# Study of leakage current and effective dopant concentration in irradiated epi-Si detectors

*I. Dolenc* , *V. Cindro, G. Kramberger, I. Mandic, M. Mikuž*
*Jožef Stefan Institue, Ljubljana*

# Motivation

## Two different applications:

- 25 µm samples: ATLAS radiation monitoring ? first use of Epi-Si detectors in HEP

  Increase of the leakage current will be used to determine NIEL

  - small full depletion voltage (~20 V), almost constant during the lifetime of the experiment (bias and readout are limited to 30 V)
  - operation temperature of ~20$^{o}$C
- 50 µm, 75 µm samples: candidate material for innermost layers of tracking detectors at SLHC
  - promising results of Hamburg group should be verified at annealing temperatures close to room temperature (annealing scenario for SLHC)
  - samples were also used for signal measurements (*G. Kramberger et al.* @ RESMDD `04)

# Samples and irradiations up to $10^{16}$ cm$^{-2}$

## Samples:

Provided by Hamburg, Epi-Si, ITME grown epi layer (50 Ωcm) on Cz substrate, diode processed by CiS

## Irradiations

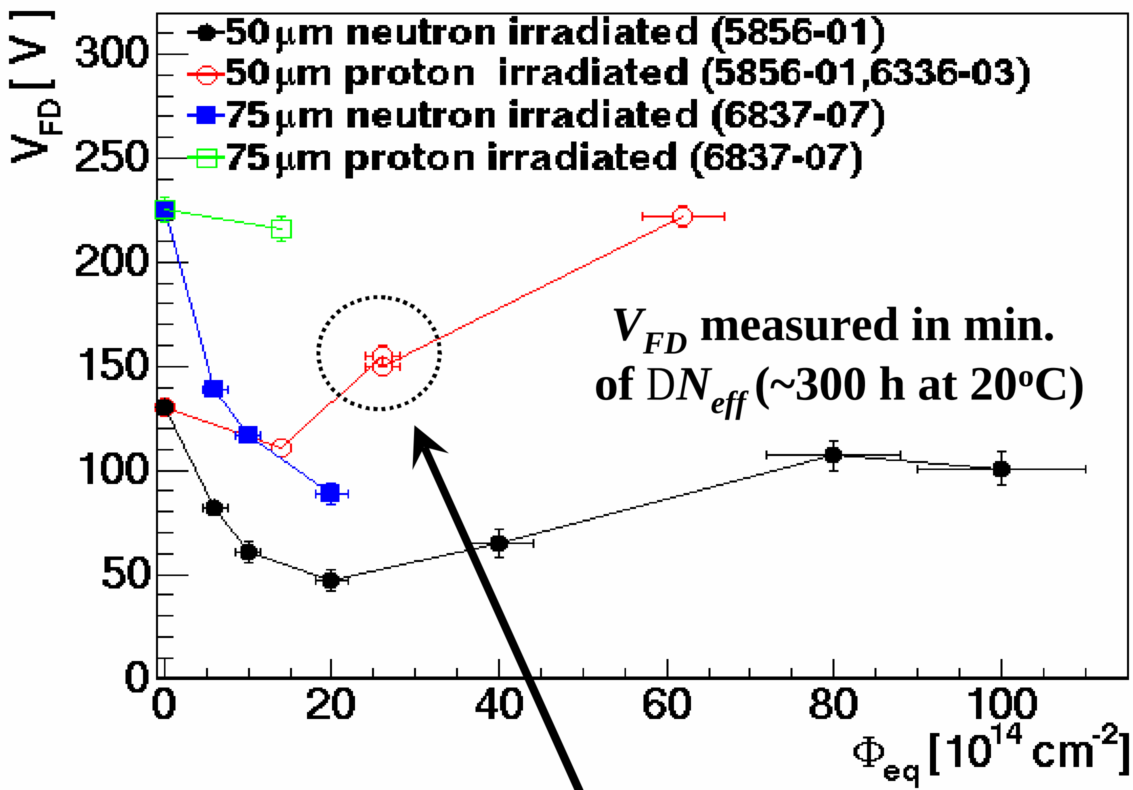
- neutrons from TRIGA II research reactor of JSI
- 24GeV/c protons from CERN PS
- after irradiation samples stored at $T < 0^{o}$C
- annealing studies at 20$^{o}$C

| Irradiation | 25 mm | 50 mm | 75 mm |
|---|---|---|---|
| **neutrons** | $F_{eq} <= 2\cdot10^{14}$ cm$^{-2}$ | $F_{eq} <= 100\cdot10^{14}$cm$^{-2}$ | $F_{eq} <= 20\cdot10^{14}$ cm$^{-2}$ |
| **protons** | $F_{eq} <= 13\cdot10^{14}$ cm$^{-2}$ | $F_{eq} <= 63\cdot10^{14}$ cm$^{-2}$ | $F_{eq} = 13\cdot10^{14}$ cm$^{-2}$ |

## Measurements:

CV performed at ν=10 kHz and 20$^{o}$C - kink in $1/C^2$ used to determine $V_{FD}$

# Dependence of $V_{FD}$ on fluence




Good reproducibility of $V_{FD}$ for samples from different wafers (two samples irradiated with protons to $\Phi_{eq}$= 26·$10^{14}$ cm$^{-2}$)

