Displacement damage – what is it

Also known as bulk damage

Distortions of the crystal lattice create additional energy levels in the Si band-gap

↓	↓
Defects act as intermediate states for thermal excitation to the conduction band	**Defects act as trapping and recombination centers**
↓	↓
The leakage current increases	**Minority carrier lifetime (signal) decreases**

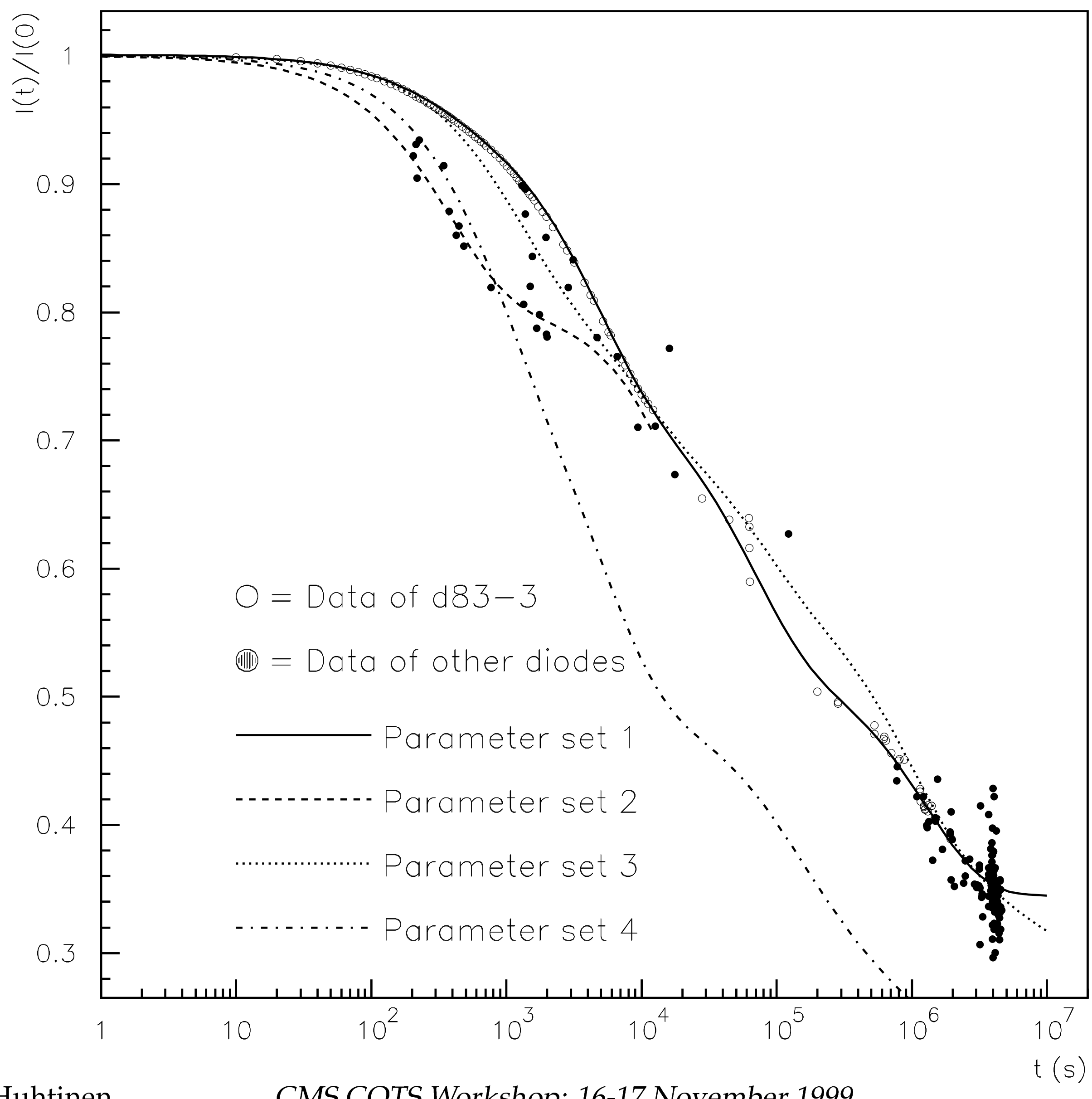
Fluence (Φ) dependence: $I(\Phi) = I_0 + \alpha\Phi$

