Evolution of pulsed current and carrier lifetime characteristics in Si structures during 25 MeV neutrons irradiation using spallator type neutrons source

E.Gaubas[1], T.Ceponis[1], A.Jasiunas[1], A.Uleckas[1], J.Vaitkus[1], E.Cortina[2], and O.Militaru[3]

[1] *Vilnius University, Institute of Applied Research, Vilnius*
[2] *Center for Cosmology, Particle Physics and Phenomenology, Universite catholique de Louvain*
[3] *Cyclotron Research Center, Universite catholique de Louvain, Louvain la Neuve*

Outline

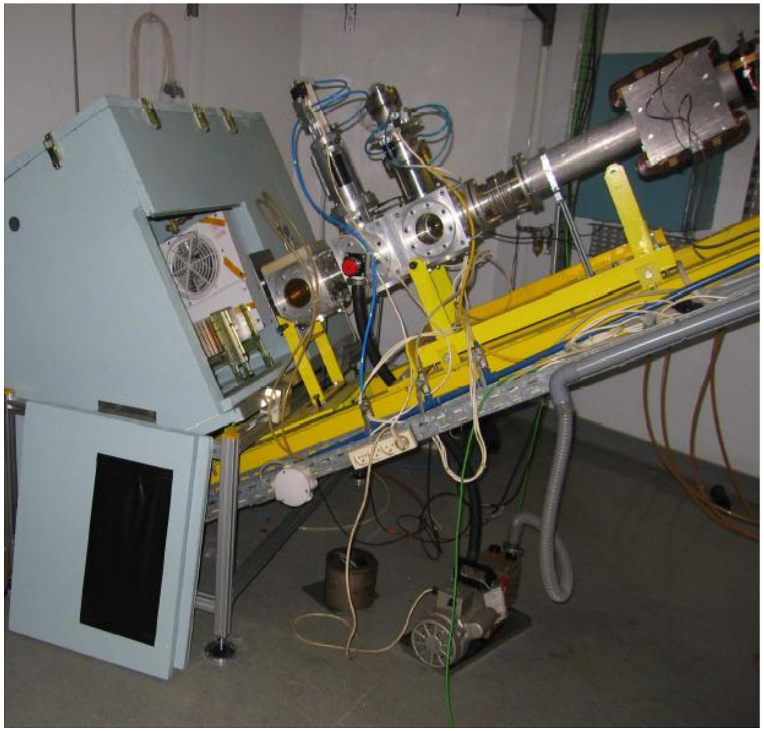
- Motivation
- Neutron source at Louvain la Neuve University
- Sketch of experiments
- Evolution of the pulsed currents and carrier recombination characteristics
- Summary

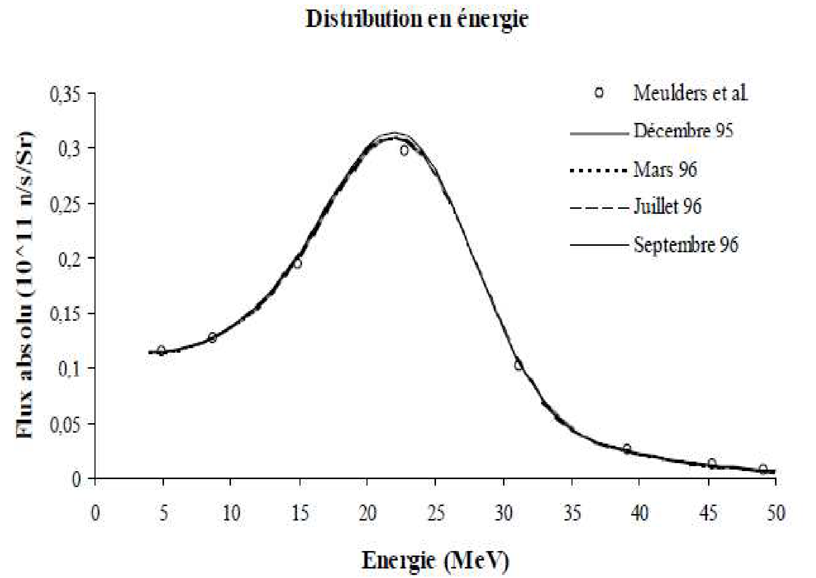
Motivation

- To predict signal changes and to foresee possible modifications of the detector performance
- Comparison of variations of carrier drift and recombination characteristics during neutron and proton irradiations

Neutron source at Louvain la Neuve University

The energy spectrum of the out-coming neutron beam is dominated by a peak in the region of 25 MeV.

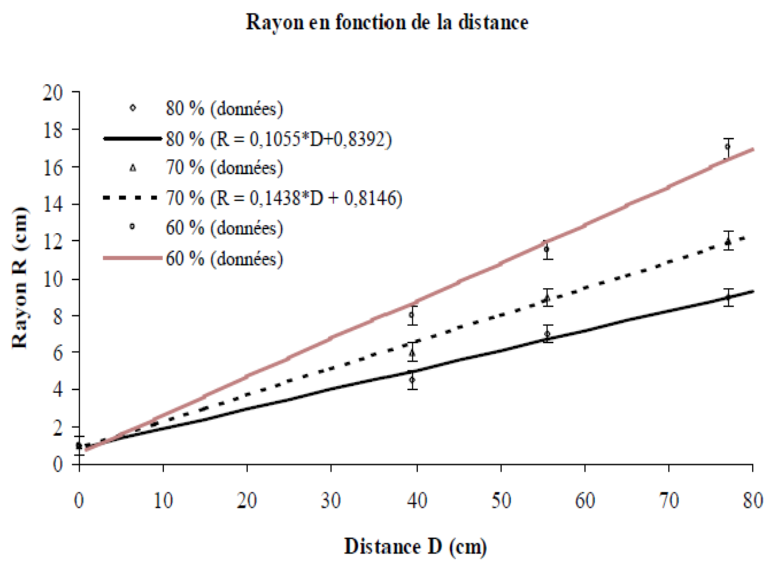




The high flux neutron line is located at the Louvain la Neuve -Cyclotron. It uses a primary 50 MeV deuteron beam that is sent on a thin beryllium target. The high cross section reaction $^{9}Be(d,n)^{10}B$ produces the high flux neutron beam.

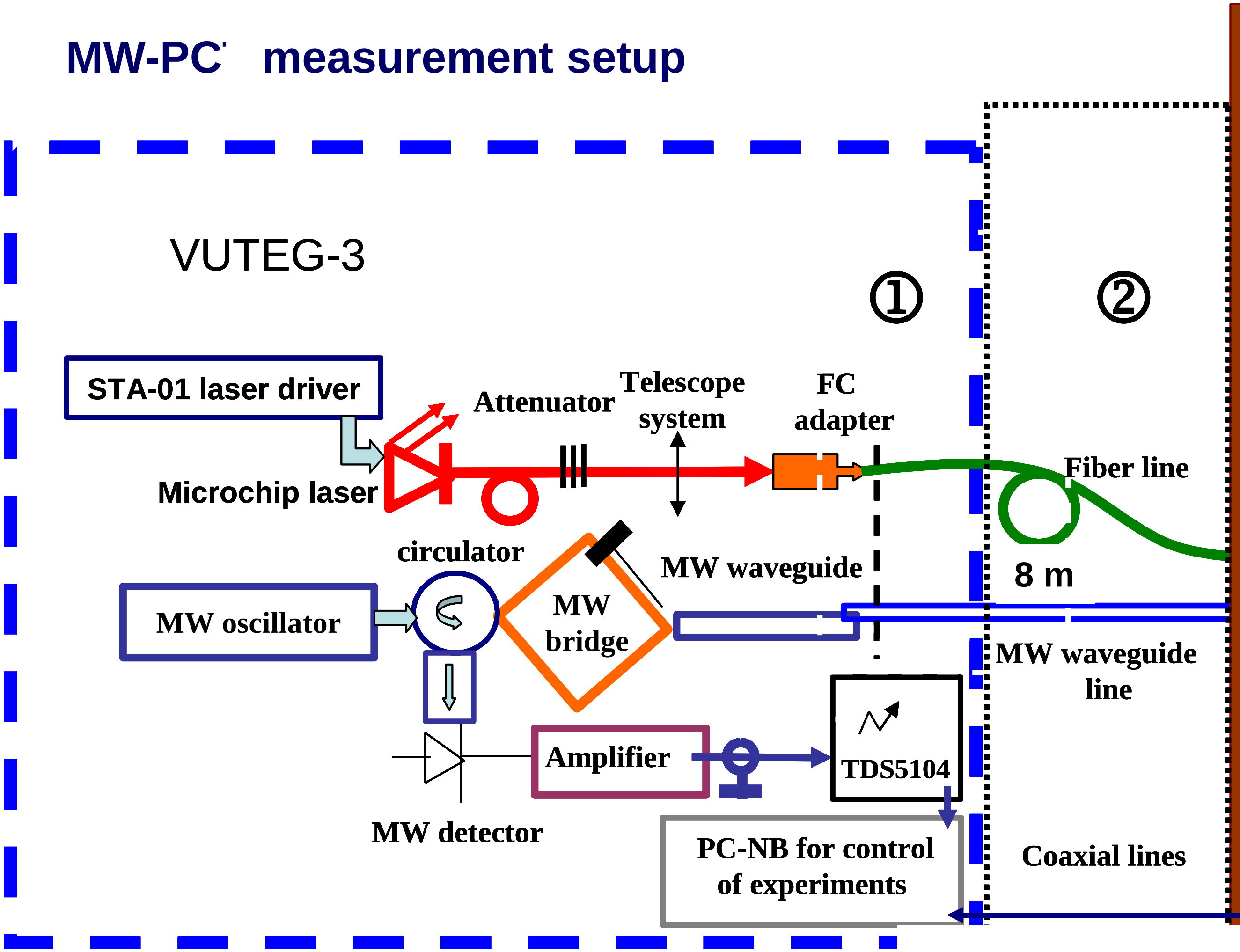
To keep the gamma and charged particle contamination as low as possible filters are placed outside the target box and fixed to the box window, made of three layers: 1 cm thick polyethylene, 1 mm Cadmium and 1 mm Lead. The filter also removes from the beam the low energy neutrons.

