Systematic study of effective trapping times

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Outline:

- Motivation
- Samples and irradiation
- Material and particle type dependence
- Temperature dependence
- Annealing of effective trapping times
- Conclusions

Motivation

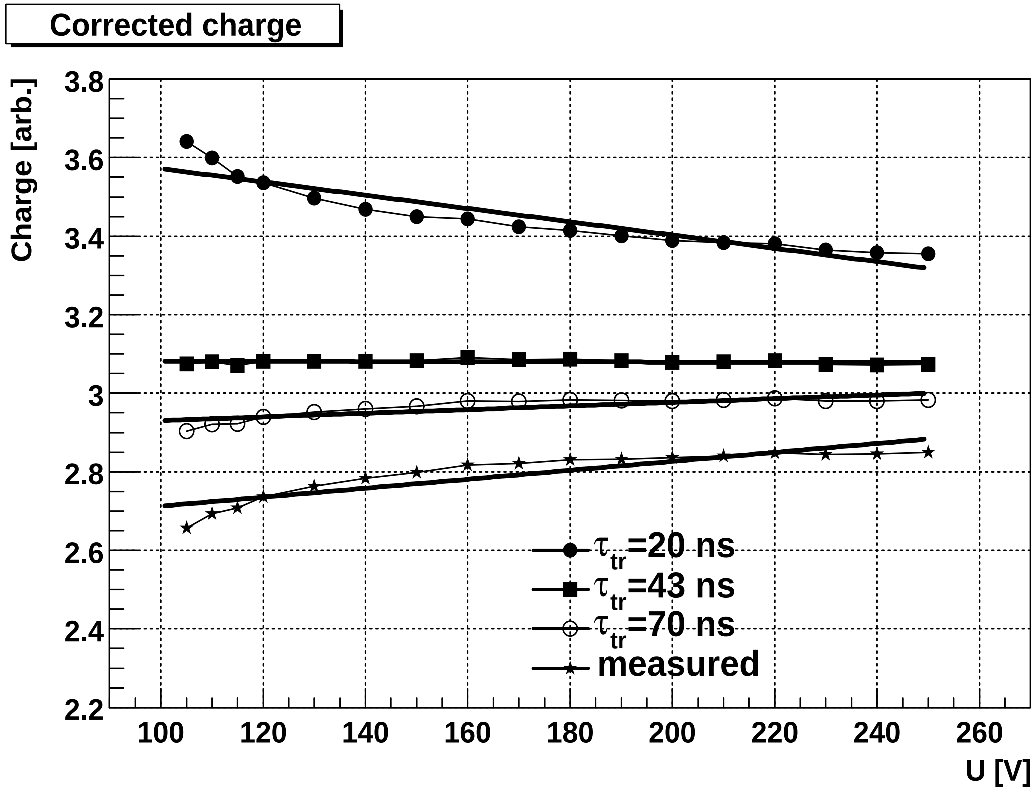
talk on Friday sec. VII

- An input to simulations of operation of irradiated silicon detectors!
  - prediction of charge collection efficiency (LHC, SLHC, etc.)
  - optimization of operating conditions
  - optimization of detector design (p^+ or n^+ strips, thickness, charge sharing)
- Characterization of different silicon materials in terms of charge trapping!
- Defect characterization?

Method

Method proposed in *5th ROSE Workshop* independently by JSI group (*CCM*) and Lancaster/Hamburg Uni. group (*ECC*)

Method is based on TCT using red light pulses →



$$I_{e,h}(t) = \left[e_0 \, N_{e,h} \frac{1}{D} v_{e,h}(t) \right] \exp\left(\frac{-t}{\tau_{eff,e,h}}\right)$$

↓ *correction*

$$I_c(t) = I_m(t) \exp\left(\frac{t - t_0}{\tau_{tr}}\right)$$

↓ *in the way that*

Q_c=constant for $U>V_{FD}$

Samples and irradiations

Samples provided by: STM (ROSE), BNL and ITE (ROSE) .

All together 40 samples!

Different materials:

- standard, oxygen rich [O]=~5x10^{17} cm^{-3}, carbon rich [C]=1.8x10^{16} cm^{-3}
- different resistivities of materials
- silicon wafer producer (Topsil, Wacker, Polovodice)

Irradiation sites used:

- JSI Ljubljana (reactor neutrons)
- PSI Villigen (200MeV pions)
- CERN PS (24 GeV protons)

STM samples: (n ,π^+ ,p^+) *10^{13} /cm^2

- W339 (15 kΩcm, standard) (0,2.5,5,7.5,10,15,20 ; 5.3,16.7 ; 5.6,10.9,19.9)
- W336 (2 kΩcm, standard) (- ; 5.3 ,16.7 ; 10.9, 19.9)
- W333 (1 kΩcm, standard) (- ; 9.5 , 24 ; 10.9, 19.9)
- W317 (15 kΩcm, oxygenated) (2.5,7.5 ; - ; 5.6,19.9)
- W309 (2 kΩcm, oxygenated) (- ; 9.5, 24 ; 10.9, 19.9)
- W301 (1 kΩcm, oxygenated) (-; 9.5, 24 ; 10.9, 19.9)

BNL samples:

- BNL-920 (~1kΩcm , standard) (10,20 ; - ; -)
- BNL-917 (~1kΩcm , oxygenated) (10,20 ; - ; -)

missing some points

ITE samples:

- P503-I-A3(~1.5 kΩcm , carbonated) (5,10,20; - ; -)

Dosimetry and post-irradiation procedure

- V_{FD} equivalent fluences accurate to ~10% !
  - Pion irradiation (Al-activation, $V_{FD}(\Phi_{eq})$ for W339)
  - Proton irradiation (Al-activation, α for dosimetry diodes , $V_{FD}(\Phi_{eq})$ for W339)
  - Neutron irradiation (Φ from reactor P and irrad. time (previously calibrated), $V_{FD}(\Phi_{eq})$ forW339)
- samples were irradiated and after that kept unbiased
- then they were mounted in Al boxes glued and kept at RT!
- the time evolution of the V_{FD} monitored with *C-V* method!
- once minimum of V_{FD} was reached samples were stored at T=-17^{o}C !

