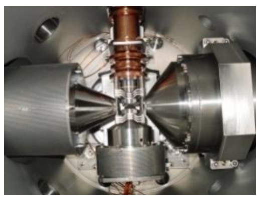
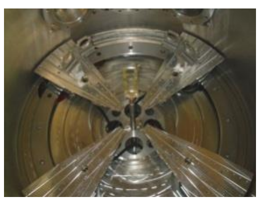
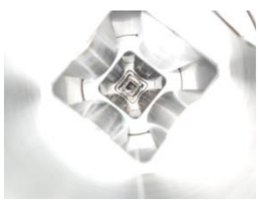






Large area diamond detectors as heavy ion beam profilers

Marian PARLOG
Laboratoire de Physique Corpusculaire de Caen

HIE ISOLDE Technical Workshop
The 28th-29th of November 2013

I Introduction:

- *Goal and framework: beam profilers – EURISOL, SPIRAL2, SPARC… & focal plane of the associated spectrometers*

***II The synthetic diamond:** (properties, fabrication, principle of detection)*

- *Single-crystal (sc-CVD) and polycrystalline (pc-CVD) sensors*
- *Response and charge collection = f(material quality & thickness, ion Z&E, U)*

III Non-segmented detectors:

- *Construction at LPC and test at GSI (classical electronics) and GANIL (sampling)*
- *Stability of the signal in time; pulse shape analysis (PSA)*

IV Double-sided multi-strip detectors:

- *construction at LPC and tests at GANIL (PSA); analysis in progress*

V Conclusions and prospective

II Diamond properties:

Excellent radiation hardness due to:
- the highest thermal conductivity
- the high energy of 80 eV to remove an ion

No p-n junction is required:
- due to the large band gap;
- simply metallic electrodes (like an ionization chamber);

High electric fields, up to 6 V/µm:
- due to the high resitivity;
- small dark current (negligible intrinsic carrier concentration at room temperature)

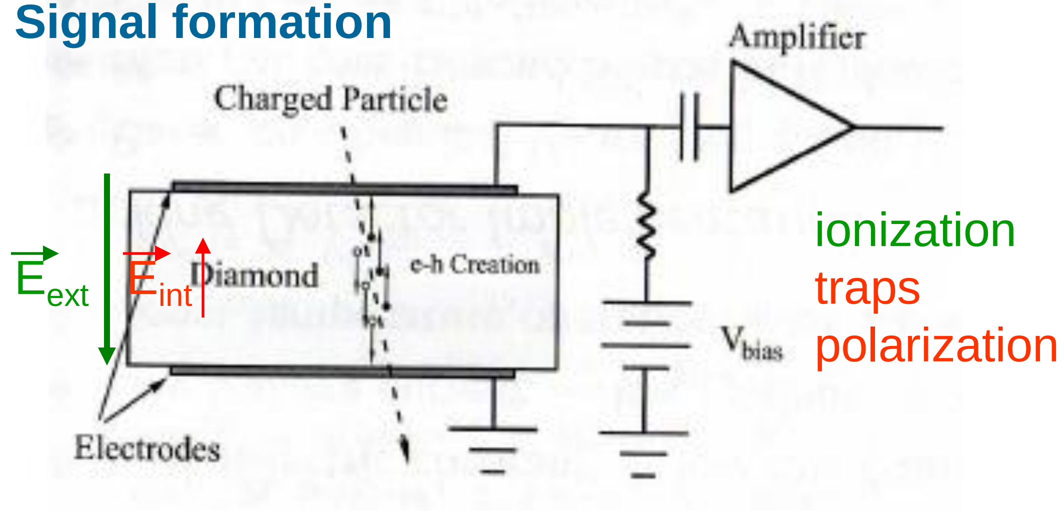
Narrow pulses, due to:
- the low capacitance;
- the high carrier mobility;

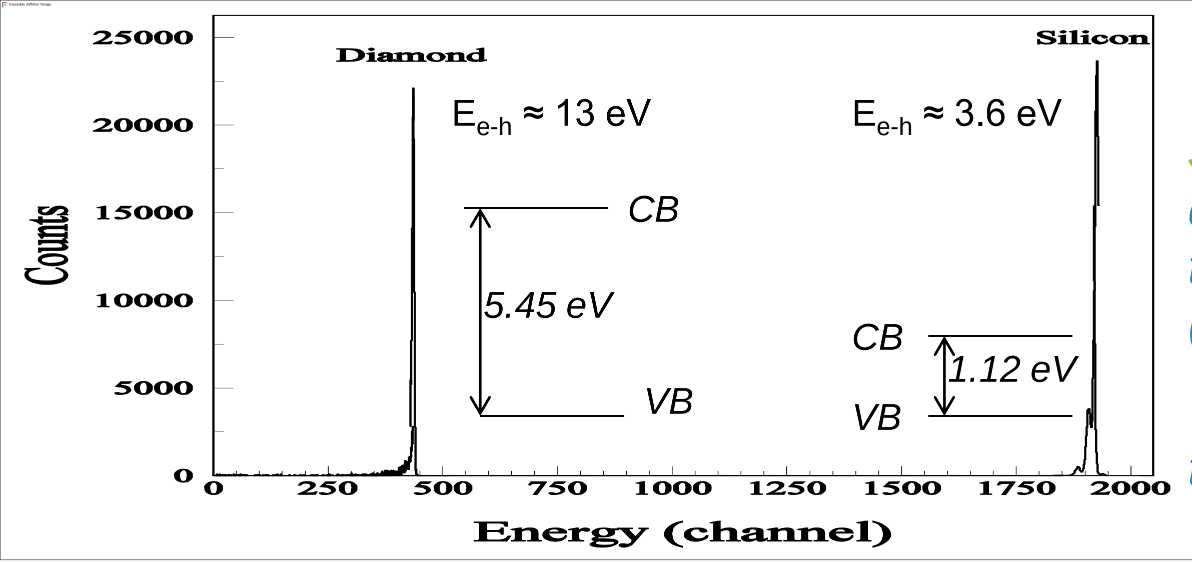
CVD diamonds:
allow big detector areas, can be metalized with any desired shape, can be wire bonded, can be operated as « noise-free » particle counter

Tab. 1. Physical Properties of Diamond and Silicon

Physical properties at 300K	Diamond	Silicon
Band Gap (eV)	5,45	1,12
Electron mobility (cm²/Vs)	1800-2200 ?	1500
Hole mobility (cm²/Vs)	1600-2400 ?	600
Resistivity ρ (Ω.cm)	$>10^{11}$	$2,3.10^{5}$
Dielectric constant ε_r	5,7	11,9
Thermal conductivity (W/cm.K)	20	1,27
Lattice constant (Å)	3,57	5,43
Energy to remove an atom from the lattice (eV)	80	28
Energy to create a pair e-h (ev)	13	3,6

Signal formation



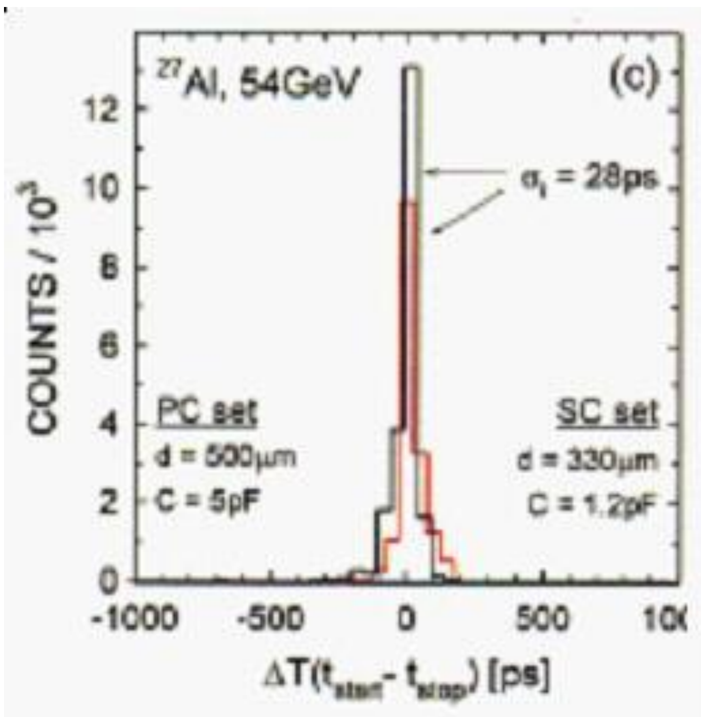


The CVD diamond detectors may behave in very different ways:

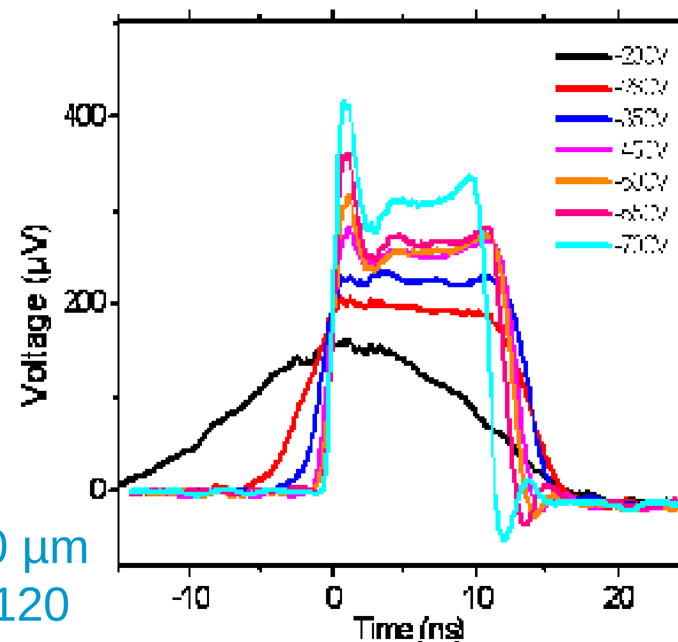
Single-crystal diamond *detector (CEA Saclay) of 20 µm thickness, adaped to the range. (courtesy of J.-L. Lecouey –LPC)*

The signal is 4 lower (left peak) than in a Si detector (right)

^{241}*Am: α of 5.5MeV Range ~15 µm*



GSI: Signals & TOFE. Berdermann for the NoRHDia collaboration

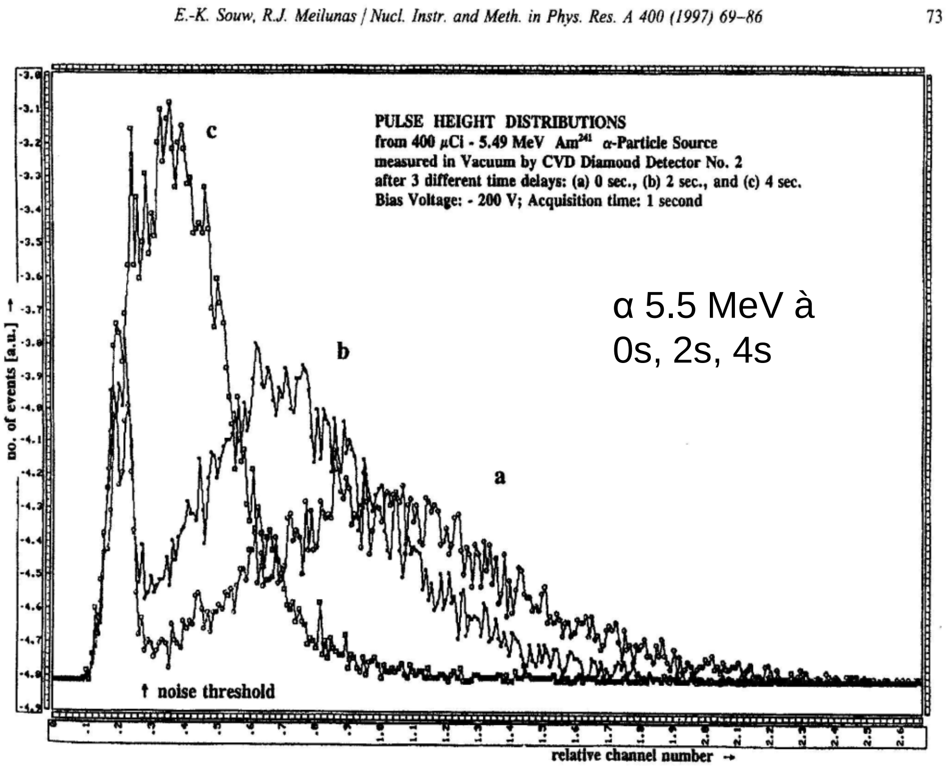


700 µm VT120 ORTEC

courtesy of Dr. H. Hamrita, LIST – CEA Saclay

II. Synthetic Diamond

II. Diamond



The CVD diamond detectors may behave in very different ways:

Polycrystalline-crystal diamond drawback:
the bulk polarization
Solutions:
- Previous radiation;
- Subbandgap light;
- Electronic procedure;
-Thermic procedure
- Good material!!!
the salutary solution

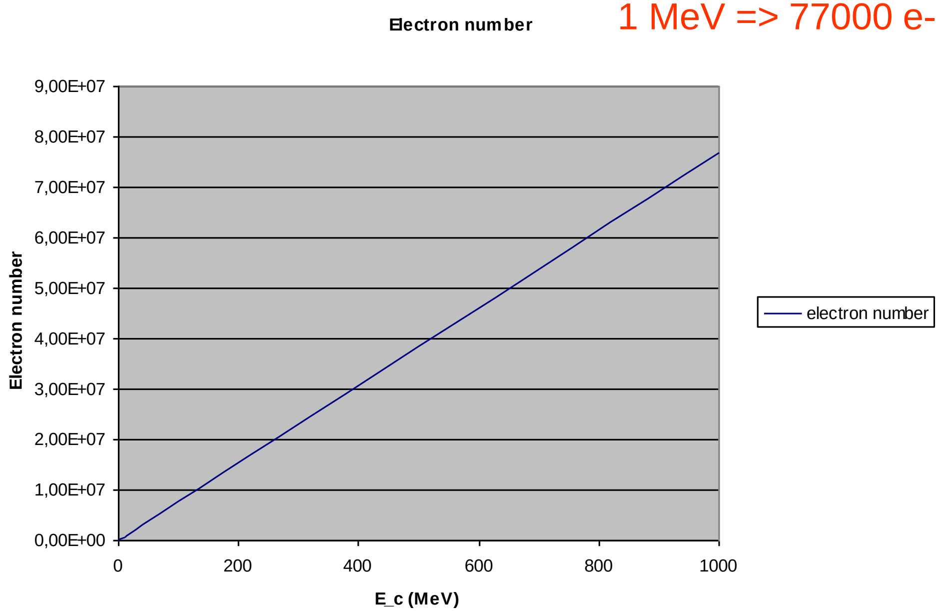
Requirements for a (radioactive) beam profiler working below 10^6 pps:

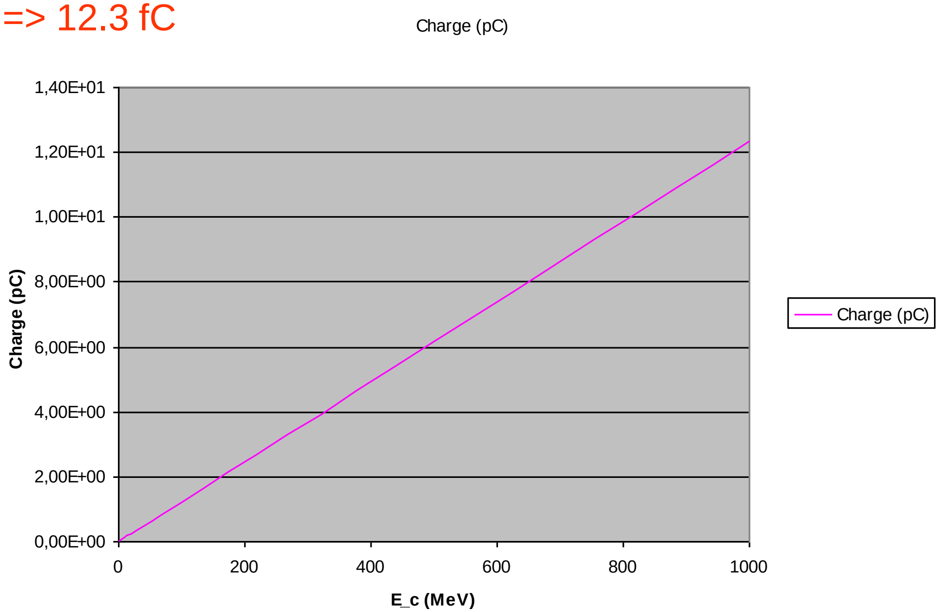
- The **beam profile** (X,Y) - **resolution of 1mm** over an **active area of up to 50x50mm^2**.
- The device should operate at **beam intensities as low as ~1 pps and up to ~10^6pps**.
- The detector should exhibit **a fast rise time** for timing applications (TOF ~0,5 ns) as well as **a short response time** to enable operation at ~1000000 pps.
- The detector should have **a large dynamic range** – both very light and very heavy ions with energies ranging from **a few to ~250 MeV/nucleon** should be detectable.
- The detectors should be **robust and radiation hard** so as to reduce to a minimum their replacement or removal for repair.
- Provide for an **accurate and precise measurement** of the intensity.
- For safety reasons the detector must have **a good vacuum integrity**.
- **Insensitive to the decay of the radioactive ions** (ie., e-,e+,g , etc).

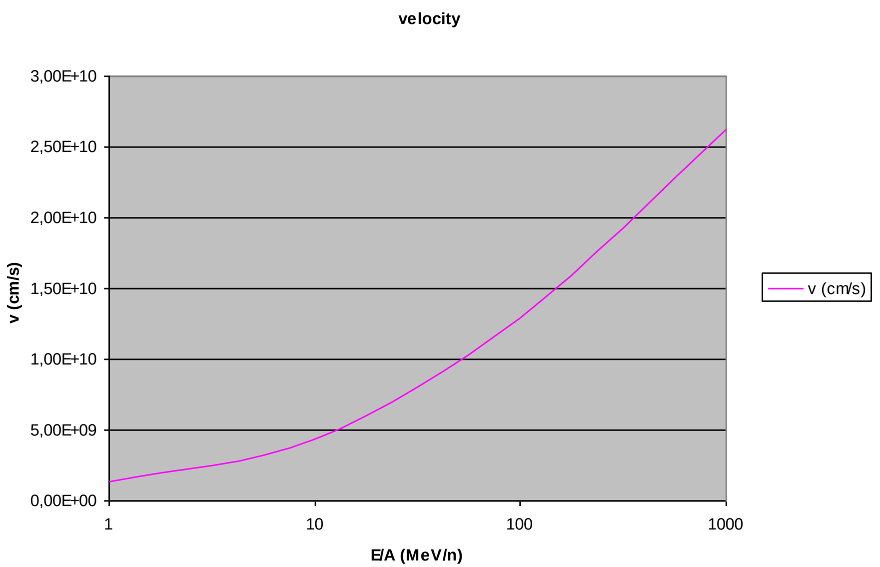
From a practical point of view (eg, use by operators during beam tuning) the detectors should be **as simple and straightforward** to operate as possible.

