Radiation Damage to Electronics at the NIF

Workshop for Applied Nuclear Data Activities (WANDA 2024)

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On behalf of the LLNL IFE team

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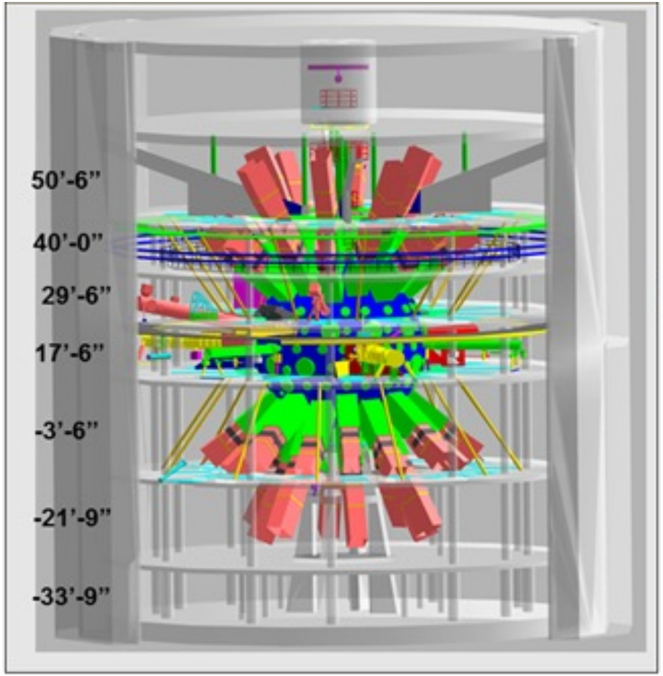
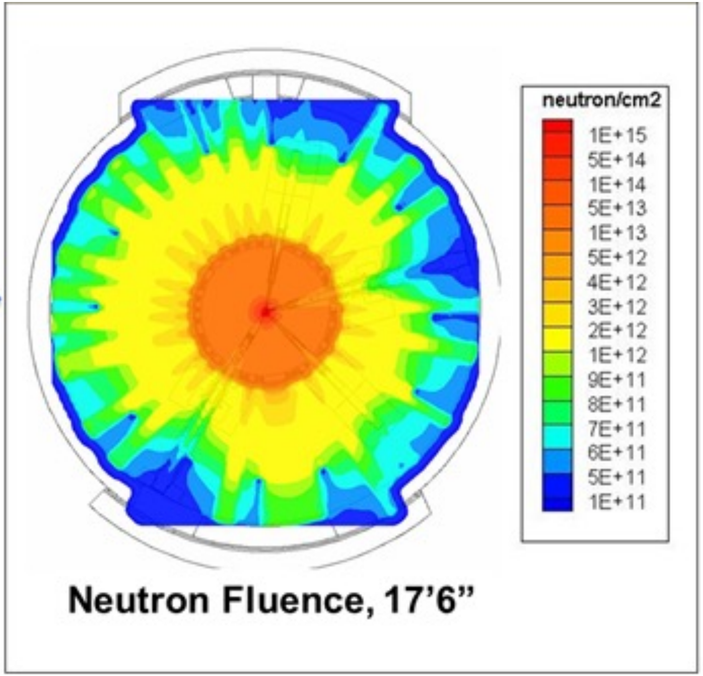
Introduction

- Exposure of electronic equipment to high level of radiation may result in a permanent or pixel damage
- The permanent damage is caused by total ionizing dose (TID) that is mostly dominated by the higher energy neutrons
- In a facility like NIF, it is easier to shield against TID due to radiation directionality from the fusion target
- Displacement damage (DD) producing hot pixels in cameras is caused by all neutrons regardless of their energy
- Shielding against DD is more difficult as scattered neutrons are everywhere inside the NIF Target Bay

Neutron fluence maps in the NIF (20 MJ yield)

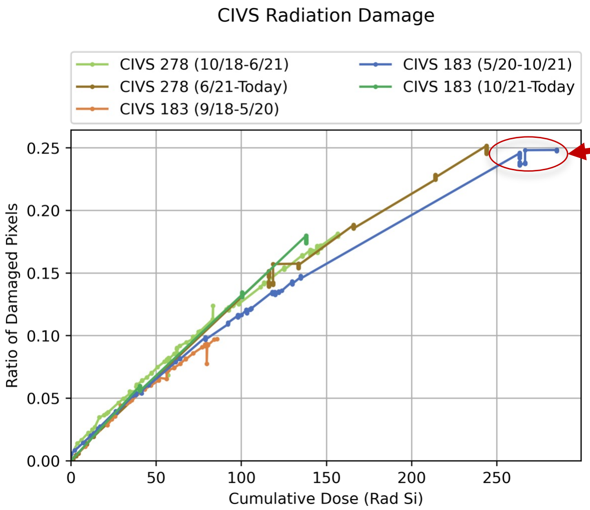


Example

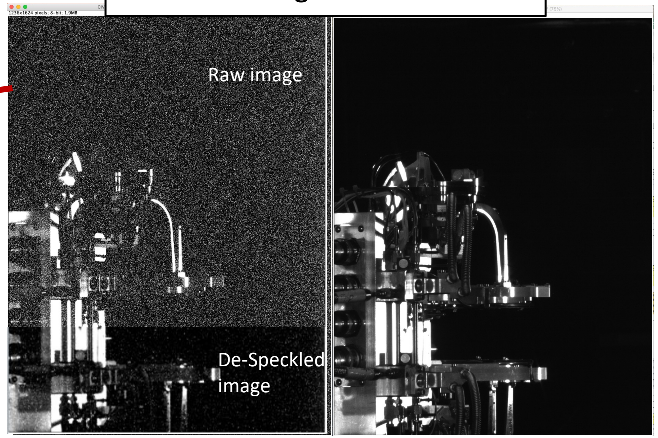


Example of neutron induced damage: CIVS CCD camera "hot" pixels

- Neutron induced damage to Chamber Interior Viewing System (CIVS) cameras generates hot pixels, resulting in loss of contrast in images
- Hot pixel defined as a pixel with a value >20% of saturation value
- MCNP simulations are used to determine neutron dose (rad-Si) at a given location