Parameterization of results!

introduction rate — occupation probability — Capture cross-section — thermal velocity

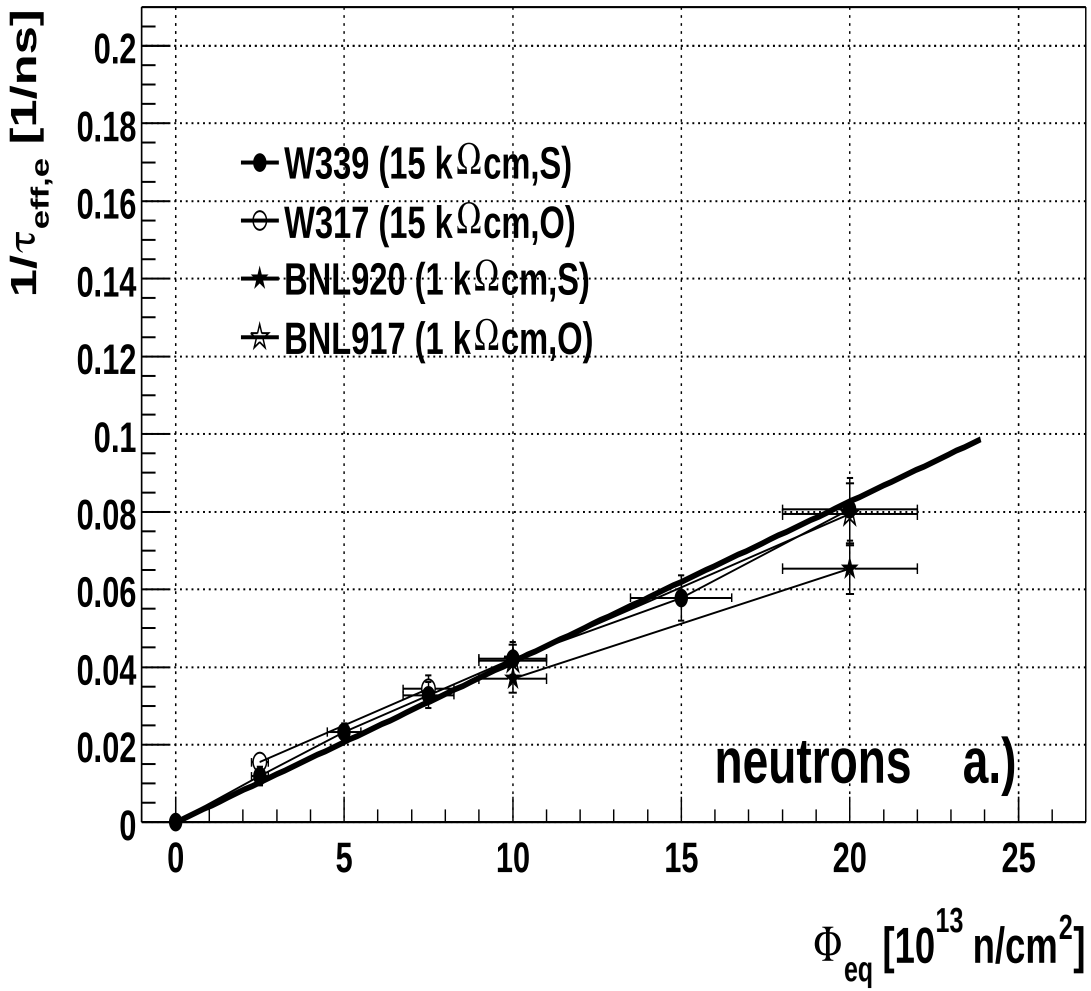
$$\frac{1}{\tau_{eff,e,h}} = \Phi_{eq}\left[\sum_t g_t\,(1-P_t^{e,h})\,\sigma_{t,e,h}(T)\,v_{th,e,h}(T)\right]$$

