Mu2e-II Workshop

Thoughts on Readout Electronics

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Dec. 8, 2017

Types of Radiation Damage

- Total Ionizing Dose (TID)
- Non-Ionizing Energy Loss (NIEL)
- Single Event Effects (SEE)

⇨ ***Radiation damage mechanisms for each are different***

⇨ ***Many HEP experiments today specify radiation tolerance limits for each separately***

⇨ ***We have done this for Mu2e***

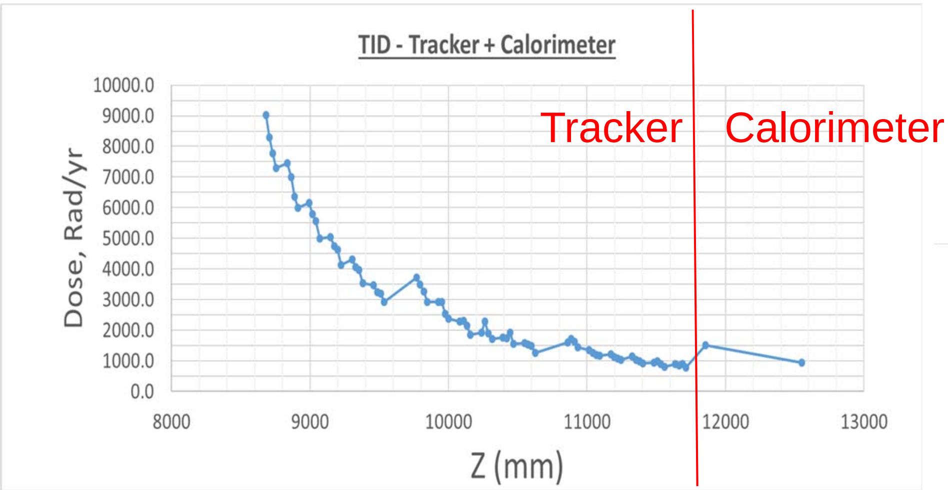
⇨ ***We will do this again for Mu2e-II***

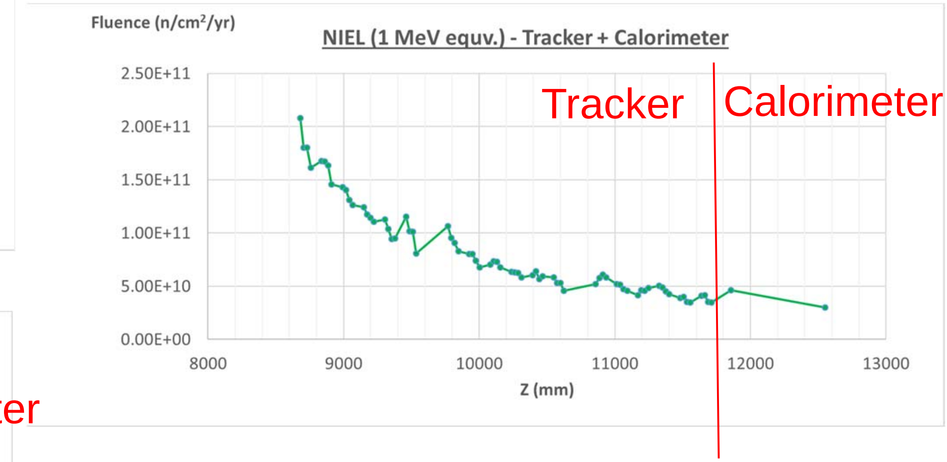
Simulating Radiation Damage

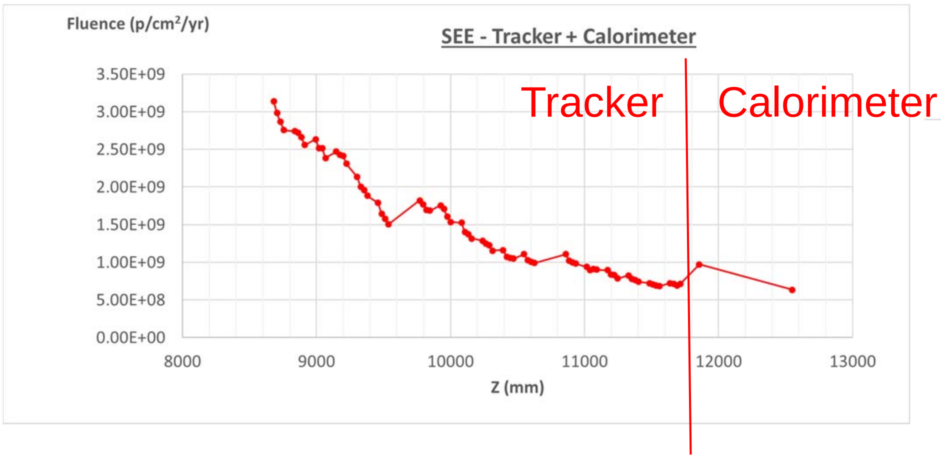
- Two parts:
  - Simulate the expected doses & fluences over 5 years of beam operation, assuming 66% duty factor ⇨***Specify levels for each: TID, NIEL, & SEE***
  - Application of Safety Factors to specify radiation tolerance testing levels of the front-end electronics
- For Mu2e, the "official" simulation tool is MARS
  - Geant4 was also being used to study mitigation strategies
    - See differences in levels by ~factor of 2 (MARS is lower) → **Believed to be understood**
    - Level of agreement approximately what was observed by ATLAS in their comparisons…
    - Generally, trends as a function of physical location are very similar between the tools
  - Perform simulations & output results on these targeted areas
- Integration Group interpreted these results & applied ***safety factors*** to obtain "radiation testing limits"

⇨ ***Simulations were often done on geometry that was a moving target***
⇨ ***MARs simulations often took ~weeks, but very comprehensive***
⇨ ***G-4 simulations faster, but less comprehensive…***

Recent MARS Simulations –Tracker+Calorimeter Yearly Doses & Fluences – Mu2e







Safety Factors

- Safety Factors:
  - Simulation: Reflects uncertainty between simulations and measurements
  - Low dose: Tests done at high dose rate; Damage at lower dose rate is greater
  - Lot variation: If test with one batch, and production uses a different batch, → uncertainty in results
- Specifications for Mu2e
  - Based upon ATLAS experience (although have been reduced for Mu2e)…
  - Use different set for inside & outside of bore
  - Safety factors are somewhat subjective, and have been the subject of debate…

Inside Bore (Tracker, Calorimeter)	Radiation Type	Simulation Safety Factor	Low Dose Rate Safety Factor	Lot Variation Safety Factor	Total Safety Factor
	TID	3	2	2	12
	NIEL	3	1	2	6
	SEE	3	1	2	6

Outside Bore (Alcoves, CRV, STM)	Radiation Type	Simulation Safety Factor	Low Dose Rate Safety Factor	Lot Variation Safety Factor	Total Safety Factor
	TID	2	2	2	8
	NIEL	2	1	2	4
	SEE	3	1	2	6

Summary of Present Requirements Doses & Fluences for Mu2e

Subsystem	TID Rad		NIEL 1 MeV Equiv. n/cm^2		SEE Had>30 MeV p/cm^2	
	MARS Expected Dose 5 -Year Total	Electronics Testing Limit 5-Year + SF	MARS Expected Fleuence 5 -Year Total	Electronics Testing Limit 5-Year + SF	MARS Expected Fleuence 5 -Year Total	Electronics Testing Limit 5-Year + SF
Tracker	4.52E+04	5.42E+05	1.04E+12	6.23E+12	1.57E+10	9.43E+10
Calorimeter	7.52E+03	9.02E+04	4.87E+09	2.92E+10	1.84E+09	1.11E+10
CRV FEB & CMB	1.58E+02	1.27E+03	1.24E+10	4.95E+10	3.14E+09	1.88E+10
Alcove	1.18E+00	9.40E+00	1.45E+08	5.80E+08	-	-
STM	?	?	?	?	?	?
Extinct. Mon.	?	?	?	?	?	?