Another manifestation of displacement damage is a gradual change of effective doping concentration. An initially n-type substrate reverts to p-type where-after the acceptor concentration seems to increase linearly with fluence.
Fluence (Φ) dependence: $N_{\mathrm{eff}}(\Phi) = N_0 \exp -c\Phi - \beta\Phi$
This probably does not affect IC:s where N_0 is much larger than in detector grade silicon.

Annealing effects - leakage current

The defects created in the bulk silicon slowly disappear with time.
Elevated temperatures speed up the process and enhance the recovery percentage.
Annealing of leakage current can be fitted with

$$I(t) = I(0) \sum_i A_i \exp(-t/\tau)$$

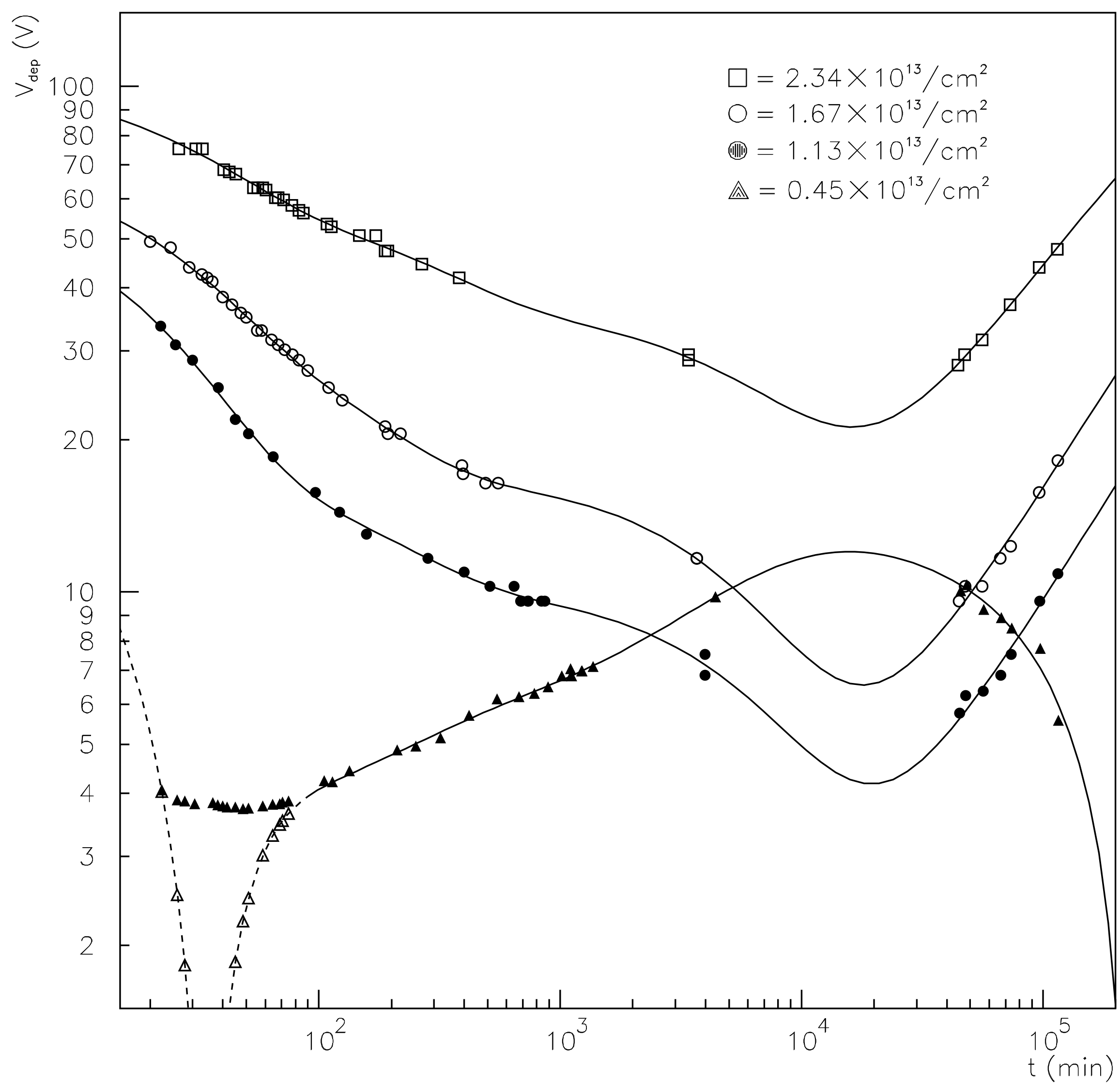


Annealing effects - N_{eff}

Annealing of the effective doping concentration is very complicated

At high temperatures ($> 0^oC$):
After a rapid initial restoration the effective doping concentration starts to evolve into the opposite direction – reverse annealing

At low temperatures ($< 0^oC$): Only 'normal' annealing



How is Bulk Damage Generated

The defects are generated by atomic cascades in the Si-lattice.