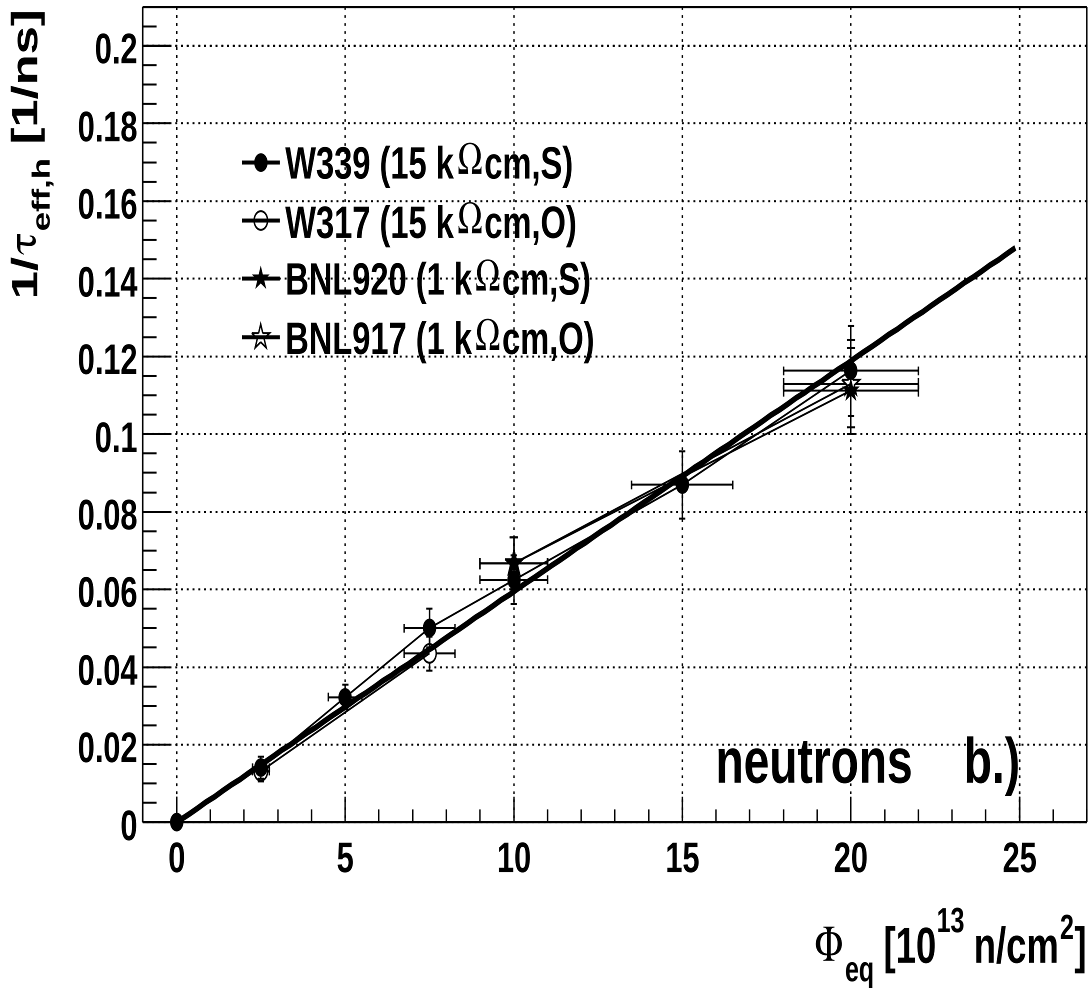
at given temperature and time after irradiation $\Rightarrow$

$$\frac{1}{\tau_{eff,e,h}} = \beta_{e,h}(T,t)\,\Phi_{eq}$$

- operational temperature at LHC ~ -10°C
- minimum in V_{FD}
- in this presentation β is given in **10^{-16} cm²/ns**

Effective trapping probability (Neutrons)