CIVS 183 images of TAS at TCC



Before replacement (dose = 285 rad-Si)

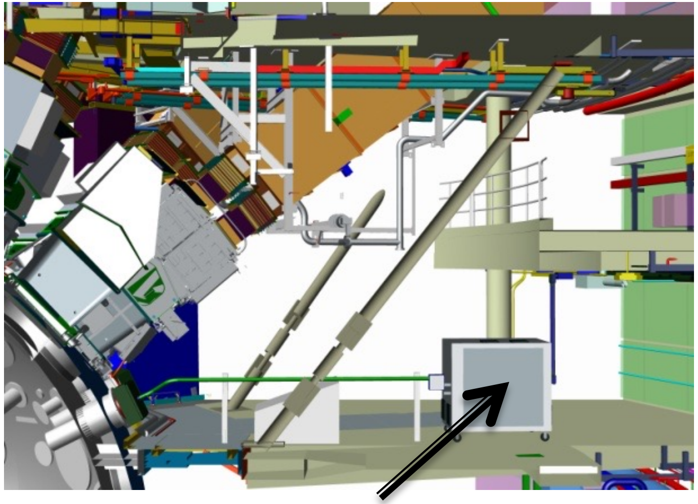
New camera

A scope failure inside the Target Bay

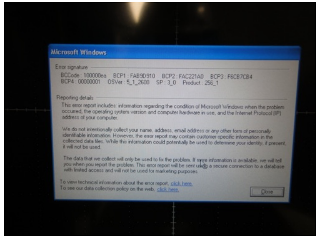
- A scope upset during a NIF shot with estimated yield of 5.7e14 neutrons with all data lost but the scope recovered

- Fluence maps showed a fluence of ~2×10^8 [n/cm^2] at the scope location

- Scope was moved outside the Target Bay



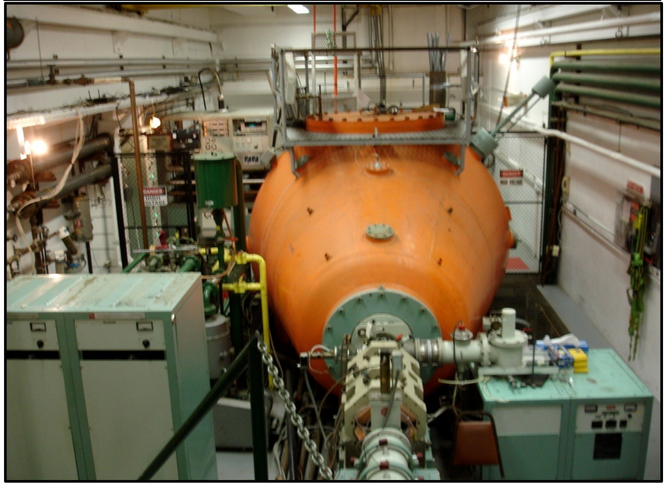
Scope Location



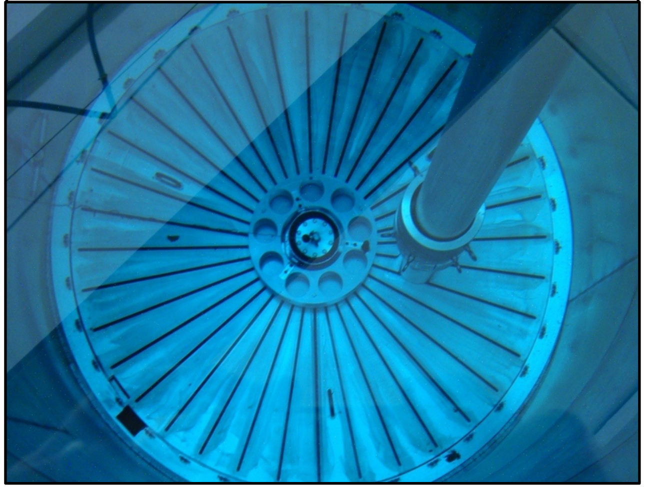
DC Error message: *"DATA ACCESS ERROR - /Dpo70604B@TCPIP::192.168.2.2::INSTR/Misc/DeviceCommunication, current value = TEKTRONIX,DPO70604B,B110291,CF:91.1CT FV:4.3.1 Build 2. RangeType:None Error/Recovery on Controller Communication"*

Radiation damage testing was performed at multiple locations

Ohio University Accelerator Facility
T (d,n) - 14MeV, $1.85x10^{7}$ (n/sr-μC)
Be (p,n)- 4.1MeV, $7.97x10^{8}$ (n/sr-μC)



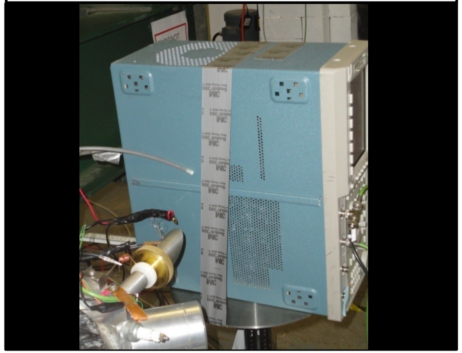
LLNL Co-60 Source
Co-60 gamma source, 1.5 krad/h (dry well)
1.54 krad/min (at source)