- ⇨ ***These values are already of order ~LHC calorimeters***
- ⇨ ***Even though SEE numbers are lower, new technologies with smaller feature size are more susceptible to SEE***

Discussion of New Requirements for Mu2e-II

- Current state of MARs (or Geant-4) simulations for Mu2e-II
  - Radiation dose & fluence simulations are just beginning
  - No real numbers yet
  - Dose & Fluences very dependent on detector materials
    - Have chicken/egg problem
    - Process was iterative last time – Will likely be iterative again
- Assumption to start thinking about electronics R&D:
  - Integrated beam power will increase ~X10-X20 for Mu2e-II over current
  - To first order, assume that radiation dose & fluences scale → Target X10 increase
- Caveats
  - Even with all else equal, dose & fluences probably do not scale directly
  - Results very dependent on detector mechanics & shielding, which will likely change from what is currently in the design
- However, what seems likely:
  - Radiation levels will go up in Mu2e-II
  - Rad environment under-estimated at the start of Mu2e; Design is marginal in some parts of the system now
  - Susceptibility to SEE likely to increase anyway with newer devices

More Discussion of New Requirements for Mu2e-II

- Are the Safety Factors reasonable?
  - ATLAS experience: SF's for current detector were large → X70…
  - ATLAS installed radiation sensors in the detector in 2014, and ran for one year
  - Result:
    - Found good agreement with simulations (FLUKA)
    - Lowered simulation uncertainty SF for HL-LHC electronics
    - But kept (rather large) SF's for lot variation and low-dose effects
  - For Mu2e:
    - We have already lowered the SF's compared to ATLAS; Attempted "reasonable" guess
  - For Mu2e-II
    - ***We should put radiation detectors in Mu2e at strategic locations → Under discussion***
    - Compare measured results with simulations, as ATLAS did
    - Revisit SF's later
    - But for now, we have no evidence that these are far off…

- What about the CRV?
  - Space is constrained; Shielding choices limited
  - For now, assume that these doses & fluences increase & scale as well…

Estimate of Future Requirements Doses & Fluences for Mu2e-II

- Applying X10 to current numbers:

Subsystem	TID Rad		NIEL 1 MeV Equiv. n/cm^2		SEE Had>30 MeV p/cm^2	
	Estimated Dose 5 -Year Total	Electronics Testing Limit 5-Year + SF	Estimated Fleuence 5 -Year Total	Electronics Testing Limit 5-Year + SF	Estimated Fleuence 5 -Year Total	Electronics Testing Limit 5-Year + SF
Tracker	4.52E+05	5.42E+06	1.04E+13	6.23E+13	1.57E+11	9.43E+11
Calorimeter	7.52E+04	9.02E+05	4.87E+10	2.92E+11	1.84E+10	1.11E+11
CRV FEB & CMB	1.58E+03	1.27E+04	1.24E+11	4.95E+11	3.14E+10	1.88E+11
Alcove	1.18E+01	9.40E+01	1.45E+09	5.80E+09	-	-
STM	?	?	?	?	?	?
Extinct. Mon.	?	?	?	?	?	?

⇨ ***These values are already of order ~LHC calorimeters***

⇨ ***Even though SEE numbers are lower, new technologies with smaller feature size are more susceptible to SEE***

Discussion of Technical Approaches for Rad-Tolerance in Mu2e-II

- For better TID tolerance: Use of ASICs on the front-ends
  - For better TID tolerance, must go to smaller feature size
  - 130 nm CMOS is proven to ~Mrads; 65 nm CMOS ASICs are emerging now
  - Mixed-signal, high channel density designs common
  - Low noise, shaping/base-line restoration amplifiers common
  - 12-14 bit dynamic range achievable (multi-ranging ADCs)
- For better NIEL tolerance: Use CMOS on front-ends
  - SiGe also good
- For SEE tolerance
  - Smaller feature sizes of ASICs & FPGAs make this worse
  - Must use mitigation techniques:
    - Triple Mode Redundant (TMR) Logic → Voting, best 2 out of 3
    - DICE (Dual Interleaved CElls) transistor design → redundancy in transistors
    - Configuration "scrubbing" (for FPGAs)
- Commercial parts?
  - Maybe, but will need to be tested → time-consuming, iterative…
  - May not know a priori what technology is…

Discussion of Technical Approaches for Rad-Tolerance in Mu2e-II (Cont.)

- Personal thoughts:
  - Reasons for using ASICs
    - Have large channel count → >~1000's of channels
    - Need customized performance
    - Have high channel density; tight space constraints
    - Need for low power & high performance
    - Need good radiation tolerance → control feature size
    - Wish to lower channel cost in production
  - Reasons to avoid ASICs
    - Have low channel count → <~ 100's
    - Can get functionality in COTS
    - No custom ASIC design expertise available
    - Have limited R&D funding (~1 man year of engineering, 2 design cycles)
    - Have limited time for R&D

Discussion of Technical Approaches for Rad-Tolerance in Mu2e-II (Cont.)

- Checklist for Mu2e-II:
  - Reasons for using ASICs
    - ✓ Have large channel count → >~1000's of channels
    - ✓ Need customized performance
    - ✓ Have high channel density; tight space constraints
    - ✓ Need for low power & high performance
    - ✓ Need good radiation tolerance → control feature size
    - ✓ Wish to lower channel cost in production
  - Reasons to avoid ASICs for Mu2e-II?
    - Have low channel count? → NO, have high channel count
    - Can get functionality in COTS → MAYBE, but may not fit in space
    - No Custom ASIC design expertise available → No – Have capability at FNAL & LBL
    - Have limited R&D funding (~1 man year of engineering, 2 design cycles) → ?
    - Have limited time for R&D → No, have time for this if start early enough

⇨ ***It would seem that Mu2e-II could benefit from custom ASICs***
⇨ ***Need to start early***
⇨ ***Need to be prepared for R&D period, & factor into cost & schedule***
⇨ ***Likely will need to justify this choice in technical reviews***

Discussion of Technical Approaches for Rad-Tolerance in Mu2e-II (Cont.)

- Existing ASICs that might be applicable (or a starting point):
  - Straw Tube Tracker:
    - RD51
    - PANDA experiment
    - ASDBLR (PENN)
    - Previous LBL development…
  - SiPM Readout
    - PETIROC, CITIROC… - Line of chips from WEEROC (IN2P3 spin-off)
    - TOFPET (CERN)
    - GM-IDEAS – 64 channels for space
- Existing commercial ASICs might be applicable (ultrasound readout):
  - Texas Instruments TI AFE5802 series; AFE5812 series; AFE5828 series
  - Analog Devices AD9270 series; AD9670 series

⇨ ***Possible alternatives to full-custom development***
⇨ ***Will take some work to evaluate***
⇨ ***If can find something appropriate, would save development costs***

Other Electronics Issues

Other Electronics Issues

- Optical Links
  - Current VTRx would work with X10 increase in TID, but they are being discontinued by CERN
  - In 5-years time, will be in ~10-40 Gbps regime
    - Will need special design techniques & PCB materials for these speeds
  - Will need to be rad-hard
  - CERN is already developing the next generation of the VTRx
  - Recommend: Cultivating & nourishing relationship with CERN, to be aligned to adopt this technology early rather than late
- Data Rates
  - Will likely increase
  - Not clear if higher link rate will support & match increased data rate
  - Will have more readout channels? → Higher granularity?
  - If true, then either:
    - Need more links
    - Need L0 trigger on front ends, i.e. coincidence between ends, etc.

Other Electronics Issues

- FPGAs
  - Issues with FPGAs as a function of radiation damage:
    - Loss of programming
    - Bit errors in signal processing
    - Instability in PLLs and increase in clock jitter
  - Currently using SmartFusion 2 → Moving to PolarFire
    - Flash-based programming → Good immunity to upsets in programming
    - PolarFire Good to ~600 KRad, but SEE performance not tested yet
  - Xilinx approach: "Scrubbing" to detect programming changes
  - Have not implemented Triple-Mode Redundant (TMR) logic yet, but may need to do so for the future to protect against bit errors
  - Recommend: Keep apprised of developments. Many experiments and applications will want to use SEE-hard FPGAs in radiation environments…

- Bit Errors in Data Transmission
  - We do not use Forward Error Correcting (FEC) in the current system
  - Guess: Upgrade environment may be more susceptible to bit errors
  - Recommend: Consider using next version of GBT (also CERN development)

Other Electronics Issues (Cont.)

