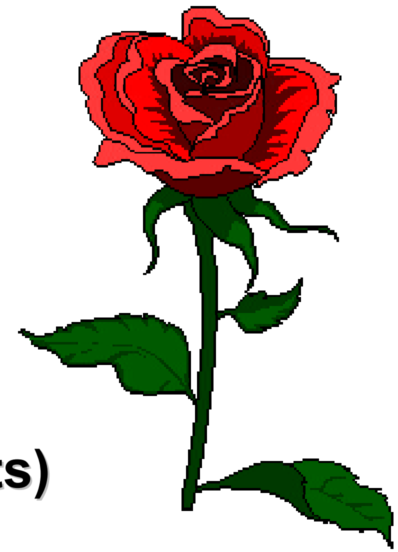
5th ROSE Workshop - CERN 16/17 March 2000

Summary of the 3rd ROSE STATUS REPORT

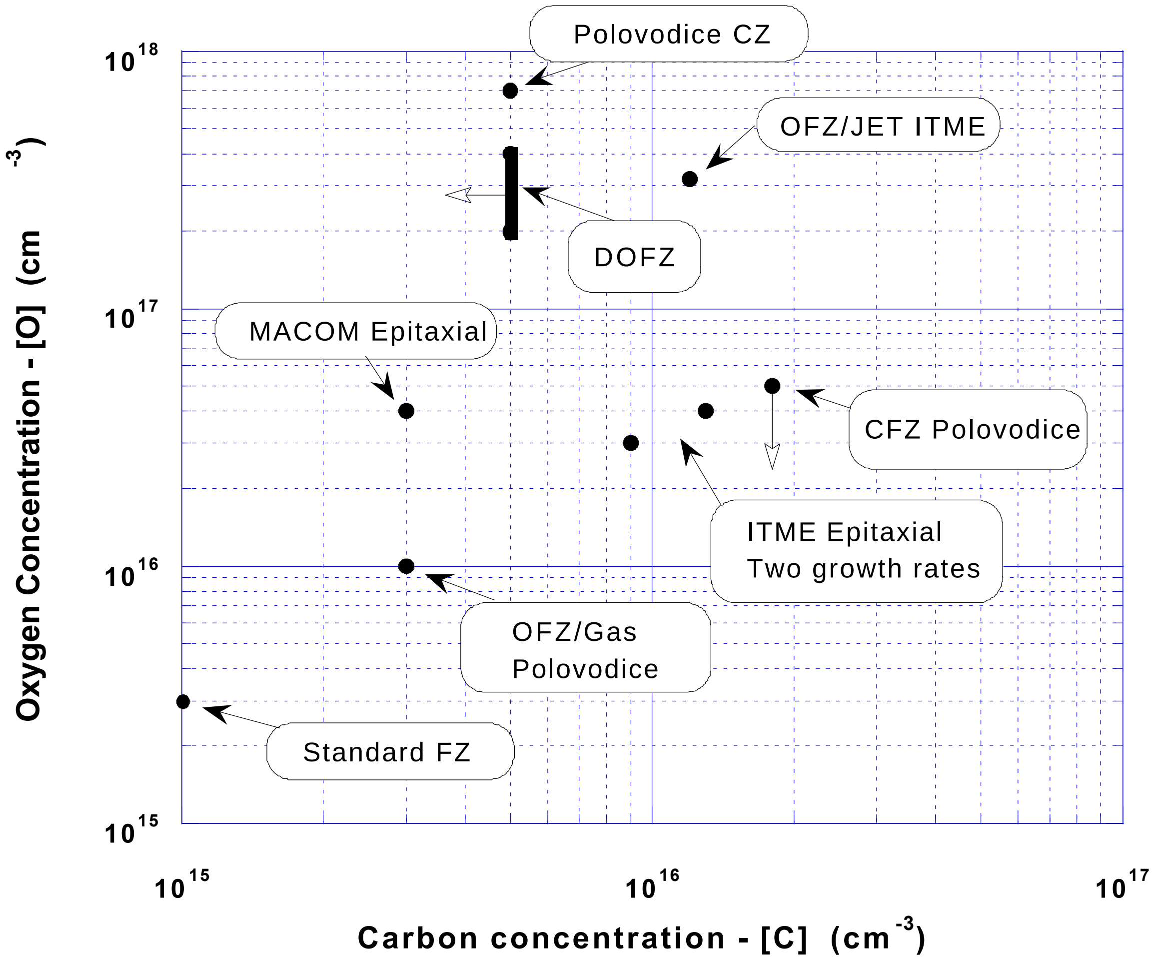
- Presented to the LEB on 13th January 2000 -



Michael Moll

The ROSE Collaboration RD48
(R&d On Silicon for future Experiments)

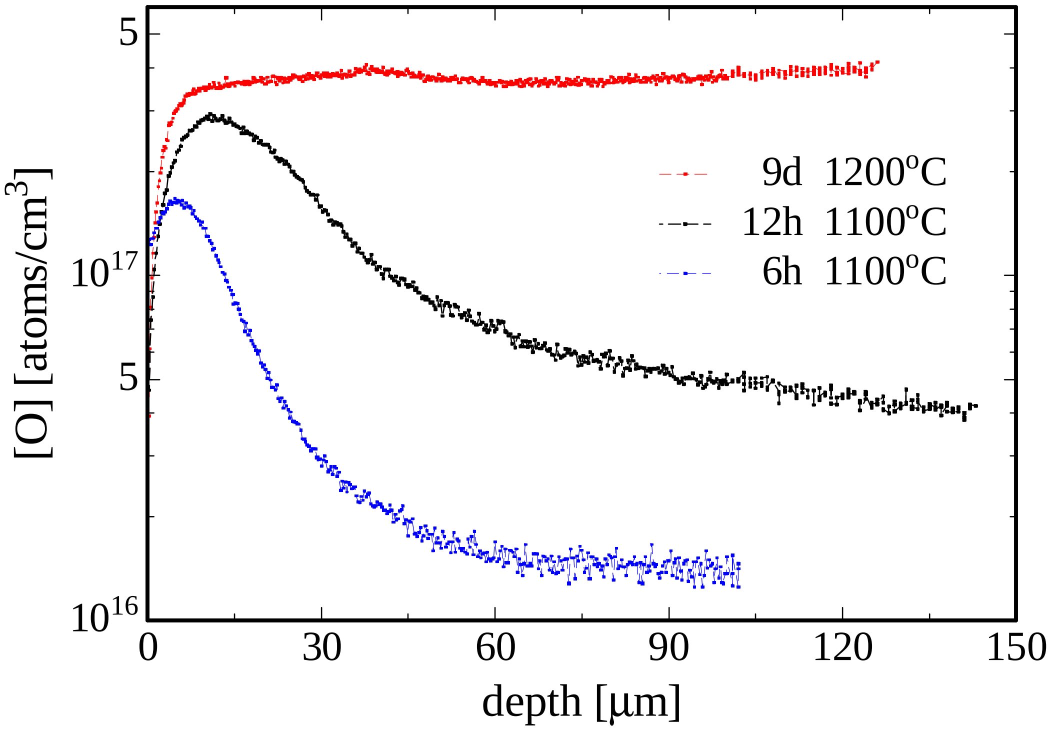
Oxygen and Carbon
- the key ingredients -



- **DOFZ Diffusion oxygenated Float Zone**

  Controlled introduction of oxygen, easily included in manufacturing process, low cost

Oxygen diffusion

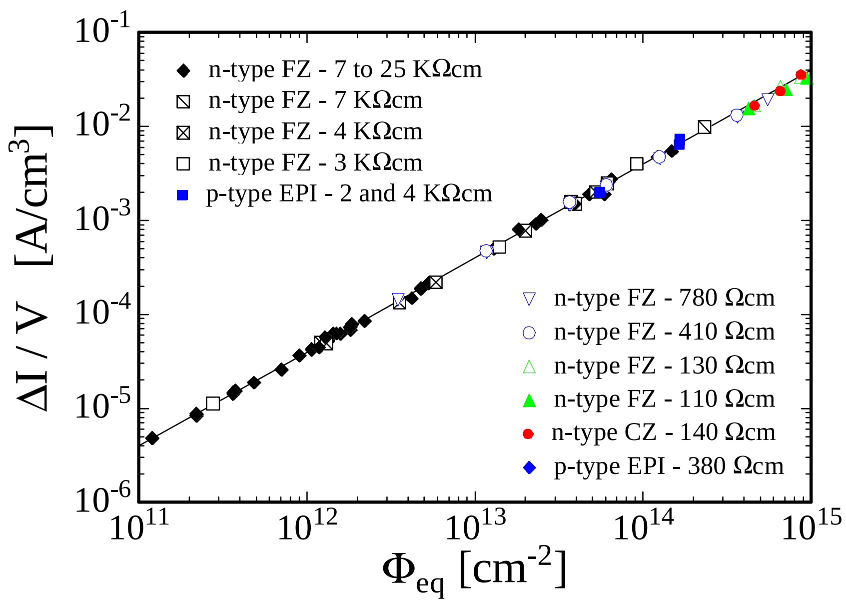


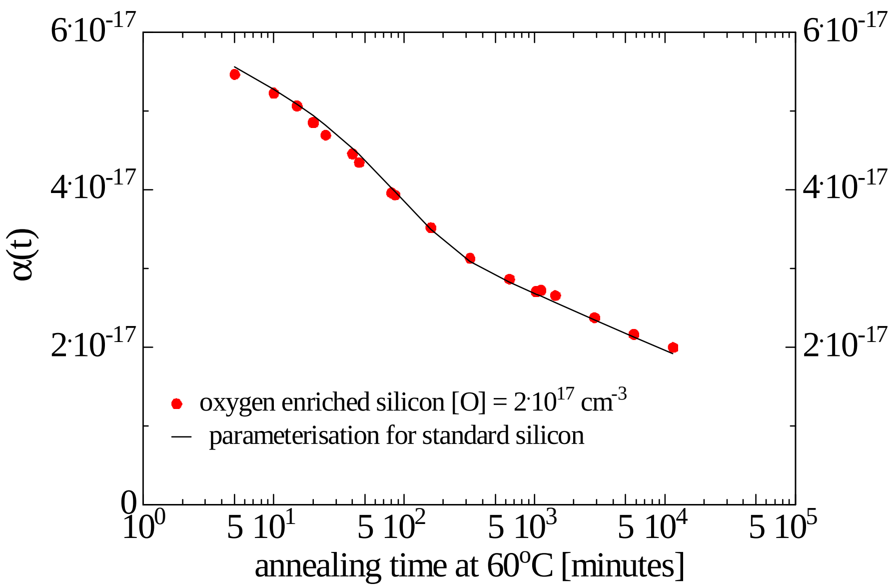
- **DOFZ   Diffusion oxygenated Float Zone**

Open question:
Diffusion time/oxygen concentration needed to get the beneficial effect?

For the moment:
16 h diffusion at 1150°C   ([O] = 1.5×10^{17} cm^{-3}) seems to be sufficient.

Leakage Current Annealing



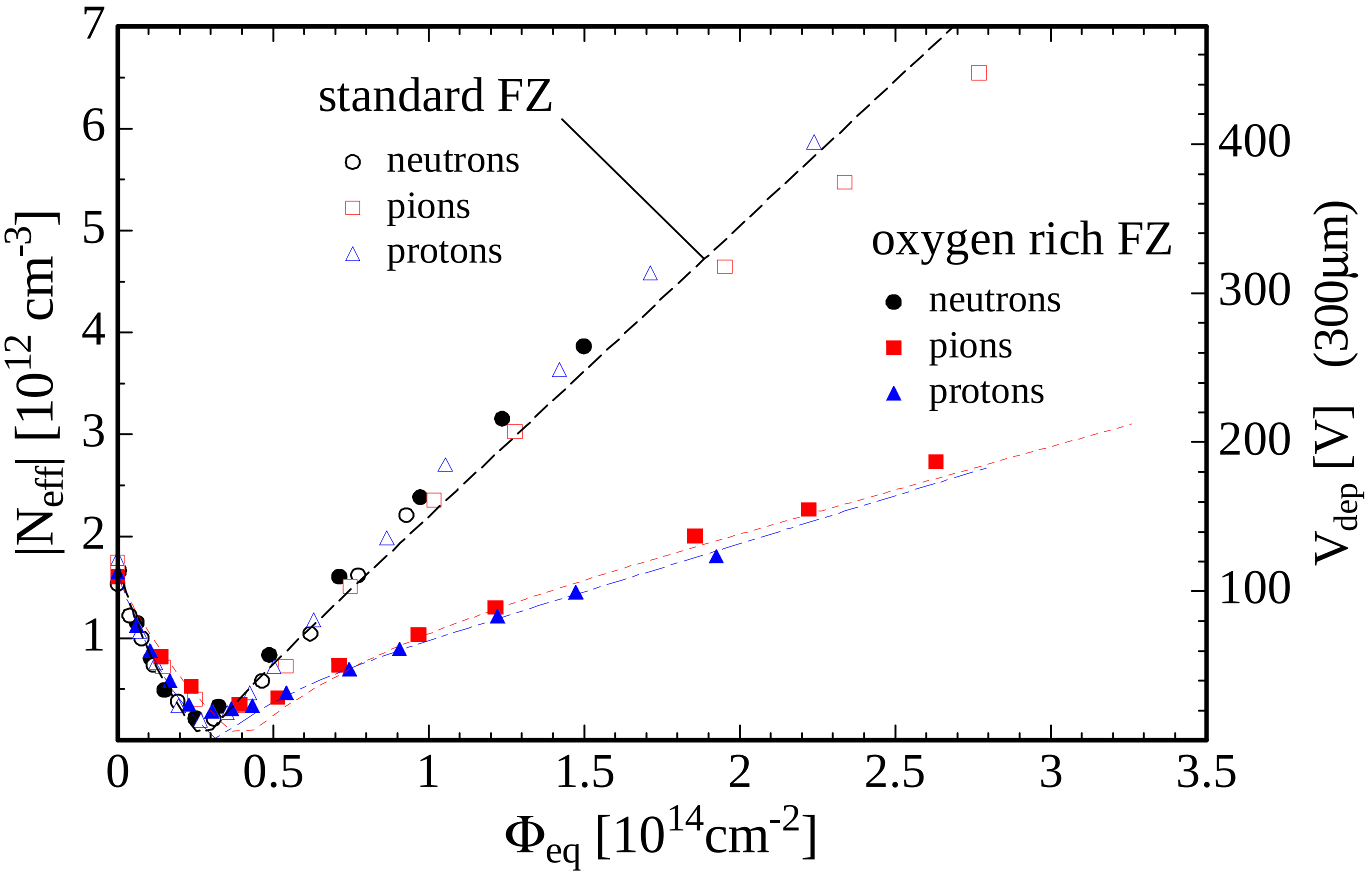


- **Oxygenated and Standard Silicon show same annealing**
- **Damage parameter α :** $a = \frac{\Delta I}{V \cdot \Phi_{eq}}$ **independent of Φ_{eq}**

