Non Ionizing Energy Loss scaling of radiation effects in silicon detectors
– a review –

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OUTLINE:

* A little bit of history
* Basics of the scaling hypothesis, definition, how to ...
* Applicability & limits

* Conclusions

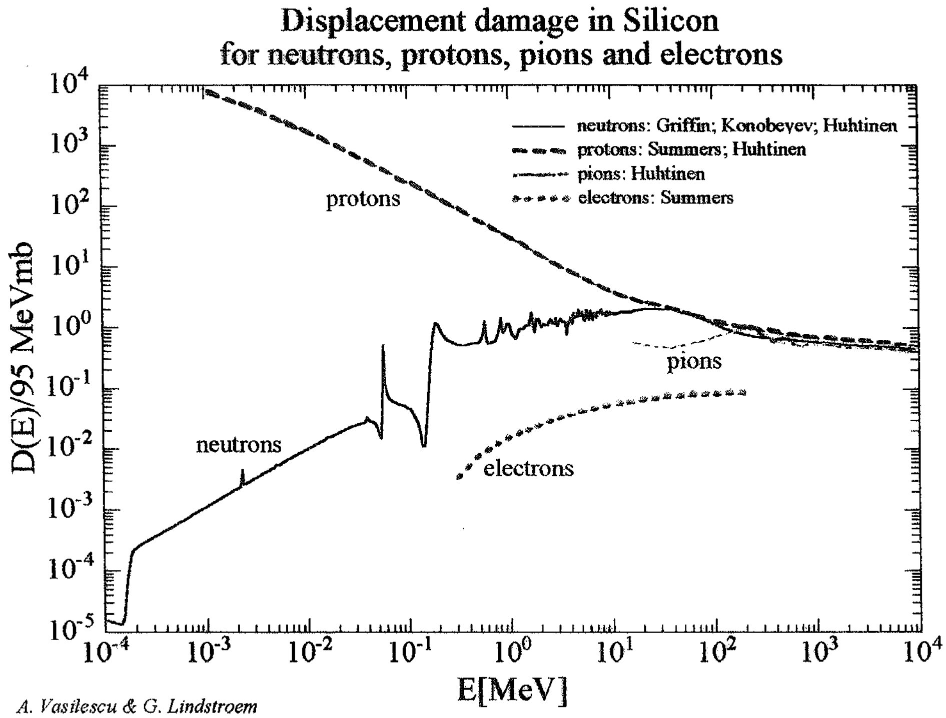
CERN . 17-18 May 2001

NIEL scaling of bulk damage in silicon

- **Naive view:** all bulk damage seen in detector behaviour is proportional to displacement damage function D
- **Revised:** Influence of particular damage caused by different type of particles cannot be neglected:

Sizeable difference between neutrons and charged hadrons !

Nevertheless NIEL scaling takes out most of the dependence on particle type and energy:



measured values of κ = D/95MeVmb:
0.62 for 24GeV/c protons,
1.2 for 300 MeV/c pions

What is the NIEL scaling?

= a method to correlate damage to semiconductor bulk due to different high particle fluences

History / background:

- appeared from research of damage to electronic components (bipolar transistors) + need for correlation with a large amount of data (databases) from reactor and nuclear weapon research

* a series of papers - charged particles
  - Dale et al - IEEE Trans NS-35, 6 (1988) 1208
  - Summers et al. - IEEE Trans NS-33 (1986), NS-34 (1987) NS-40 (1993) 1372

* standardization and work on neutrons (introducing reference of 1 MeV n)
  - ASTM standard practice
  - Dugnay et al - IEEE Trans NS-37 (1990) 2219
  - Namenson et al - IEEE Trans NS-29 (1982) 1018 (1 MeV)
  - Griffin et al - SAND 92-0094 (1993)

* correlations, first calculations based on nuclear physics, HEP, atomic collision theory
  - van Ginneken - FNAL note FN-522 (1989)
  - Konobeyev et al - J. Nucl. Mat 186 (1992) 117

* simulations for PKA spectra - explanation from solid state physics
  - Mori, Spitznagel - Rad. Effects (1982) 60, 27
  - S. Wood et al ---- etc

* new interest - related to HEP applications
  - M. Huhtinen, A. Aarnio - NIM A 335 (1993) 580 (protons + pions)

- the most systematic work:
  on neutrons up to 20MeV — Lazo et al, Ougouag et al, Griffin et al

- still very good:
  on neutrons up to 800MeV (even if E_d thresh $= 2E_d$) — Konobeyev et al
  on protons up to ~200MeV — Summers et al
  (also on e^- — same authors — BUT ... !)

- less systematic for higher energies (estimate for π)
  reasonable estimates by Huhtinen & Aarnio
  based on scarce experimental data, comparative model $p-\pi$, neutron data = p data − Coulomb inter.

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* another attempt for π, based on cross-section data compilation, but not confirmed by systematic experimental data
  Lazanu et al

* to be mentioned as history – the "compilation" by A van Ginneken

Model assumptions: "infinite bulk"
Cascading leading to stable defects

formal definition:

THE NIEL (NON-IONIZING ENERGY LOSS) SCALING HYPOTHESIS:

$$\Phi_{n\text{-}eq}^{1MeV} = \kappa \Phi$$

the hardness parameter

$$\kappa = \frac{EDK}{EDK(1MeV)}$$

ASTM: EDK(1MeV n in Si) = 95 MeV mb

DISPLACEMENT KERMA : $EDK = \frac{\int D(E)\phi(E)dE}{\int \phi(E)dE}$ [averaged over the energy spectrum]

DISPLACEMENT FUNCTION : $$D(E) = \sum_k \sigma_k \int dE_R f_k(E,E_R) P(E_R)$$

$f_k(E,E_R)$ – the probability that a neutron with energy E produces a recoil with energy E_R in reaction k

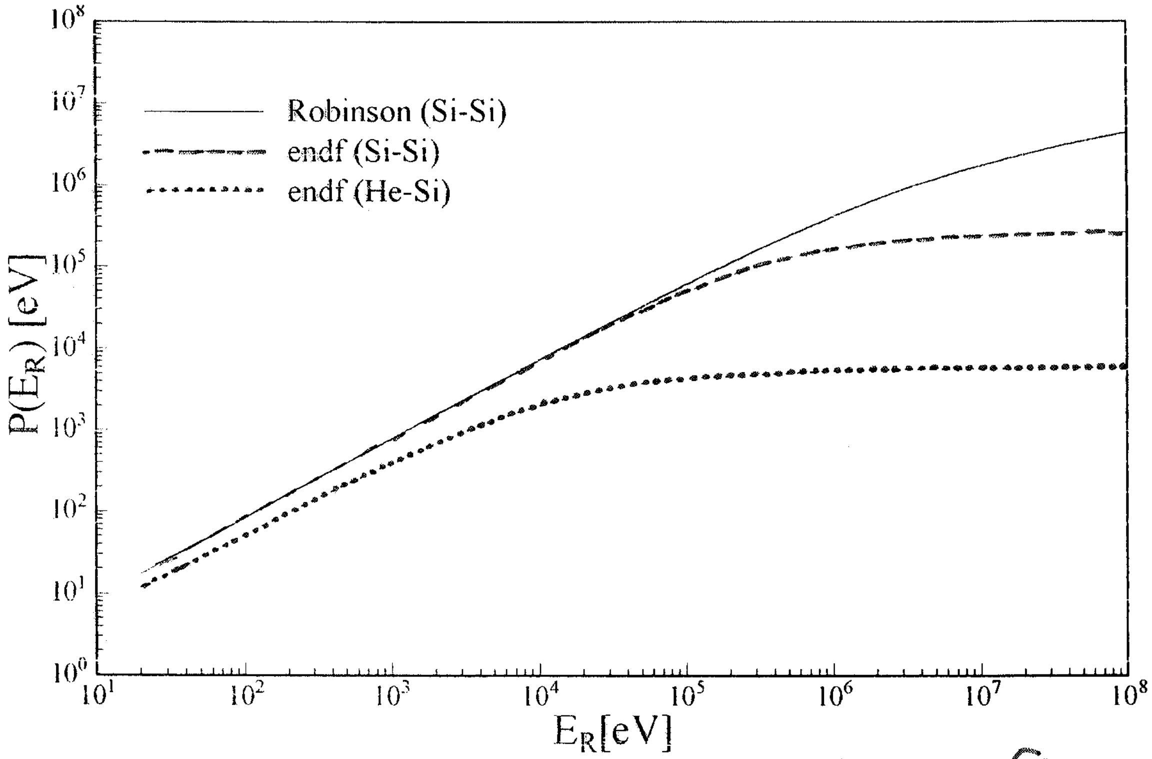
$P(E_R)$ – the partition function (Lindhard theory)

The sum is over all possible reactions.