↓

The cascade is initiated by the Primary Knock-on Atom PKA

↓

The PKA is the nuclear fragment emitted in hadronic interactions

↓

The PKA collides with lattice atoms and dislodges them

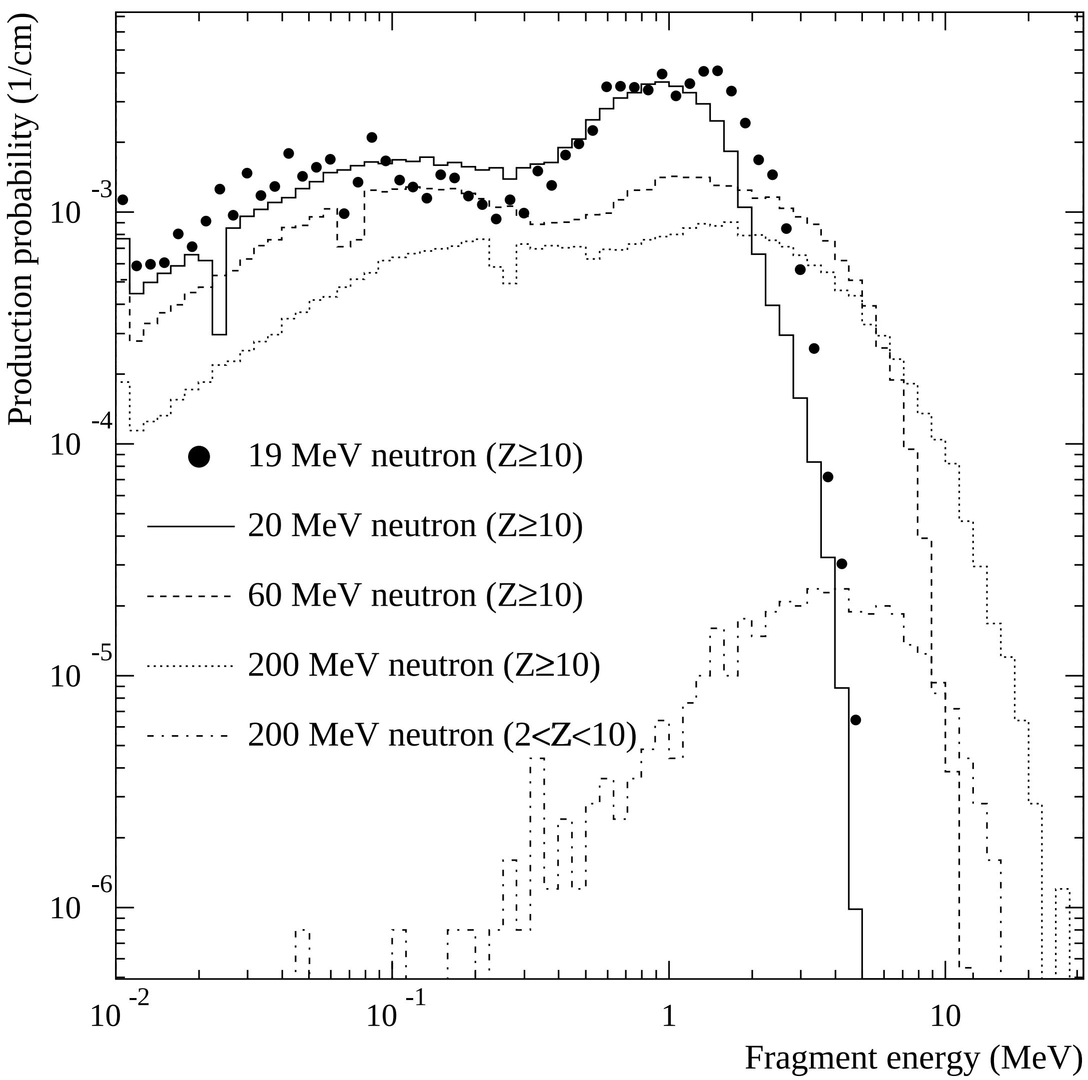
↓

Dislodged atoms can further propagate the cascade until the dislocation energy of about 20 eV cannot be transferred any more