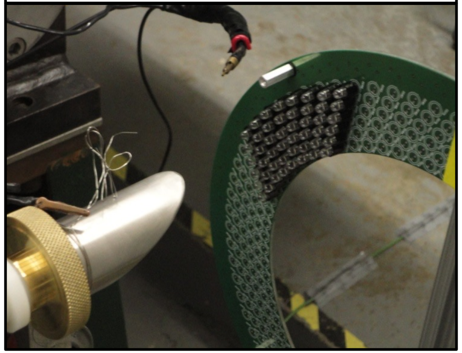
- Test facilities are used to establish radiation effects on vulnerable electronics
- Neutron sources providing higher neutron fluxes are needed for testing off-the-shelf electronics

Component testing at Ohio University

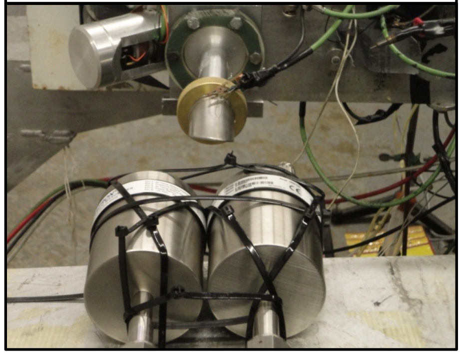
Scope



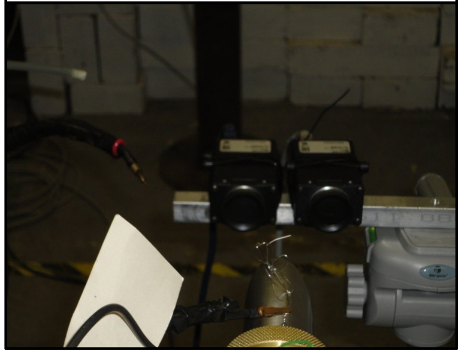
LED Ring



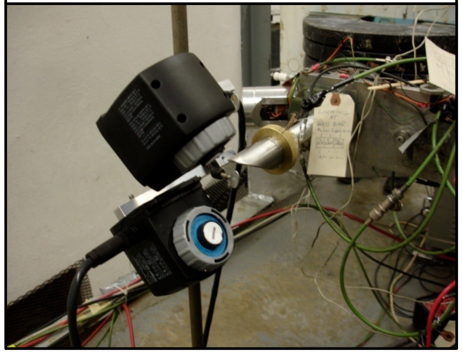
Pressure Sensor



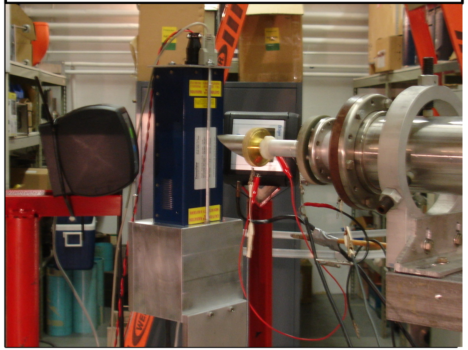
Camera



Oxygen Sensor

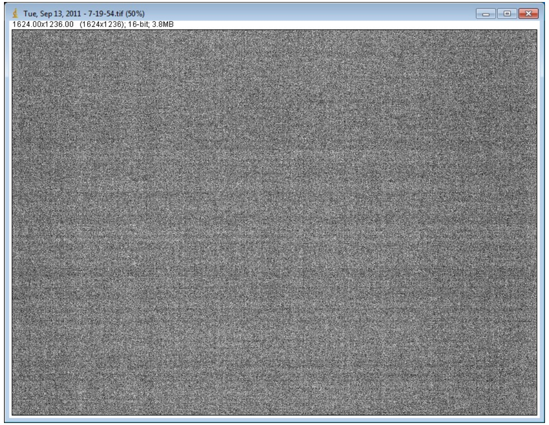


X-ray Generators

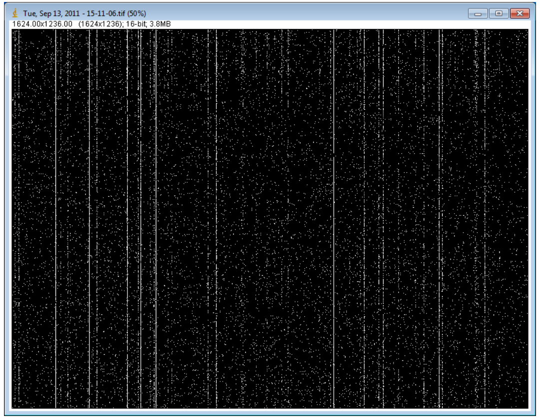


Sensor damage to CCD pixels and CCD columns, and CCD arrays

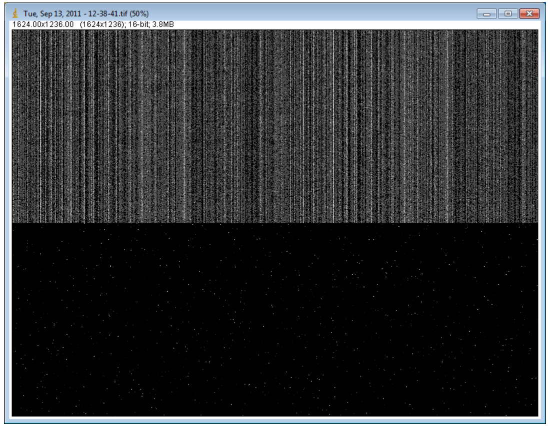
- Two types of cameras were tested at Ohio University accelerator
  - Basler, 641f, Sony Sensor – ICX-274AL (TAS)
  - Pixelink, PL-B771F-BL, Micron Sensor - MT9M001C12STM



