Neutron Irradiation of Silicon Sensors for the Phase 2 Upgrade

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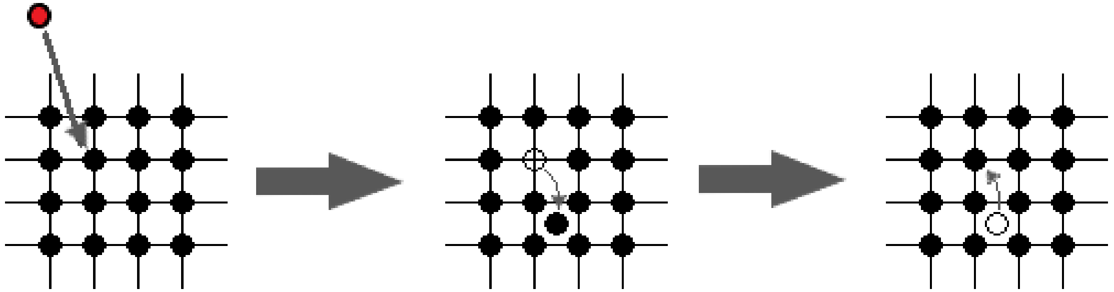
Why is Irradiation Testing Important?

- A silicon lattice can acquire defects from radiation
- During the run of the HL-LHC the innermost part at the CMS detector will receive an unprecedented radiation dose of $2.3 \cdot 10^{16}$ n_{eq}/cm^2
- There are vital parts of the Phase 2 CMS detector which are largely composed of silicon. We need to make sure that these parts will perform optimally throughout the lifetime of the CMS detector

Silicon Semiconductor Lattice Defects

- Lattice defects can occur when heavy particles scatter off and displace nuclei in a semiconductor lattice
- These defects can trap charge carriers
- Through annealing, some detector defects can be recovered.



Incoming baryon strikes nuclei in semiconductor lattice

Nuclei is knocked out of the lattice

Through beneficial annealing, some lattice defects can improve

Neutron Irradiation

- Test sensors will be irradiated at nuclear reactors to test radiation hardness of materials
- Neutron irradiation will happen at the Rhode Island Nuclear Science Center (RINSC) located near Brown University
- Two different delivery methods
  - Beam port
    - Samples placed in beam port before ramp up and removed after ramp down
    - 6” diameter and 8” diameter ports
  - Pneumatic Rabbit System
    - Samples are delivered and removed from reactor when it is at full power
    - Only samples 35 mm by 90 mm can fit in rabbit system carrier

Beam Port Fluence Measurements

Beam port fluence has been measured using two methods

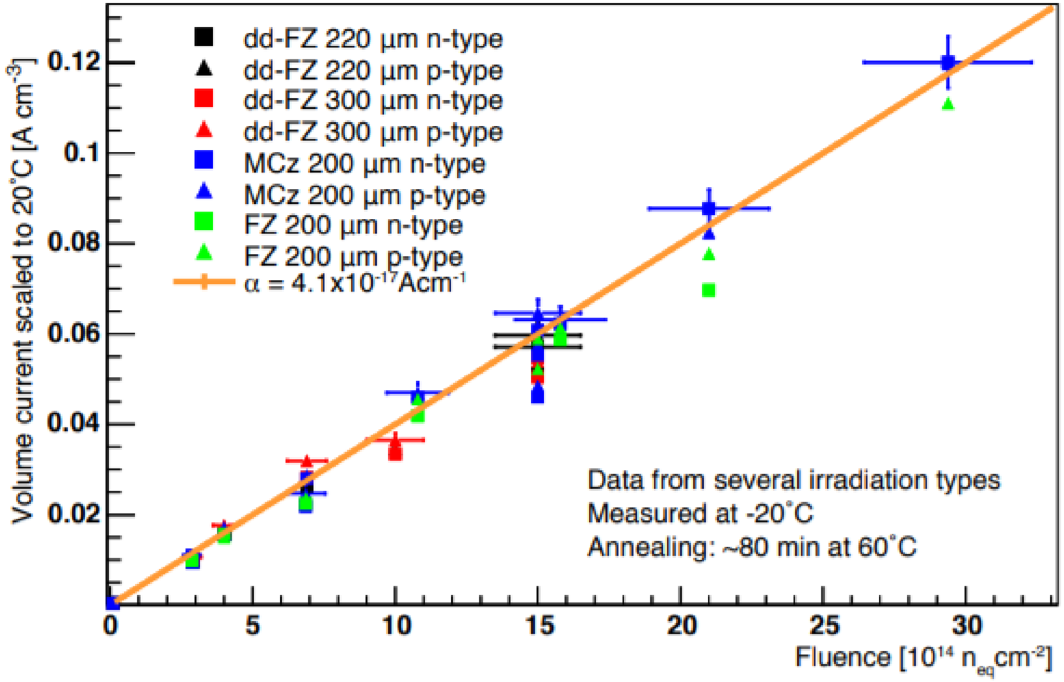
- **Silicon Diodes**
  - D0 diodes were irradiated in reactor
  - The increase in leakage current of the fully depleted diode is proportional to the 1-MeV equivalent fluence that the diode received.
- **Spectrum Unfolding Via Foil Activation**
  - Foils composed of different pure elements are irradiated in reactor
  - Activity is measured via gamma spectroscopy
  - A parametrized model of the flux spectrum is used to predict the activation of the foils
  - The parameters are varied until the predicted activations agree with the observed values
  - Silicon damage function can be used to obtain a 1 MeV equivalent flux