J. Lindhard & V. Nielsen
Danske Vidensk. Selsk. Mat. Fys. Medd.
33 (1963) 1

BASICS (1)

• From the theory of atomic collisions: partition to ⟨ ionising / non-ionising energy



$$P(E_R) = \frac{E_R}{1 + F_L(\epsilon + 3.4008\,\epsilon^{1/6} + 0.40244\,\epsilon^{3/4})} \quad ; \quad \epsilon = \frac{E_R}{E_L}$$

$$E_L = 30.724\, Z_R Z_L (Z_R^{2/3} + Z_L^{2/3})^{1/2}\, \frac{A_R + A_L}{A_L}$$

$$F_L = \frac{0.0793\, Z_R^{2/3} Z_L^{1/2} (A_R + A_L)^{3/2}}{(Z_R^{2/3} + Z_L^{2/3})^{3/4} A_R^{3/2} A_L^{1/2}}$$

R = recoil
L = lattice (Si)

Maximum limits for energy transfer to NIEL $\lim_{E_R \to \infty} P(E_R)$

incident particle	$P(E_R)$ [keV]
p	0.56
α (He)	5.95
Si	280.4
C	51.8
O	91.8

- Interactions which contribute to NIEL

  - for hadrons

    n — elastic reactions →

    charged hadrons p, π — elastic, dominated by Coulomb scattering reactions

    - for π — special (bare particles with nuclear force)

    inelastic interactions produce average recoils 10× larger than Coulomb in (above 10 keV E_R, it is >90%)

  - electrons, muons, gammas

    need a separate discussion

    - specific interactions
    - small or no mass, different length of interaction

    (we do not use the NIEL scaling, mostly)

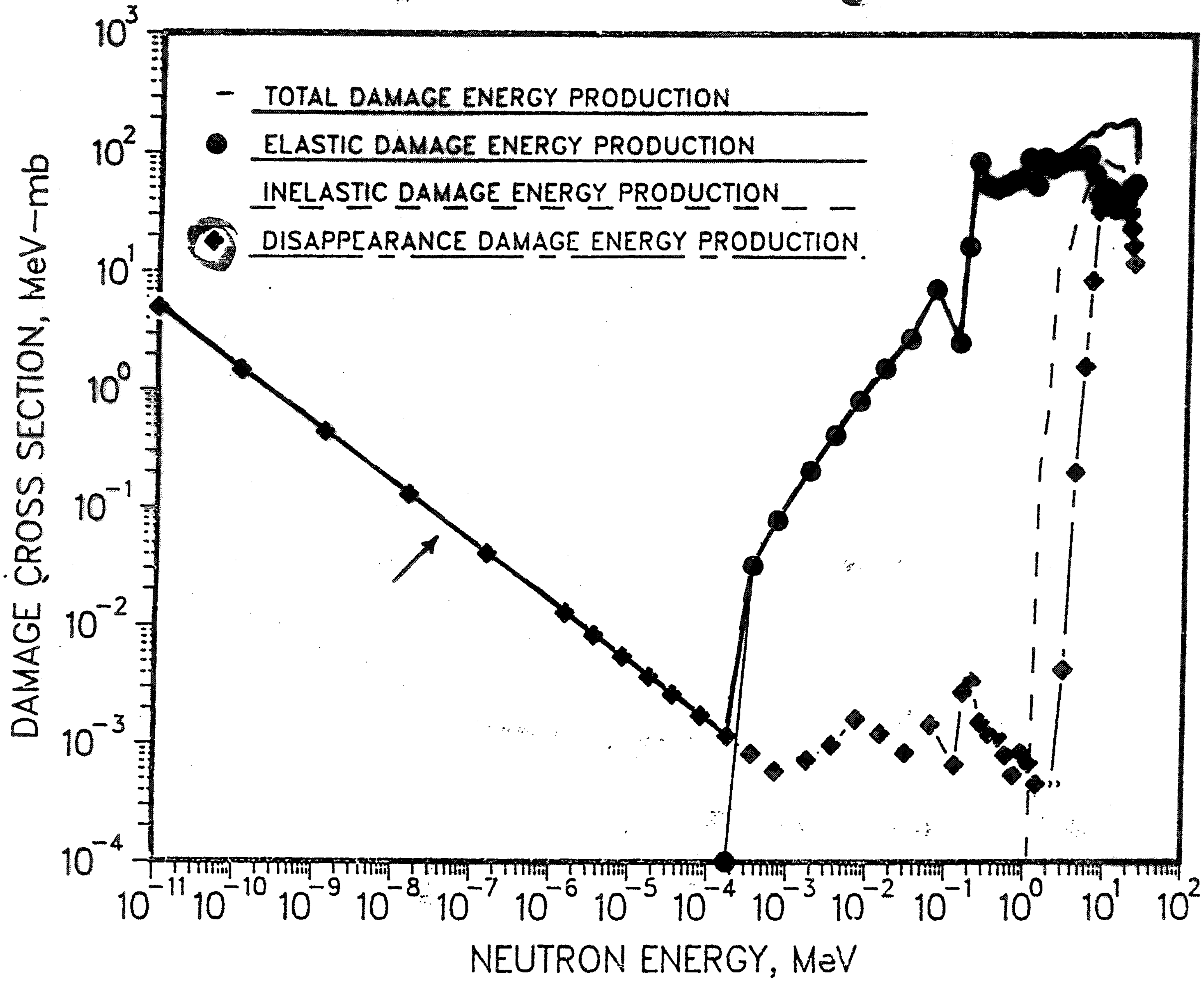
- The damage function (obtained from displacement KERMA) (compilation available on the ROSE web pg) →

- Recipe for any spectrum (measured or calculated)
  - analyze it to choose interpolation method
  - choose $D(E)$
  - folding ⟹ κ (hardness parameter)

  (we can predict the expected accuracy from the shape of the spectrum)

→ an example:

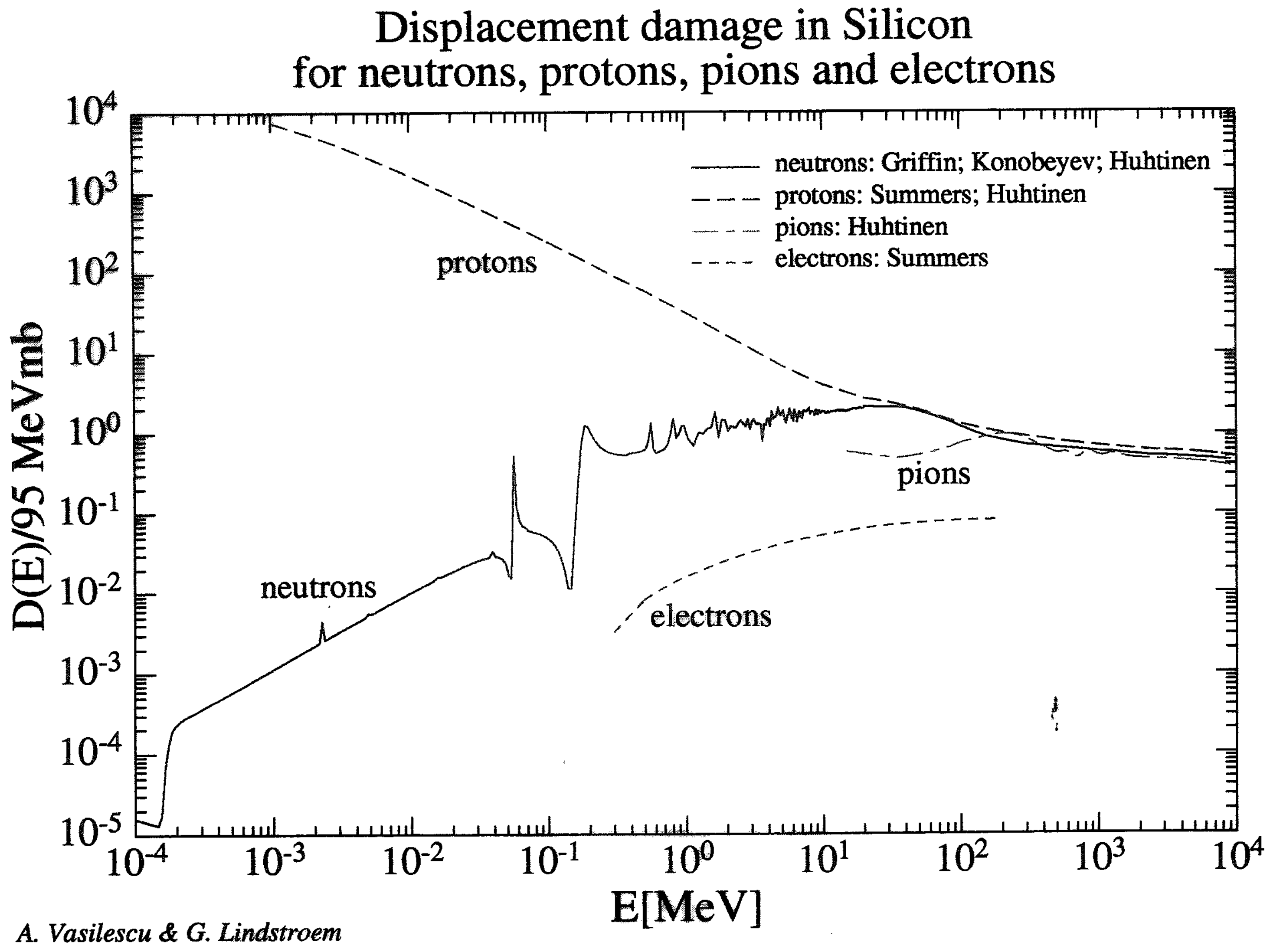
→



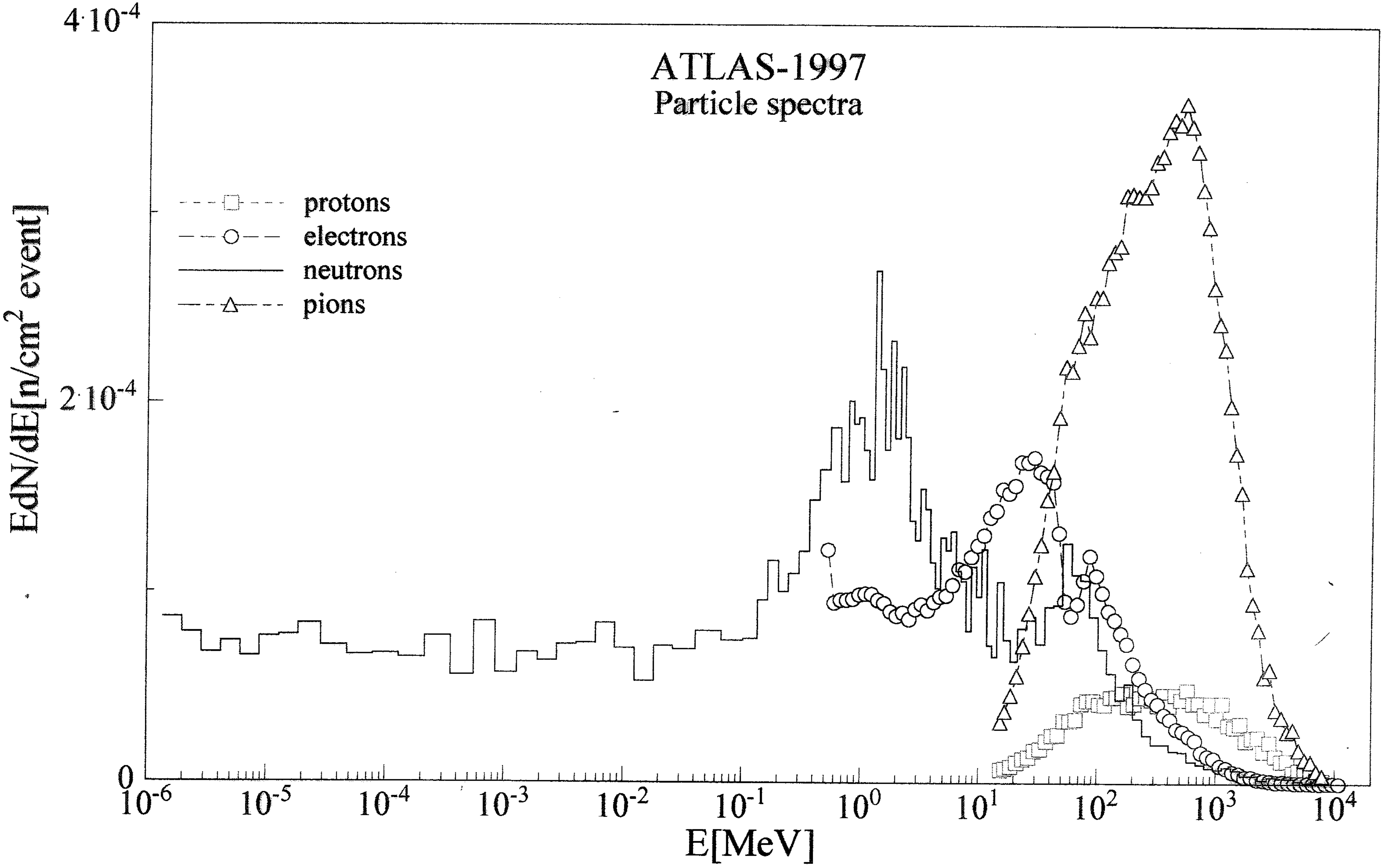
$D(E) = \sigma(n,\gamma) * 1$ ke
?

$Q = 8.475$ MeV
for (n,γ)
Si recoil: 1.28k

Figure 2. Components of Radiation Damage-Energy Production for Silicon

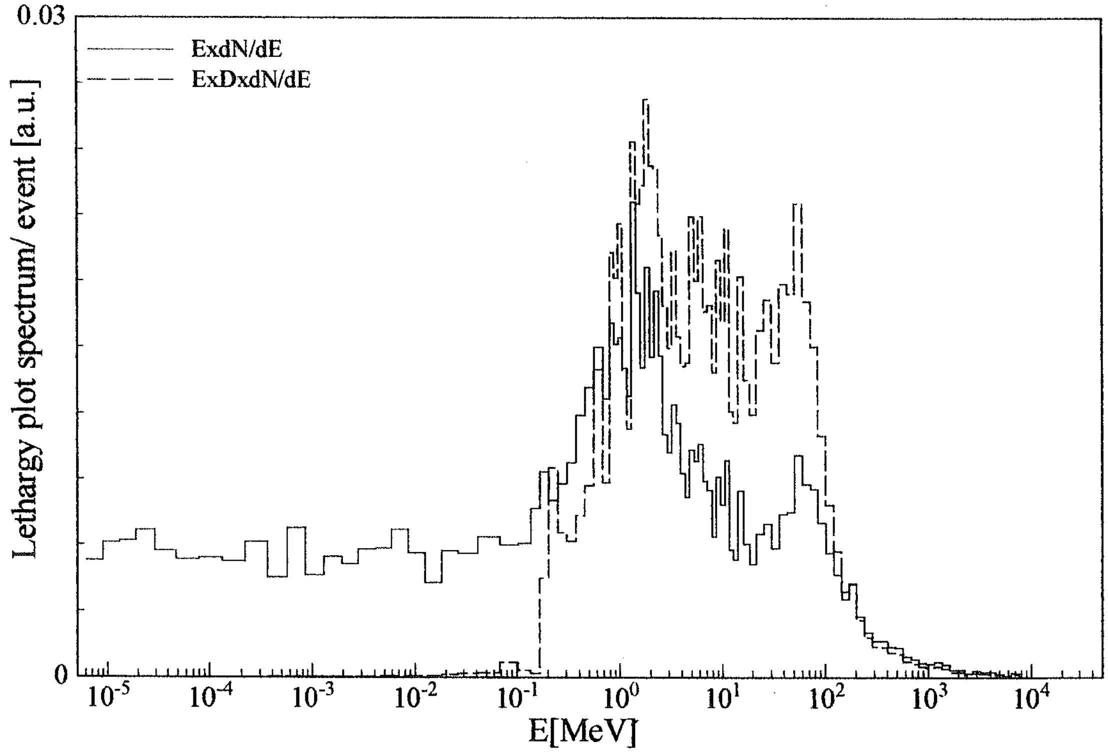


Displacement damage in Silicon
for neutrons, protons, pions and electrons
D(E)/95 MeVmb
E[MeV]
neutrons: Griffin; Konobeyev; Huhtinen
protons: Summers; Huhtinen
pions: Huhtinen
electrons: Summers
protons
neutrons
pions
electrons
A. Vasilescu & G. Lindstroem

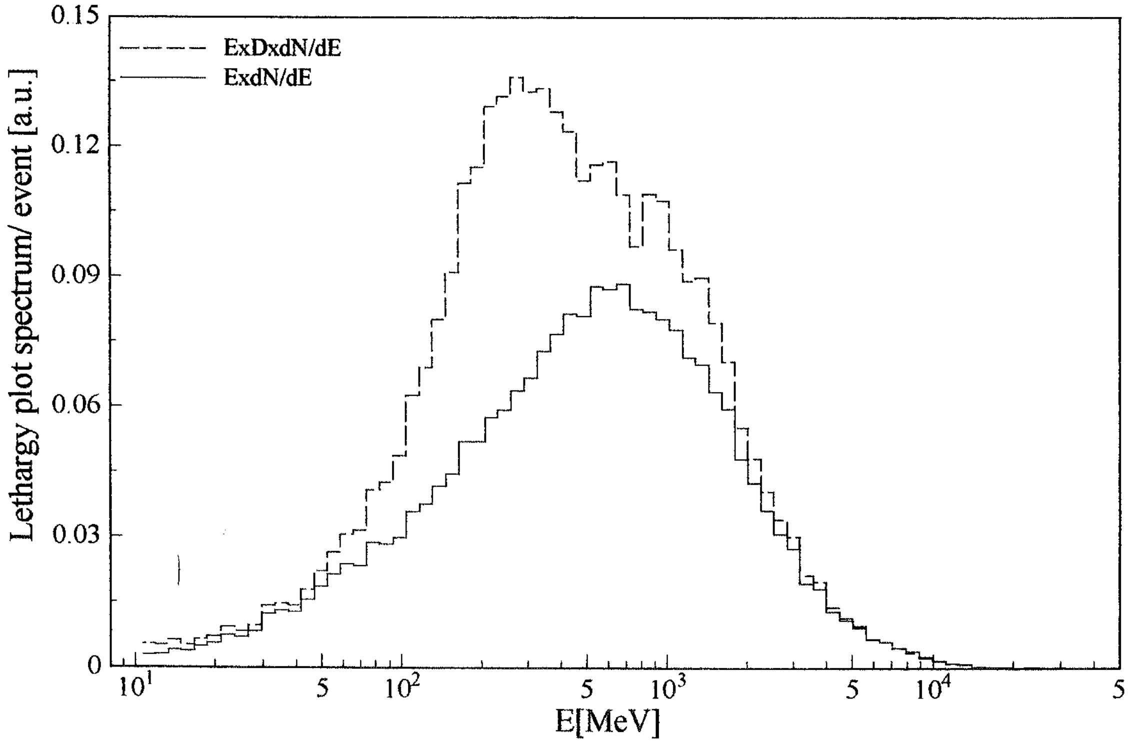


ATLAS-1997
Particle spectra
protons
electrons
neutrons
pions
EdN/dE[n/cm² event]
4·10⁻⁴
2·10⁻⁴
0
10⁻⁶
10⁻⁵
10⁻⁴
10⁻³
10⁻²
10⁻¹
10⁰
10¹
10²
10³
10⁴
E[MeV]