- **Proton irradiated samples do not invert**
- **What about the neutron irradiated ones?** (previously assumed they do)

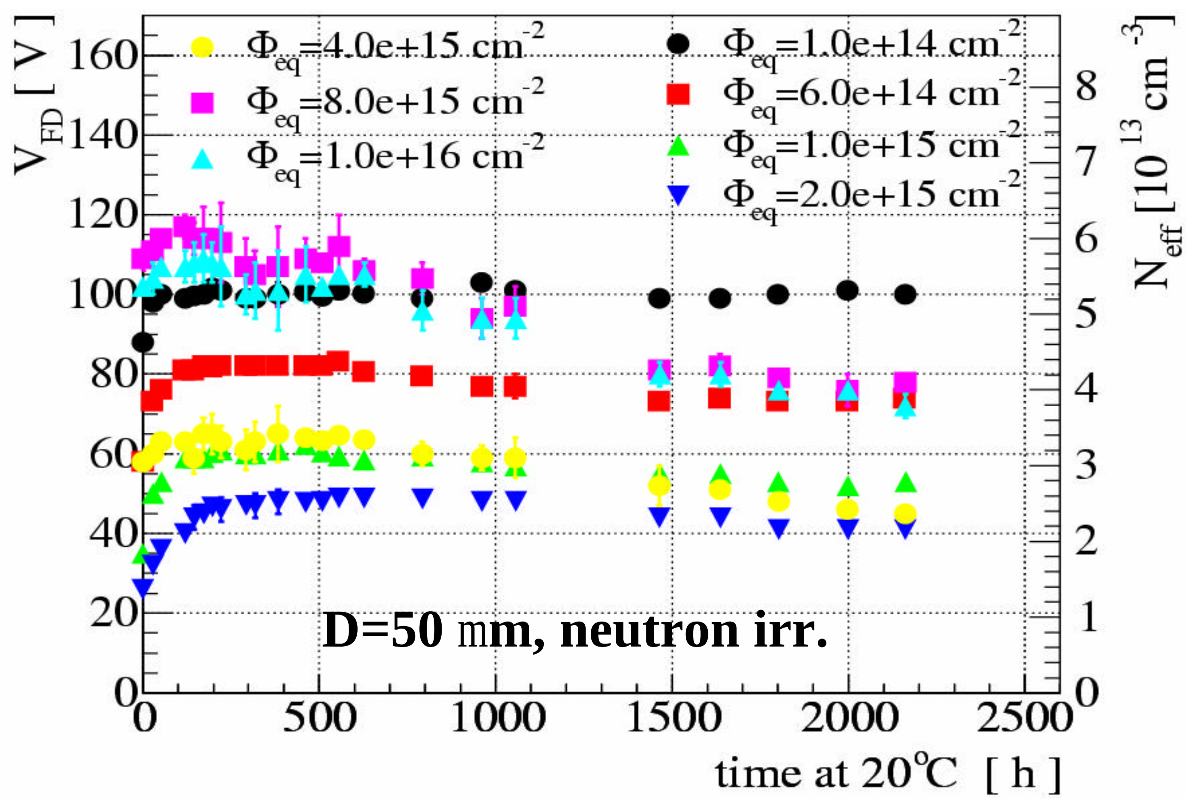
➢ **It appears that neutron irradiated samples do not invert !**

# Annealing of $N_{eff}$ at 20°C

Hamburg parameterization:

$$\Delta N_{eff} = N_{eff0} - N_{eff}(t) = N_A(\Phi_{eq}, T, t) + N_C(\Phi_{eq}) + N_Y(\Phi_{eq}, T, t)$$

**Initial annealing** **Stable damage** **Long term annealing**




Same shape of annealing plots, also at highest fluences!

$N_Y$ are effective acceptors with long annealing times

**$N_{eff} > 0$: $V_{FD}$ should decrease**

$N_{eff} < 0$: $V_{FD}$ should increase

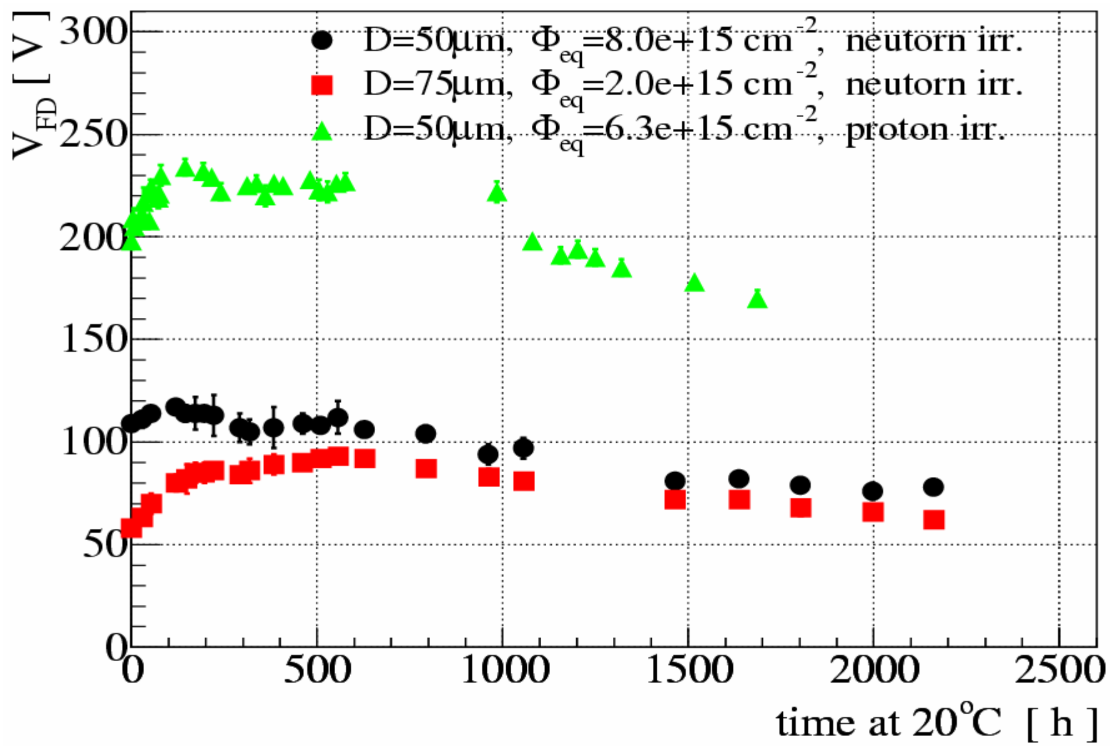
**Annealing confirms no inversion for neutron irradiated samples**