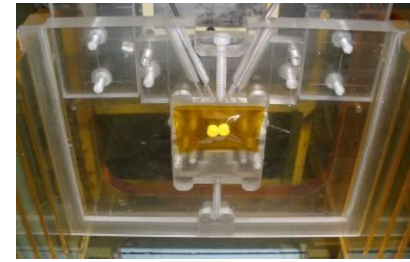
Neutron spatial distribution variation with distance from the target



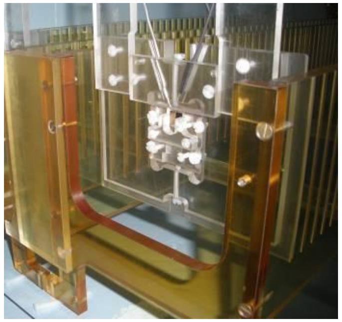
Sketch of experiments

MW-PC measurement setup





Comparison of results of the in situ changes of recombination lifetime during 8 MeV protons, nuclear reactor and spallator 25 MeV neutrons irradiation

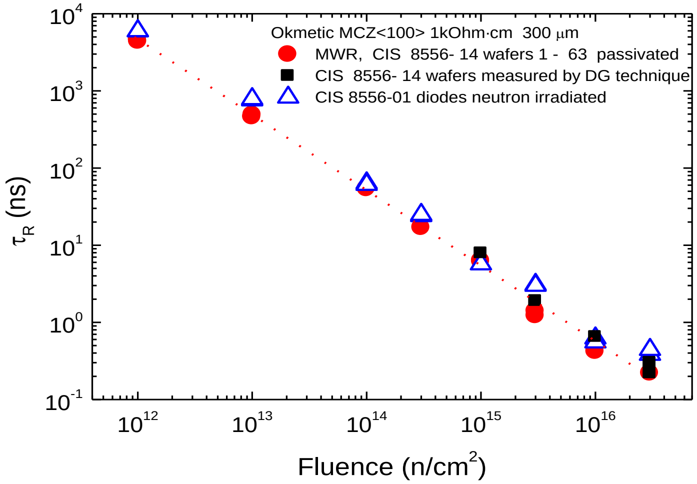


$$\tau_{R,cluster} = \frac{1}{v_T \sigma_{cl} N_{cl}} = \frac{1}{v_T \sigma_{cl}(\Phi)(N_{cl,0} + N_{cl}(\Phi))}$$

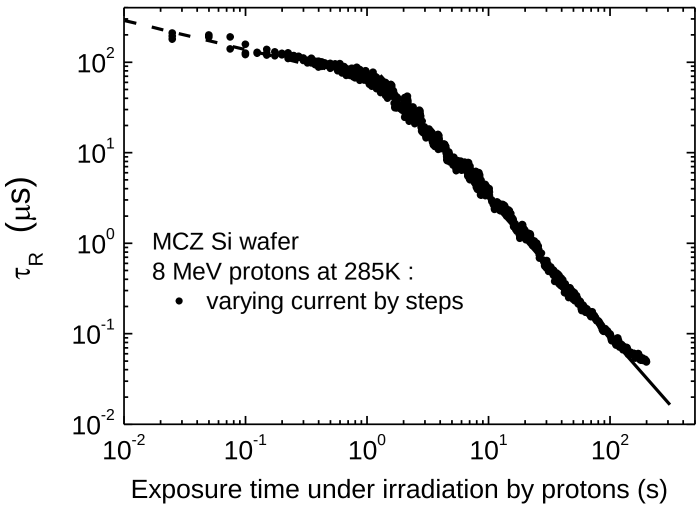
$$\sigma_{cl} = \sigma_0 \exp(eV_{b,cl}/kT)$$

$$\tau_{R,cluster} \cong \frac{1}{v_T \sigma_0 [\frac{N_D}{n_i^2}(\sum_{n=1}^{V_n} \frac{\partial N_{A,n}}{\partial \Phi}\Phi]^c \, (N_{cl,0} + \frac{\partial N_{cl}(\Phi)}{\partial \Phi}\Phi)} \propto \frac{1}{a\Phi^c + b\Phi^{c+1}}$$

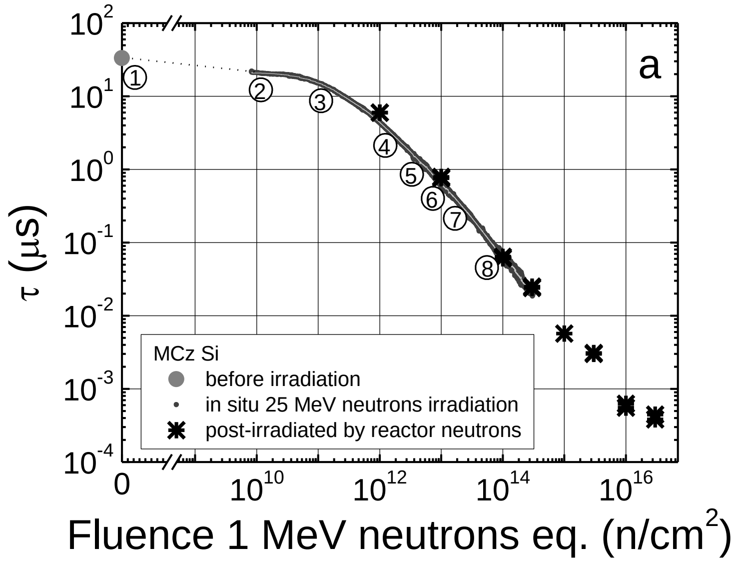
Reactor neutrons



8 MeV protons



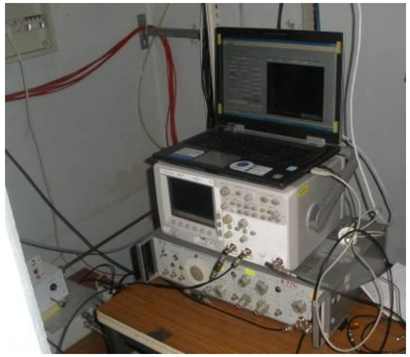
Spallator neutrons

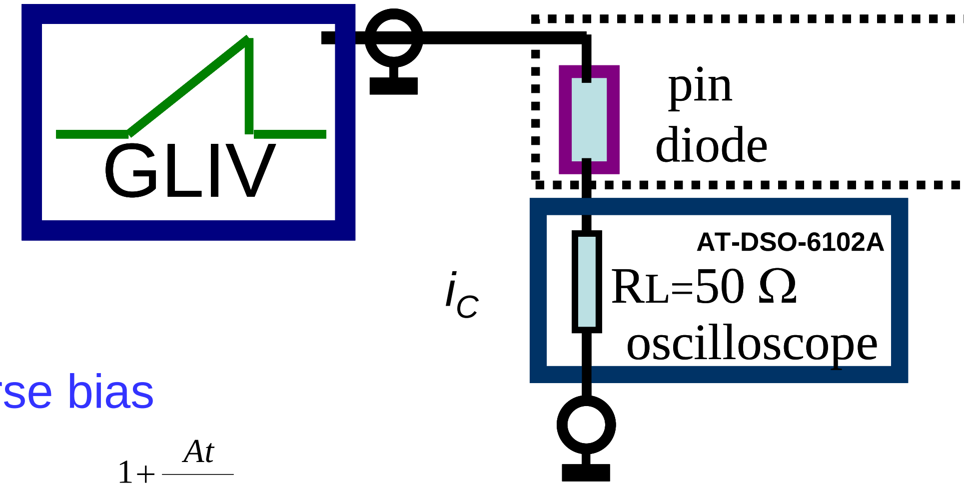


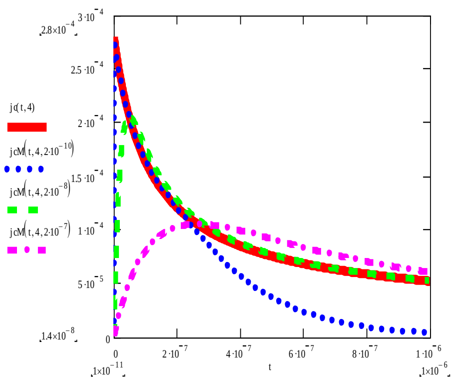
Setup for implementation of BELIV technique

