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

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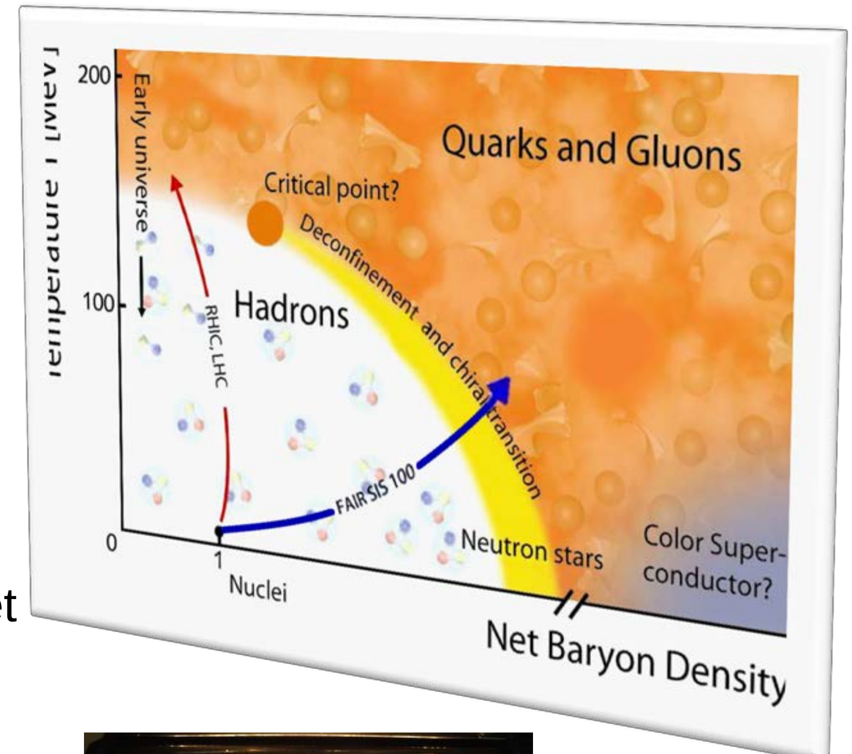
What is the task and why MAPS can do it?

Study matter at extreme conditions by reconstructing secondary vertices of dileptons and open charm particle

