Radiation damage caused by neutron capture in boron doped silicon pixel sensors

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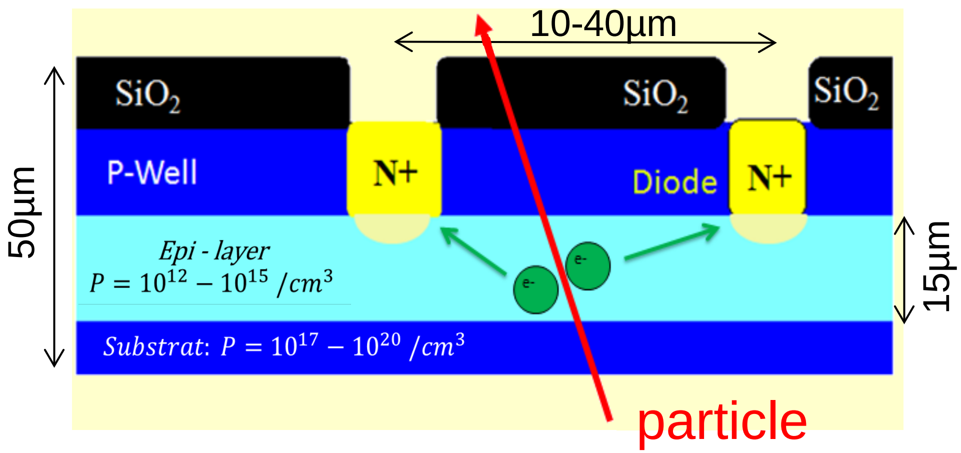
The question:



CMOS Monolithic Active Pixel Sensors

- Are being optimized to tolerate extremely high radiation doses (ionizing and non-ionizing).
- Base typically on P-doped silicon

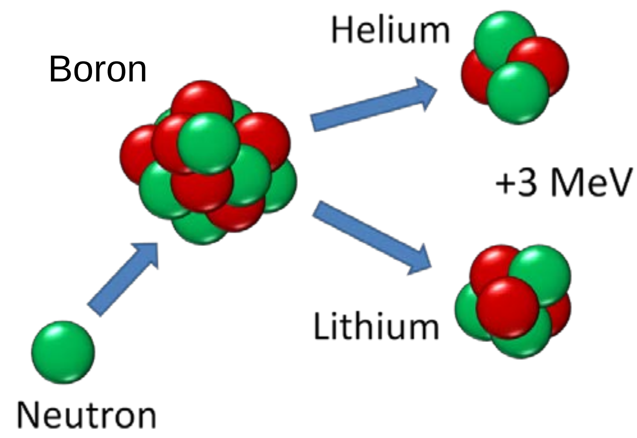
=> Contains Boron

Boron (^{10}B) is known to:

- Capture thermal neutrons with huge cross section (~1000 b)
- Decay n+^{10}B => ^{7}Li + ^{4}He + 3 MeV

⇒ Fast ions are created in Si

⇒ Additional bulk damage is created



Does ^{10}B cause sizable additional radiation damage w.r.t standard NIEL model?

Theoretical estimate

(Natural) Boron doping [1/cm³]

Neutron flux [n/cm²]

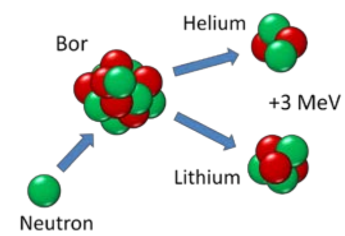
Energy dependent cross section

+

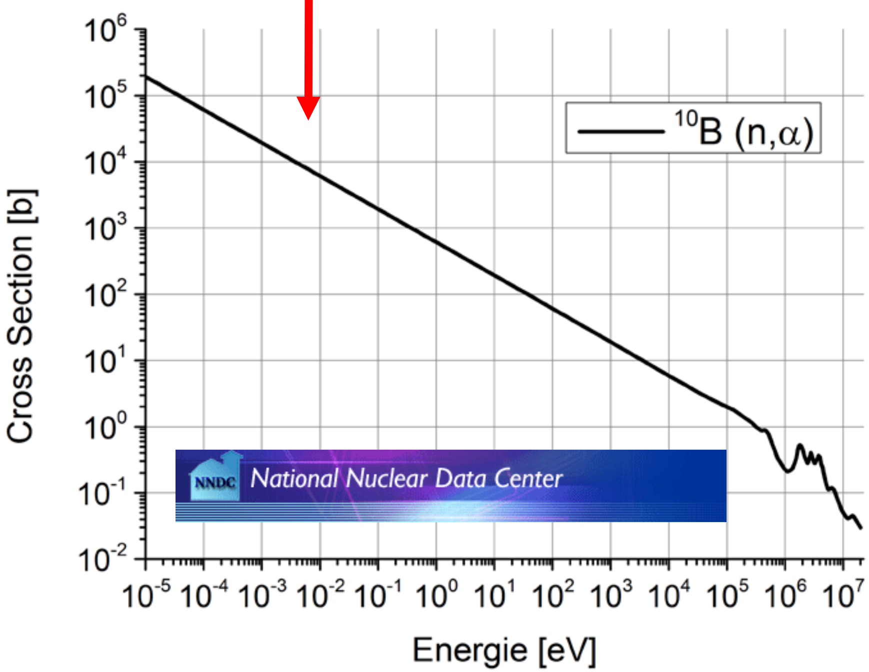
Boron decays [1/cm³]

Decay energy

+



Energy deposit [J/cm³]



http://www.nndc.bnl.gov/sigma/getPlot.jsp ?evalid=14969&mf=3&mt=107&nsub=10

Most energy deposit ionizing.
How to get NIEL?