# Annealing of $N_{eff}$ at 20°C (*cont.*)

**Same annealing behaviour for samples irradiated with neutrons and protons:**

Three most irradiated samples:

- **50 mm** : $\Phi_{eq}$= 6.3·10$^{15}$ cm$^{-2}$ (protons) and 8·10$^{15}$cm$^{-2}$ neutrons
- **75 mm** : $\Phi_{eq}$= 2·10$^{15}$ cm$^{-2}$ (neutrons)




Same behaviour for all three diodes also confirmed with m.i.p. signal measurements (*G. Kramberger et al.* @ RESMDD `04)

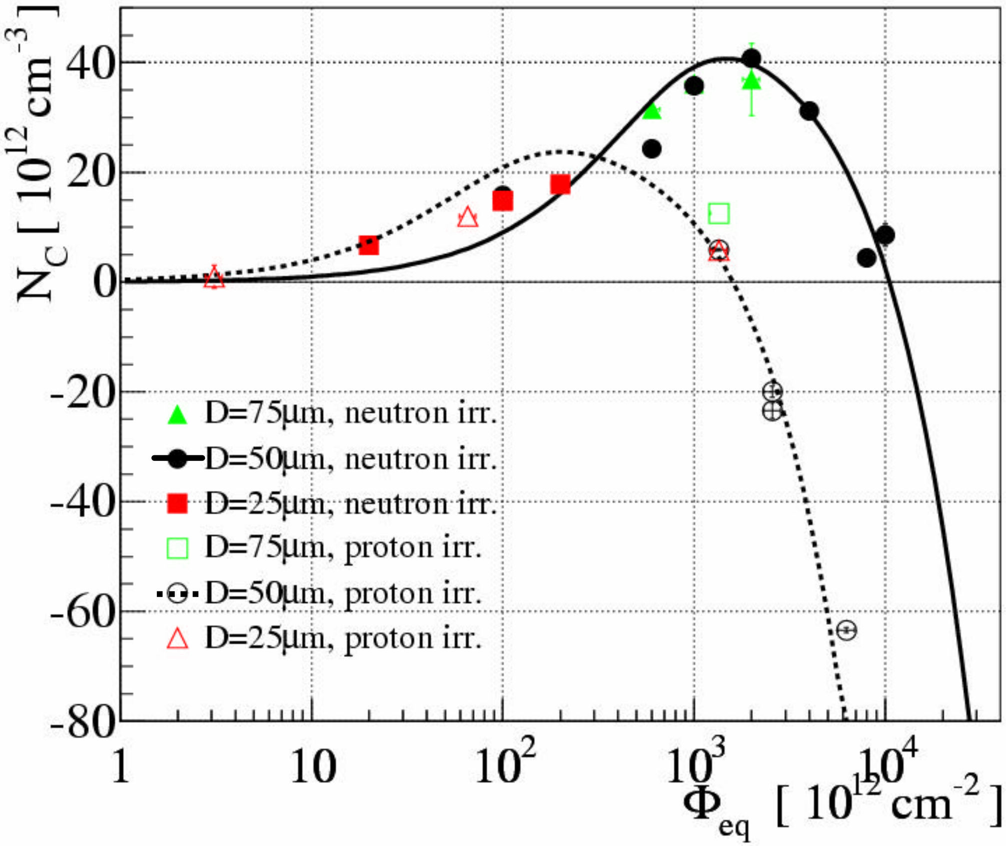
Same behaviour for all three samples → All three samples must have equal sign of the space charge.