Diode Measurements

- Post irradiated diode leakage current is measured after 80 minutes of annealing at 60^{o}C
- Leakage current is proportional to fluence received by diode

Diode measurements for 8” beam port:

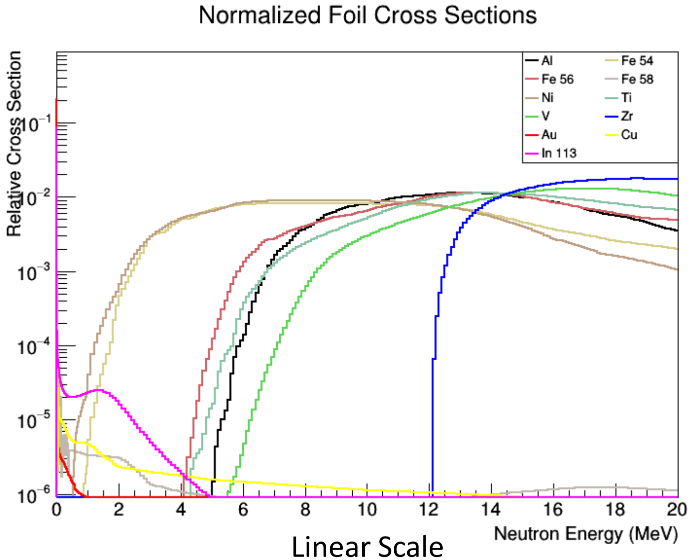
Diode	Ileak	Flux
CO16	0.73 mA	5.7×10^{11} n/cm^2/s
CO17	0.73 mA	5.7×10^{11} n/cm^2/s
CO18	0.77 mA	6.0×10^{11} n/cm^2/s
CO19	0.79 mA	6.1×10^{11} n/cm^2/s
Average	**0.76 mA**	**5.9×10^{11} n/cm^2/s**



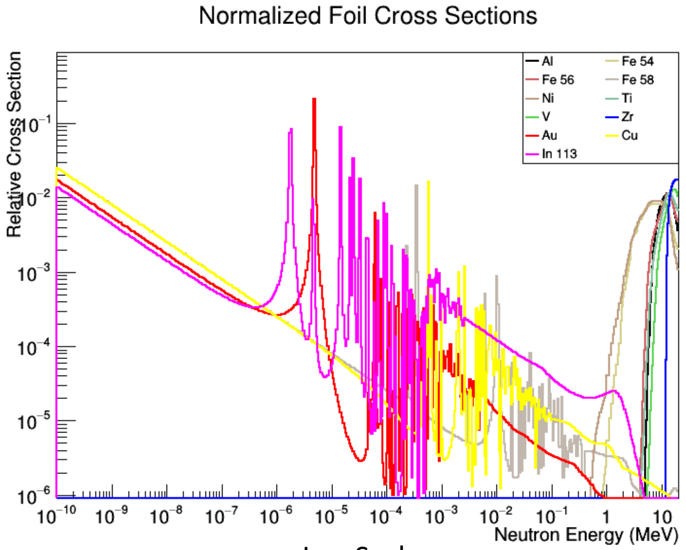
Plot taken from **The Phase 2 Upgrade of the CMS Tracker** 2017 TDR