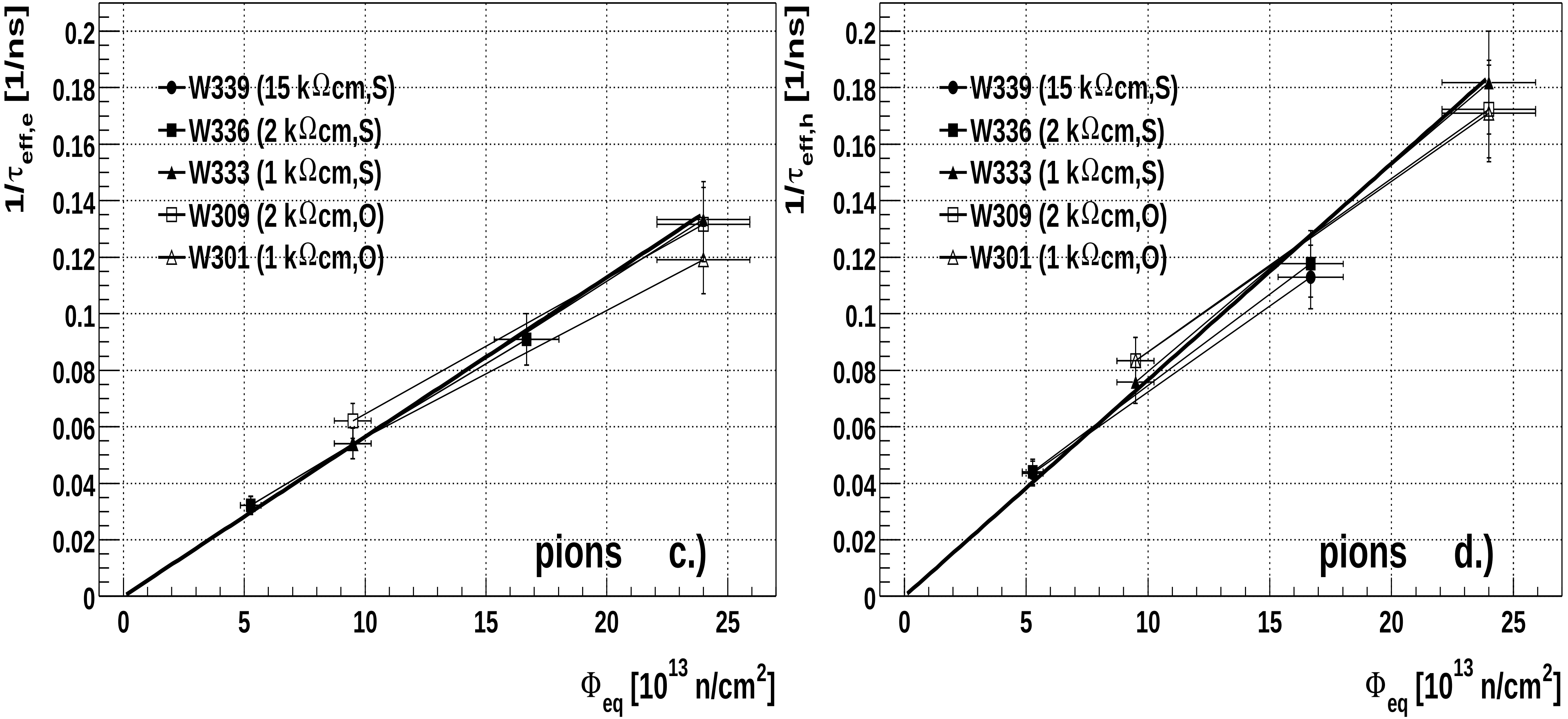




$$\beta_{electrons}^{neutrons}(T=-10^o C)=4.1\pm 0.1$$

$$\beta_{holes}^{neutrons}(T=-10^o C)=6.0\pm 0.2$$

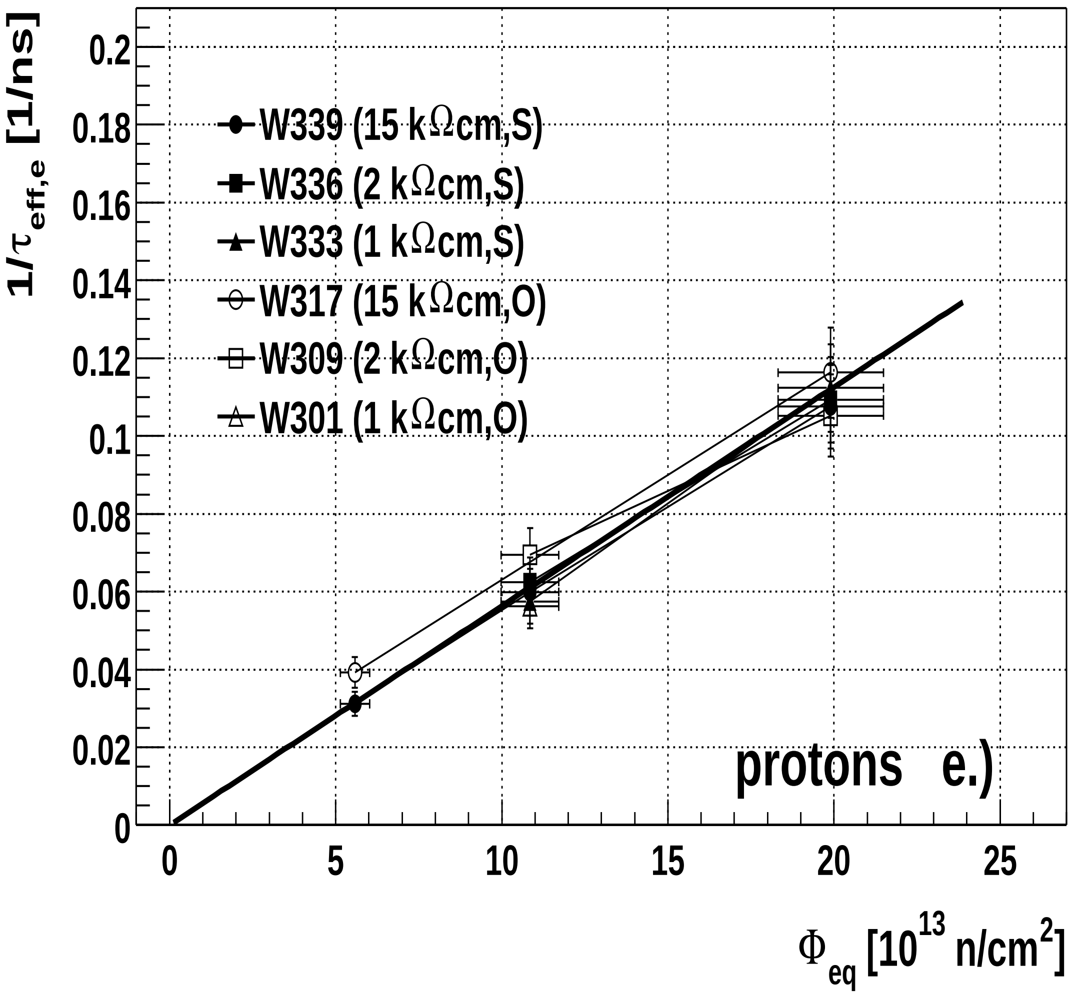
Effective trapping probability (Pions)