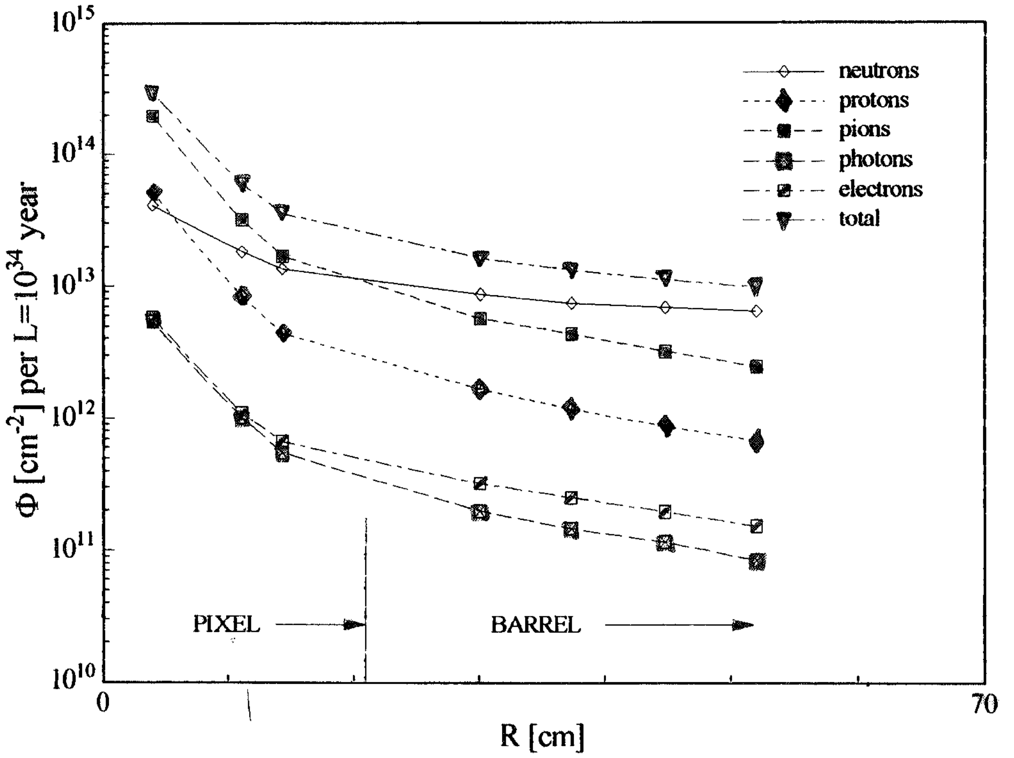
ATLAS Ferrari data (June 1997) barrel 1 neutrons



ATLAS Ferrari data (June 1997) mpix pions



position	photons	electrons	protons	pions	neutrons	annual total fluence
B-layer pixel	1.79%	1.91%	17.6%	65.1%	13.6%	$3.03\ 10^{14}$
layer 1 pixel	1.72%	1.88%	14.24%	54.24%	27.93%	$5.87\ 10^{13}$
layer 2 pixel	1.52%	1.83%	12.15%	47.0%	37.5%	$3.63\ 10^{13}$
wheel 1 pixel	1.32%	2.40%	13.40%	46.6%	36.3%	$3.66\ 10^{13}$
wheel 4 pixel	1.15%	3.09%	13.14%	46.5%	36.1%	$2.70\ 10^{13}$
barrel 1	1.16%	1.87%	9.76%	36.16%	51.03%	$1.71\ 10^{13}$
barrel 2	1.10%	1.86%	8.77%	32.4%	55.8%	$1.34\ 10^{13}$
barrel 3	1.02%	1.73%	7.66%	28.3%	61.3%	$1.13\ 10^{13}$
barrel 4	0.86%	1.55%	6.82%	25.12%	65.6%	$9.88\ 10^{12}$
SCT wheel 2	0.99%	2.27%	8.6%	25.9%	62.2%	$1.18\ 10^{13}$
SCT wheel 3	1.0%	2.54%	9.2%	28.2%	59.1%	$1.22\ 10^{13}$
SCT wheel 9	0.63%	1.85%	6.2%	18.7%	72.6%	$1.46\ 10^{13}$



1 MeV ~ neutron equivalent fluences in ATLAS SCT for different particles

Simulations : A. Ferrari

Calculations : A. Vasilescu 1998

Our R&D experience proved up to now:
(FOR HADRONS)

* an almost universal applicability for NIEL scaling as to α (leakage current)

* a limited applicability to N_{eff} behaviour

We would expect NIEL scaling for any quantity $\sim \phi$ (at least for 1st order dependence!)

- However:
  - violations reported for p
    - low energy
    - $\sim 10 \div 20$ MeV

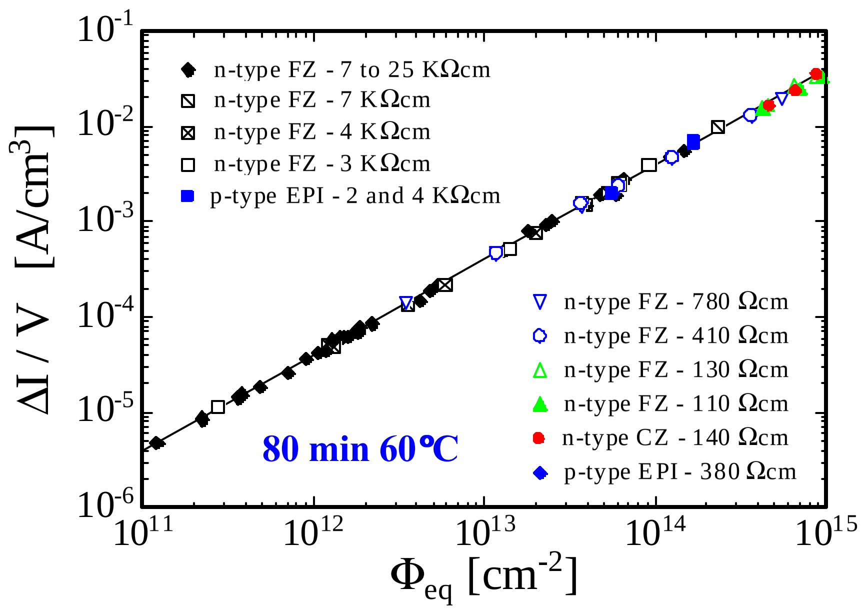
    reconfirmed?

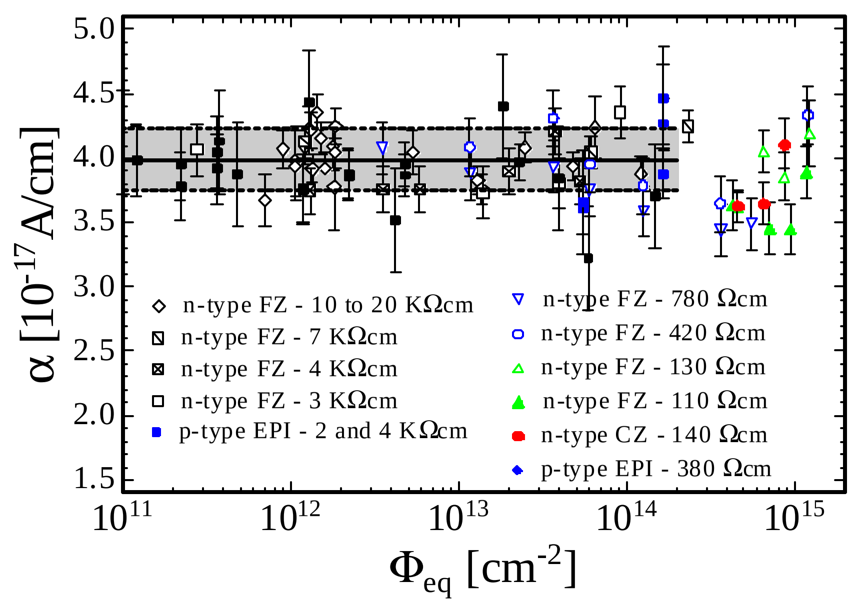
  - presently k values (from experiment) accepted by ROSE

for 24 GeV/c p with about 20-25%
for 300 MeV/c π 10%

above D(E) curves by M. Huhtinen

Increase of Leakage Current





♦ Increase of leakage current independent of:

- Conduction type (p or n), resistivity
- oxygen and carbon content
- crystal orientation <111>, <100>

♦ Temperature dependence:

$$I \propto \exp\left(-\frac{E_g}{2k_B T}\right)$$

cooling strongly reduces current

♦ Damage parameter a

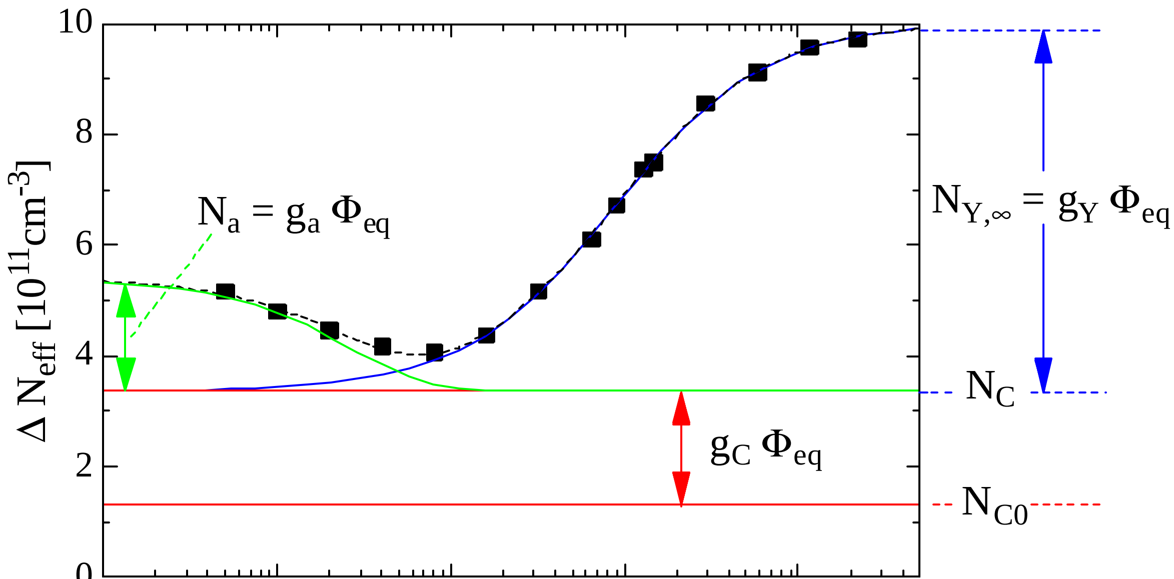
- definition: $$a = \frac{\Delta I}{V \cdot \Phi_{eq}}$$
- measured after 80min at 60C:

  $a_{80/60}$ = (3.99 ± 0.03)10^{-17} A/cm
- used for fluence (NIEL) calibration

Annealing behavior of N_{eff} - Hamburg model -

$$\Delta N_{eff}(\Phi_{eq},t) = N_{eff\,0} - N_{eff}(\Phi_{eq},t)$$

ΔN_{eff} = Change of N_{eff} with respect to $N_{eff\,0}$ (value before irradiation)



<u>long term reverse annealing:</u>

$$N_Y = N_{Y,\infty}\cdot\left(1-\frac{1}{1+t/t_y}\right)$$

second order parameterization (with $N_{y,\infty}=g_y\times\Phi_{eq}$).gives best fit

<u>But:</u>

τ_y independent of Φ_{eq}

⇒ underlying defect reaction based on **first order** process!

$$\Delta N_{eff}(\Phi_{eq},t) = N_a(\Phi_{eq},t) + N_C(\Phi_{eq}) + N_Y(\Phi_{eq},t)$$

<u>short term annealing:</u>

$$N_a = \Phi_{eq}\times\sum_i g_{ai}\times\exp\left(-{t}/{t_i}\right)$$

first order decay of acceptors introduced proportional to Φ_{eq} during irradiation

<u>stable damage:</u>

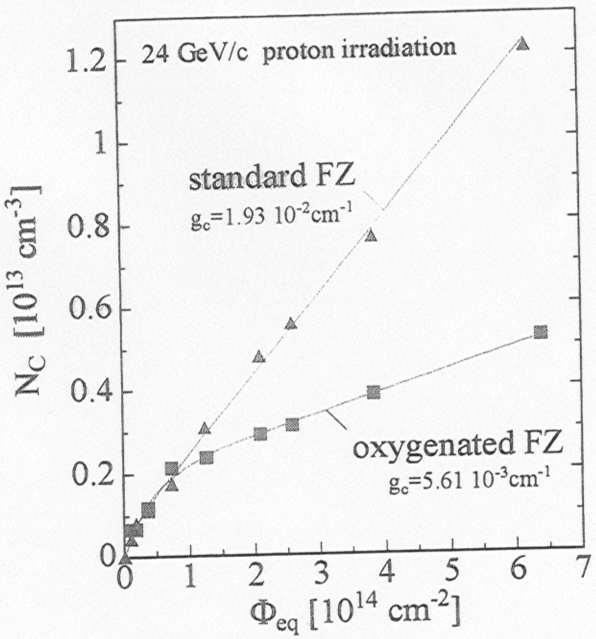
$$N_C = N_{CO}\cdot(1-\exp(-c\cdot\Phi_{eq})) + g_C\cdot\Phi_{eq}$$

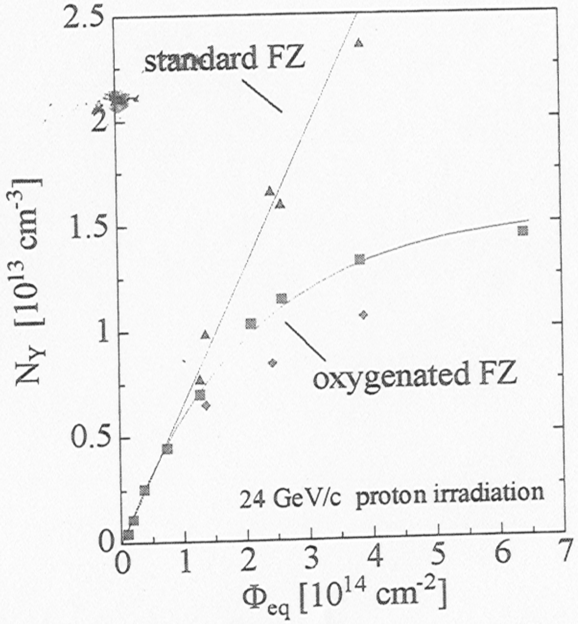
incomplete „donor removal“

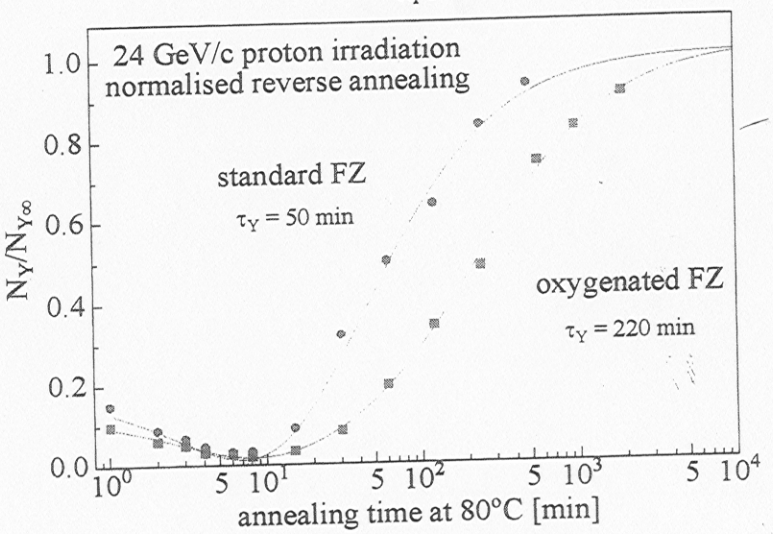
+ introduction of stable acceptors

Michael Moll - CERN -

Extraction of damage parameters





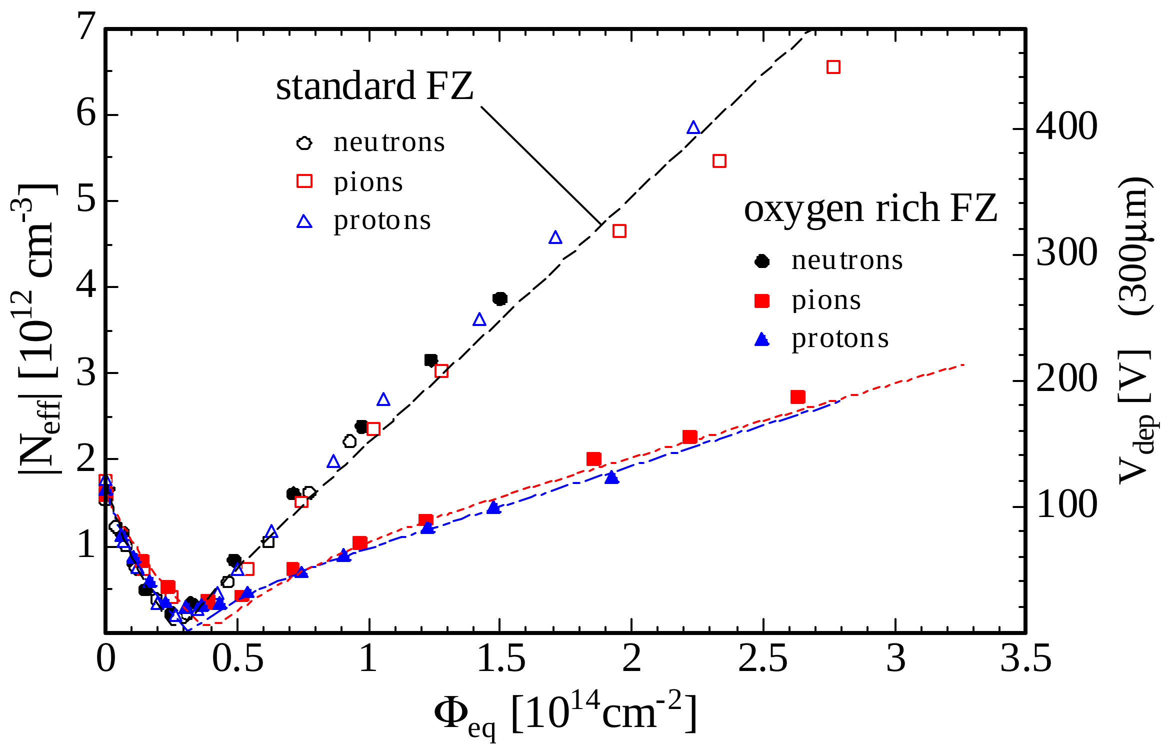


- **proton irradiated** O-rich diodes
- g_c improved by a factor of 3
- saturation of reverse annealing
- delayed reverse annealing

