

Towards a beam-tagging diamond hodoscope for online ion range monitoring



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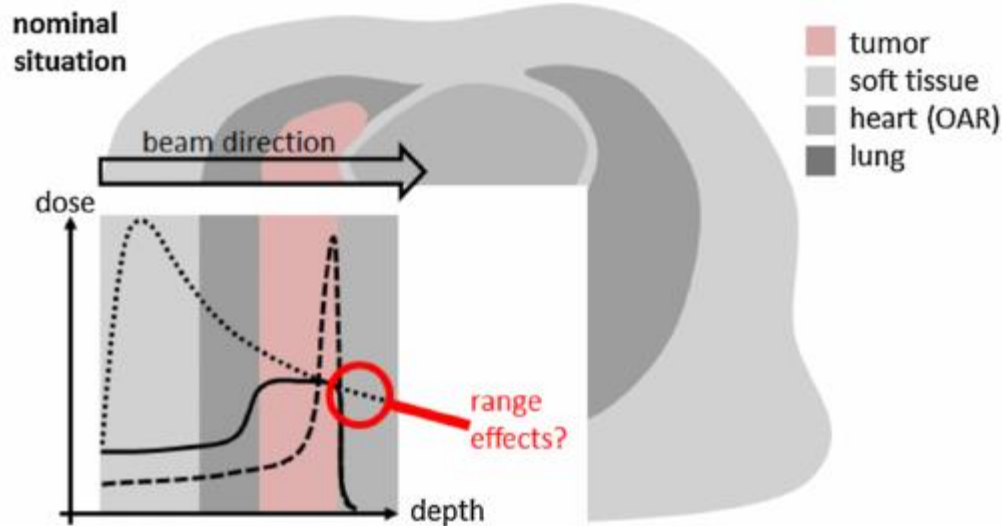
E. Testa



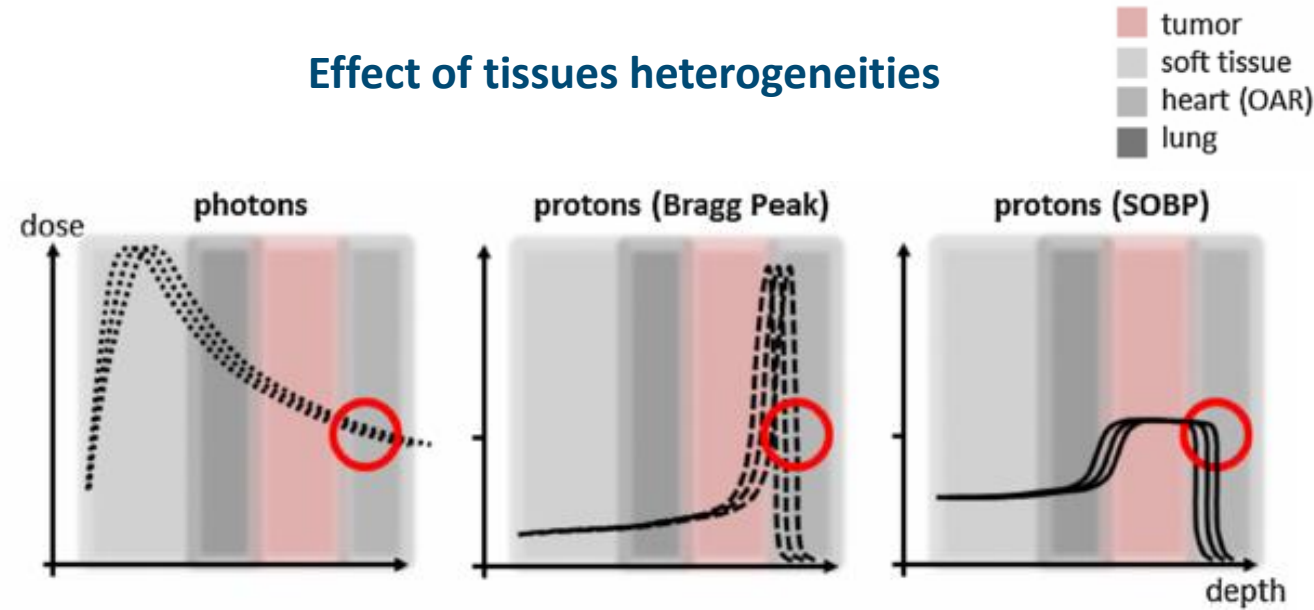
JM. Létang

Ion range uncertainties

Ideal treatment plan



Effect of tissues heterogeneities



Knopf and Lomax, Phys. Med. Biol. 58 (2013) R131–R160

Uncertainties

- Treatment planning
- Patient positioning
- Organ motion
- Morphological evolution of tumor volume through treatment



Security margins on actual range (ex : 1 cm for 20 cm prescribed range)