Foil Activation

- Foils which were irradiated
  - 6” beam port – Al, Au, Cu, Fe, In, Ni, Ti, V, Zr
  - 8” beam port – Al, Cu, Fe, Zr
- Neutron interactions we looked at:
  - Al27 (n,α) Na24
  - Ti48 (n,p) Sc48
  - V51 (n,α) Sc48
  - Fe54 (n,p) Mn54
  - Fe56 (n,p) Mn56
  - Fe58 (n,γ) Fe59
  - Ni58 (n,p) Co58
  - Cu63 (n,γ) Cu64
  - Zr90 (n,2n) Zr89
  - In113 (n,γ) In114
  - W186 (n,γ) W187
  - Au197 (n,γ) Au198



Linear Scale



Log Scale

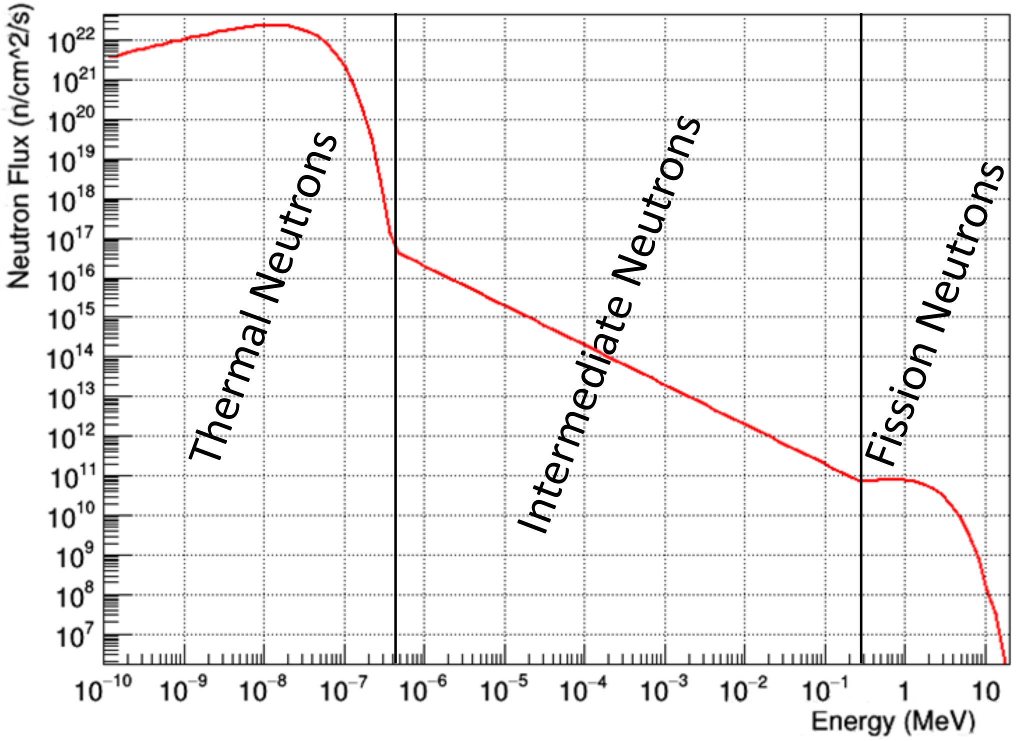
Foil Activation

- Spectrum is modeled using the following form:
  - Maxwellian energy distribution for thermal spectrum:

$$\varphi(E) \propto \sqrt{\frac{E}{(kT)^3}}\, e^{-E/_{kT}}$$

    - Where:
      - k = Boltzman's Constant
      - T = temperature of thermal neutrons
        - approximated as the temperature of the water the core is submerged in ≈70ºF
  - $^1/_E$ distribution for intermediate neutrons
  - Watt Distribution for fission neutrons