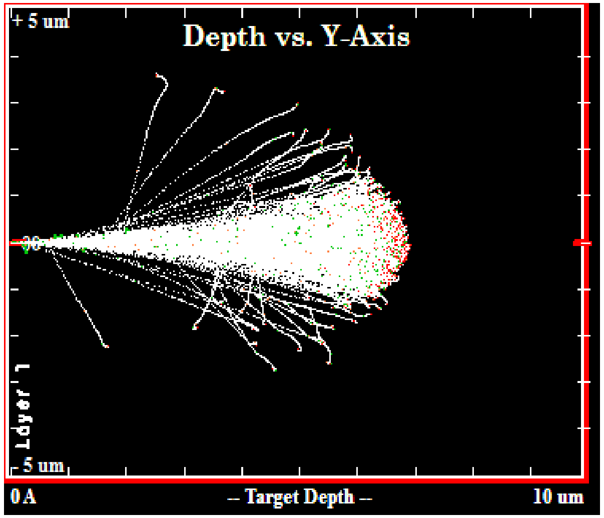
From ion energy to NIEL

Idea: Compare number of vacancies:

- caused by fission ions (unknown hardness factor)
- caused by protons (known hardness factor)

Tool: SRIM (software and references: www.srim.org)

Simulates flight of ions in matter (~MeV energies)
⇒ Simulate vacancies cause by p, ^{4}He and ^{7}Li

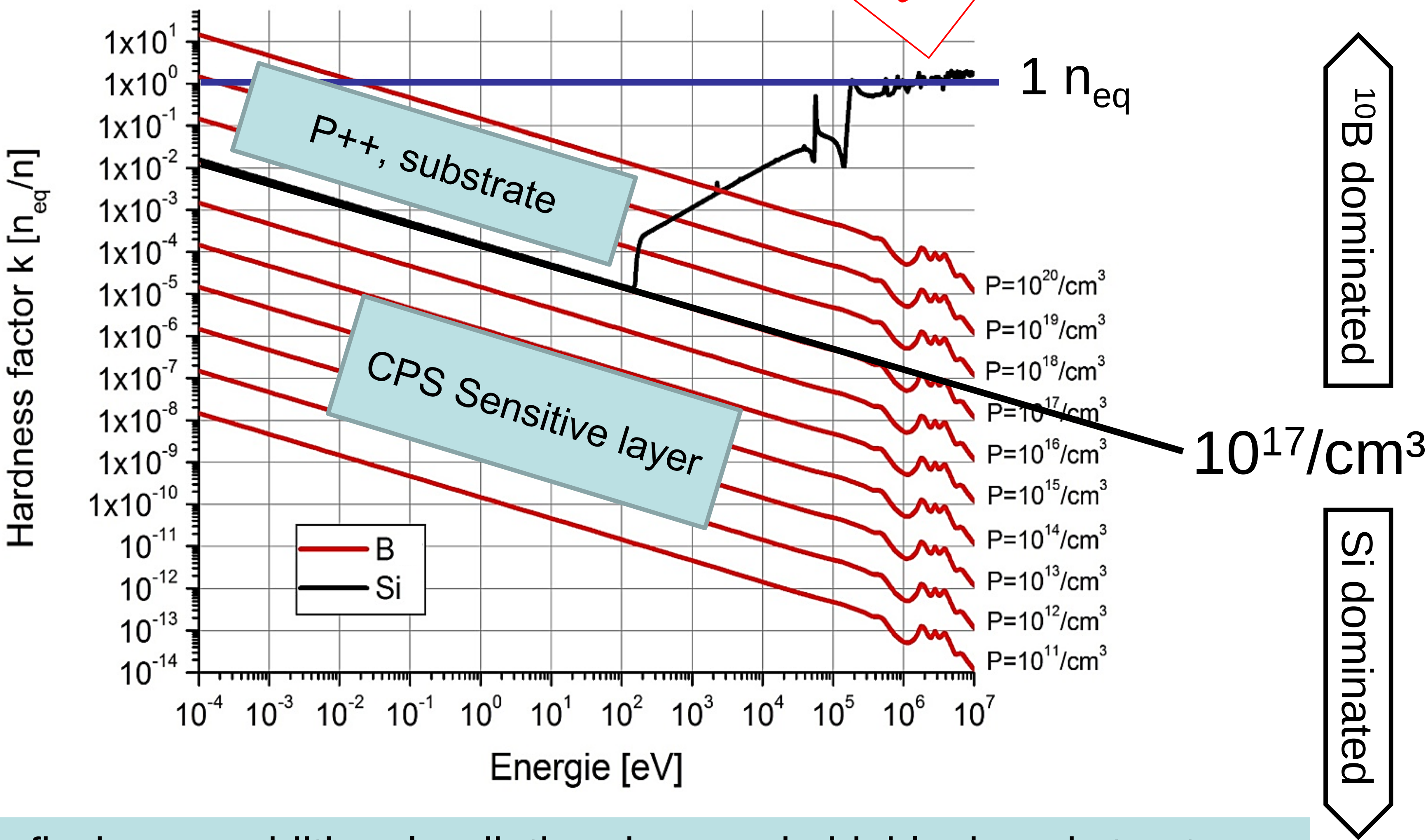


Results:

	Vacancies
p (30 MeV)	0.7 / 40µm
^{4}He	277 / ion
^{7}Li	613 / ion

40µm Si target: Avoid energy loss
=> const. hardness factor

Result after normalization:

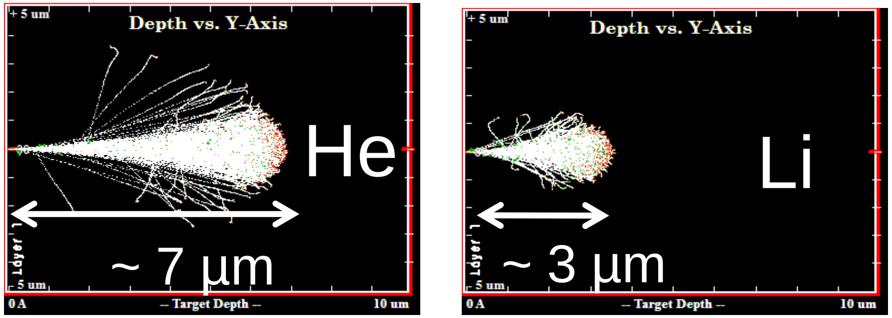


^{10}B – fission => additional radiation damage in highly doped structures

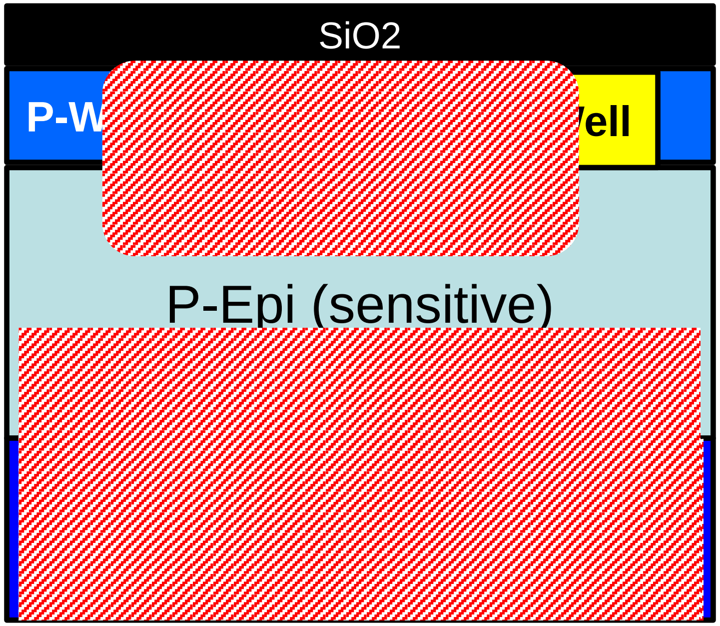
Why does it matter?

In first order:

- Lowly doped sensitive volume not affected
- Ions are created in highly doped volumes.



Penetration depth of ions (SRIM)



Possible damage mechanism:

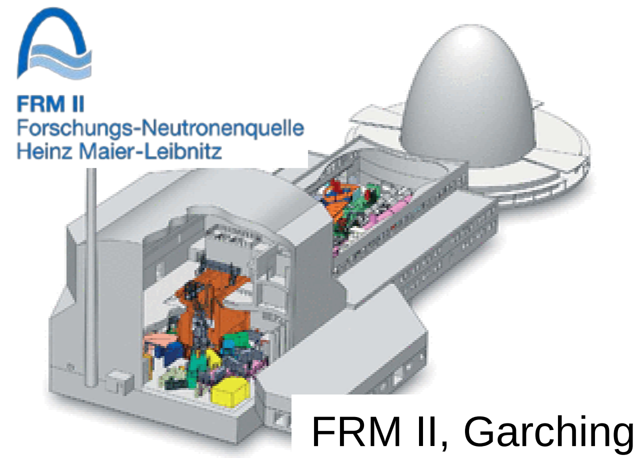
- Ions are created in P++
- Ions enter sensitive volume, create sizable (?) damage here

Likely:

- Only part of sensitive volume affected
- „Effective“ hardness factor depending on sensor geometry, etc...

Getting experimental

Idea: Compare radiation damage cause by fast and cold neutrons



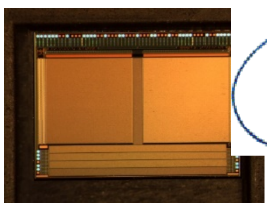
FRM II, Garching

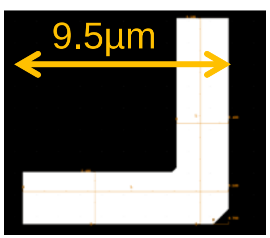
MEDAPP

- Direct ^{235}U fission neutrons
- 99% of all neutrons >100 keV
- Ionizing dose: <100 krad/$10^{13} n_{eq}/cm^2$

PGAA

- Cold neutrons 1.8 x 10^{-3} eV
- Ionizing dose: Unknown





Sensor: MIMOSA-19, IPHC, Strasbourg

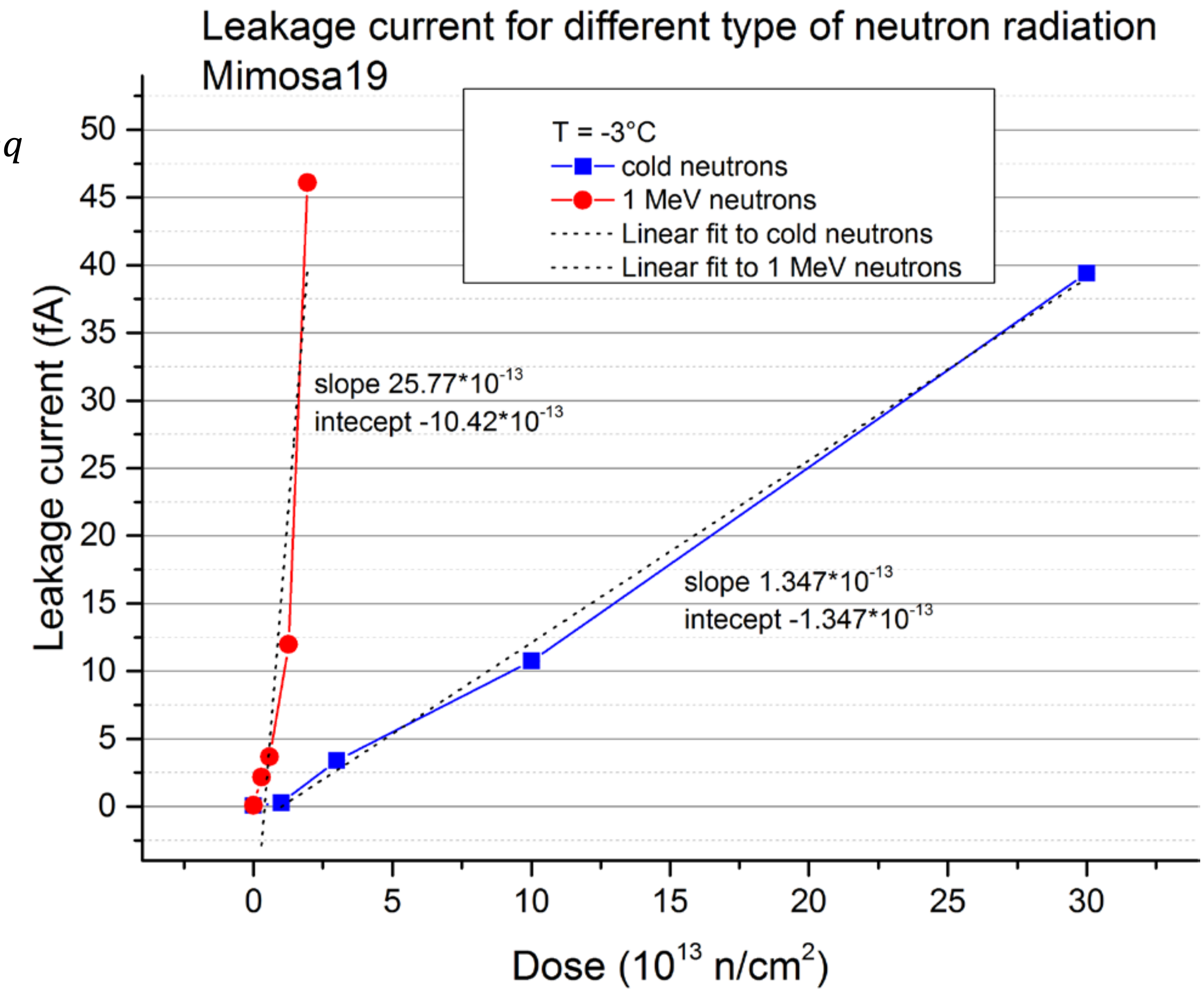
- Design: AMS 0.35 LR, Year 2006 (outdated design)
- Pixel: 12 µm pitch, L-shaped diode
- Doping assumption: $\sim \mathbf{10^{15}}\ (\boldsymbol{epi}), \sim\mathbf{10^{19}}(\boldsymbol{substrate})$
  => Not depleted, charge collection by diffusion
- Feature: 3T-pixel, easy acces to $I_{Leakage}$