Before neutron irradiation

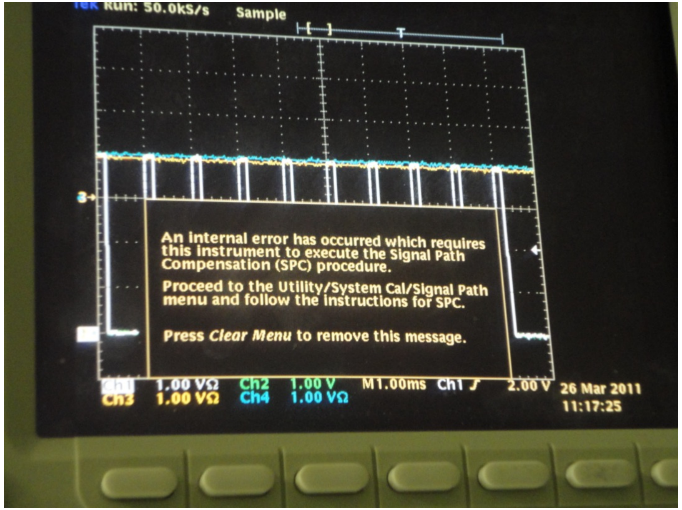


Neutron irradiation,
dark current increase

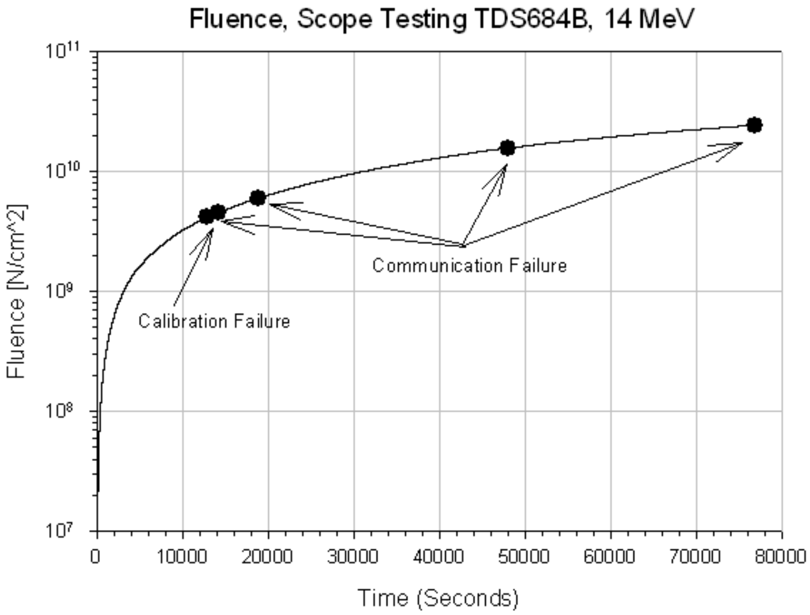


Neutron irradiation,
array access failure

Oscilloscope suffered several upsets and a loss of calibration file

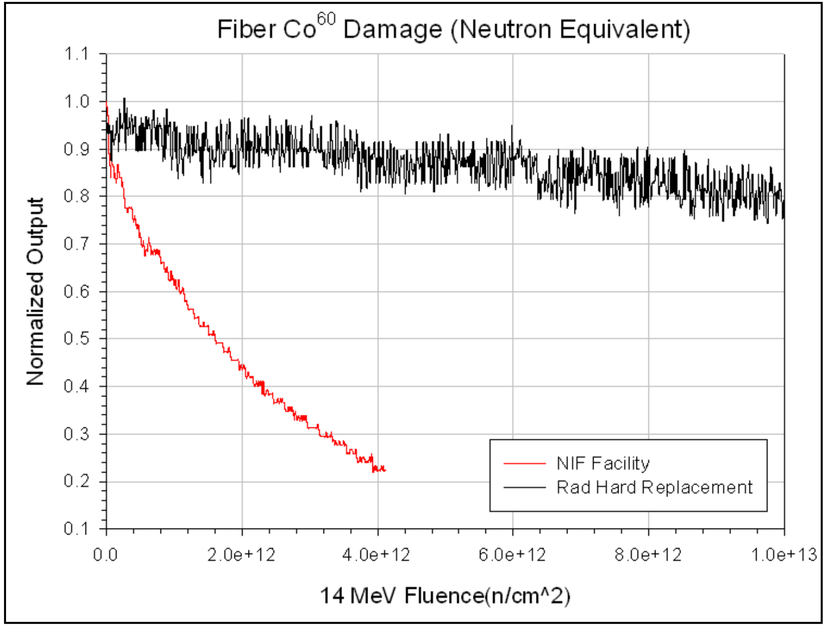


Communication and calibration failures



Facility timing fiber testing

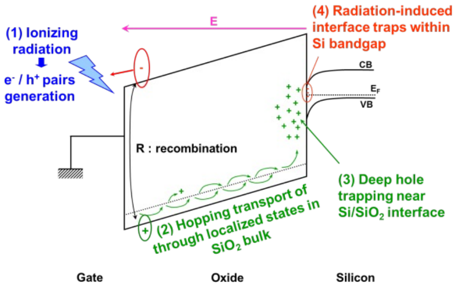
- Gamma Source at LLNL, 1.5 krad/hour at the bottom of the well
- $2x10^9$ (γ/cm2) = 1 rad [Co-60], based on equivalent energy deposited
- Tested several fibers at the wavelength of interest
- Investigation of the standard NIF timing fiber showed radiation damage and was replaced with a radiation hard fiber
- Optical fibers have the same radiation responses regardless of the particles depositing the TID



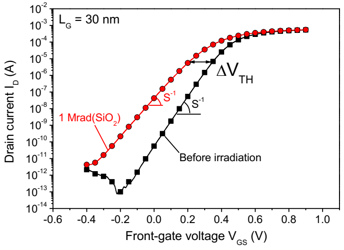
Radiation effects in electronic devices

Permanent Degradation **Transient Degradation**

Total Ionizing Dose (TID)