used for fluence (NIEL) calibration

Oxygen and standard silicon
- Particle dependence -

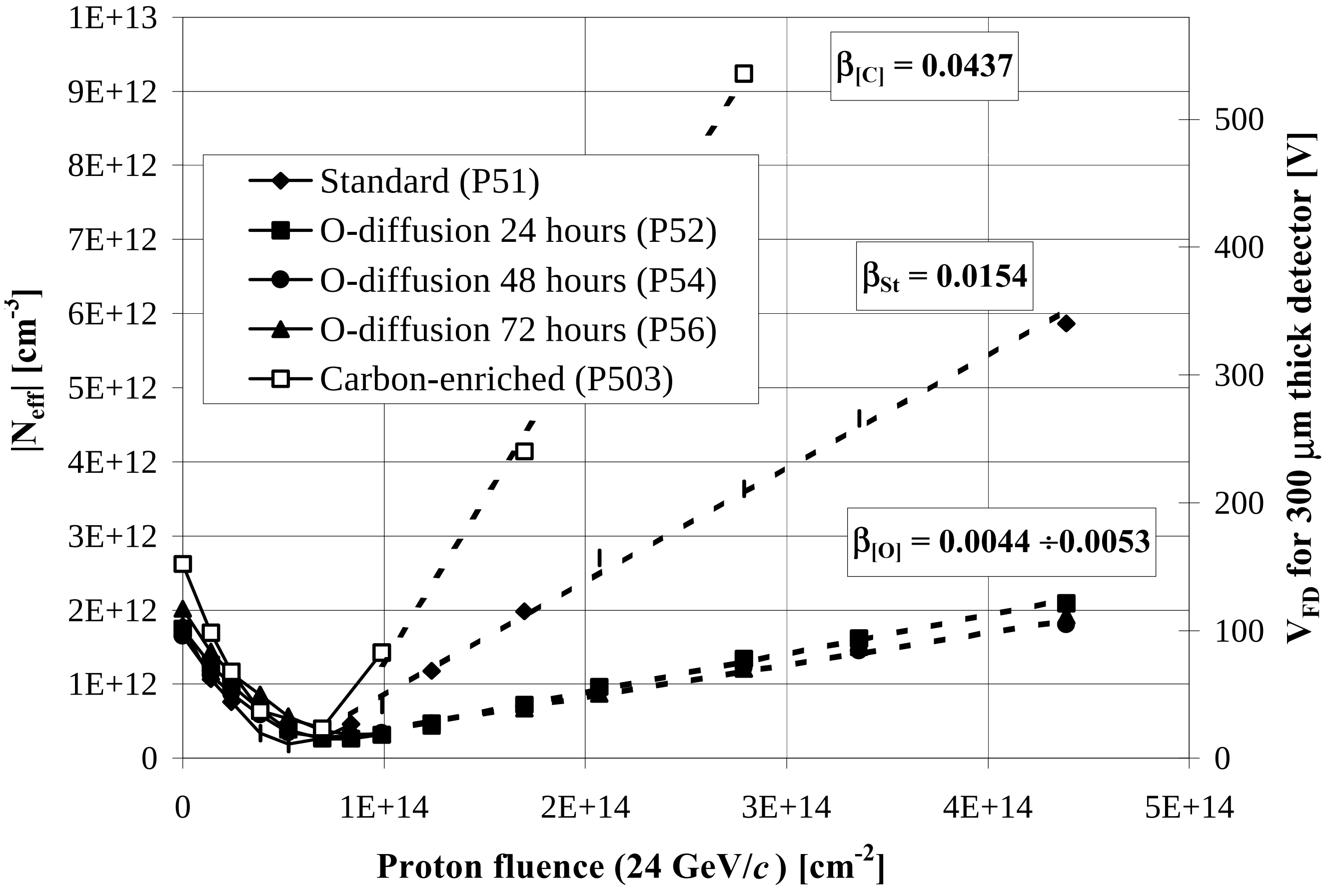
24 GeV/c protons - 192 MeV pions - reactor neutrons



- Strong improvement for pions and protons
- No improvement for neutrons

Influence of Carbon and Oxygen concentration

24 GeV/c proton irradiation

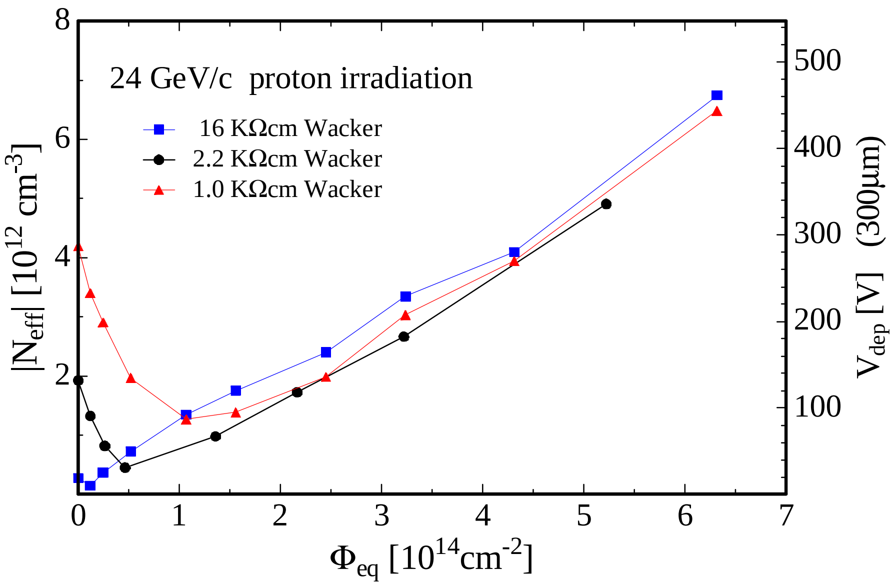


Compared to standard silicon:

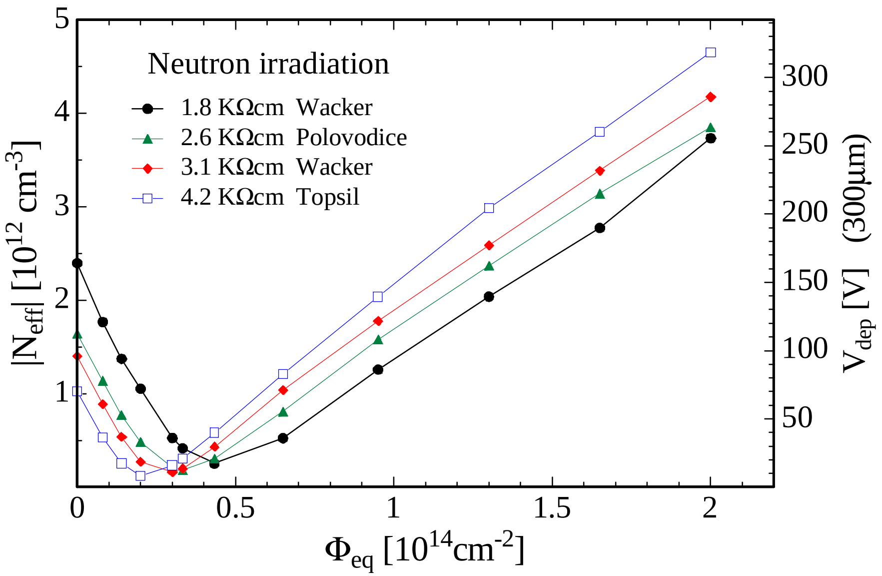
- **High Carbon ⇒ less radiation hard**
- **High Oxygen ⇒ radiation harder**

Influence of initial resistivity on Oxygen rich material

24 GeV/c proton irradiation



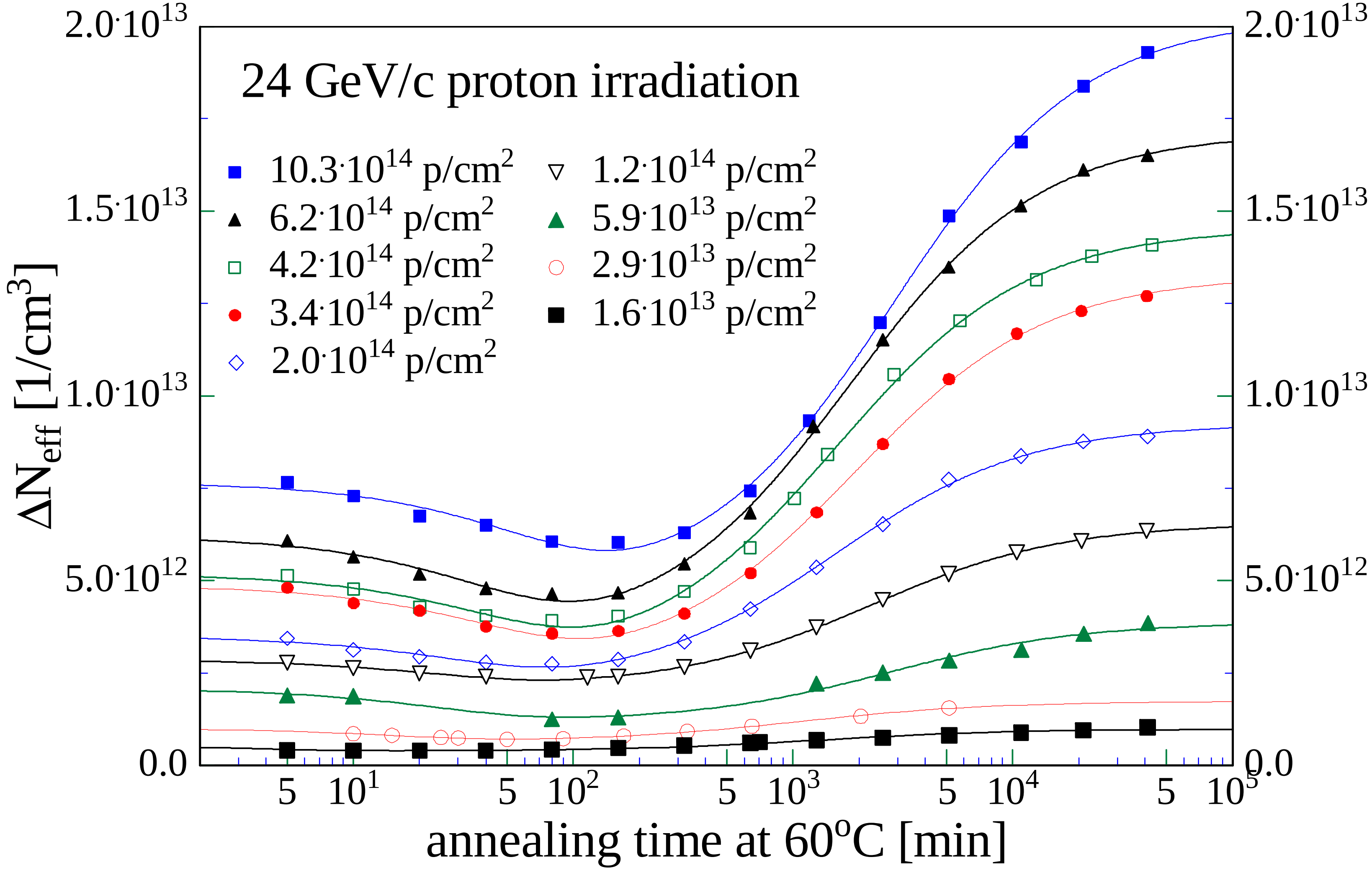
Reactor neutron irradiation



- **Measured after annealing equivalent to 10 days at room temperature**
- **Low resistivity material beneficial for neutron irradiation**