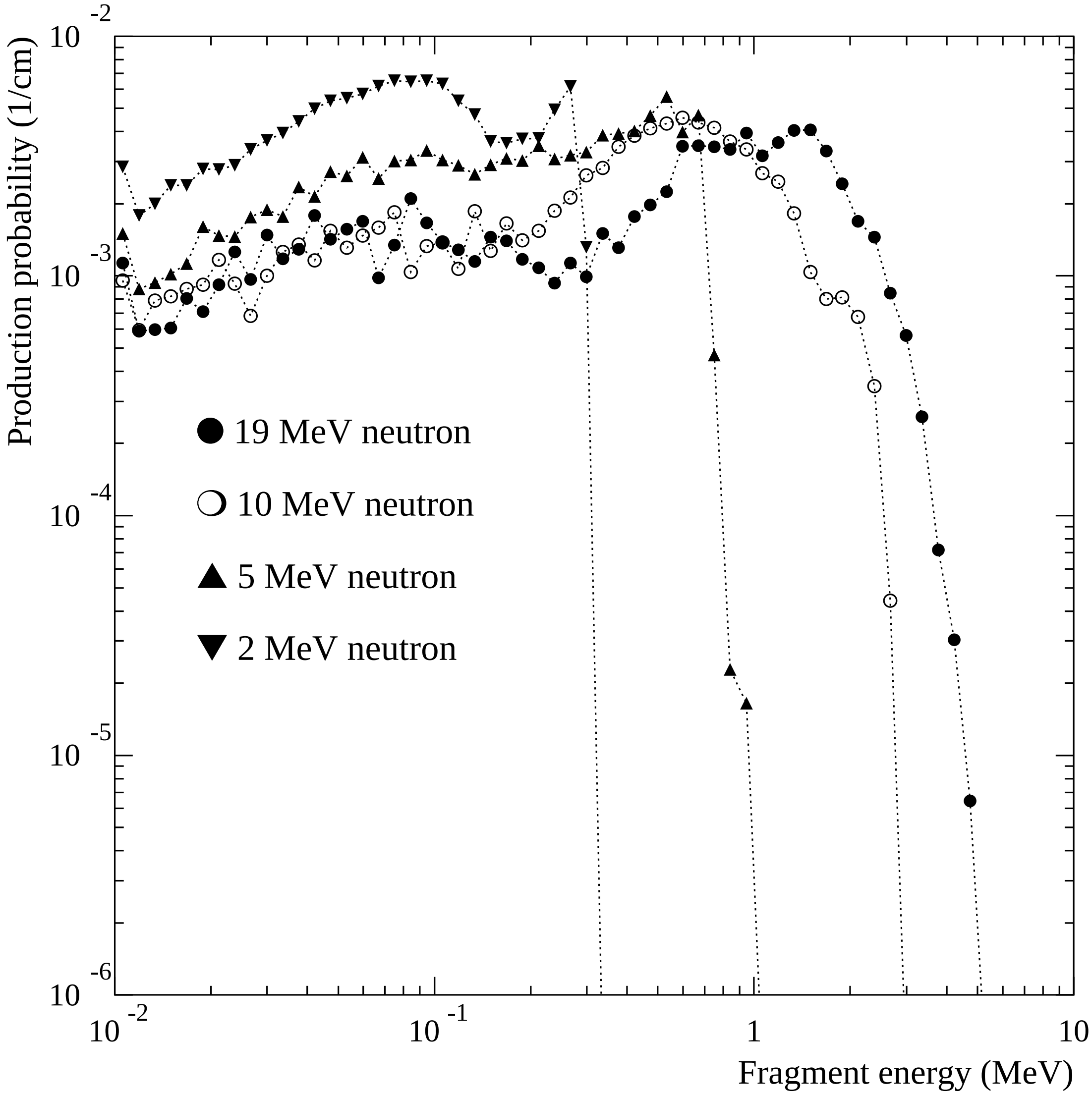
↓

Many of the slightly displaced atoms recombine with the vacancy but some remain as (meta)stable defects