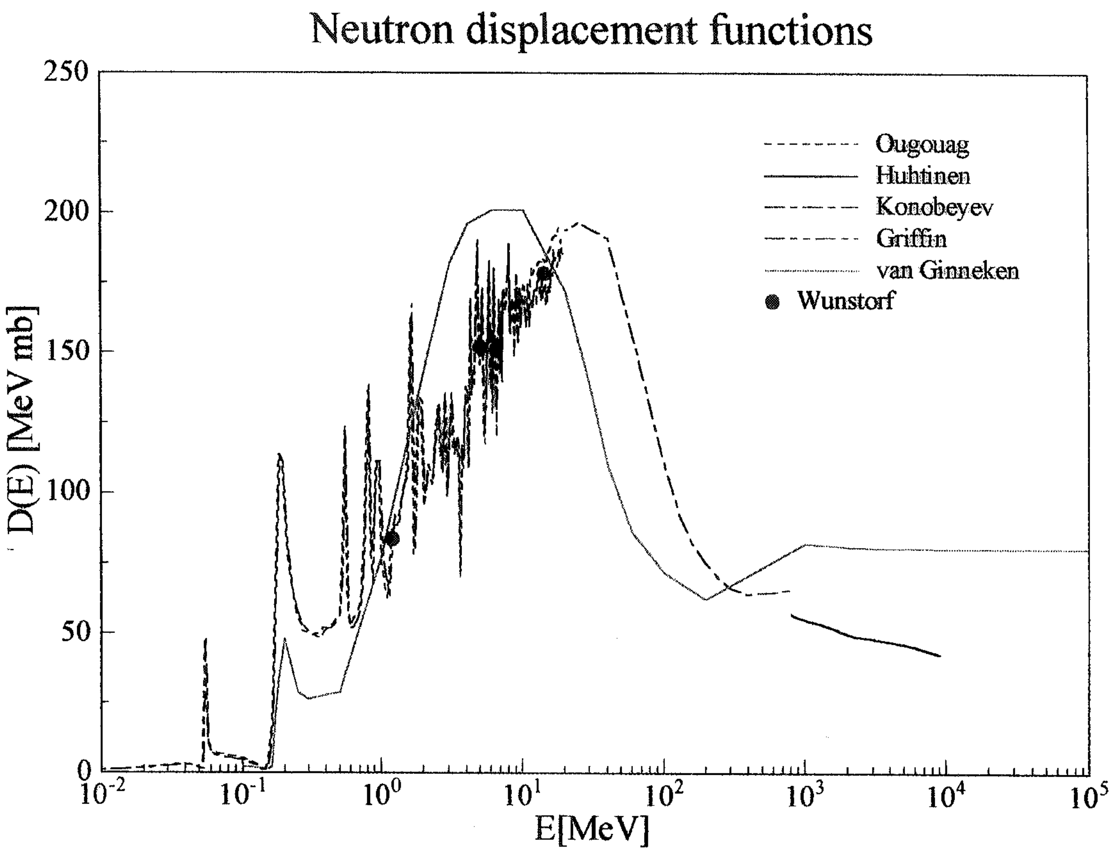
G. Lindstroem, University of Hamburg, CERN-RD48, LEB-workshop, Cracow 11/15-Sep-00

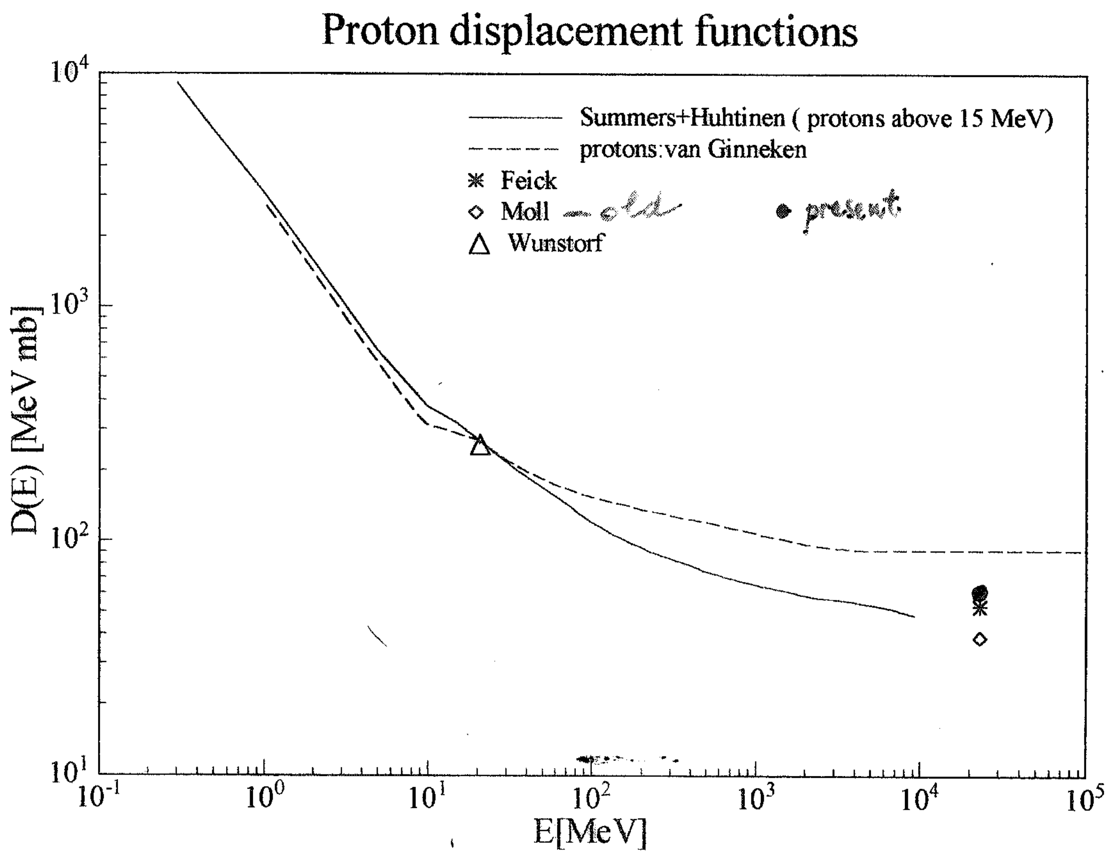
Oxygen and standard silicon
- Particle dependence -

23 GeV protons - 192 MeV pions - reactor neutrons

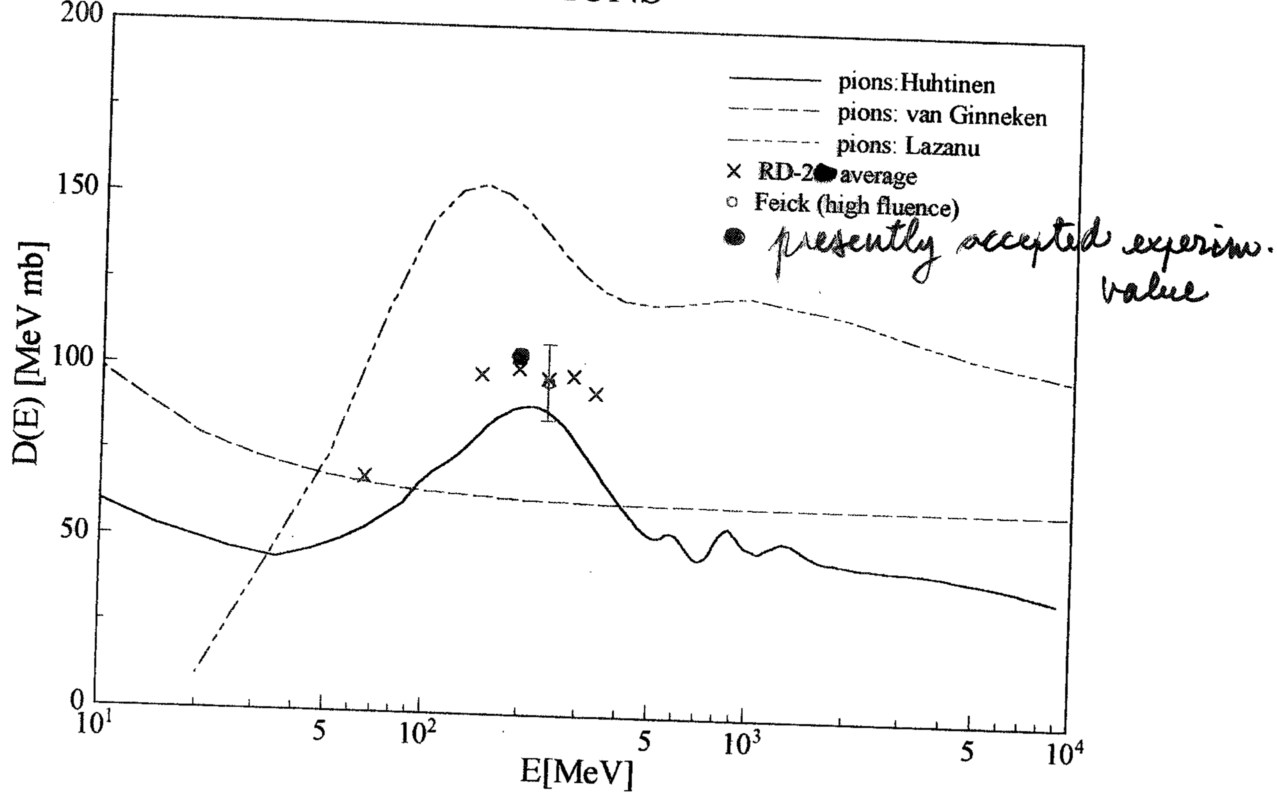


- **Strong improvement for pions and protons**
- **Almost no improvement for neutrons**

