Reverse annealing studies on standard diodes irradiated with 34 MeV proton beam.

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Outline

- Structures description;
- irradiation conditions;
- measurements of diode leakage current → k factor estimation;
- measurements of depletion voltage as a function of fluence and annealing time → annealing parameters;
- study of Bistable effect on diode leakage current and depletion voltage → time constant;
- conclusions

Structures description – Irradiation

Characterisation before and after irradiation of:

- Diodes: p+/n

  0.24*0.24 cm^2 300 μm thick

- Baby detectors: 128 strips p+

  3.22 cm long - 61 μm pitch

Built on two different kind of standard substrates:

- Low resistivity: 1.5 -2 KΩcm

  Crystal orientation <100>

  } **LR <100>**

- High resistivity : 6 -10 KΩcm

  Crystal orientation <111>

  } **HR <111>**

Irradiated with

- **34 MeV protons**, at **4** different fluences, up to 10^{14} pcm^{-2}, at the Cyclotron of the Research Centre of Karlsruhe **FZK** (Germany)

Characterisation of the samples (*)

Before Irradiation C/V and I/V on all samples.

After 34 MeV proton irradiation

- diode leakage current → Φ^N → k
- diode depletion voltage vs. Φ^N → β
- $|\Delta N_{eff}|$ vs. annealing time → ann. parameters
- V_{dep} and I_{leak} vs. time after heating 80^0C → τ

(*) All the measurements of I/V and C/V were performed on diodes with guard ring to 0V

Measurements

After 34 MeV proton irradiation the structures were kept at 0^0C;

Measurements performed:

- ***during*** 10 days of annealing at $T_a = 22\pm1^0$C

After benefical annealing the structures were kept for ~ 1y at 0^0C;

Measurements performed:

- ***during*** 95 hours of annealing at $T_a = 60$ and 80^0C
- ***during*** 98 hours of annealing at $T_a = 120^0$C

All the measurements were performed at $T_m = 22\pm1\ ^0C \rightarrow T=21^0C$

$$I(T) = I(T_m)\cdot\left(\frac{T}{T_m}\right)^2 \cdot e^{-\frac{E_g}{2k_B}\left(\frac{1}{T}-\frac{1}{T_m}\right)}$$

$$V_{dep}(T) = V_{dep}(T_m)\cdot\frac{1.0526}{1+0.00936\cdot e^{T_m/11.58}}$$

Leakage current

$$\Delta I = \alpha(t, T_a) \cdot \Phi^N \cdot V$$

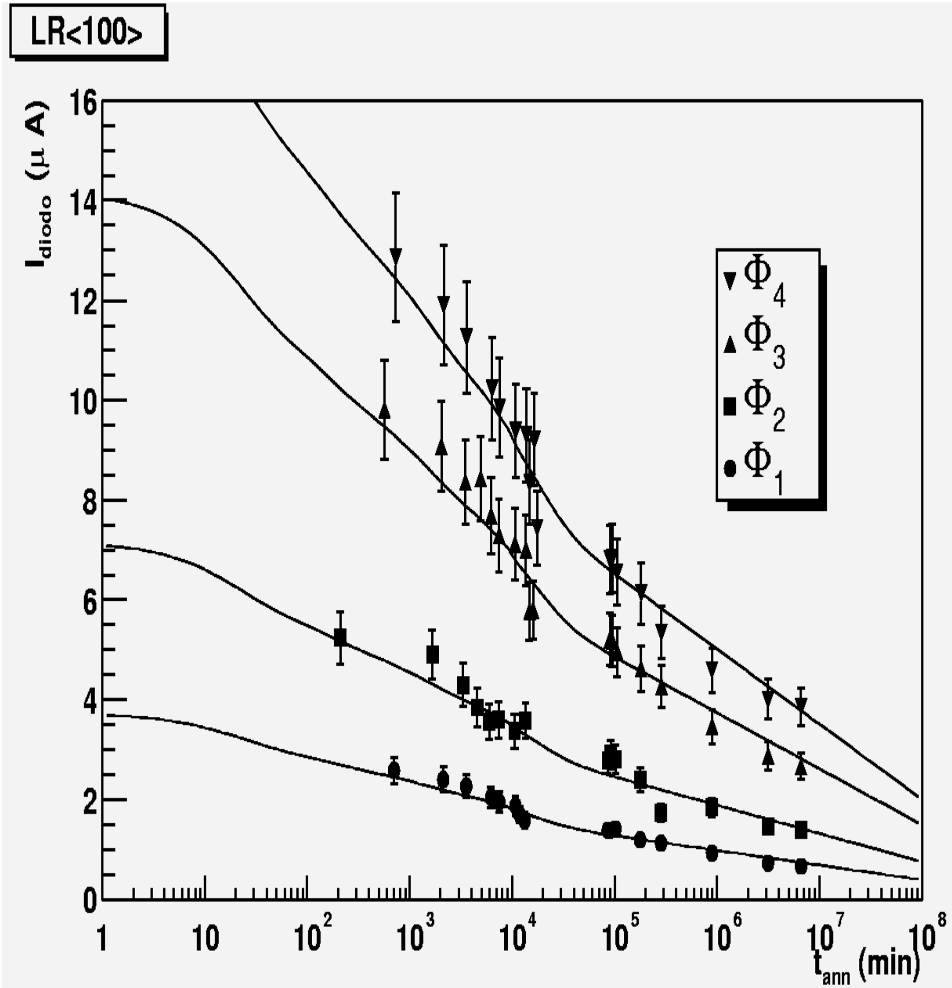
$$\alpha^{short}(t, T_a) = \alpha_\infty \sum_i \frac{b_i}{b_\infty} \cdot e^{\left(-\frac{t}{\tau_i(T_a)}\right)}$$ (*)

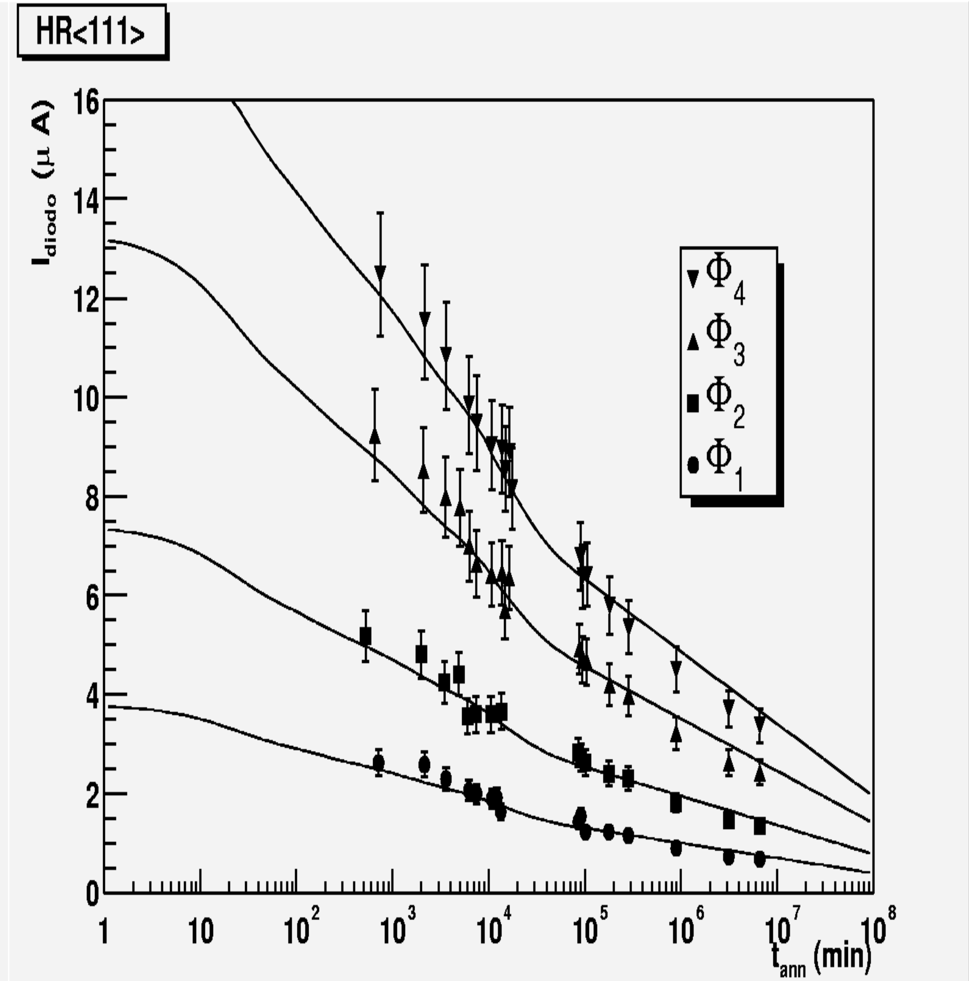
$$\alpha^{long}(t) = \alpha_I \cdot e^{-\frac{t}{\tau_I}} + \alpha_0 - \beta \cdot \ln\left(\frac{t}{t_0}\right)$$ (*)

We can determine the hardness factor → $k = \Phi^N / \Phi^P$

(*) Standard parameterisation for α(t,Φ) and parameters value from M. Moll PhD thesis