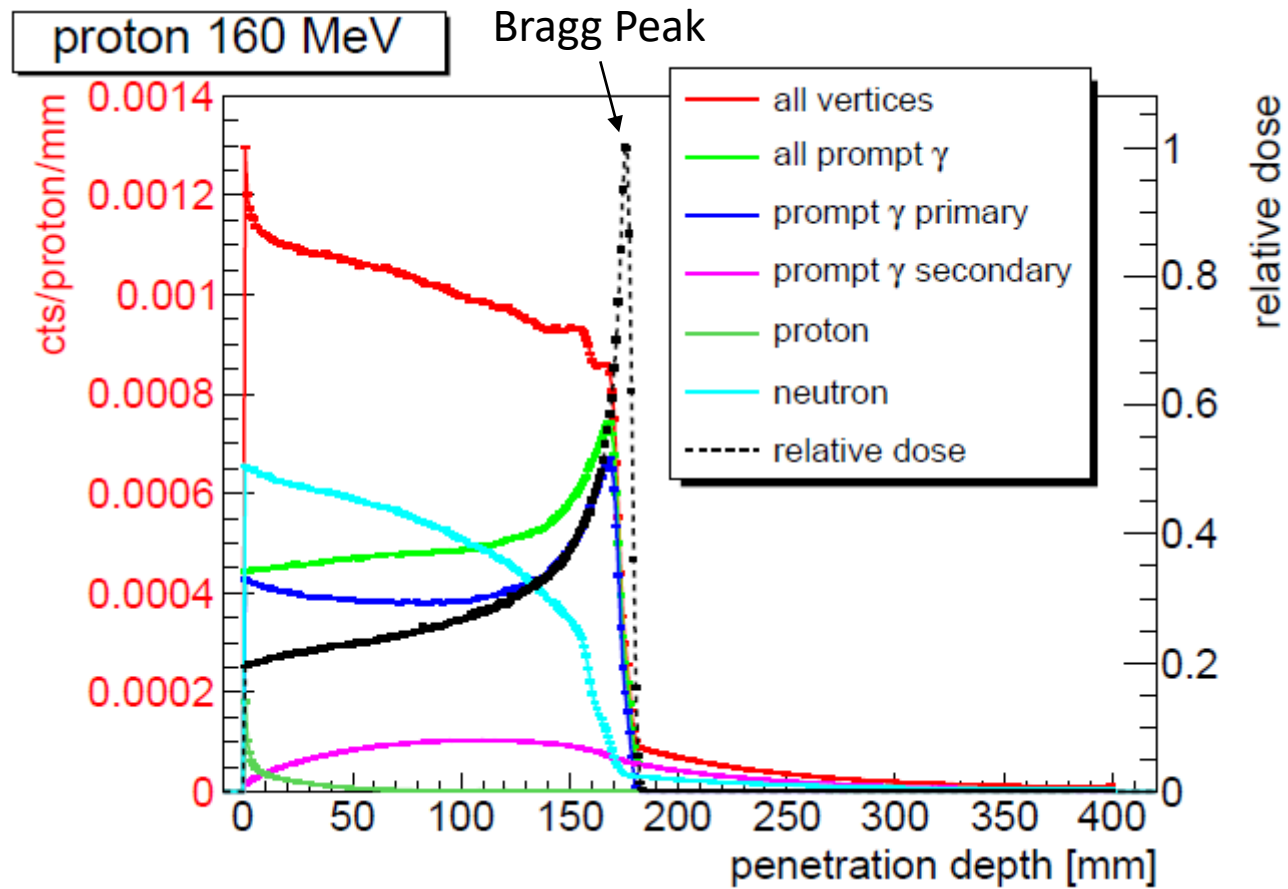


Need for an online ion range monitoring system

Production of secondary particles

Geant4 simulation

160 MeV protons
in water target

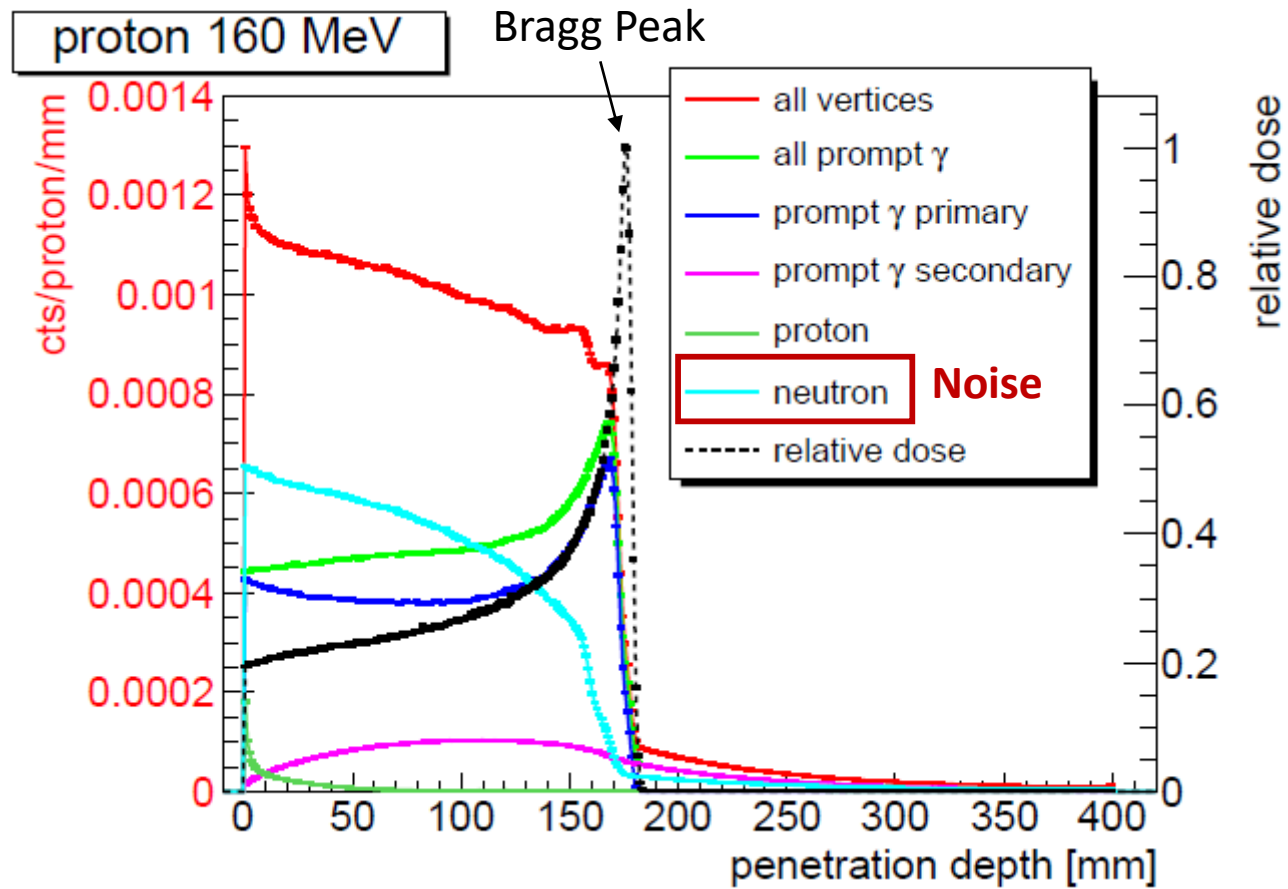


Krimmer et al., Nucl. Instr. Meth. A, **878** (2017) 58-73

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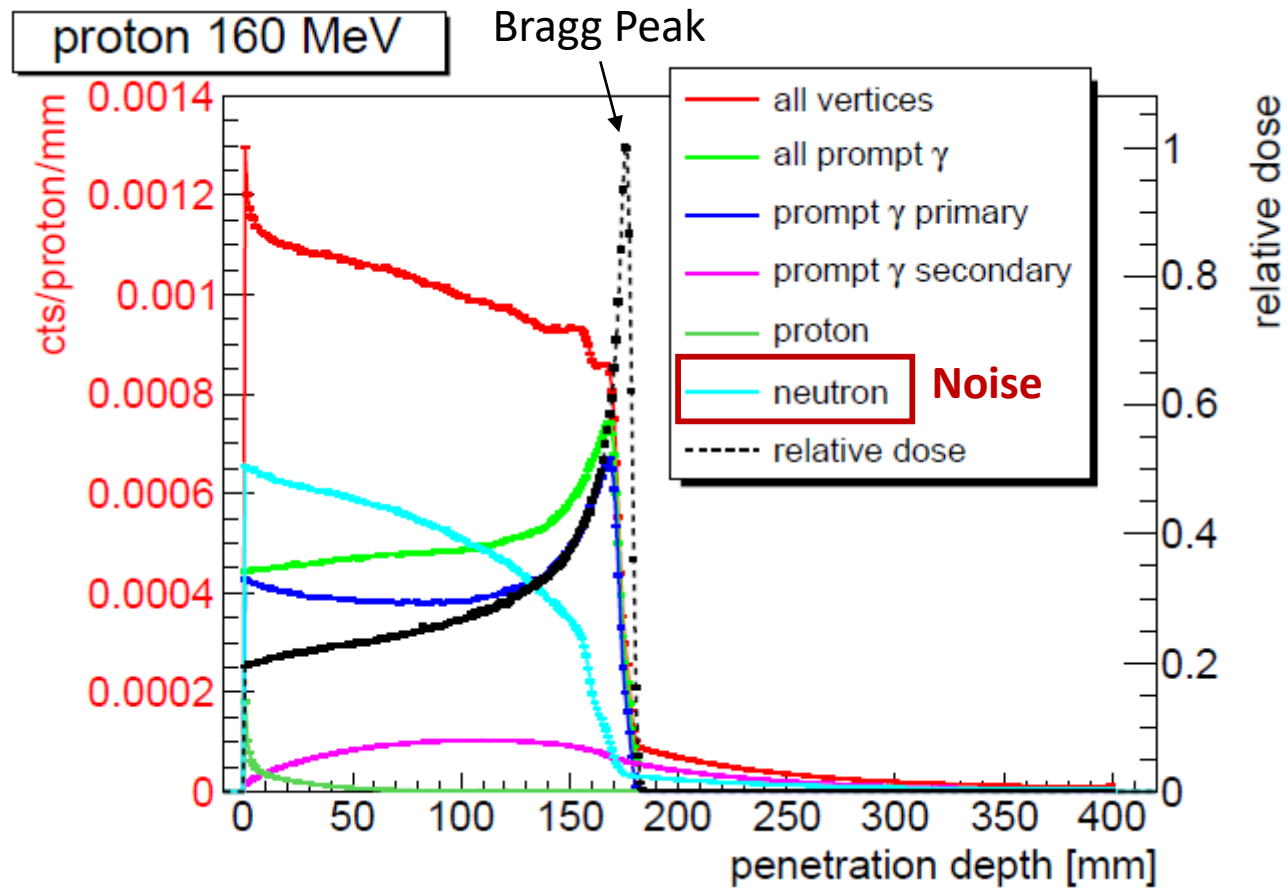