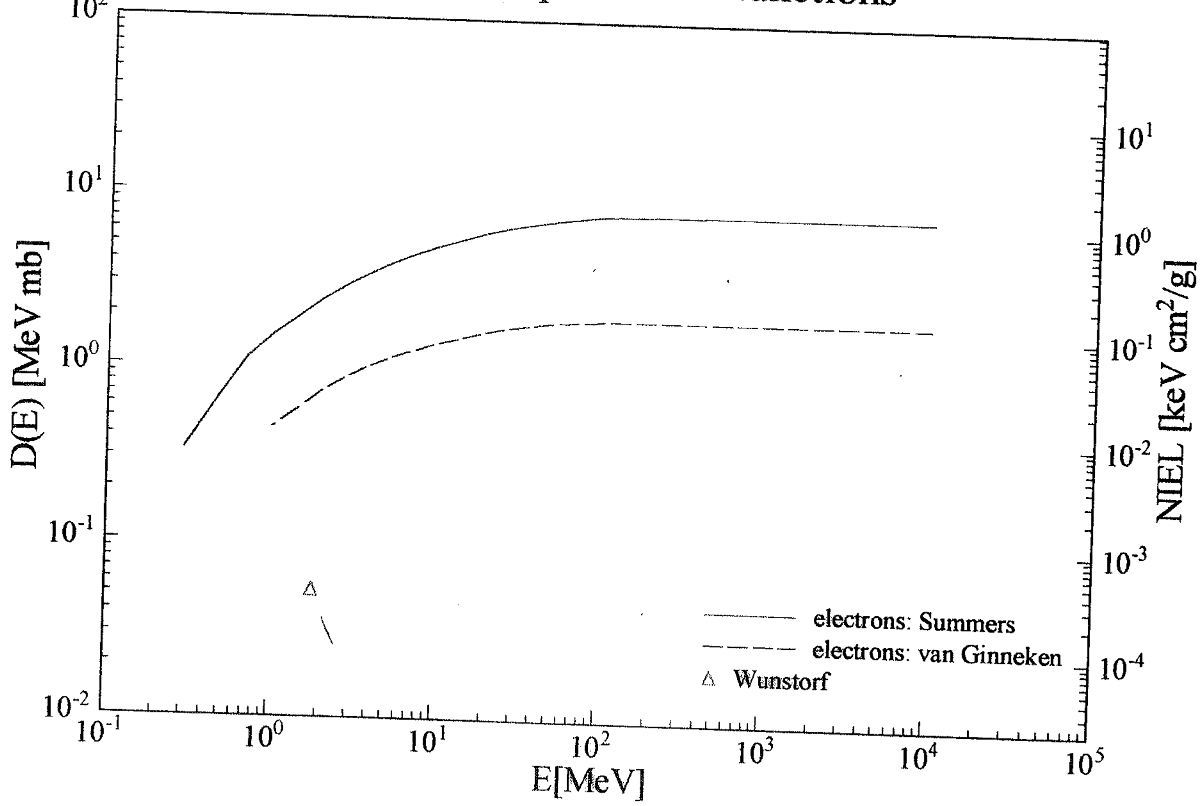

Neutron displacement functions
Ougouag
Huhtinen
Konobeyev
Griffin
van Ginneken
Wunstorf
D(E) [MeV mb]
E[MeV]


Proton displacement functions
Summers+Huhtinen (protons above 15 MeV)
protons:van Ginneken
Feick
Moll — old
present
Wunstorf
D(E) [MeV mb]
E[MeV]

PIONS



Electron displacement functions



Why does it work?

In first order - the nature of displacement damage does not depend on the energy spectrum of the PKA

? (consistent with MC simulations by Mueller et al, etc which predict the final distribution of defects produced in Si by PKAs with different energies)

More & Spitznagel divide PKAs in 3 groups:

- low energy PKAs (< 2 keV)
  produce ONLY isolated defect pairs + small clusters
- intermediate energy PKAs (2 ÷ 12 keV)
  produce single cascades
- high energy PKAs (> 12 keV)
  produce multiple subcascades separated by regions of free defects

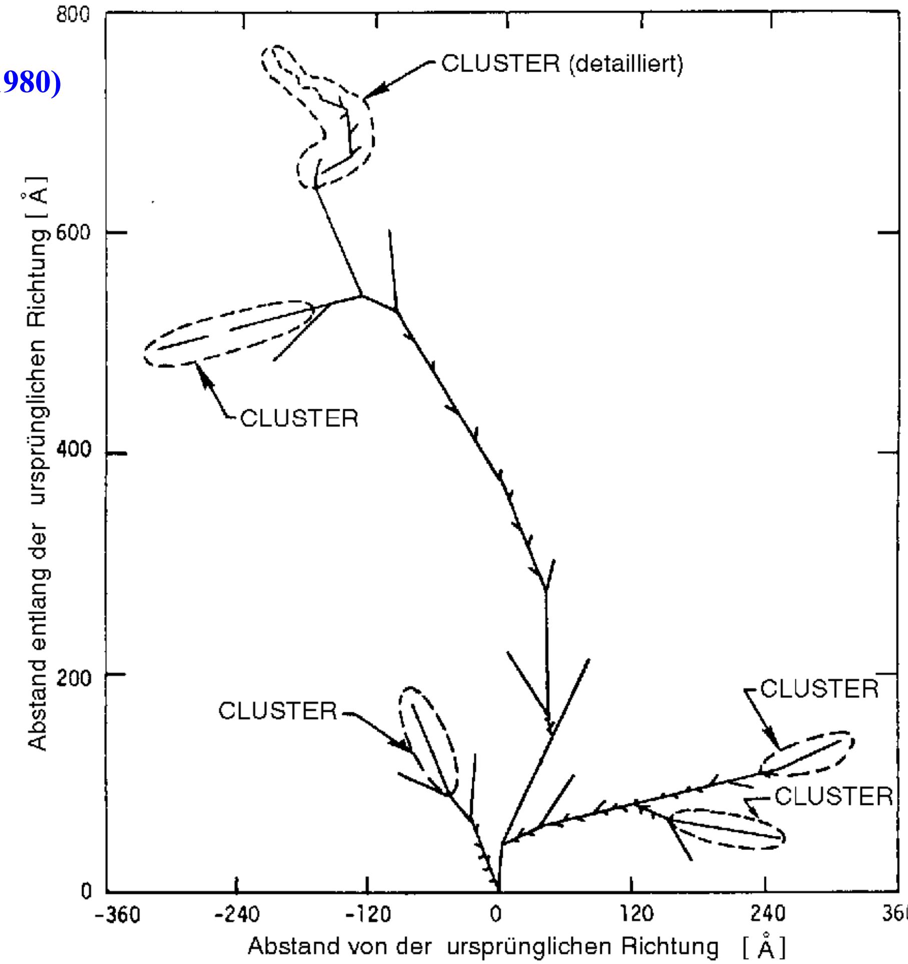
Higher energy PKAs produce MORE damage, but the microscopic nature of the damage is not significantly different.

Maximum energy transferred to a PKA is much higher, but the AVERAGE is relatively small!

ex: 10 MeV p   max: 1.33 MeV
                    ave: 272 eV

Primary Damage

- **PKA - Primary Knock on Atom**
- **Simulation** **(Fig.: van Lint 1980)**
  - **50 KeV PKA**
    (average recoil energy for PKA
    produced by 1 MeV neutrons)
- **Displacement threshold in Silicon:**
  - **Single lattice atom (Frenkel pair):**
    E_d » 25 eV
  - **Defect cluster**
    E_C » 5 keV
- **Neutrons (elastic scattering)**
  - **E_n > 185 eV for single displacement**
  - **E_n > 35 keV for cluster**
- **Electrons**
  - **E_e > 255 keV for single displacement**
  - **E_e > 8 MeV for cluster**
- **60Co-gammas**
  - **Compton Electrons with max. E_g »1 MeV (no cluster production)**



Why does it NOT work?

NIEL scaling – a model (with limits)

- leptons and γ – a more complicated situation
  as to: description of the interacti
  collision theory model
  "infinite bulk"

- charged hadrons and neutron differences?

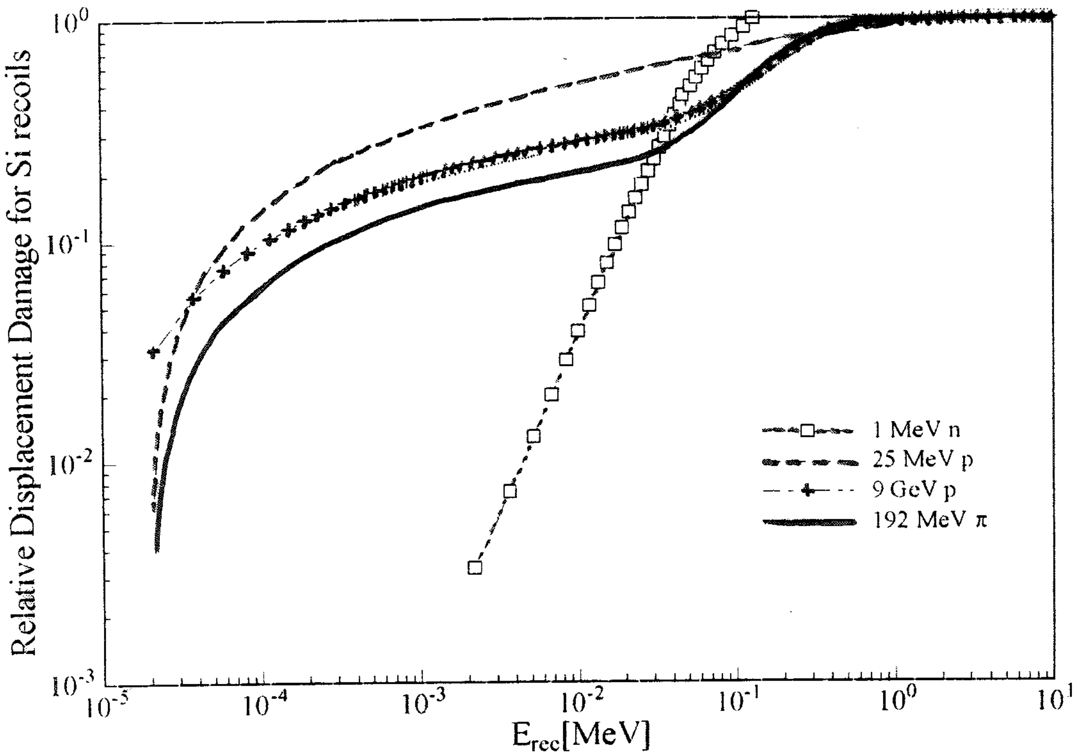
An attempt to explain oxy/std differences:
study of recoil spectra →

- Coulomb scattering → smaller recoils
  (charge – the only difference between p and n at the HE limit!)
- π–N at HE limit cross section ratio ~ ratio no. quarks

But material dependence (oxy/std) should appear (or not) in all studies (α, N_{eff})// **generation rates**?
- for influence in D(E) in primary damage – concentration is low

Reasonable: the later **kinetics** can be different
(model refining)
microscopic studies →