- DC-DC Converters
  - Using commercial converters on the detector now
  - Current converters not likely to survive with X10 TID increase
  - Guess: commercial DC-Dc converters will not be viable for Mu2e-II
  - Recommend: Might initiate development of rad-hard regulators…
    - GaN devices show promise; May want/need ASIC controller
    - CERN also has development, but they are pricey; designed for inner trackers…
- DAQ
  - Will likely have higher event rate
  - May need more processing power in FPGAs of DAQ
    - Discussions on-going as to whether want/need this now…
  - May be coupled with increased number of links
  - Not an urgent R&D issue, but does have implications for infrastructure

Other Related Electronics Issues

- Power consumption & cooling needs on the detector
  - Will go up if link speeds increase
  - Will go up if number of links increase
  - May go down if use low-power custom ASICs
  - May go down if optimize DC-DC converters
  - May go down if use multi-channel custom ASICs
- Power consumption & cooling needs in the DAQ room
  - Will go up if link speeds increase
  - Will go up if number of links increase
  - Will go up if processing power on DAQ front end increases

⇨ ***These are just a few…***

⇨ ***May be some difficult infrastructure & integration issues related to the electronics upgrade…***

Summary

- Radiation Doses & Fluences will likely increase
  - Current use of commercial components is marginal already
  - Will likely need better TID performance → ASICs
  - Will likely need better SEU performance
    - Trend toward smaller feature size means higher SEU rate
    - May need SEU tolerant firmware and/or ASIC design
  - Discussions on installing rad monitors in Mu2e in progress → Will learn a lot

  ⇨ ***COTS parts probably not viable for Mu2e-II***

  ⇨ ***May require ASIC design for the front-ends; Early planning needed***

  ⇨ ***Existing custom and semi-custom chips might be worth looking into***
- Other Electronics Issues
  - Optical links: → 10-40 Gbps; → Rad-hard optical transceivers
  - Data rates: → Likely to increase; Higher bit rate may not be enough
  - FPGAs: SEUs are problematic with small feature sized
  - Bit errors: Likely to increase; → May need Forward Error Correction
  - DC-DC Converters: Will need better rad-tolerance; → Custom designs
  - DAQ: Will likely need more processing power at front end of DAQ
  - Power & cooling will need to be looked at, along with other infrastructure issues

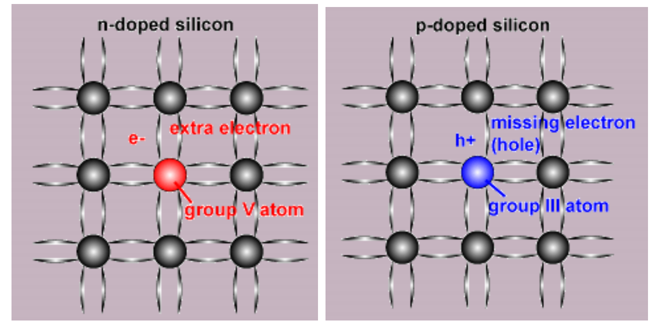
  ⇨ ***Requirements likely to evolve; Technology will evolve as well***

  ⇨ ***Will be challenges from constraints from existing building & infrastructure***

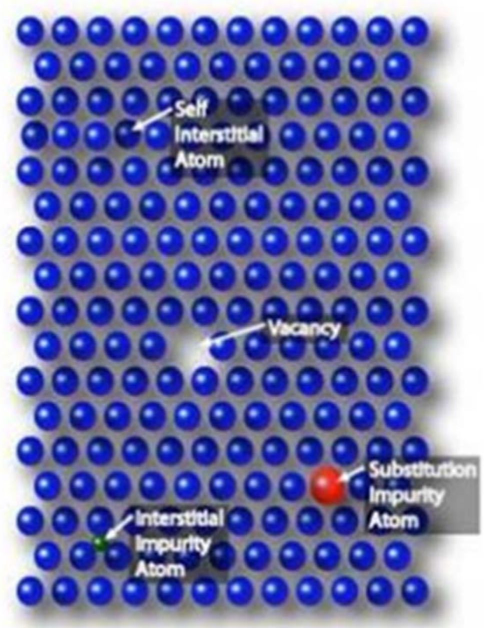
Backup

Radiation Damage in Electronics

- The nature of Semiconductors
  - Fabricated as a crystal lattice
  - Semiconductors function by carefully controlling the imperfections and impurities in the lattice
- Performance is sensitive to alteration
  - Particles that go crashing through the lattice cause damage and create imperfections
- Types of defects from damage include:
  - Introduction of foreign atoms
  - Creation of vacant lattice sites (vacancies)
  - Atoms knocked out of position (interstitials)
  - Creation of electrons or holes in excess of their equilibrium concentration



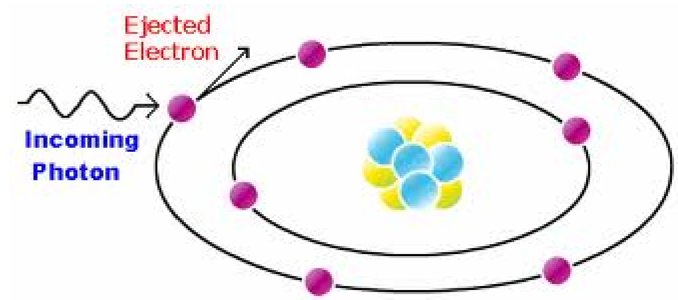
http://www.asdn.net/asdn/physics/semiconductor.shtml

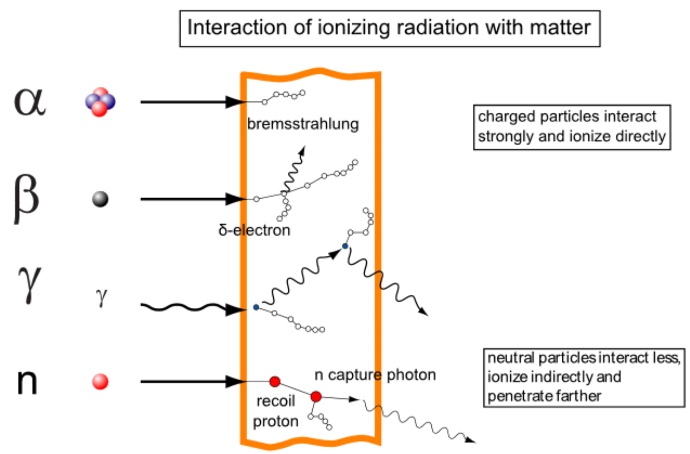


https://sites.google.com/site/ganeshbilla/

Total Ionizing Dose

- Ionizing Radiation
  - Occurs when an incident particle hits an atom and imparts enough energy to release an electron from the bound states of the atom
    - Compton effect or photoelectric effect
  - The atom that is hit is now left with an net positive charge, and is ionized
  - Damage in materials occurs both from the ionized atom that is left, and by the electron that has been released
  - Type of ionizing radiation include:
    - Alpha particles (or ions)
    - Beta particles
    - Neutrons
    - Photons (< 10-33 eV)
    - Other (muons, mesons, positrons…)

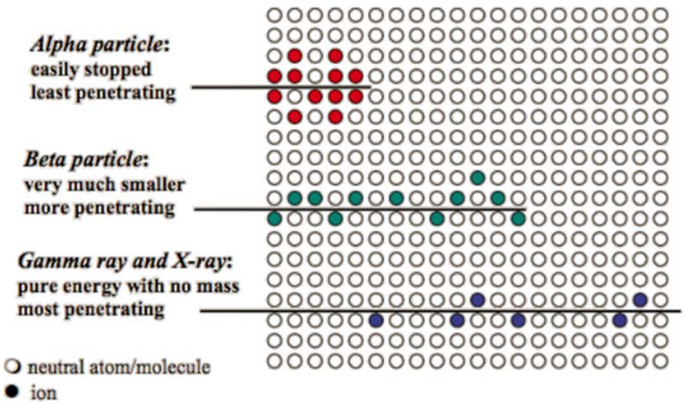




Graphic by Napy1kenobi, Apr. 24, 2008

Total Ionizing Dose

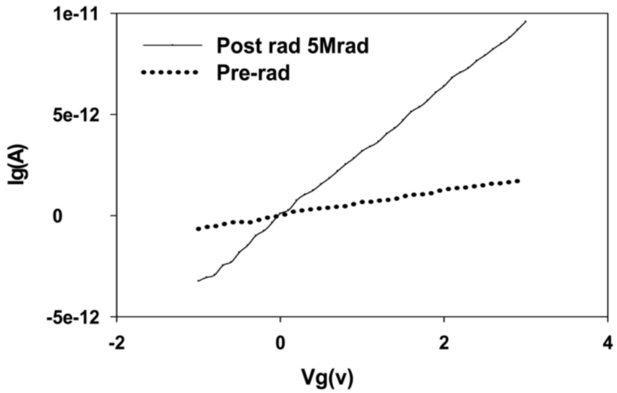
- Damage to Electronics
  - Primary damage: Liberation of electron-hole pairs
    - Temporarily increases conductivity, permitting high currents that can cause other damage
  - Secondary damage: Damage to the bulk
    - Liberated electron can cause displacement damage in the bulk
    - Formation of defects or recombination centers, which act like impurities in the semiconductor
  - At lower energies, incident particle does not have enough energy to completely remove an electron from the bound states
    - Electrons orbiting the nucleus may be promoted to higher energy state
    - Causes changes in the rotational, vibrational or electronic valence configurations of molecules and atoms → thermal effects
  - Can partially recover by annealing