$U(t)=U_P/\tau_{PL}t=At$
LIV ramp $A=U_P/\tau_{PL}=\partial U/\partial t$

τ_{PL}= 10 ns $\Rightarrow$ 500 µs
U_P= 0.01 $\Rightarrow$ 5 V



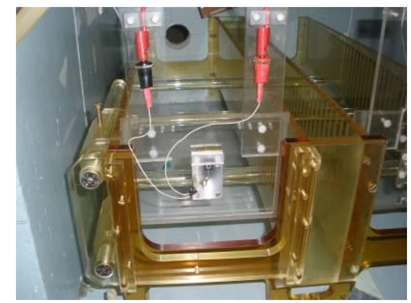


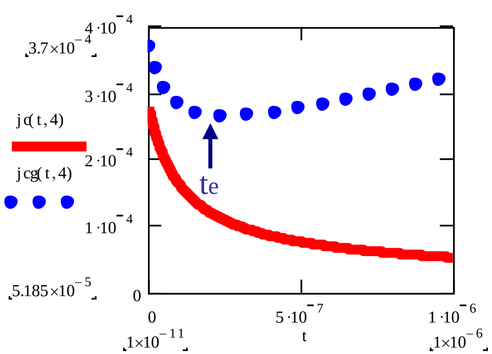


Reverse bias

$$i_C(t)=\frac{dq}{dt}=AC_{b0}\frac{1+\frac{At}{2U_{bi}}}{(1+\frac{At}{U_{bi}})^{3/2}}$$

$$i_{CM}(t)=\frac{1}{\tau_{RC}}\int_0^t i_C(x)\exp[-\frac{(t-x)}{\tau_{RC}}]dx$$



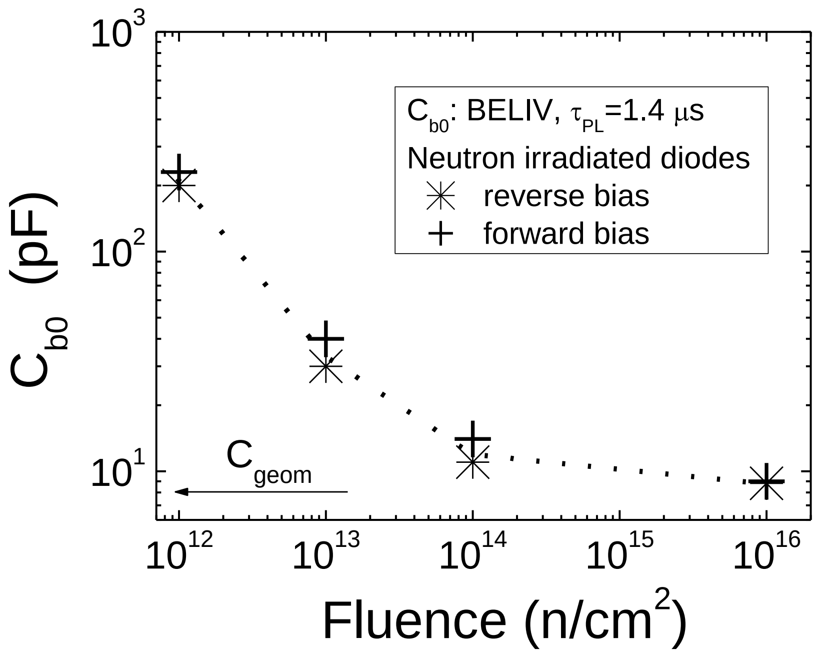


$$i_{R\Sigma}(t)=i_C(t)+i_{diff}(t)+i_g(t)=AC_{b0}\frac{1+\frac{At}{2U_{bi}}}{(1+\frac{At}{U_{bi}})^{3/2}}+i_{diff\infty}(1-e^{-\frac{eAt}{k_BT}})+\frac{emSw_0}{\tau_g}(1+\frac{At}{U_{bi}})^{1/2}$$

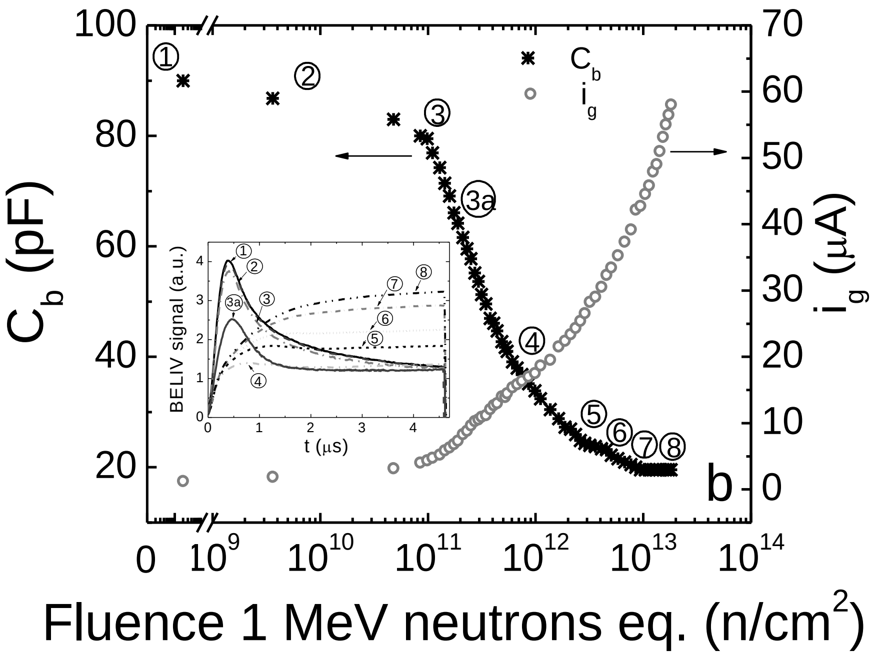
$$t_e=\frac{U_{bi}}{Ai_g(0)}[\frac{i_C(0)}{4}-i_g(0)+\sqrt{(\frac{i_c(0)}{4})^2+\frac{3}{2}i_c(0)i_g(0)}]$$

Comparison of results of changes of the barrier capacitance charging and thermal-generation current changes under nuclear reactor and spallator 25 MeV neutrons irradiation, measured in situ by BELIV technique

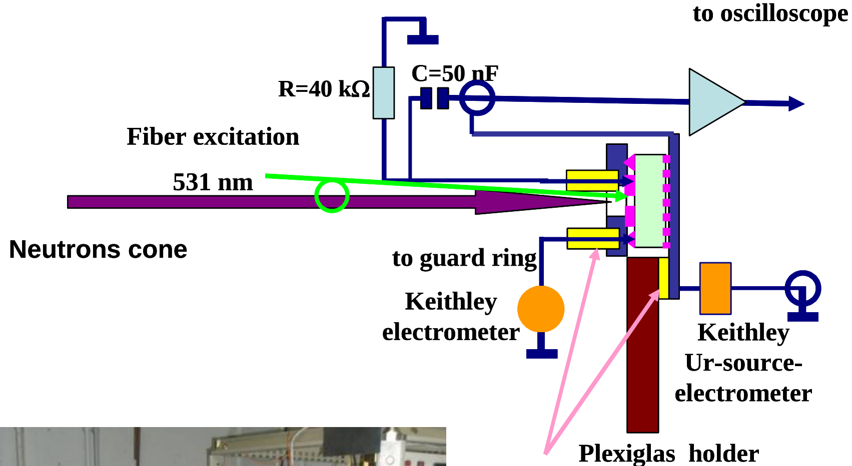
Reactor neutrons

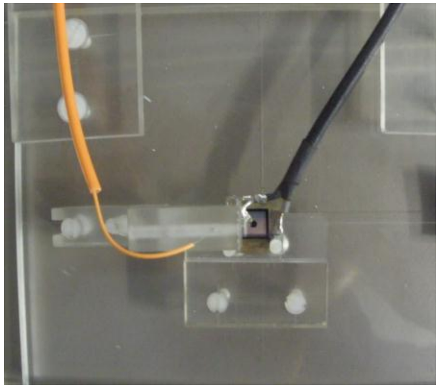


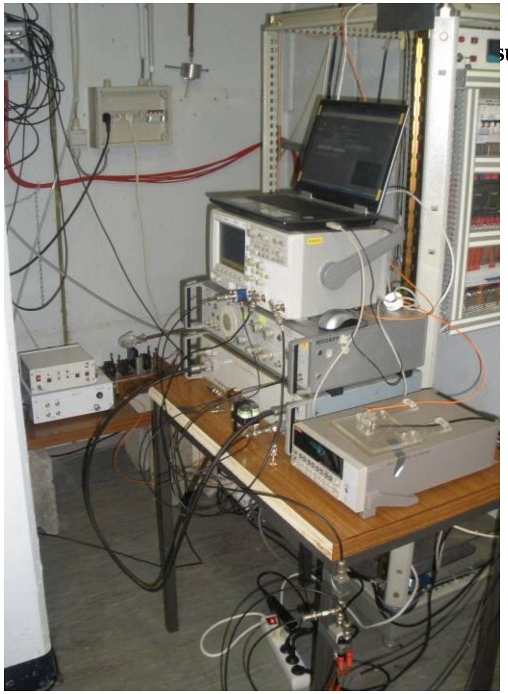
Spallator neutrons



ICDC- induced surface charge domain drift currents: measurement setup







$U>U_{FD}$

$$j(t) = q(t)\frac{dy}{dt} + \frac{q(t)}{\tau_R}[1 - y(t)] + \frac{ed}{2}\frac{dm}{dt}$$

$$v(y) = d\,\frac{dy}{dt}$$

$dy/dt - [\tau_m^{-1}(t) + \tau_q^{-1}(t) - \tau_{Ndef}^{-1}]\, y(t) - [\tau_{dr}^{-1} - \tau_m^{-1}(t)] = 0$, with $y(t=0)=y_0$ and $y(t=t_{dr})=1$