Observables: CCE, diode leakage current

Results: Comparision of leakage current

Slopes suggest:

$$1\, n_{cold} \approx 7.5 \times 10^{-2}\, n_{eq}$$

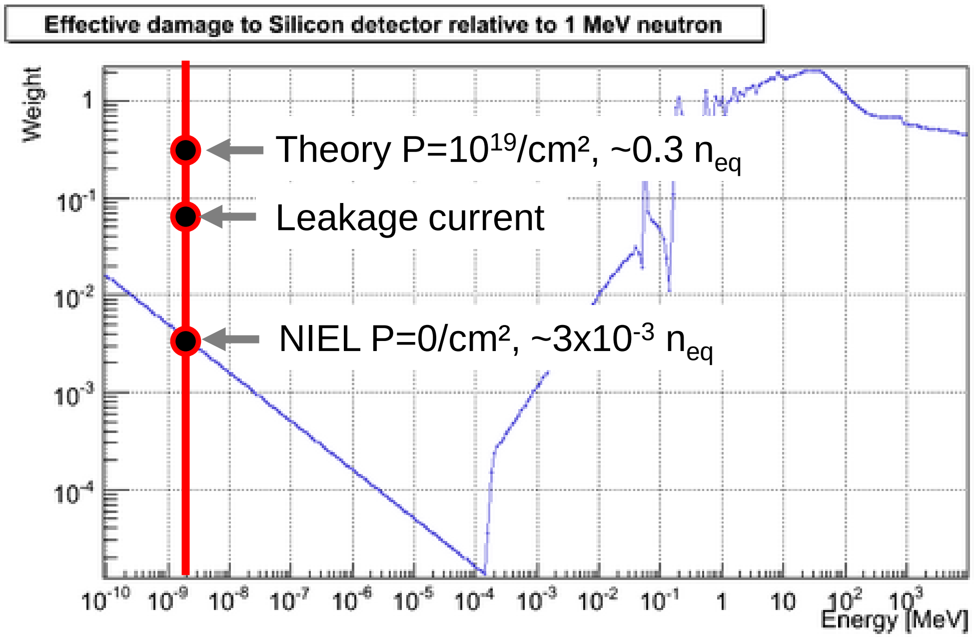


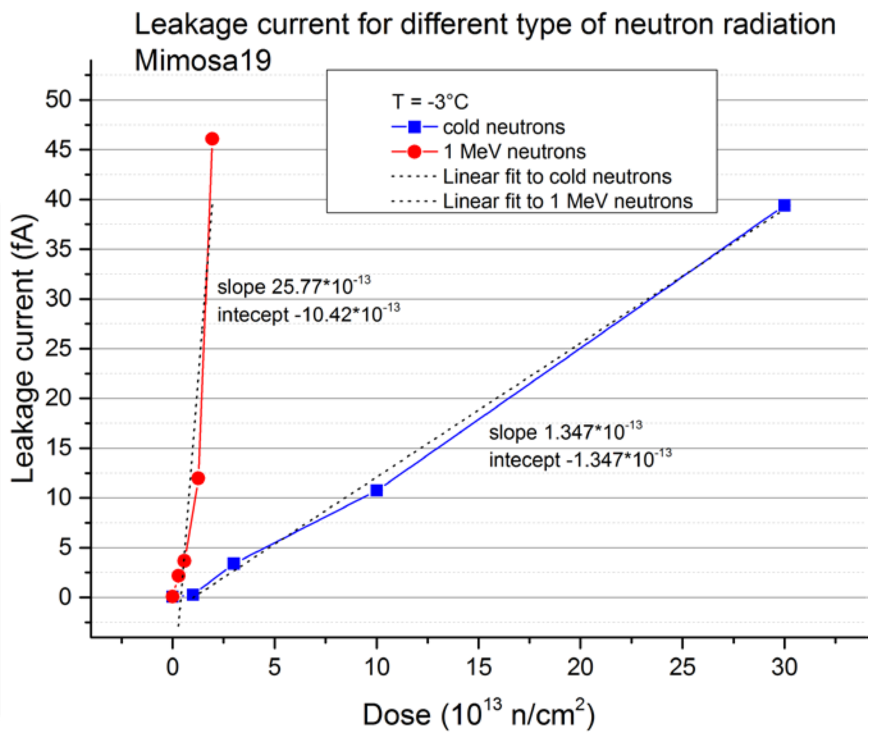
Measurement procedure : M. Deveaux, „radiation hardness studies on Monolithic Active Pixel Sensors", PhD, Goethe University Frankfurt / ULP Strasbourg (2008), http://www.iphc.cnrs.fr/Michael-DEVEAUX.html

Experimental result: Leakage current

Slopes suggest:

$$1\, n_{cold} \approx 7.5 \times 10^{-2}\, n_{eq}$$





Observation compatible with theoretical expectetion but:

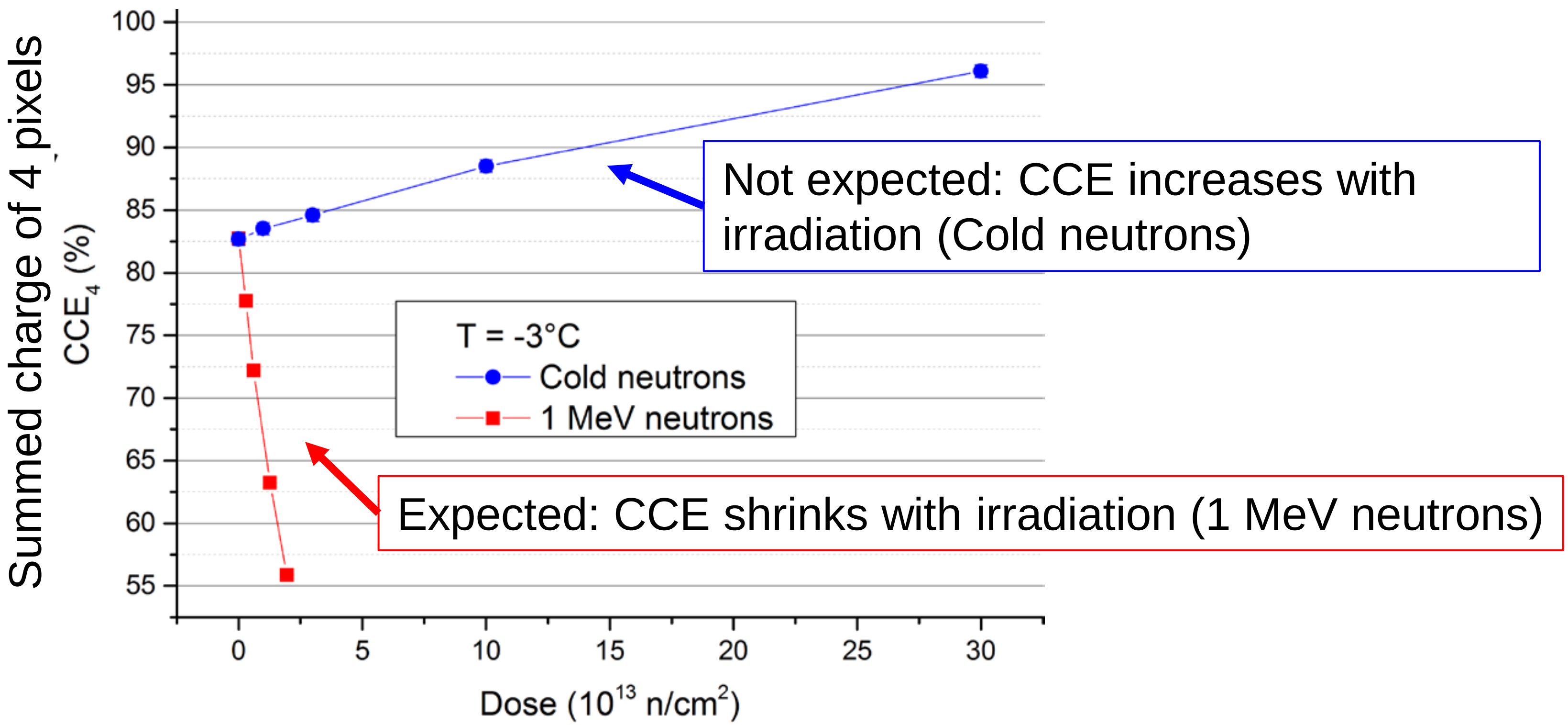
- Potential bias by parasitic γ-doses.

Next step: Try to eliminate surface damage by annealing

- Work in progress, not yet conclusive => Stay tuned

Experimental results: CCE

Sensor illuminated with ^{109}Cd (22.1 keV X-ray), detect clusters



Response differs fundamentally between cold ⇔ 1MeV Neutrons
Effective hardness factor cannot be extracted

Experimental results: CCE

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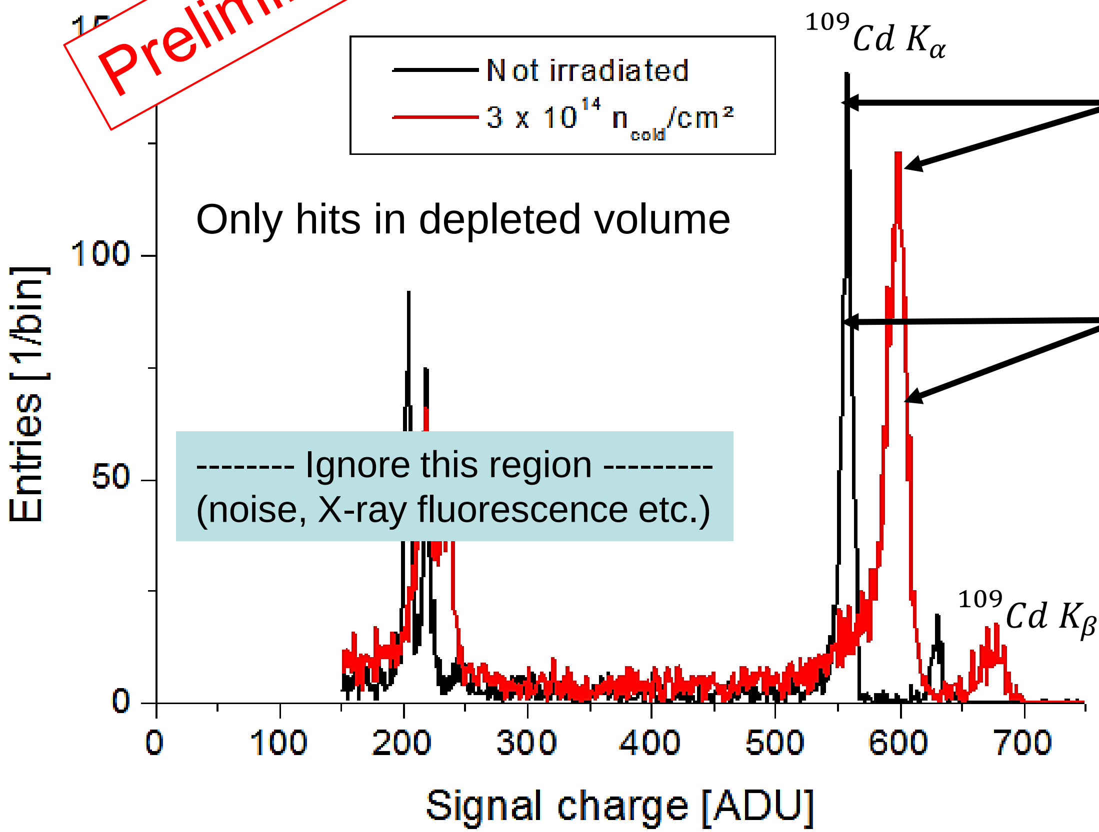
Preliminary!