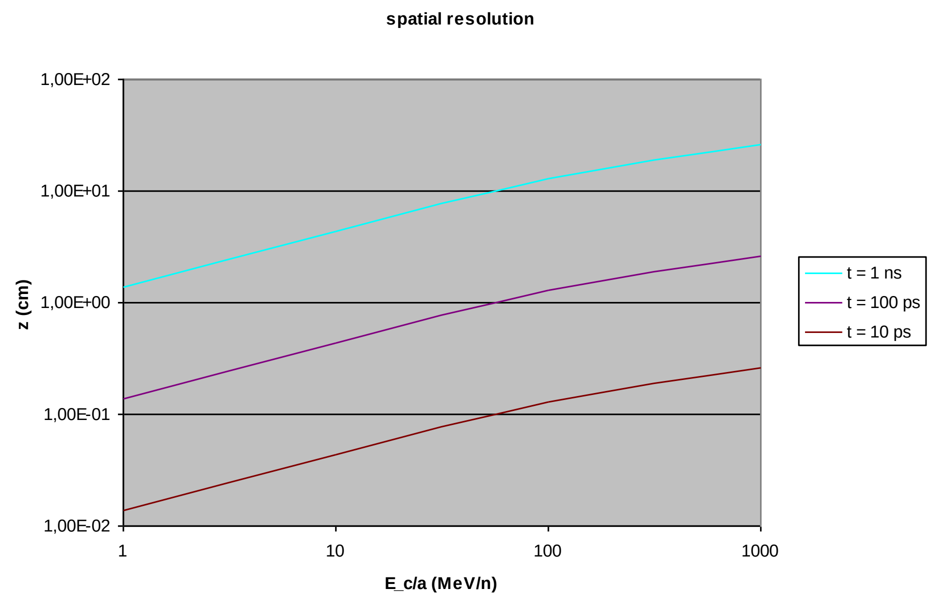
Alternative: the large area synthetic polycrystalline diamond (chemical vapour deposition – CVD), have properties matching very closely those needed to fulfil the above requirements (**R&D SPIRAL2 in LPC and SPARC Task 4.1 at FAIR)**

1 MeV => 77000 e- => 12.3 fC





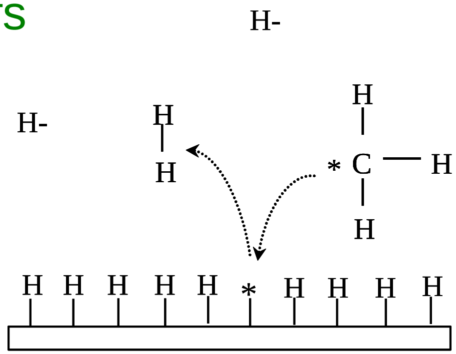


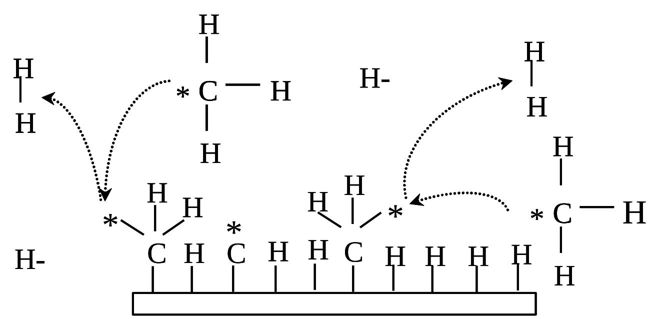


Croissance du diamant Chemical Vapor Deposited (CVD)

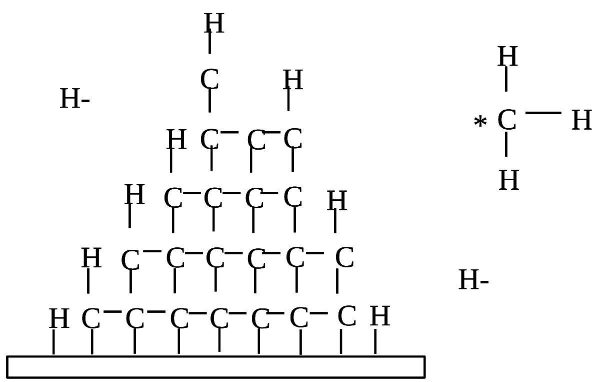
Synthèse à partir du méthane CH_4 et d'hydrogène H_2

Réaction des atomes d'hydrogène avec la surface, création de sites actifs





Extraction d'hydrogène



Liaison des atomes de carbone avec leurs voisins : formation du cristal du diamant

H. Hamrita - CEA

III Not-segmented detectors: pollycristalline diamond

Cleaning: eau régale + ultra-sounds

($1/5\ H_2O + 3/5\ HCl + 1/5\ HNO_3$)

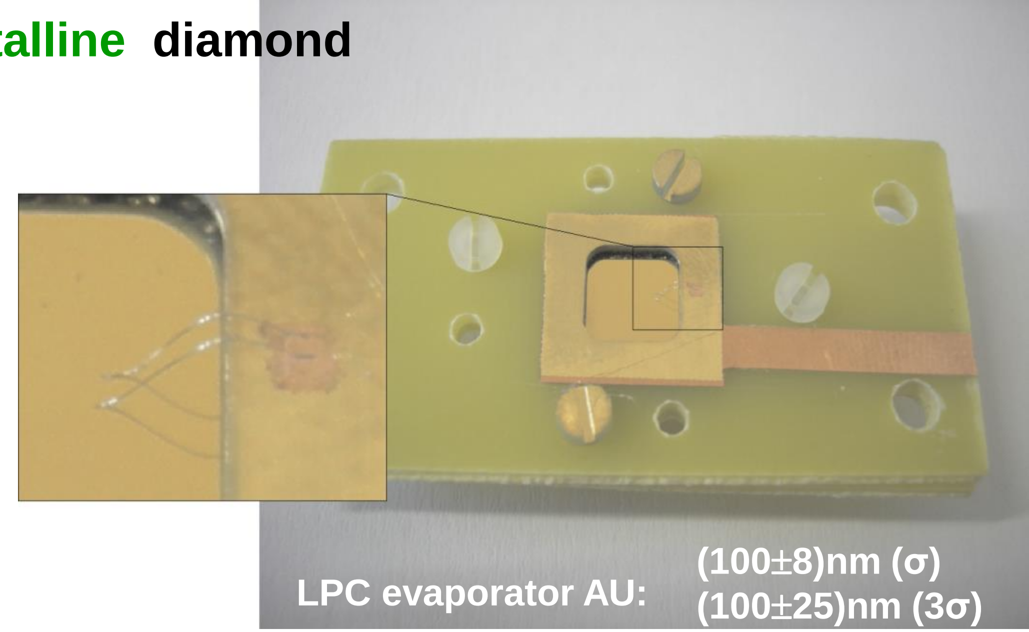
Electrodes: Au (ageing) or Al;

if not: **CrAu, NiAu, TiPtAu**)

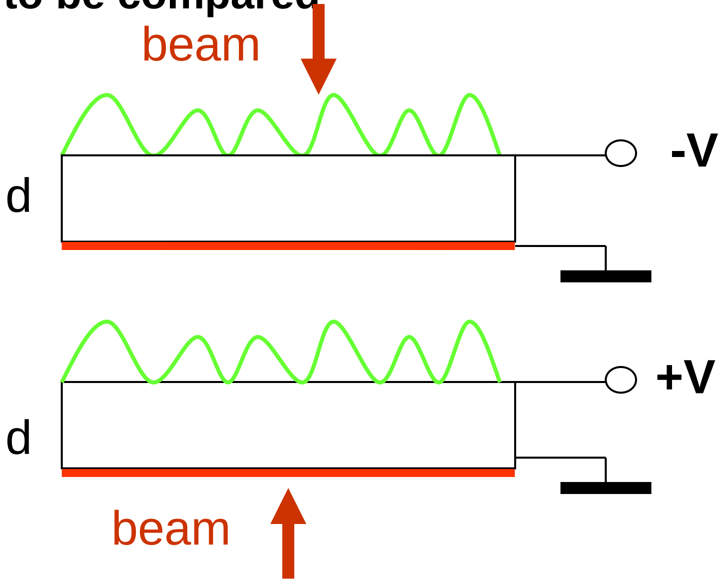
Contacts: bonding

(Al wire – soldering T + ultra-sounds)

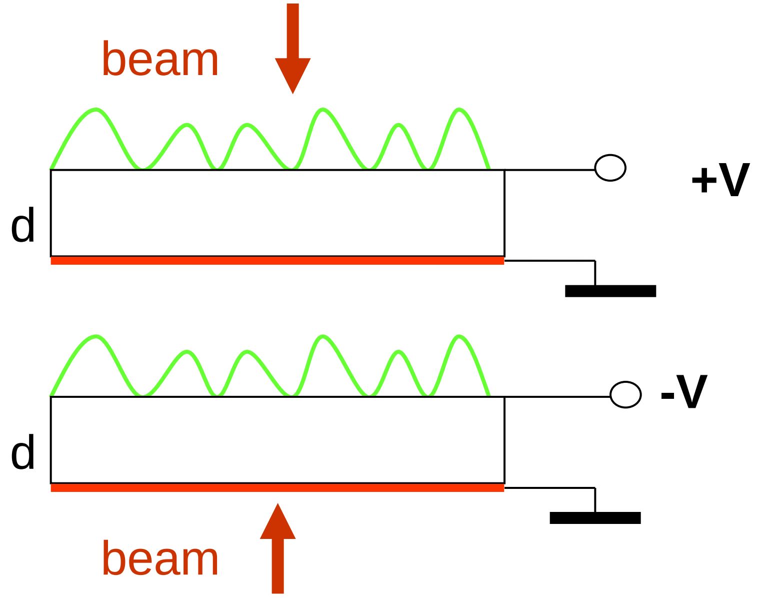
Voltage: ± 1V/ μ or higher



Irradiation: growth face or nucleation face – to be compared



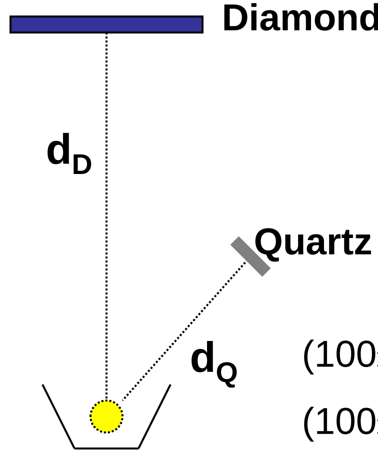
Range<<d: transit electrons



Range<<d: transit holes

III Not-segmented detectors: polycristalline diamond

The LPC evaporator



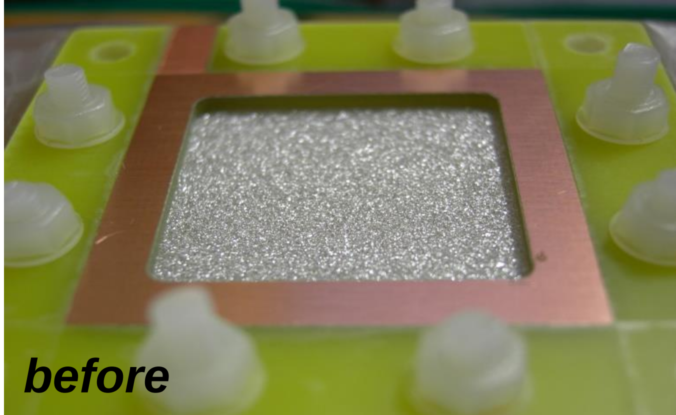
(100±8)nm (σ)

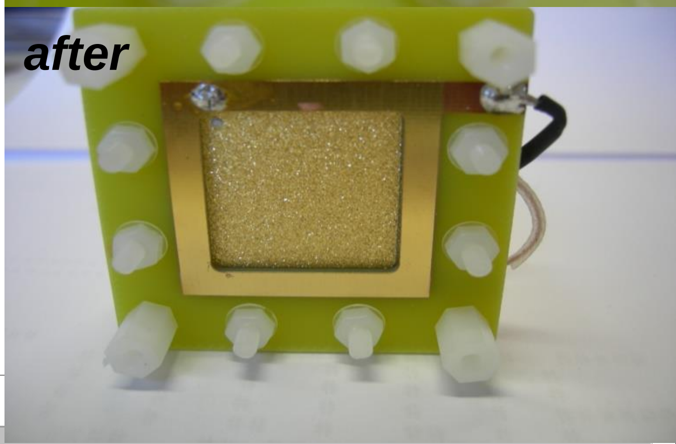
(100±25)nm (3σ)

$$e_Q = e_D (d_D/d_Q)^2$$

e – thickness

d - distance



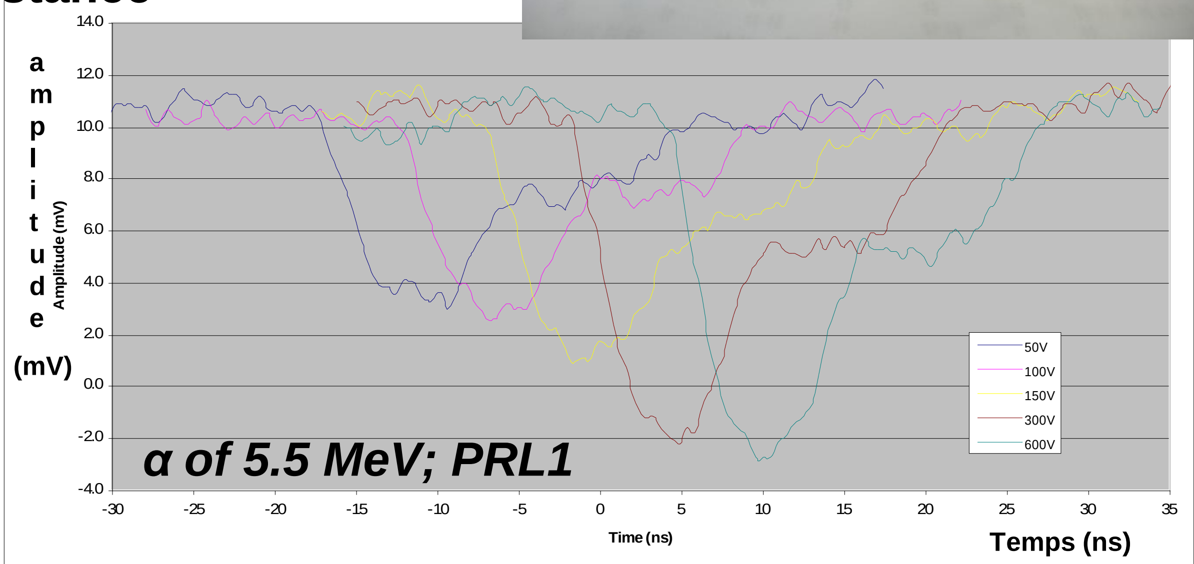


Incomplete collection of charge carriers: when the HV increases, the amplitude increases, the collection being improved

Company 1:

det1: P1N ELA (as grown) 300 µ

det2: P2 ELP 500 µ



Amplitude variation of signals - different voltages HV

Tests of not-segmented detectors in HI beams

Electronics & Acquisition:

GSI:
- **classical**

GANIL:
- **MATACQ – VME (400 MHz BW -> 0,9ns; 2GHz sampling)**
- **oscillo LeCroy 64Xi (600 MHz BW -> 0,6ns; 10Gs/s)**

Alumine

det1 **Comp1 P1N ELA** 300 μm

det2 **Comp1 P2 ELP** 500 μm

det3 **Company 2** 630 μm

det4 **Company 2** 200 μm

Company 3

det5 165 μm
det6 100 μm
det7 70 μm

& a 500μ sc tested in 6AMeV 238U beam

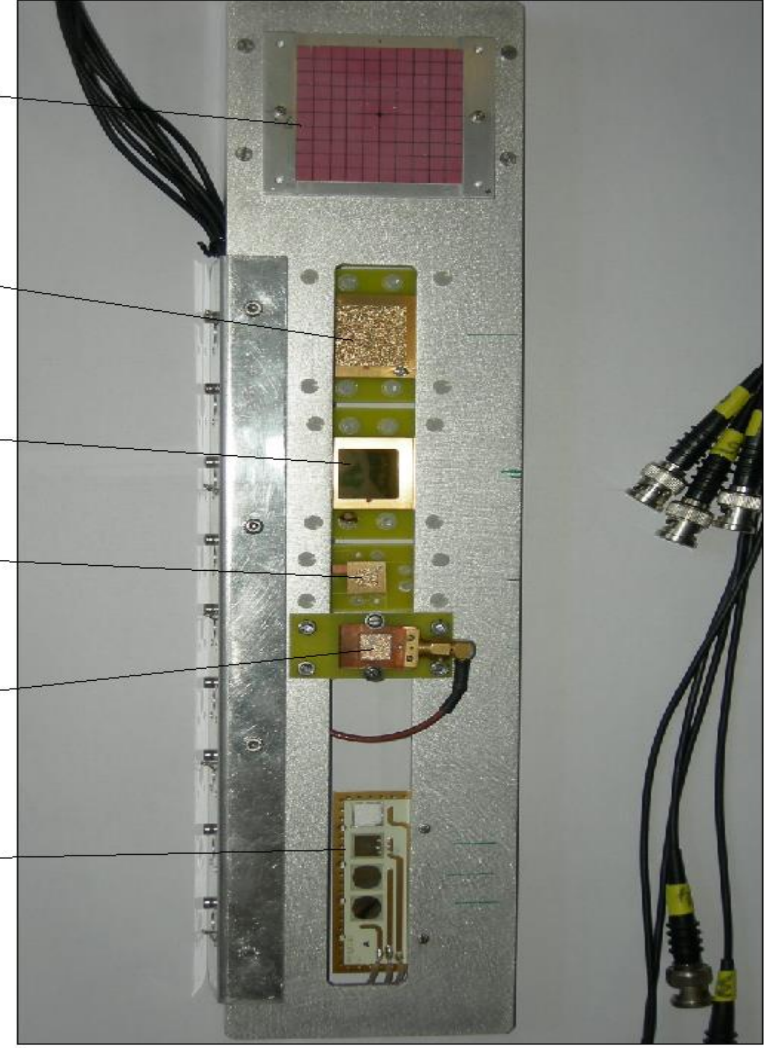
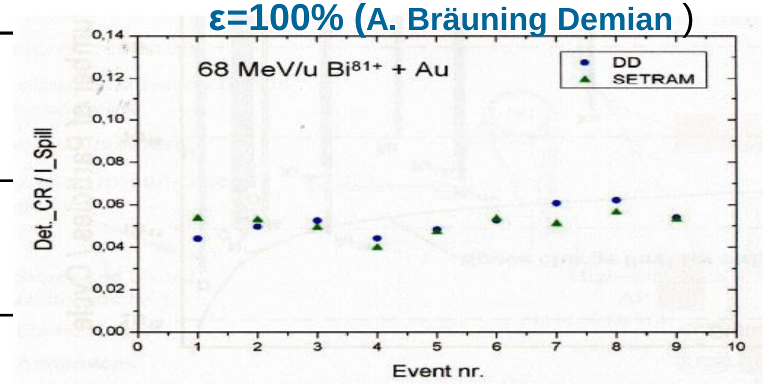


Table 2. Energy per nucleon and range of the ions which have served to test the uni-strip diamond detectors.

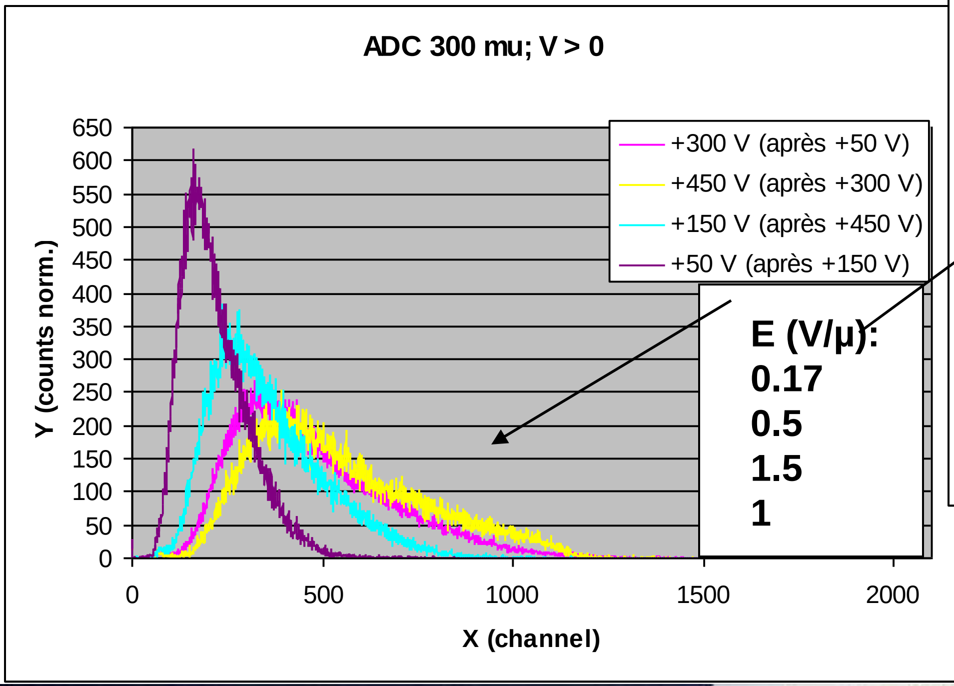
~50 m	GSI ^{124}Xe	GANIL ^{58}Ni	GANIL ^{13}C	GANIL ^{13}C	LPC α
E/A (MeV)	50	10.9	11.1	7.3	1.2
Range (μ)	440	63	196	98	15

ε=100% (A. Bräuning Demian)

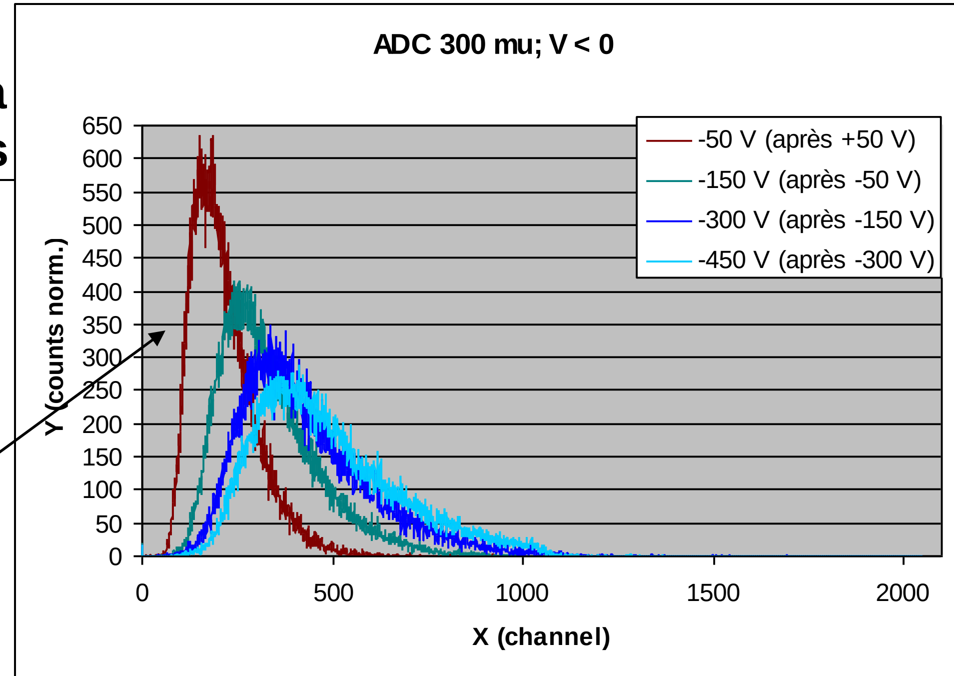


6.2 GeV ^{124}Xe (3.4 GeV in 300 μ)

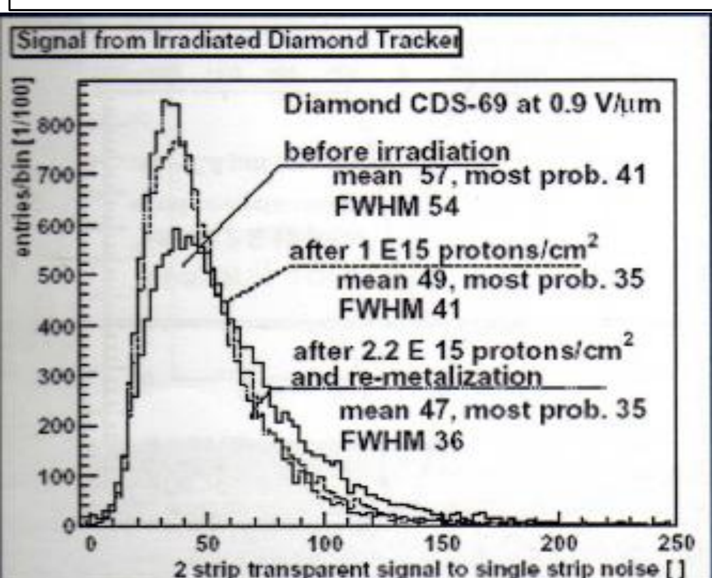
GSI: ~$3 \cdot 10^7$ p/spill; ~$3 \cdot 10^6$ p/det **runs of a few min, for hours**