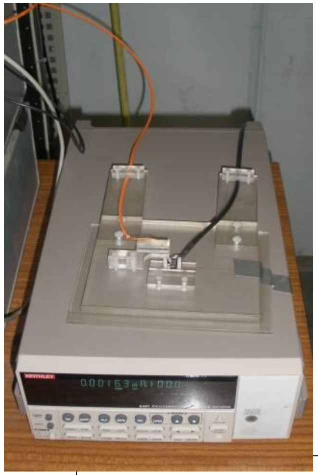
$\tau_{Ndef}=\varepsilon\varepsilon_0/e\mu N_{def}$; $\tau_m(t)=2\varepsilon\varepsilon_0/e\mu m_0(1-\exp(-t/\tau_g))$, $m(t)=m_0(1-\exp(-t/\tau_g))$;

$\tau_q(t)=\varepsilon\varepsilon_0/\mu[q_0\exp(-t/\tau_R)/d]$, $q(t)=q_0\exp(-t/\tau_R)$; $t_{dr}\approx\tau_{dr}=d^2/\mu U$

$j(t)\cong[q_0\exp(-t/\tau_R)/\tau_{dr}]+[q_0\exp(-t/\tau_R)/\tau_R]+[em_0 d\exp(-t/\tau_g)/2\tau_g]$.

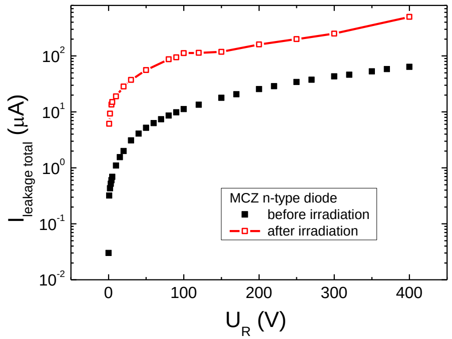
$j(t)\approx[q_0/\tau_{dr}]$, if τ_R & $\tau_g >> \tau_{dr}$

Comparison of results of the on-line changes of the ICDC during 8 MeV proton beam and spallator 25 MeV neutrons irradiation