Gain increases after irradiation
⇒ Decrease of diode capacity?
⇒ More depletion?

Number of entries increases after irradiation by factor x2.
Scales with depleted volume
⇒ More depletion!
⇒ Less doping
Abrupt flat junction (?):
Doping decreases by factor x4

Potential explaination:
Intense acceptor removal (factor x4 from P=10^{15}/cm³)
⇒ Additional depletion improves CCE, dominates trapping
! No significant acceptor removal observed with 1 MeV neutrons for <$2x10^{13} n_{eq}$/cm²

Summary and (very cautious) conclusion

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Does ^{10}B fission cause sizable rad. damage in P-doped Si?

Theoretical estimate:

- P>10^{17}/cm³ => Expect additional damage w.r.t standard NIEL curve
- Fission ions may damage lowly doped silicon indirectly due to 7µm range

Experimental study (MIMOSA-19, ~10^{15}/cm³ epi layer, ~10^{19}/cm³ substrate):

Observation:

- Leakage currents:
  - Cold neutron cause factor ~20 more damage than according to standard NIEL
  - Risk of sizeable bias due to parasitic ionizing doses (work in progress)
- CCE:
  - Cold neutrons cause strong acceptor removal, CCE increases
  - Acceptor removal exceeds finding for $2x10^{13} n_{eq}/cm^2$ (1MeV)

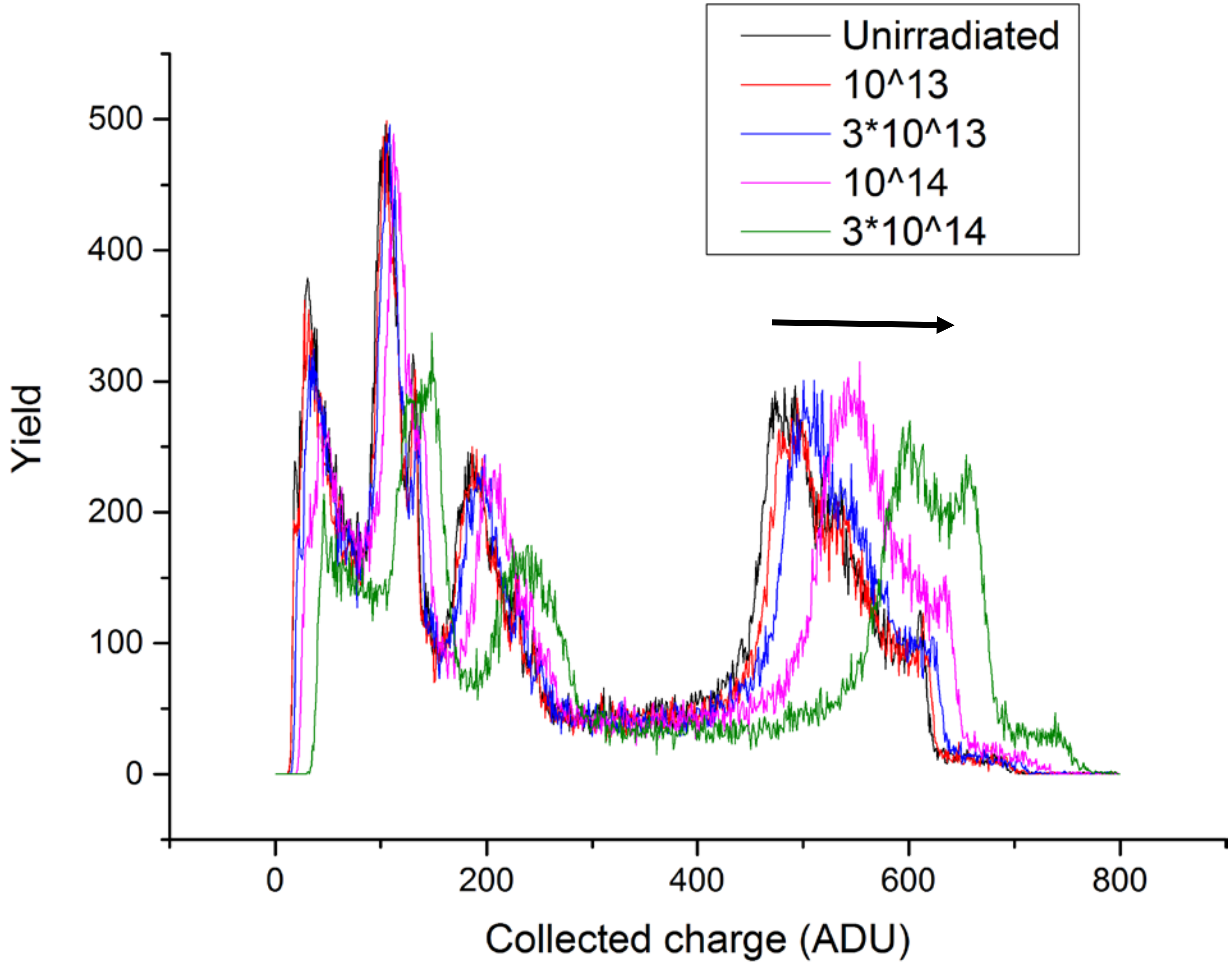
Preliminary conclusion (of a not-yet-fully-conclusive study):

- ^{10}B fission seems to cause rad. damage beyond standard NIEL
- Plausibly no risk for vertex detectors (dominated by direct radiation)
- Risk of unexpected effects in case of high thermal neutron doses.