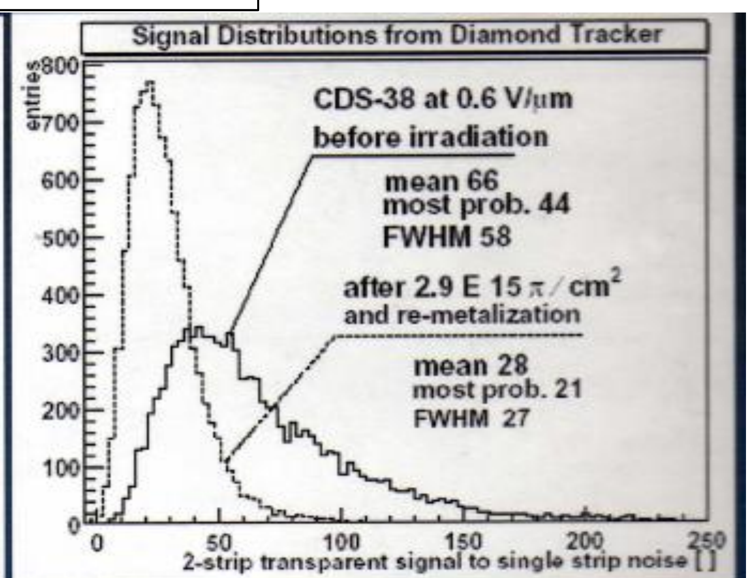


E (V/μ):
0.17
0.5
1.5
1



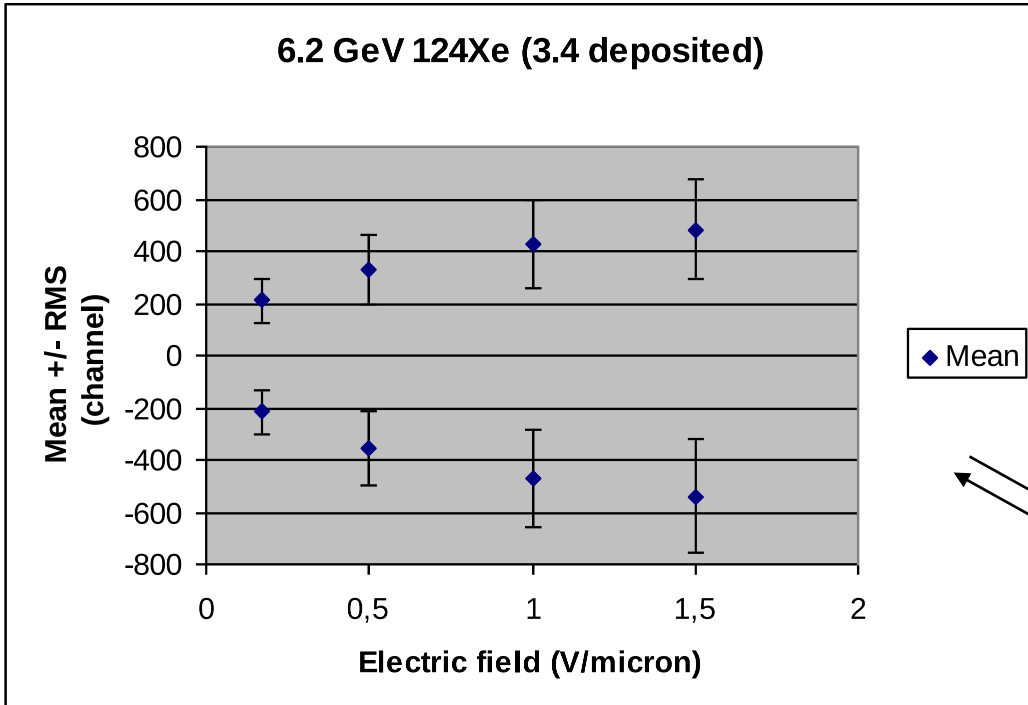
Amplitude spectra: the distribution becomes narrower when the electric field diminishes.





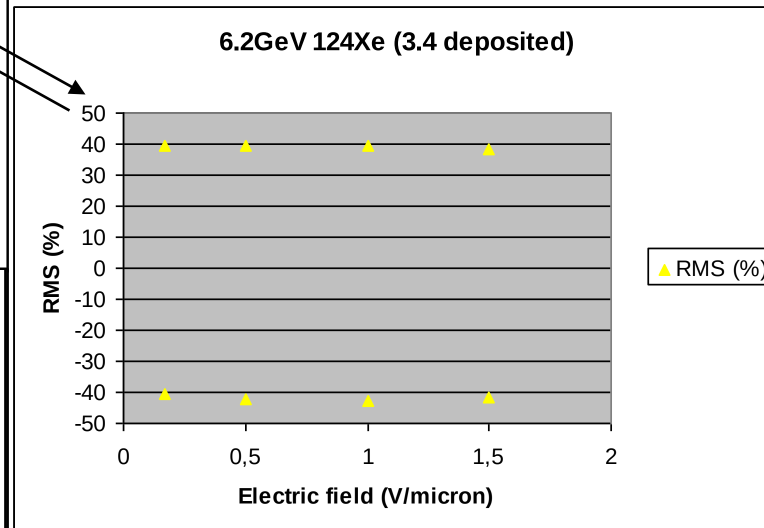
P. Delpierre, RD 42
Journées de prospective du CPPM, 2006

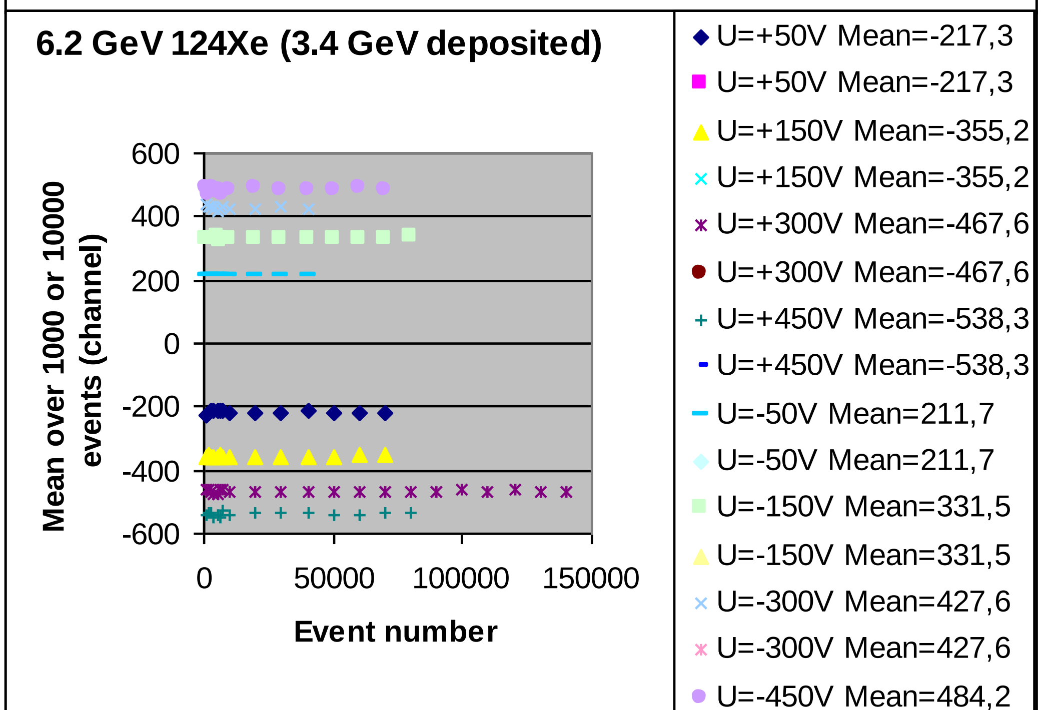
Conjecture: during the irradiation, the electric field may diminish due to the progressive bulk polarization.



Slightly better collection (~10%) for U > 0, i.e. when the holes coming from the higher carrier density have a shorter drift road.

The relative RMS (%) remains practically the same





Groups of 1000 or 10000 events, chronologically taped, show the same distribution ==> no signal attenuation observed

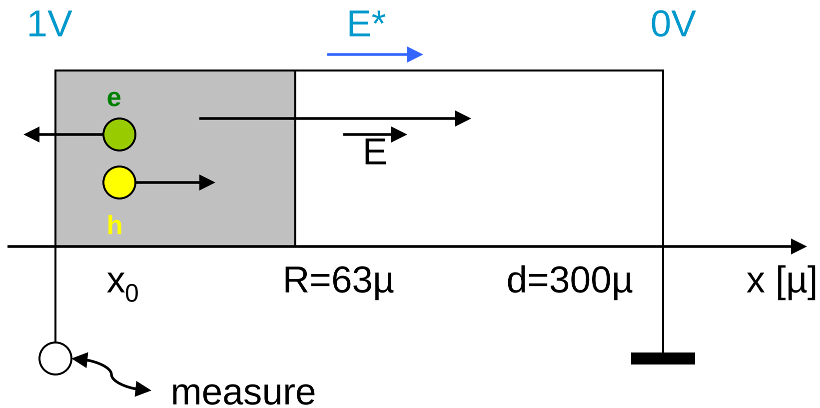
Ramo-Shockley theorem: $i(t)=-q(t).\vec{v}(t).\vec{E}^*/1V$

$$i(t) = -q\begin{pmatrix} v \\ 0 \end{pmatrix} \bullet \begin{pmatrix} 1V/d \\ 0 \end{pmatrix}$$

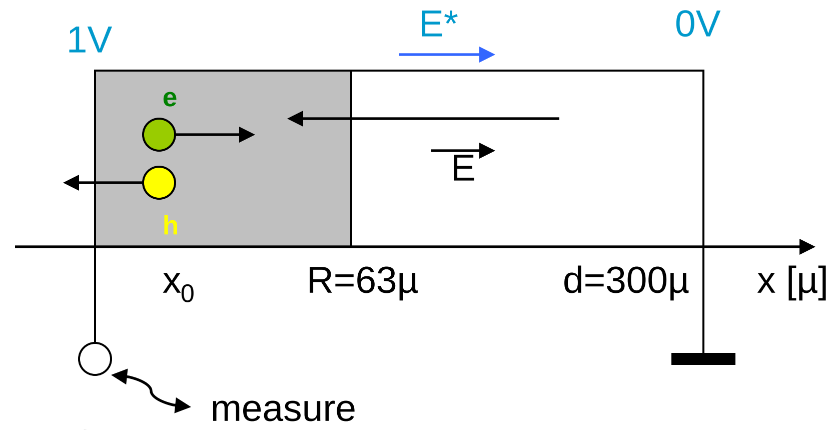
$q_e=-e$; $q_h=e$

$v_e=\mu_e*E$; $v_h=\mu_h*E$

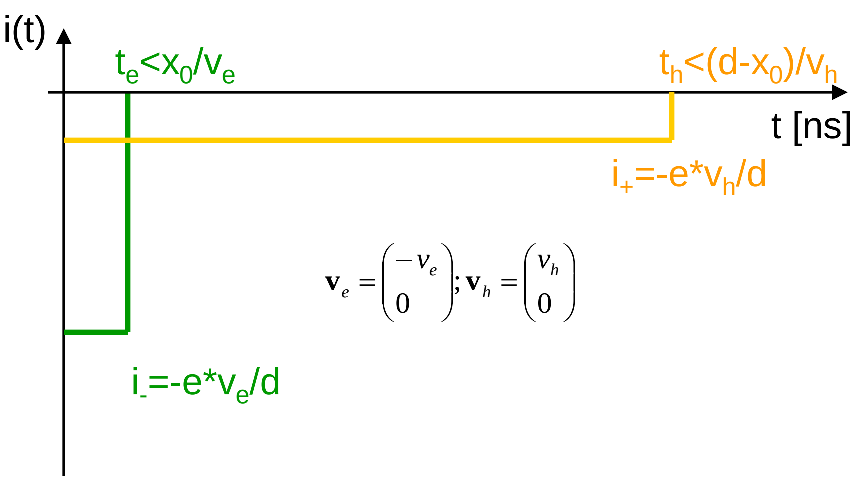
$$\mathbf{v}_e = \begin{pmatrix} \pm v_e \\ 0 \end{pmatrix}; \mathbf{v}_h = \begin{pmatrix} \pm v_h \\ 0 \end{pmatrix} \qquad E^* = \begin{pmatrix} 1V/d \\ 0 \end{pmatrix}$$



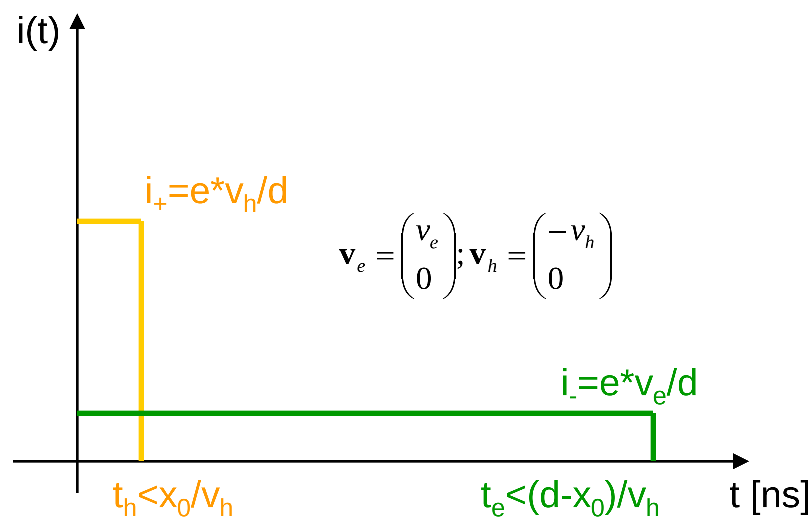
+750V



-750V



$$\mathbf{v}_e = \begin{pmatrix} -v_e \\ 0 \end{pmatrix}; \mathbf{v}_h = \begin{pmatrix} v_h \\ 0 \end{pmatrix}$$



$$\mathbf{v}_e = \begin{pmatrix} v_e \\ 0 \end{pmatrix}; \mathbf{v}_h = \begin{pmatrix} -v_h \\ 0 \end{pmatrix}$$

E =750V/300µ=2,5V/µ; v_h=v_e=v_sat=120µ/ns

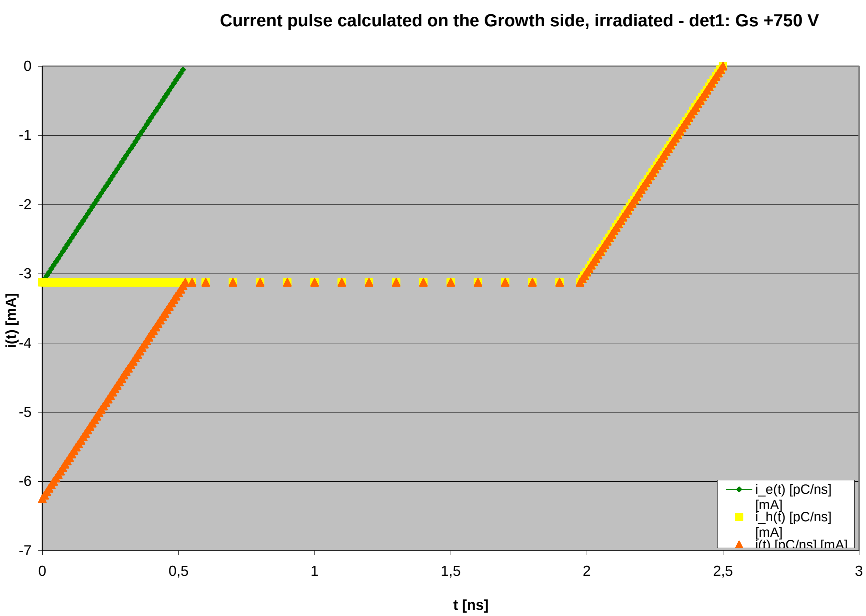
^{58}Ni; E=634MeV; R=63µ; Q_G=7,813 pC

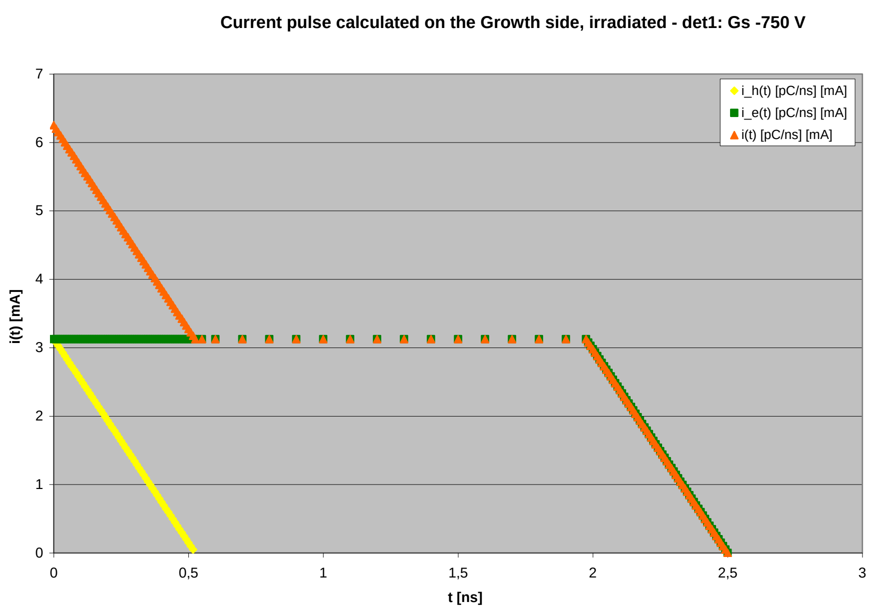
^{58}Ni; E=634MeV; R=63μ;

$Q_G = 634 * 10^{+6} eV / 13 eV * 1,602 * 10^{-19} C = 7,813$ pC

Q_{e_i}=-0,807 pC;
Q_{h_i}=-6,979 pC;
Q_i=7,787pC

Q_{e_i}=6,979 pC;
Q_{h_i}=0,807 pC;
Q_i=7,787pC





E =750V/300μ=2,5V/μ; v_h=v_e=v_sat=120μ/ns

electrons: short drift way

electrons: long drift way

$-dq/dx=q/w_s$ $w_s \approx 200\ \mu$ (E. Griesmayer et al., “High-Resolution Energy and Intensity Measurements with CVD Diamond at REX-ISOLDE”, CERN BE-Note-2009-028)

$q(x)=q_0 \exp(-x/w_s)$

$q(t)=q_0 \exp(-t/t_s)$

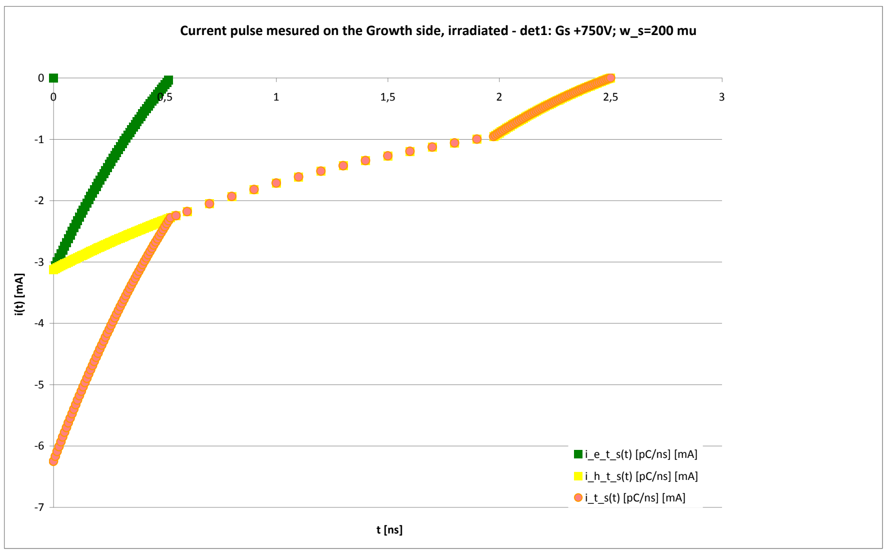
$t_s=w_s/v\_sat=1,67\text{ns}$

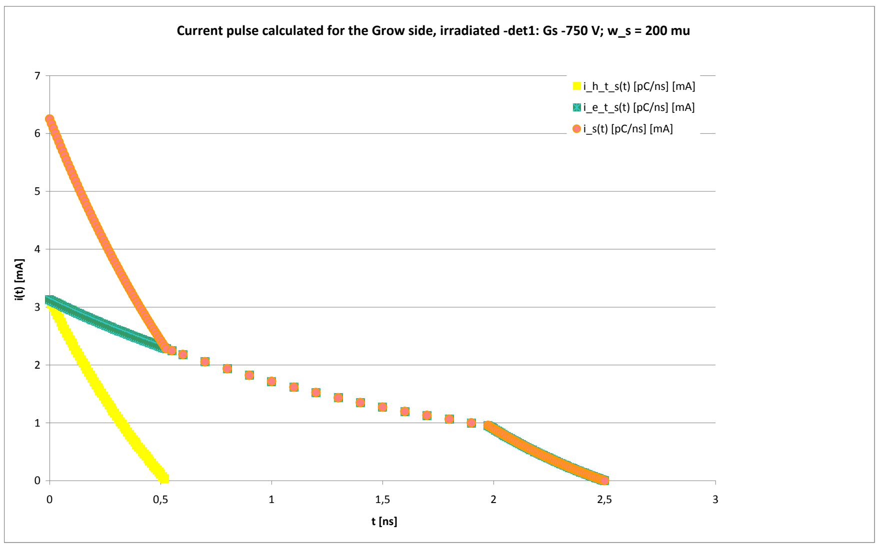
$$Q_{e\_C}=Q_G\frac{w_s}{R}\left(1-e^{-\frac{R}{ws}}\right) = -6,072\ \text{pC};$$

$$Q_{h\_C}=Q_G\frac{w_s}{R}\left(1-e^{-\frac{R}{ws}}\right) = +6,072\ \text{pC};$$

$$Q_{h\_C}=Q_G\frac{w_s}{R}\left(e^{-\frac{d-R}{ws}}-e^{-\frac{d}{ws}}\right) = -2,049\ \text{pC};$$

$$Q_{e\_C}=Q_G\frac{w_s}{R}\left(e^{-\frac{d-R}{ws}}-e^{-\frac{d}{ws}}\right) = +2,049\ \text{pC};$$