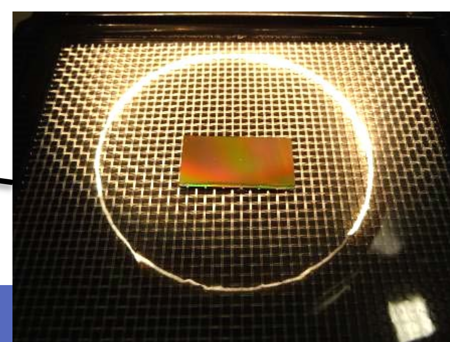


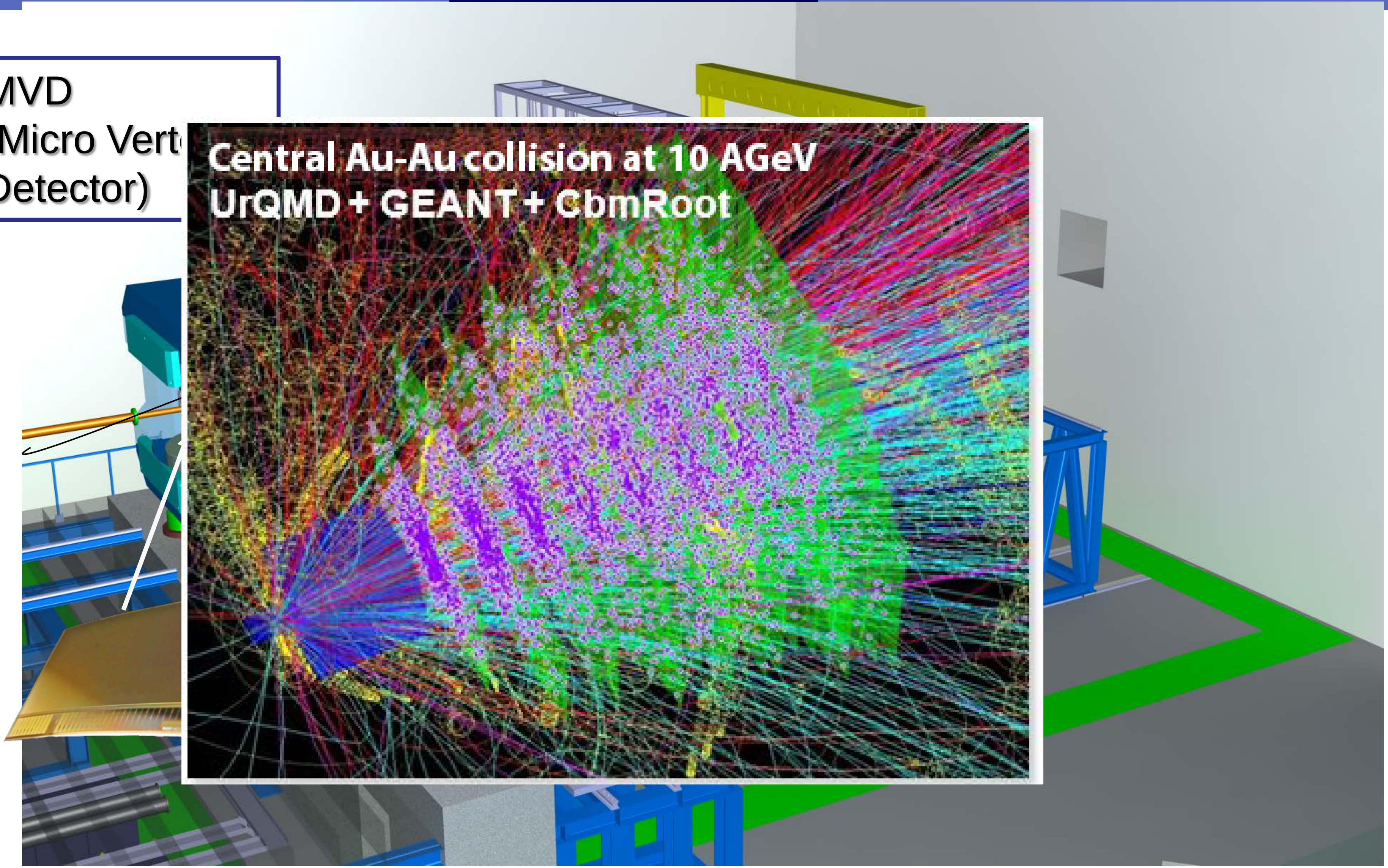
Need:

- Good spatial resolution
- High granularity
- Vacuum compatible design
- Radiation tolerant
- Low material budget