Krimmer et al., Nucl. Instr. Meth. A, **878** (2017) 58-73

Production of secondary particles

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CLaRyS collaboration

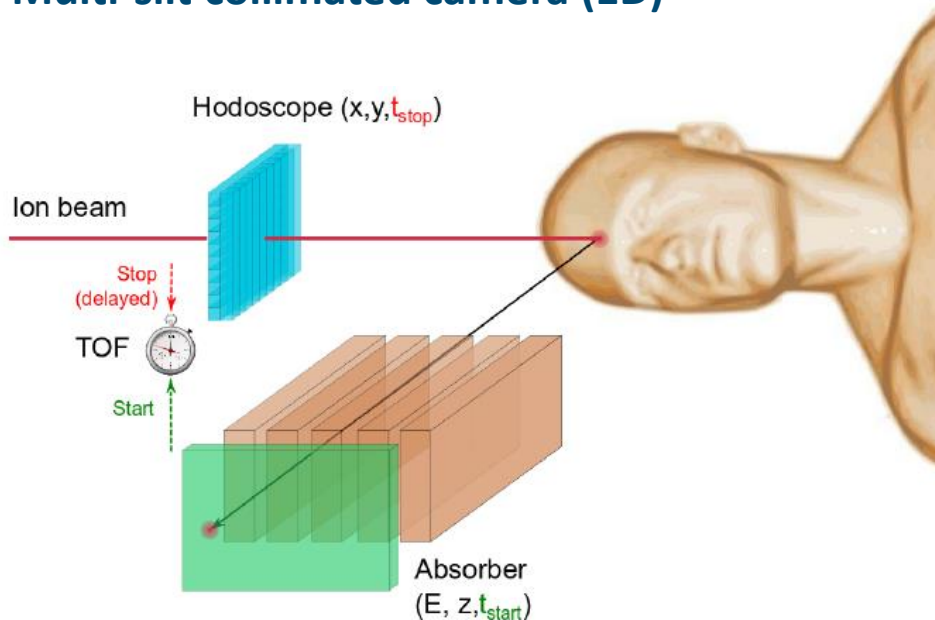
CLaRyS: Contrôle en Ligne de l'hadronthérapie par détection de Rayonnements Secondaires

4 laboratories: LPSC, IPNL, CPPM, CREATIS Lyon

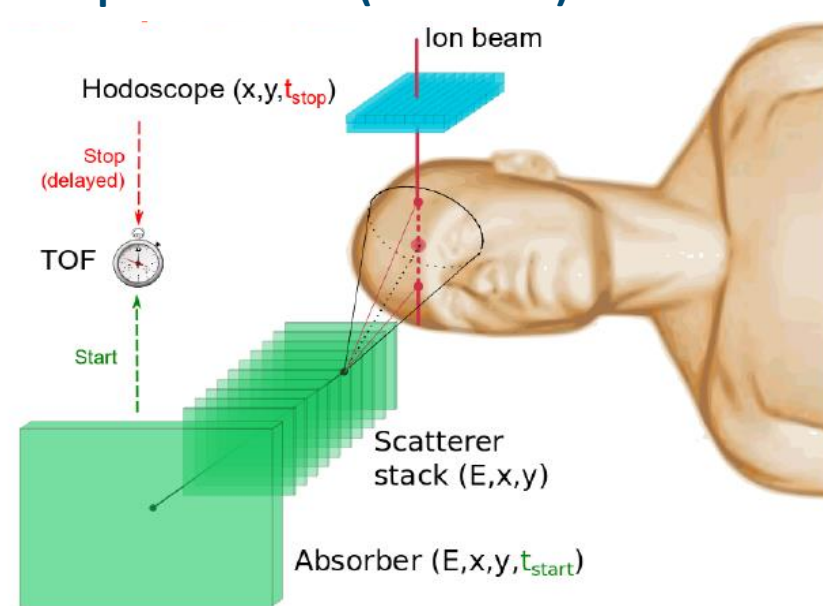
Prompt-gamma detection devices

Time-of-Flight resolved Prompt-Gamma Imaging

Multi-slit collimated camera (1D)



Compton camera (2D or 3D)

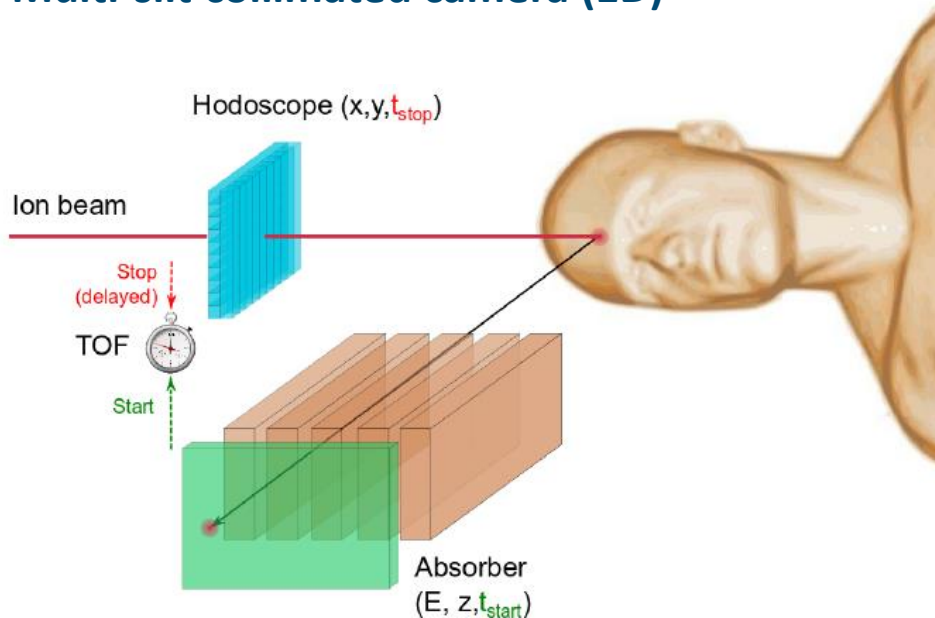


Hodoscope : neutron-induced background reduction & transverse position

Prompt-gamma detection devices

Time-of-Flight resolved Prompt-Gamma Imaging

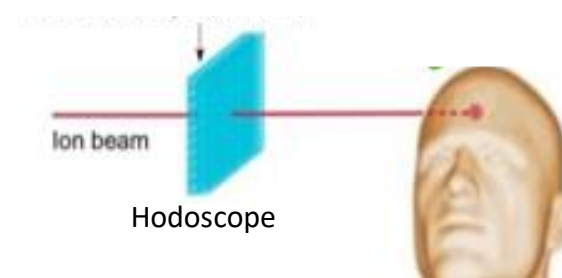
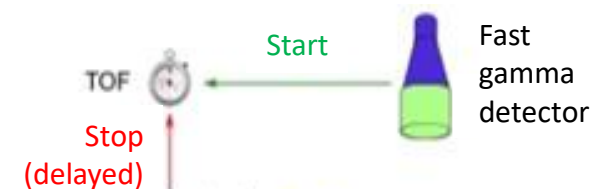
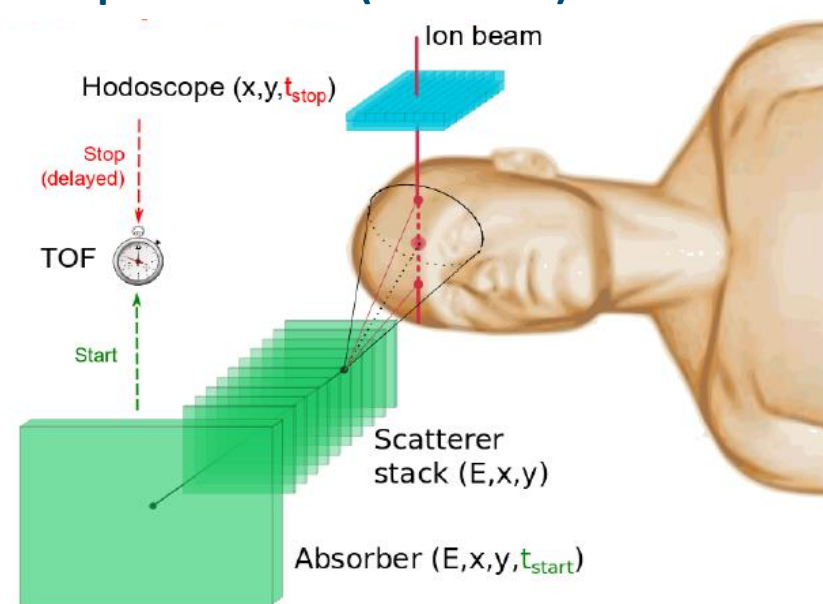
Multi-slit collimated camera (1D)