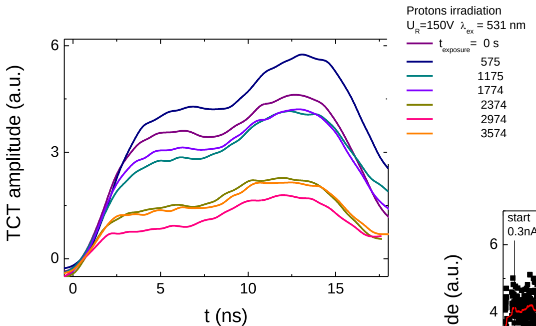


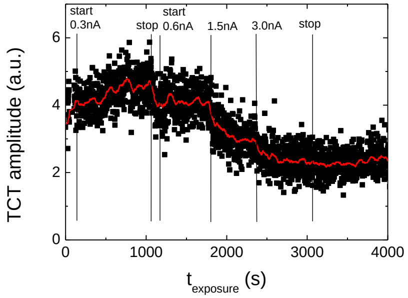
8 MeV protons

Leakage current

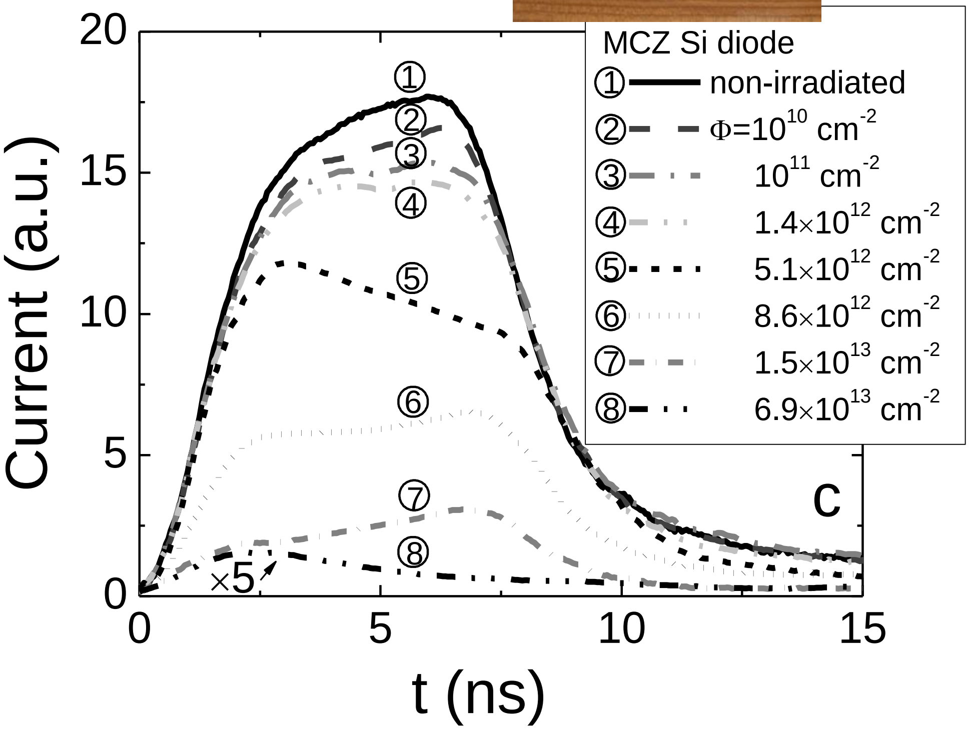


Induced charge current transients



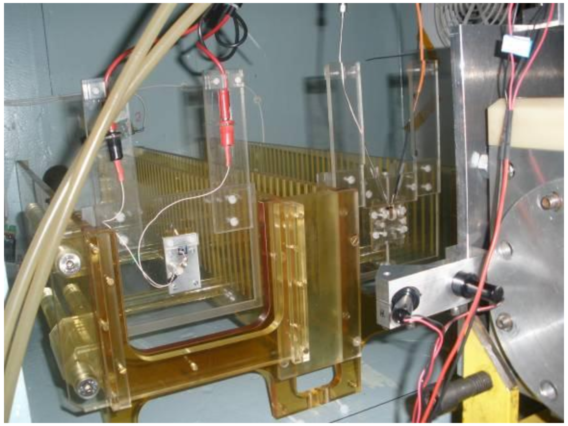


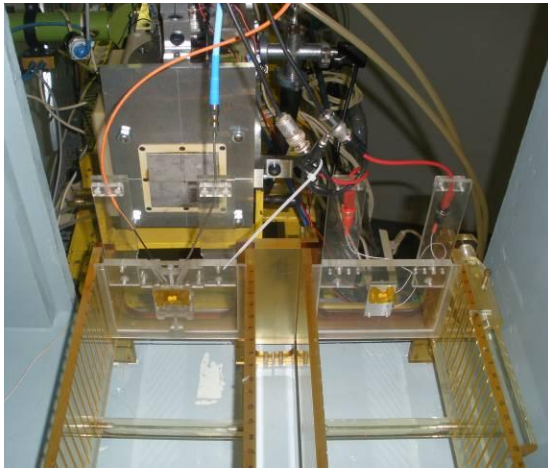
Spallator neutrons

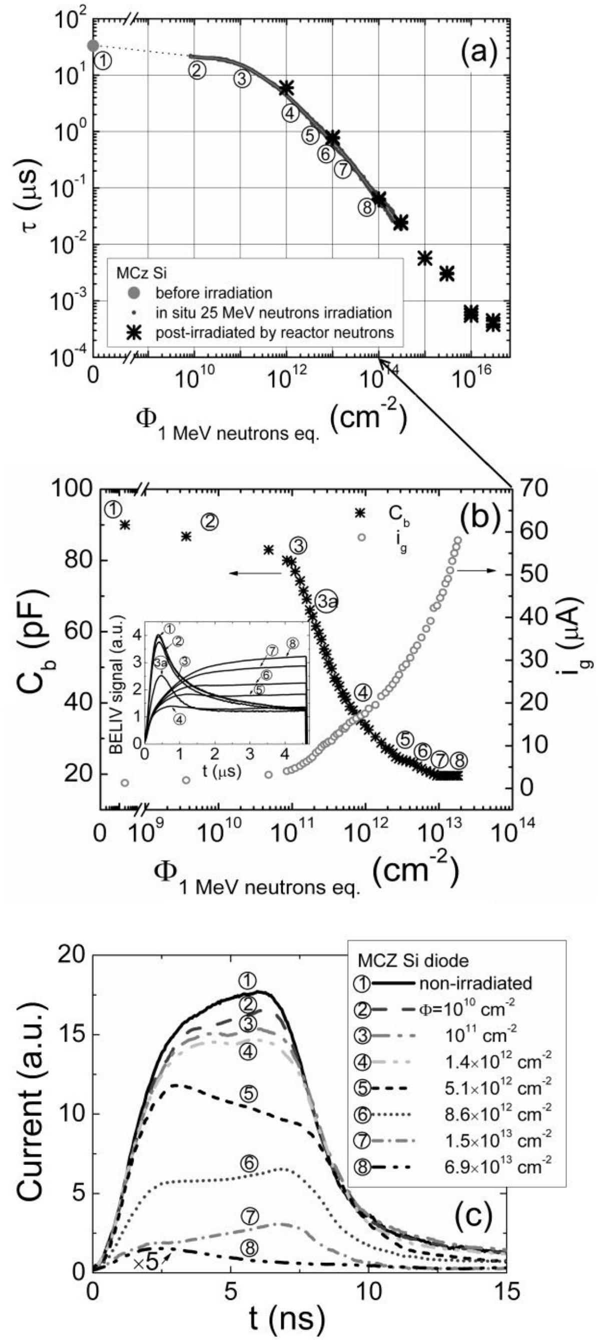


Correlated evolution of the MW-PC, BELIV and ICDC characteristics during spallator neutrons irradiation:

transients registered every 10 ms, - more than 10^5 on each curve; irradiation - bunches of 4 ns duration







Summary

- **Spallator neutron irradiations are extremely useful for in situ experiments, as electrical noises are sufficiently small in comparison with those in proton beam chamber. On-line experiments are useful to predict detector behavior in operation regime.**

- **The observed changes of MW-PC, BELIV and ICDC transients well correlate mutually when considered relatively to an increasing fluence value. Thus, MW-PC correlated lifetime changes, measured in contact-less and distant manner, calibrated with other parameters is a powerful tool for examination in a wide dynamic range of carrier lifetimes, modified by radiation defects. Increased recombination rate in the heavily irradiated detectors may mask carrier drift. Thus, carrier recombination lifetime values, measured by MW-PC technique, can be employed in prediction of detector performance.**

- **Approach of carrier lifetime values to those of charge drift specific time scale leads to the non-operational junction. The observed increase of generation current within BELIV transients will cause a considerable increase of detector noise level.**

Acknowledgements.

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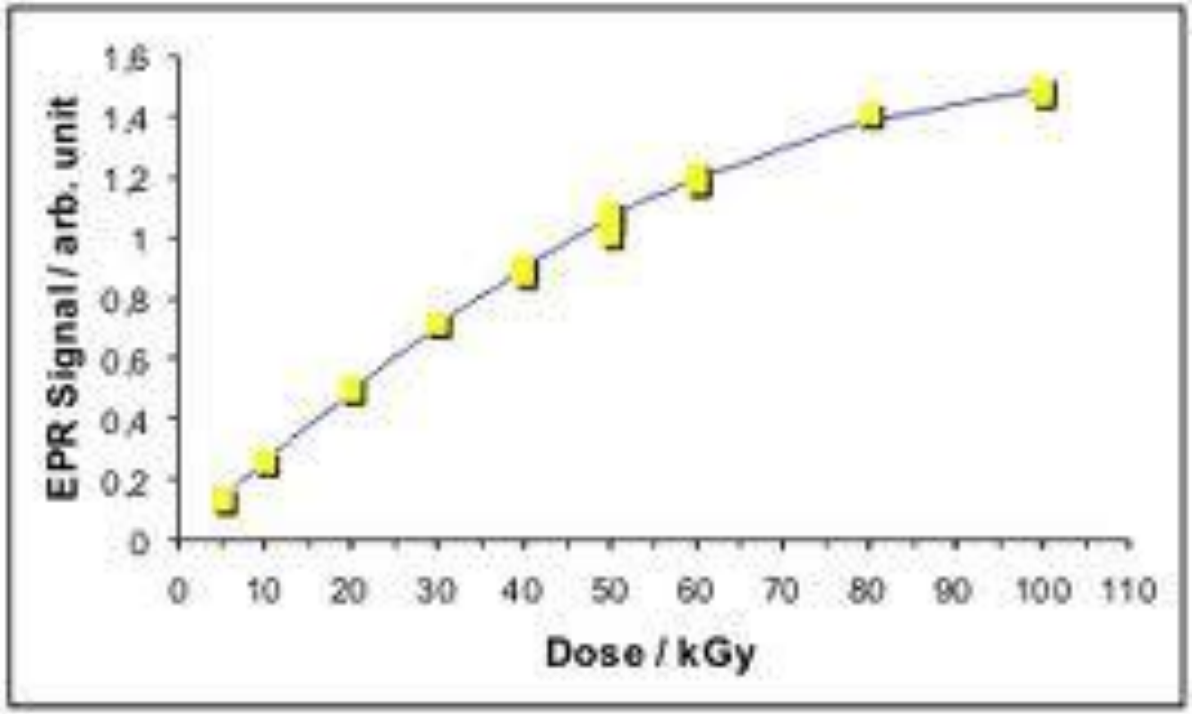
E.Tuominen, J.Harkonen, and J.Raisanen are appreciated for Si samples and detectors.

Thank You for attention!

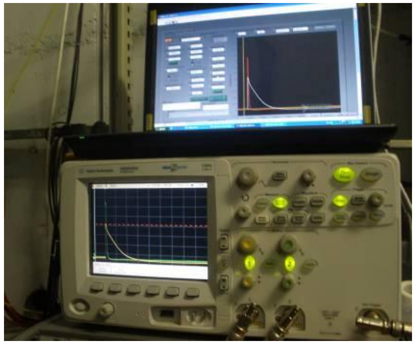
Dosimetry using alanine [$CH_3CH(NH_2)COOH$ –organic acid]
EPR spectroscopy, - ESR of radiation created free radicals

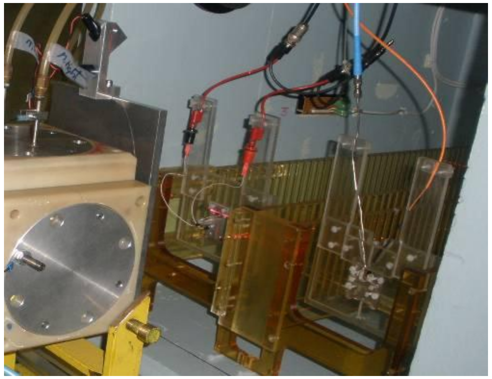


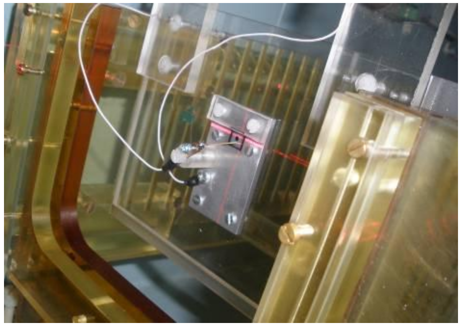
Dosimetry is based on the generation of the free radicals within the alanine pellets. Quantification of the radicals is implemented by detecting the free electrons using Electron Paramagnetic Resonance (EPR) Bruker spectrometer. Alanine dosimeter reader is calibrated to register doses between 0.05 kGy (corresponding to neutron fluence of 10^{12} n/cm^2) and 80 kGy (corresponding to neutron fluence of 1.8 x 10^{15} n/cm^2).

Sketch of experiments

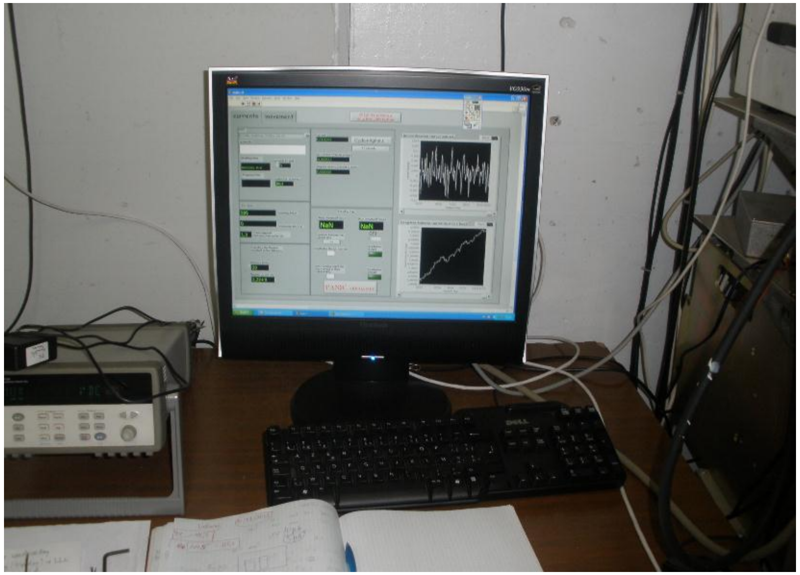
The parallel on-line measurements of MW-PC, BELIV and ICDC characteristics have been performed keeping the same experimental conditions