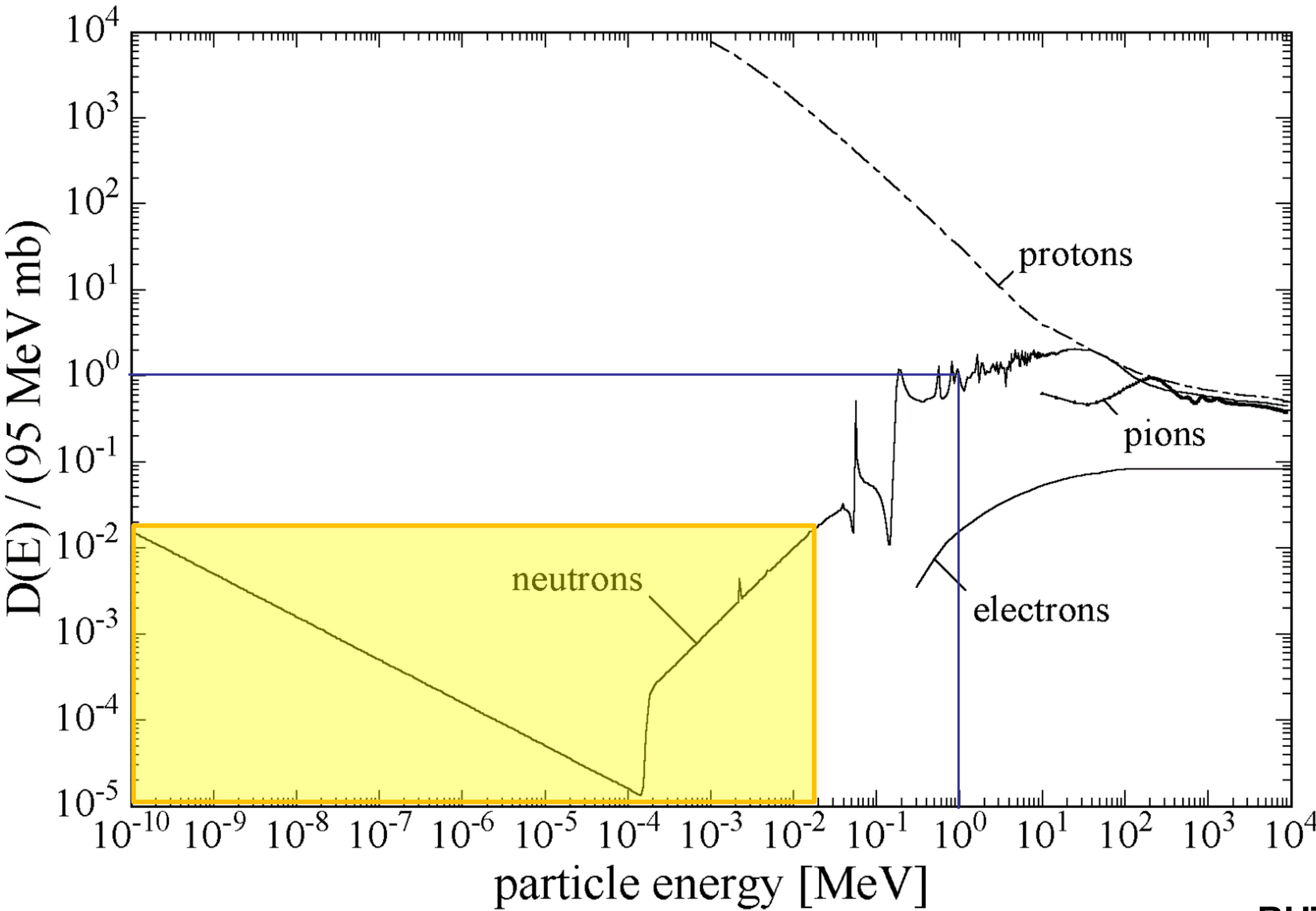
MAPS:

- CMOS sensors have low material budget
- Excellent spatial resolution
- Good time resolution
- Radiation tolerant




MVD
(Micro Vert
Detector)
Central Au-Au collision at 10 AGeV
UrQMD + GEANT + CbmRoot

How do we test for radiation hardness?



Damage in pure silicon can be rescaled with the NIEL model

By definition a 1 MeV neutron has a hardness factor of 1

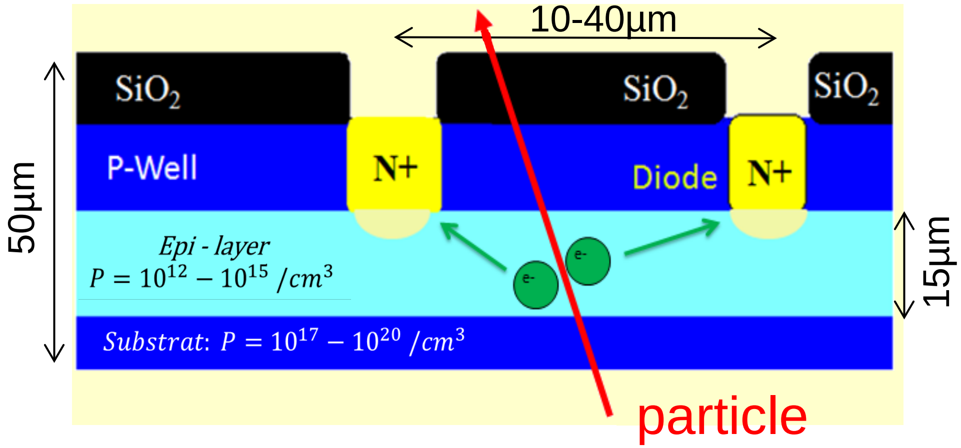
NIEL is correct for pure silicon

Neutron energys below 20 keV are often considered neglectable

Sensors are often irradiated for test purposes with higher energetic neutrons only

…BUT

Is the NIEL hypothesis valid for P-doped sensors?