PKA spectra from HE hadronic collisions

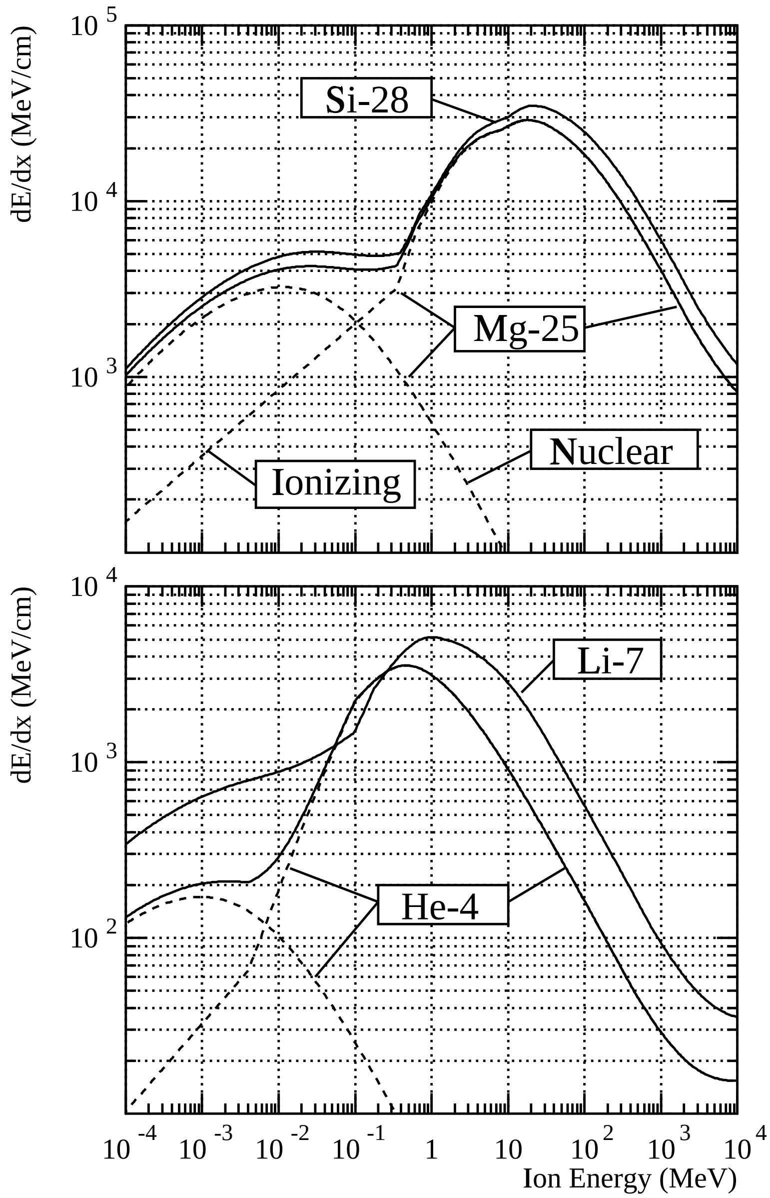


PKA spectra from LE-neutron interactions



Non-ionizing energy loss (NIEL)