Diode leakage current vs. annealing time at 20^0C



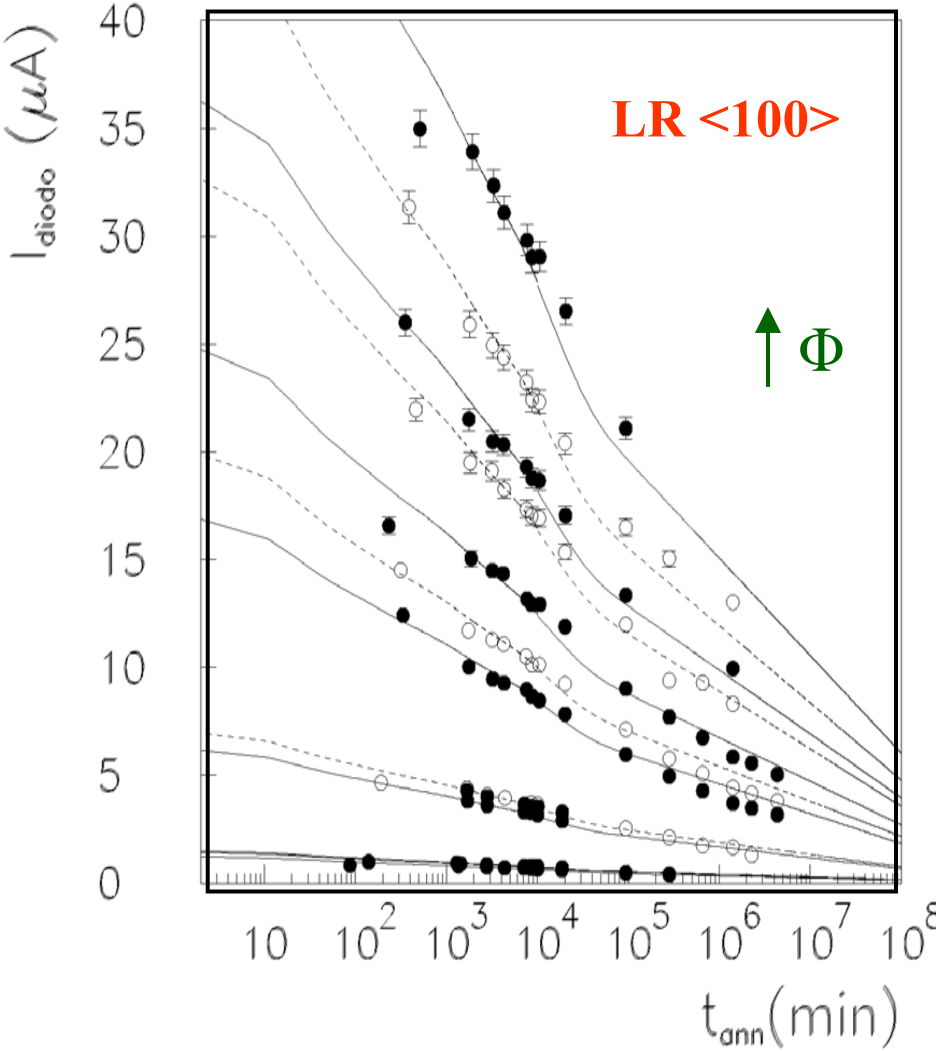


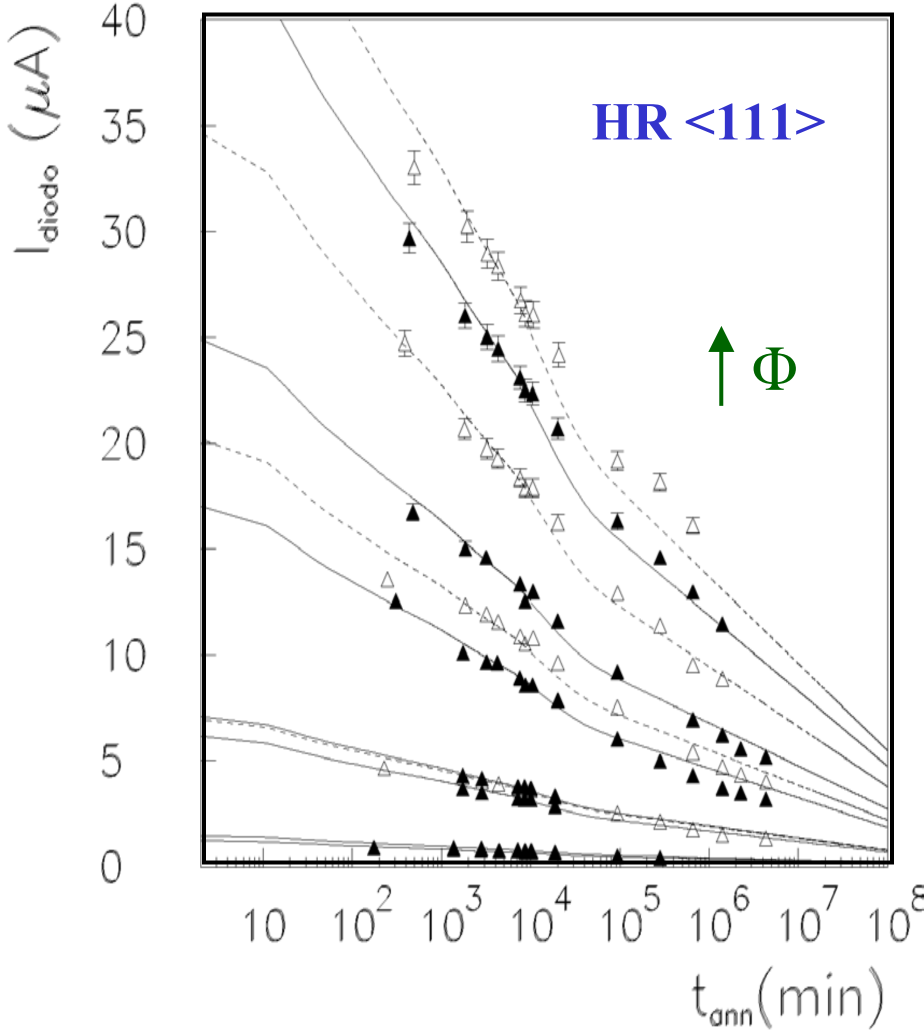
α^{short} α^{long} α^{short} α^{long}

$$\bar{k} = 1.3 \pm 0.3$$

$$k^{th} = 2$$

24 GeV/c proton irradiation





$$\overline{k} = 0.63 \pm 0.07$$

$$k^{ex} = 0.62; \; k^{th} = 0.5$$

The effective doping concentration N_{eff}

$$N_{eff}^{\Phi} = N_{eff}^{0} - N_A(\Phi, t(T_a)) - N_C(\Phi) - N_Y(\Phi, t(T_a))$$

Short term annealing:

$$N_A = g_A \Phi \cdot e^{-t/\tau_A}$$

Stable damage component:

$$N_C = N_{C0}\left(1 - e^{-C\Phi}\right) + g_C \cdot \Phi$$

Long term annealing:

$$N_Y = g_Y \Phi \cdot \left(1 - e^{-t/\tau_Y}\right)$$

first order process

$$N_Y = g_Y \Phi \cdot \left(1 - \frac{1}{1 + t/\tau_Y}\right)$$

second order process: with τ_Y ind. on Φ

$$N_Y = g_Y \Phi \cdot \left(1 - \frac{1}{1 + k_2 g_Y \Phi t}\right)$$

second order process: with $\tau_Y \propto 1/\Phi$

N_{eff} vs. Φ:

For a fixed annealing time t at the minimum of the ann. curve: $\tau_A << t << \tau_Y$

$$N_{eff}{}^{\Phi} = N_{eff}{}^{0} - N_{C0}\left(1 - e^{-C\Phi}\right) - \beta \cdot \Phi$$

- **Proton** irradiation: $N_{C0} \cong N_{eff}{}^{0}$ ← ***Complete donor removal***

$$N_{eff}{}^{\Phi} = N_{eff}{}^{0} e^{-C\Phi} - \beta \cdot \Phi \xrightarrow{High\Phi} -\beta \cdot \Phi$$