CMOS Monolithic Active Pixel Sensors

- Are being optimized to tolerate extremely high radiation doses (ionizing and non-ionizing).
- <u>Based typically on P-doped silicon</u>

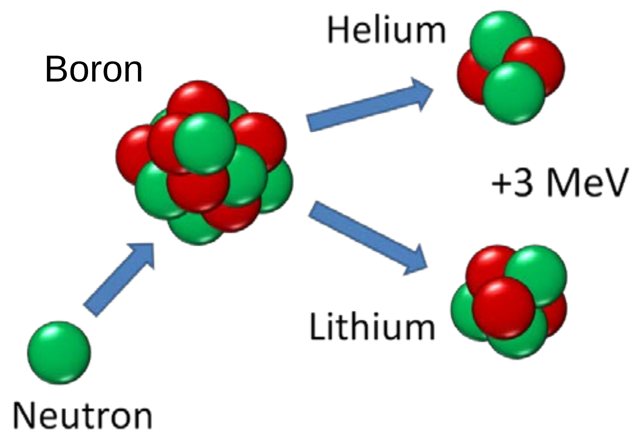
=> Contains Boron

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]

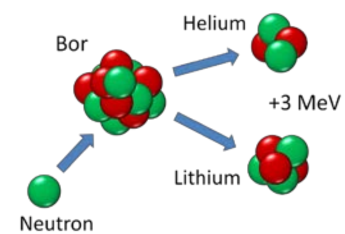
Energy dependent cross section

+

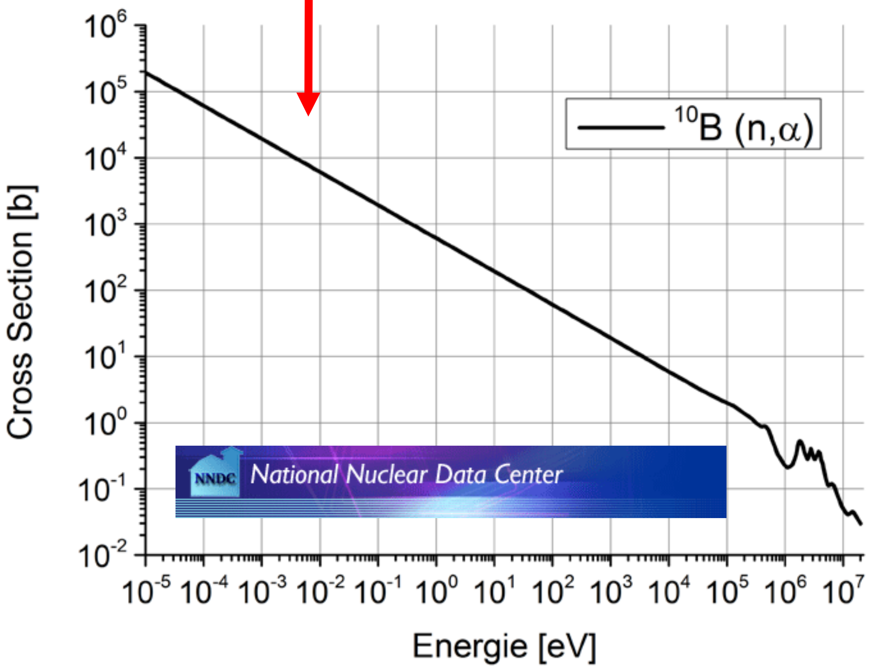
Boron decays [1/cm³]

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?