Hodoscope : neutron-induced background reduction & transverse position

CLaRyS-Ultra-Fast Timing goal : 100 ps resolution

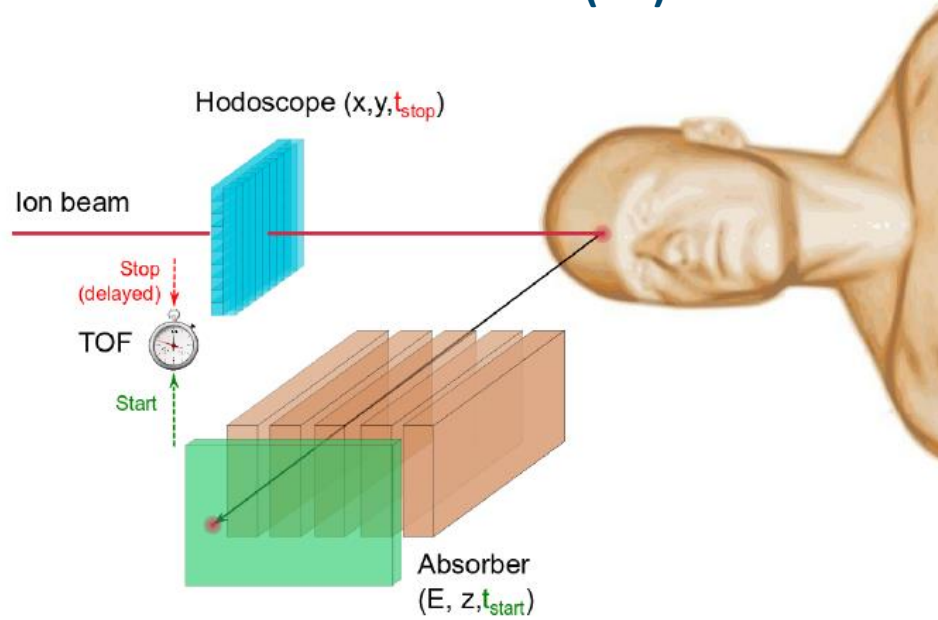
Compton camera (2D ou 3D)



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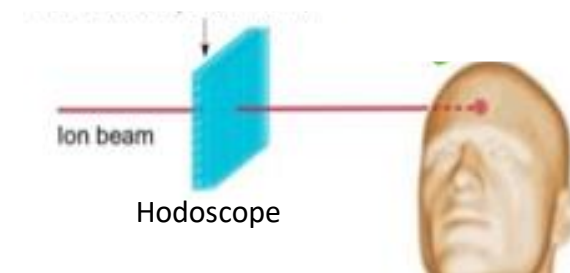
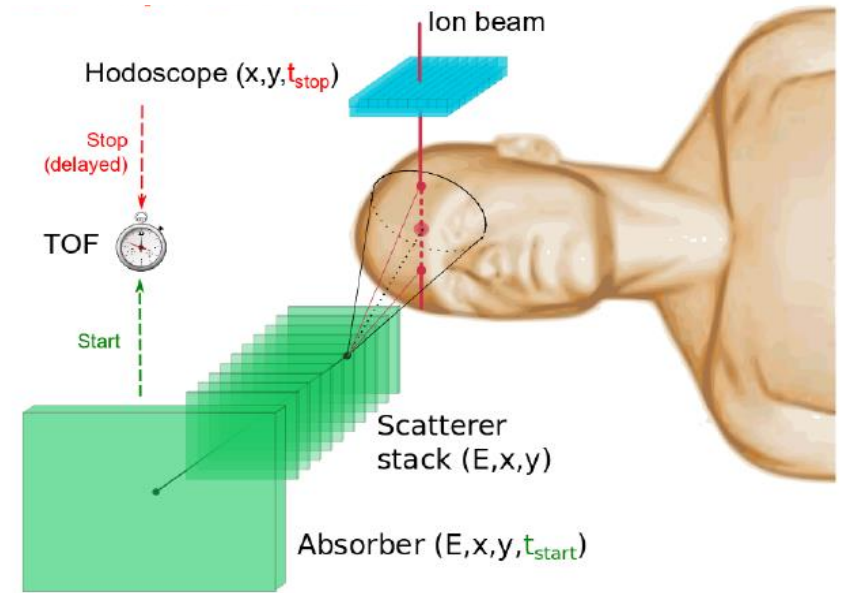


Hodoscope : neutron-induced background reduction & transverse position

CLaRyS-Ultra-Fast Timing goal : 100 ps resolution

→ Prompt-Gamma Timing

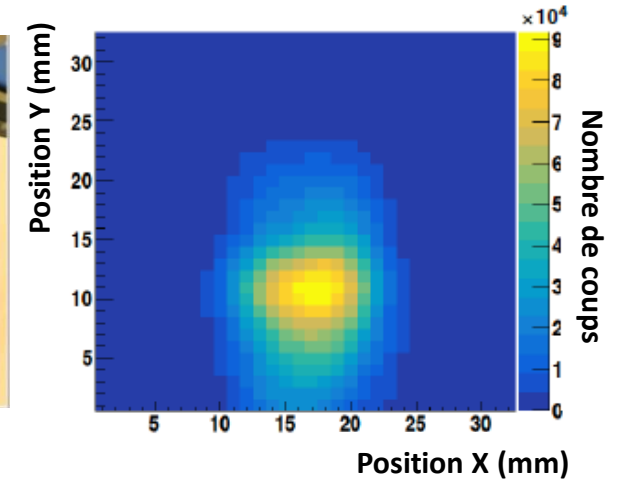
Compton camera (2D ou 3D)



Development of a beam hodoscope

IPNL : Scintillating fiber hodoscope

- $\sigma_t \sim 1 \text{ ns} \rightarrow$ background rejection
- Photomultipliers (512 channels)
- Sensitive area: $12.8 \times 12.8 \text{ cm}^2$
- Currently under tests at Centre Antoine Lacassagne (Nice)



Mattia Fontana's Thesis, Univ. Lyon (2018)

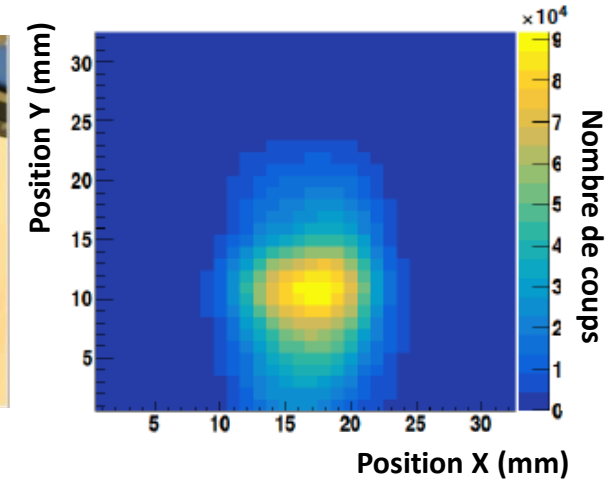
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Strong interest in developing a new hodoscope with:

- Excellent time resolution
→ Prompt-Gamma Timing is foreseen
- Radiation hardness
- High count rate