# Annealing of D$N_{eff}$ at 20ºC: *stable damage*

$$N_C = N_{C0}(1\text{-}\exp[\text{-}cF_{eq}]) + g_C\,\Phi_{eq}$$

**Observations:**

- Good agreement between samples of different thickness
- Incomplete donor removal for both irradiation particles
- Donor removal less efficient for proton irradiated samples
- $g_c$ negative - effective donor introduction
- $g_c$ smaller for neutron irradiated samples




| *irradiation* | *D* [mm] | $N_{C\,0}$ / $N_{eff\,0}$ | $g_C$ [cm$^{-1}$] | *c* [$10^{-15}$ cm$^2$] |
|---|---|---|---|---|
| **neutron** | **50** | 0.73 ± 0.02 | (-4.8 ± 0.4)·$10^{-3}$ | 2.1 ± 0.1 |
| **Proton** | **50** | 0.42 ± 0.07 | (-18 ± 2)·$10^{-3}$ | - |

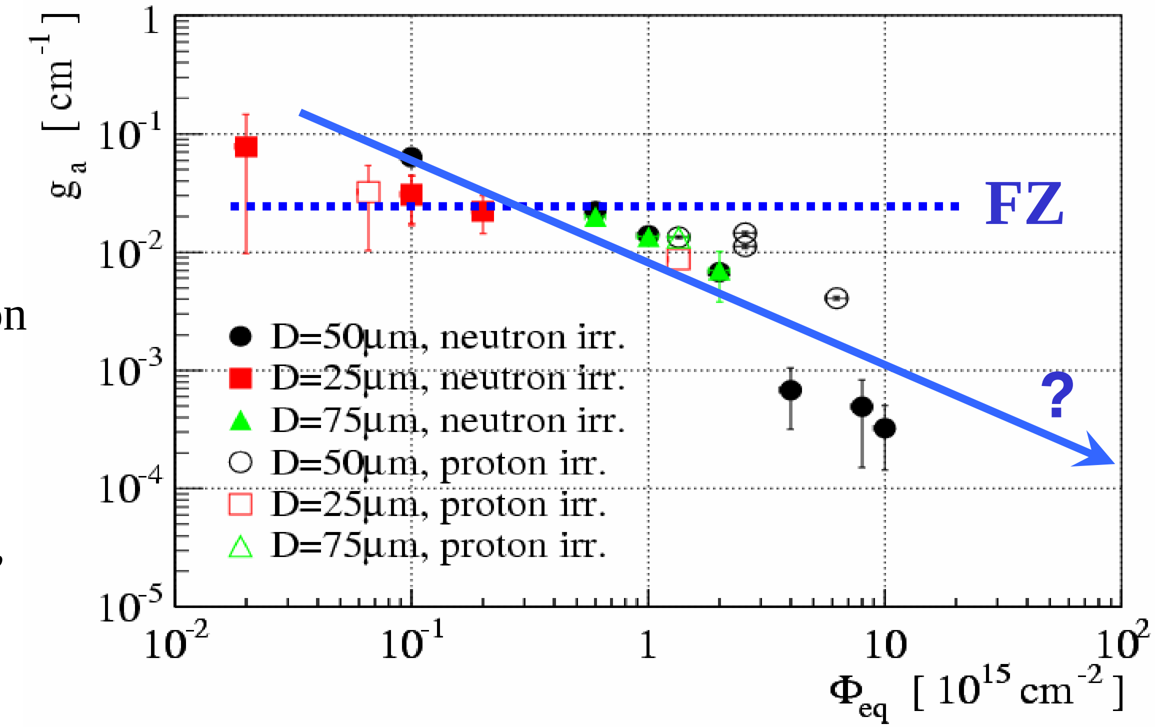
# Annealing of $\Delta N_{eff}$ at 20°C: *initial annealing*

Parameterization: $N_A = g_a \Phi_{eq} \exp(-t/\tau_a)$

- Observation:
  - $g_a$ appears to depend on fluence (solid line)
  - In the region mostly studied so far (up to $10^{15}$ cm$^{-2}$) comparable with previous measurements in FZ material (dotted line)

**Note:**

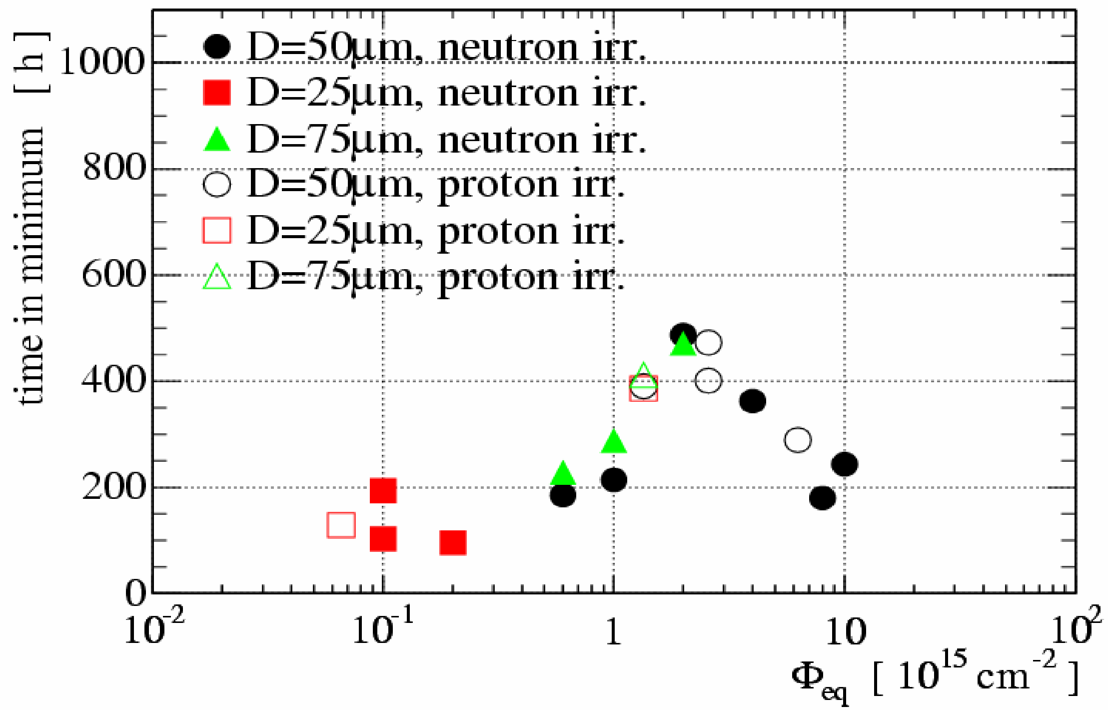
- the longest irradiation time for neutron irradiated sample was ~30 min after which the samples were stored at T<0°C
- Much longer proton irradiation times, but still shorter than $\tau_a$