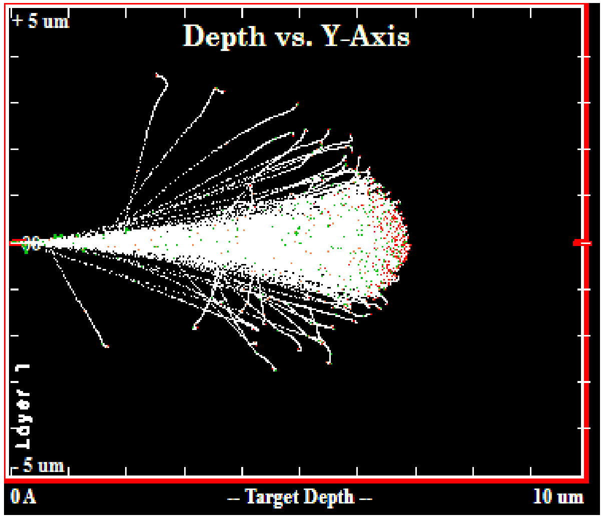
From ion energy to NIEL

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

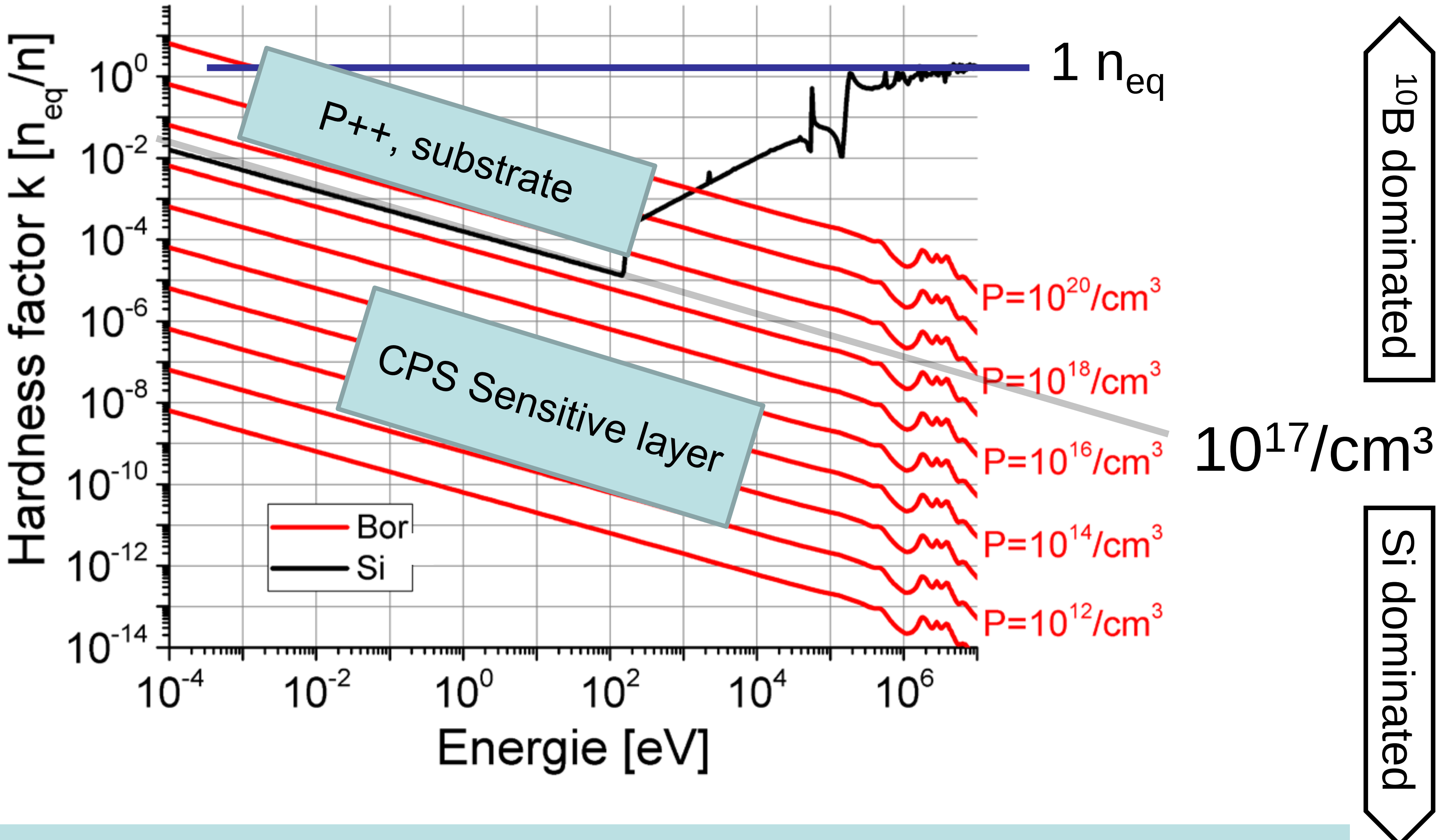


Results:

	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

Does boron decay additionally damage the sensor?