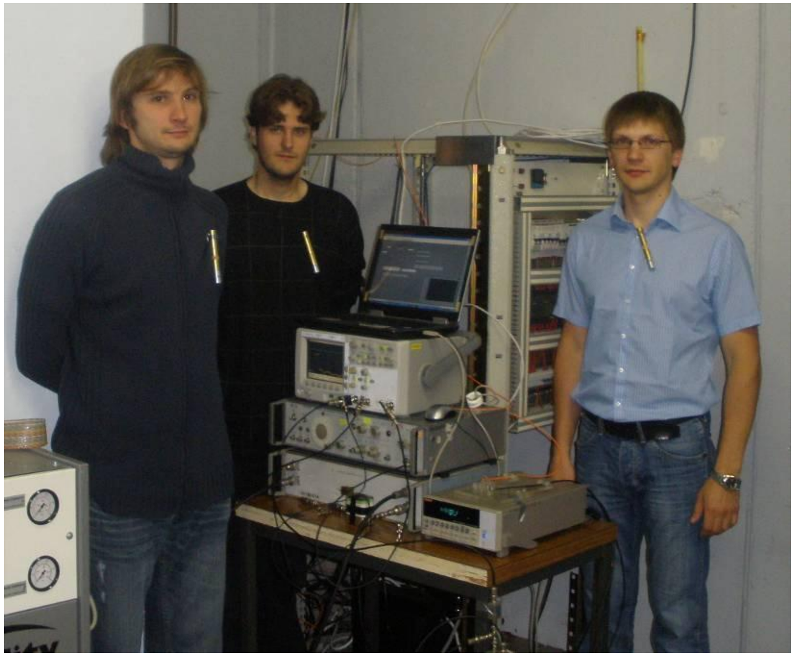






Sketch of experiments





Neutron source at Louvain la Neuve University

Fluence Φ (particles/cm^2) is calculated from the integrated current, by the following formula:

$$\Phi(particles/cm^2) = \frac{10^{14} x I(Integrated, \mu A)}{0.079 x d^{1.902}}$$

Fluence (n/cm^2) is directly proportional to *I*, integrated deuteron current (expressed in μA x hour), and inverse proportional to the distance *d* between the target and the sample (centimeters).

Alanine dosimeter reader is calibrated to read doses between 0.05 kGy (corresponding to neutron fluence of 10^{12} n/cm^2) and 80 kGy (corresponding to neutron fluence of 1.8 x 10^{15} n/cm^2).
The hardness factor is defined as the ratio between the displacement damage cross-section for a specific particle energy distribution and the displacement damage cross-section of neutron of 1 MeV that has a known value of 95 MeV mb.

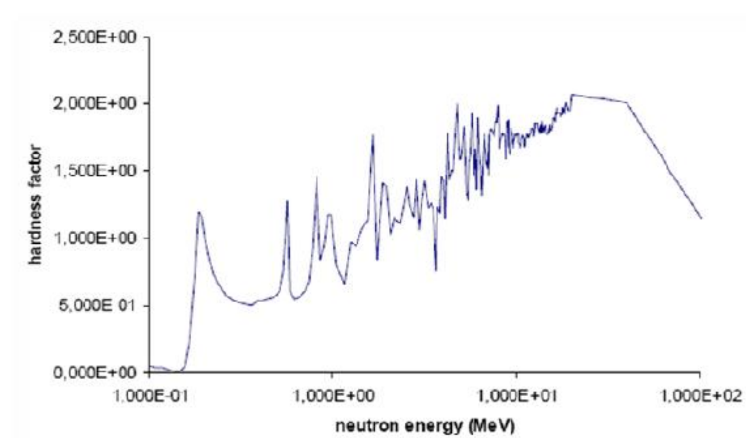
$$\Phi\ eq\ \left(1\ MeV\ eq\ \frac{n}{cm2}\right) = K\ \Phi\left(\frac{n}{cm2}\right)$$

$$K = \frac{D(E)}{95\ MeV\ mb} = \frac{\int_E \frac{d\varphi(E)K(E)dE}{dE}}{\varphi\ total}$$

Calculation of the equivalence between neutron and proton irradiation and between absorbed dose (kGy) and fluence (1 MeV eq n/cm^2)

Number of neutrons for several energy values and the total flux calculation

Energie moyenne pondérée (MeV)	Meulders et al. [42]	Période 1 (14/12/95)	Période 2 (13/03/96)	Période 3 (17/07/96)	Période 4 (06/09/96)
	Flux absolu (10^{-16} µC^{-1} Sr^{-1})				
4,91	0.115	0,1153	0,1154	0,1155	0,1154
8,68	0.126	0,1273	0,1273	0,1276	0,1274
14,91	0.194	0,1997	0,1997	0,2023	0,2003
22,78	0.297	0,3083	0,3082	0,3138	0,3089
31,22	0.102	0.103	0.103	0.1033	0.1031
39,09	0.024	0,024	0,024	0,024	0,024
45,32	0.0115	0,0115	0,0115	0,0115	0,0115
49,09	0.0068	0,0068	0,0068	0,0068	0,0068
	Flux absolu total (10^{11} n µC^{-1} Sr^{-1}) de 4 à 50 MeV				
	5.8	6.0981	6.0979	6.1668	6.1086
		Flux absolu total moyen (10^{11} n µC^{-1} Sr^{-1}) de 4 à 50 MeV			
		6.12			



Neutron source at Louvain la Neuve University

Equivalence between fluence (particles/cm^2) and dose (Gy)

To evaluate the correspondence between the neutron fluence and the absorbed dose in different materials (for our purpose: **silicon** and **alanine**) the KERMA values were used (sum of the kinetic energies of all the charged ionizing particles produced in the interactions: elastic scattering (n,n), inelastic scattering (n,n'γ), or (n,2n),(n,p),(n,α)…).

Neutrons absorbed dose (expressed in Gy) = $\int \Phi(E)K(E)dE$ (integral over energy domain, 5 to 45 MeV); $\Phi(E)$ is the energy distribution of the neutron beam, K(E) is the KERMA factor of the materialexpressed in fGy m^2.

$$K = \frac{\int_0^{\infty} \varphi(E)K(E)dE}{\int_0^{\infty} \varphi(E)dE} = \frac{\int_0^{\infty} \varphi(E)K(E)dE}{\varphi \text{ total}}$$

Neutron kerma factor for H, C, O, N, Si (fGy m^2)

E (MeV)	H	C	O	N	Si
15	48.1	2.06	1.31	1.5	1.21
20	47.0	3.10	1.85	2.04	1.53
25	45.85	3.41	2.08	2.46	1.74
30	44.51	3.64	2.37	2.78	2.02
40	42.92	4.0	3.0	3.62	2.51
50	40.75	4.39	3.67	4.44	3.08
60	39.04	4.97	4.4	5.24	3.62
70	37.72	5.49	4.96	5.9	4.16
80	36.74	6.03	5.6	6.58	4.73
90	36.05	6.69	6.3	7.2	5.33
100	35.58	7.54	6.94	8.0	5.86
120	35.23	9.03	8.35	9.34	6.93
150	35.82	11.05	10.2	11.34	8.48

The Φ total as 6.1 x 10^{11} neutrons/μC*Sr. The result of the integral considering the flux values and the KERMA factor is 1.52 fGy m^2 . Therefore for **Silicon**:
Dose (Gy) = 1.52 (fGy m^2) x Φ (n/cm^2).

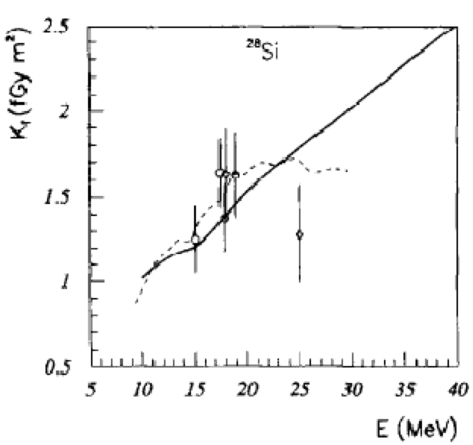


Fig. 12. Neutron kerma factor for silicon calculated with the ALICE code (solid line), with the measured (symbols) [3] and calculated (dashed line) results included.