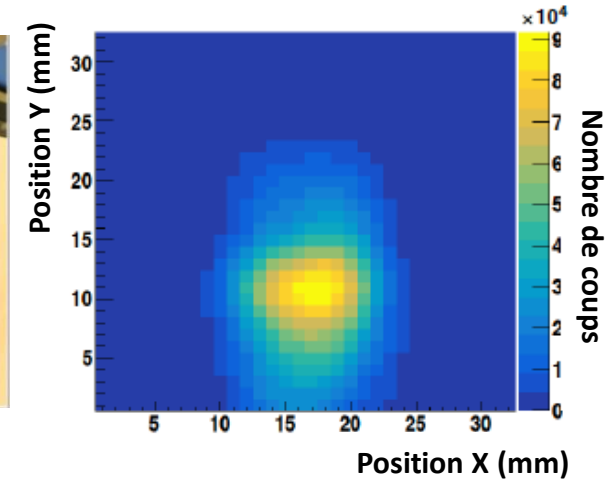


Mattia Fontana's Thesis, Univ. Lyon (2018)

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Synthetic diamond

Diamond : an intrinsic semi-conductor

Specifications at 300 K

	Diamond	Silicon
Resistivity ($\Omega.m$)	$> 10^{13}$	$2.3 \cdot 10^7$
Gap (eV)	5.5	1.1
e ⁻ /h pair creation energy (eV)	13.1	3.6
Threshold displacement energy (eV)	43	25
Charge carrier mobilities ($cm^2.V^{-1}.s^{-1}$)	> 2000	800 – 1400
Thermal conductivity ($W.cm^{-1}.K^{-1}$)	18	2



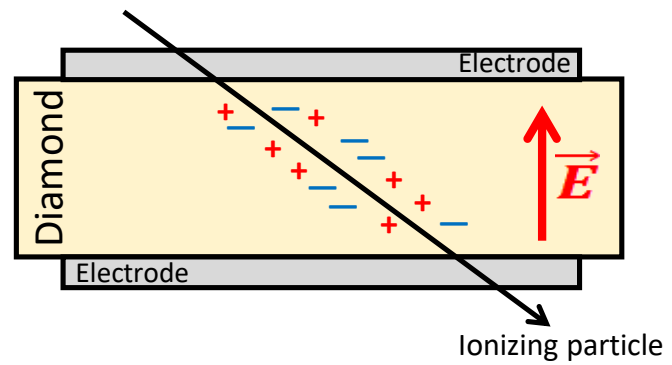
- **Very low leakage currents**
- **Low noise**
- **Radiation hard**
- **Very fast**
- **Room temperature operation**

Electronic grade diamonds Chemical Vapor Deposition (CVD)

- Single-crystal (mono)
- Polycrystalline (poly)
- Diamond On Iridium (DOI)

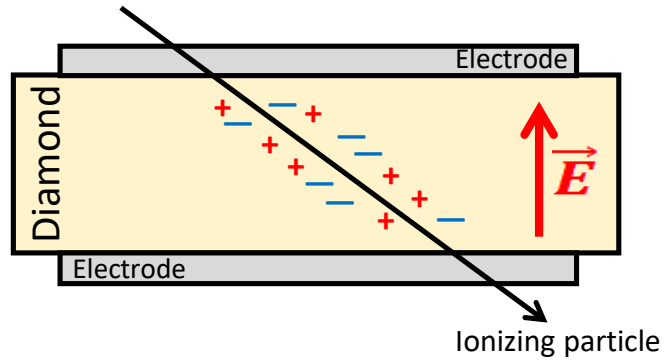
Synthetic diamond as radiation detector

Solid-state ionization chamber



Synthetic diamond as radiation detector

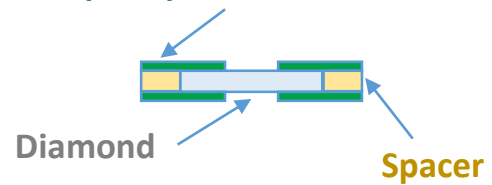
Solid-state ionization chamber



Detector assembly

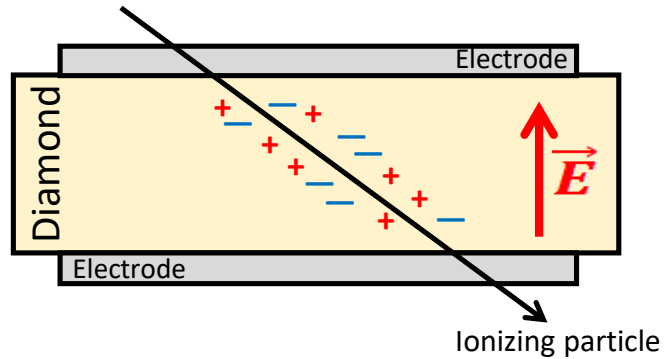


50Ω-adapted printed circuit board

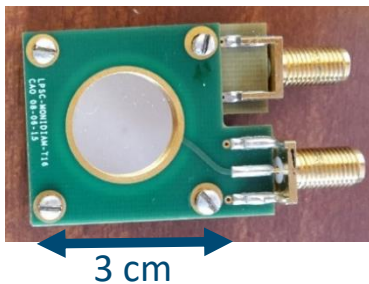
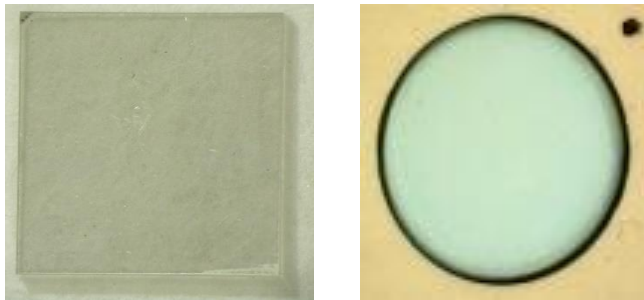


Synthetic diamond as radiation detector

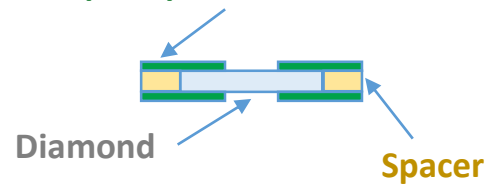
Solid-state ionization chamber



Detector assembly



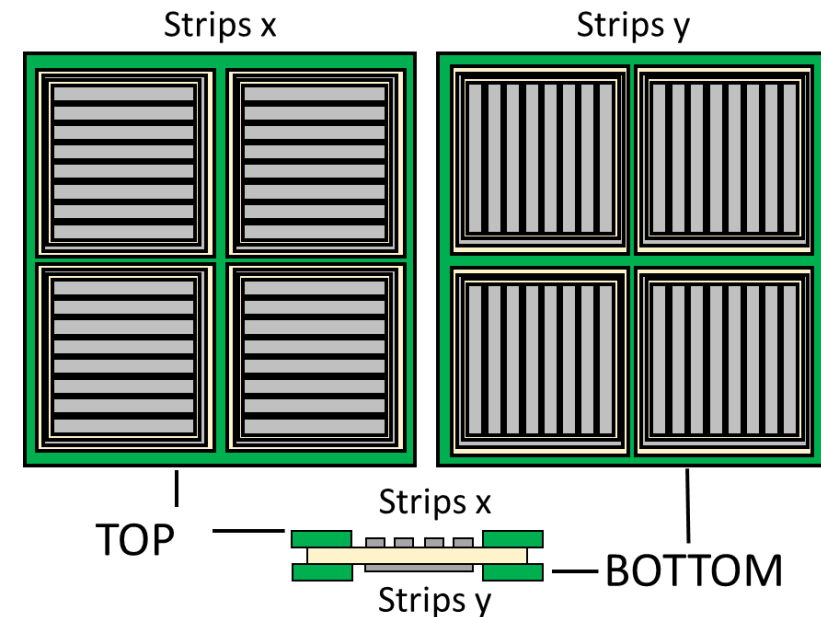
50Ω-adapted printed circuit board



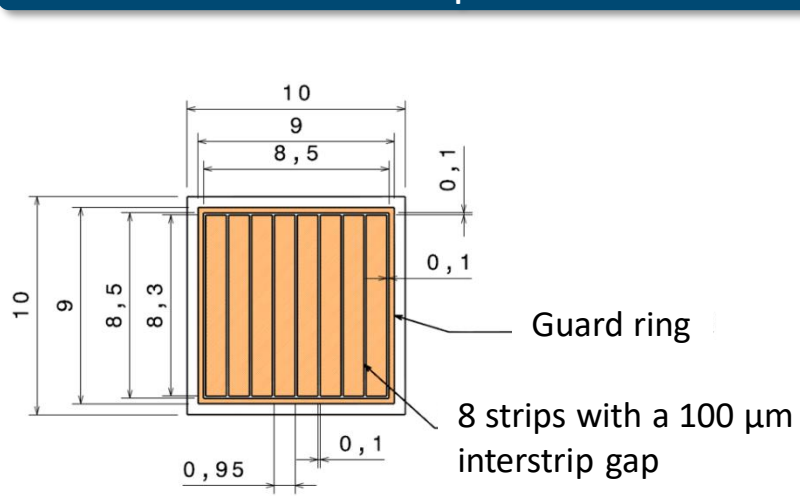
Our project (LPSC) : Diamond hodoscope

Specifications:

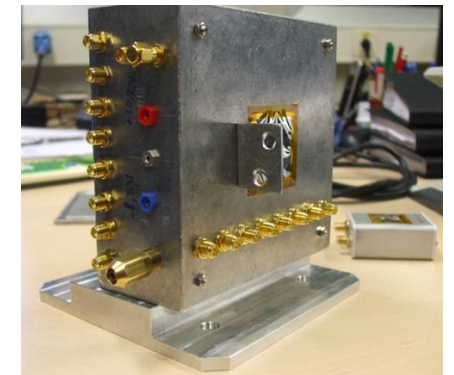
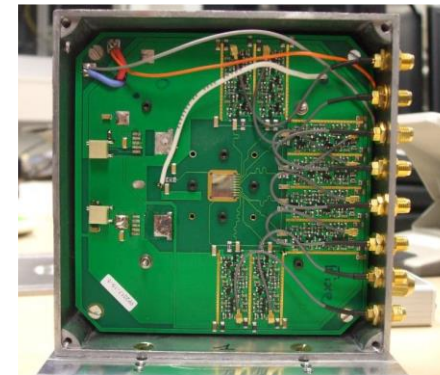
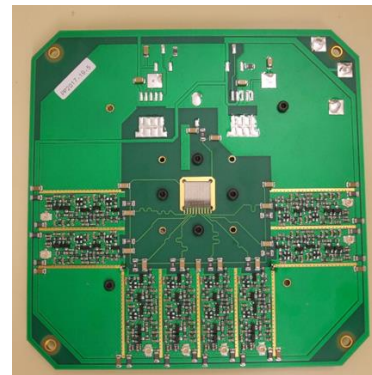
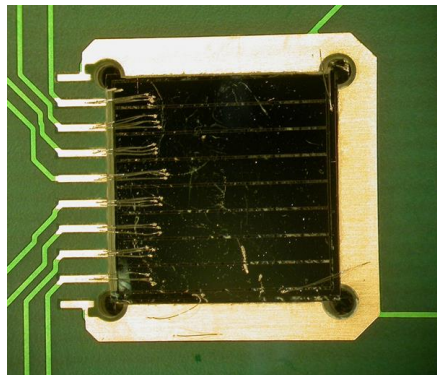
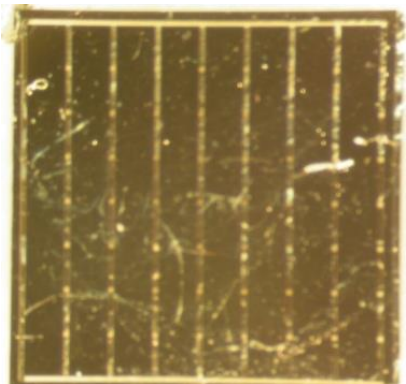
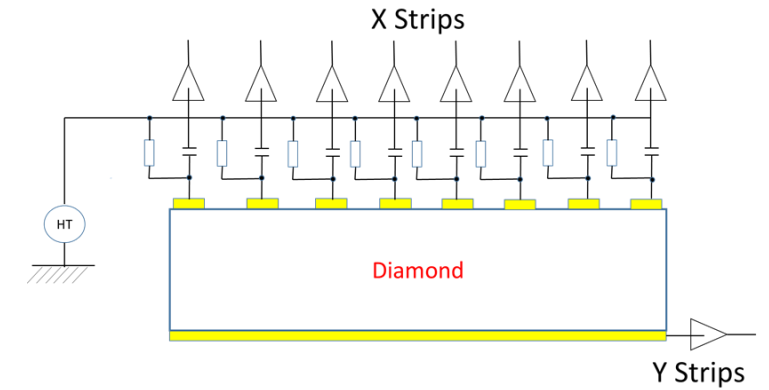
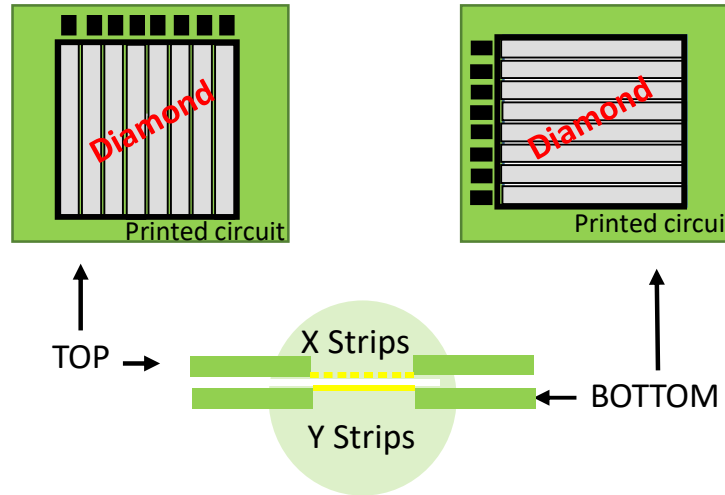
- $\sigma_t \sim 100 \text{ ps}$
- Count rate $\sim 10 \text{ MHz/voie}$
- Spatial resolution $\sim 1 \text{ mm}$
- Radiation hard



Strip detectors



1 cm² poly



NANOFAB plateform @ Néel Insitute, Grenoble

- Strips by UV lithography
- Wire bonding

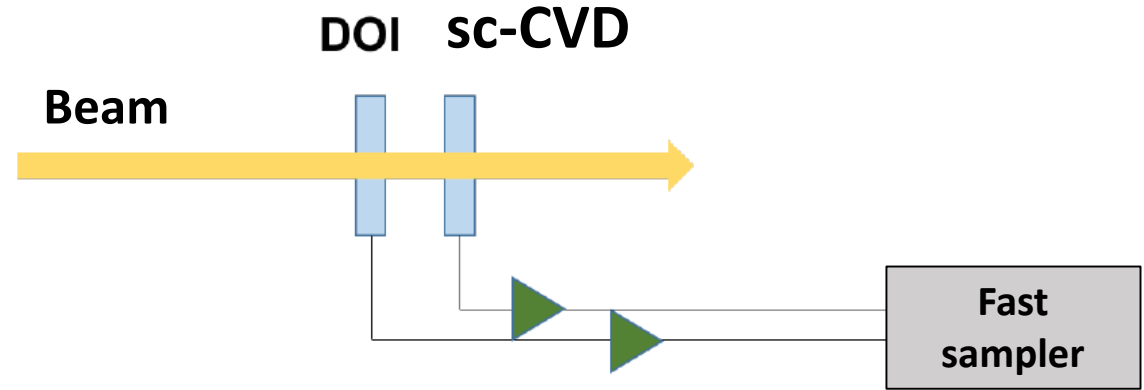
LPSC Grenoble

- Printed Circuit Boards
- Discrete current preamplifiers
- Mounting and assembling