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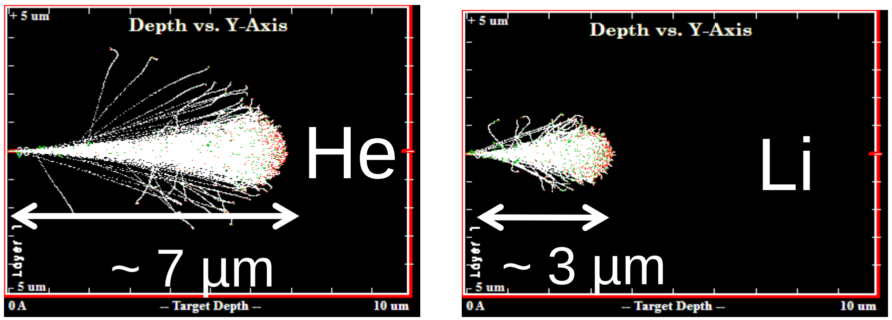
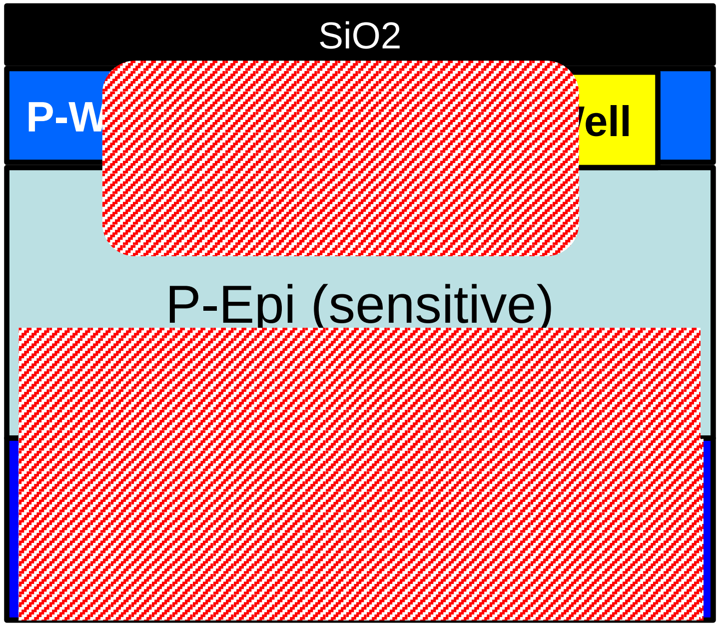
In first order:

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



Penetration depth of ions (SRIM)



Possible damage mechanism:

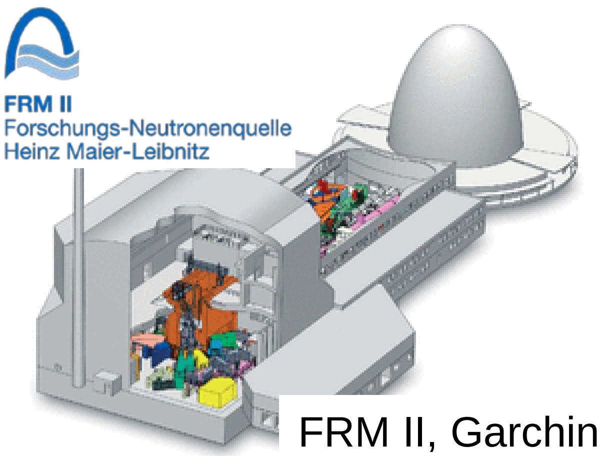
- Ions are created in P++
- Ions enter sensitive volume, create sizable (?) damage here

Likely:

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

How do we test for additional damage?