# Annealing of D$N_{eff}$ at 20°C: *initial annealing*

Time of the minimum in $\Delta N_{eff}$ taken as a measure for completion of initial annealing.

Determination unreliable, especially for the very shallow minima.




## Observations:

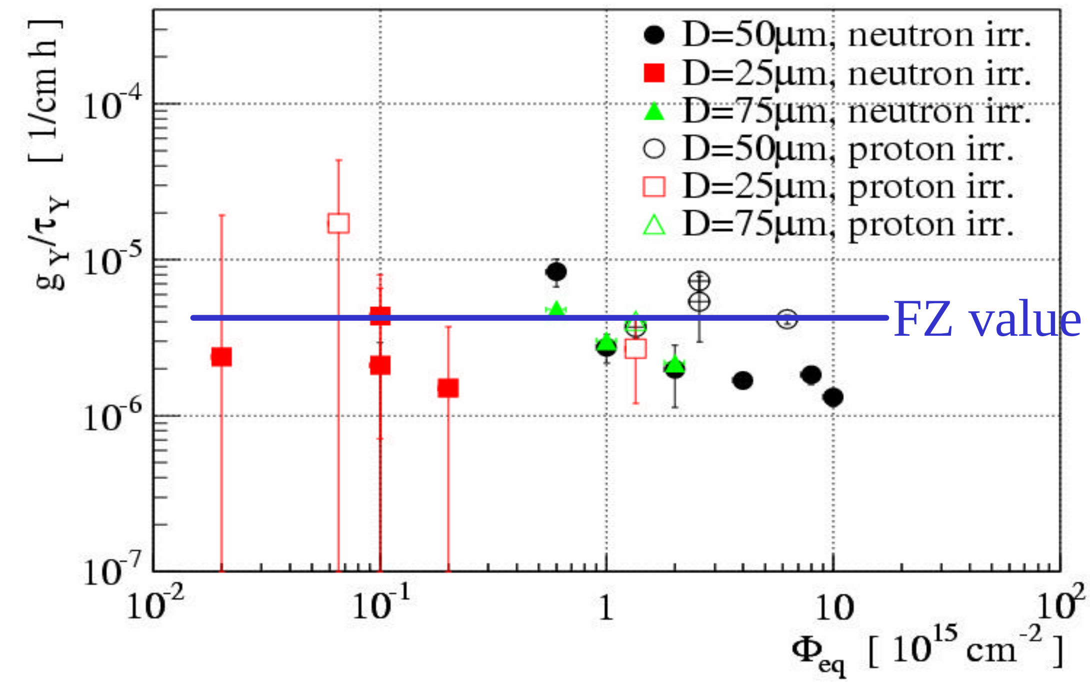
- $t_{min}$ seems compatible with what one expects from FZ detectors
- There is no difference between proton and neutron irradiated devices nor between devices of different thickness

# Annealing of $\Delta N_{eff}$ at 20°C: *long term annealing*

$$N_Y = N_{Y\infty}(1-\exp[-t/\tau_Y])$$

After 4 months at 20°C only initial slope could be determined:

$$\frac{N_Y}{\Phi_{eq}} \approx \left(\frac{g_Y}{t_Y}\right) \cdot t$$

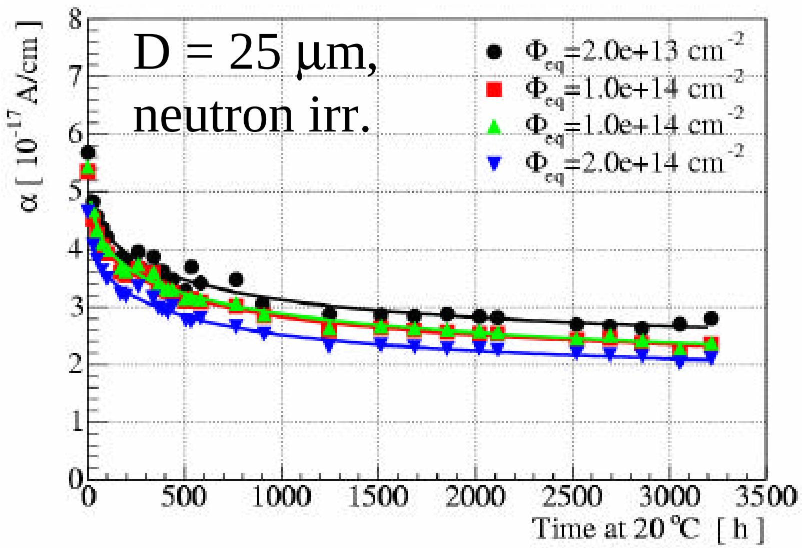


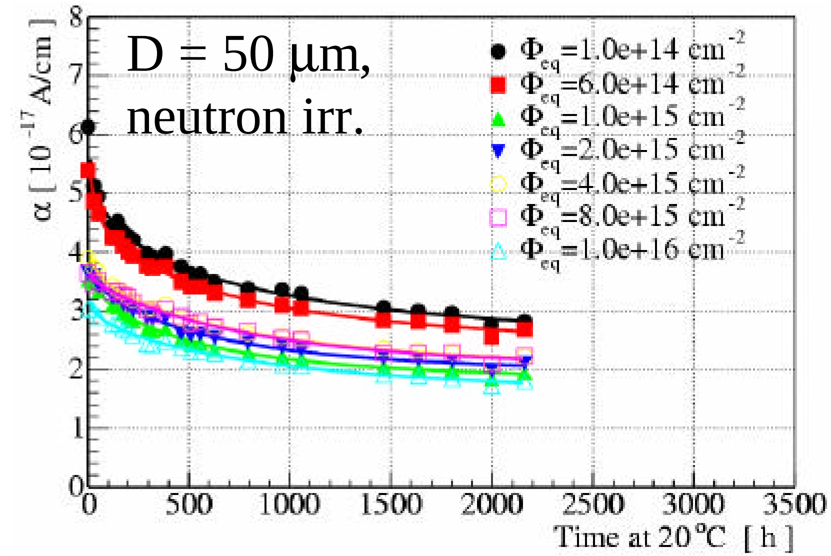

## Observations:

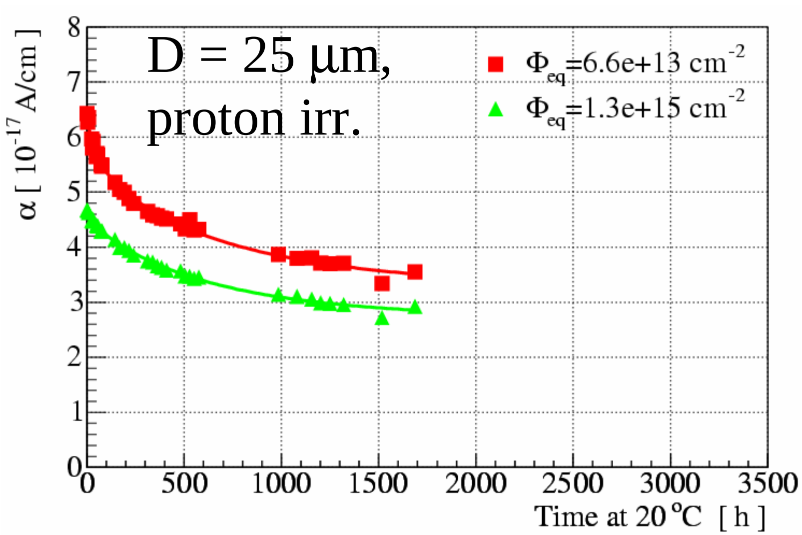
- no increase of initial slope with fluence – initial part 1st order process ?
- average value of initial slope $(g_Y/\tau_Y) = 2.4 \cdot 10^{-6}\ \mathrm{cm^{-1}h^{-1}}$

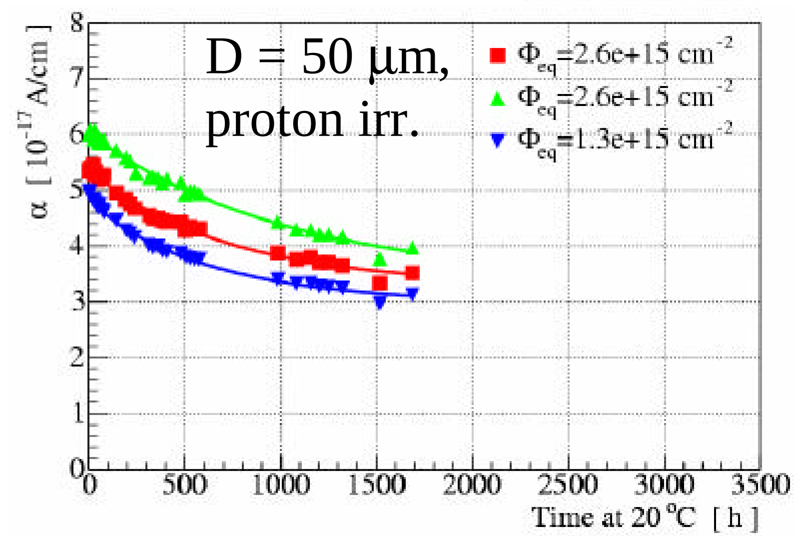
# Annealing of leakage current at 20ºC

Parametrization: $\alpha(t) = (I/V)/F_{eq} = \alpha_I \exp(-t/t_I) + \alpha_0 - b \ln(t/t_0)$