Backup

Shift of CCE

Cold neutrons (Cd-109 source)



Effect also observed with Fe-55 source

Experimental result: CCE, fast neutrons

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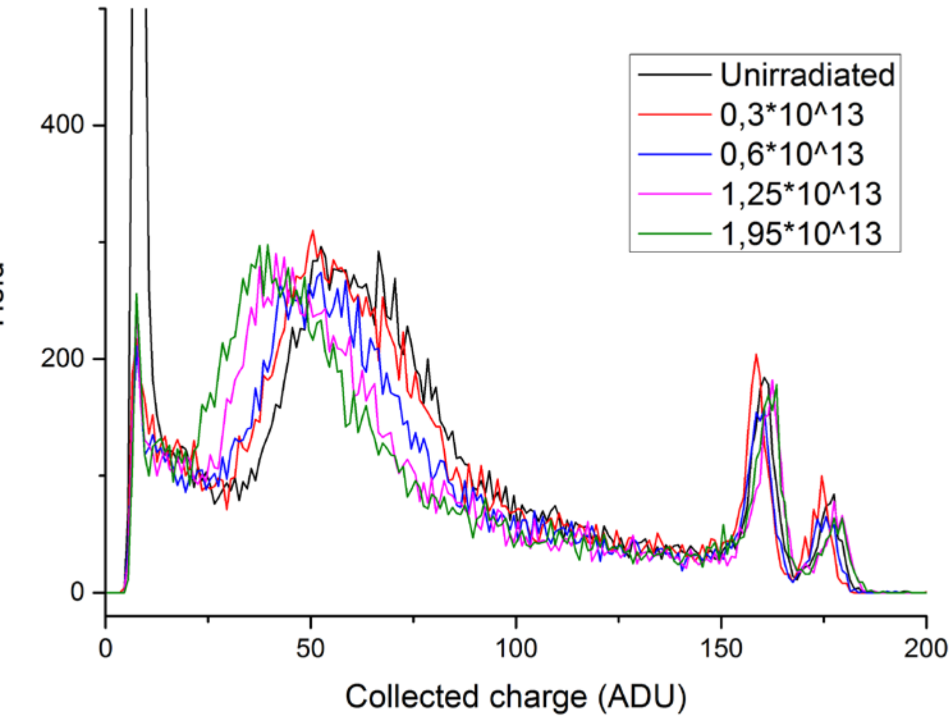
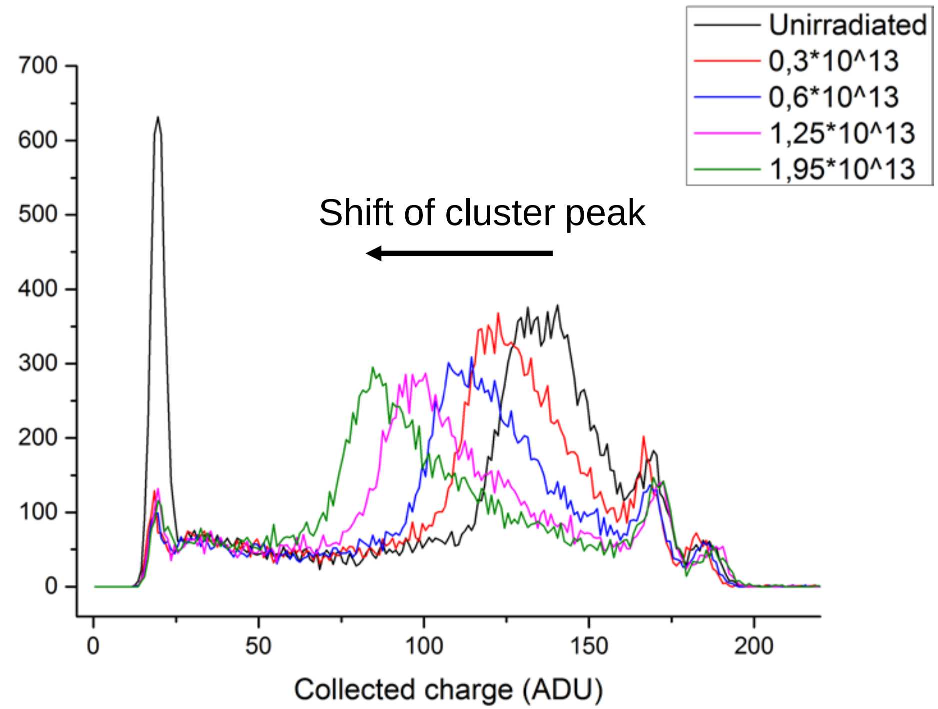
Fe^{55}, -3°C