$Q_{e\_i}=-0,728$ pC;

$Q_{h\_i}=-3,773$ pC;

$Q\_i=-4,500$ pC

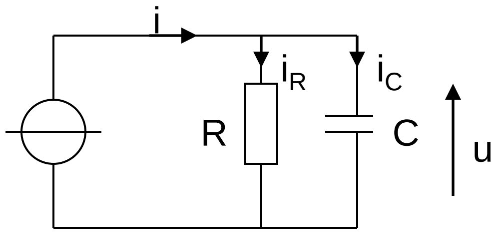
electrons: short drift way

$Q_{e\_i}=+0,728$ pC;

$Q_{h\_i}=+3,773$ pC;

$Q\_i=+4,500$ pC

electrons: long drift way



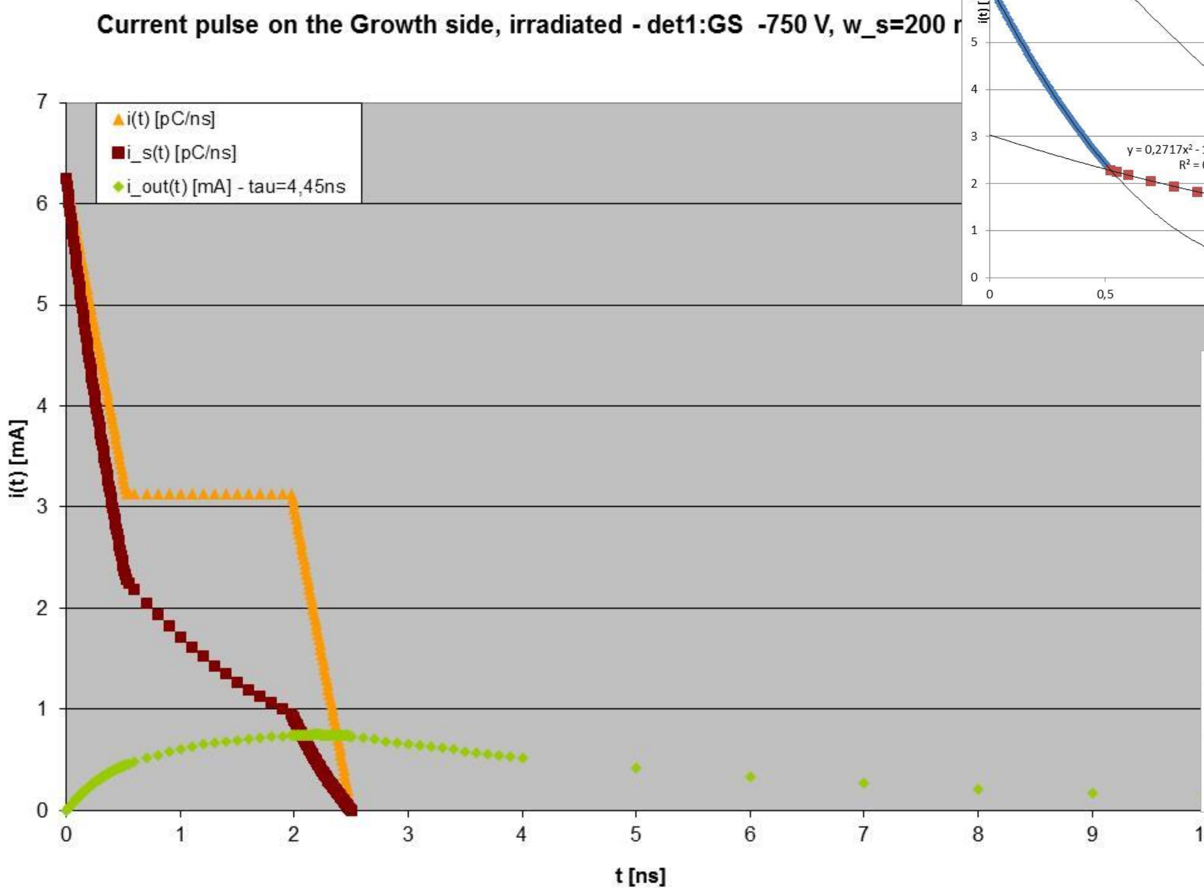
C = 89 pF;
R = 50 Ω;
τ=RC=4,45 ns

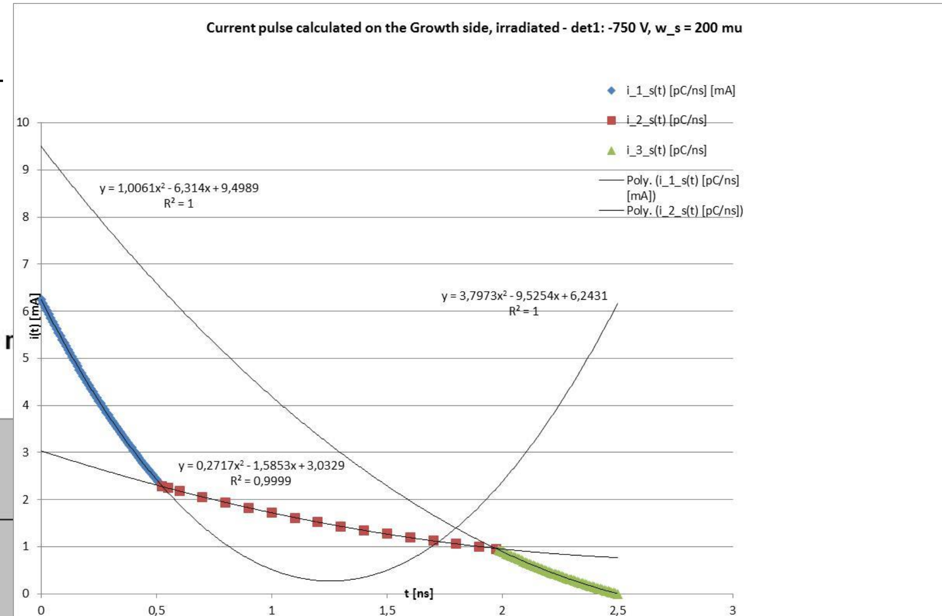
w(1/3) = 7,8 ns
tr(10%90%) = 1,4 ns
Q_i~4,5 pC

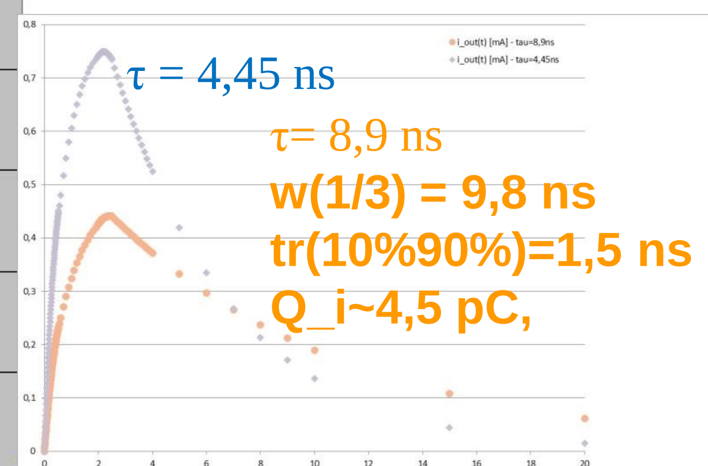
MATACQ – VME (400 MHz BW) 0,9ns 70 m cable

$$i(t) = \frac{u(t)}{R} + C\frac{du(t)}{dt}$$

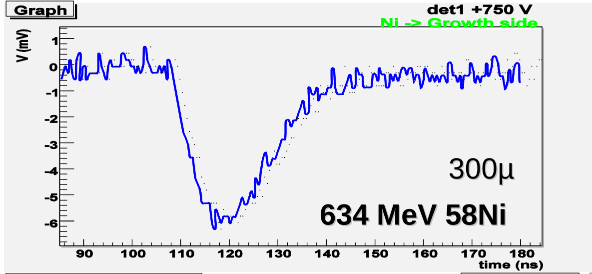
$i(t)=I_{0j}+a_jt+b_jt^2$; j=1,2,3
$u(t)=D_i*\exp(-t/\tau)+V_{0i}+A_it+B_it^2$

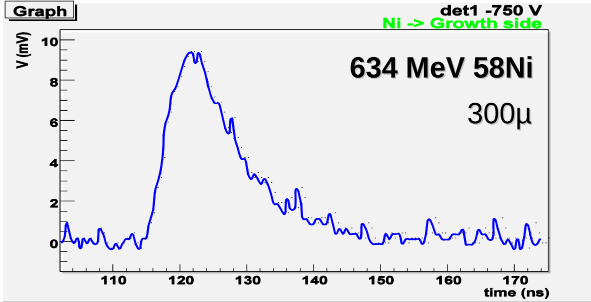


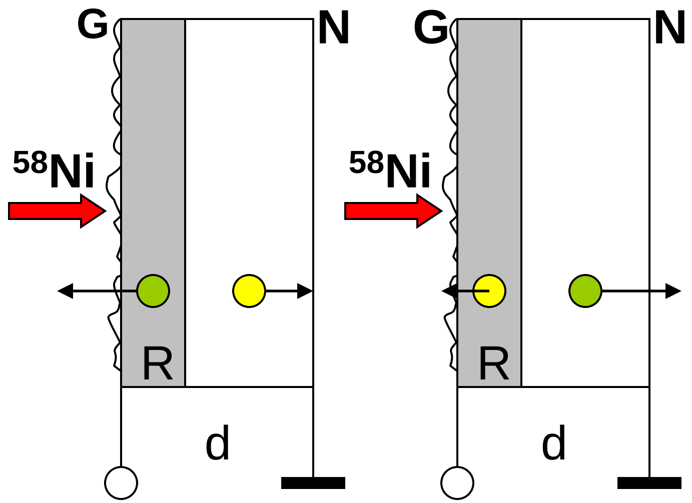


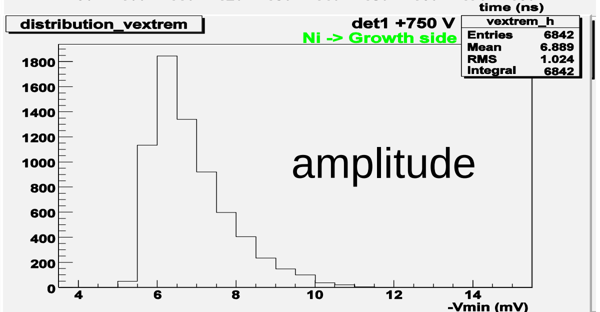


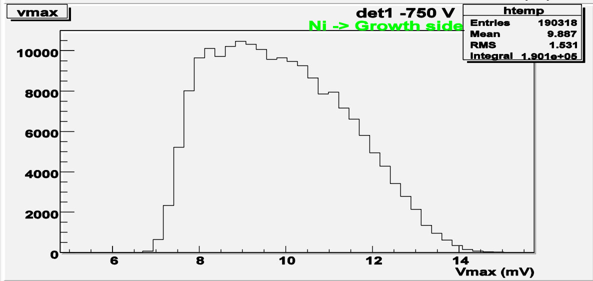
d - thickness; R – range: R<<d











+750V

$0 \leq S_e \leq R$

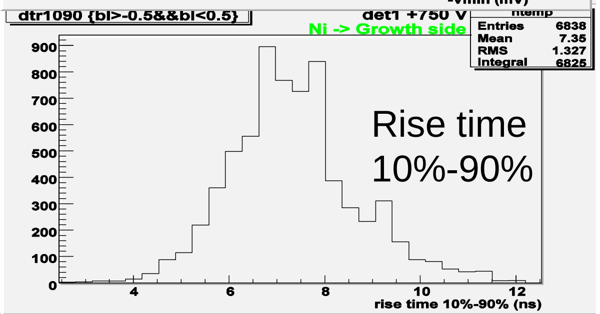
$d\text{-}R \leq S_h \leq d$

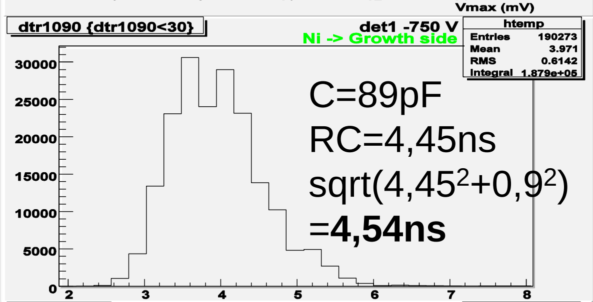
-750V

$0 \leq S_h \leq R$

$d\text{-}R \leq S_e \leq d$

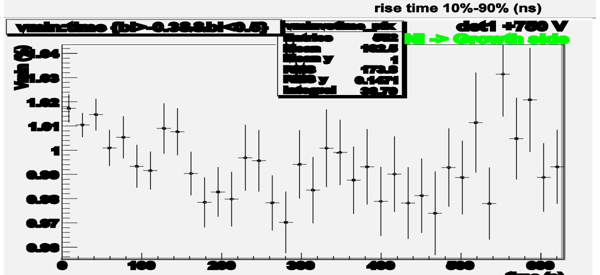
favourable

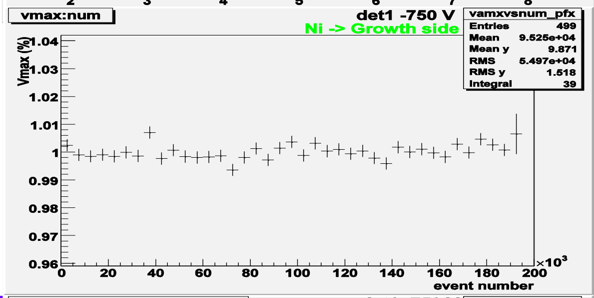




S_e – drift **électrons -**

S_h – drift **holes +**



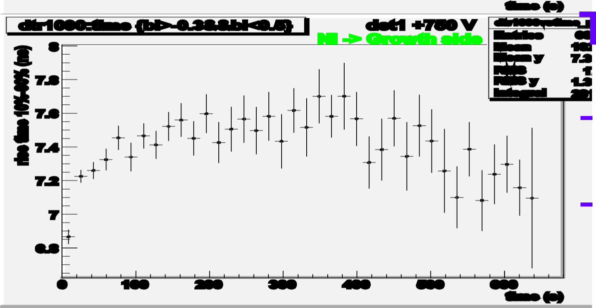


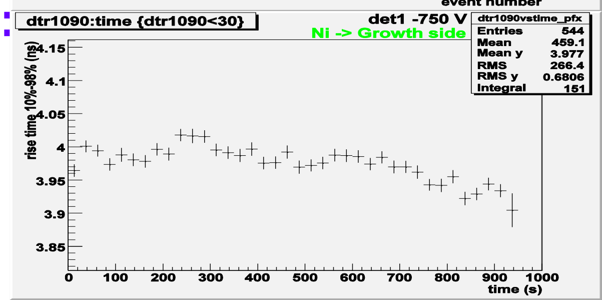
Tests - not-segmented detectors:

- $S_h < S_e$ – favourable
- d adequate to R

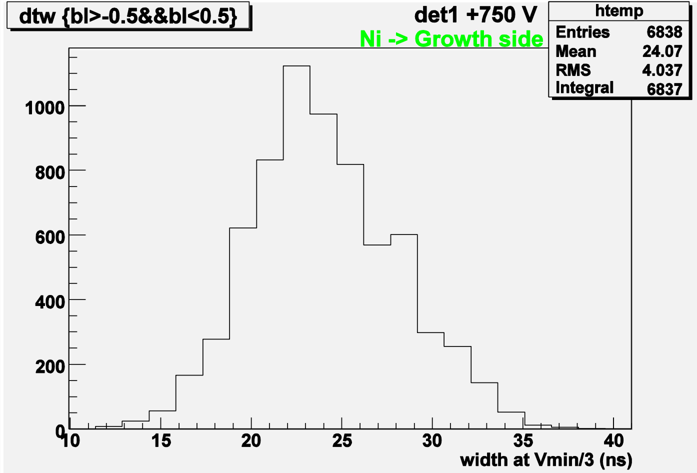
E=2,5V/µ

GANIL – SME: ~10^4 pps

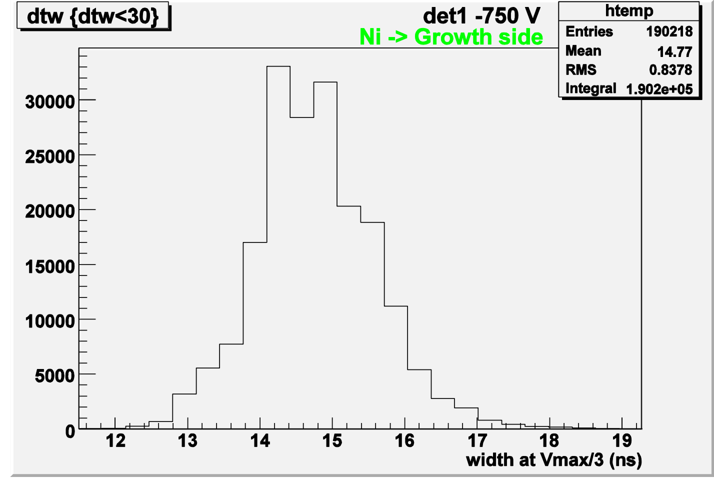


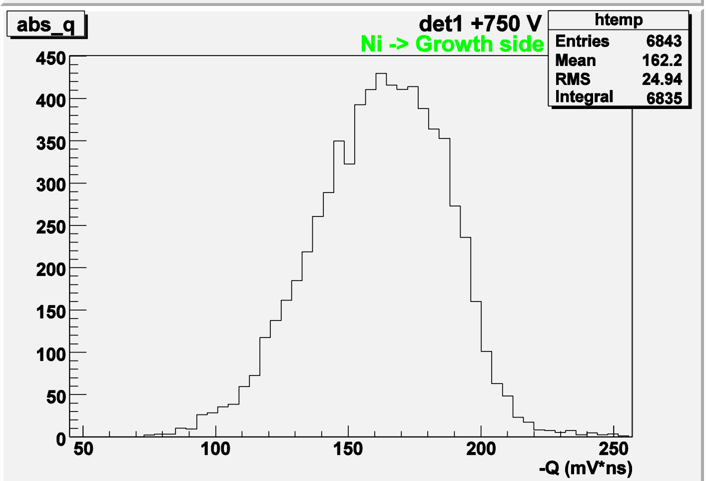


300 μ; E = 2,5 V/μ

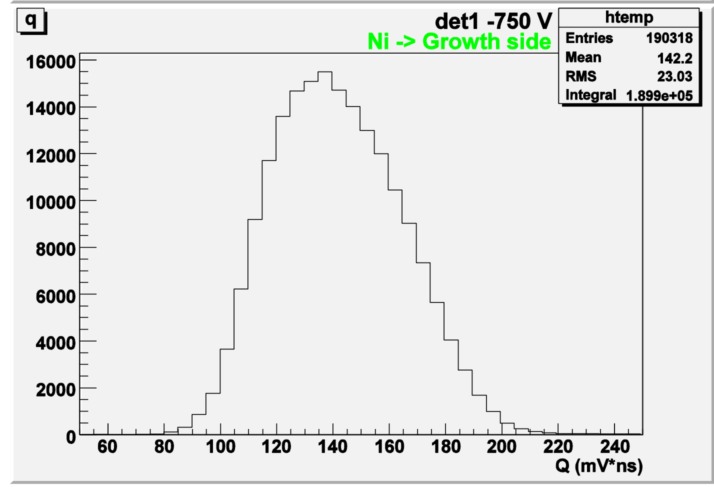


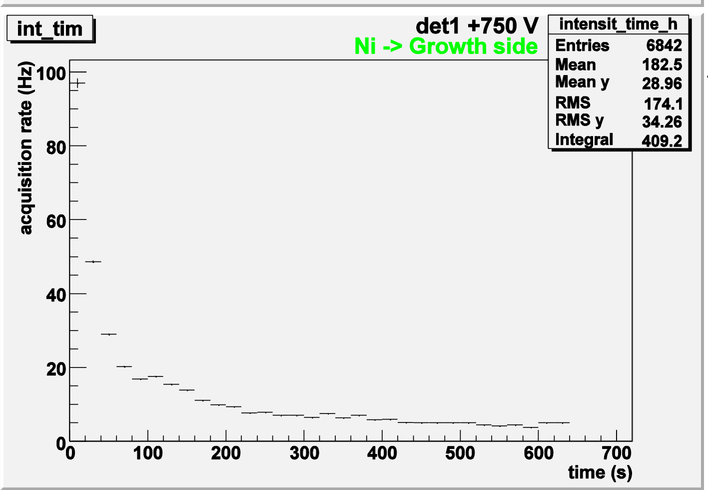
Width at 1/3Vextrem (ns)