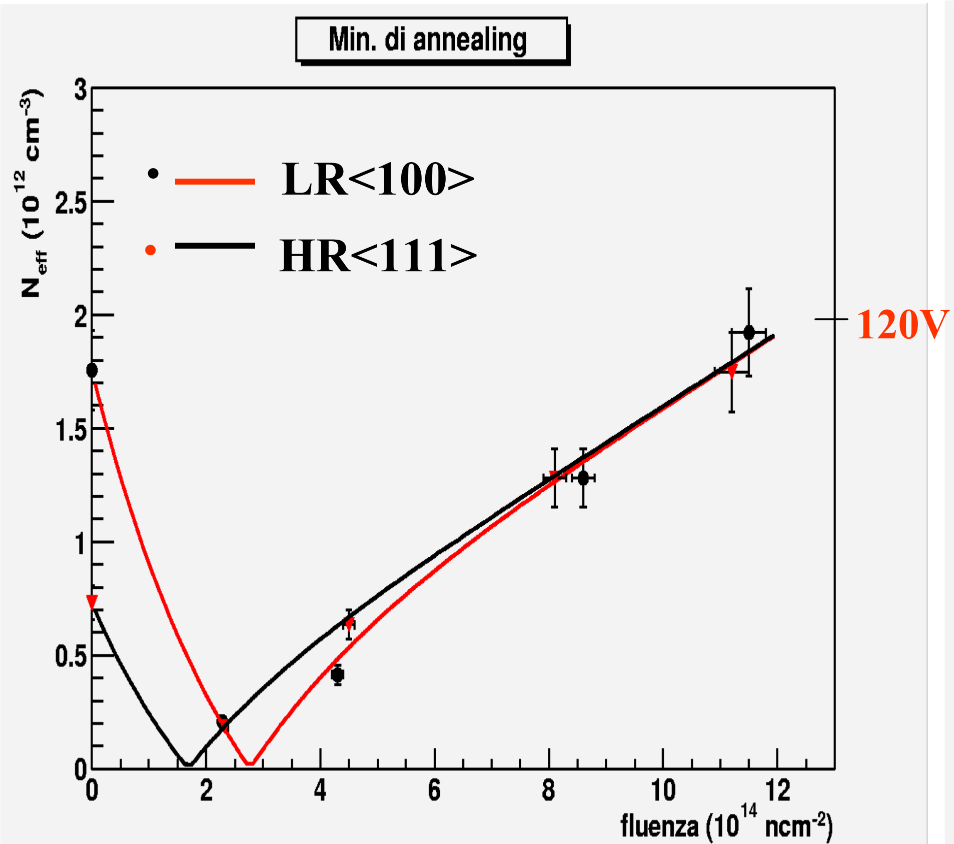
→ $\beta \approx g_C$

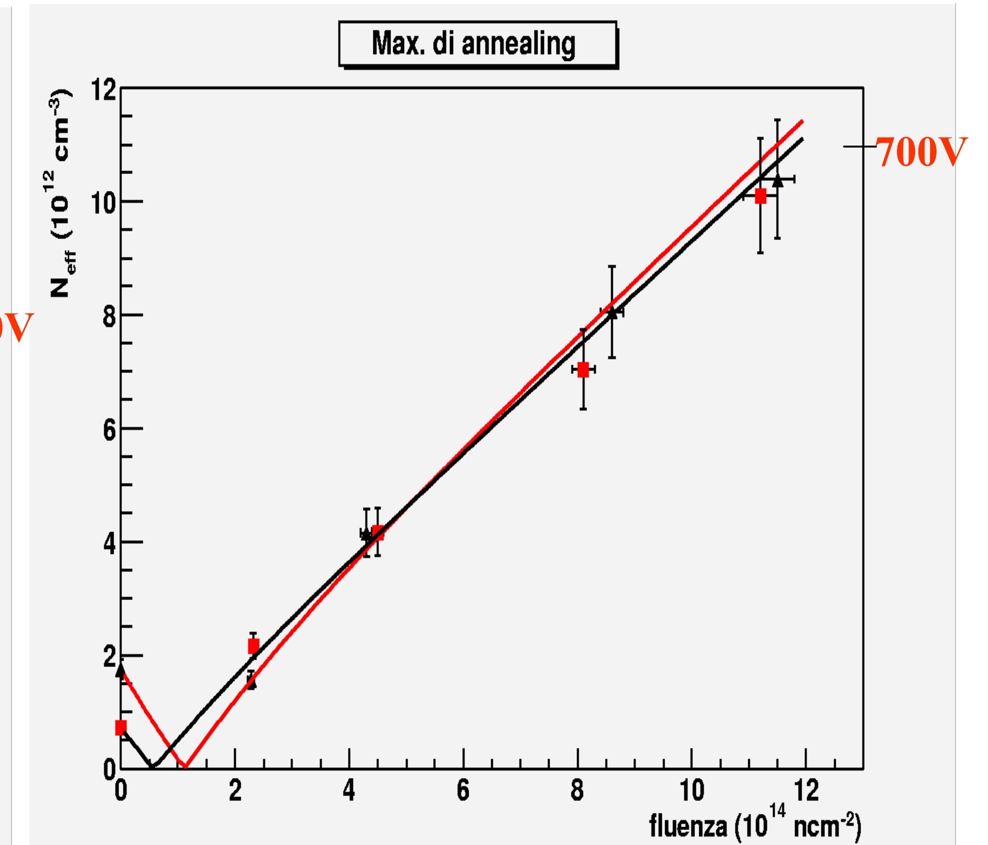
For a fixed annealing time t at the maximum of the ann. curve: $t >> \tau_Y$

$$N_{eff}{}^{\Phi} = N_{eff}{}^{0} e^{-C\Phi} - (g_C + g_Y) \cdot \Phi \xrightarrow{High\Phi} -\beta' \cdot \Phi$$

$$\beta' = g_C + g_Y$$

V_{dep} vs. fluence





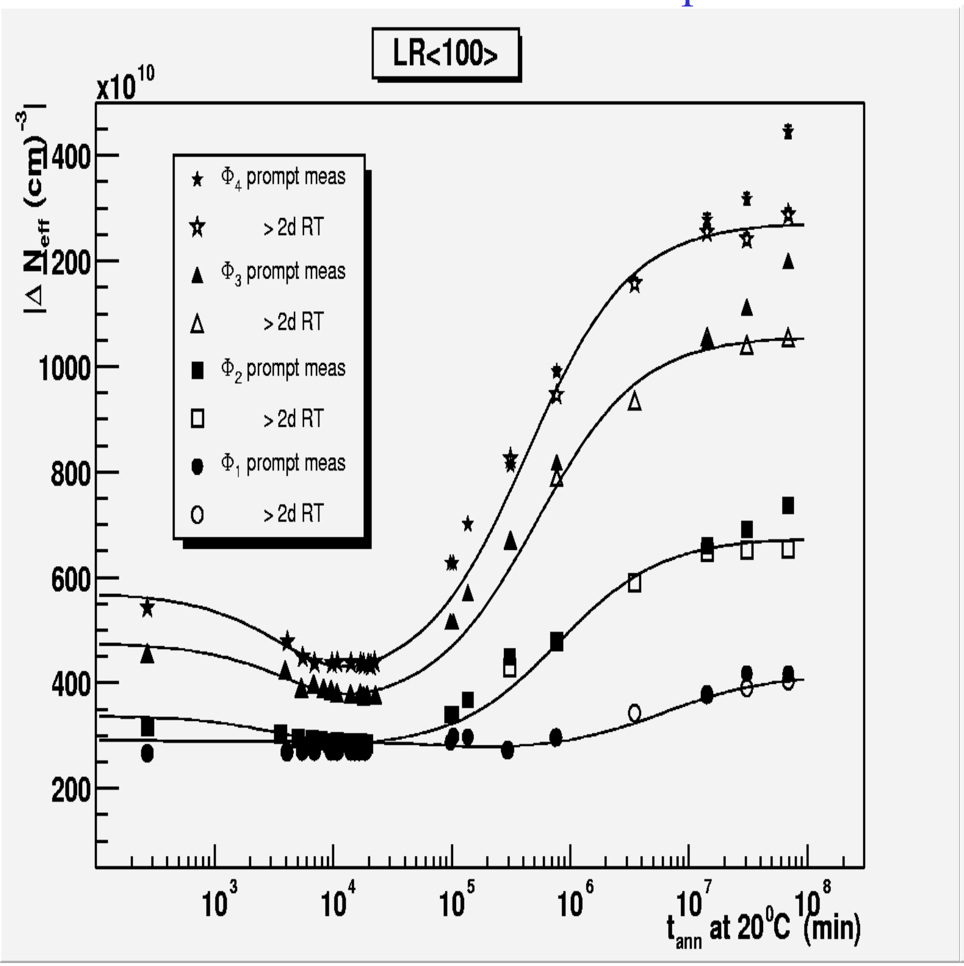
Diode	Energy	t_{ann}	β (cm^{-1})	C (cm^{-2})
LR<100>	24 GeV/c	min	$1.4*10^{-2}$	$2.3*10^{-14}$
HR<111>	24 GeV/c	min	$1.3*10^{-2}$	$4.5*10^{-14}$
LR<100>	34 MeV	min	$1.6*10^{-2}$	$5*10^{-14}$
HR<111>	34 MeV	min	$1.6*10^{-2}$	$5.5*10^{-14}$
LR<100>	34 MeV	max	$9.6*10^{-2}$	$4.5*10^{-14}$
HR<111>	34 MeV	max	$9.3*10^{-2}$	$5.5*10^{-14}$