CCE_1 Seed pixel



CCE_4 Cluster of four pixel



Annealing parasitic ionizing radiation

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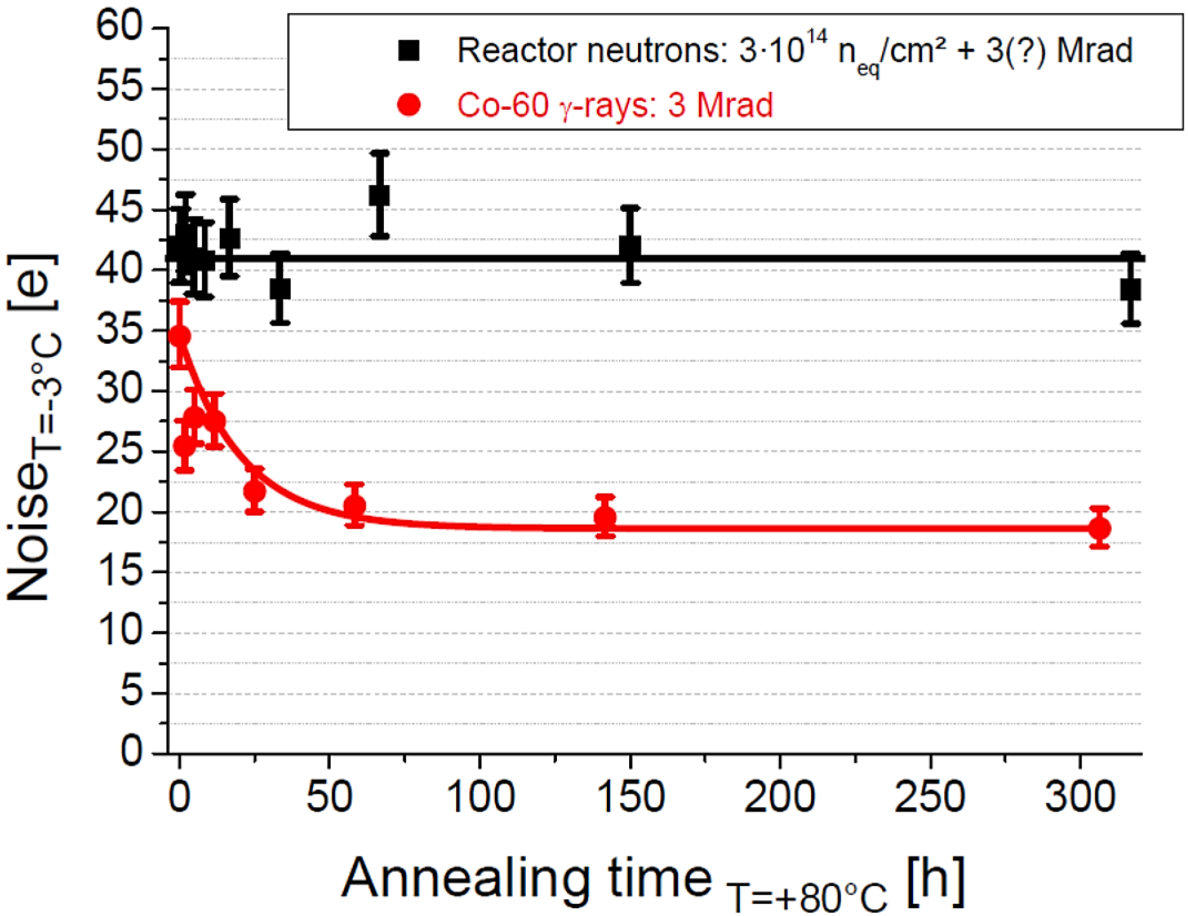

Sensor:
MIMOSA-18 (AMS 0.35 HR)

Experiment:
Irradiate sensors according to protocoll for reactor neutrons with gamma rays (not powered during irraditation)

Observation:
Gamma rays may provide significant contribution to leakage current/shot noise. This contribution is eliminated after annealing while the bulk damage persists.

Why do we have more damage then expected?

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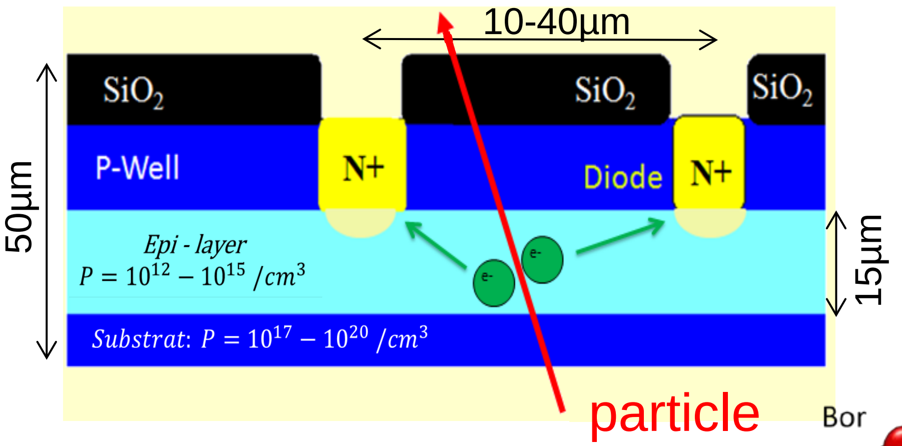
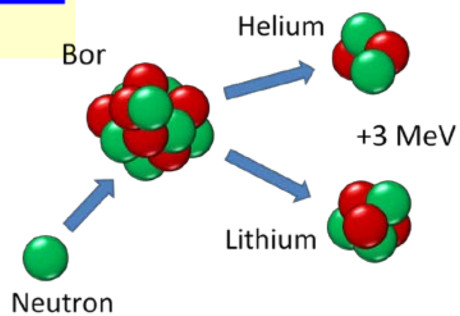
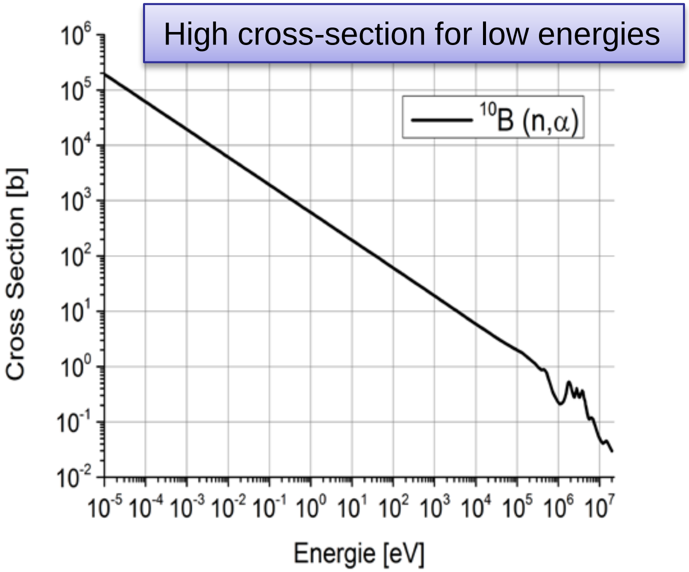
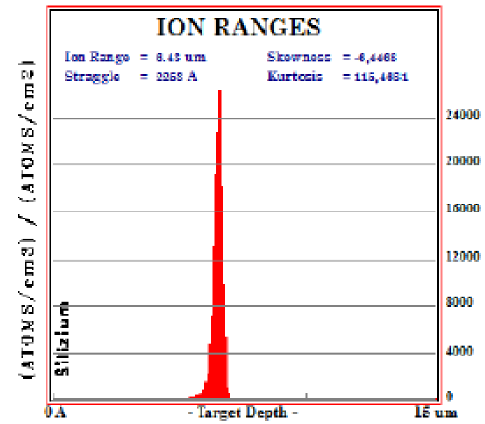






Can we see radiation damage from cold neutrons?



T. Bus, bachelor thesis 2015