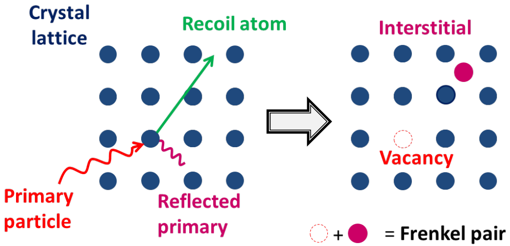


Charge trapping in dielectrics

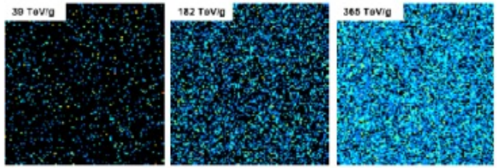


Electrical characteristic modifications

Displacement Damage Dose (DDD)

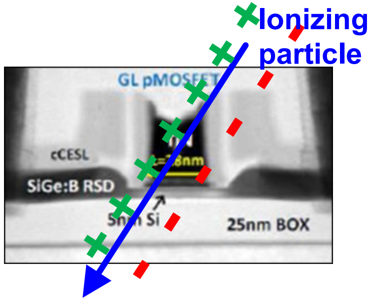


Point defect/cluster generation
Energy levels in bandgap

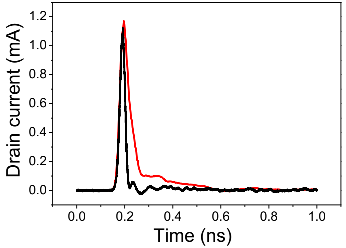


Increase of dark current with increasing DDD

Single-Event Effects (SEE)



Charge generation in semiconductor



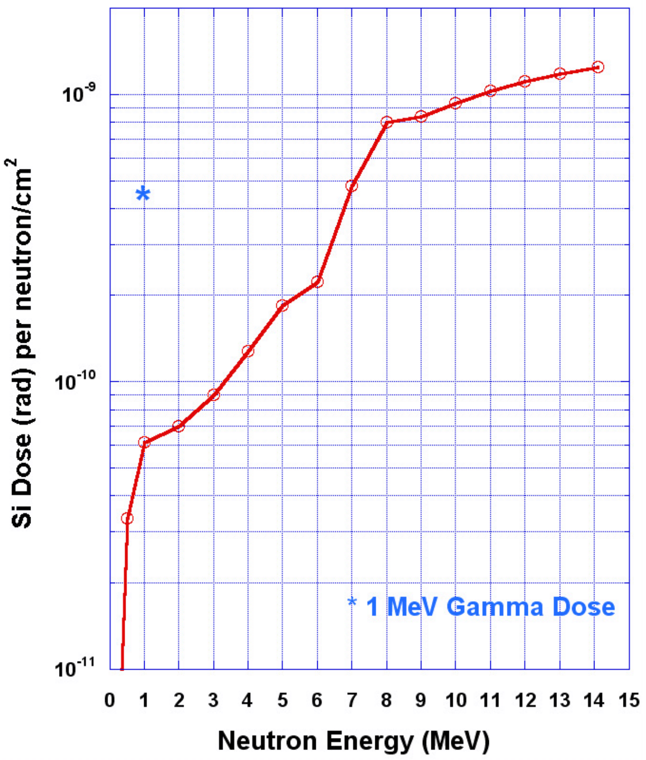
Current pulses generation

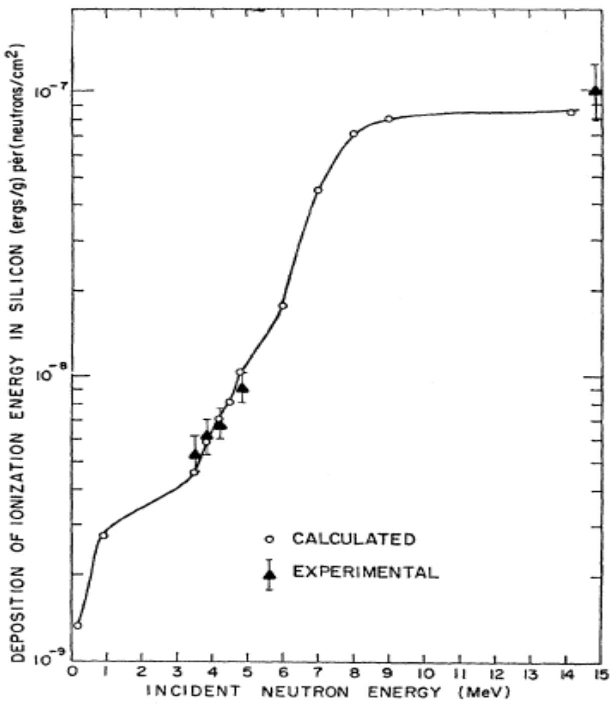
Courtesy of Philippe, Paillet, CEA

Radiation damage in CCD/CMOS cameras due to TID

- Ionizing radiation generates electron-hole pairs within the oxide structure of the CCD
- Number of electron hole pairs generated in the material per unit volume is proportional to the absorbed TID
- If no electric field is applied, then these electron-hole pairs are most likely to recombine again with no damage
- If an electric field is generated by the gate voltage, the electrons will quickly leave the structure
- A fraction of remaining holes will be trapped at the interface layer, causing a negative shift of the threshold voltage and possible degradation of the camera performance