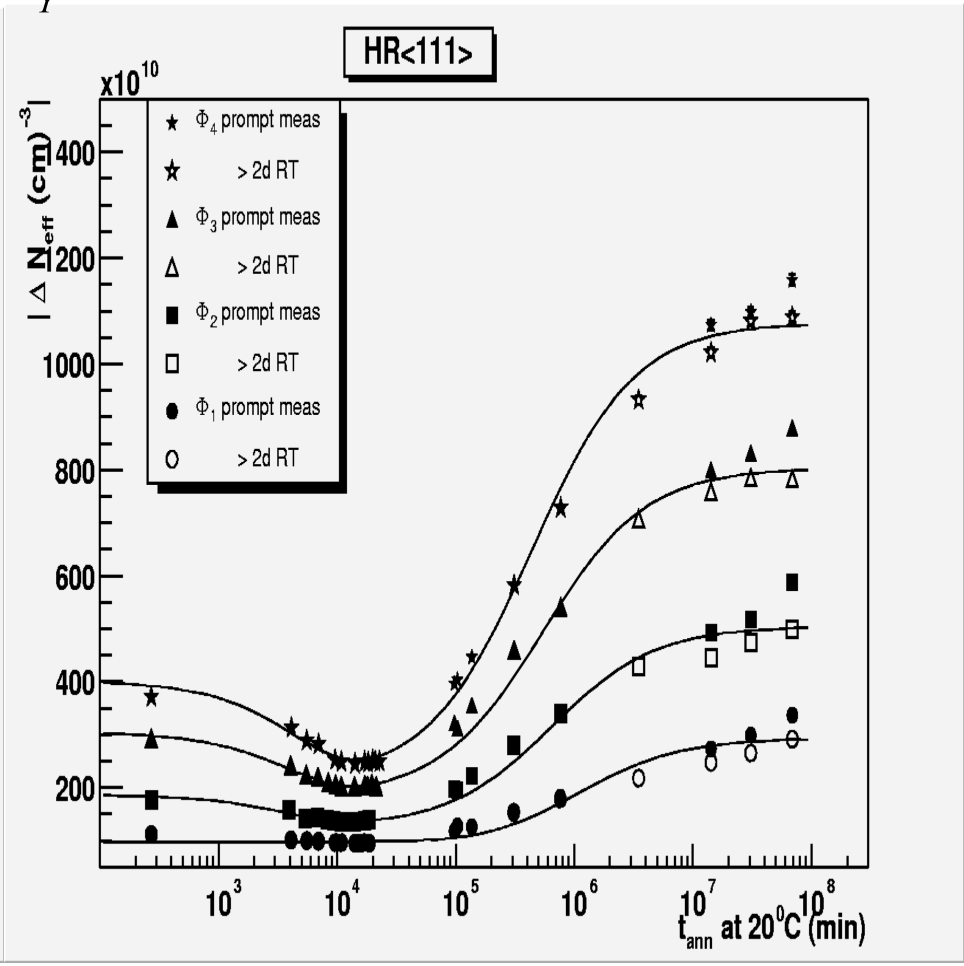
Rough estimation of

$g_Y = (\beta' - \beta) = 7.8*10^{-2}\ cm^{-1}$

Annealing behaviour of $|\Delta N_{eff}|$ at 20^0C

FIT- second order process with $\tau_Y \propto 1/\Phi$





$\bar{g}_Y = 7.8 \cdot 10^{-2} cm^{-1}$

$^{(*)}\bar{g}_C = 1.3 \cdot 10^{-2} cm^{-1}$

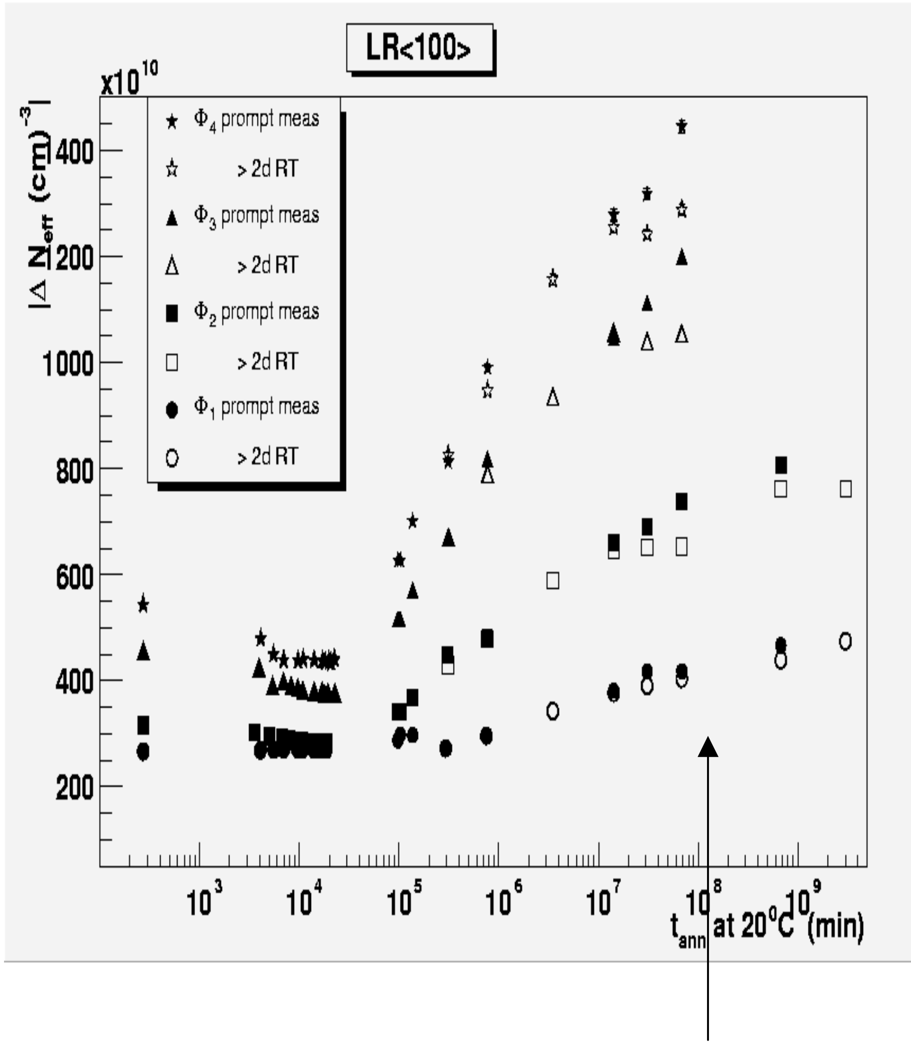
$(g_C(\Phi_1) = 4.5 \cdot 10^{-2} cm^{-1})$

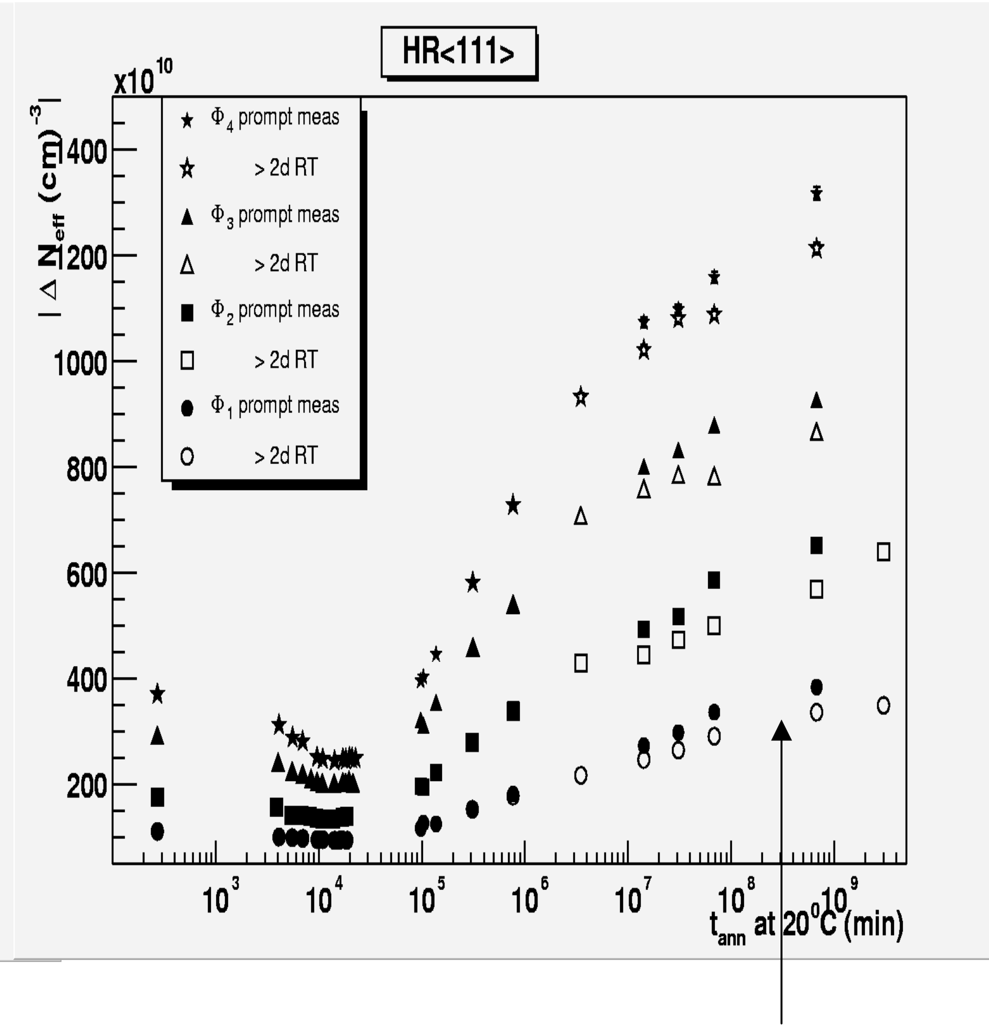
Similar to the 24 GeV values

$\bar{g}_Y = 8.2 \cdot 10^{-2} cm^{-1}$

$\bar{g}_C = 1.3 \cdot 10^{-2} cm^{-1}$

Annealing behaviour of $|\Delta N_{eff}|$ at 20^0C



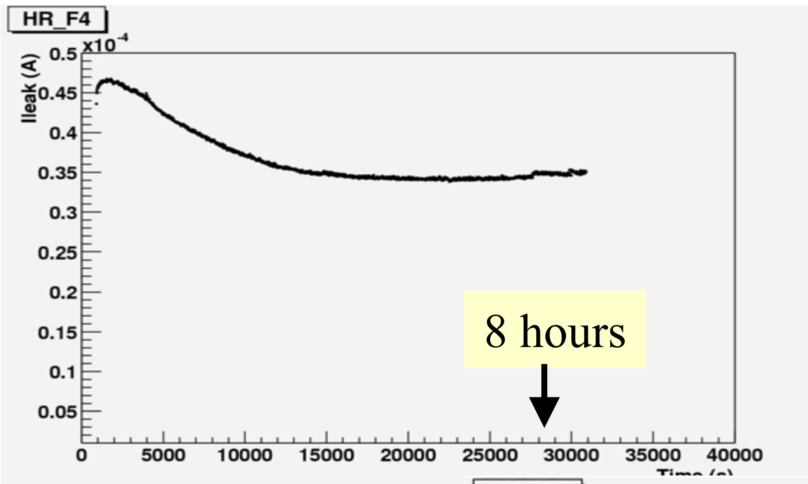


120^0C

120^0C

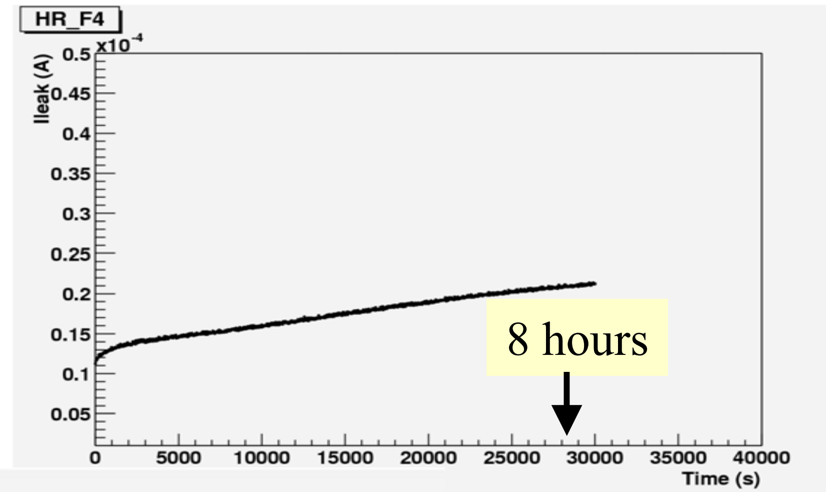
I_{leak} vs. relaxation time HR<111> Φ_4

The measurement of leakage current vs time (V_{bias}=400V) starts immediately after the heating at 80^0C.