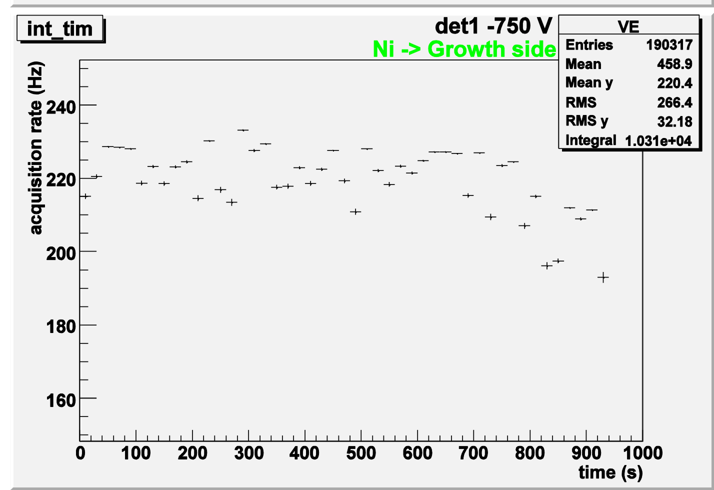


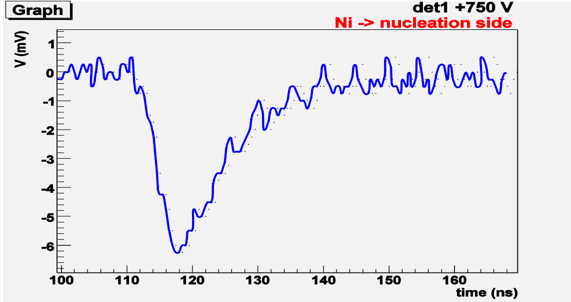
Charge (mV*ns)

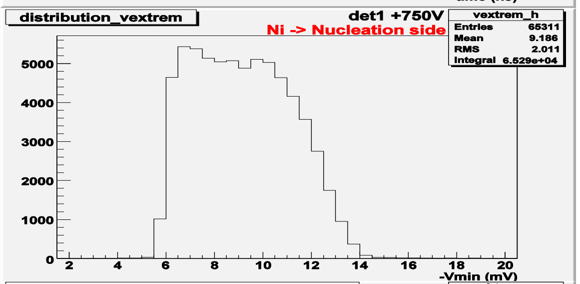


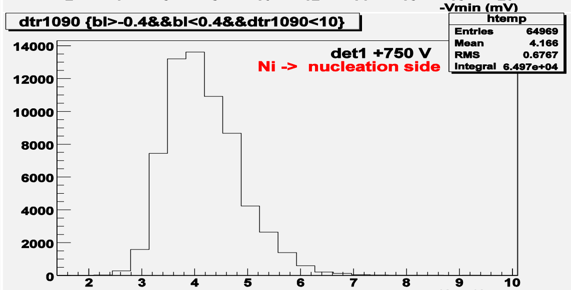


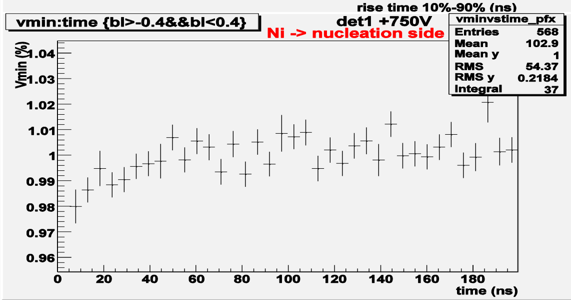
Acquisition rate (Hz)

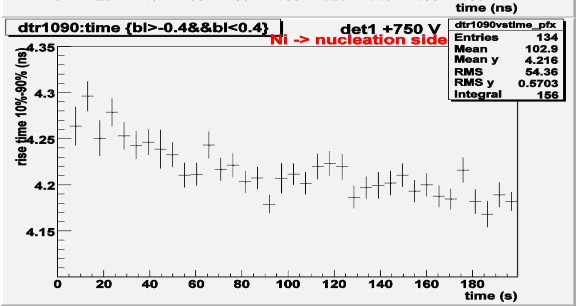




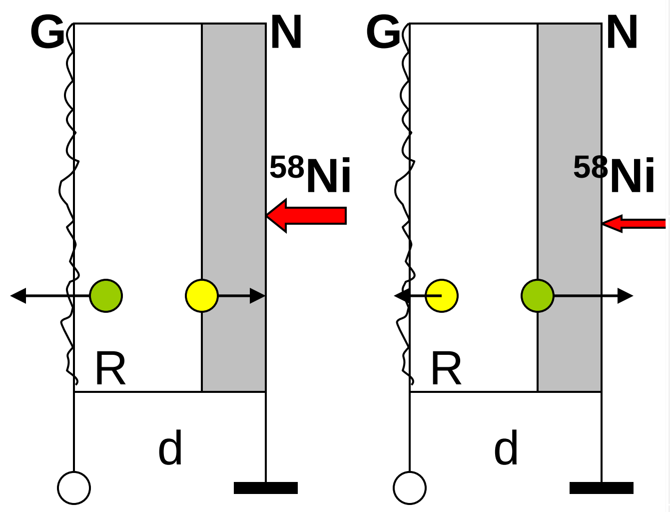








d - thickness; R – range: R<<d



+750V

$0 \leq S_h \leq R$

$d-R \leq S_e \leq d$

favourable

-750V

$0 \leq S_e \leq R$

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S_e – drift **électrons -**

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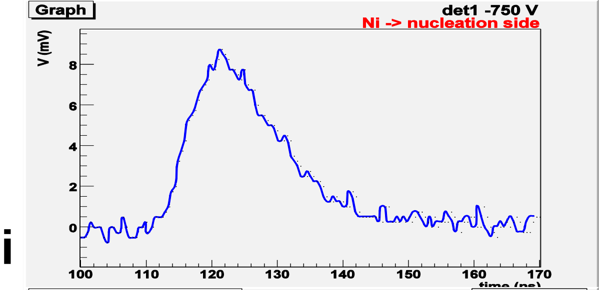
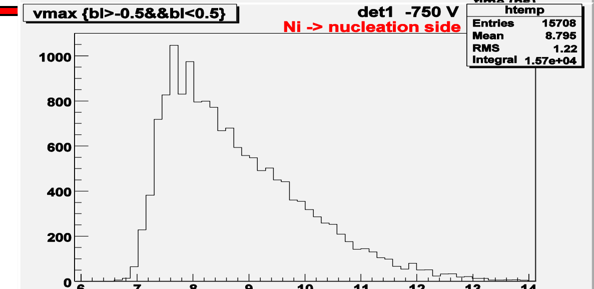
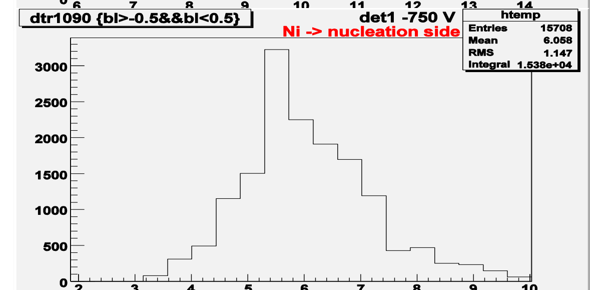
Tests - not-segmented detectors:

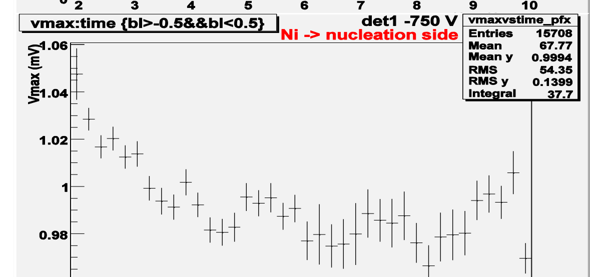
- $S_h < S_e$ – favourable
- d adequate to R

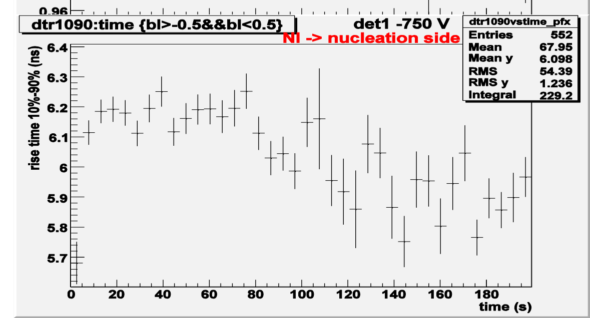
GANIL – SME: ~10^4 pps



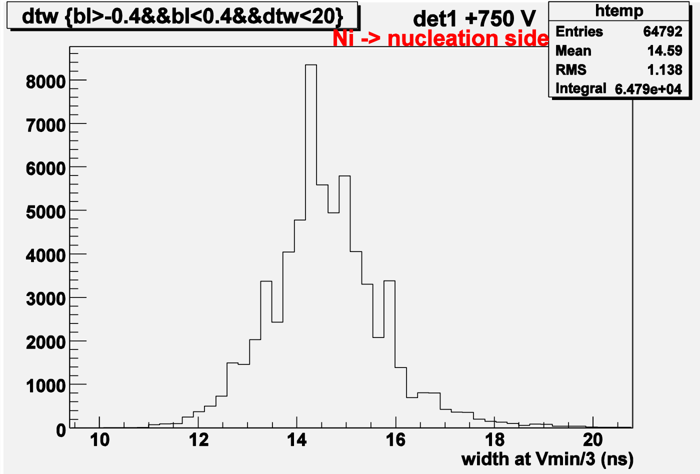


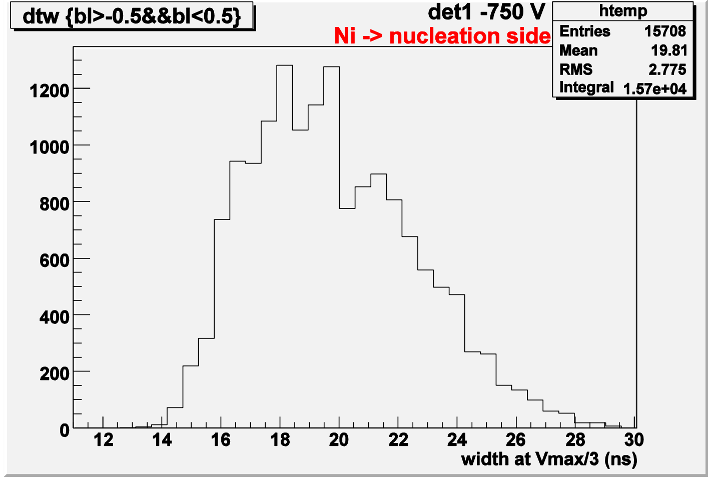




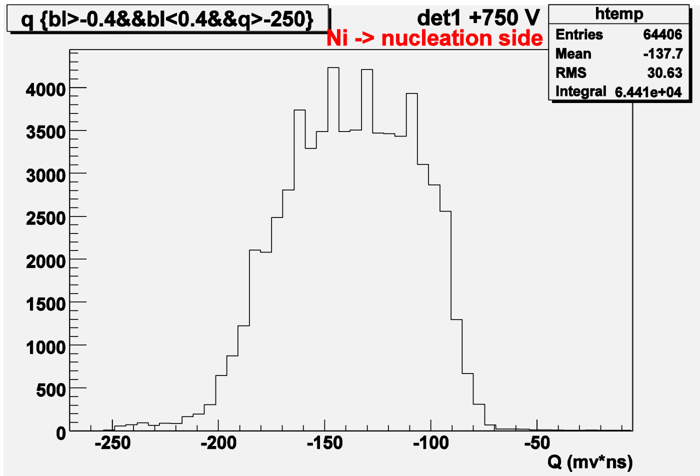


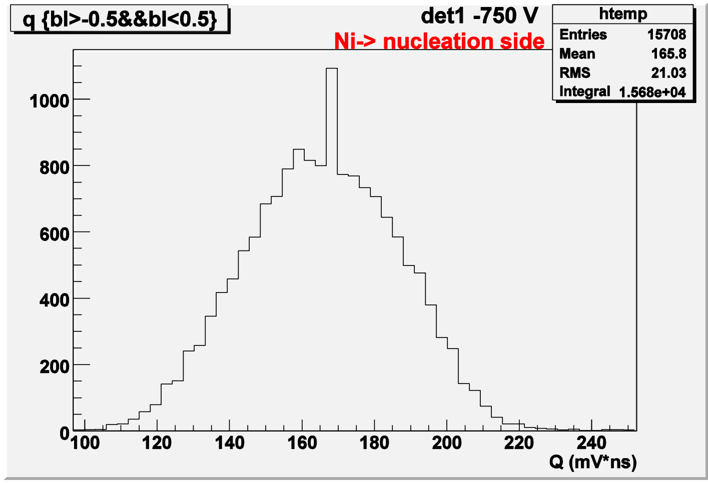
300 μ; E = 2,5 V/μ



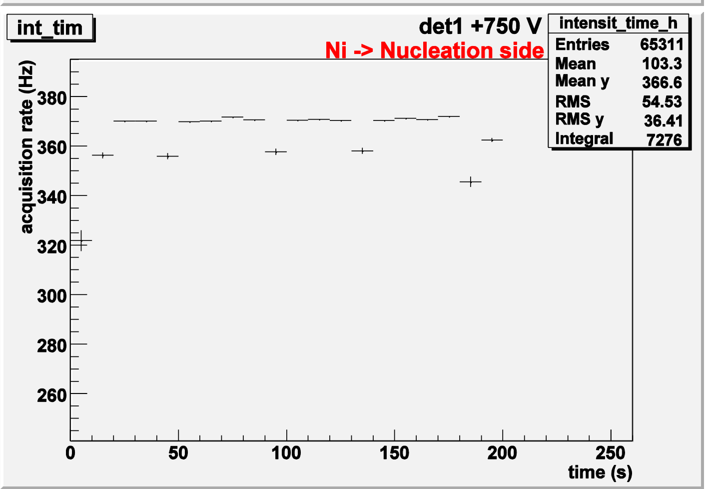


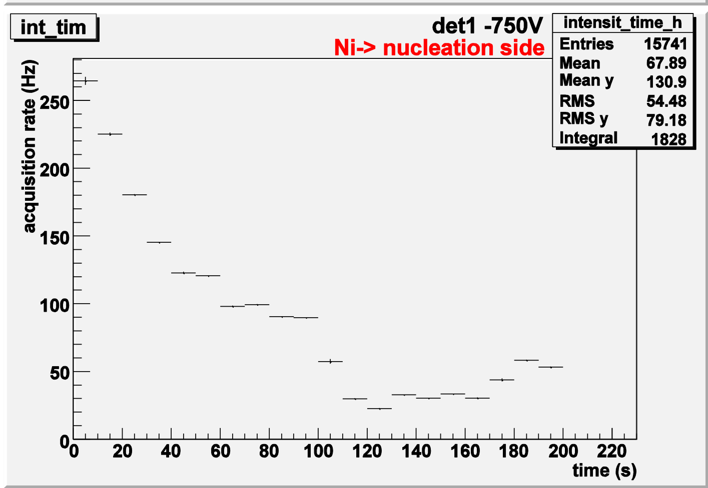
Width at 1/3Vextrem (ns)





Charge (mV*ns)



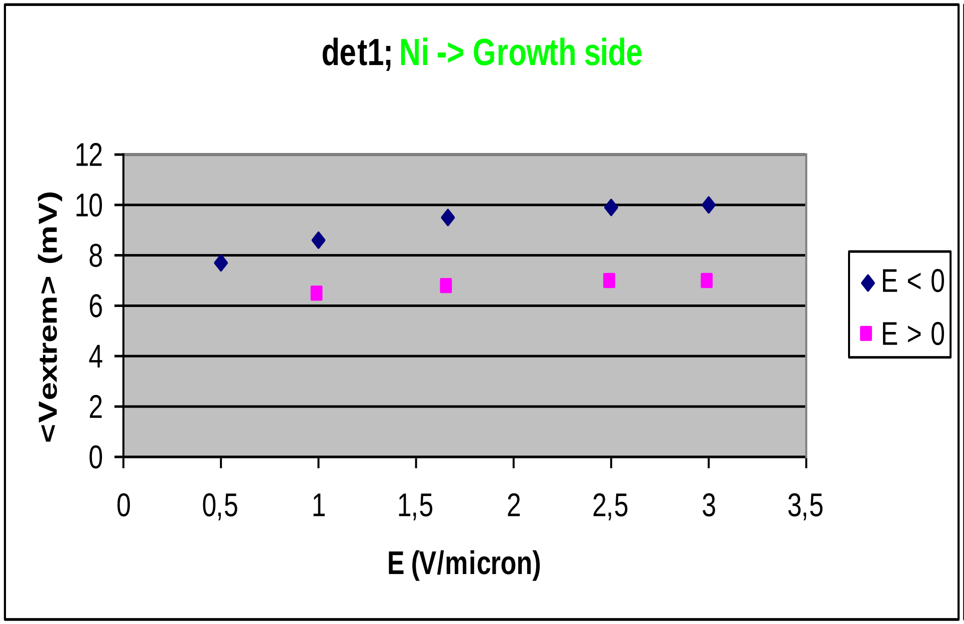


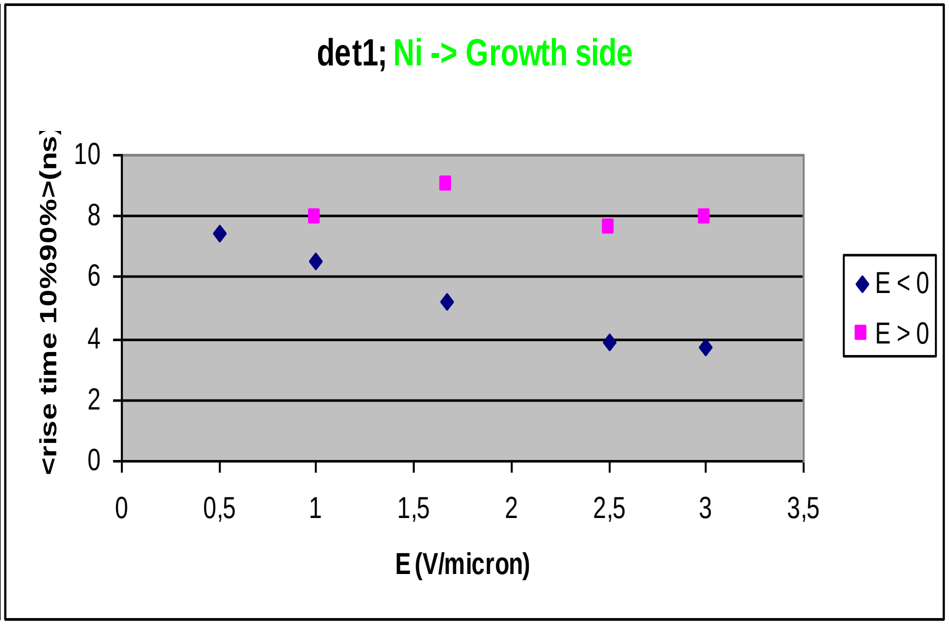
Acquisition rate (Hz)

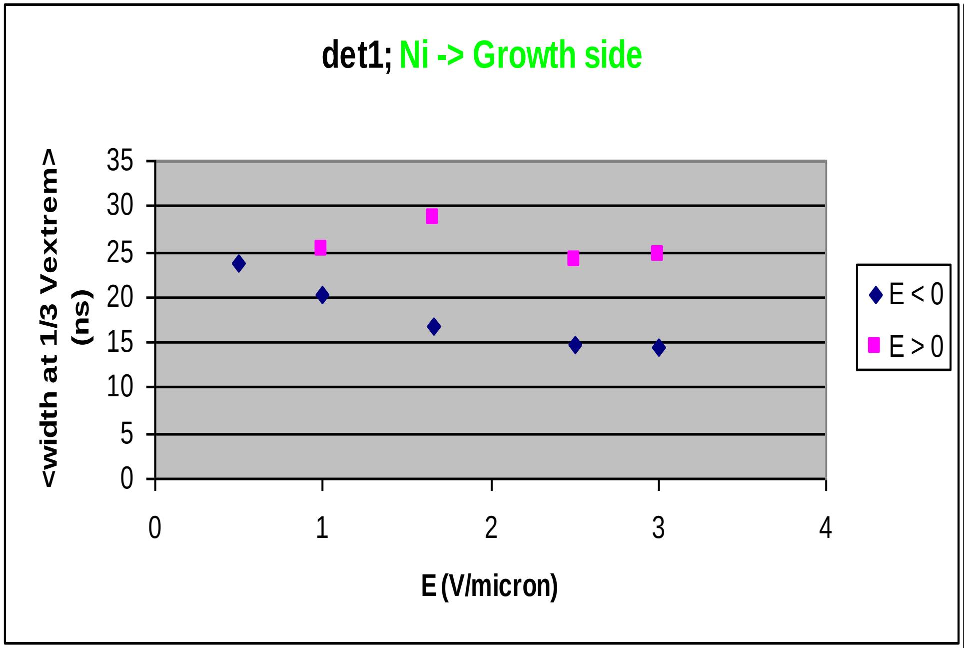
Table 3. Synthetic results concerning the shape of the signal induced by **634 MeV ^{58}Ni** ions, having a **range of ~ 60 μm** in a uni-strip diamond detector **P1N ELA of 300 μm** at **E = 2,5 V/μ** .