Idea: Compare radiation damage caused by fast and cold neutrons



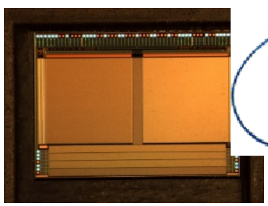
FRM II, Garching

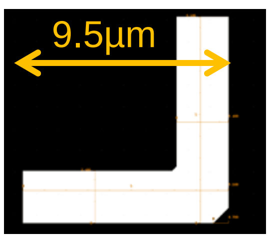
MEDAPP

- Direct ^{235}U fission neutrons
- 99% of all neutrons >100 keV

PGAA

- Cold neutrons 1.8 x 10^{-3} eV





Sensor: MIMOSA-19, IPHC, Strasbourg

- Design: AMS 0.35 LR, Year 2006
- Pixel: 12 µm pitch
- Doping assumption: $\sim \mathbf{10^{15}}\ (\boldsymbol{epi}), \sim\mathbf{10^{19}} (\boldsymbol{substrate})$

  => Not depleted, charge collection by diffusion

Observables: Charge collection efficiency

What are our results on the additional damage?

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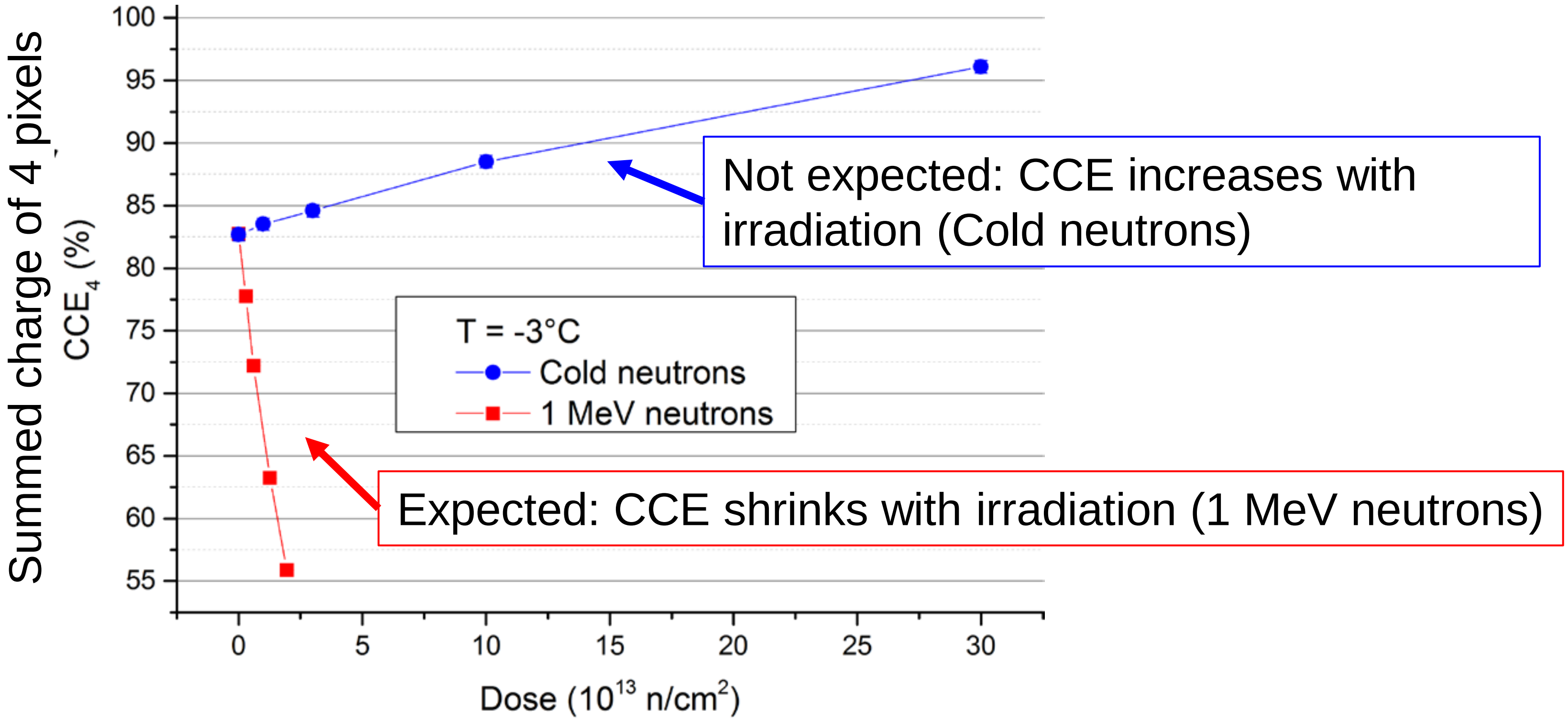
Sensor illuminated with ^{109}Cd (22.1 keV X-ray), detect clusters



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

Experimental results: CCE

Preliminary!