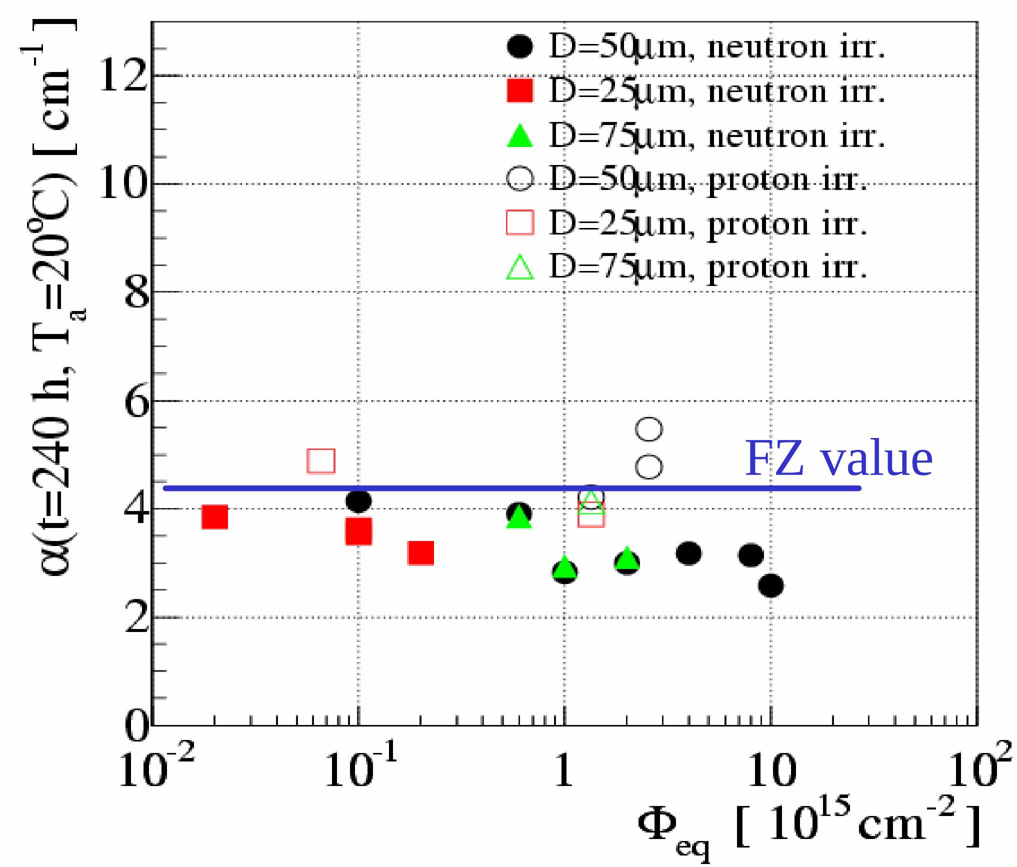



# a **after 240h at 20°C** (~ equivalent to 80 min at 60°C)

Average value:

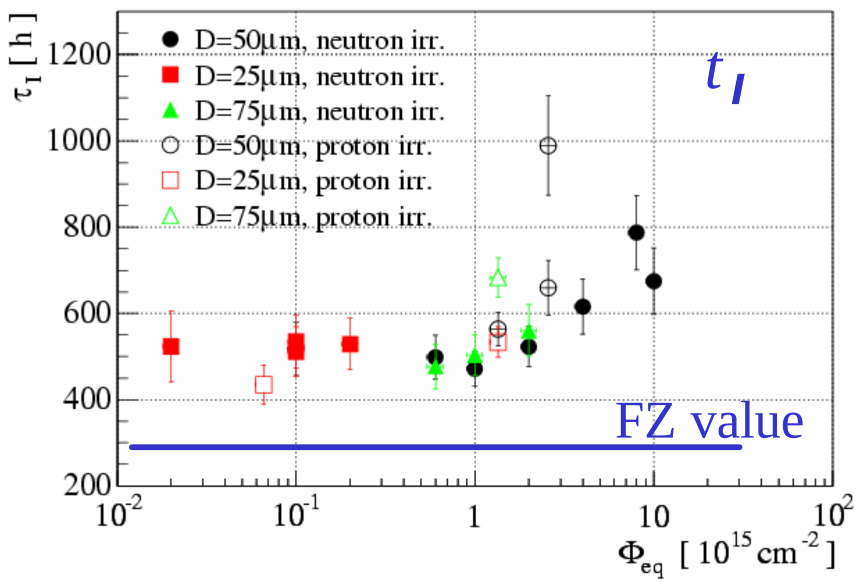
$\langle \alpha(240\text{ h}, 20^{o}\text{C}) \rangle = (3.7 \pm 0.2) \cdot 10^{-17}$ A/cm