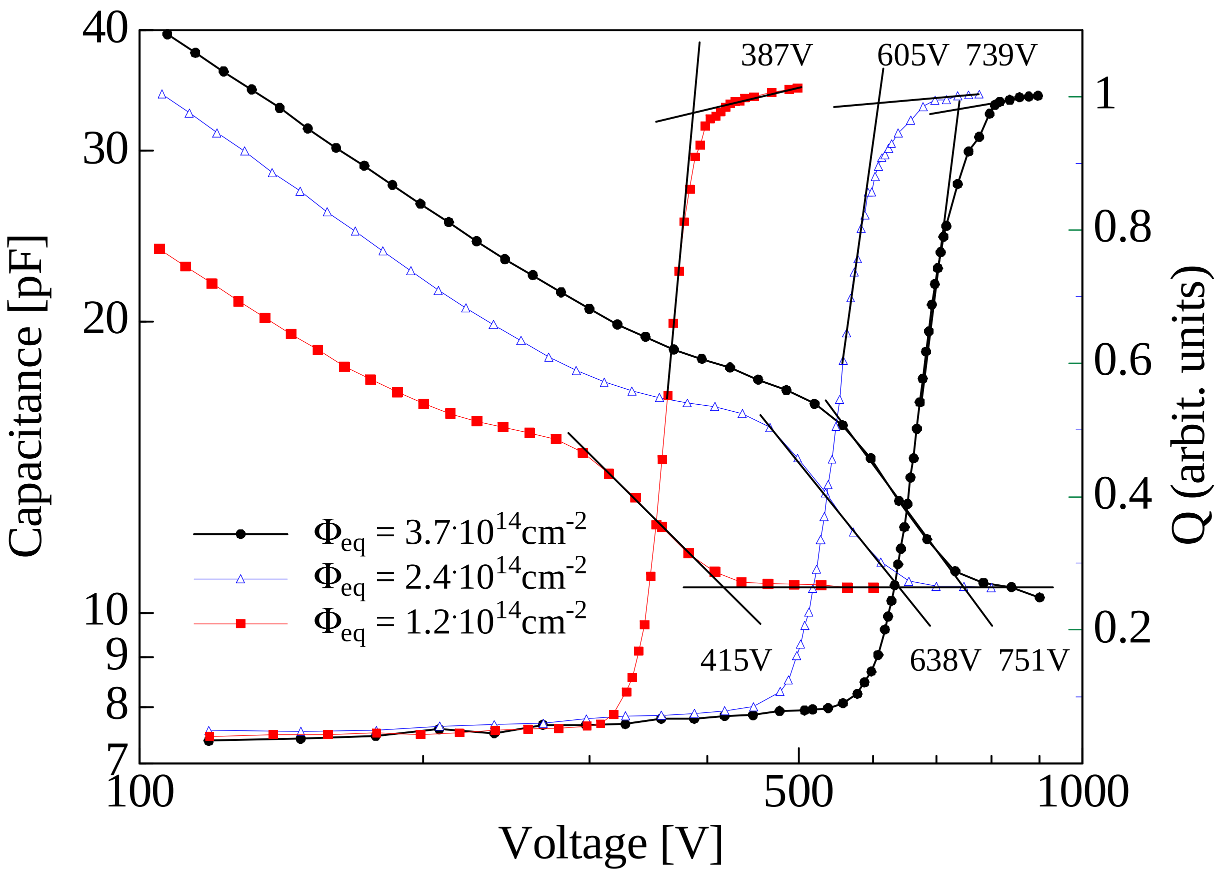
Systematic analysis of annealing data

Example: oxygen enriched silicon after proton irradiation



TCT and CV measurements

- proton irradiated oxygenated silicon -



- Measured after complete annealing
- TCT: 670nm, front illumination
- V_{dep}: Coincidence between CV and TCT

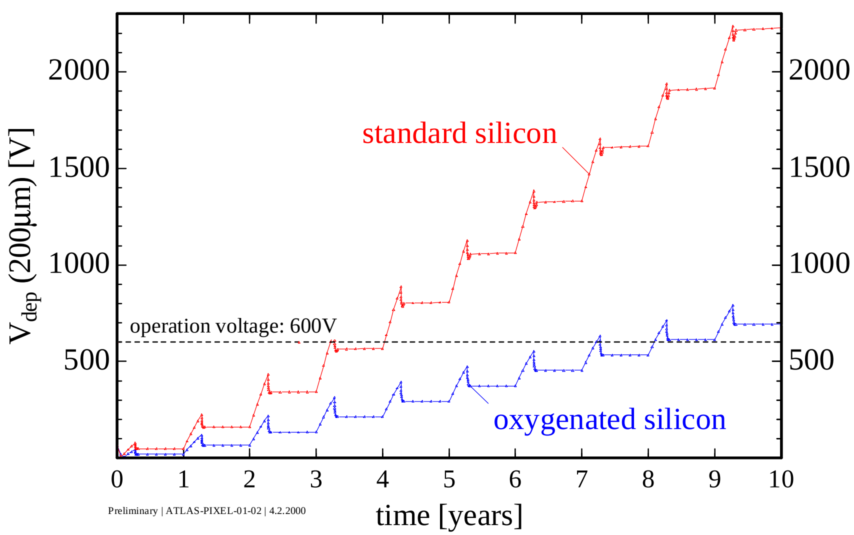
Damage Parameters for standard and oxygen-enriched silicon

	Standard Silicon		Oxygen-enriched Silicon	
	Neutrons	Protons	Neutrons	Protons
g_a	1.8×10^{-2} cm^{-1}	-	1.4×10^{-2} cm^{-1}	-
$\tau_a(20°C)$	55 h	-	70 h	-
g_C	1.5×10^{-2} cm^{-1}	1.9×10^{-2} cm^{-1}	2.0×10^{-2} cm^{-1}	5.3×10^{-3} cm^{-1}
N_{C0}/N_{eff0}	0.70	-	0.45	1.0
g_Y	5.2×10^{-2} cm^{-1}	6.6×10^{-2} cm^{-1}	4.8×10^{-2} cm^{-1}	2.3×10^{-2} cm^{-1} (♣)
$\tau_Y(20°C)$	480 d	-	800 d	950 d

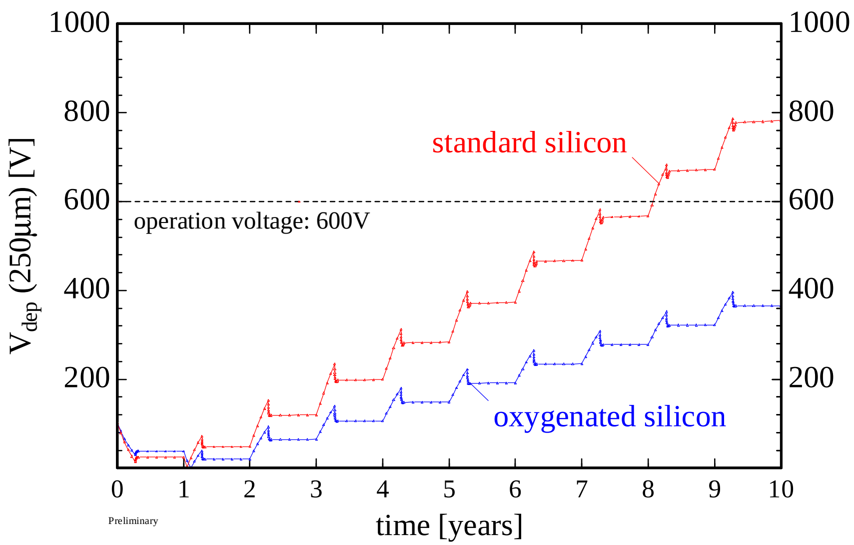
(♣) saturation value measured for $\Phi_{eq} = 6\ 10^{14}$cm^{-2}

⇒ Simulation of LHC scenarios; Example: ATLAS Pixel layers

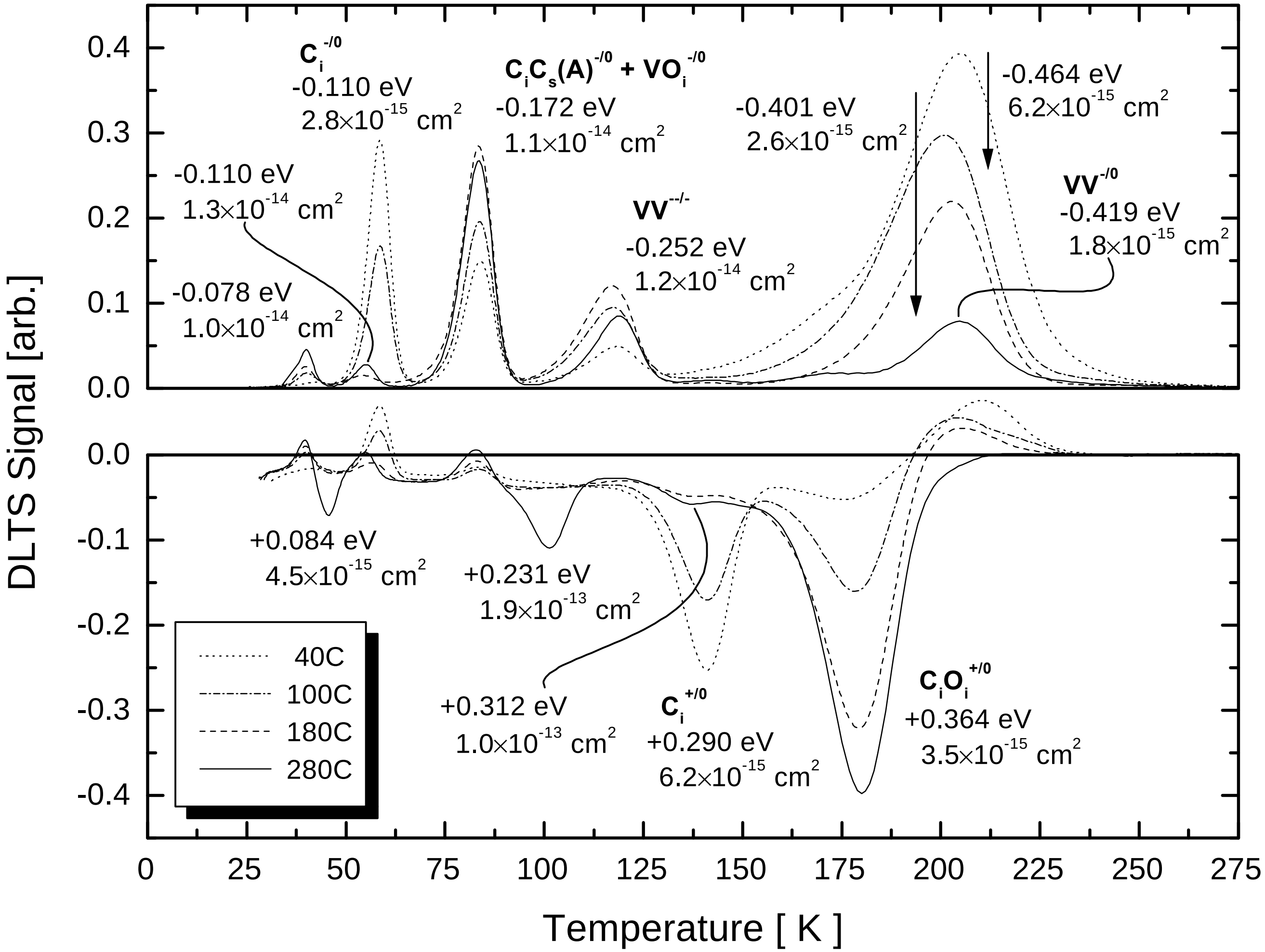
B-Layer (4cm)



1st Layer (10cm)