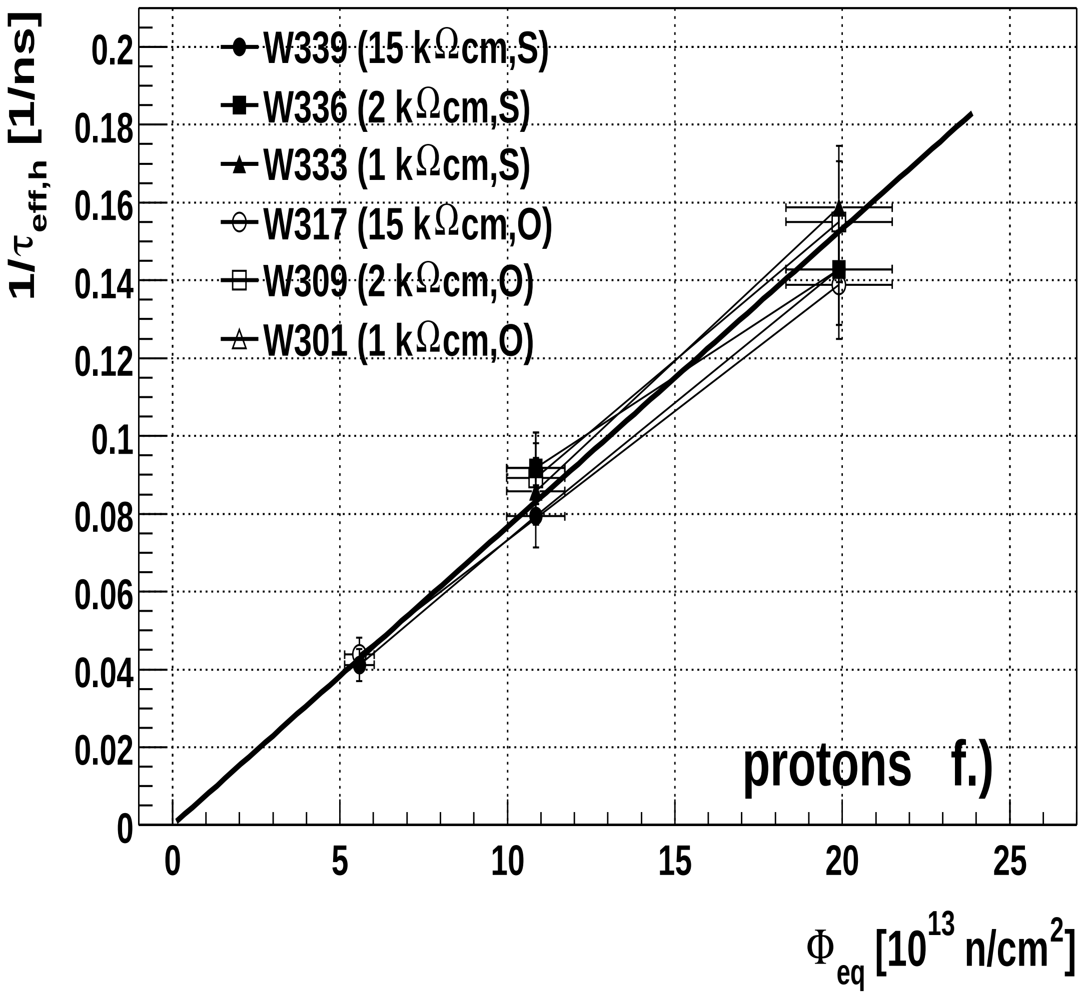


$$\beta_{electrons}^{pions}(T=-10^{o}C)=5.7\pm0.2$$

$$\beta_{holes}^{pions}(T=-10^{o}C)=7.7\pm0.2$$

Effective trapping probability (Protons)

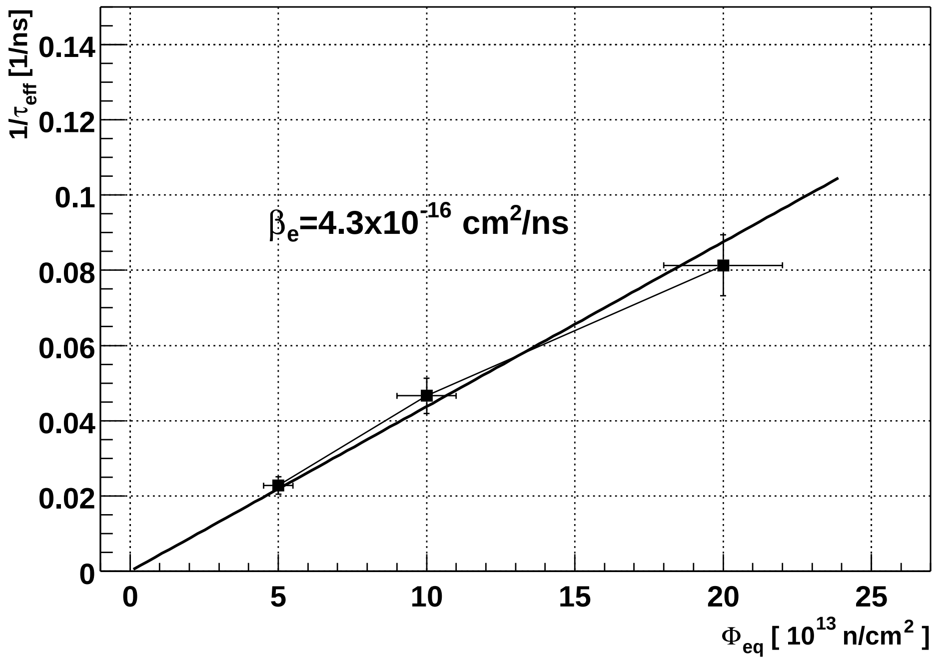


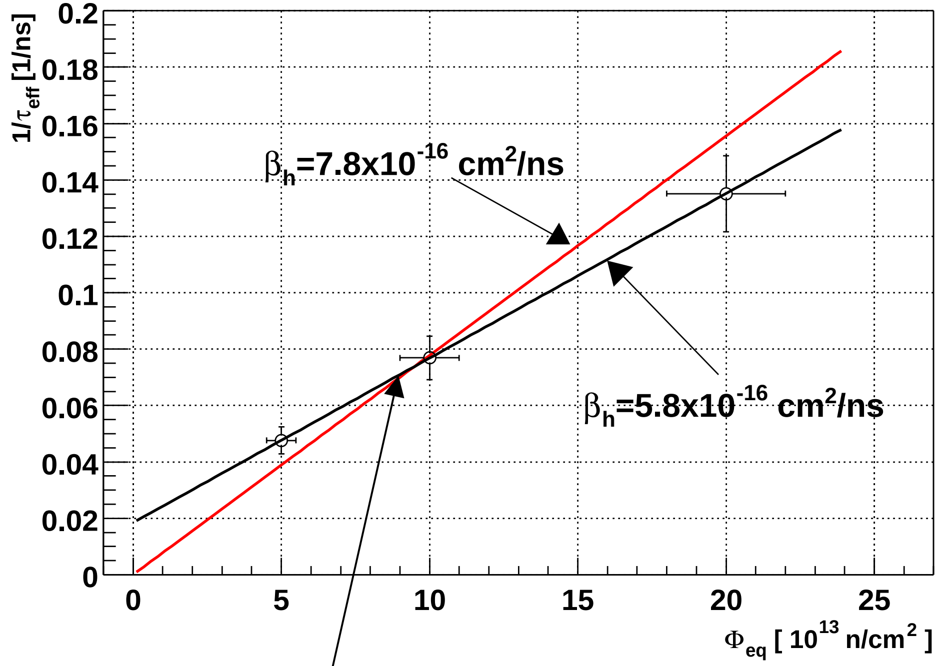


$$\beta^{protons}_{electrons}(T=-10^o C)=5.6\pm 0.2$$

$$\beta^{protons}_{holes}(T=-10^o C)=7.7\pm 0.2$$

Carbonated samples irradiated with neutrons





electrons

holes

$[C]=1.8\text{x}10^{16}$ cm^{-3}
Results compatible with other materials.

trapping centers present before irradiation???
However, slope is ok.