Neutron kerma factors for composite materials (fGy m^2)

E (MeV)	Tissue	CH	NaI	CsI	BaF_2	CeF_3	BGO	LS	$PbWO_4$
15	6.12	5.6	0.08	0.02	0.46	0.62	0.20	0.36	0.18
20	6.55	6.45	0.21	0.08	0.52	0.69	0.36	0.50	0.27
25	6.66	6.67	0.35	0.16	0.59	0.78	0.44	0.58	0.33
30	6.78	6.75	0.47	0.25	0.68	0.89	0.56	0.69	0.41
40	7.16	6.99	0.77	0.47	0.91	1.15	0.83	0.94	0.62
50	7.52	7.19	1.08	0.72	1.21	1.49	1.13	1.23	0.85
60	7.98	7.59	1.40	0.99	1.50	1.82	1.44	1.54	1.11
70	8.35	7.97	1.72	1.24	1.82	2.18	1.72	1.82	1.35
80	8.82	8.39	2.02	1.49	2.11	2.51	2.01	2.12	1.59
90	9.37	8.95	2.29	1.72	2.38	2.80	2.26	2.40	1.82
100	9.93	9.70	2.57	1.94	2.66	3.12	2.54	2.70	2.06
120	11.2	11.0	3.15	2.42	3.28	3.79	3.12	3.32	2.58
150	12.9	13.0	3.97	3.08	4.08	4.68	3.95	4.16	3.28

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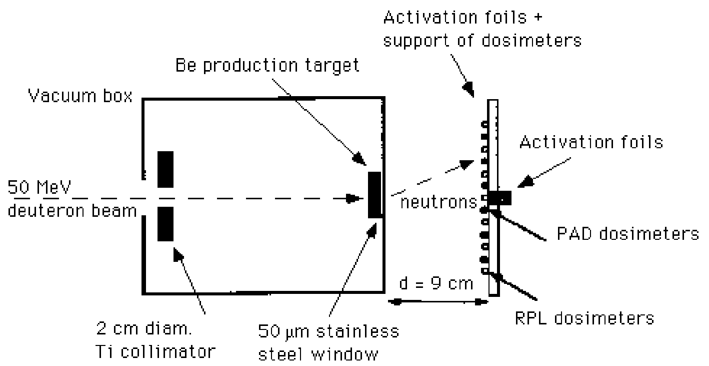
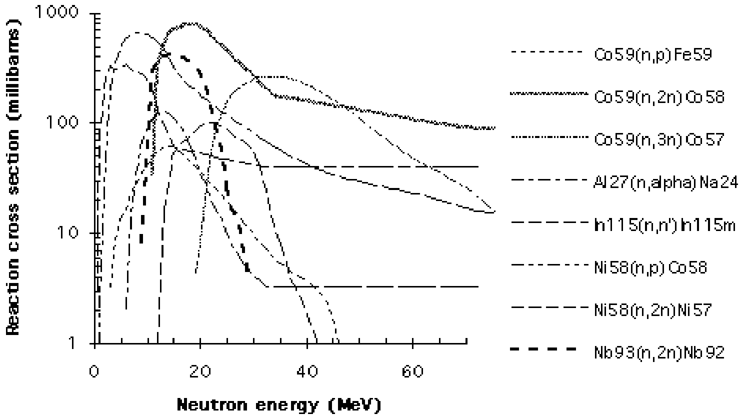
Neutron source at Louvain la Neuve University

The deuteron beam has a time structure made of 4 nanosecond wide bunches with a repetition period of about 80 nanoseconds. This time structure is also reflected in the secondary neutron beam.



The absolute neutron flux is estimated from the activation [4] of several metallic foils through reactions (Table 1) of known cross-sections (Fig. 2) [5].

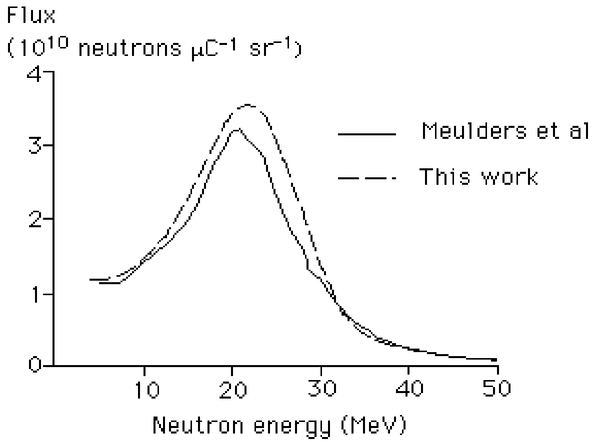


Particle type	Fraction	Average energy (MeV)	Maximum energy (MeV)
Neutron	1.0	20	50
Proton	$1.5\ 10^{-4}$	12.61	25
Electron	$1.6\ 10^{-4}$	1.57	6
Gamma	$2.4\ 10^{-2}$	1.93	10

Beam contamination after the filter

Table 1: Production reactions,neutron energy range of sensitivity and half life [5] of the induced radioactive nuclei.

Reaction	Neutron energy range (MeV)	Half-life $T_{1/2}$
^{115}In (n,γ) ^{116}In	thermal	54.15 min
^{115}In (n,n?) ^{115m}In	1-14	4.49 h
^{27}Al (n,α) ^{24}Na	7-27	14.96 h
^{58}Ni (n,p) ^{58}Co	2-20	70.916 d
^{58}Ni (n,2n) ^{57}Ni	12-40	1.5 d
^{59}Co (n,γ) ^{60}Co	thermal	5.27 y
^{59}Co (n,p) ^{59}Fe	4-30	44.5 d
^{59}Co (n,2n) ^{58}Co	14-50	70.916 d
^{59}Co (n,3n) ^{57}Co	>20	271.77 d
^{93}Nb (n,2n) ^{92m}Nb	9-30	10.15 d



The calculated production yield is 6.6 10^{11} neutrons μC^{-1} sr^{-1}. This is compatible with the one measured previously by Meulders et al. [7]. The maximum neutron flux achievable in this set-up, at a distance of 9 cm from the target, is 7.3 10^{10} neutrons cm^{-2} s^{-1}. It also means that a fluence equivalent to 10 years of LHC operation is reached in 23 minutes.

The measured the dose rate using different methods:

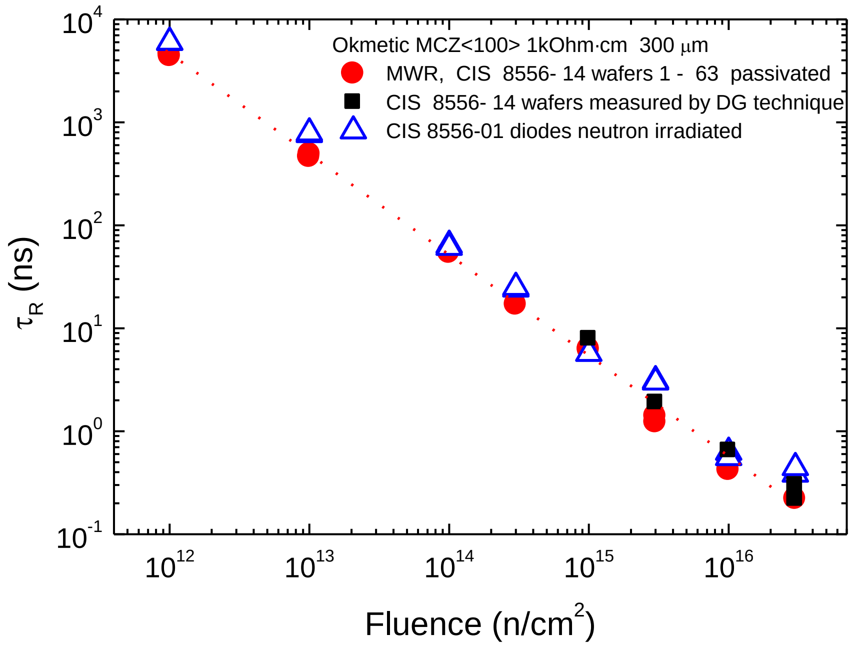
- a calibrated ionization chamber mounted according to the ICRU-45 protocol [8] with a 20 cm thick polystyrene phantom. The tissue equivalent dose rate at the build-up is 28 cGy μC^{-1} with a relative error of 5 %;
- RPL (Radio Photo Luminescent) and PAD (Polymer Alanine Dosimeter) dosimeters provided and read by the TIS-TE group of CERN [5]. The values where comparable to the one measured with the ionization chamber.

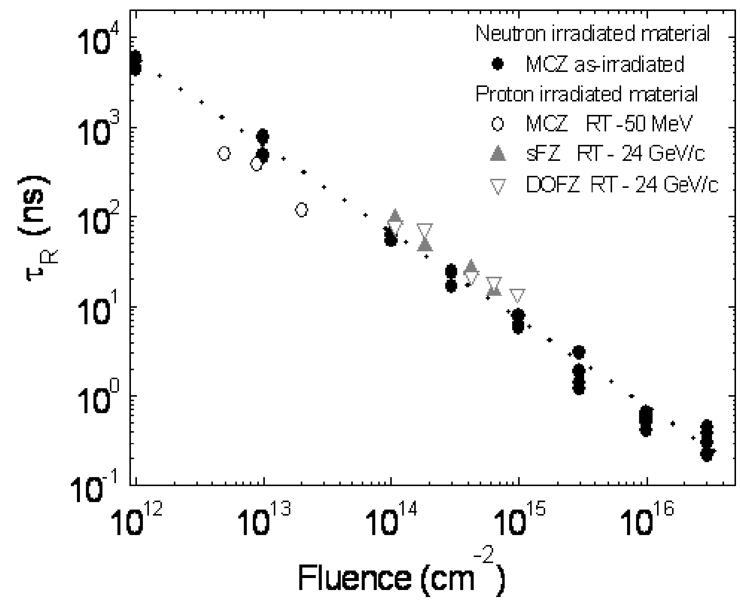
The beam profile at 9 cm from the production target is evaluated using TLD's (Thermo Luminescent Dosimeter) (Fig. 4).