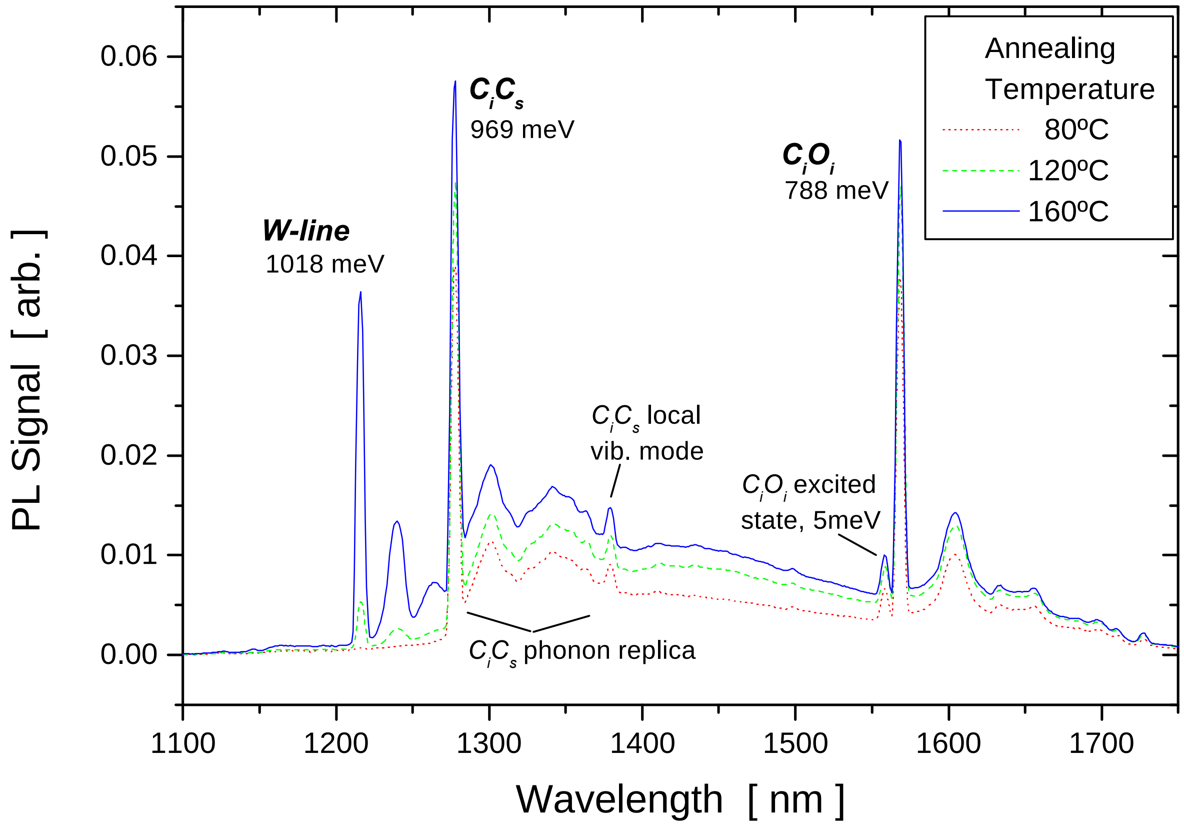
Example of defect spectroscopy
- DLTS, isochronal annealing -



Measurement of defect parameters:

defect concentrations, energy levels, cross sections, annealing behaviour

Example of defect spectroscopy
- Photo Luminescence, isochronal annealing -

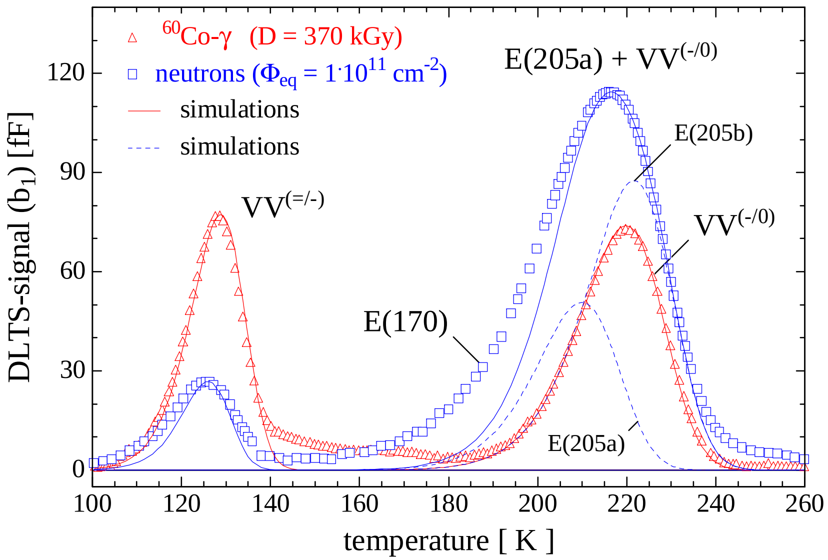


55 MeV proton irradiated standard silicon (5×10^{13} p/cm^2)

W-line (1018 meV) related to reverse annealing

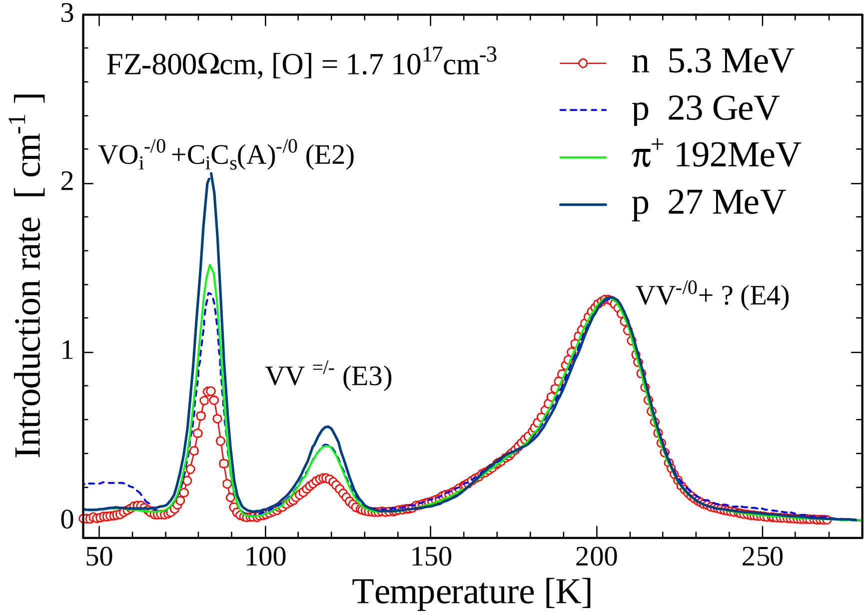
Gamma-irradiation ⇔ Neutron-irradiation

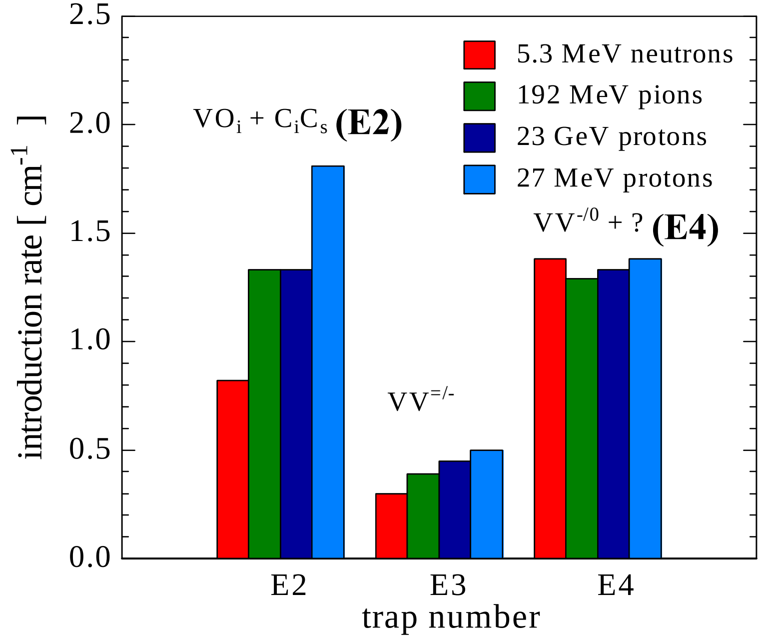
only point defects ⇔ cluster and point defects



ratios of introduction rates	gamma irrad.	neutron irrad.	interpretation
$\frac{[CO]}{[CC]}$	3.2	2.8	C_i migration not influenced by type of irradiation
$\frac{[VO]}{[CC]+[CO]}$	0.9	0.5	**n-irrad.**: more V than I are captured in primary damage region
$\frac{[VO]+2\times[VV]}{[CC]+[CO]}$	1.0	(1.7)	**γ-irrad.**: ratio of vacancy related to interstitial related defects is 1:1
$\frac{[VV^{(-/0)}]}{[VV^{(--/-)}]}$	1.0	3.3	**n-irrad**: VV are mostly localized in clusters (lattice strain)

DEPENDENCE ON PARTICLE TYPE
- Introduction of Microscopic Defects -



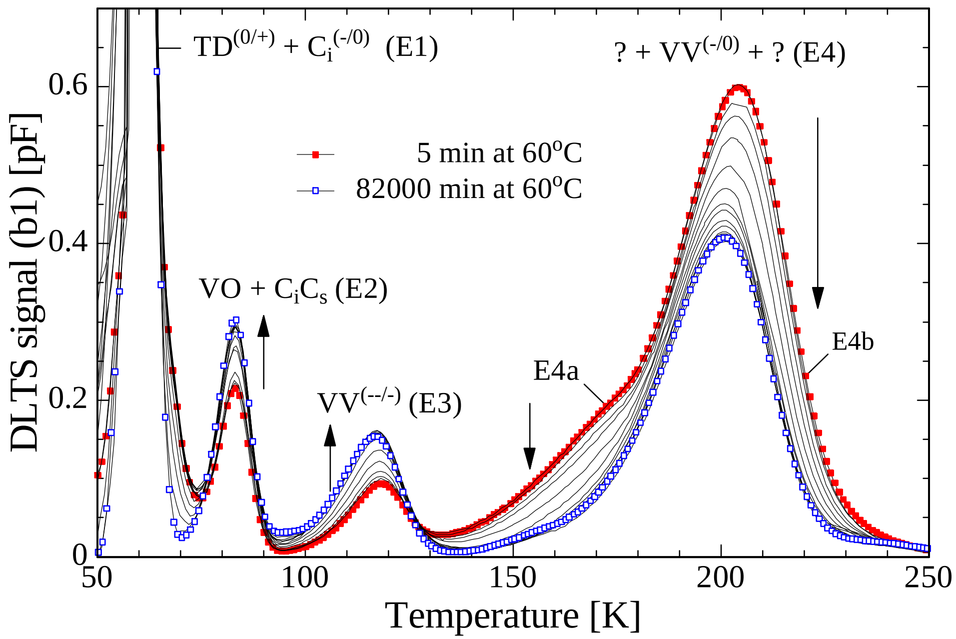


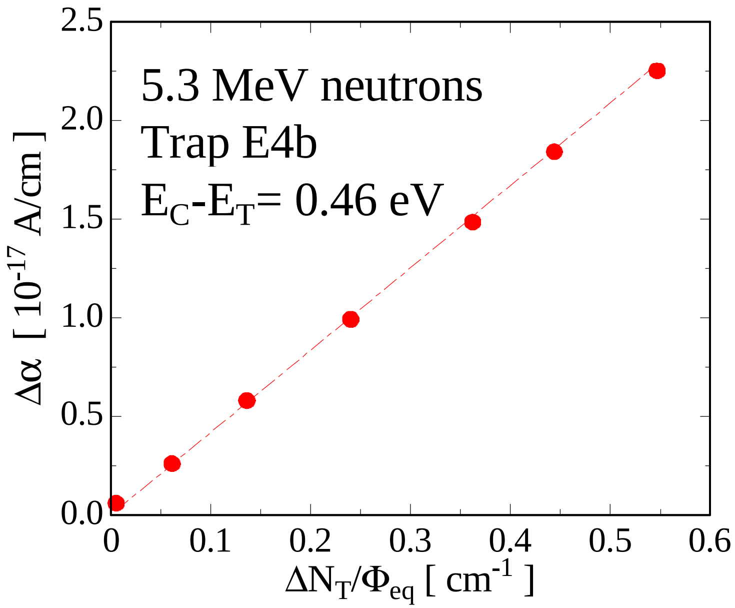
- **DLTS spectra measured after irradiation with different particles**

- **ratio of rates g(E2)/g(E4):**
  neutrons: 0.59
  192 MeV pions: 1.03
  23 GeV protons: 1.00
  27 MeV protons: 1.31

- **charged hadrons produce more point defects than reactor neutrons**
- **27 MeV protons produce more point defects than 23 GeV protons**