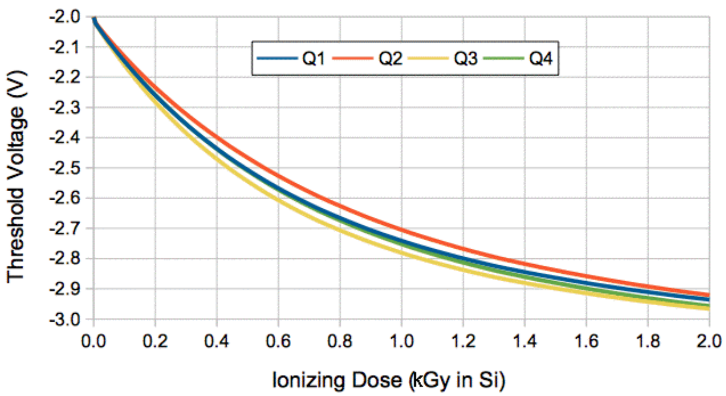


http://www.creativeelectron.com

Total Ionizing Dose

- Damage to Electronics
  - Net effects in electronics:
    - Increased leakage currents – creation of electron-hole pairs in the gate insulation layer
    - Changes in threshold voltages
    - Greater power consumption
    - Creation of asymmetry in how n and P transistors switch on and off
    - Changes in clock frequencies & timing
    - Increased power supply current
    - Catastrophic failure

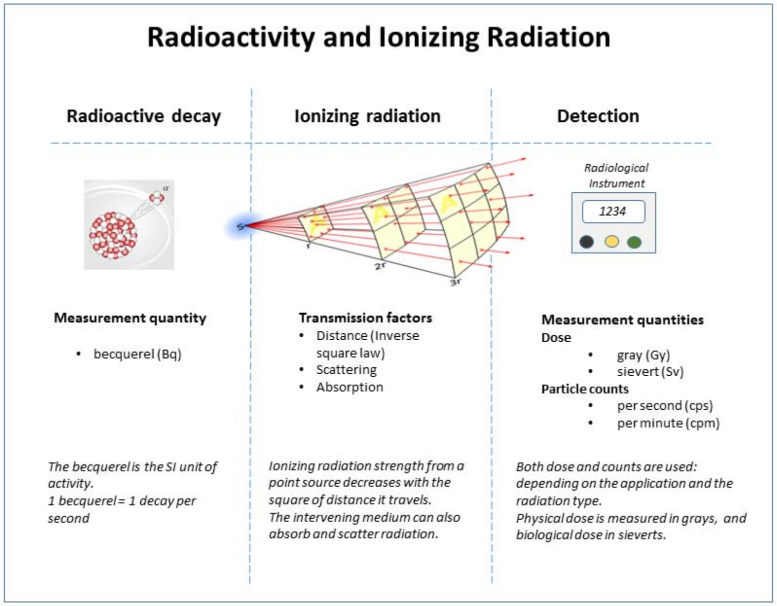




http://alignment.hep.brandeis.edu/Irradiation/Tests.html

Total Ionizing Dose

- Measuring TID
  - Geiger Ciunter
  - Counts or radiation dose
  - Thermoluminescent Dosimeter (TLD)
  - Scintillation Counter
  - Gaseous ionization detectors
  - Semiconductor detectors
  - …
- Some typical numbers
  - Acute radiation syndrome: > 10 rad ~ 100 rem
  - Astronaut (1 trip): ~ 0.1 – 1 rad
  - ATLAS Inner Detector: 0.5 – 10 Mrad/yr
  - ATLAS Hadron Calorimeter: 3 krad/yr



"Radioactivity and radiation" by Doug Sim

Conversions

1 Bq = 1 decay/sec

= 2.7E-11 Curies

1 Gy = 1 J/kg

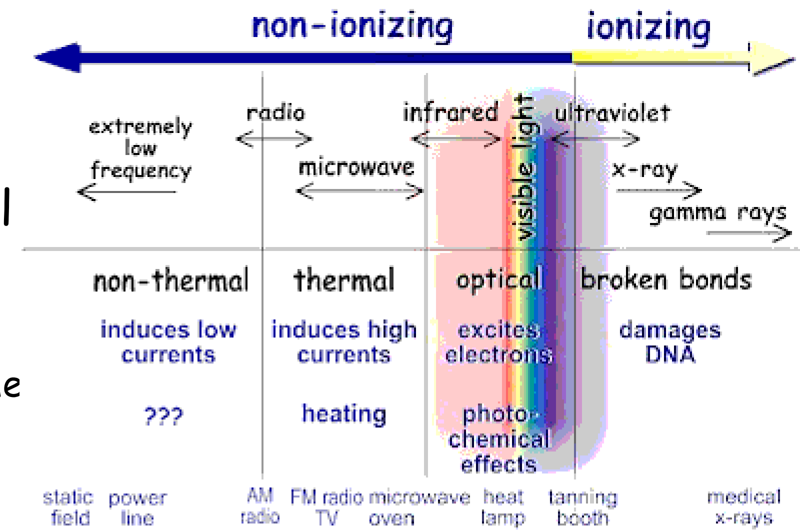
= 100 rad

1 Sv = 1 m^2/s^2

= 100 rem

Non Ionizing Energy Loss

- Non-Ionizing Radiation
  - Occurs when energetic particles collide with an atom in the lattice
  - If sufficient energy is transferred, the atom is displaced from its normal position in the lattice
    → threshold displacement energy
    - The freed atom then becomes lodged in the lattice in an interstitial position
    - Creates vacancy-interstitial pair
    - Incident energies ~ 1 MeV
  - Can partially recover by annealing
  - Types of non-ionizing radiation include:
    - Alpha particles (or ions)
    - Neutrons



"EM-spectrum". Licensed under Public Domain via Wikipedia

Definitions (Neutrons):

< 1 MeV → "thermal+…"

1-20 MeV → "fast"

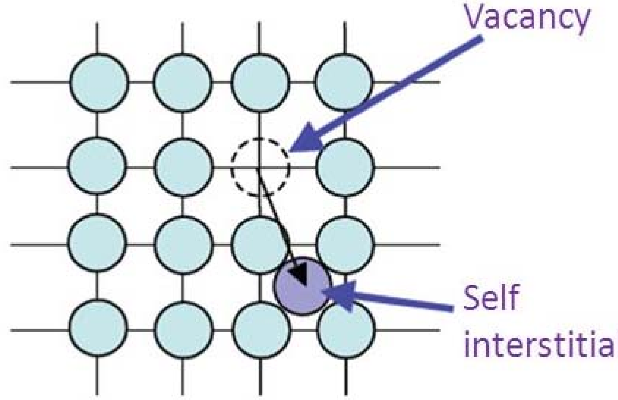
> 20 MeV → 'relativistic"