TID to electronics is dominated by high energy neutrons





Average ionization energy deposited in Si per incident neutron

A. Sattler and F. Vook, Physical Review, vol. 155, no 2, 1967

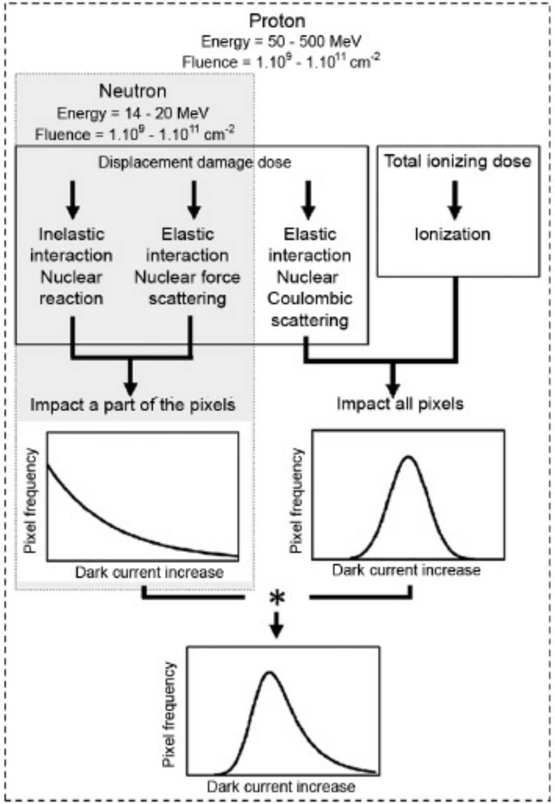
Displacement damage causes "hot pixels" in CCD/CMOS cameras

- Displacement damage is mostly caused from neutrons scattering a silicon atom, thereby creating a damage cascade of secondary knock-on atoms in the silicon lattice
- Displacement damage creates "hot" pixels that have dark current rates that exceed full well under even the shortest integration times of normal pixels
- There are other effects in CCDs including reductions in charge transfer efficiency (CTE) that are less impactful for CMOS image sensors
- Displacement damage for 14 MeV neutrons is approximately a factor of 2 higher than the damage at 1 MeV
- Attenuating neutrons to lower energies does not significantly reduce displacement damage that causes hot pixels

Damage to image sensors due to neutron and proton irradiation

- Total ionizing dose effects are related to the surface and interface layers of the electronics device (e.g., build up of interface states in CIS oxides and increases the overall dark current)
- Displacement damage is related to displacement of atoms in the crystal lattice and produces a bulk damage effects
- Displacement damage function (D) can be related by the NIEL scaling hypothesis

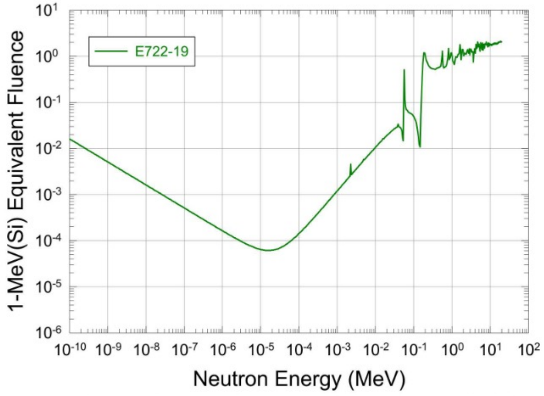
$$NIEL = (N_A/A) \times D$$

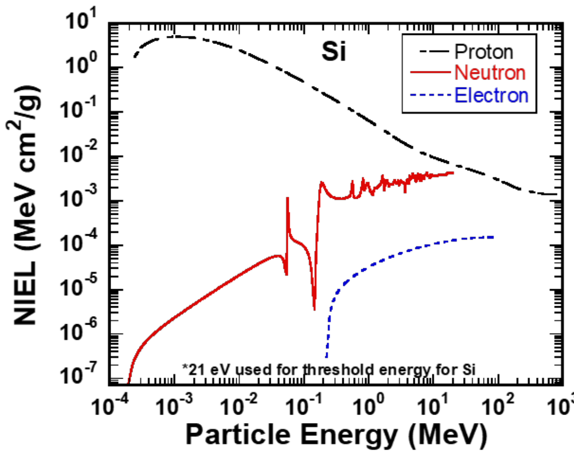


C. Virmontois et al., IEEE Trans. On Nuclear Science, 59(4), 2012

NIEL scaling hypothesis

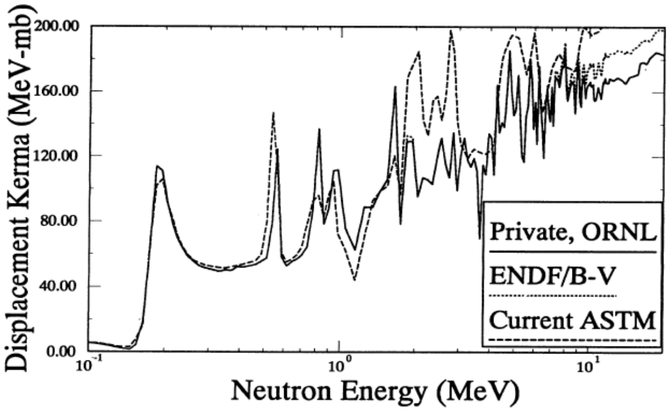
- NIEL is a physical quantity describing the non-ionizing energy loss as the particle travels through a material and can be correlated to the amount of radiation damage to electronics
- Equivalent fluence method (ASTM E722-19) represents the displacement damage effect for different particles and for different energies by a specific fluence of mono-energetic particles
- Displacement damaged is normalized to a value of one for 1 MeV neutrons
- The displacement damage cross section for 1 MeV neutrons is set as a normalizing value of *95 MeVmb*