	$\beta_e[10^{-16}cm^2/ns]$	$\beta_h[10^{-16}cm^2/ns]$
reactor neutrons	4.1±0.1 (~5-8)	6.0±0.2 (~2-3)
pions	5.7±0.2	7.7±0.2
protons	5.6±0.2	7.7±0.2

Survey of results at $T=263$ K in min. of V_{FD}

old data!!

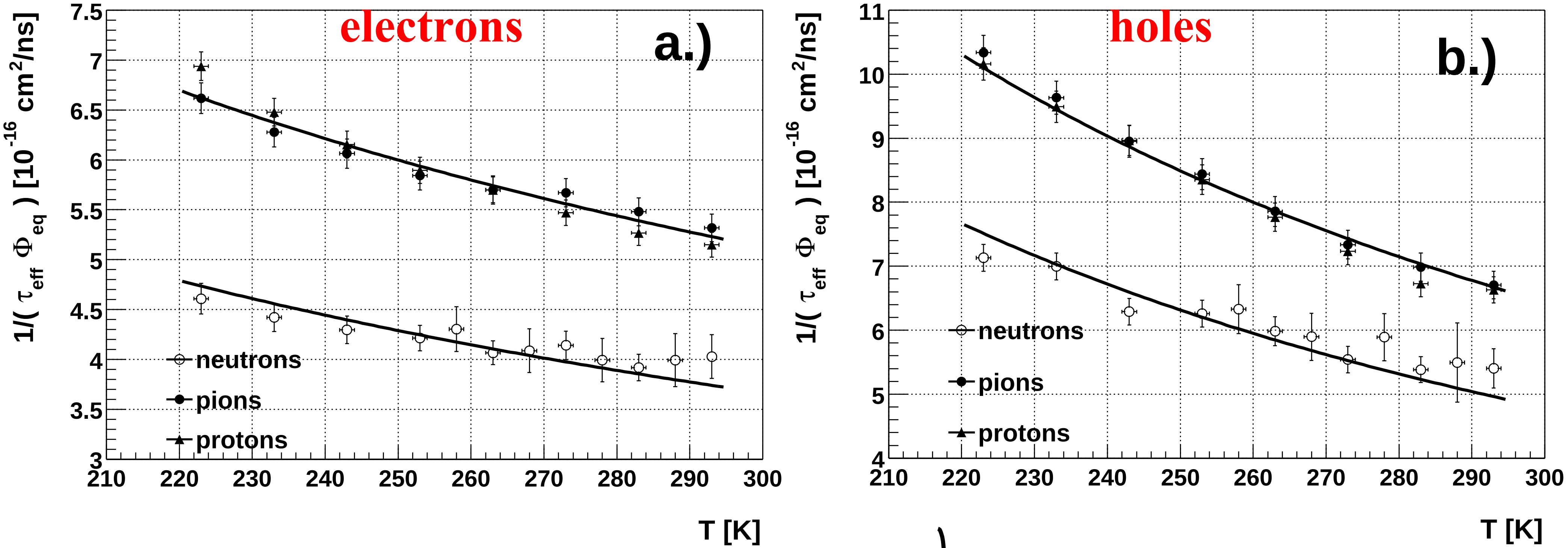
Observations:

•initial N_{eff} (resistivity), oxygen content, carbon content (checked for neutrons only) and silicon producer do not significantly influence $\tau_{eff,e,h}$

•charged hadrons (24 GeV protons, 200 MeV pions) appear to be more damaging than reactor neutrons in terms of charge trapping ("NIEL hypothesis" violation)

•$1/\tau_{eff,h} > 1/\tau_{eff,e}$ (contrary to earlier measurements!!)

Temperature dependence of effective trapping probability



•average of all $\beta_{e,h}$ for standard and oxygenated diodes irradiated with same particle type is shown

•similar behavior for neutrons and charged hadrons

↓

same defects introduced at different rates????

} Can we learn something about the dominant defect?

Even with simple assumption of one dominant trap center there are problems!!

Temperature dependence of $\tau_{eff,h}$ is hidden in:

$$\sigma_{e,h}(T) \propto T^m \quad m \in [-2,2]$$

$$P_t(T) = \frac{1}{\frac{c_n}{c_p}\chi_t^2 + 1} \quad , \chi_t = \exp\left(\frac{E_t - E_i}{k_B T}\right) \quad , c_{n,p} = \sigma_{e,h} v_{e,h},$$

$$v_{th} \propto \sqrt{T} \qquad p \sim n \sim 0$$

free parameters $\sigma_{e,h}, m, E_t$

$$\beta_{e,h}(T) = \beta_{e,h}(263\,\mathrm{K}) \frac{1 - P_t^{e,h}(T)}{1 - P_t^{e,h}(263\,\mathrm{K})} \left(\frac{T}{263\,\mathrm{K}}\right)^{m+\frac{1}{2}}$$