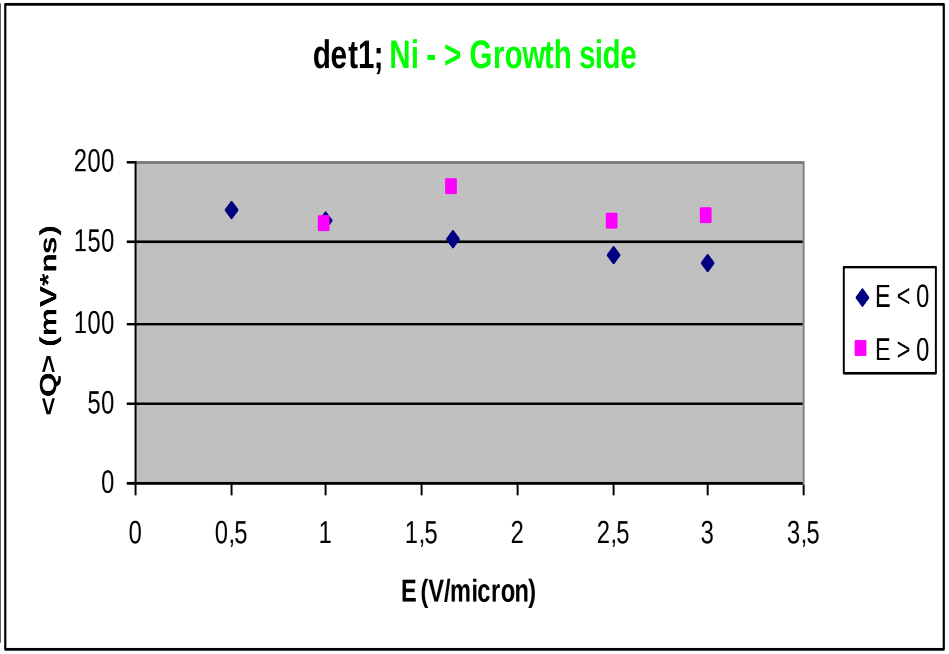
irradiated face	**G face U (V) long tranzit**	$<V_{extrem}>$ (mV)	Rms V (mV)	<Q> (mV*ns)	Rms Q (mV*ns)	tr (ns)	rms tr (ns)	$<w_{1/3}>$ (ns)	Rms w (ns)
G	+750 holes	6.9	1.0	162	25	7.4	1.3	24.1	4.0
G	-750 electrons	9.9	1.5	142	23	4.0	0.61	14.8	0.84
N	+750 electrons	9.2	2.0	138	31	4.2	0.68	14.6	1.1
N	-750 holes	8.8	1.2	166	21	6.1	1.1	19.8	2.8

Faster and higher signals are generally preferred for beam monitoring. The conclusion emerging from Table 2 is that, when **the range of the ion is much shorter then the detector thickness** and the distances of drift for the two types of carriers to the electrodes are different, **the voltage has to be chosen in such a way that the holes have the shortest drift road, regardless of the irradiated side**. This will have several beneficial effects: **higher signal amplitude, shorter signals, characterized by a faster rise time and a shorter fall too.** The quality of the signals, somehow better on the fourth line of the table as compared to that on the first line - both of them concerning the long drift distance for the holes – may show that the signal degradation is a little bit smaller when their road leads to the growth side, with bigger diamond crystallites and therefore a higher quality (for the fourth line) than when their road leads towards the nucleation side, including more graphite (first line).







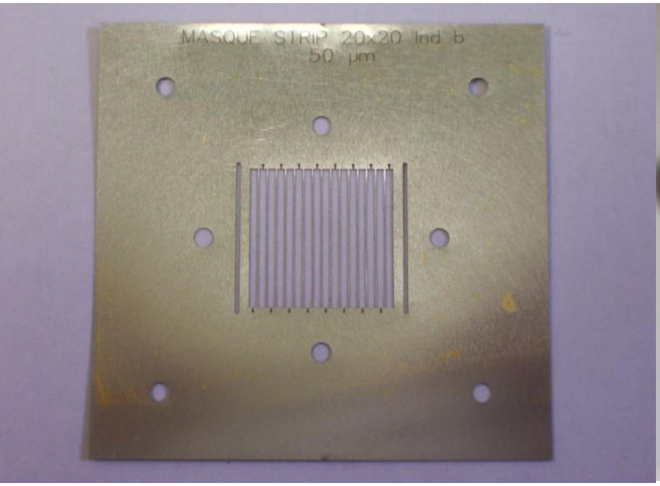


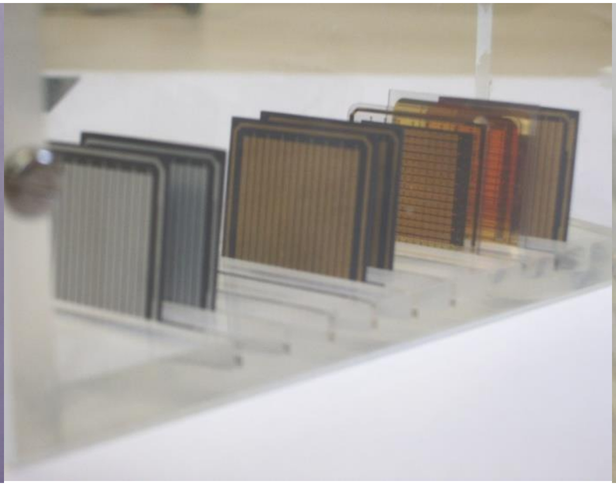
When R<d, the signal is higher and faster when the **electrons** drift on a **longer** way then the **holes**.

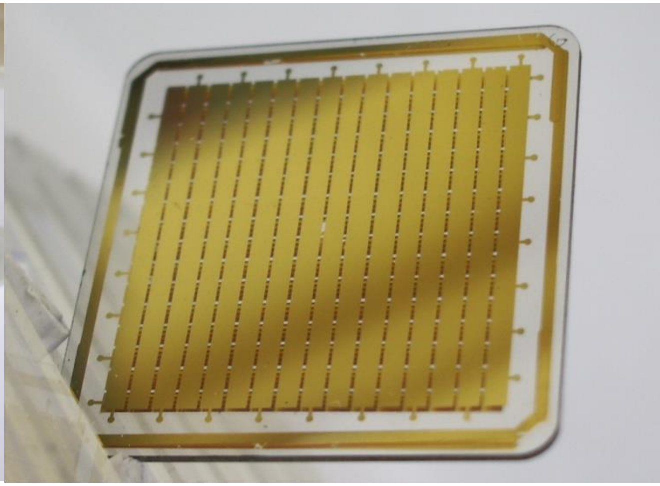
Similar results for det2

IV Multi-strip detctors: Company 1 - ELP vs ELS

ELP (Electronic Premium Grade) – processed from a polycrystalline wafer with a starting thickness of 1 mm; the final thickness is achieved by removal from the nucleation surface; therefore, thinner the thickness of an ELP plate is, higher its quality; but under 0.2 mm, the risk of breaking in the process of lapping and polishing is much increasing;
ELS (Electronic Standard Grade) – processed from a polycrystalline wafer with a minimum removal of 100 μm. Comparing the two types of material was one of the objectives of our study.



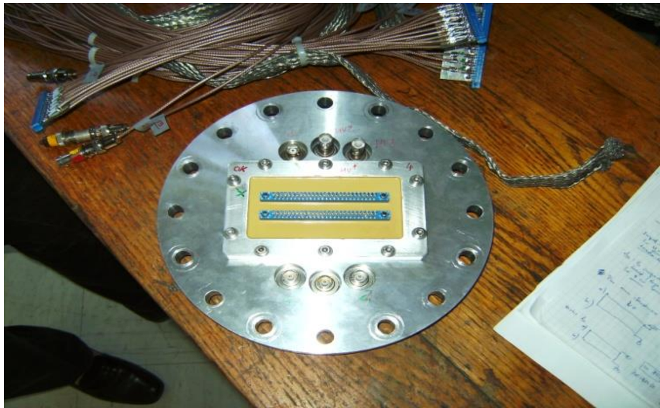




Strip pitch: 0.9mm inter-strip gap: 0.1mm
efficiency: 90%

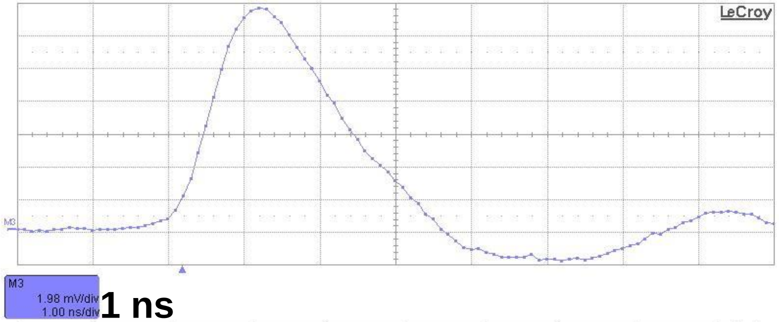
The BERGER files for the masks & PCBs were done at LPC

Flange and connectors

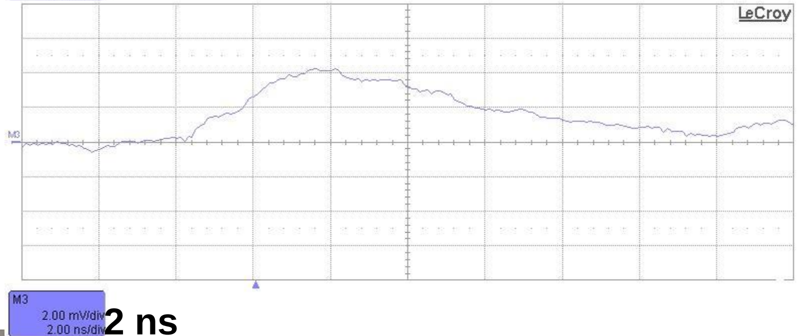


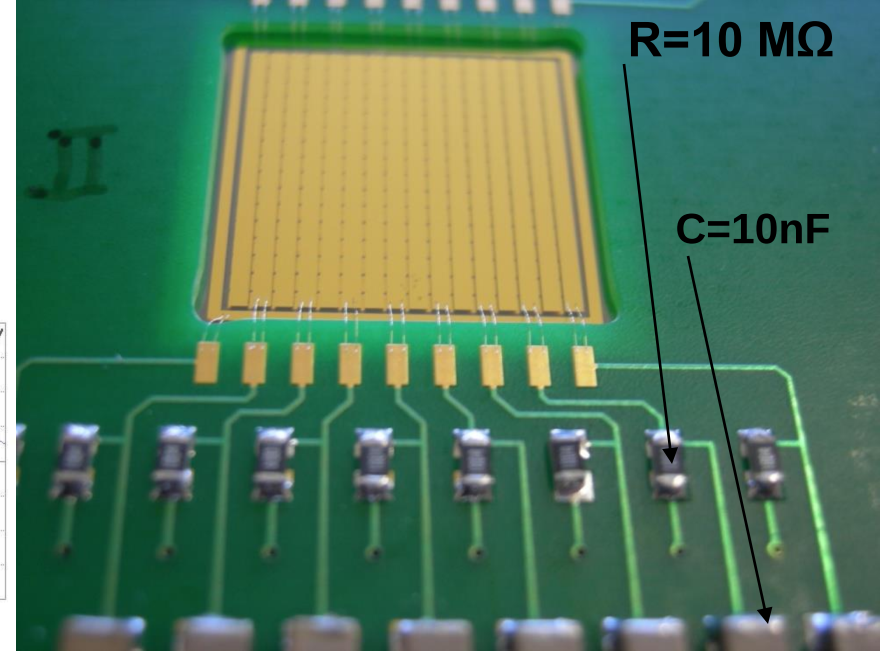
Det III:

5.5 MeV α



PRL: developped at LPC





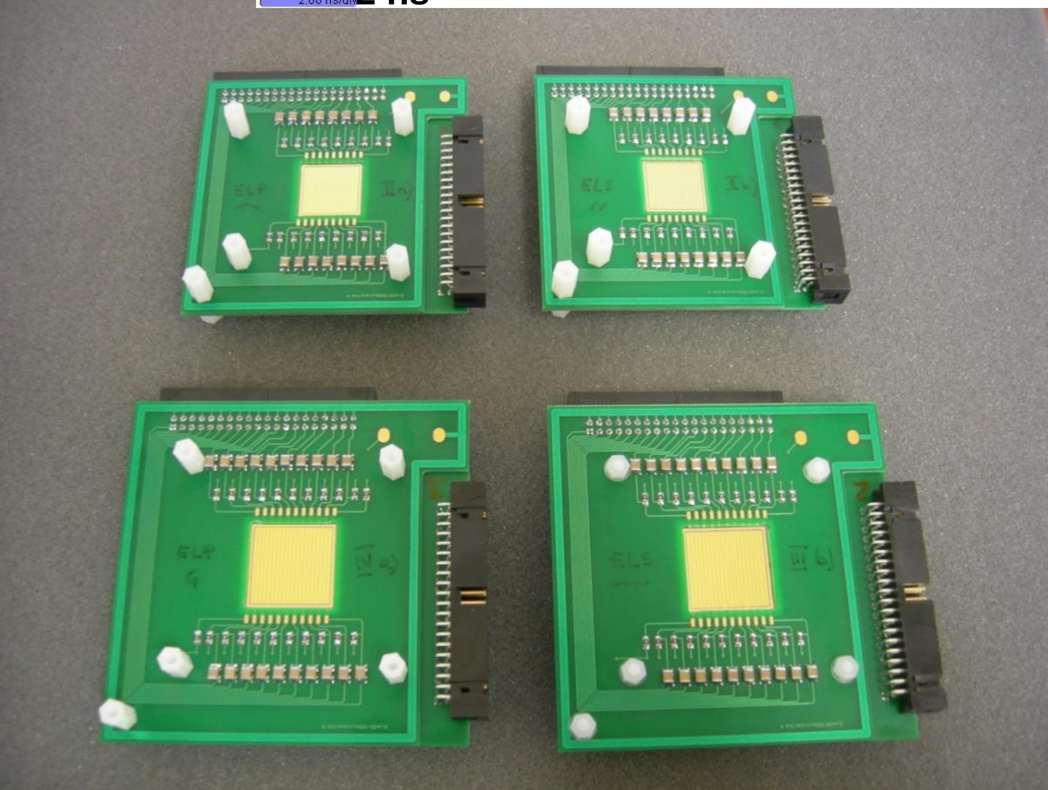
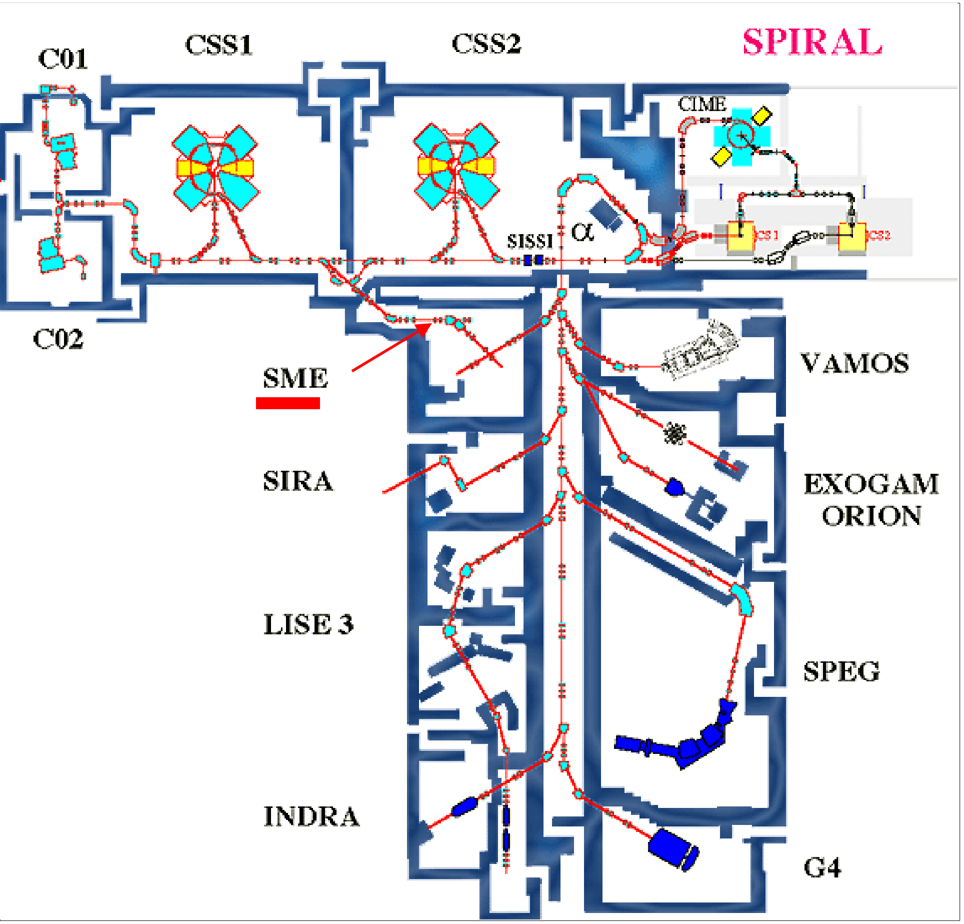


Table 3. the multi-strip detectors built at LCP; a) and b) are the 2 faces

Detecteur	P2 - Type	Densité (g/cm3)	Epaisseur (µm)	Surface active (mm2)	Nombre de pistes
I	ELS	2.9	565	16x16	a)16 G b)16 N
II	ELP	3.4	575	16x16	a) 16 b) 16
III	ELS	2.9	240	20x20	**a) 1 b) 20**
IV	ELP	3.4	350	20x20	a) 20 b) 20

Les tests au GANIL: sur la ligne SME (sortie moyenne énergie)



Installation des détecteurs

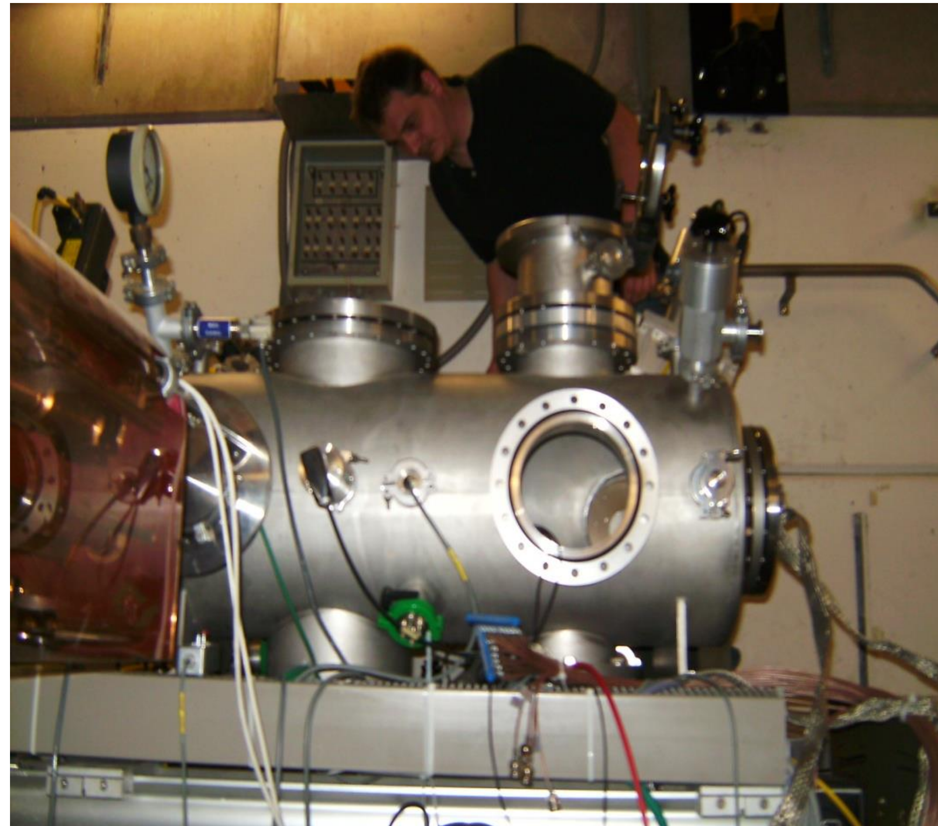
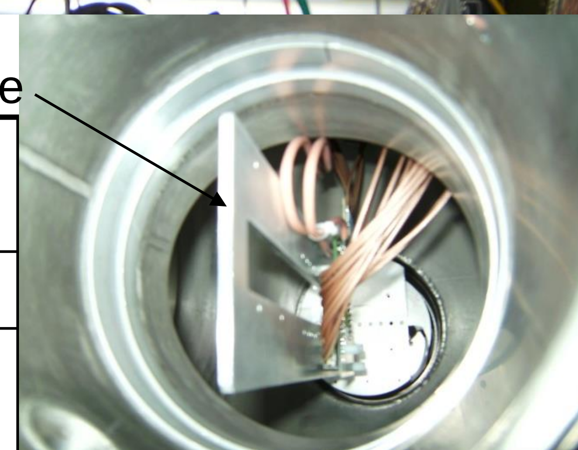