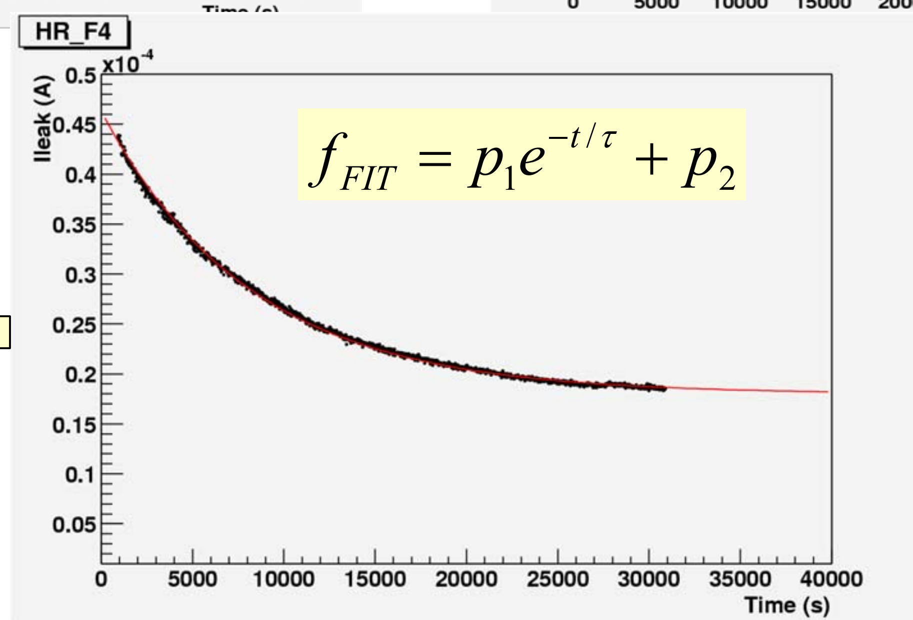


+

The measurement of leakage current vs time (V_{bias}=400V) starts after 24 hours from the heating.