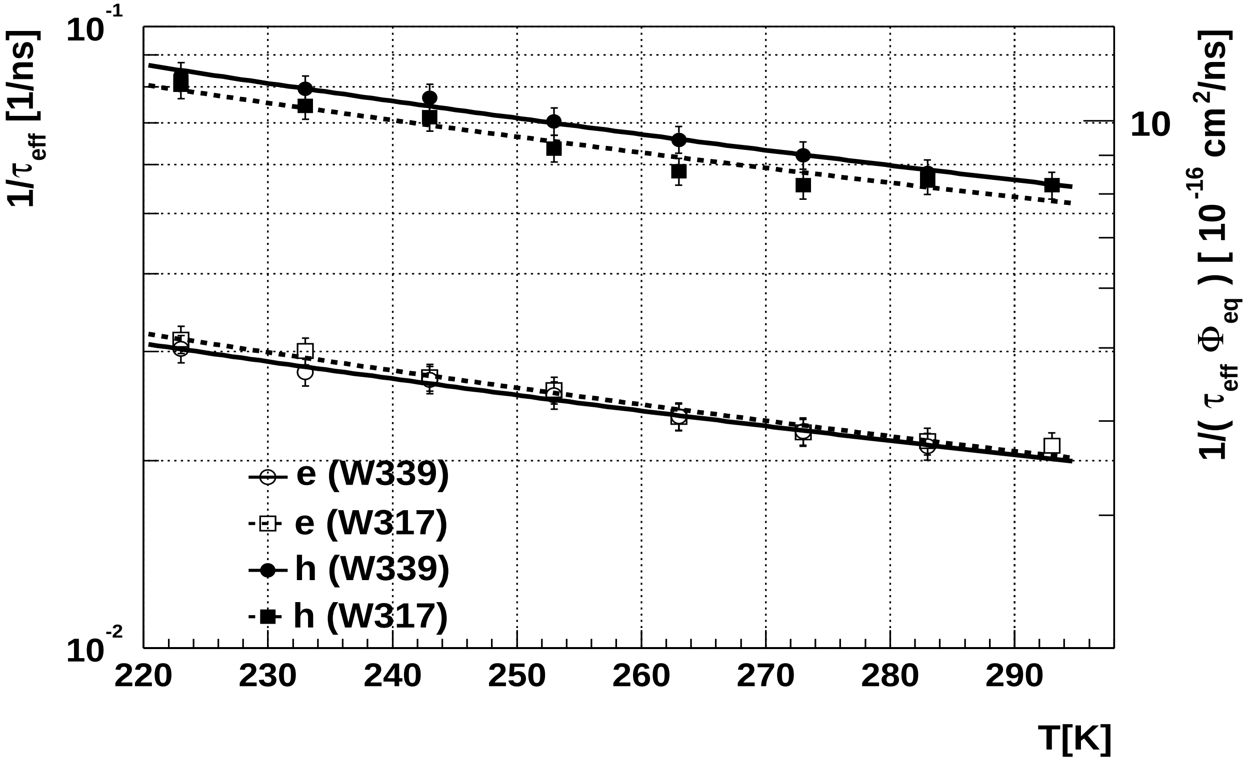
Unstable χ^2 minimization with theoretical model!

Only effective parameterization can be used:

$$\beta_{e,h}(T) = \beta_{e,h}(263\ \mathrm{K}) \left(\frac{T}{263\ \mathrm{K}}\right)^{\kappa_{e,h}}$$

$$\kappa_h = -1.58 \pm 0.07 \quad , \quad \kappa_e = -0.86 \pm 0.06$$

Temperature dependence after annealing ~200h@60^{o}C



$$\beta_{e,h}(T) = \beta_{e,h}(263\,\mathrm{K}) \left(\frac{T}{263\,\mathrm{K}} \right)^{\kappa_{e,h}}$$

unchanged → $\kappa_h = -1.57$, $\kappa_e = -1.50$ ← changed by almost a factor of 2

Effective trapping probability evolution with time

•Diodes used in studies:

•two diodes irradiated to Φ_{eq}= 7.5x10^{13} n cm^{-2} (Oxygenated , Standard, 15 kΩcm)

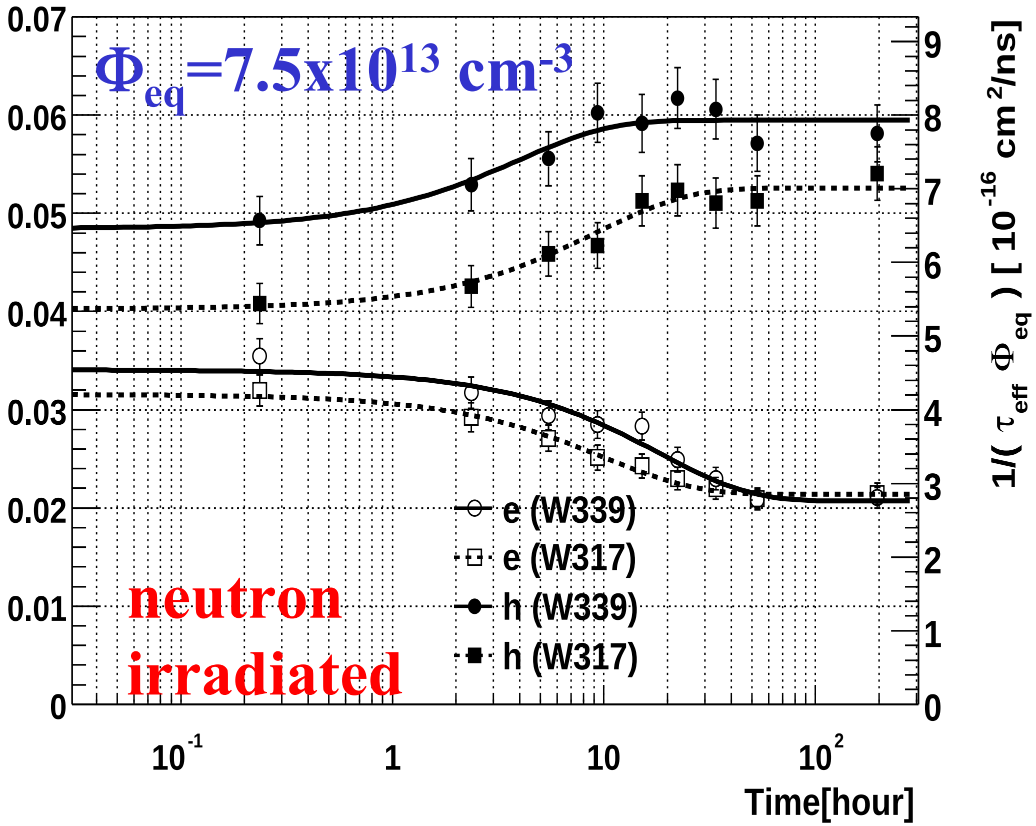
•two diodes irradiated to Φ_{eq}=5.5x10^{13} p cm^{-2} (Oxygenated , Standard, 15 kΩcm)