The number of lattice defects in the silicon is proportional to the non-ionizing energy loss, i.e. the dE/dx with the ionization subtracted.



It has been shown that the observed damage also very accurately follows a NIEL scaling

NIEL dependence on radiation type

The NIEL becomes dominant only at low energies
The NIEL of a Si-ion in Si is saturated to about 300 keV

$\downarrow$

The maximum energies in the primary PKA spectrum are often insignificant (contrary to the case of SEU !!!)

However,

Enough energy is needed to generate a PKA

$\downarrow$

Photons and electron create negligible NIEL

$\downarrow$

Displacement damage is NOT proportional to dose

NIEL (Xsec) for hadrons

NIEL is often expressed in units of MeV mb
″MeV″ comes from the fact that each interaction deposits a certain NIEL
″mb″ is the cross section of the interaction

↓

A large cross section can compensate for a low average NIEL per interaction

↓ ↓

Low-E Neutrons	**High-E hadrons**
Small energy transfer to PKA → small average NIEL per interaction	**Large energy transfer to PKA → large average NIEL per interaction**
High interaction cross section	**Small interaction cross section**

↓ ↓

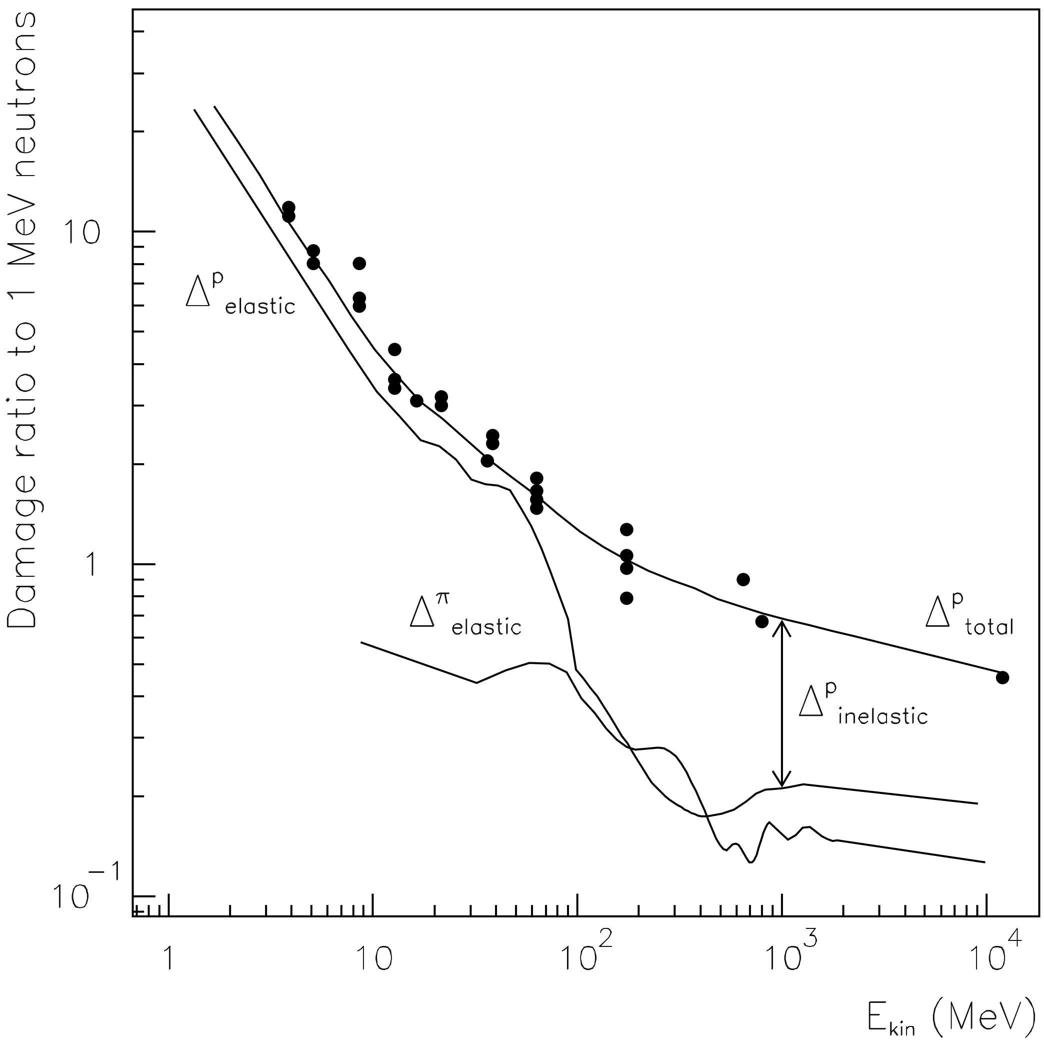
Low-energy neutrons and high-energy hadrons have roughly the same NIEL Xsec in silicon