Current annealing ⇔ Electron trap at E_C-0.46 eV

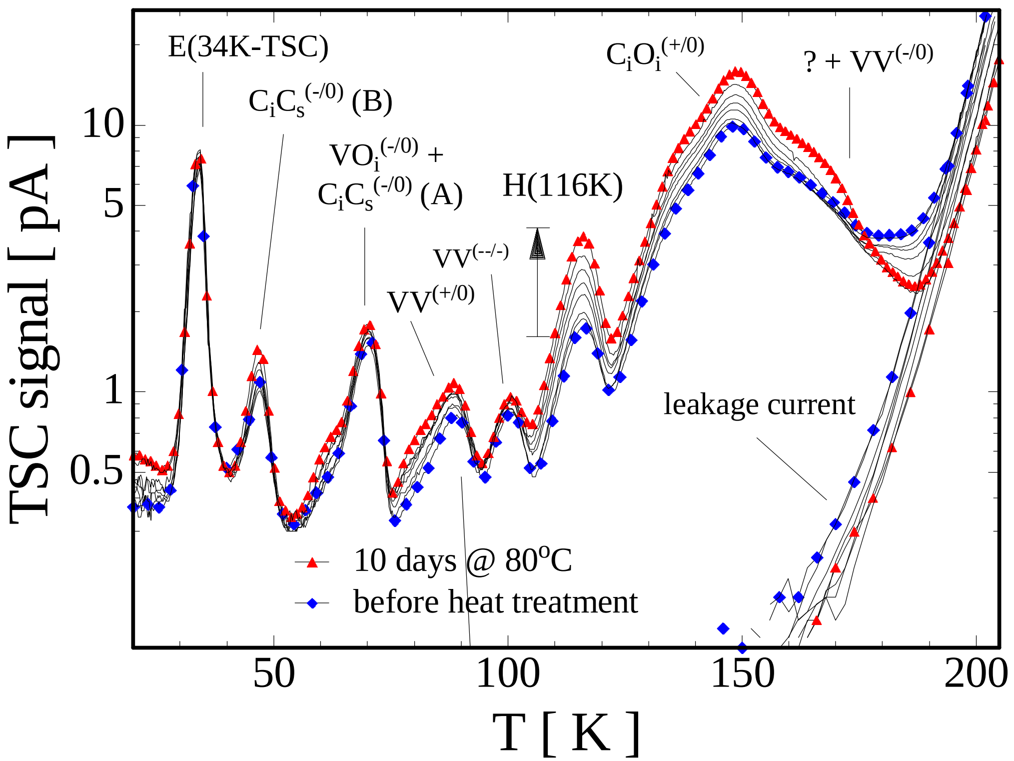


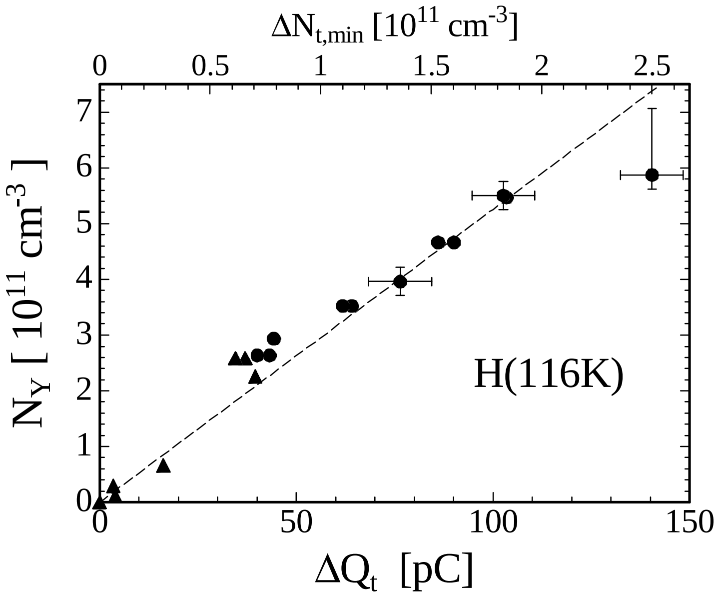


- **Parallel measurement: DLTS (defect parameters) and I/V (current)**
- **Defect level E(210) produces leakage current (generation center)**
- **Level parameters:** E_C-0.46eV and $\sigma_n = 8.6\times10^{-16}cm^2$
  $\sigma_p = 3.1\times10^{-13}cm^2$

Reverse Annealing ⇔ Hole trap at E_V+0.29 eV

- **Parallel measurement: TSC (defect parameters) and C/V (N_{eff})**

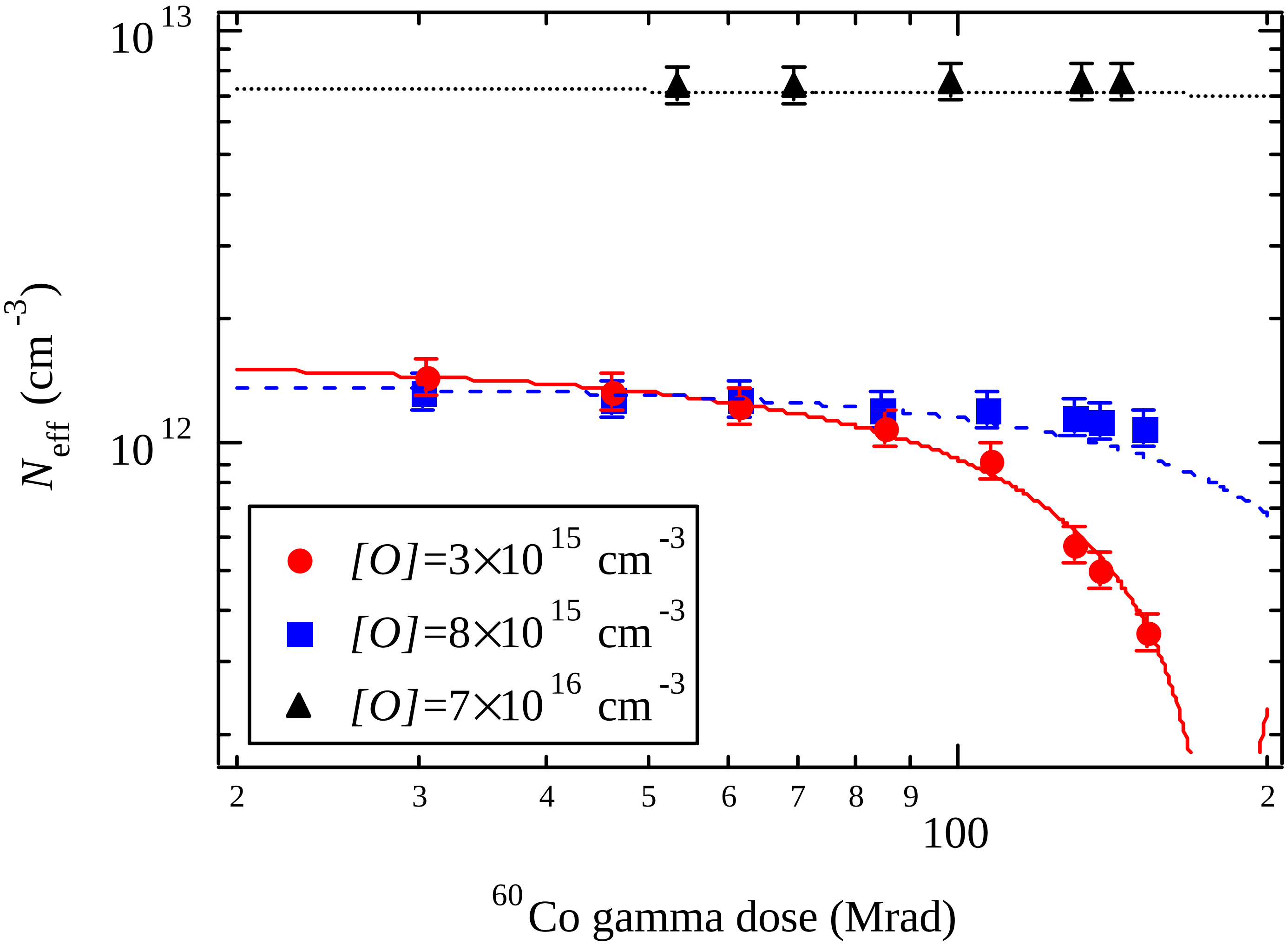




- **Reverse annealing is related to hole trap H(116K)**

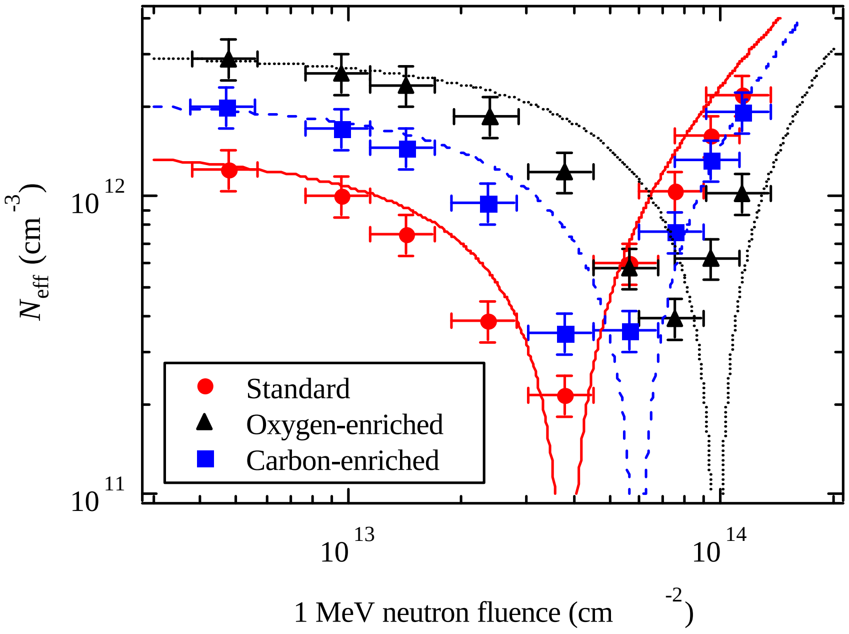
- **Level parameters:** E_V+0.285eV and $\sigma_p = 4\times10^{-15}$cm^2

^{60}Co gamma irradiation
Model predictions and experimental data

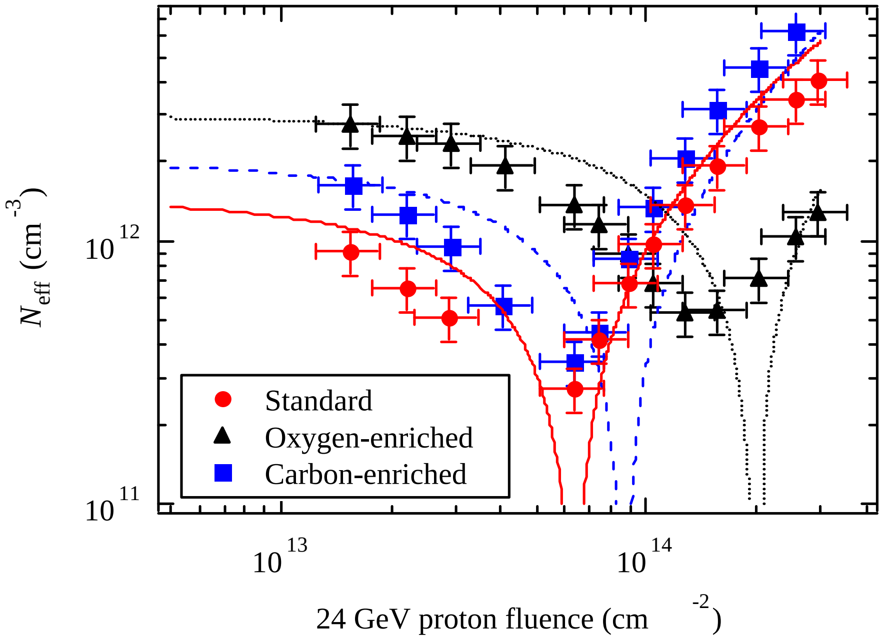


Neutron and proton irradiation
Model predictions and experimental data

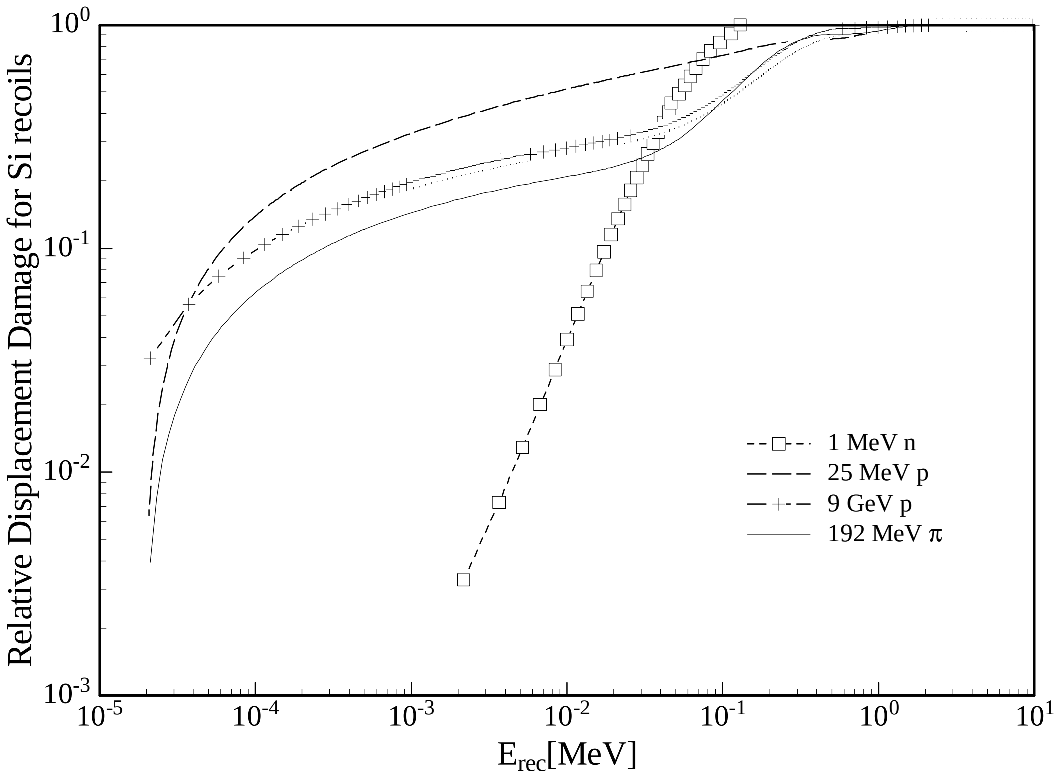
1 MeV neutron irradiation



24 GeV/c proton irradiation



Damage efficiency for different particles as function of Si-recoil energy (elastic scattering only)