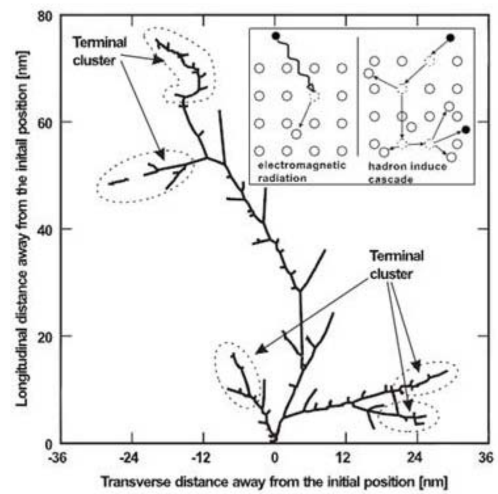
Non Ionizing Energy Loss

- Damage to Electronics
  - Primary damage: Lattice Displacement
    - Changes arrangement of atoms in a crystal lattice (→ semiconductor substrate)
    - Damage to a semiconductor lattice causes the formation of recombination centers, which act like impurities in the semiconductor
      - Depletion of minority carriers → BJTs
      - Affects semiconductor junctions and surface states
      - Decreases minority carrier lifetime & mobility
    - Net effects in electronics:
      - Increased leakage currents
      - Changes in threshold voltages
      - Creation of asymmetry in how n and P transistors switch on and off
      - Changes in clock frequencies
      - Catastrophic failure

$$(Si)_{Si} \rightarrow Si_I + Si_V$$

I: interstitial; V: vacancy



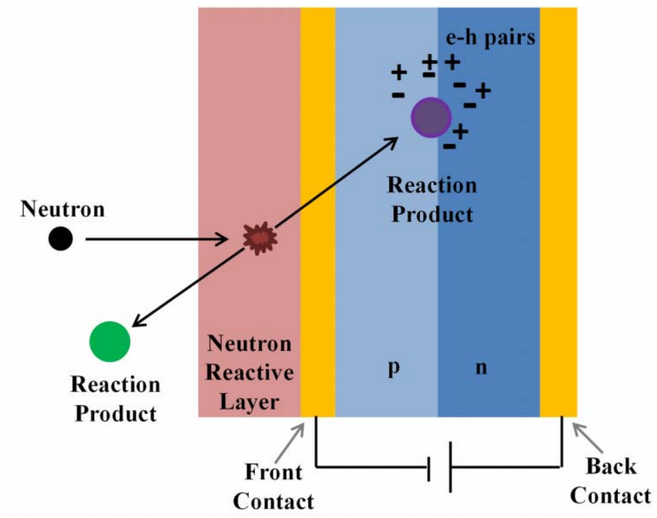


⇨ ***Particularly affects bipolar transistors & diodes***

⇨ ***CMOS is less sensitive***

Non Ionizing Energy Loss

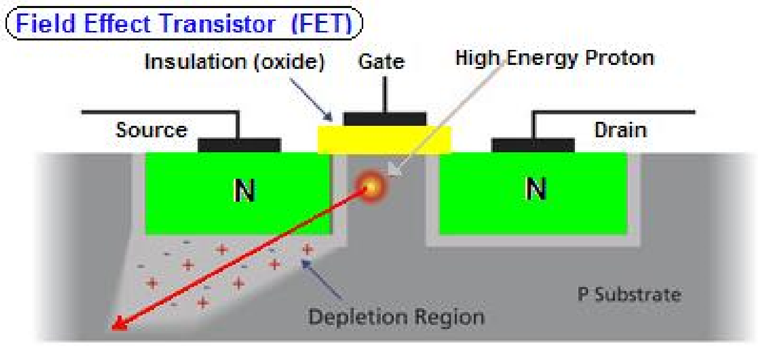
- Measuring TID
  - He gas-filled proportional detectors
  - BF3 gas-filled proportional detectors
  - Boron-lined proportional detectors
  - Scintillation neutron detectors
  - ...



- Some typical numbers
  - ATLAS Inner Detector: ~5E12 – 250E12 n/cm^2/yr
  - ATLAS Hadron Calorimeter: ~2E11 n/cm^2/yr
  - On the earth: 0.025 n/cm^2/sec = ~8E5 n/cm^2/yr

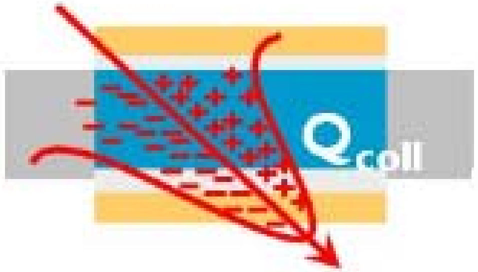
Single Event Effects

- Single Event Upset
  - Occurs when an incident particle hits a sensitive node in a digital circuit with sufficient energy to cause a change of state
  - State change caused by free charge created by ionization of atoms in the substrate
  - Generally, not catastrophic
  - Produces "soft errors"
  - Other types of Single Event Effects include:
    - Latchup
    - Single Event Transient
    - Gate Rupture
    - Single Event Burnout



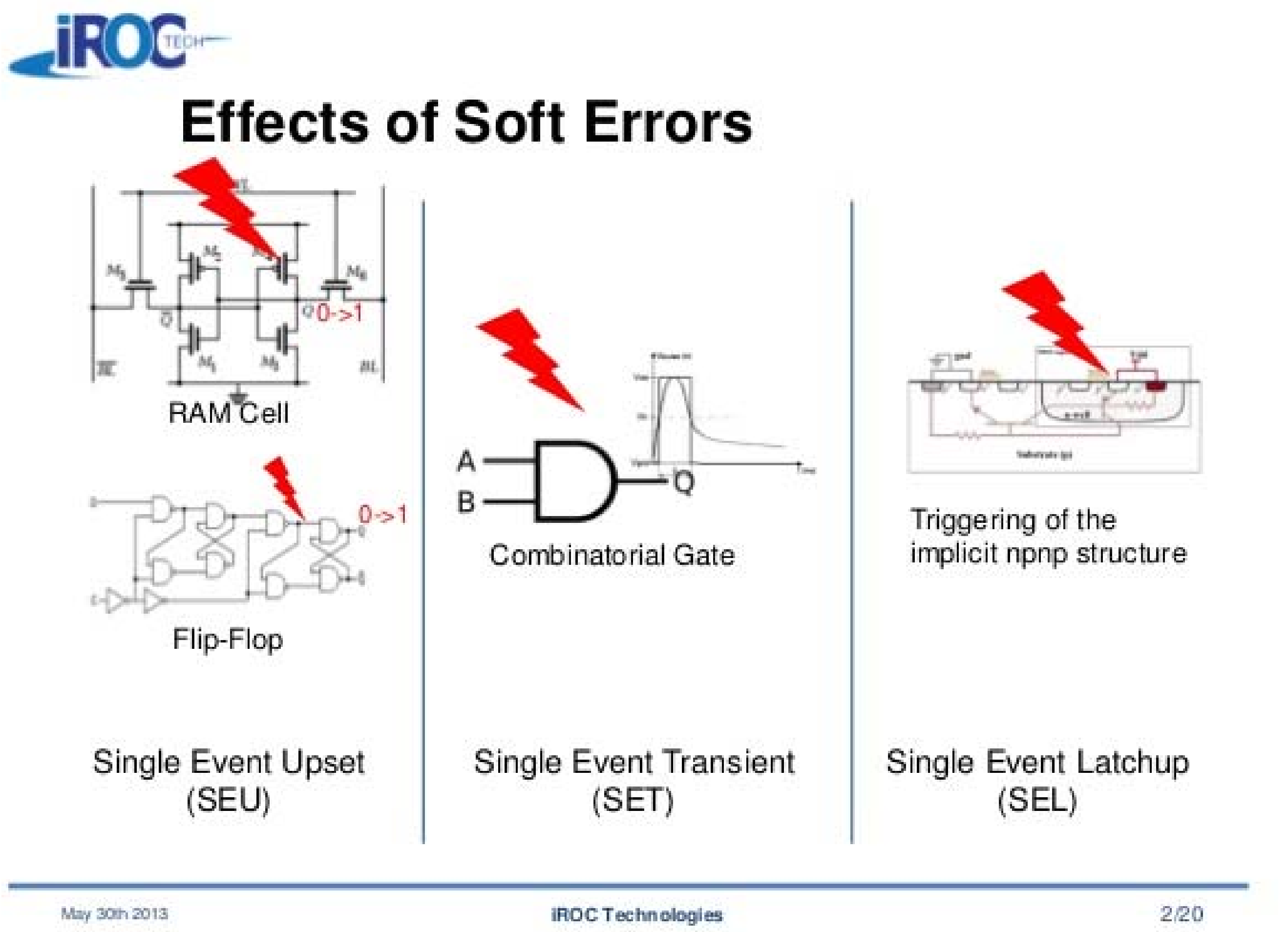
http://www.spaceacademy.net.au/env/spwx/spwxssa.htm