(this is not the case in GaAs where the NIEL saturates at about 3 MeV thus HE-hadrons create much more damage than LE-neutrons)

Elastic and inelastic NIEL

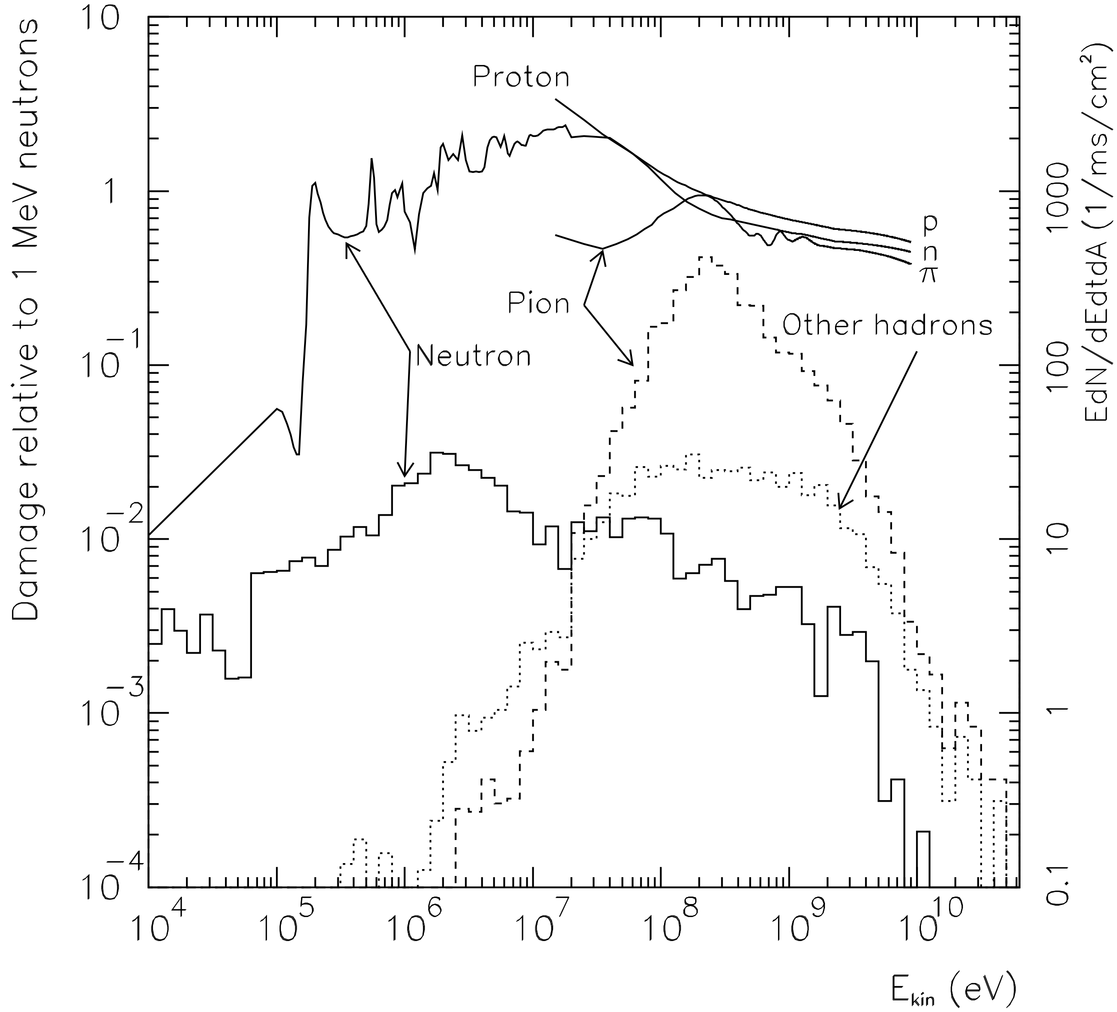
For low-energy protons NIEL is mostly due to elastic scattering (small energy transfer compensated by huge cross section)

