields)

Recommendations for FREND

- Results suggest similar neutron-sensitivity in JFETs to CMOS
- Wide bandgap transistors – GaN, SiC
- Increase rail voltages, asymmetric logic towards direction of drift in threshold voltage and drain currents
- **Incorporate design into rad-hard wide-bandgap ASIC**
  - Smaller, allow for on chip redundancy
  - More stable

Concluding Remarks

- Irradiation-ready FREND with modest improvements
- Preamplifier boards to support different I&C
- Irradiated with neutron only (^{252}Cf) and mixed gamma-neutron (PULSTAR)
- Whole system failure in range 10^{14} n/cm^2
- Clocks survived beyond 10^{15} n/cm^2 – suggest could redesign to survive to similar range
- Neutron effects on JFETs previously unknown
- No SEU's observed
- Recommend wide bandgap FREND ASIC as next step

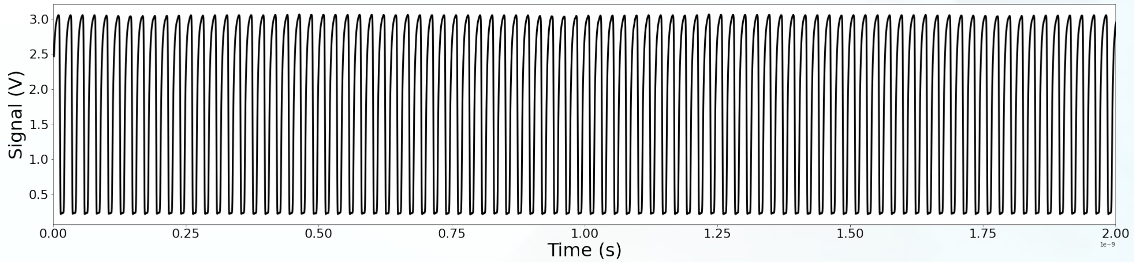
Successful FREND irradiation campaign demonstrated utility of COTS electronics for nuclear applications!

Callie Goetz
R&D Staff
Goetzkc@ornl.gov
(615)830-4475

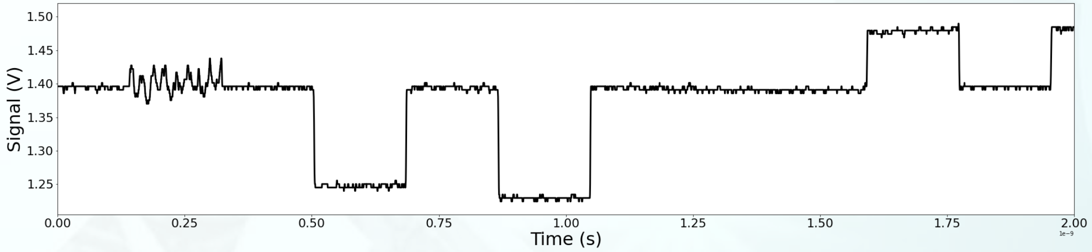
Thank You

Board Signal Example – Pre Irradiation

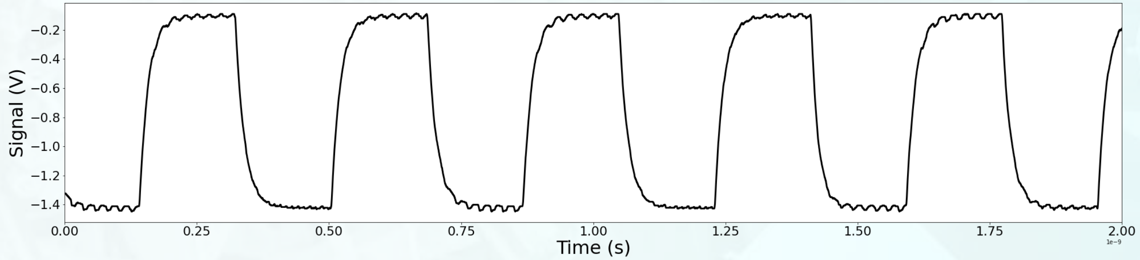
Clock



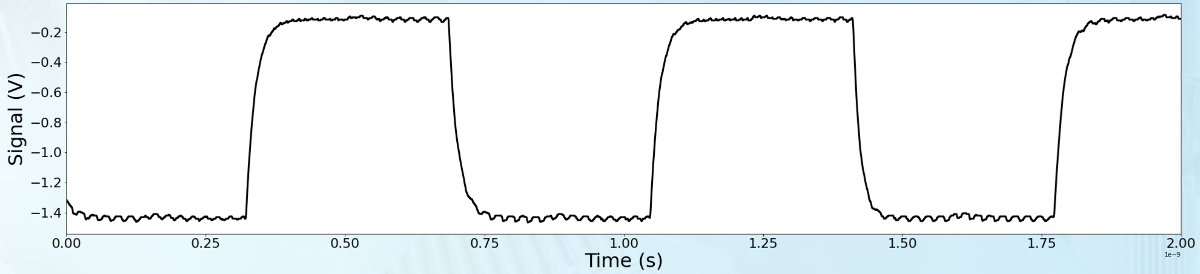
Summer



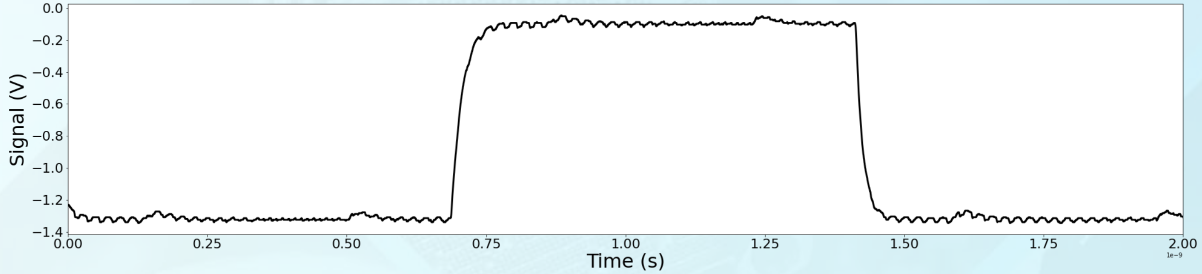
DFF0



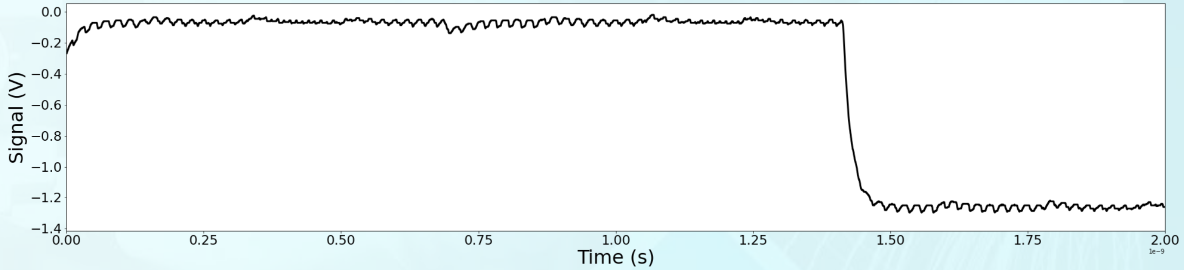
DFF1



DFF2



DFF3



Board Output Example - Pre Irradiation