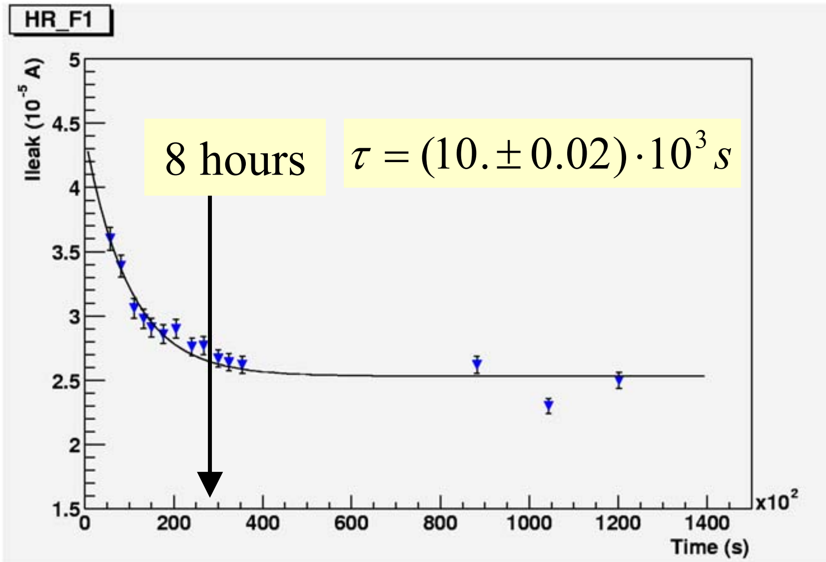
rescaled

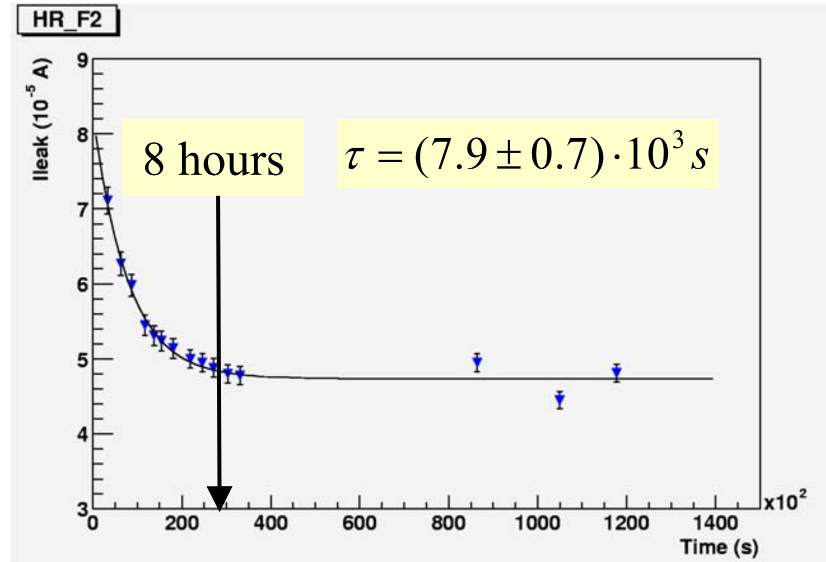


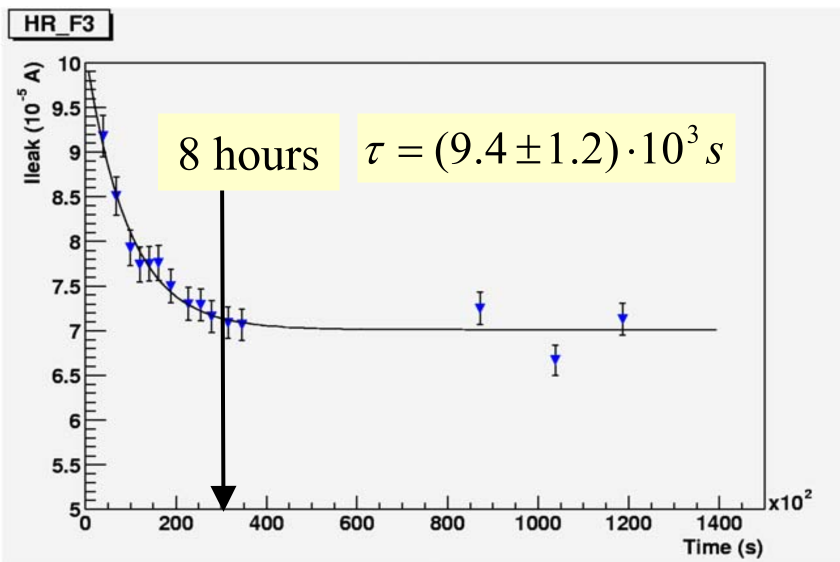
$\tau = (8.2 \pm 3) \cdot 10^3 s$

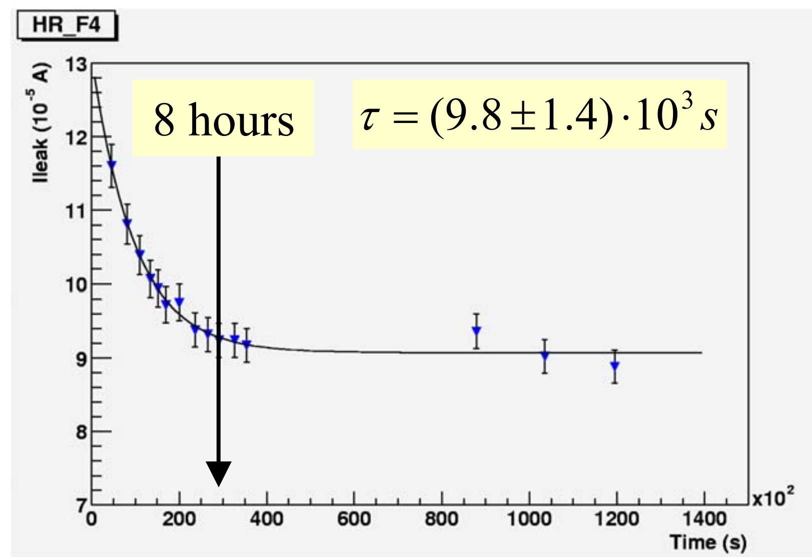
2.3 hours

I_{leak} vs. relaxation time HR <111>



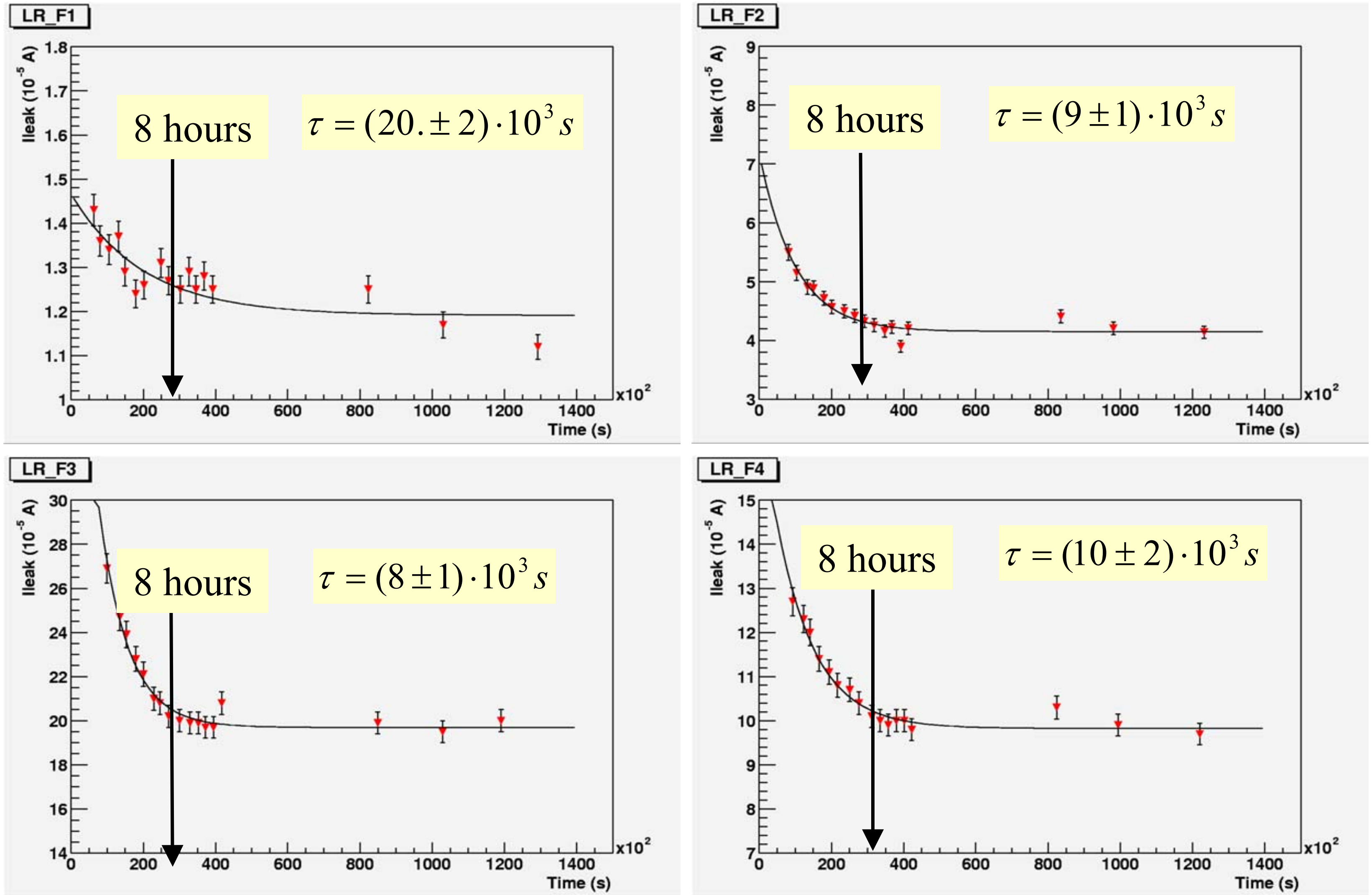






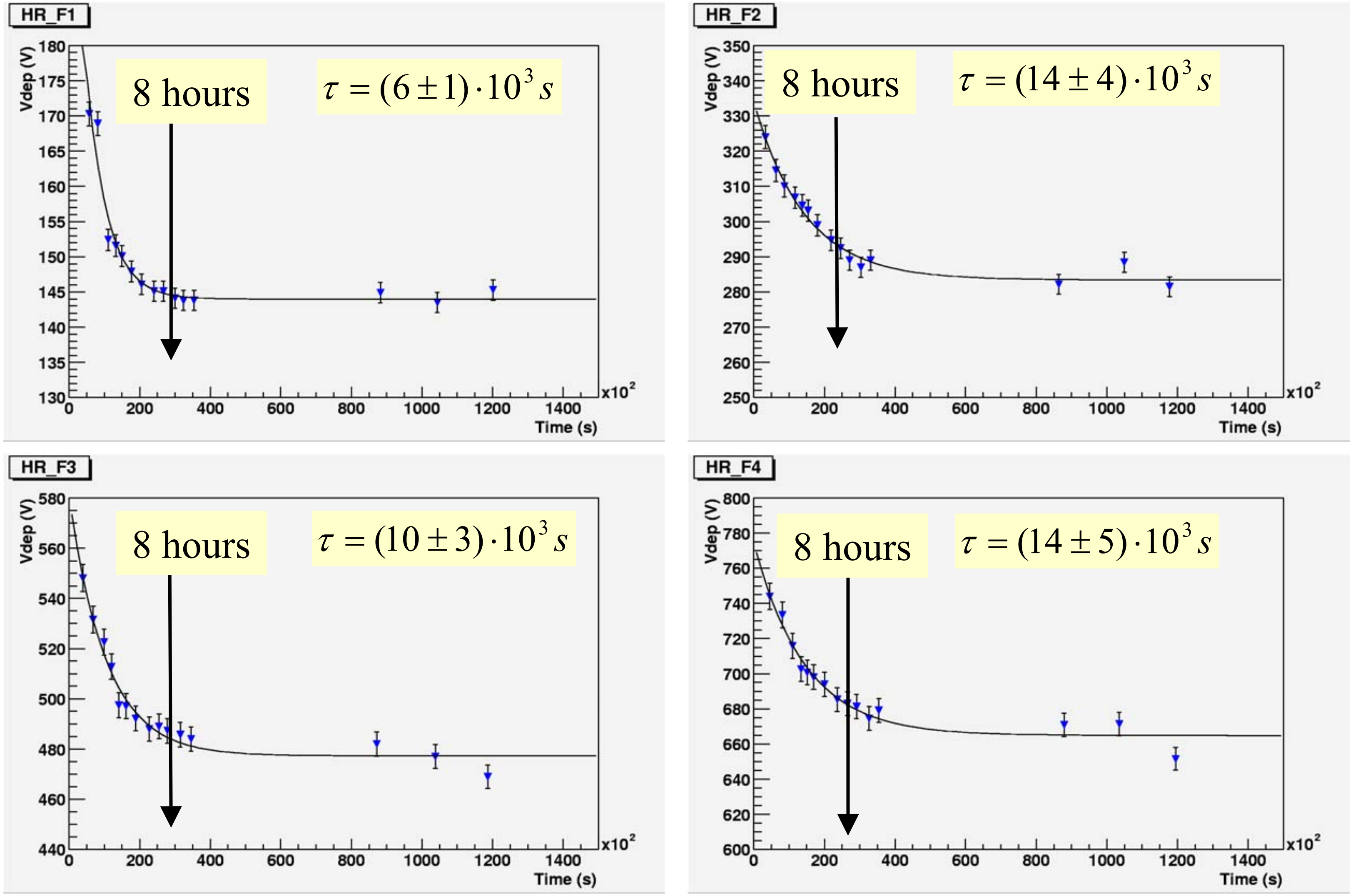
$\tau = 9\cdot 10^3 s$ → 2.6 hours

I_{leak} vs. relaxation time LR <100>



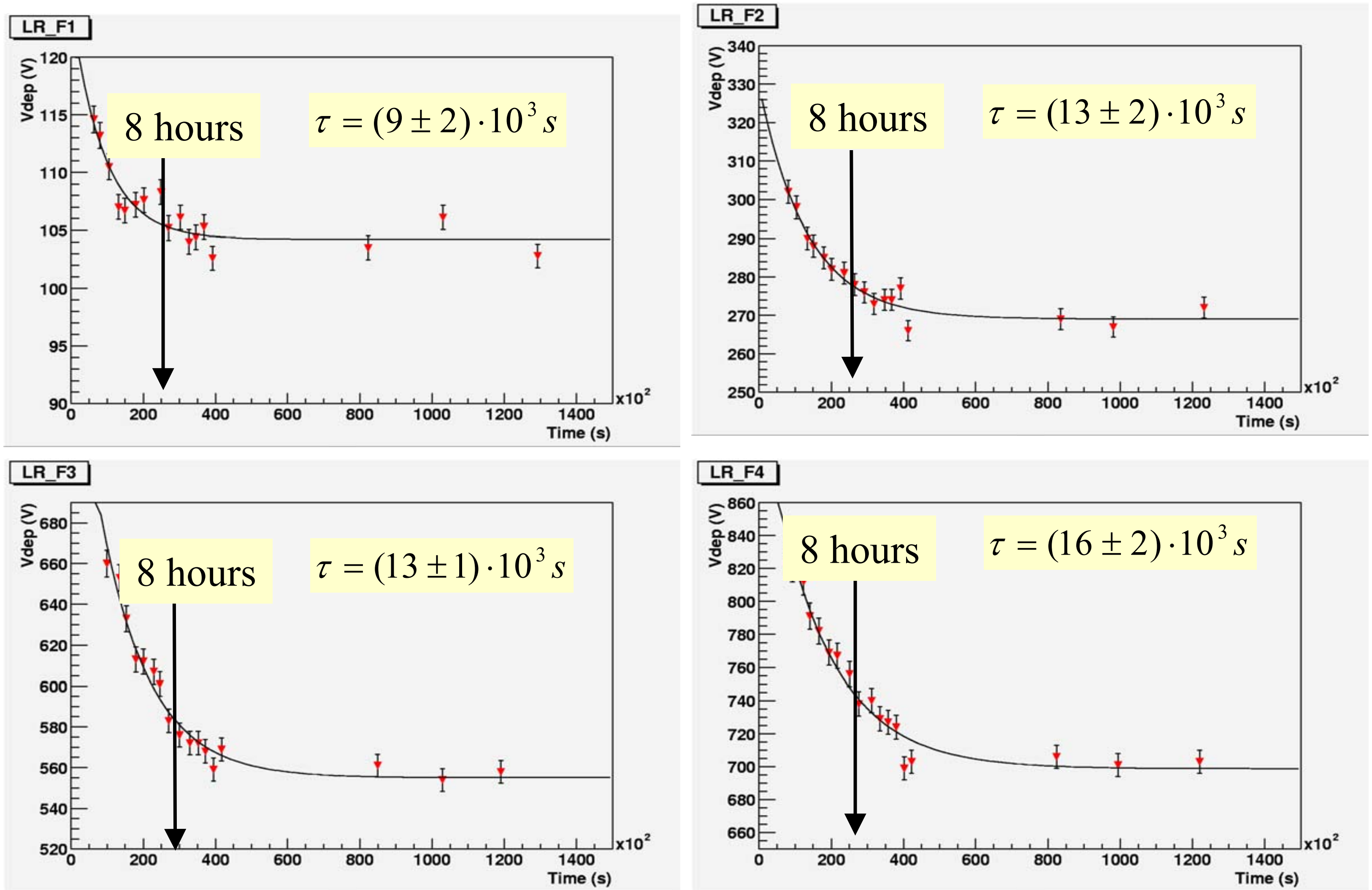
$\tau = 12 \cdot 10^3 s$ → 3.3 hours

V_{dep} vs. relaxation time HR <111>



$\tau = 11 \cdot 10^3 s$ → 3 hours

V_{dep} vs. relaxation time LR <100>



$\tau = 13 \cdot 10^3 s$ → 3.5 hours

Conclusions

- As expected, leakage current doesn't depend on the substrate resistivity and orientation.

- The measurement of I_{leak} vs. annealing time allows a good estimation of Φ^N and a determination of the k factors both for 34 MeV and for 24 GeV/c protons. We have extracted:

k=1.3±0.3 for **34 MeV** proton irradiation → less than the theoretical value of $k^{th} \sim 2$ obtained from displacement damage function (NIEL hypothesis).