Damage efficiency for different particles vs. Si recoil energy (elastic scattering only)



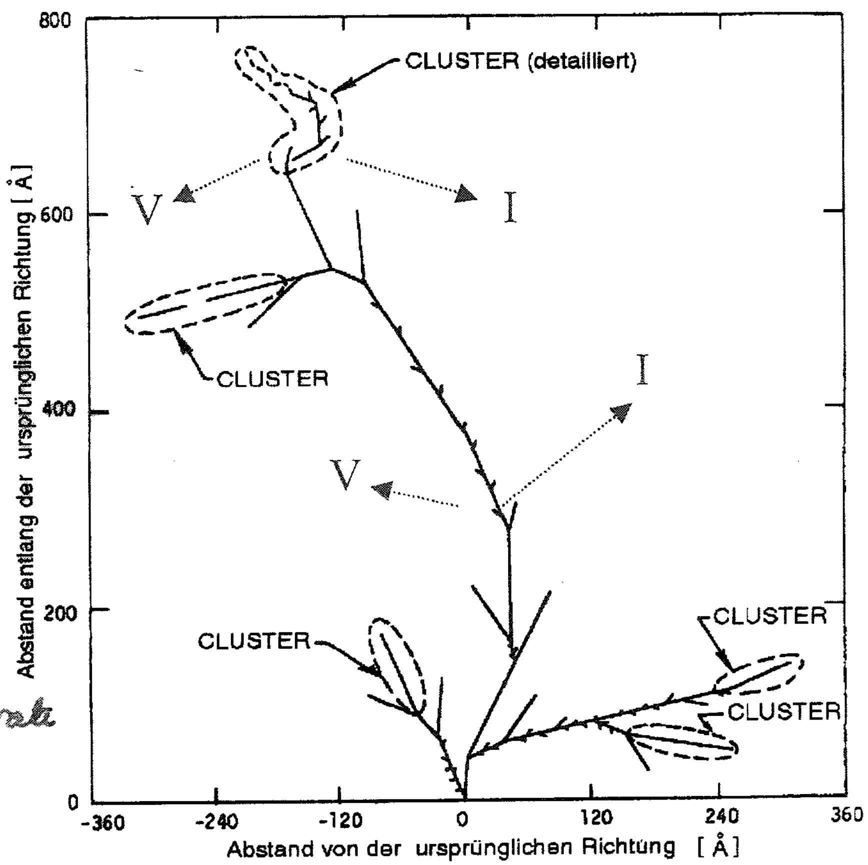
Relative damage produced by Si recoils with energies < 5 keV
(5 keV= threshold for cluster generation)

25 MeV p	**50%**
9 GeV p	**30%**
200 MeV π	**20%**
1 MeV n	**1.5%**

Primary and secondary defect generation

Simulation: 50 KeV PKA (**P**rimary **K**nock on **A**tom)
(average recoil energy for PKA produced by 1 MeV neutrons)

I - Silicon Interstitial   V - Vacancy



- **Primary defect generation**:
  - I,   higher order I (?)
  - V, V_2,   higher order V (?)
  - $\Rightarrow$ CLUSTER(?)

  particle independent generation rate

- **Secondary defect generation** (reaction scheme):

$I+C_s \rightarrow C_i \Rightarrow C_i+C_s \rightarrow C_iC_s$
$C_i+O_i \rightarrow C_iO_i$
$C_i+P_s \rightarrow C_iP_s$

g indep. of O conc. — *generation rate dep. on O conc.*

$V+V \rightarrow V_2$ $V+V_2 \rightarrow V_3$
$V+O_i \rightarrow VO_i \Rightarrow V+VO_i \rightarrow$ **V_2O_i** $\Longleftarrow$ **Damage! (V_2O-model)**
$V+P_s \rightarrow$ **VP_s**

indep. of O conc.

radiation hardness of oxy material could be explained by suppression of V_2O

$I+V_2 \rightarrow V$ $I+VO_i \rightarrow O_i$ ....

- *results from M. Kuhnke*

Concluding remarks:

NIEL scaling = a method / useful tool for correlation of experimental results from radiation damage testing with different energies & particles

A naive view → risk of unrealistic interpretation (results), if background not understood

- We should not be tempted to "scale" everything as a rule!
- No reason for universal NIEL scaling for complex phenomena due to secondary damage formation and kinetic (can be material-, particle- and process-dependent)

<u>What could be improved?</u>

- an experimental database of results (ROSE at least)
- systematic D(E) calculations for particles and energy ranges with ???
- more microscopic modelling to explain "violation" cases

* HOT NEWS:

1. a VERY INTERESTING paper (preprint) submitted to NIM A (May 2001)

M. Huhtinen - Simulation of non-ionising energy loss and defect formation in Silicon

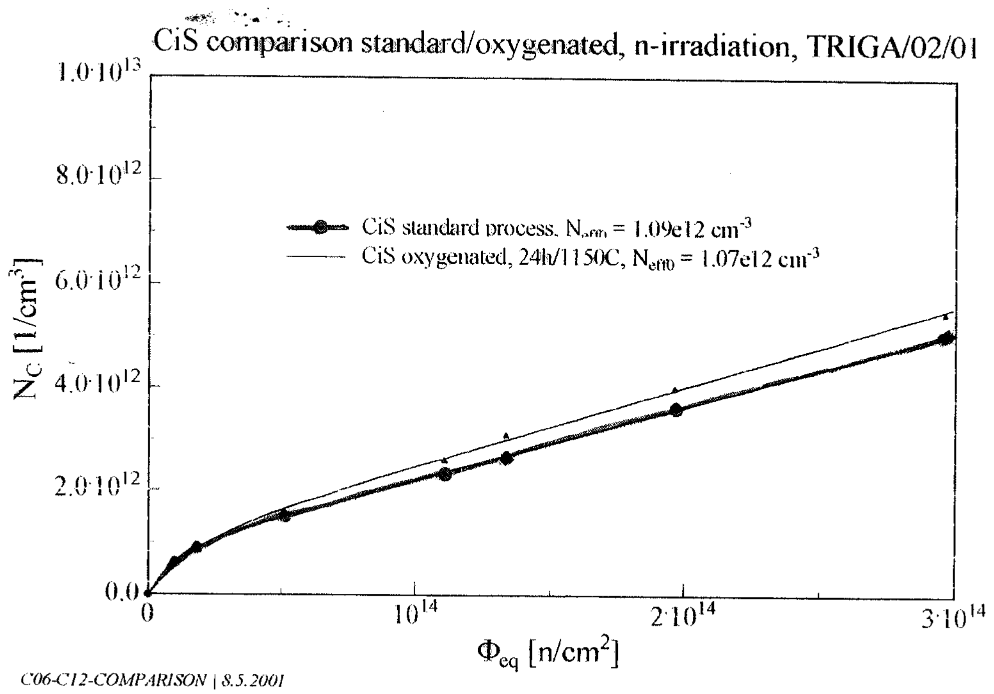
- an updated simulation oriented towards the problems we have encountered in ROSE
- very detailed / lengthy discussion of defect formation in Si, both standard and oxy
- reasonable reference to previous work (but ...)
- some conclusions of the paper need however MORE ANALYSIS and if tabulations were available, an extensive comparison with experimental data and previous damage function tabulation would be welcome!

2. very preliminary data from experiment →

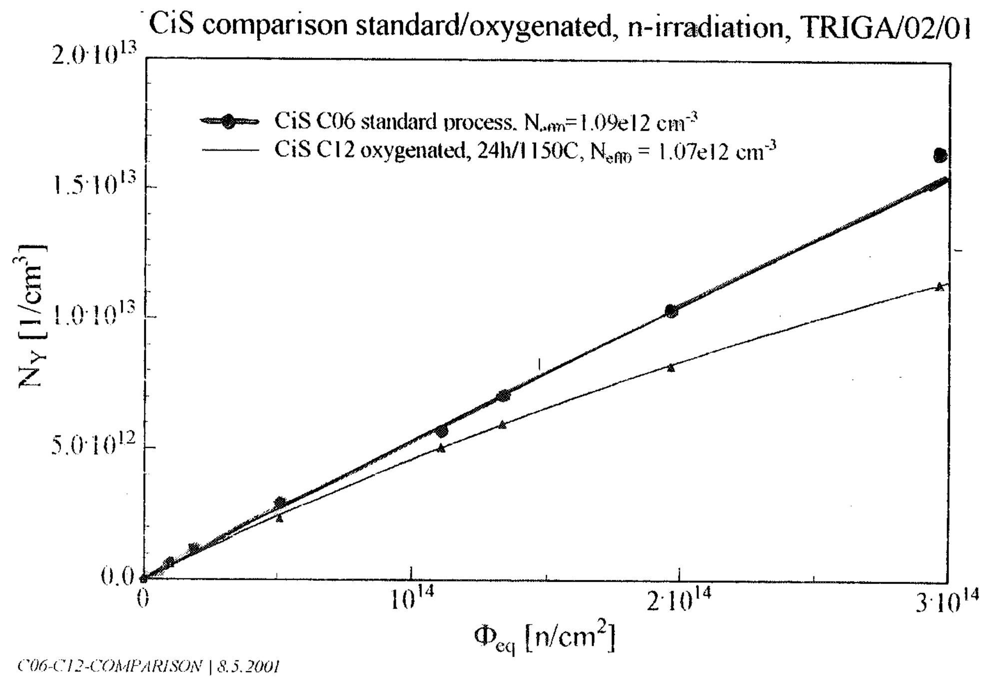
similar behaviour for standard and oxy ?? in neutron irradiation

N_c scaling

For N_C : practically NO difference between standard and oxy material



Oxy material is also good for neutron irradiation but the improvement is smaller!!



VERY PRELIMINARY !

(preliminary, courtesy of G. Lindstroem)