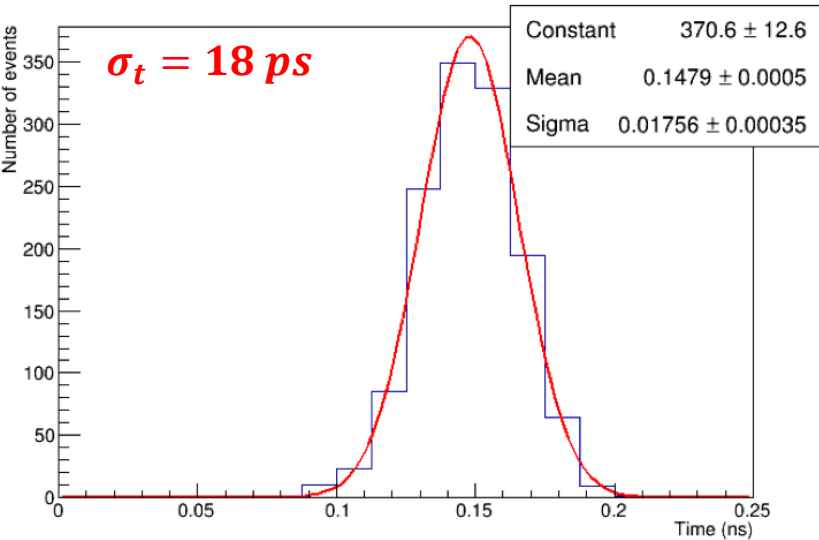
Time-of-Flight resolution

Time resolution assessment

- Digitization of signals
- Normalized threshold discrimination
- Fitting

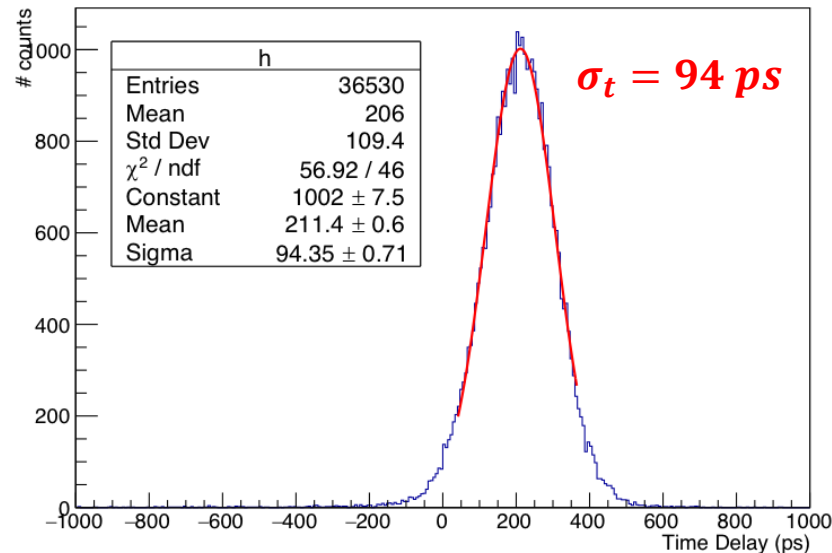


95 MeV/u ^{12}C ions @ GANIL



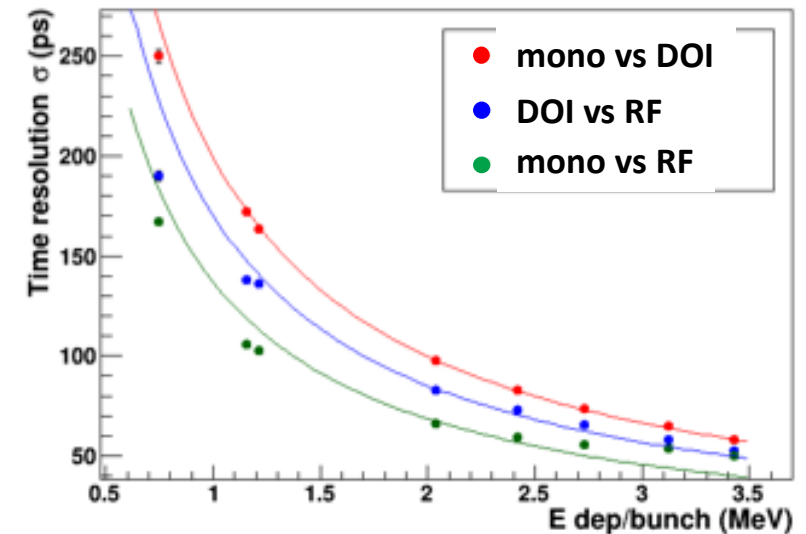
$\Delta E = 25 \text{ MeV}$ (300 μm diamond)

68 MeV protons @ ARRONAX



$\Delta E = 1 \text{ MeV}$ (300 μm diamond)

8.5 keV photons @ ESRF

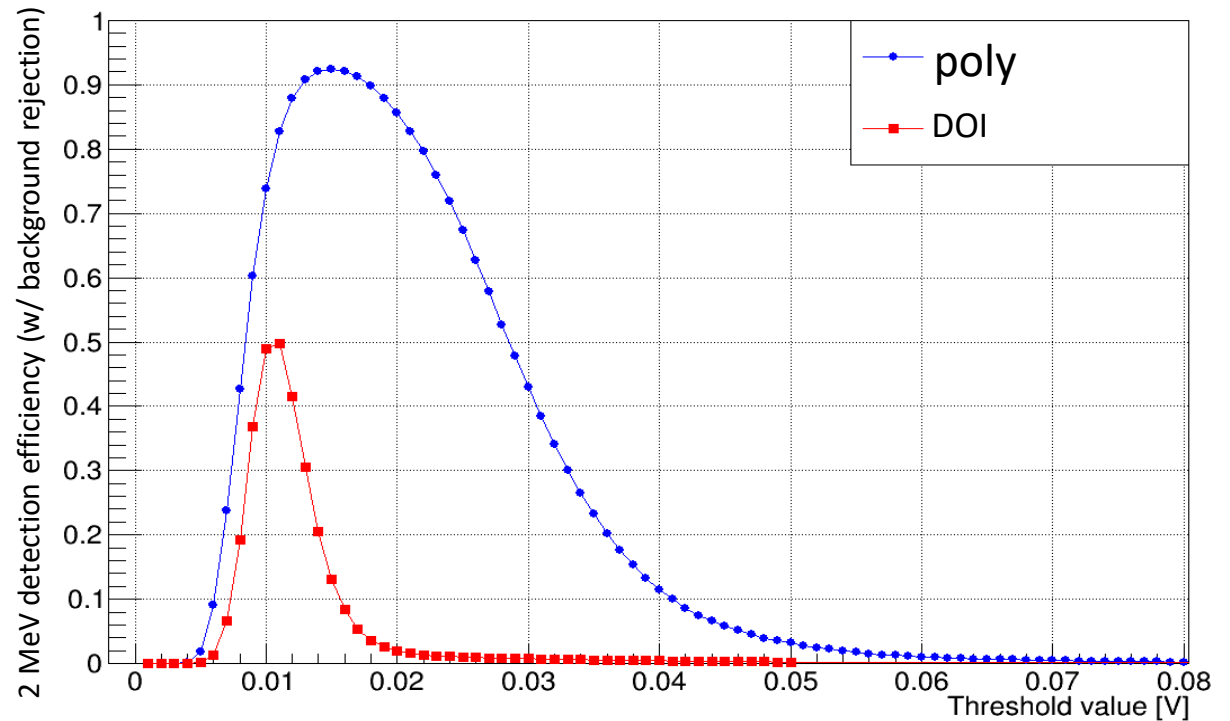
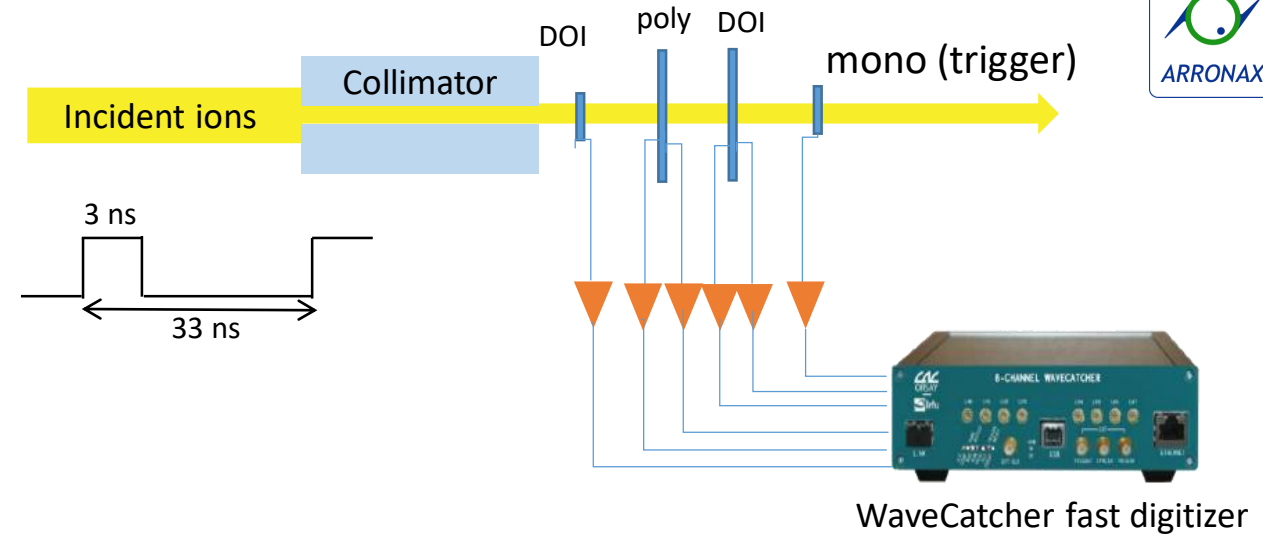