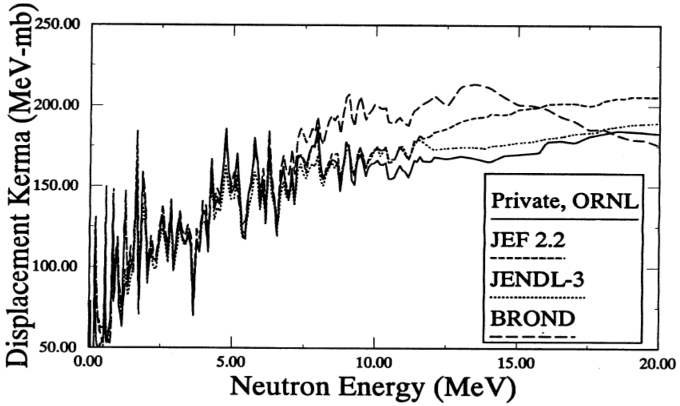




Neutron induced displacement damage in Si

- Displacement damage in Si at different neutron energies can be found in the SAND92-0094 report
- Damage ratios for 14 MeV spectra and a wide variety of fission spectra were validated to within experimental uncertainty of 6%
- The silicon displacement kerma was calculated with NJOY version 91.38 and was included in the ASTM E722-93 standard on 1-MeV equivalent damage to Si

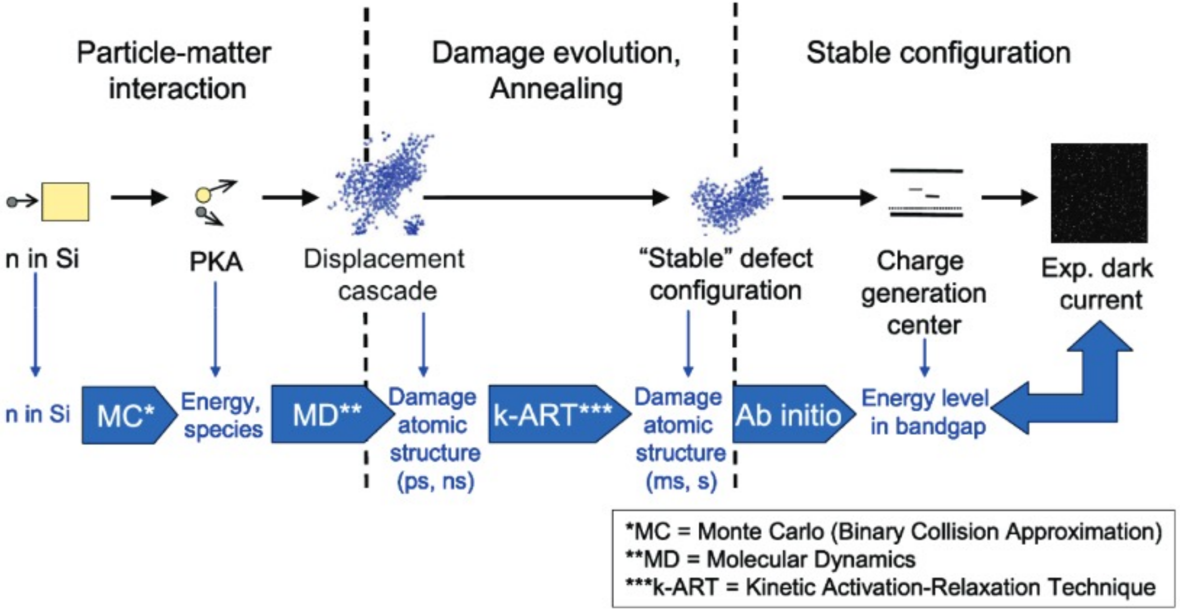




Multi-physics aspects in displacement damage are non-negligible

- Anomalies in the linear relationship between damage and non-ionizing dose have challenged the concept o NIEL scaling for displacement damage

- Theoretical analyses of thermal spikes and local melting showed the need for multi-physics modelling

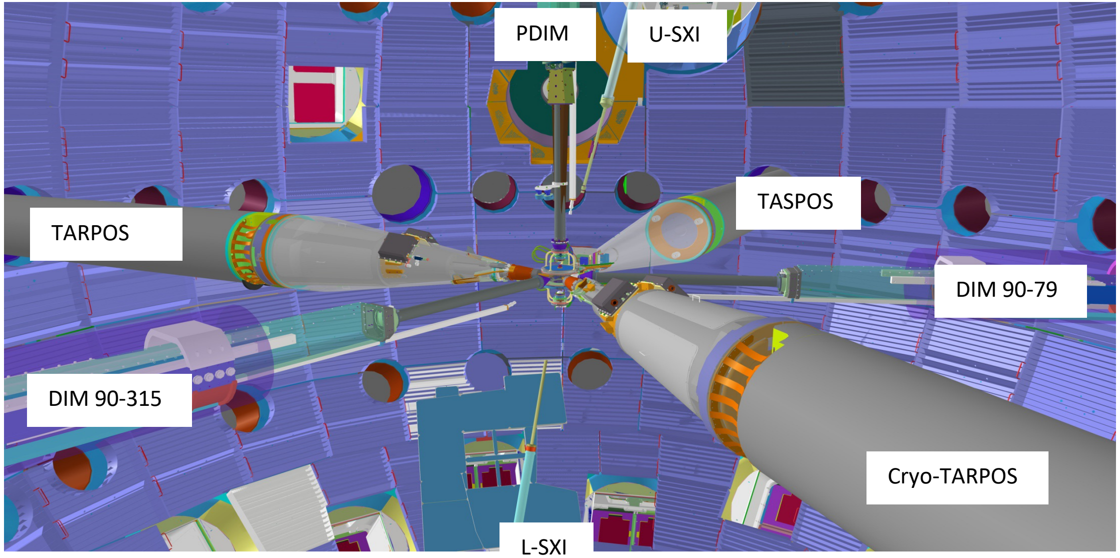


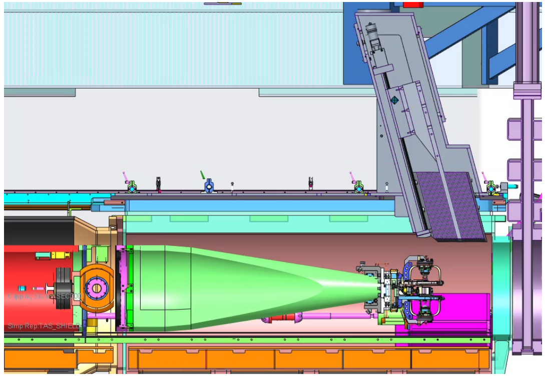
Schematic of the global simulation chain for displacement damage effects