⇨ Think of a parasitic capacitor with stored charge



http://www.nanohub.org

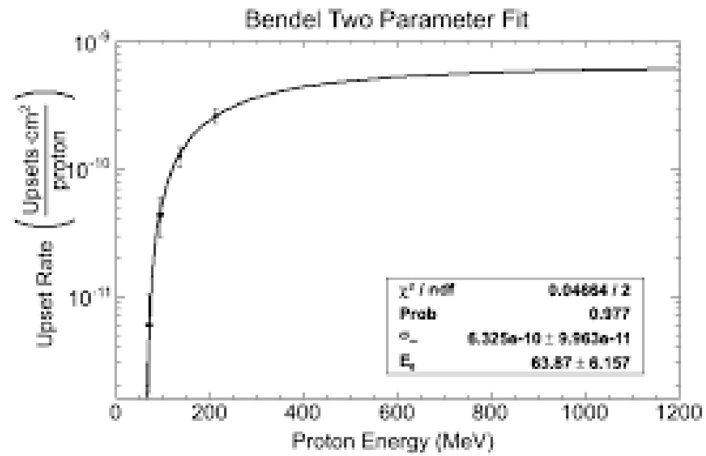
Single Event Effects

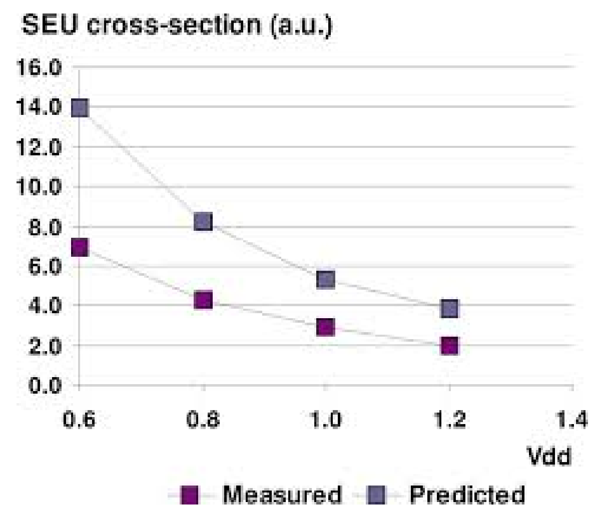


http://www.iroctech.com

Single Event Effect

- Threshold Effect
  - Generally, need incident particle to have sufficient energy to create an SEU → $E_{Critical}$
    - Dependent on technology
    - As feature size decreases, SEU sensitivity increases, since "capacitors" are smaller and have less charge to upset
    - Also, as feature size decreases, voltage rails decrease, further decreasing the amount of stored charge to upset
  - Types of particles that can produce SEE include:
    - Alpha particles (or ions)
    - Neutrons





L. Wissel, et al., IEEE Trans. Nucl. Sci., 55:6, pp. 3375-3380

Specifying Radiation Damage

- Example: ATLAS Detector (Cont.)
  - From these simulations, identify critical locations in detector (i.e. specific electronics locations), and calculate expected annual dose and fluence

REGION	ZLO cm	ZHI cm	RLO cm	RHI cm	NIEL 1 MeV Neut Equiv $/cm^2/yr$	TID Gy/Yr	SEE Fluence $/cm^2/yr$
LAR Barrel	300	350	290	340	0.185E+12	0.477E+01	0.378E+11
LAR Endcap	620	670	290	340	0.285E+11	0.639E+00	0.384E+10
TILE HV micro	210	210	400	400	0.475E+10	0.167E-01	0.139E+09
TILE HV opto	200	200	400	400	0.375E+10	0.987E-03	0.223E+09
TILE Mother	275	275	410	410	0.242E+11	0.216E+00	0.557E+10
TILE Integrator	210	210	410	410	0.433E+10	0.161E-01	0.244E+09
TILE Adder	260	260	410	410	0.175E+11	0.163E+00	0.295E+10
TILE Digitiser PC	275	275	410	410	0.242E+11	0.216E+00	0.557E+10
TILE Low Z Region	200	210	400	410	0.429E+10	0.551E-02	0.226E+09
TILE Med Z Region	270	280	400	410	0.254E+11	0.271E+00	0.615E+10
TILE S-link	150	150	410	410	0.213E+10	0.187E-01	0.605E+08
TILE LVPS	275	300	390	420	0.274E+11	0.378E+00	0.674E+10
TILE LVPS	610	635	390	420	0.370E+10	0.602E-01	0.779E+09
TILE Cal	300	300	410	410	0.205E+11	0.240E+00	0.545E+10
TILE Cal/Mezz	232	232	410	410	0.676E+10	0.298E-01	0.515E+09

⇨ ***Sensors placed in detector during 2014 run show reasonably good agreement with simulations***

Measuring Radiation Damage

- TID
  - Ideal: ~few MeV gamma source, no p or n → Co60
    - Co60 decay produces 1.17 and 1.33 MeV photons
    - Excellent facility at BNL
- NIEL
  - Ideal: Fast neutrons ((~1 MeV) from a Reactor, no p, γ, or high energy n
    - Decay produces ~1 MeV neutrons
    - Uses shielding to block γ's and slow down relativistic n's
    - Excellent facility at Univ. of Mass. – Lowell (~$500/hr)
  - Another facility: LANSE at Los Alamos
  - Need to ensure low photon fluence – typical problem with n sources
- SEE
  - Ideal: Relativistic n (> 20 MeV), no p, γ, or low energy n → n beam
    - Good facility at LANSE, free, but hard to get in
  - Another approach: p beam at cancer therapy facilities
    - 216 MeV protons (best facilities can control energy and rate)
    - Excellent facility at Mass. Gen. Hospital(~$700/hr)
    - Another at Northwestern Medicine (Formerly CDH - Warrenville)
    - Do have some TID damage, however…

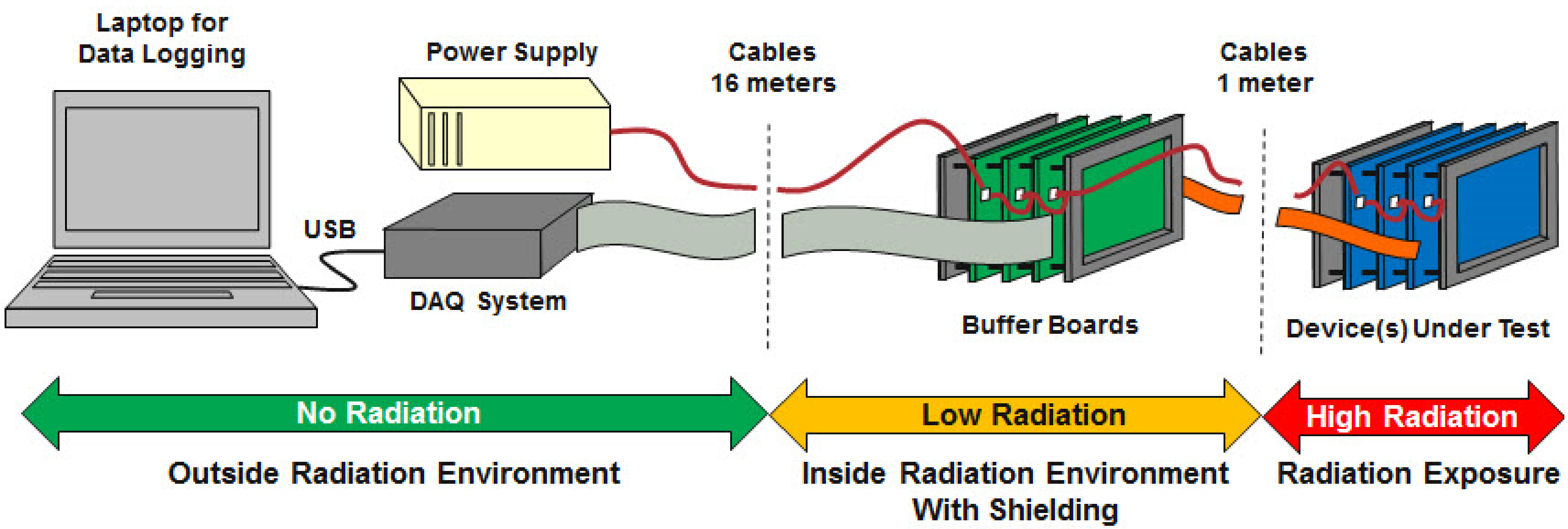
⇨ ***Units: Dose in krad or grays (1 MeV equiv.)***