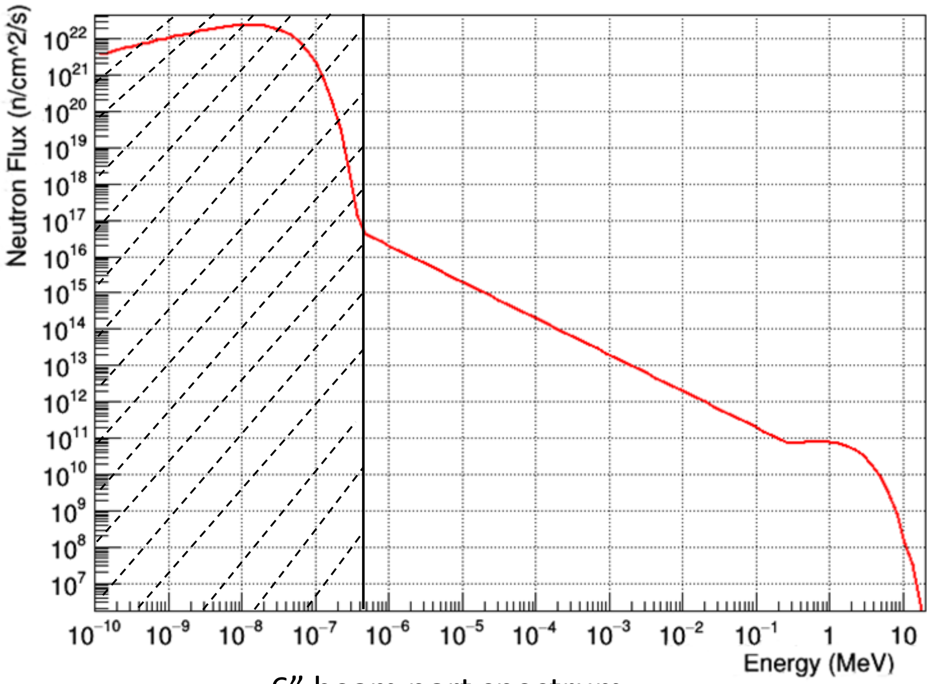
$$\varphi(E) \propto \sinh\left(\sqrt{2.29E}\right) e^{-E/_{0.965}}$$



Foil Activation

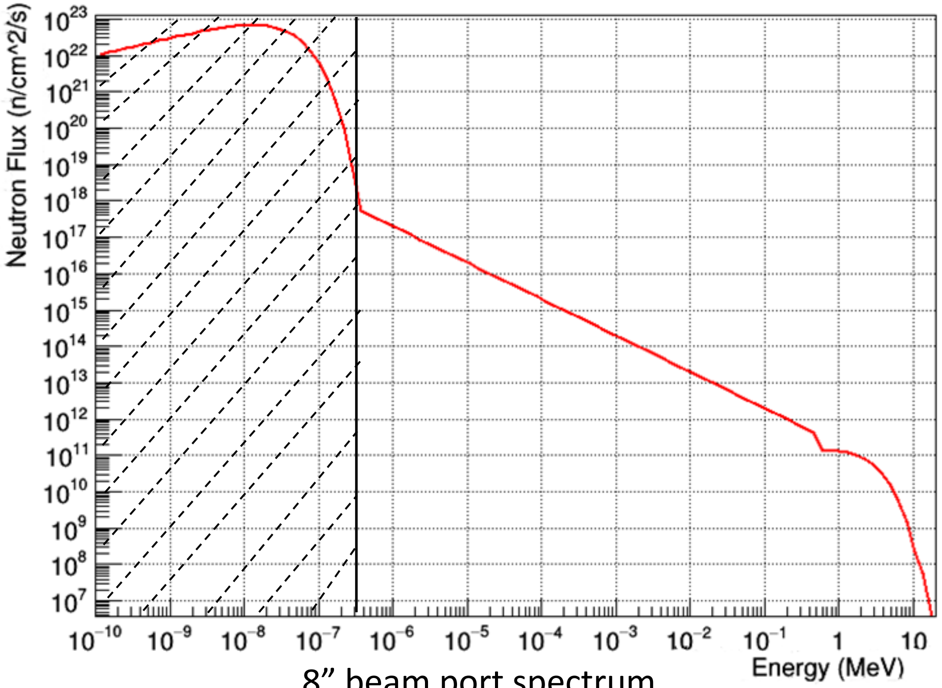
- All elements sensitive to thermal neutrons have an exponentially falling cross section for thermal neutrons, causing the low energy portion of the fit to be poorly constrained.