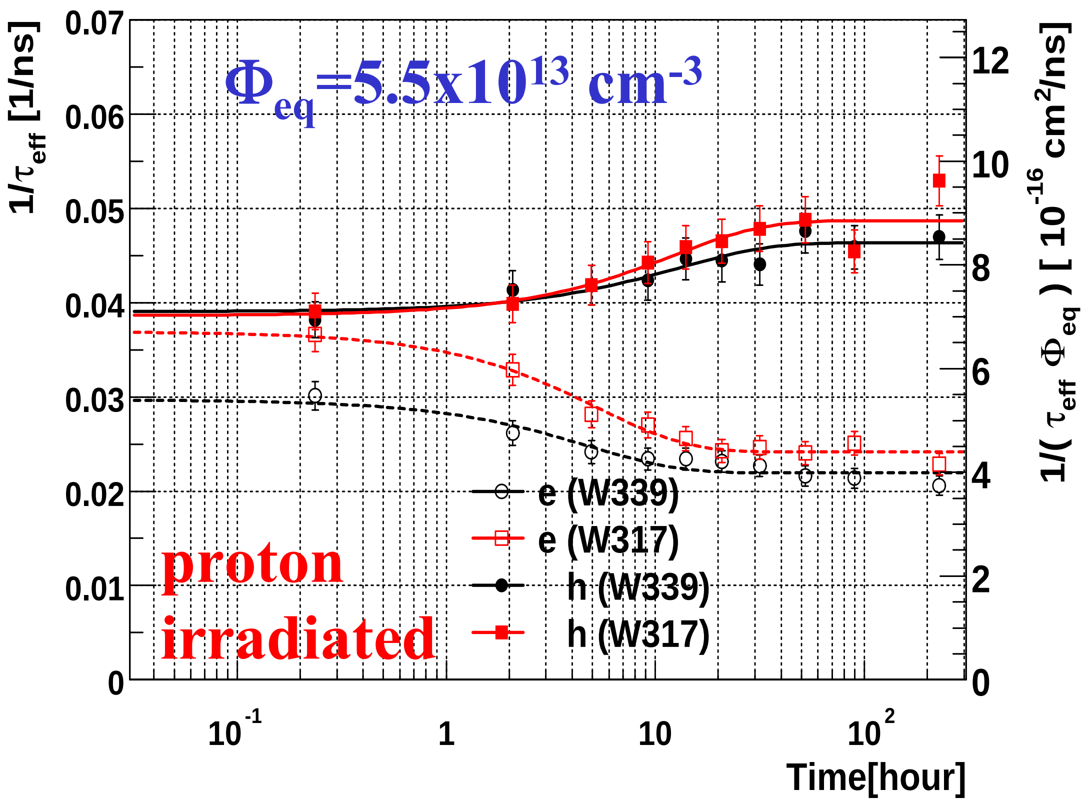
•mounted together to the Peltier cooler (same temperature history)

•accelerated reverse annealing at 60^{o}C in steps for more than 200 h

•TCT measurements between the steps done at T=10^{o}C!

15 kΩcm samples irradiated with protons and neutrons





$$A \longrightarrow B \quad \text{or} \quad A + C \longrightarrow A + D$$

Two defect model:

hole : **C** inactive **D** active

elec.: **C** active **C** inactive

$$\beta = \beta_0 \exp\left(-\frac{t}{\tau_{ta}}\right) + \beta_\infty \left[1 - \exp\left(-\frac{t}{\tau_{ta}}\right)\right]$$

relative change $\left|\frac{\beta_0 - \beta_\infty}{\beta_0}\right|$

change in β	standard neutrons	oxygen. neutrons	standard protons	oxygen. protons
holes	22%	30%	21%	26%
electr.	37%	33%	38%	35%

$\tau_{ta,e,h}$ [h@60°C]

holes	4.2±2.5	10±4.5	13±5	10±3.5
electr.	19±5	10±3.5	5±3.5	5.3±1.5

$\tau_{ta,e,h}$ of order 10 h@ 333 K

Better statistics is needed to claim more precise results!

Summary of the $\tau_{eff,e,h}$ measurements

- No significant dependence of $\beta_{e,h}$ on material (oxygen, carbon, resitivity, producer) for given particle type was observed!
- Effective trapping probability of electrons is lower than of holes!
  - protons and pions: $\beta_e(-10^oC)=5.7x10^{-16}$ cm^2/ns , $\beta_h(-10^oC)=7.7x10^{-16}$ cm^2/ns
  - neutrons: $\beta_e(-10^oC)=4.1x10^{-16}$ cm^2/ns , $\beta_h(-10^oC)=6.0x10^{-16}$ cm^2/ns
- Dependence of $\beta_{e,h}$ on temperature was found the same for all particle types! $\beta_{e,h}$ decreases with temperature for both electrons and holes.
- 15 kΩ cm samples irradiated with neutrons and protons show:
  - increase of β_h with time after irradiation by ~22-30%
  - decrease of β_e with time after irradiation by ~33-38%