⇨ ***Units: Fluence in n/cm^2 (1 MeV equiv.)***

⇨ ***Units: Fluence in p/cm^2***

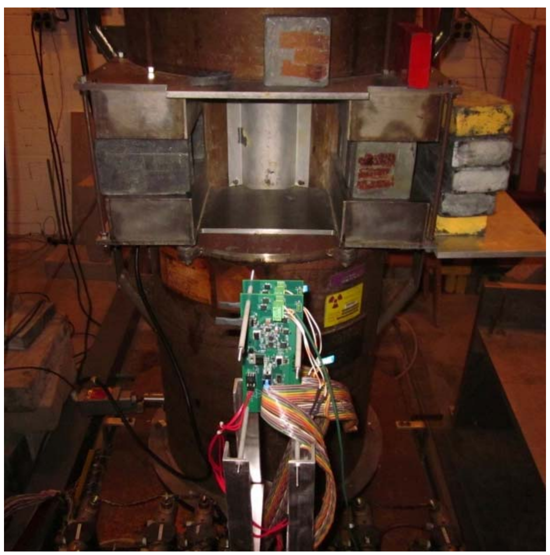
General Setup in Radiation Testing

- Personal experience & techniques used in radiation testing
  - Develop instrumentation & DAQ to read out during irradiation session, to measure degradation as a function of dose
  - Shield DAQ from radiation
  - Customize DAQ for each component test
  - Often requires signal buffering and remote powering

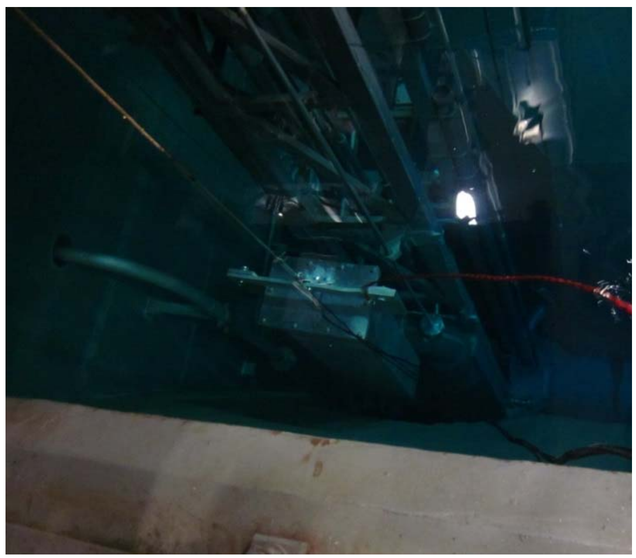


Radiation Test Facilities used by Argonne

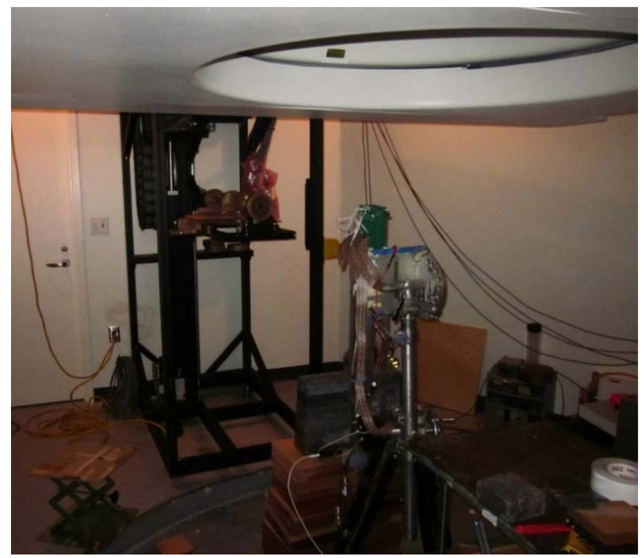
Facility	Locati on	Radiation Type	Radiation Source & Test Type
Brookhaven National Laboratory	Upton, NY	1 MeV Gammas	Decays from a ^{60}Co source; Test for TID
University of Mass. – Lowell	Lowell, MA	1 MeV (equiv) Neutrons	Neutrons from U235 decay in a nuclear reactor; Test for NIEL
Mass. General Hospital	Boston , MA	10-200 MeV Protons	Cyclotron for cancer therapy; Test for SEE



Co-60 Source @ BNL
(Dedicated research facility)



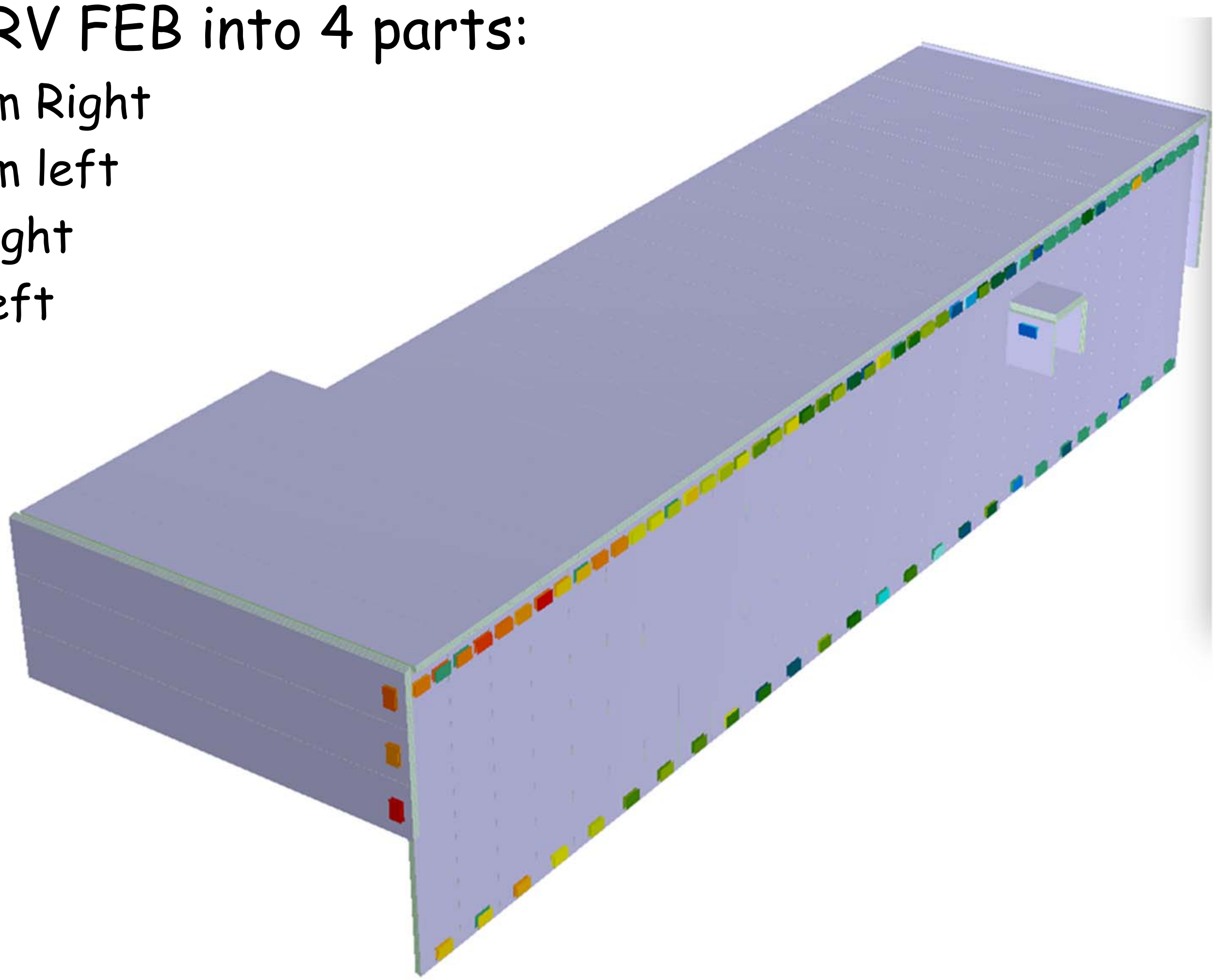
1 MeV Neutron Source (Reactor) @ UMass-Lowell
(Submerse into cooling pond)