1 MeV Equiv Flux = 2.4E11 ± 0.5E11 $n_{eq}/cm^2/s$



6” beam port spectrum

1 MeV Equiv Flux = 5.6E11 ± 1.2E11 $n_{eq}/cm^2/s$



8” beam port spectrum

Reactor 1 MeV Equivalent Flux

	6” Port	8” Port
1 MeV Equiv Flux (foils)	2.4E11 ± 0.5E11 $n_{eq}/cm^2/s$	5.6E11 ± 1.2E11 $n_{eq}/cm^2/s$
1 MeV Equiv Flux (diodes)	2.3E11 ± 0.2E11 $n_{eq}/cm^2/s$	5.9E11 ± 0.6E11 $n_{eq}/cm^2/s$

When ignoring the thermal neutron’s contribution to the 1 MeV equivalent flux measured found using the foil activation method, good agreement is seen between the two measurement methods

Irradiation time needed to reach desired fluences

Delivery Method	6” Beam Port	8” Beam Port
Approximate Irradiation Time For $1 \cdot 10^{15}$ n_{eq}/cm^2	1 Hours 10 Mins	$^1/_2$ Hour
Approximate Irradiation Time For $2.3 \cdot 10^{16}$ n_{eq}/cm^2	28 Hours	11 $^1/_2$ Hours

Summary

- Silicon sensors need to undergo irradiation testing to make sure they will still work after withstanding the predicted irradiation dose of the HL-LHC
- Neutron irradiation tests will take place at the RINSC reactor located near Brown University
- Reactor flux at the different irradiation delivery sites have been measured using two different methods
  - Measuring the leakage current of irradiated D0 diodes
  - Obtaining a spectrum of the neutron energy flux using foil activation
  - After correcting for overestimation of the thermal spectrum in the 6” and 8” port, diode and foil measurements show good agreement

Backup

Irradiation Times

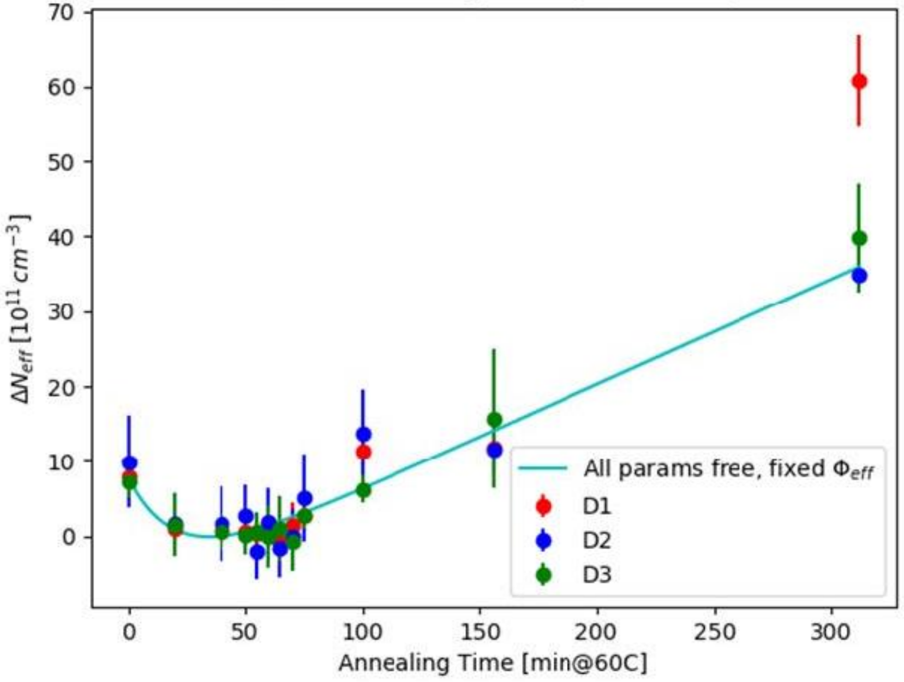
Desired Fluence	Approximate Irradiation Time	
	6 – inch port	8 – inch port
10^{14} n_{eq}/cm^2	7 minutes	3 mins
10^{15} n_{eq}/cm^2	1 hours 10 mins	$^1/_2$ hour
10^{16} n_{eq}/cm^2	12 hours	5 hours
$2.3 \cdot 10^{16}$ n_{eq}/cm^2	28 Hours	11 $^1/_2$ Hours

Expected fluence of inner tracker after 3000 fb^{-1} of data is approximately $2.3 \cdot 10^{16}$ n_{eq}/cm^2

Silicon Sensor Annealing

Post-irradiation diode leakage current and depletion voltage improves with annealing. After a threshold, further annealing will cause damage to the sensor.

N_{eff} vs Annealing Time (F512, 1kHz)



I_{leak} vs Annealing Time at -400V (F512)