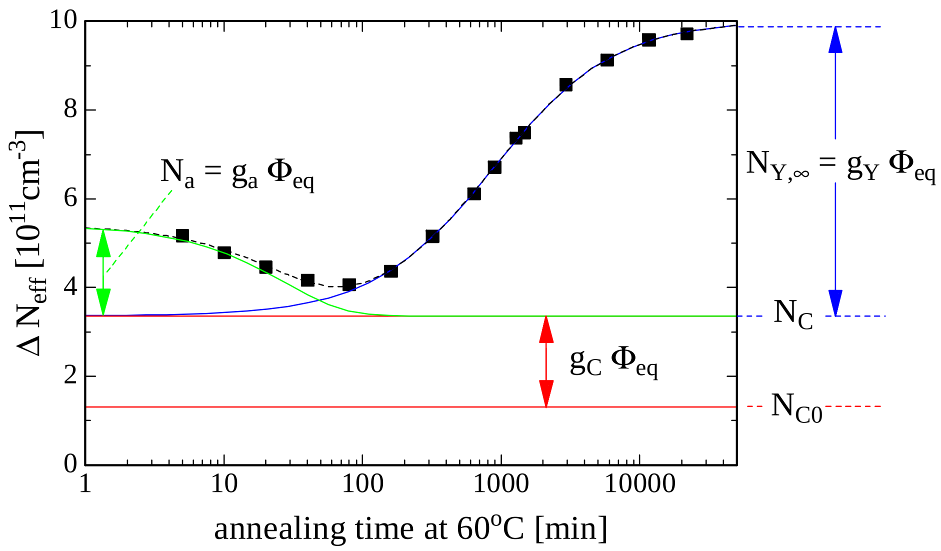
Relative damage produced by Si recoils with energies < 5 keV
(5 keV assumed to be threshold for cluster generation)

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

Annealing behaviour: N_{eff}
- Hamburg Model -

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

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



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

short term annealing:

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

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

stable damage:

$$N_C = N_{C0} \cdot \left(1 - \exp\left(-c \cdot \Phi_{eq}\right)\right) + g_C \cdot \Phi_{eq}$$

incomplete „donor removal“
\+ introduction of stable acceptors

long term reverse annealing:

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

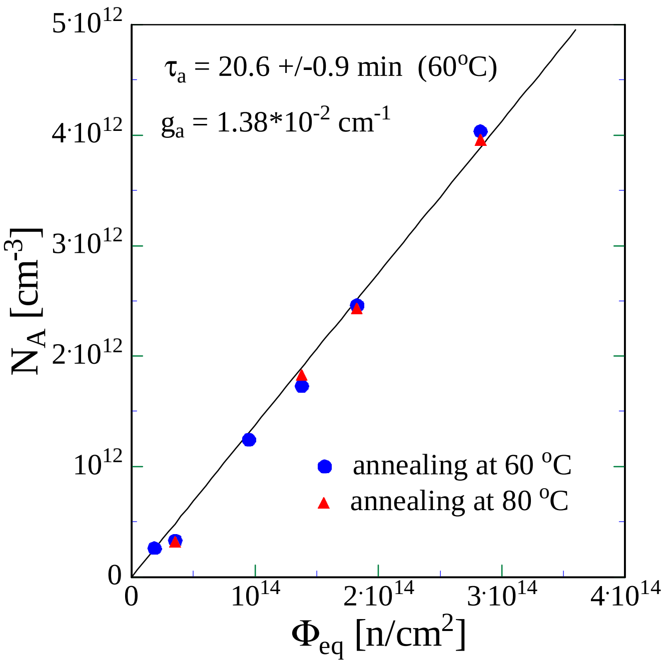
second order parameterization (with $N_{y,\infty} = g_y \times \Phi_{eq}$).gives best fit

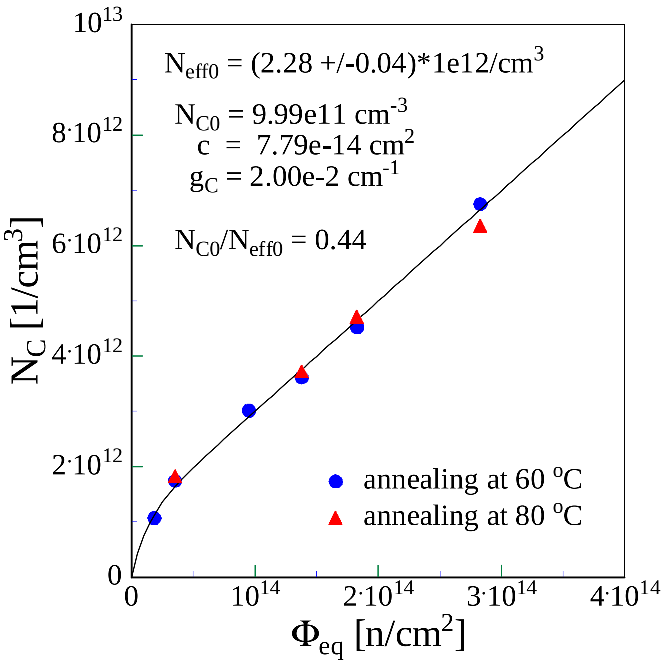
But:

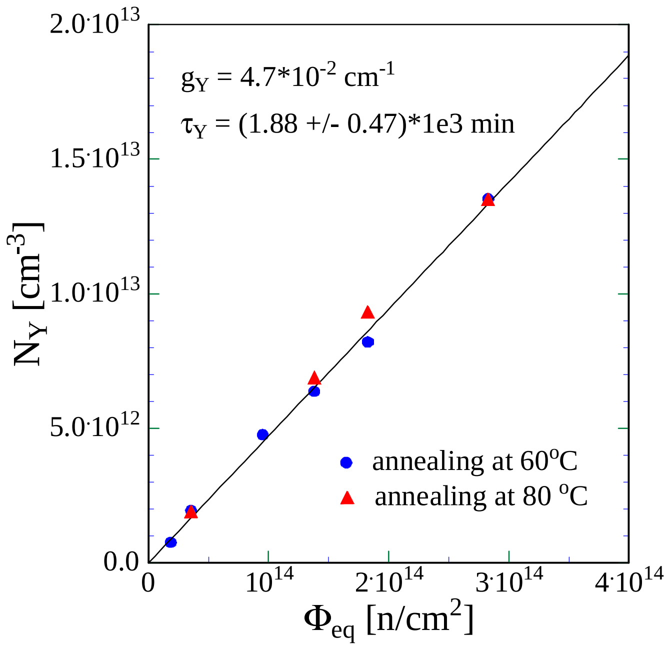
τ_y independent of Φ_{eq}

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

Extraction of damage parameters for neutron irradiated O-rich diodes

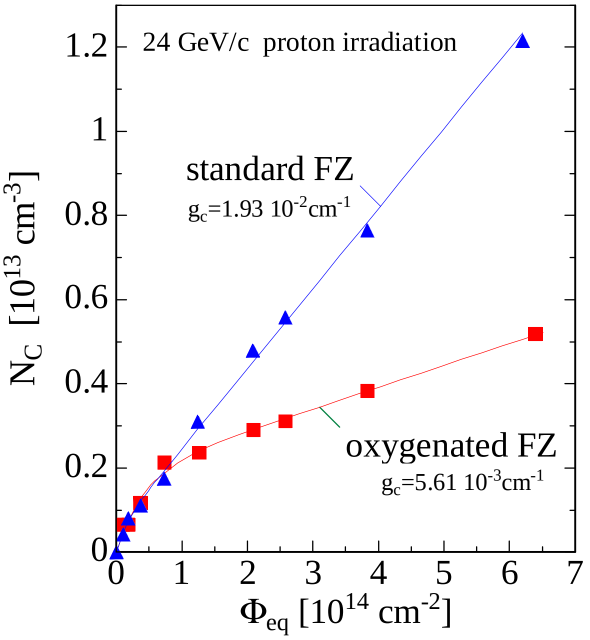


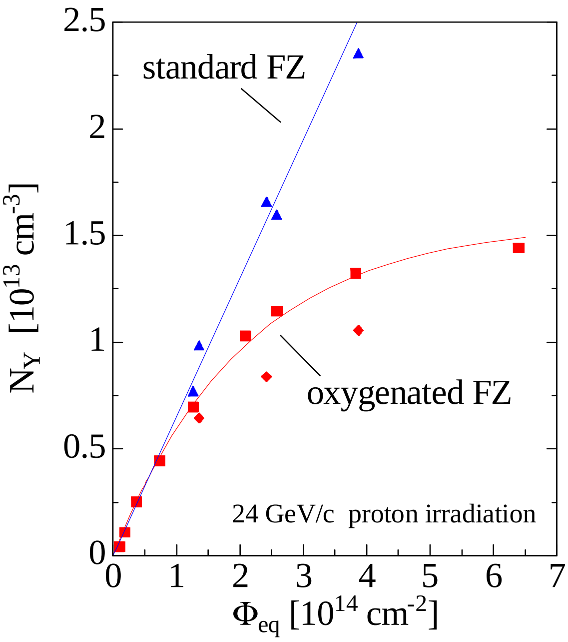


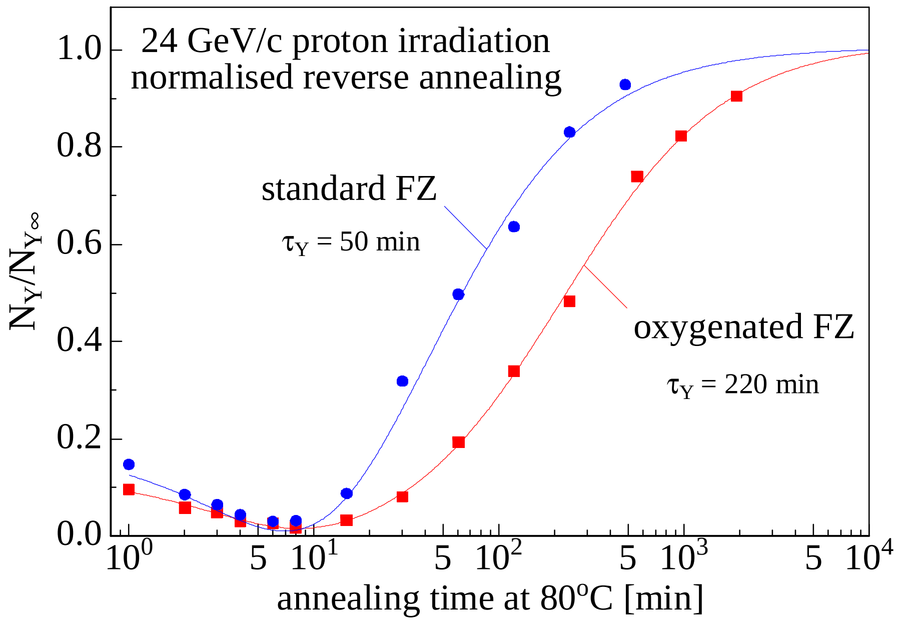


- **Extracted parameters independent of annealing temperature (60°C, 80°C)**

Extraction of damage parameters for proton irradiated diodes





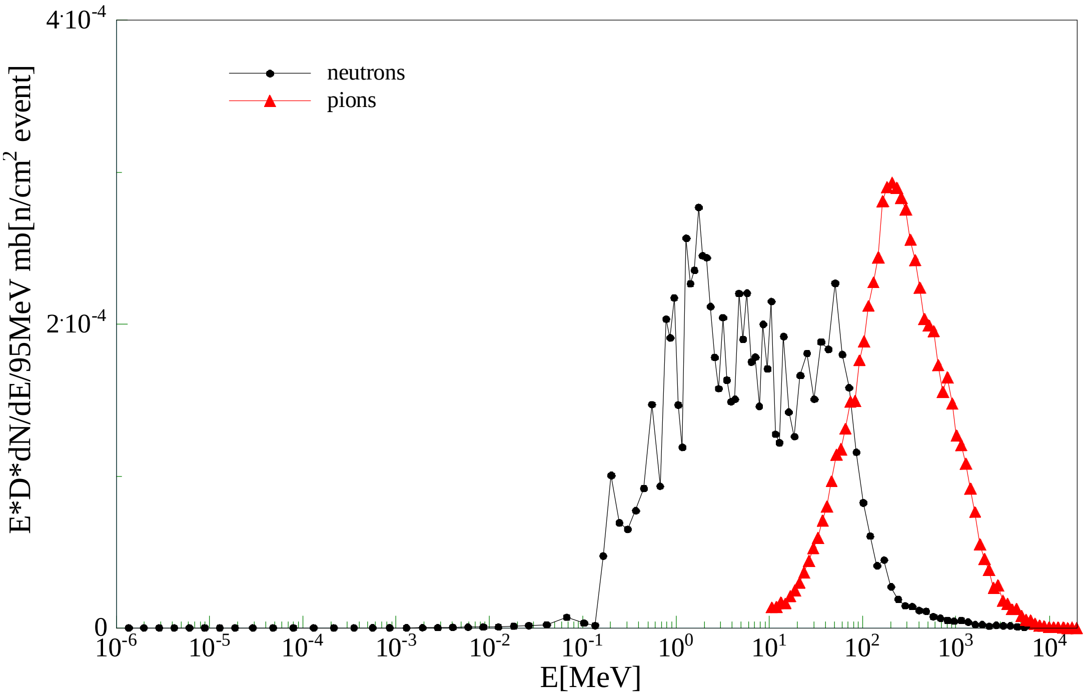


Oxygen enriched silicon:

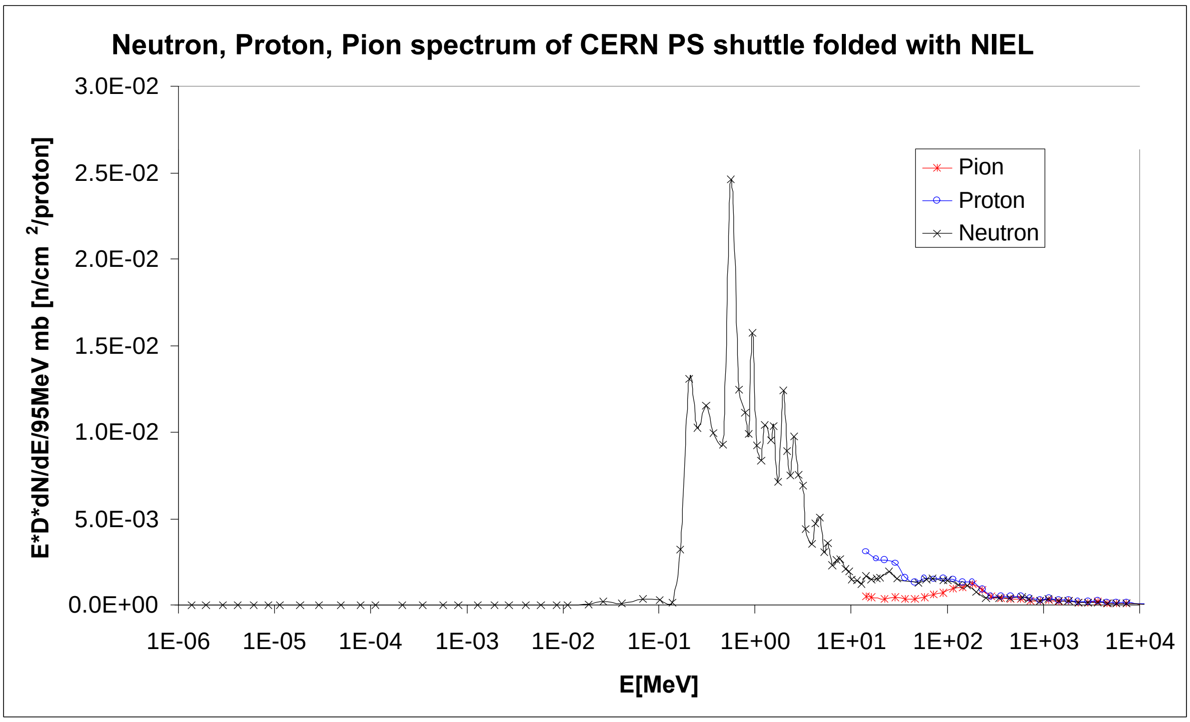
- g_c improved by a factor of 3
- saturation of reverse annealing
- delayed reverse annealing

Energy Spectra folded with NIEL

- ATLAS-SCT

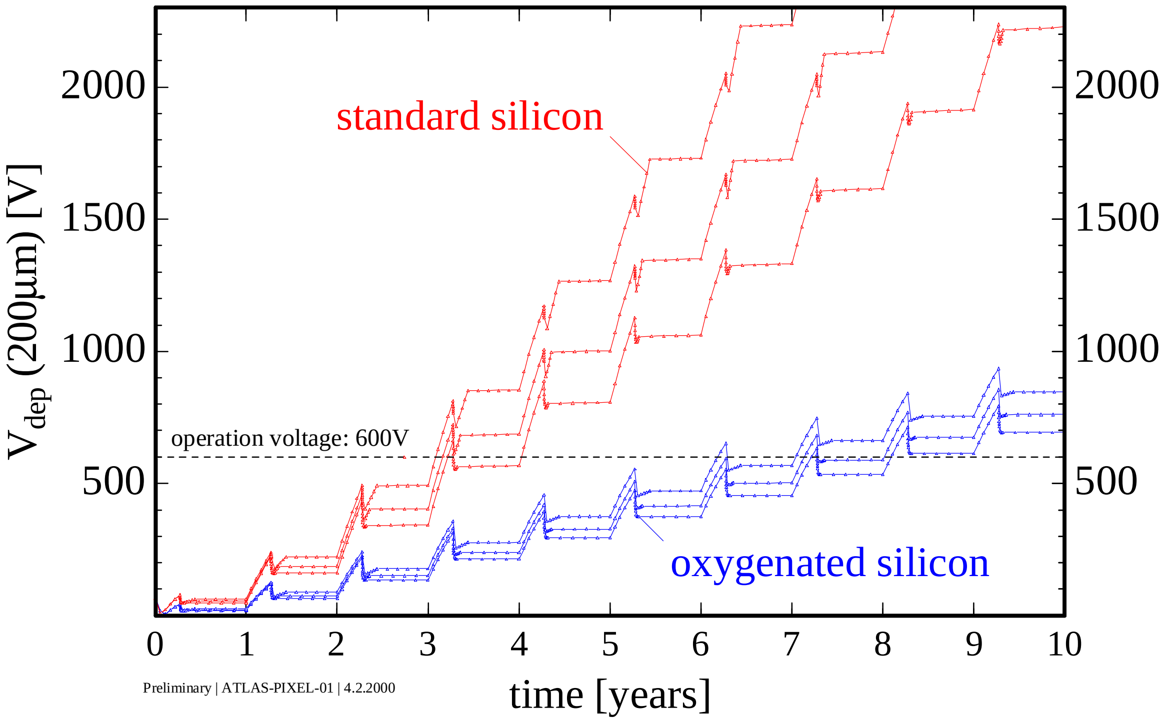


- Neutron Irradiation facility in PS Eeast Hall (IRRAD2)



Damage Projection ATLAS Pixel Detector B-Layer

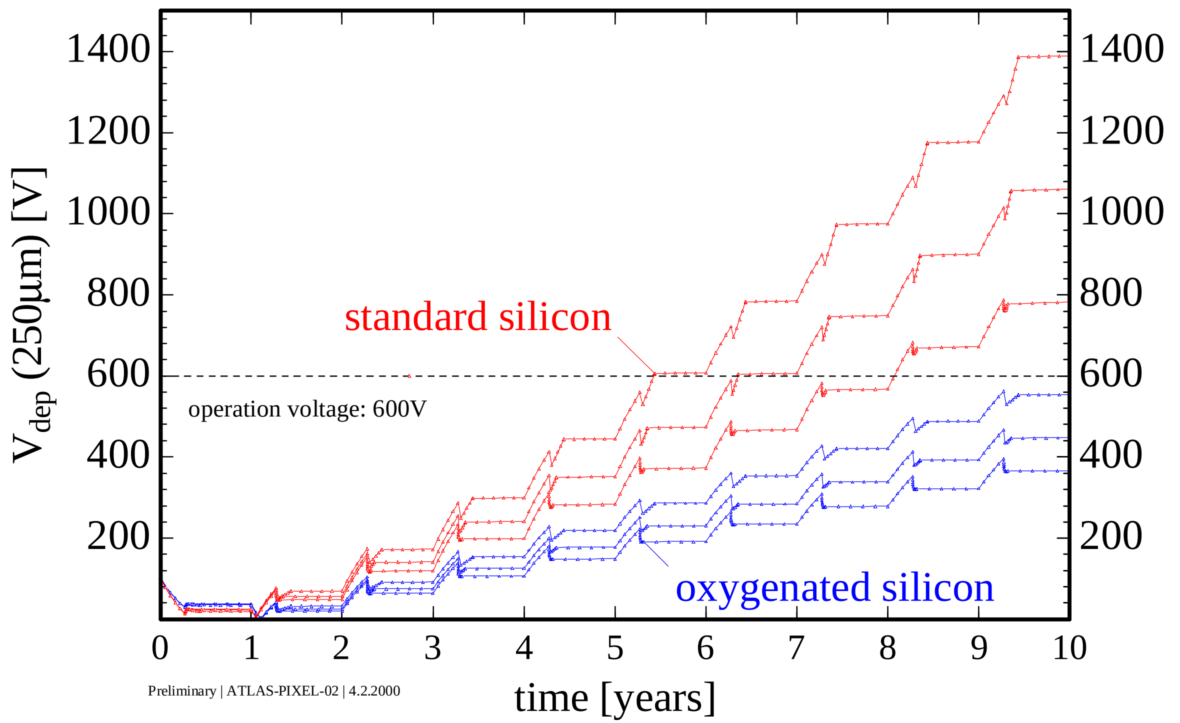
- **Radiation level for B-Layer :** $\Phi_{eq}(year) = 3.5 \times 10^{14}$ cm^{-2} (full luminosity)
  > 85% charged hadrons
- **Three scenarios :** 1 year = 100 days beam (-7°C)
  - (1) 3 days 20°C and 14 days 17°C
  - (2) 30 days 20°C
  - (3) 60 days 20°C
  - Rest of the year: no beam (-7°C)



Damage Projection ATLAS Pixel Detector 1^{st}-Layer

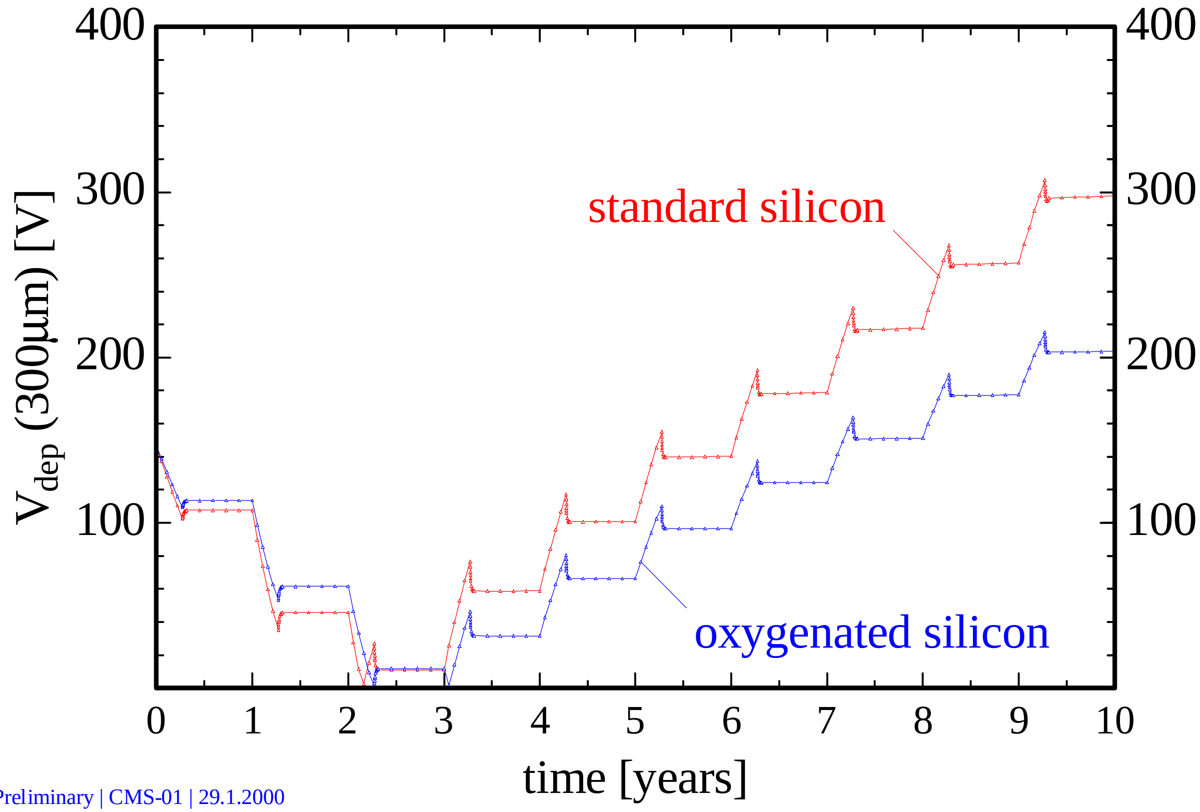
- **Radiation level for 1^{st}-Layer :** Φ_{eq}(10 years) = 6.6×10^{14} cm^{-2}
  ≈ 70% charged hadrons
- **Three scenarios :** 1 year = 100 days beam (-7°C)
  - (1) 3 days 20°C and 14 days 17°C
  - (2) 30 days 20°C
  - (3) 60 days 20°C