(**k=0.63±0.07** for **24 GeV/c** proton irradiation)

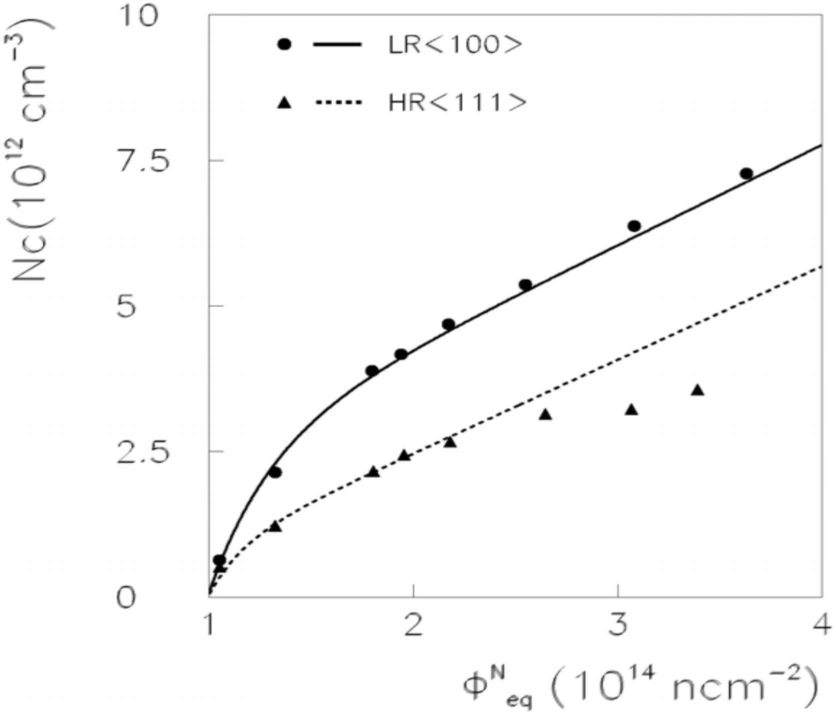
- As for high energy protons, also for 34 MeV proton irradiation N_{eff}^{Φ} is characterized by a **complete donor removal.**

- The **annealing parameters** were extracted for 34 MeV proton irradiation after the complete relaxation of the bistable defects, using the II order - fluence depending- parameterisation.

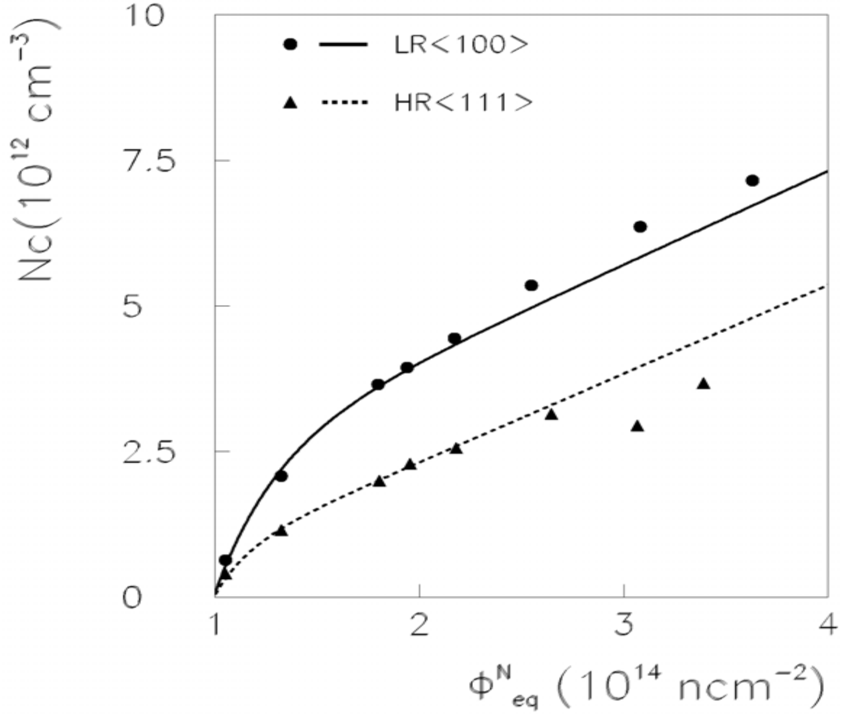
- Both current and depletion voltage relaxation time constants have been estimated for the full samples heated at 80^0C and $\tau_{rel} < 3.5$hours.

N_C vs. Φ^N

I order



II order



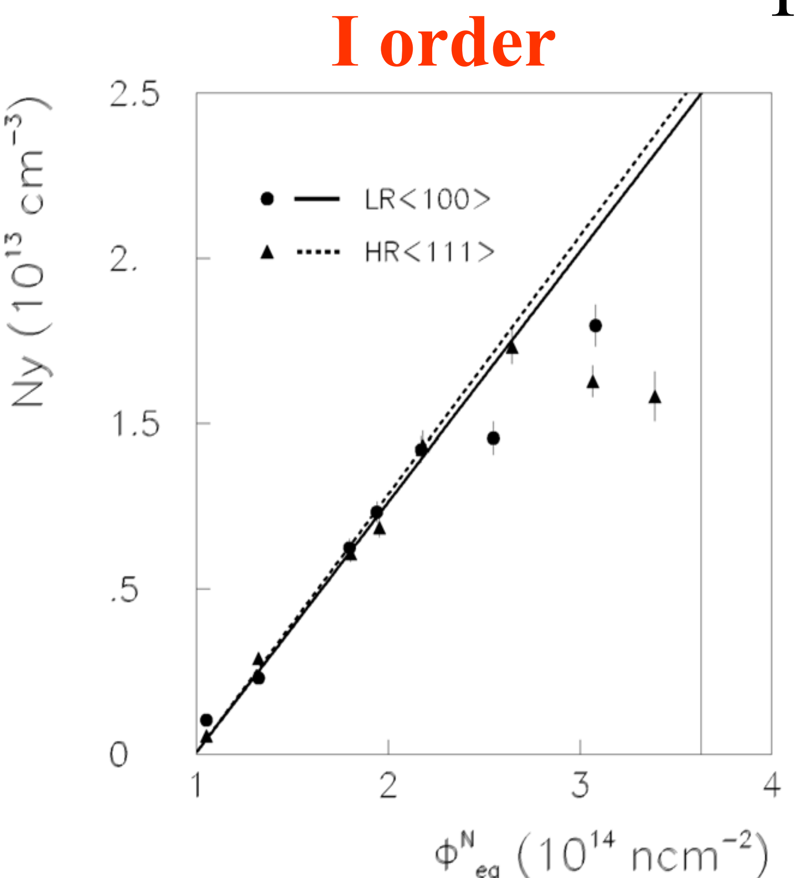
	N_{eff0} (10^{12} cm^{-3})	N_{C0} (10^{12} cm^{-3})	g_C (10^{-2} cm^{-1})	N_{C0}/N_{eff0}
LR I	2.34	2.58±0.06	1.29±0.05	1.1
HR I	0.73	0.84±0.01	1.21±0.01	1.1
LR II	2.34	2.48±0.06	1.21±0.06	1.1
HR II	0.73	0.8±0.1	1.1±0.1	1.1

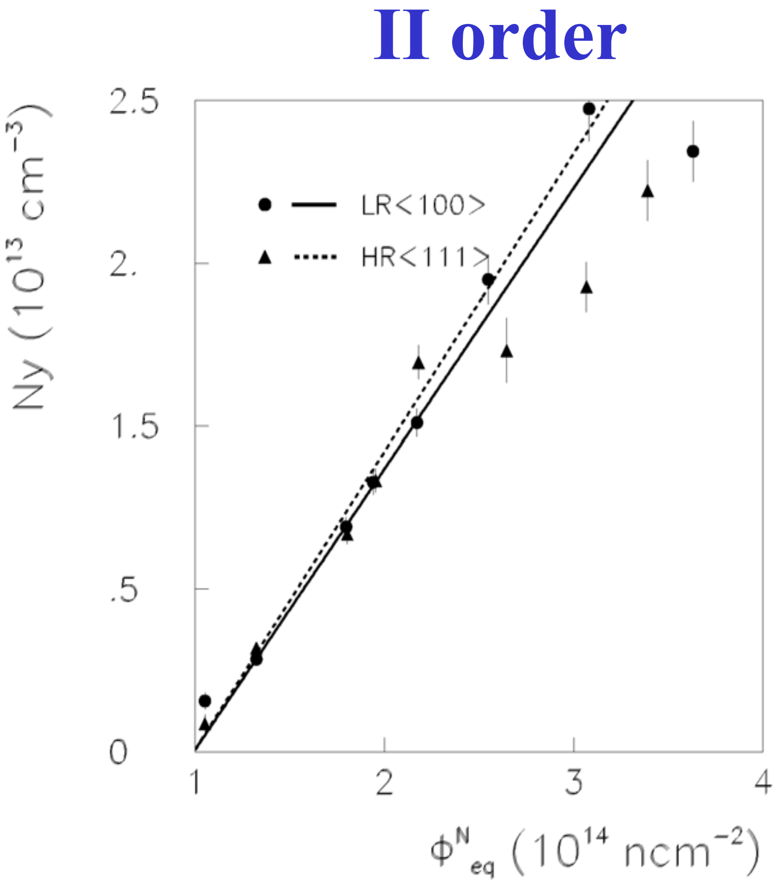
—— • LR<100>

······ ▲ HR<111>

Complete donor removal

N_Y vs. Φ^N





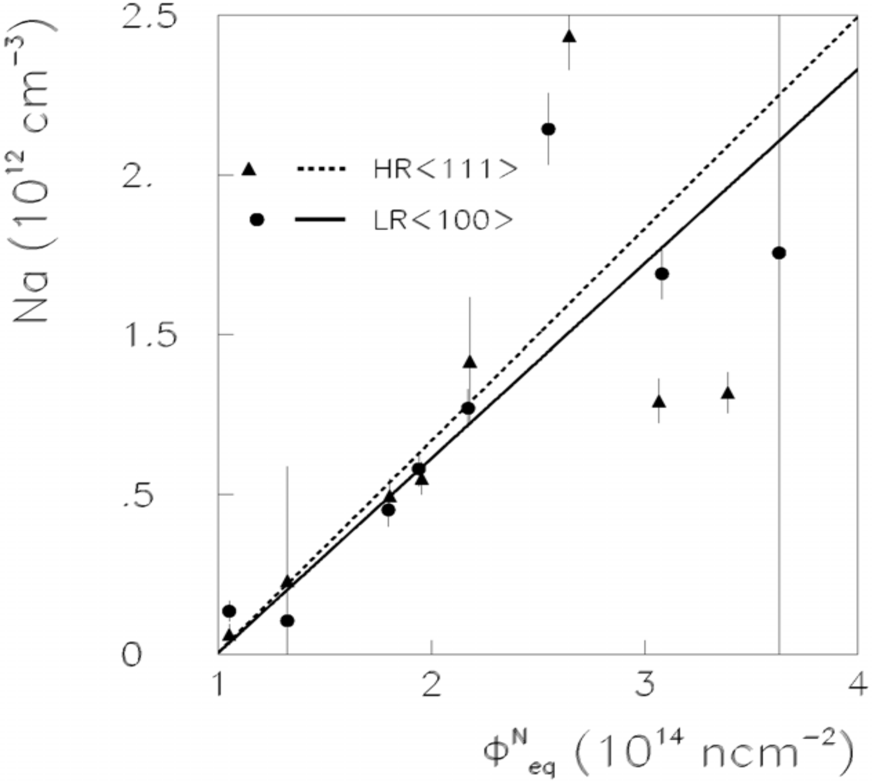
	N_{eff0} (10^{12} cm^{-3})	g_y (10^{-2} cm^{-1})	τ_y (10^6 min)
LR I	2.34	7.11±0.03	1.67±0.03
HR I	0.73	7.34±0.04	1.52±0.02
LR II	2.34	8.10±0.03	1.13±0.01
HR II	0.73	8.60±0.04	1.23±0.02