Table 4. Ions used in GANIL

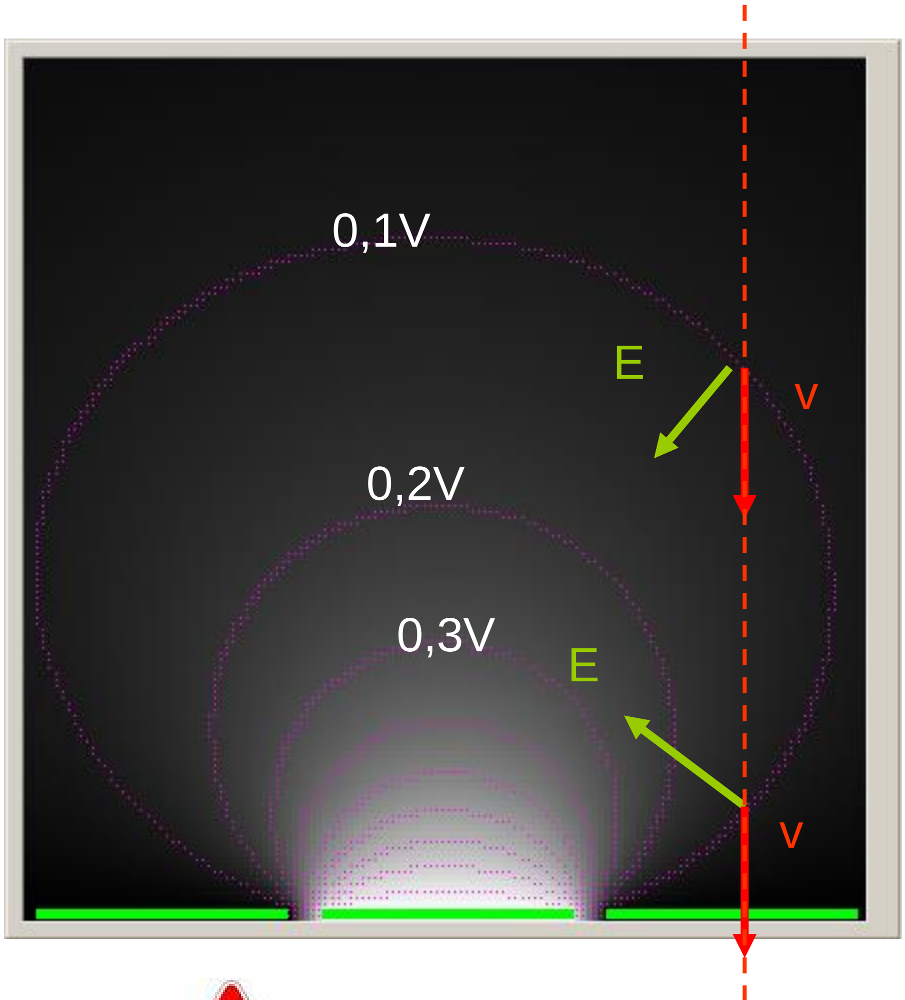
Plaque + détecteur + alumine

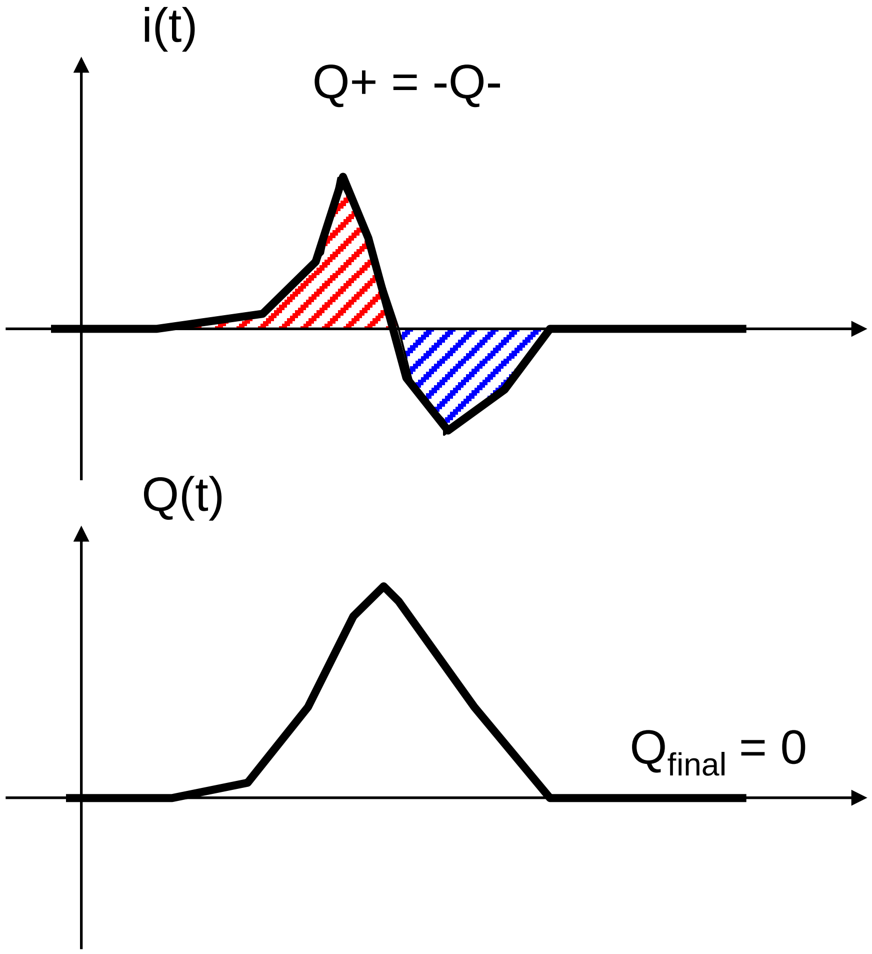


~2,5 m	GANIL ^{70}Zn	GANIL ^{36}S	GANIL ^{36}S	GANIL ^{16}O	LPC α
E/A (MeV)	8.7	7.2	3.9	13.7	1.2
Range (μ) ELS range (μ) ELP	63 55	48 42	26 22	225 198	15 13

Cours Jean-Marc Fontbonne

Induction d’un signal transitoire sur les pistes adjacentes

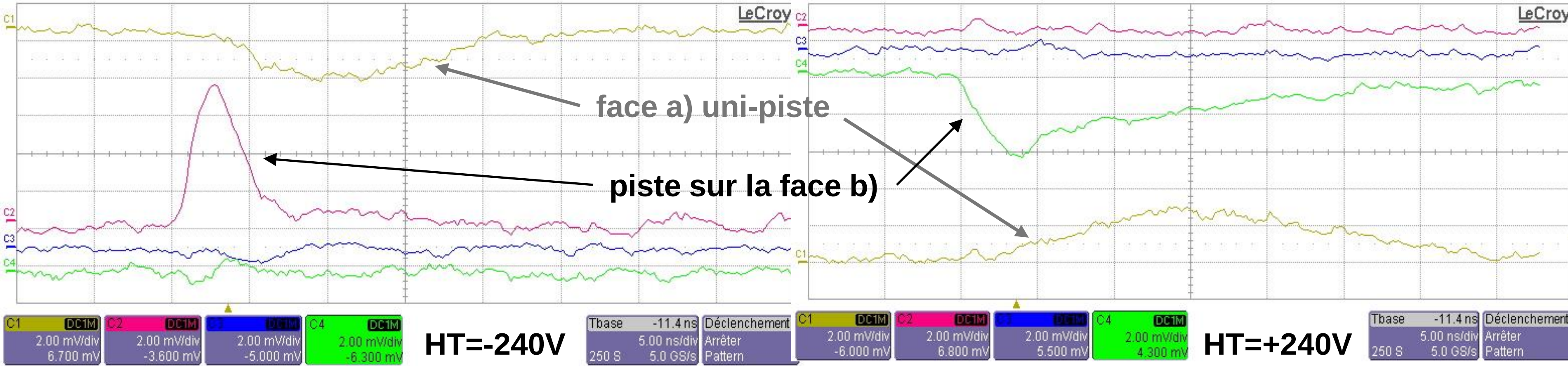




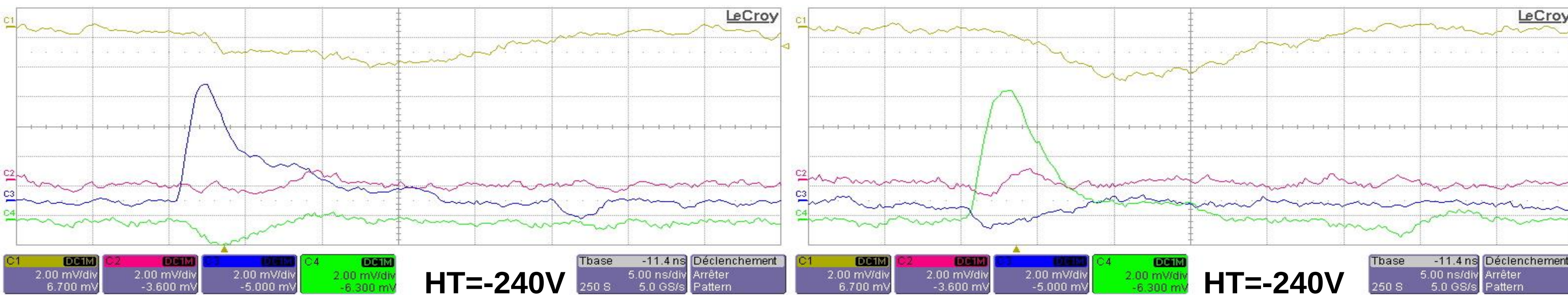
Il peut également y avoir des problèmes sur les interpistes
→ Répartition du signal sur des pistes contigües

Résultats pour les détecteurs multipiste: *images prises sur l'oscilloscope LeCroy*

HT sur la face b) irradiée (1V/µ)



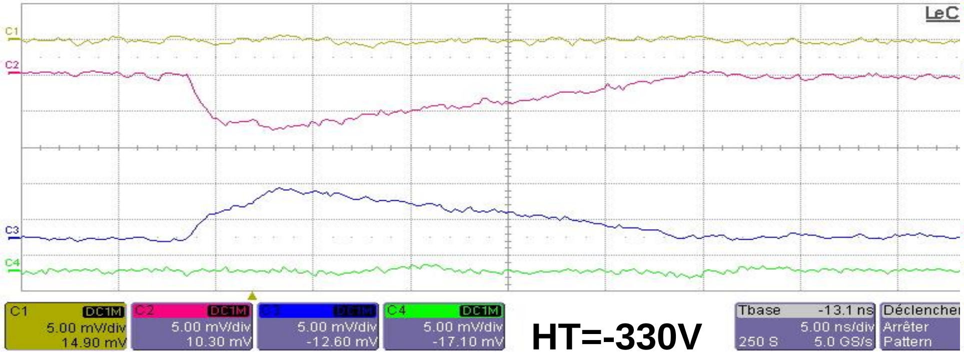
Signals induced by ^{36}S of 7.2 AMeV in the detector III of ELS type



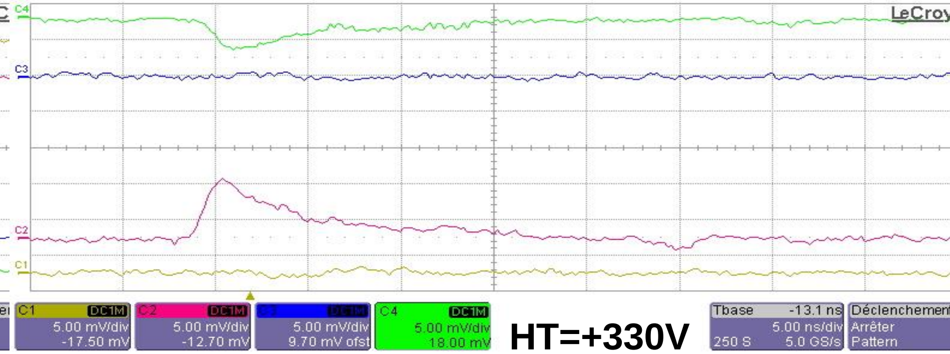
Signals induced by ^{36}S of 7.2 AMeV in the detector III of ELS type: examples of cross-talk between neighbouring strips on the irradiated face (blue and green)

Résultats pour les détecteurs multipiste: *images prises sur l'oscilloscope LeCroy*

Coincident signals on the two sides of the detector **HT sur la face a) irradiée (1V/µ)**

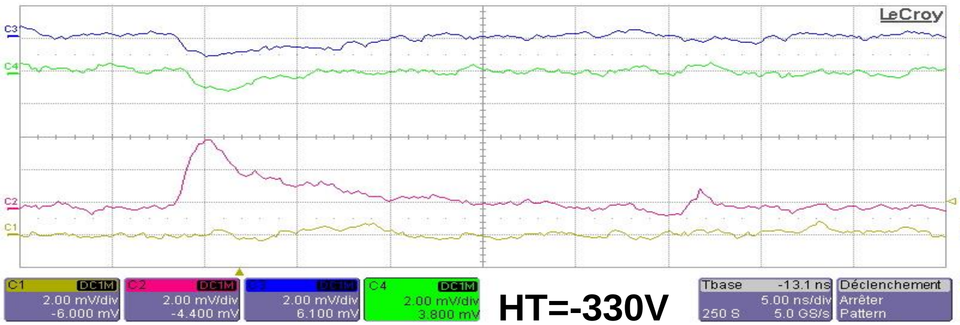


HT=-330V

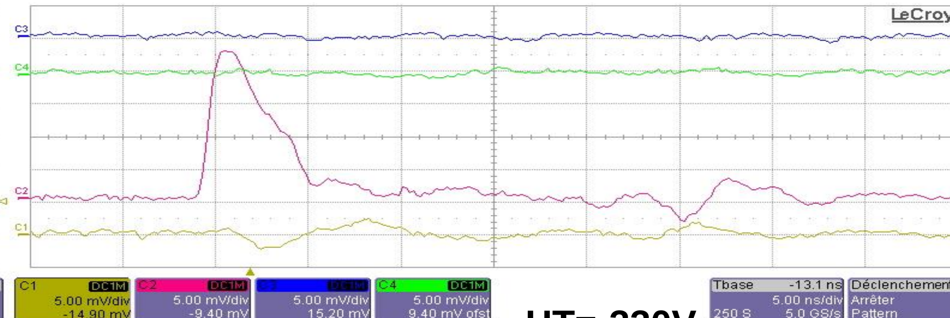


HT=+330V

Signals induced by ^{36}S of 7.2 AMeV in the detector IV of ELP type

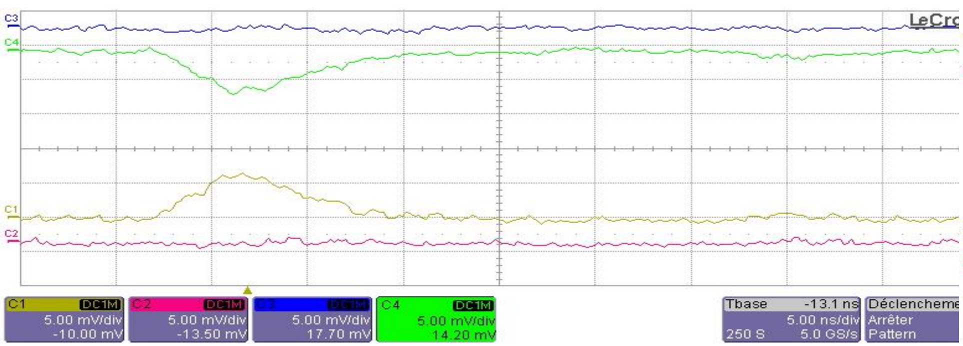


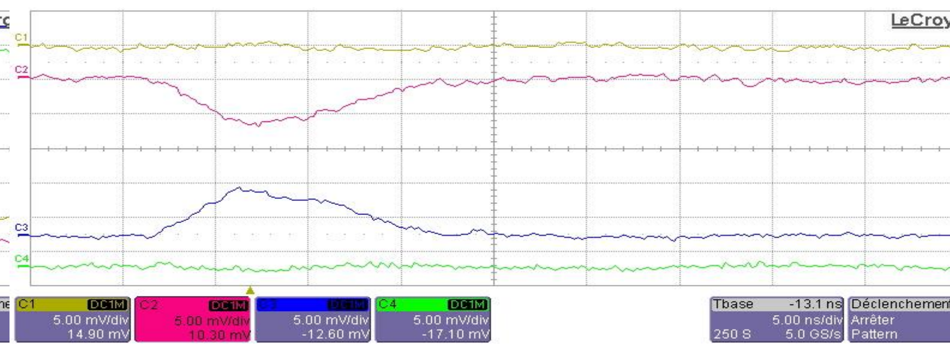
HT=-330V



HT=-330V

The particle is probably passing between strips (left); example of cross-talk (right)





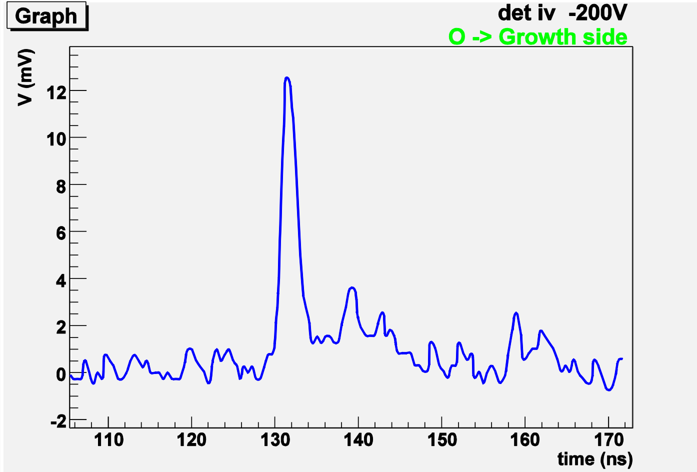
Signals induced by ^{36}S of 3.9 AMeV in the detector IV of ELP type (-330 V)

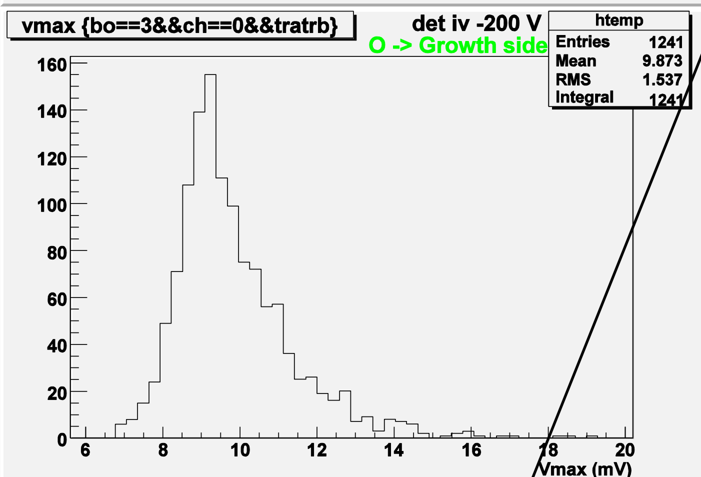
Det iv ELP, 350 µ, -200 V, E=0.6V/µ board 3, channel 0;