  Rest of the year: no beam (-7°C)



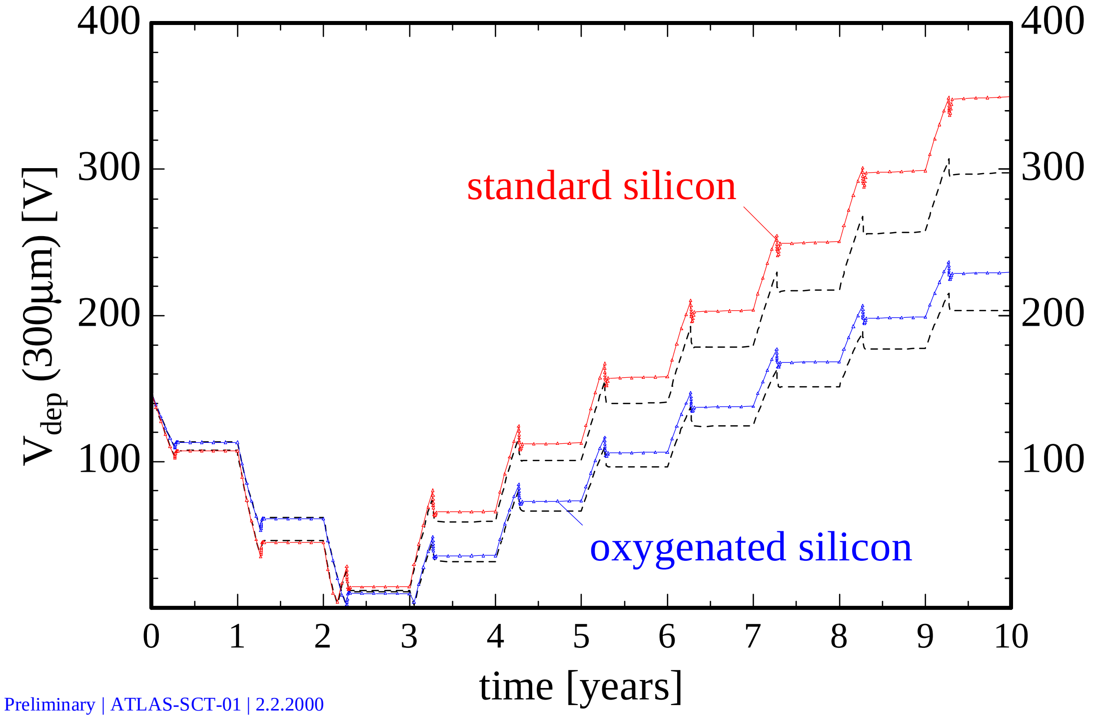
Damage Projection   Strip Detector   30cm

- **Radiation level :** $\Phi_{eq}(10\text{years}) = 2 \times 10^{14}\ \text{cm}^{-2}$
  $\approx$ 50% charged hadrons
- **Scenario:** 1 year = 100 days beam (-7°C)
  2 days 20°C
  14 days 14°C
  249 days no beam (-7°C)

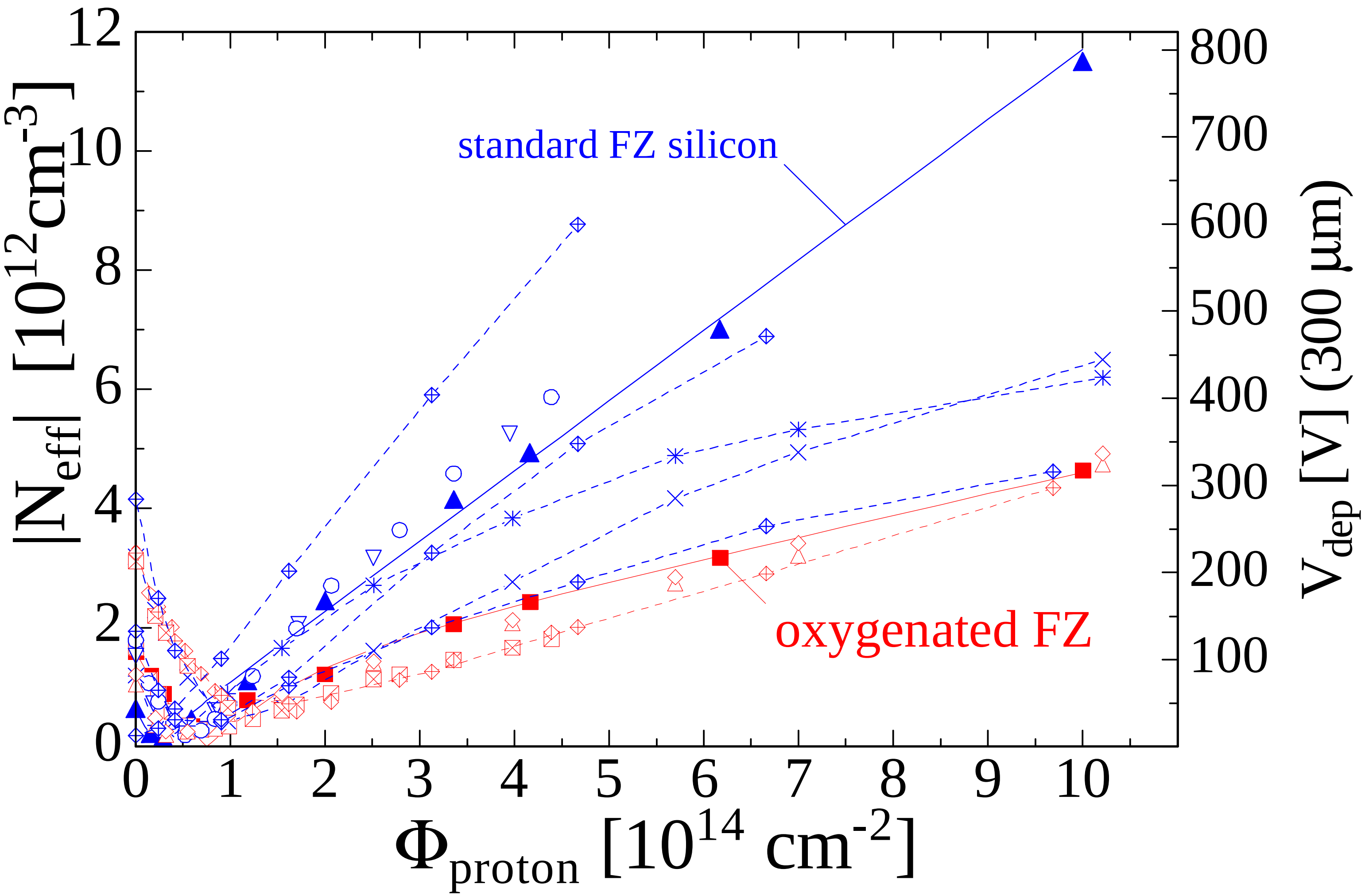


Damage Projection   Strip Detector   30cm

- **Radiation level :** $\Phi_{eq}(10\text{years}) = 2 \times 10^{14}\ cm^{-2}$
  ≈ 50% charged hadrons
- **Scenario:** 1 year = 100 days beam (-7°C)
  14 days 20°C
  251 days no beam (-7°C)



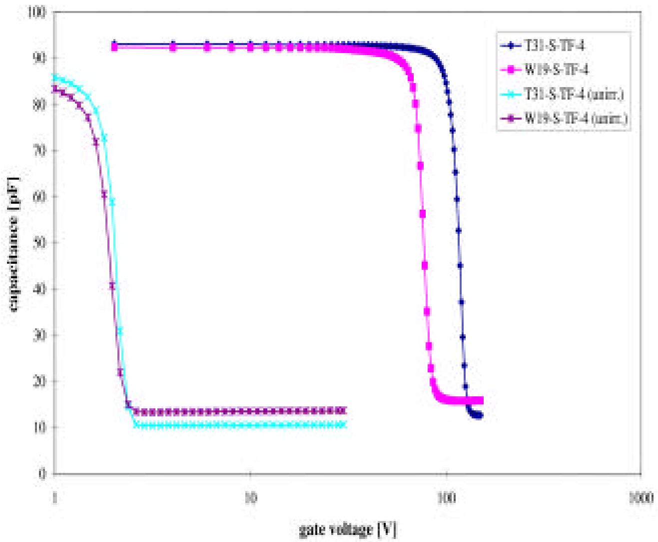
Variation of standard material



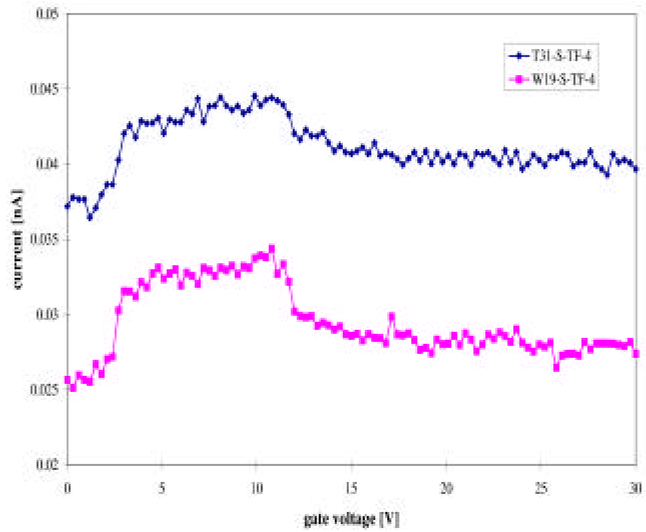
- **Strong variation of standard silicon**
- **Reproducible results for oxygenated silicon**

Effects at the Si/SiO_2 Interface

Gate-controlled diodes



Shift in flatband voltage
Oxide charge density



Interface generation current

Device	N_{ox} [10^{11}/cm^2]	D_{it} [10^{10}/cm^{2}eV]	Dose [kGy]
W19-S-TF-4 (oxy)	0.6	0.7	0
T31-S-TF-4 (std)	0.6	0.7	0
W19-S-TF-4 (oxy)	21	30	200
T31-S-TF-4 (std)	35	30	200

Summary: Key scientific results

◆ Macroscopic Damage Effects

Leakage current damage parameter is material independent (no impurity, resistivity or conduction type dependence)

Effective doping changes can be improved by oxygenation of the material (factor 3 for stable damage parameter gc). Such improvement is only observed when the radiation environment contains a significant charged particle component.

Lower resistivity oxygenated material is beneficial for detectors that operate in a radiation environment dominated by reactor energy neutrons.

Reverse annealing is found to saturate at high fluences (2×10^{14} p/cm^2) for oxygen enriched silicon. Time constant for the process is found to be by a factor of 2-4 larger allowing detectors to remain at room temperature for longer periods during maintenance periods

◆ Damage at the Microscopic Level

Reverse annealing and leakage current are linked to defect clusters

Several correlations between microscopic defects and macroscopic parameters found

Charged particle irradiation produces more point defects than irradiation with reactor energy neutrons

Defect kinetics models and device models can predict macroscopic behavior

Summary: Key technological results

- **Oxygen Enrichment**

  Two methods were found to highly oxygenate silicon. Firstly, at the ingot growing stage. Secondly by diffusion of oxygen into ANY wafer using a high temperature drive in (a minimum of 16 hours at 1150°C seems to be sufficient).

  Technology has been successfully transferred to several silicon detector manufacturers (SINTEF, Micron, ST, CIS) and full-scale microstrip detectors produced.

- **Oxygenated/Standard:**
  No differences in detector surface properties:

  Diffusion Oxygenated Float Zone wafers produce detectors which prior to irradiation are no different to those produced on standard material.

  Irradiated standard and oxygenated test structures (gate-controlled diodes) show same increase in interface generation current and oxide charges.

Open Questions   Further Work

- **Minimum diffusion time required ?**

  The minimum diffusion time required to give radiation hardening needs further study.

- **Reason for the strong variation of standard silicon ?**

  After proton irradiation a broad variation with respect to the radiation hardness of "standard silicon" has been observed while oxygenated silicon showed reproducible results.

- **Saturation of reverse annealing ?**

  The beneficial effect that oxygen has on the reverse annealing process needs more work. As this effect is crucial to the maximum maintenance period that can be used by the experiments, it needs further investigation. This work is extremely time consuming.

- **Comparison: Strip detectors vs. Simple test structures !**

  The physics of bulk damage should be the same in full-scale detectors as in simple diodes. Nevertheless, bulk damage parameters should be extracted from irradiated strip detectors and compared to the well-measured parameters obtained with diodes.

- **The proton   neutron puzzle: Violation of NIEL ?.**

  The violation of NIEL by charged hadrons in oxygenated material needs further study. Testing with radiation sources that better represent the environment in the LHC experiments needs to be performed. The neutron spectrum in the LHC experiments extends to much higher energy than for reactor sources. There are good reasons to believe that oxygenated silicon will perform better than standard material in such a neutron environment.