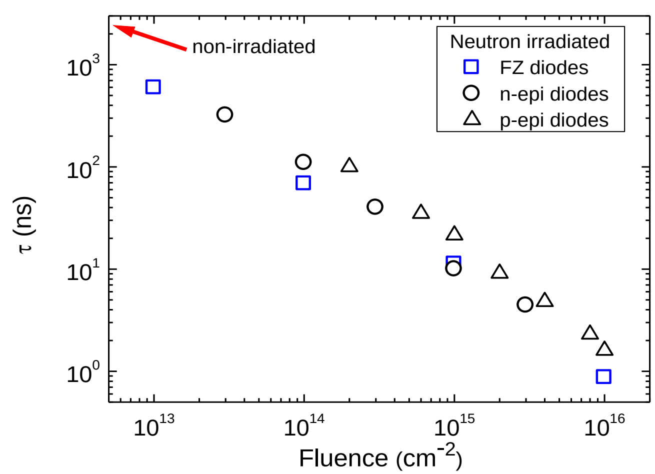
An intense fast neutron beam in Louvain- la- Neuve

K. Bernier[1], H. Boukhal[2], J.-M. Denis[3], T. E1 Bardouni[2],
Gh. Grégoire, O. Grégoire[4], V. Tran[5]
Nuclear Physics Institute, Université Catholique de Louvain
Louvain-la-Neuse, Belgium

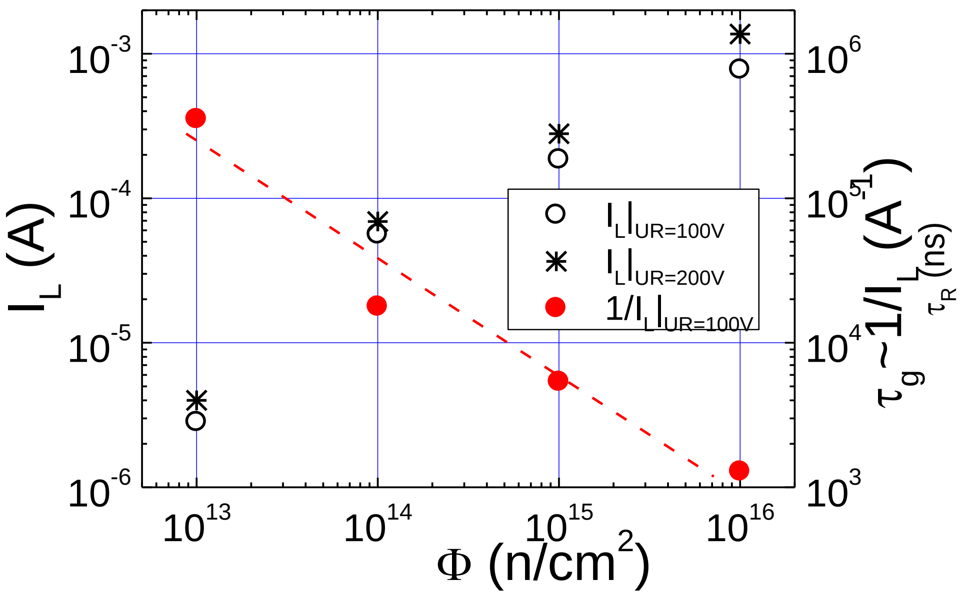
Experience of VU team in monitoring of radiation impact on carrier recombination and generation lifetime control: Post-irradiation

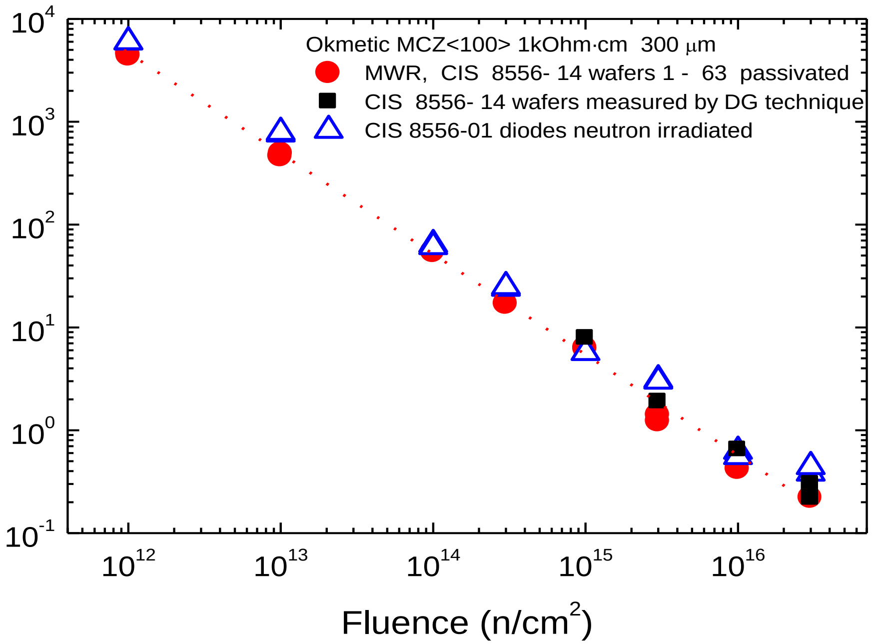






Carrier generation/emission and recombination lifetimes in Si detectors (for $M_{rad} >> n_0$)





Qualitative emission/ thermal generation lifetime dependence on fluence can be estimated from I-V's

Nearly linear reduction of generation lifetime with enhancement of fluence is similar to that of of recombination lifetime characteristic

after E.Gaubas et al JAP, **110** (2011) 033719

Carrier recombination lifetimes (for $M>>n_0$)

Single-species (type) traps

$$\tau_p = \frac{\tau_{n0}(P_0 + P_{vM}) + \tau_{p0}\left[n_0 + N_{cM} + M\left(1+\frac{n_0}{N_{cM}}\right)^{-1}\right]}{p_0 + n_0 + M\left(1+\frac{n_0}{N_{cM}}\right)^{-1}\left(1+\frac{N_{cM}}{n_0}\right)^{-1}}$$

$$m_0 = \frac{M}{e^{\frac{-\Delta E_M - F}{kT}} + 1} = \frac{M}{\frac{N_{cM}}{n_0} + 1} = M - \frac{M}{\frac{P_{vM}}{p_0} + 1}$$

$$\tau_n = \frac{\tau_{p0}(n_0 + N_{cM}) + \tau_{n0}\left[p_0 + P_{vM} + M\left(1+\frac{p_0}{P_{vM}}\right)^{-1}\right]}{p_0 + n_0 + M\left(1+\frac{p_0}{P_{vM}}\right)^{-1}\left(1+\frac{P_{vM}}{p_0}\right)^{-1}}$$

Although relaxation to equilibrium/steady-state is kept by $M=p_M+n_M$

$M\rightarrow 0$, $\Delta n \rightarrow 0$, S-R-H

$$\tau = \tau_p = \tau_n = \tau_{p0}\frac{n_0 + N_{cM}}{n_0 + p_0} + \tau_{n0}\frac{p_0 + P_{vM}}{n_0 + p_0}$$

$M\rightarrow\infty$, $M>>n_0$, S-R-H invalid

$$\tau_p = \tau_{p0}\left(1+\frac{N_{cM}}{n_0}\right) = \frac{1}{\gamma_p m_0} = \tau_{p0}$$

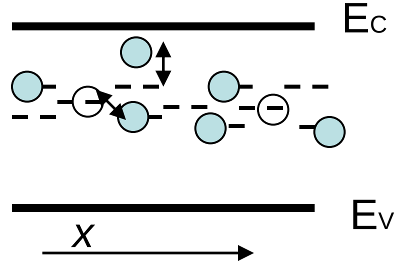
$$\tau_n = \tau_{n0}\left(1+\frac{P_{vM}}{p_0}\right) = \frac{1}{\gamma_n (M - m_0)} = \tau_{n0} = \frac{1}{\gamma_n M}$$

Capture coefficient $<\gamma_n>$ should be used instead of $v\sigma$ within rigorous analysis

$$r = n\langle\gamma_n\rangle N_f P_h(E_f)$$

$$r = N_f P_h(E_f)\int_{E_c}^{\infty}\gamma(E)P_e(E)g_c(E)dE$$

$$\langle\gamma_n\rangle = \frac{\int_{E_c}^{\infty}\gamma(E)P_e(E)g_c(E)dE}{\int_{E_c}^{\infty}P_e(E)g_c(E)dE}$$



$$\tau_n \neq \tau_p$$

$$\tau_{rec} = \frac{1}{v\sigma M} = \frac{1}{<\gamma_n> M}$$

$$\tau_{gen} = \frac{\exp(\frac{E_C - E_M}{kT})}{v\sigma N_C} = \frac{\exp(\frac{E_C - E_M}{kT})}{<\gamma> N_C}$$

J.S. Blakemore, in: *Semiconductor Statistics, Ch. 8,* Pergamon Press, (1962)