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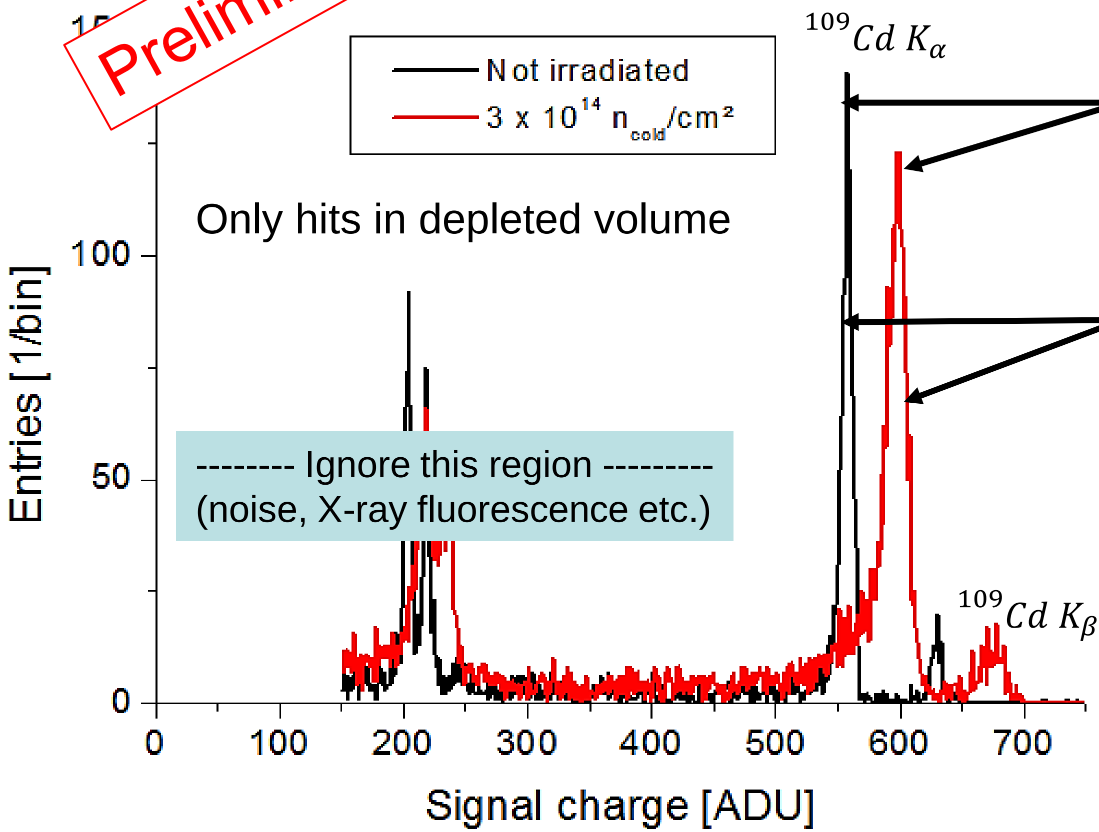

Gain increases after irradiation
⇒ Decrease of diode capacity?
⇒ More depletion?

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=$10^{15}/cm^3$)
⇒ Additional depletion improves CCE, dominates trapping
! No significant acceptor removal observed with 1 MeV neutrons for <$2x10^{13} n_{eq}/cm^2$

Summary and cautious conclusion

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

Theoretical estimate:

- $P>10^{17}/cm^3$ => 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, $\sim 10^{15}/cm^3$ epi layer, $\sim 10^{19}/cm^3$ substrate):

Observation:

CCE:

- Cold neutrons cause strong acceptor removal, CCE increases
- Acceptor removal exceeds finding for $2x10^{13} n_{eq}/cm^2$ (1MeV)

Preliminary conclusion:

- ^{10}B fission seems to cause rad. damage beyond standard NIEL
- Risk of unexpected effects in case of high thermal neutron doses.