200 MeV Proton Beam @Mass Gen Hospital
(Hijack patient beamline)

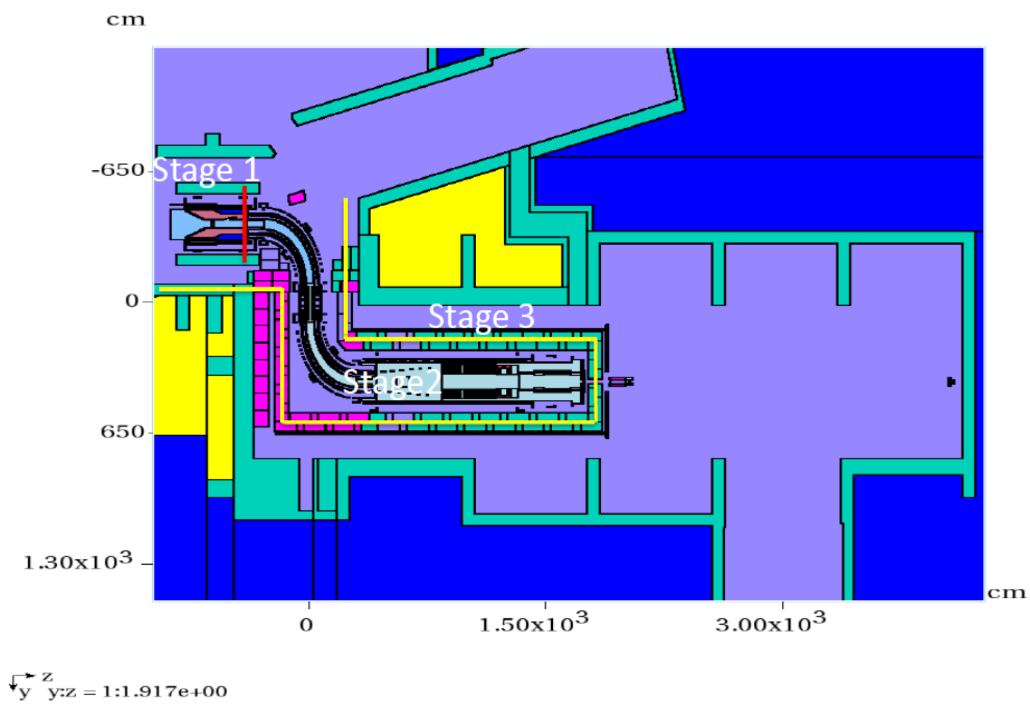
Current Simulations - Yearly Dose & Fluences
Cosmic Ray Veto (FEB)

- Break CRV FEB into 4 parts:
  - Bottom Right
  - Bottom left
  - Top Right
  - Top Left



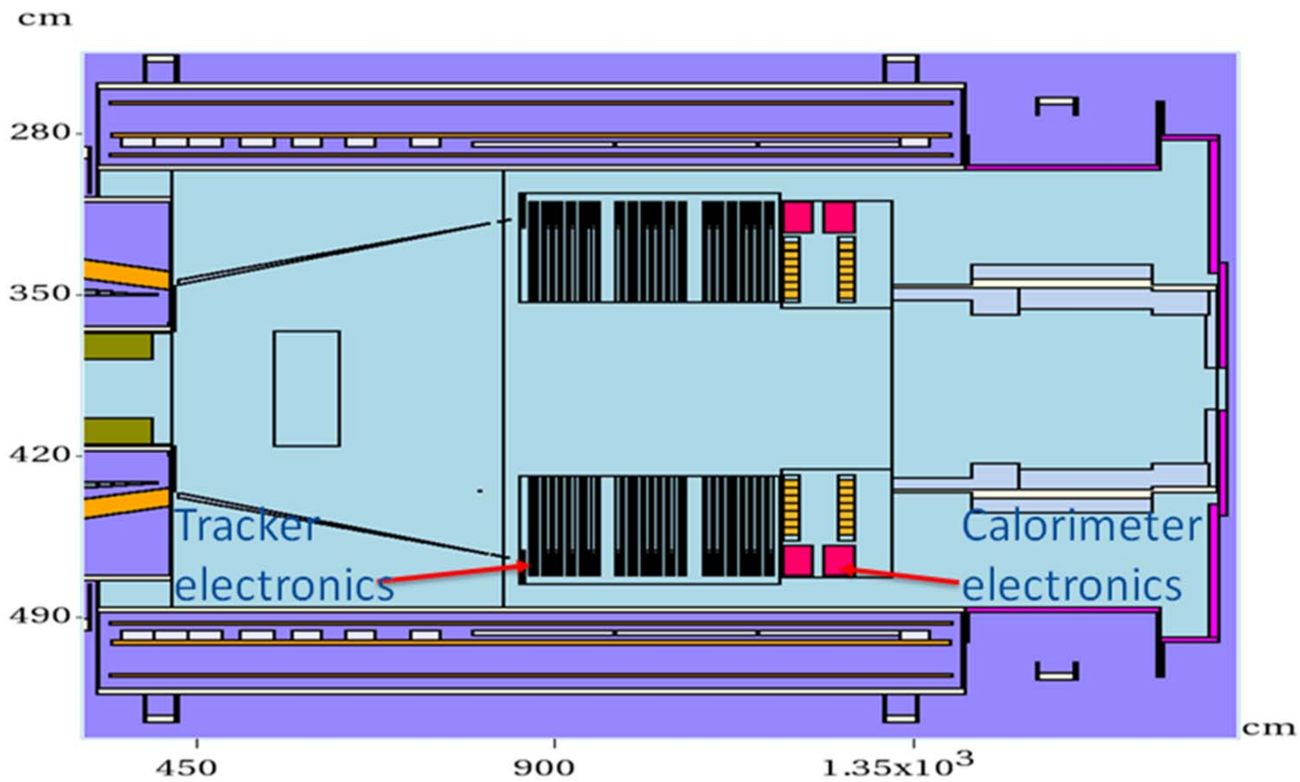
Simulating Radiation Damage

- Simulation process:
  - Events simulated in 3 stages:



- Results to follow
  - Good statistics for Tracker & Calorimeter
  - Marginal statistics for CRV FEB
  - Poor statistics for CRV CMB & Alcove
  - STM needs further analysis
  - No data on the EM

Current Simulations –Tracker & Calorimeter Yearly Doses & Fluences



Safety Factors

- Safety factors:
  - Simulation: Reflects uncertainty between simulations and measurements
  - Low dose: Tests done at high dose rate; Damage at lower dose rate is greater
  - Lot variation: If test with one batch, and production uses a different batch, → uncertainty in results
- Numbers from ATLAS
  - Based upon ATLAS experience
  - Being used for the LHC Phase 2 Upgrade

Radiation Type	Simulation Safety Factor	Low Dose Rate Safety Factor	Lot Variation Safety Factor	Total Safety Factor
TID	1.5	5	4	30
NIEL	2	1	4	8
SEE	2	1	4	8

Safety Factors (Cont.)

- Comparing

ATLAS Current	Radiation Type	Simulation Safety Factor	Low Dose Rate Safety Factor	Lot Variation Safety Factor	Total Safety Factor
	TID	3.5	5	4	70
	NIEL	5	1	4	20
	SEE	5	1	4	20

ATLAS Phase 2	Radiation Type	Simulation Safety Factor	Low Dose Rate Safety Factor	Lot Variation Safety Factor	Total Safety Factor
	TID	1.5	5	4	30
	NIEL	2	1	4	8
	SEE	2	1	4	8

Inside Bore (Tracker, Calorimeter)	Radiation Type	Simulation Safety Factor	Low Dose Rate Safety Factor	Lot Variation Safety Factor	Total Safety Factor
	TID	3	2	2	12
	NIEL	3	1	2	6
	SEE	3	1	2	6

Outside Bore (Alcoves, CRV, STM)	Radiation Type	Simulation Safety Factor	Low Dose Rate Safety Factor	Lot Variation Safety Factor	Total Safety Factor
	TID	2	2	2	8
	NIEL	2	1	2	4
	SEE	3	1	2	6