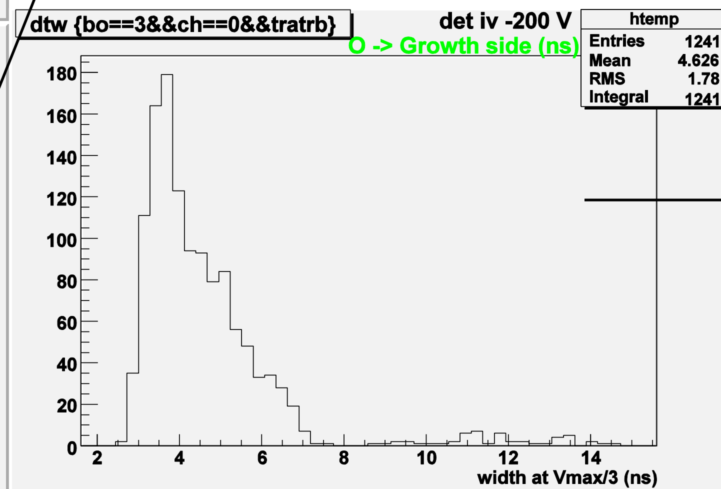
O –> Growth side: 13.7 AMeV

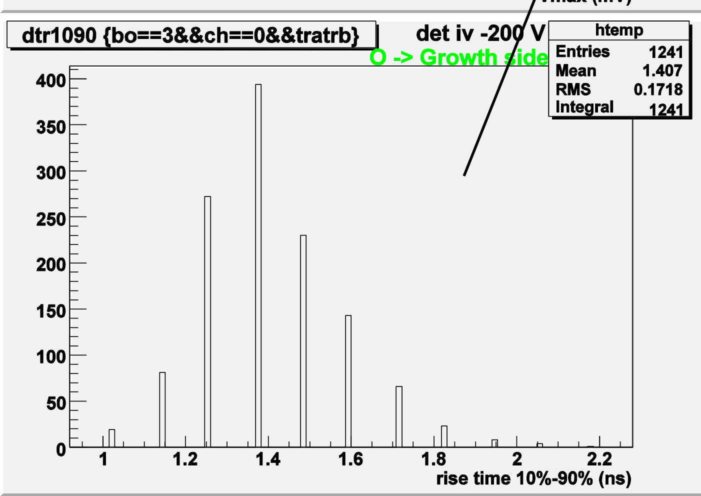
S=18mm2; C=2,57 pF RC=0,13ns

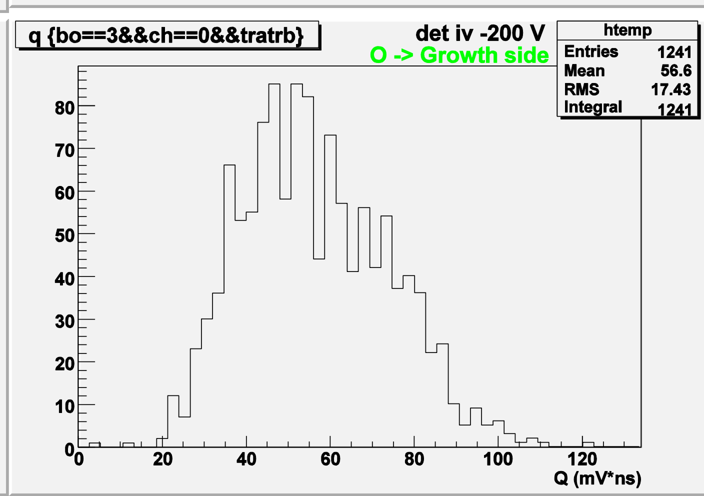
Matacq -> 0,9 ns



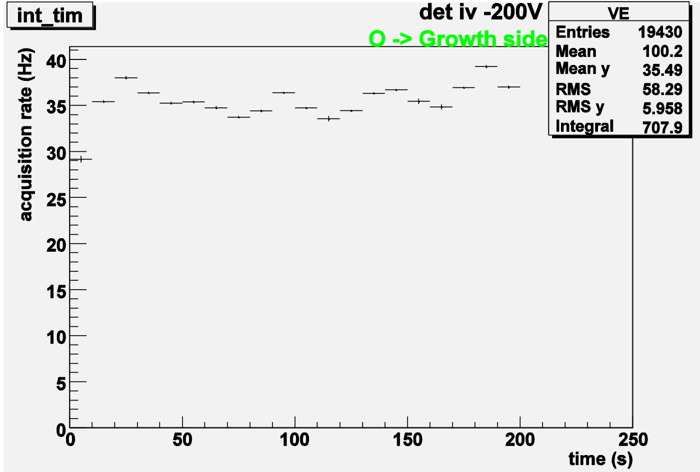


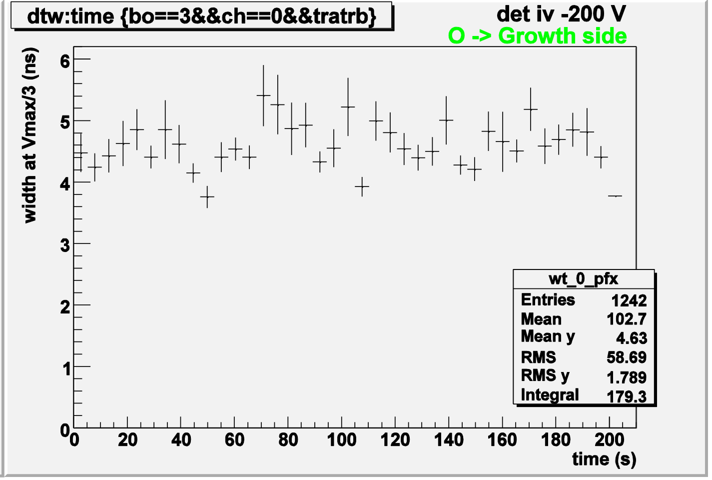


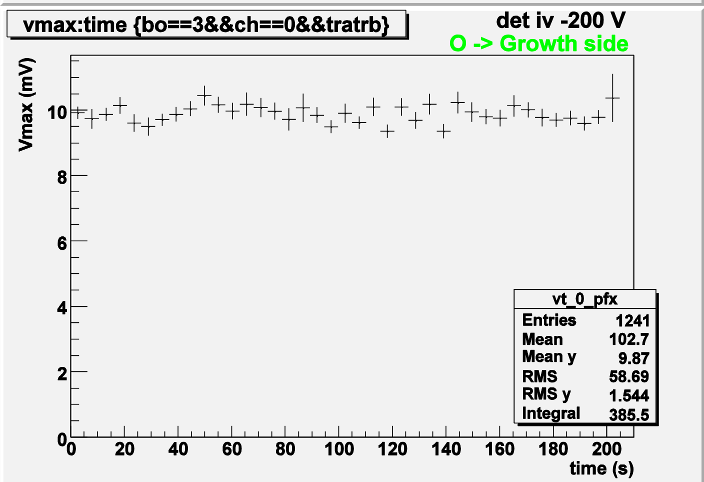


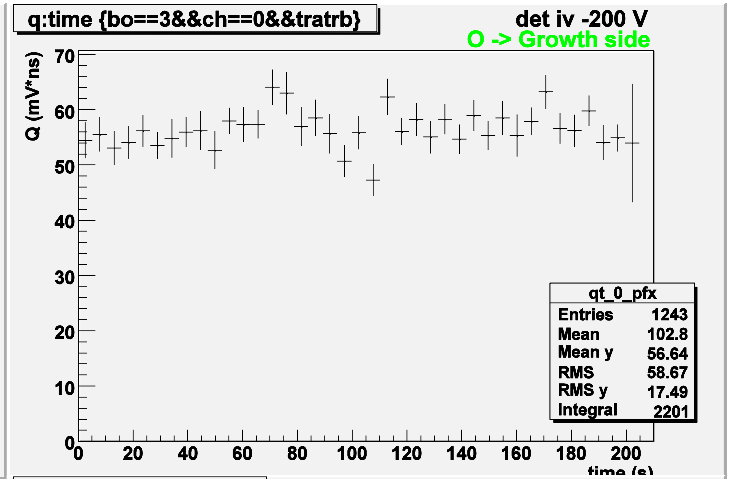


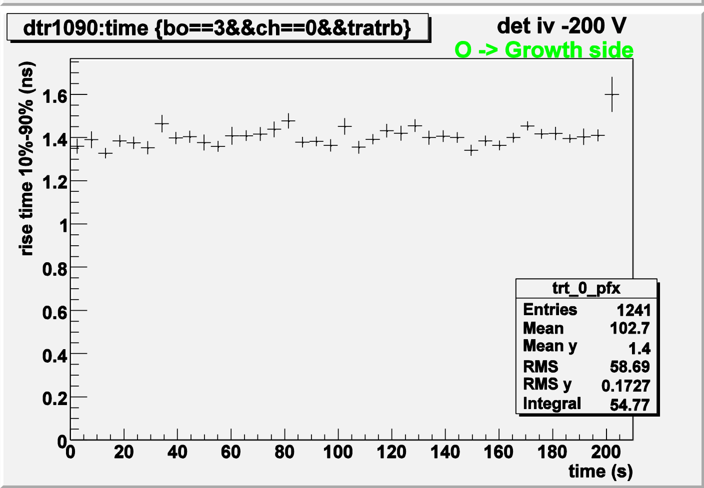
Acquisition:
MATACQ – VME (400 MHz BW; 2GHz sampling) – 12 channels
- oscillo LeCroy 64Xi (600 MHz BW; 10Gs/s) – 4 channels

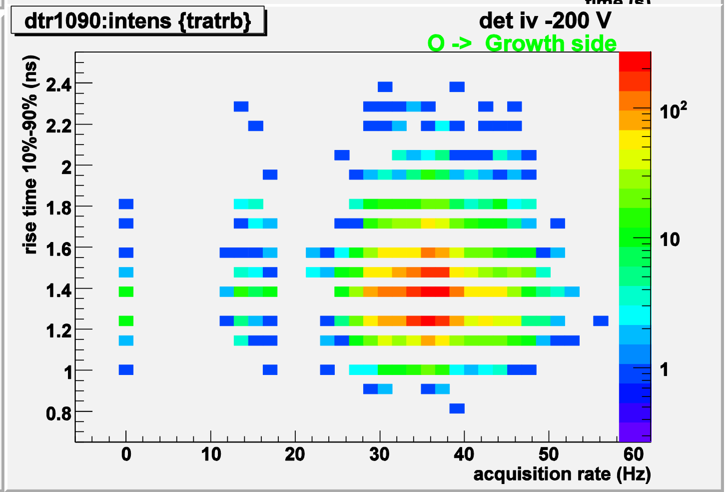












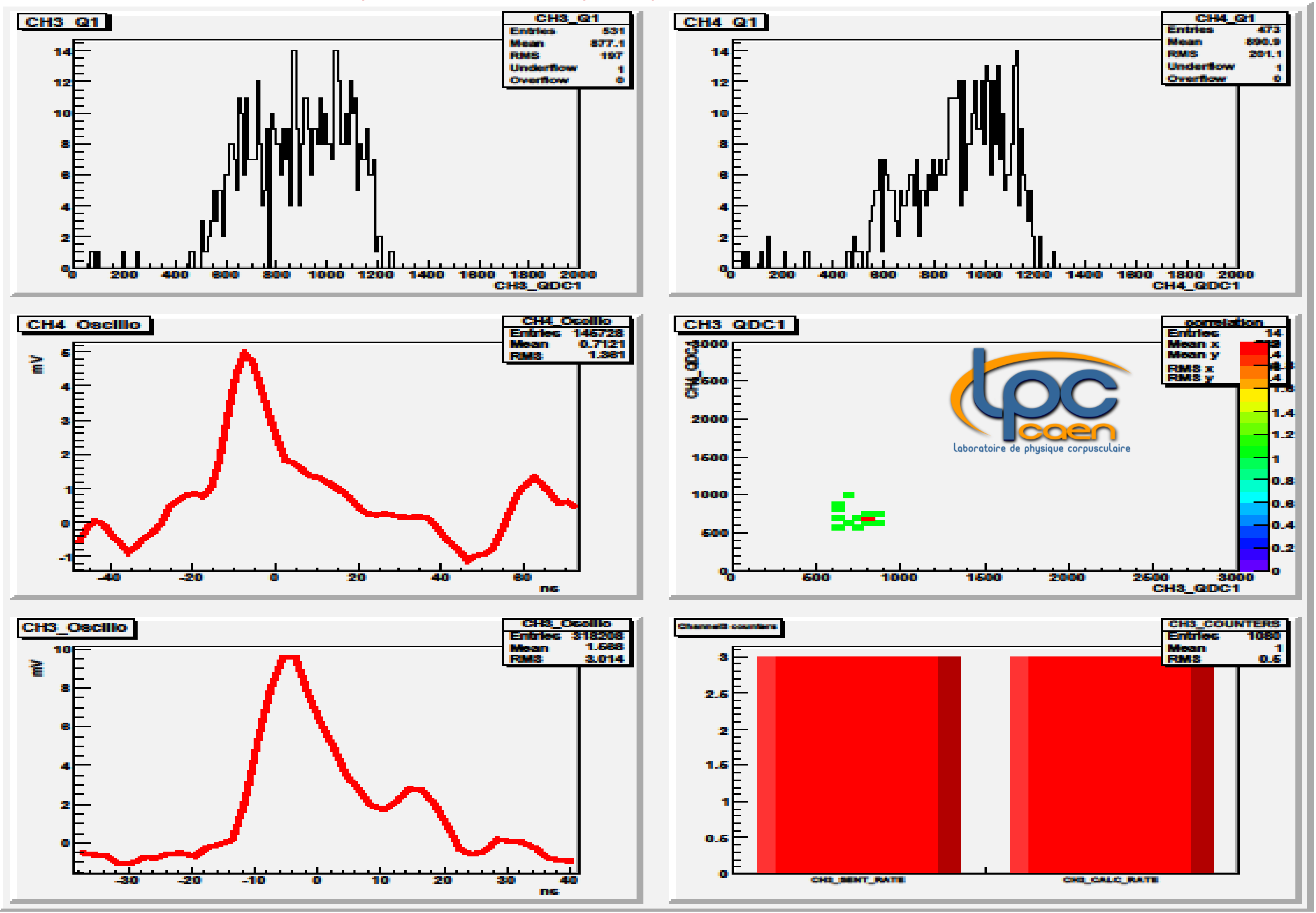
Det iv ELP, 350 μ -200 V, E=0.6V/μ board 3;

O: 13.7 AMeV

Det_8x8_pistes (ELS - 300µm: TiPtAu);

HV = -750 V on Nucleation; source α on Growth, PRL1, FASTER

Piste4_4_-750V_nuclear



V. Conclusions & prospective:

-**The CVD polycrystalline diamond based double sided strip detectors seems to be well suited to the requirements for a beam profiler for characterising low intensity radioactive heavy ion beams:**

- material: ELP (small bulk polarization; signal stable in time); P2 from Company 1, for example
- thickness: 200-300 µ adequate for R~50 µ
- electric field ~1V/µ; HV though Sh < Se
- strip: 1 mm pitch (0.9mm strip, inter-strip gap: 0.1mm), efficiency: 90-99% (localization with 1 mm resolution)
- small cross-talk effects
- signal shape study: ~1.5 ns rise time for 1 strip; PSA may bring interesting information ($\Delta Q < \Delta V_{extrem}$)

-**The further characterisation of such detectors and the engineering of the readout electronics and other associated elements of a fully fledged profiler are expected to be carried in the near future:**

- tests for radiation hardness
- more robust electric contacts between PCB and strips?
- line receiver multi-channel preamplifiers for low energies
- acquisition system: FASTER + SCATS .

SCATS (Sixteen Channel Absolute Time Stamper)

To be used by a new 50 X 50 diamond BEAM PROFILER

- Note: The study of the diamond detector has already been subject for a few student stages

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[5] P.Bergonzo, D. Tromson, H. Hamrita, C. Mer, N. Tranchant, M. Nesladek, Diamond and Related Materials 16 (2007) 1038.

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We are in collaboration with:

GSI (Darmstadt): Angela Bräuning-Demian, Elèni Berdermann, M. Traeger, M. Ciobanu & Detector Laboratory

LIST (CEA Saclay): Hassen Hamrita, Philippe Bergonzo

NIPNE Bucharest: Dana Dimitriu, Daniela Fluerasu

LPC Caen:

Jean-Marc Fontbone, Jérôme Perronnel, Hervé Plard, Jean-François Cam

Jean Hommet – acquisition; Yvan Merrer – mécanique + atelier mécanique

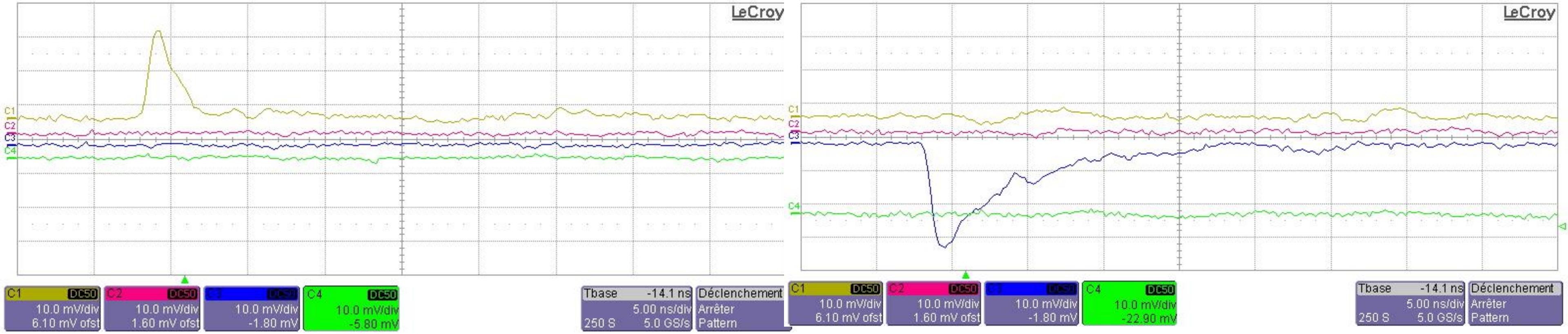
Lynda Achouri, Giacomo Randisi, Nigel Orr, Marian Pârlog

Remerciements:

Fac. Chimie: M. Ledauphin CRISMAT: Yohann Thimont, Séverine Mouchel

IPN Lyon: Michel Chevalier

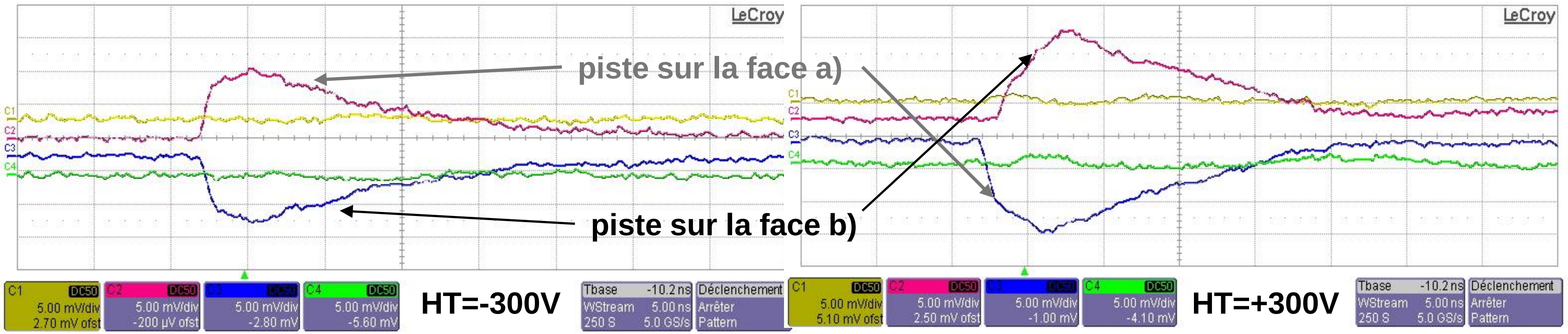
CIMAP: Emmanuel Balanzat, Jean-Marc Ramillon, Stéphane Guillos
LPC: Joel Brégéault, Jean-Louis Gabriel, Albert Leconte, Christophe Vandamme, l'équipe informatique



Signals from the strip no. 9 of the face a) - left (yellow curve) and from the strip 9 of the face b) - right (blue curve), amplified with the new preamplifier PRL developed at LPC; the signals were induced by the ^{70}Zn ions of 8.7 AMeV in the detector IV of ELP type for a voltage of -300 V applied on the face a) (growth), irradiated

Signaux coincidentes sur les deux faces du détecteur

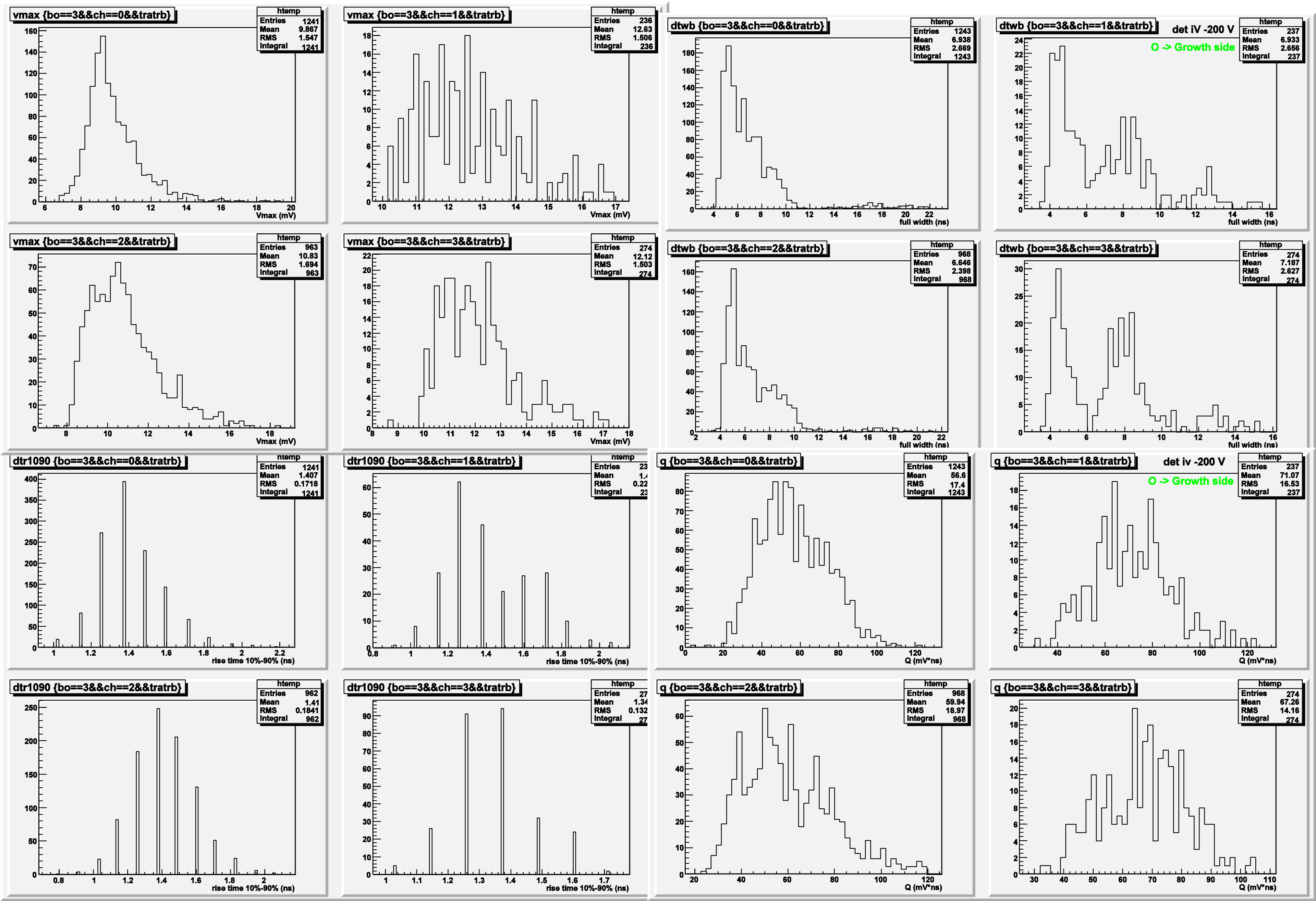
HT sur la face a) irradiée (1V/µ)



Signals induced by 70Zn of 8.7 AMeV in the detector IV of ELP type

Det iv ELP, 350μ, -200 V, E=0.6V/μ, board 3; O:13.7 AMeV

the 4 channels of Matacq board 3 give similar results



Det iv ELP, 350μ -200 V, E=0.6V/μ, board 3; O :13.7 AMeV