Above ∼30 MeV inelastic scattering becomes increasingly important (large energy transfer but small cross section)



NIEL for different hadrons

Figure shows NIEL Xsec and typical LHC tracker spectra



For a typical LHC spectrum all hadrons (E>100 keV) have about same NIEL Xsec = unit of flux generates same damage.

(this of course is not true for mono-energetic beam-test)

NIEL in numbers

Below we give NIEL Xsec values in MeV mb for different particle types

Neutrons:

<20 MeV ENDFB (NJOY calculation)
20-400 MeV INC calculations (Konobeyev et al)
>400 MeV scaled from proton data (Huhtinen et al)

Protons:

Fit to experimental data

Pions:

Rescaled from proton data (Huhtinen et al)

Energy (MeV)	Neutron	Proton	Pion
0.01	1	?	?
0.1	5	?	?
0.2	106	?	?
0.5	60	?	?
1.0	72	?	?
2.0	177	?	?
5.0	194	?	?
15.0	216	320	?
50.0	171	171	?
100.0	111	119	68
200.0	75	94	90
300.0	66	85	77
500.0	62	74	52
1000.0	55	65	49

NIEL of "1 MeV neutrons" DEFINED to be 95 MeV mb

Hardness factors for CMS spectra

We can fold the spectra with the damage curves to obtain the average NIEL Xsec of the spectrum

Location	NIEL (MeV mb)
On top of Q1 platform	122
Around HF lateral shielding	120
At cavern lateral wall z$\sim$ 20 m	119
In cavern around Muon barrel	105
In endcap HCAL FEE boxes	83
In barrel HCAL FEE boxes	94
At back of endcap ECAL	111
MSGC tracker	104–109
Silicon tracker	82–100
Pixel detector	62–75

Reminder:

NIEL of "1 MeV neutrons" DEFINED to be 95 MeV mb

Conclusion

The average NIEL Xsec of spectra in CMS is so close to 95 MeV mb that the whole hadron flux (above 100 keV) can be assumed to be "1 MeV neutron Equivalent"

The ±50% NIEL Xsec variation should be compared with the large uncertainties in

- **flux estimation (factor of ∼3 in cavern and muon system)**
- **damage sensitivity of different devices**
- **uncertainties in annealing behaviour (operational conditions, temperature...)**

Nevertheless,

A proper NIEL scaling should be done to the test results if these are obtained in a monoenergetic beam.

NIEL Xsec in Cavern (muon is the same) varies from 105-122

NIEL Xsec of protons:	**171 at 50 MeV** **119 at 100 MeV** **94 at 200 MeV**

↓

∼100 MeV protons would provide perfect test for Cavern COTS

(but few-MeV neutrons are also very good)