—— ● **LR<100>**

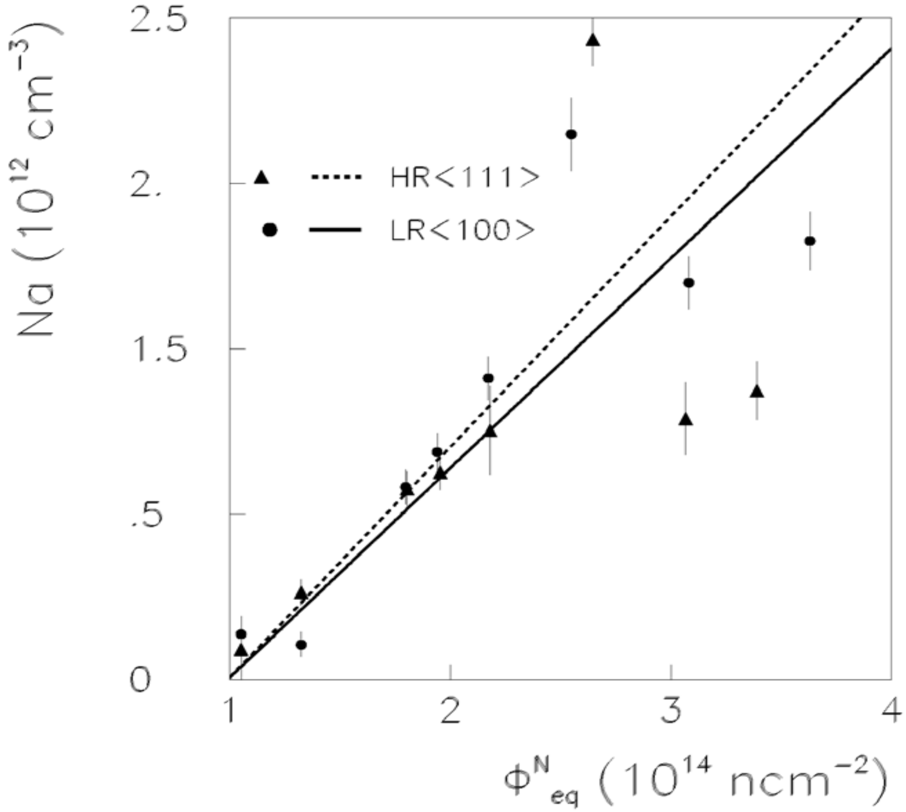
······ ▲ **HR<111>**

N_A vs. Φ^N

I order



II order



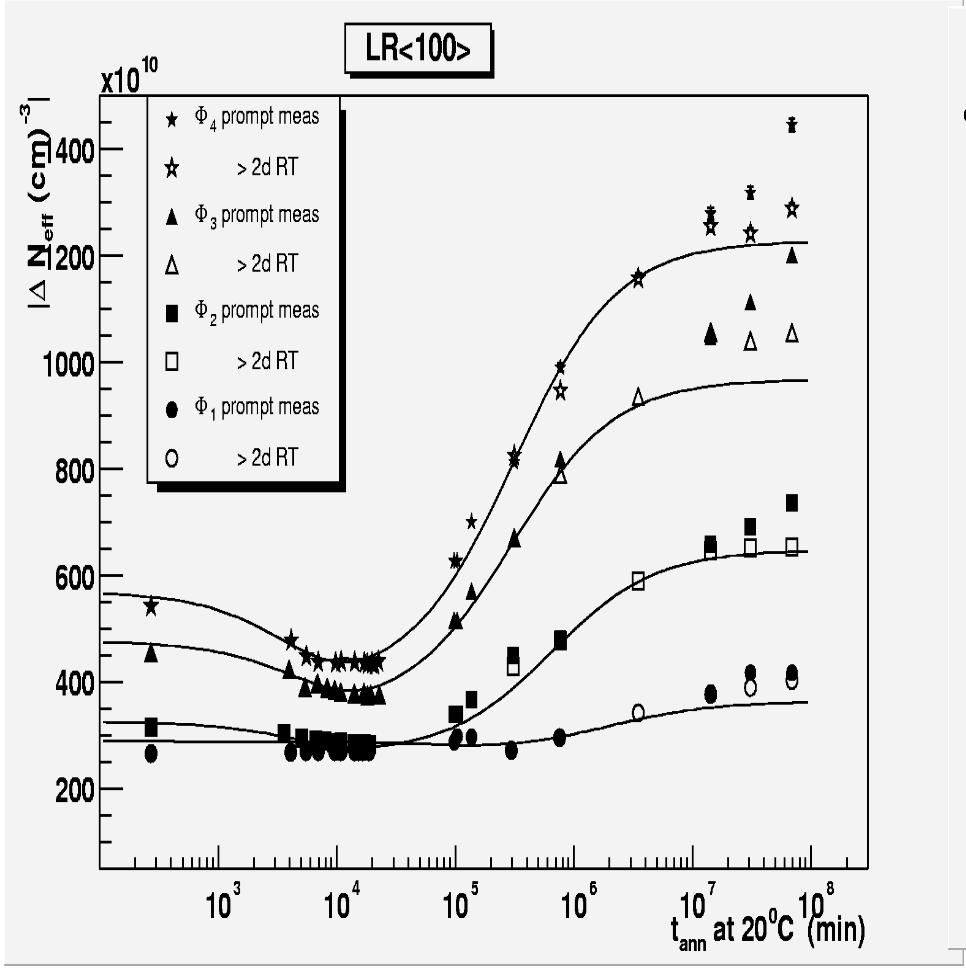
	N_{eff0} (10^{12} cm^{-3})	g_A (10^{-2} cm^{-1})	τ_A (10^3 min)
LR I	2.34	0.57±0.03	2.1±0.2
HR I	0.73	0.6±0.7	2.1±0.4
LR II	2.34	0.60±0.07	3.5±0.4
HR II	0.73	0.65±0.05	3.8±0.9

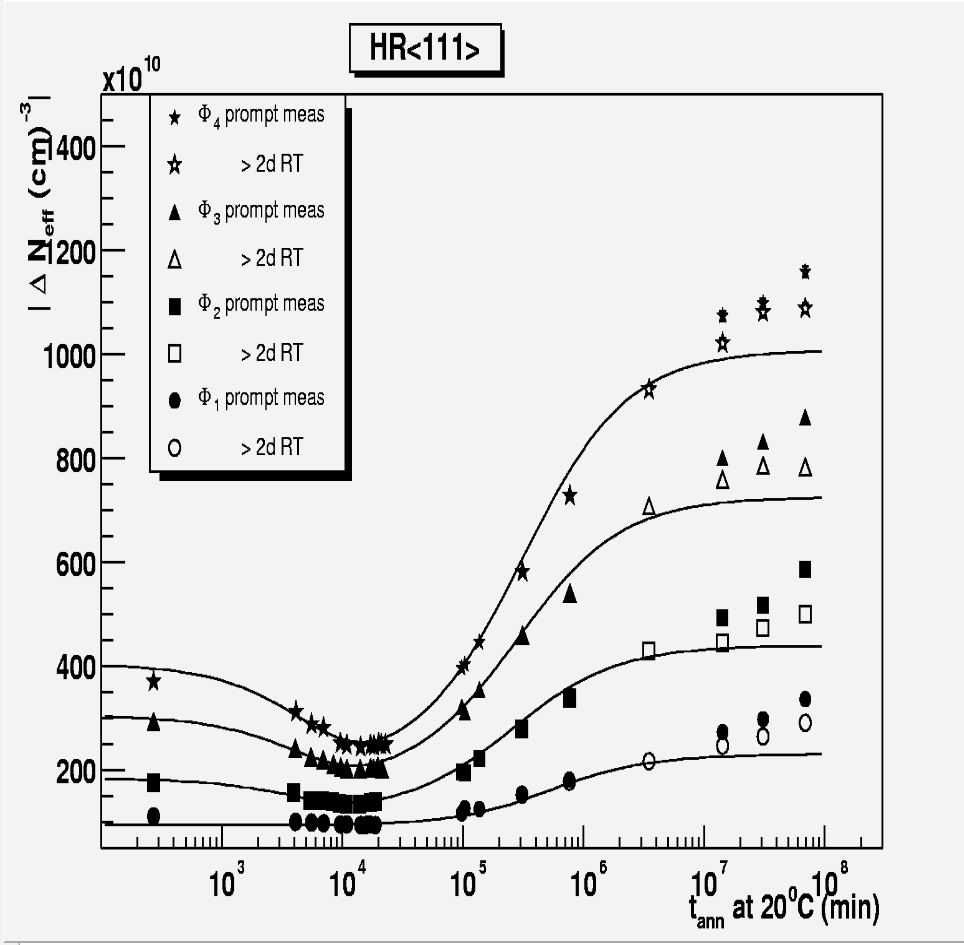
—— • **LR<100>**

...... ▲ **HR<111>**

Annealing behaviour of $|\Delta N_{eff}|$ at 20^0C

FIT- second order process with τ_Y const.





Annealing behaviour of $|\Delta N_{eff}|$ at 20^0C