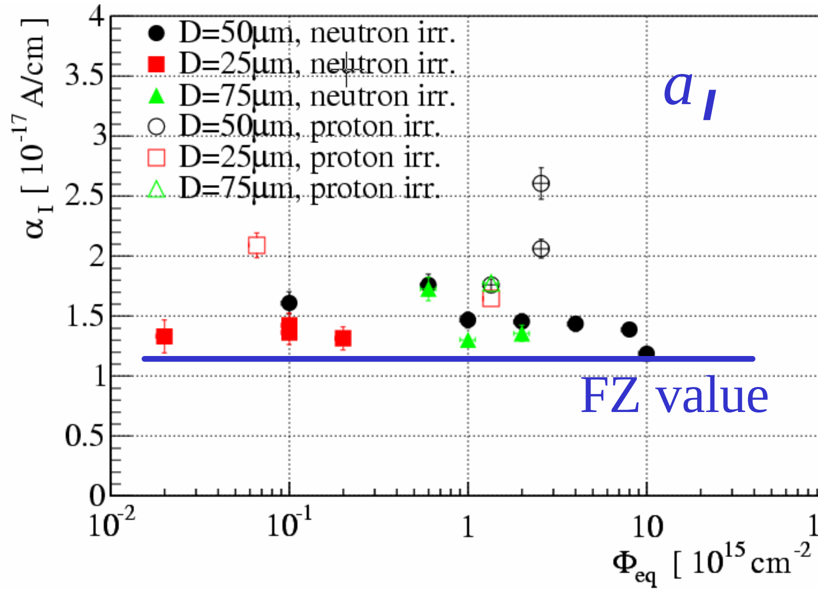


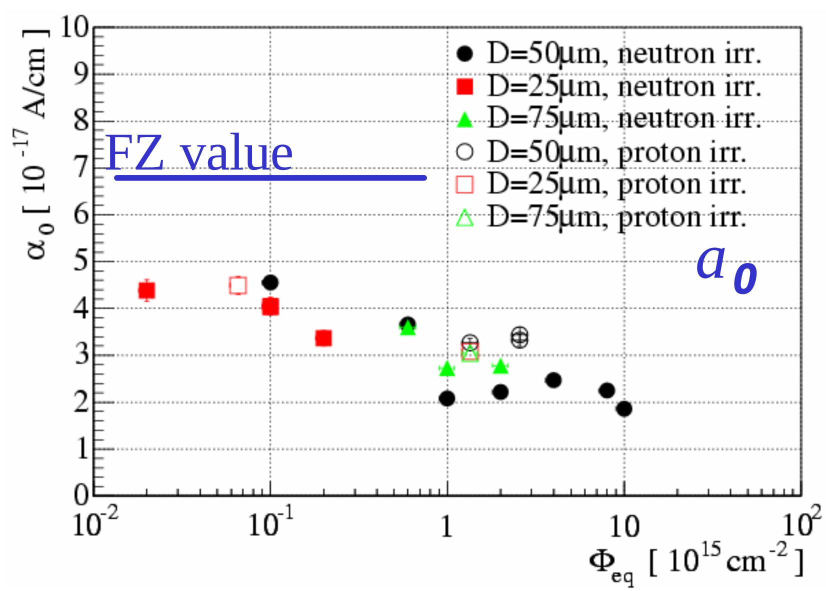

Note:

- Large spread observed between samples
- Proton irr. samples exhibit systematically larger values

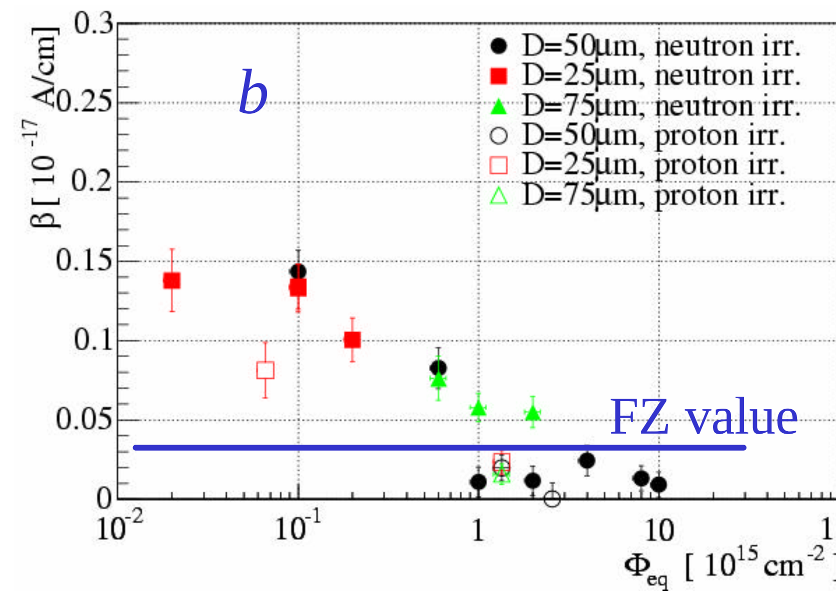
# Annealing of leakage current at 20°C: *fit parameters*




**$a_0$ and b correlated**



# Conclusions

- Measurements of $N_{eff}$
  - Epitaxial samples irradiated with protons <u>and</u> neutrons up to $10^{16}$ cm$^{-2}$ show no space charge sign inversion.
  - Effective stable donor introduction rate is ~ 4 times smaller for neutrons.
  - Donor removal is ~ 2 times more efficient for neutrons.

➢ Epitaxial material exhibits supreme radiation hardness for neutrons

- Measurements of leakage current
  - FZ leakage current annealing model fits epitaxial data well
  - Fit parameters somewhat different, but stable with fluence up to $10^{15}$ cm$^{-2}$

➢ Epitaxial diodes suitable for radiation monitoring of NIEL at LHC