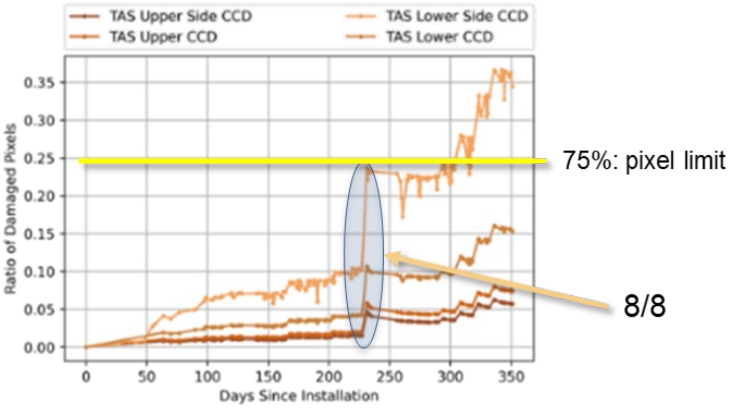
M. Raine et al., IEEE Transactions on Nuclear Science, 64(1), 2017

Protection of to the TASPOS cameras is important

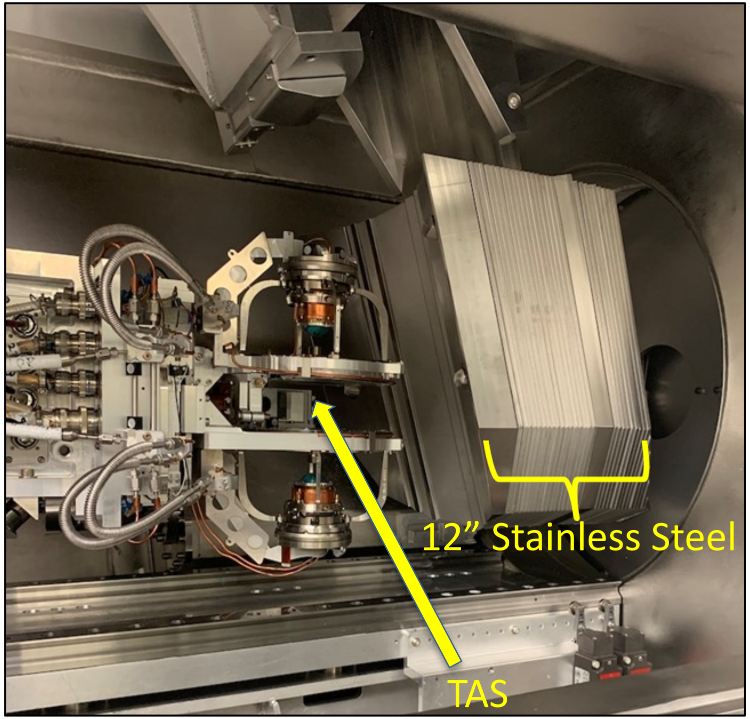
- A 1.35 MJ shot on 8/8/2021 damaged 6-12% of the pixels
- The allowed TAS pixel damage threshold is ~ 25%

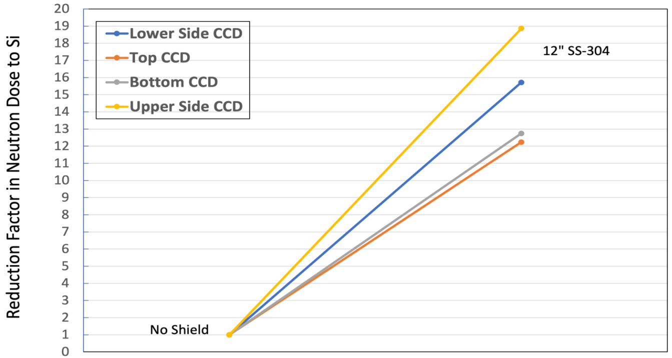




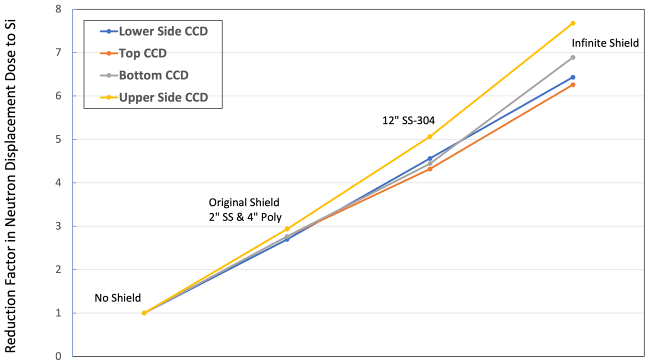


New TAS shielding was installed to increase its life-time





Shielding effect on TID



Shielding effect on DDD

Summary

- Permanent damage to electronics is caused by total ionizing dose (TID) that is mostly dominated by high energy neutrons
- The macroscopic electrical effect in image sensors (dark current) is linked to microscopic damage structures at the atomic level
- Displacement damage (DD) may produce hot pixels in cameras and is caused by all energies
- Accurate prediction of the displacement damage cross section or non-ionizing energy loss (NIEL) is essential for establishing a relation between the radiation environment and survivability of critical electronic component
- NIEL may not be always linearly proportional to DD, NIEL scaling violation reported in oxygen enriched silicon samples (LHC-RD48)
- Data for 1-MeV (Si) equivalent neutron fluence are available from ASTM E722-19, what type of improvement can be made?

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