Specific detection efficiency

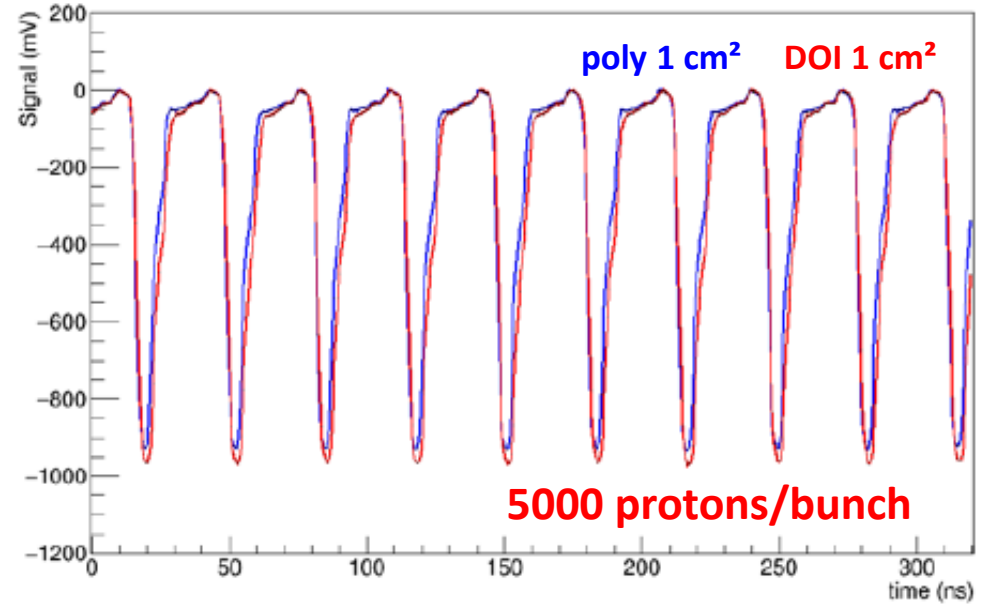
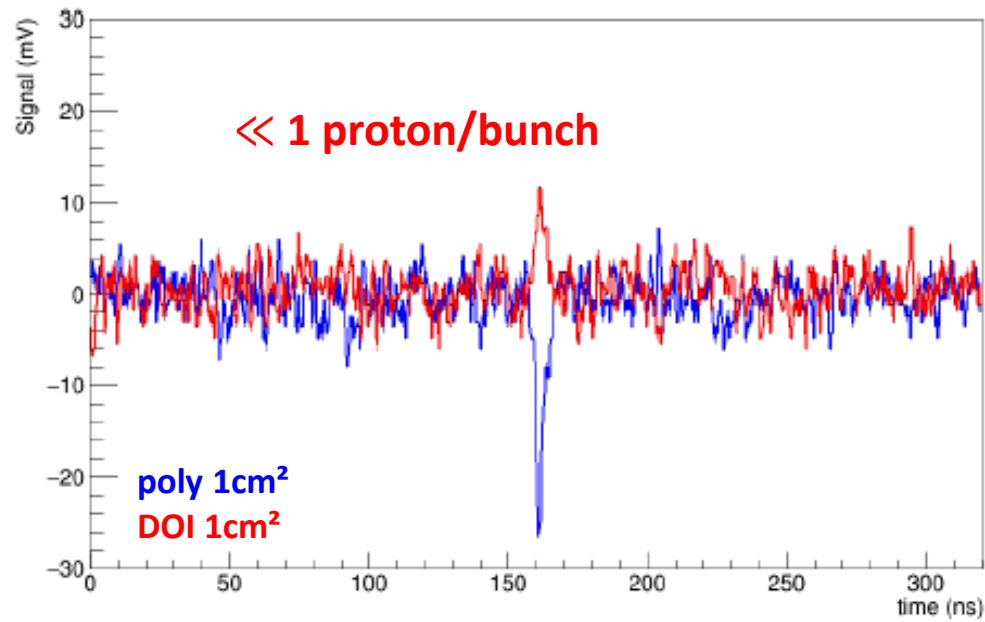
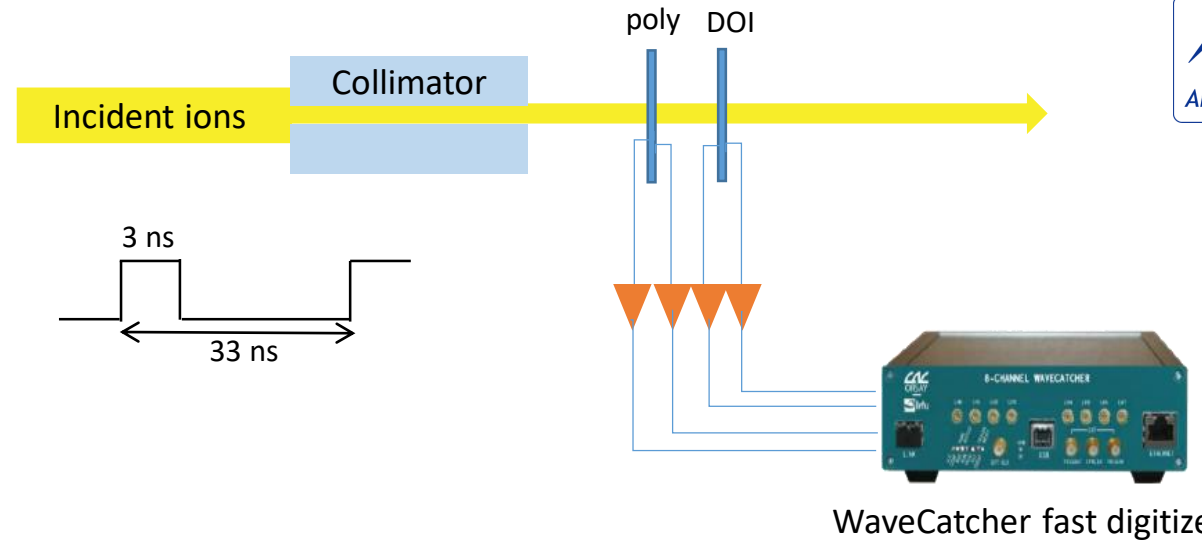
Pulsed beam - 68 MeV protons
 $\Delta E = 2 \text{ MeV}$ (2 protons in 300 μm diamond)

- Event filtering (amplitude and Time-of-Flight)
- Opposite faces signal summation:
 \rightarrow Signal-to-noise ratio $\times \sqrt{2}$
- Offline absolute threshold-based scanning

$$\varepsilon = \frac{N_{\text{triple}}}{N_{\text{double}}} \left(1 - \frac{N_{\text{random}}}{N_{\text{double}}} \right)$$



High beam current response



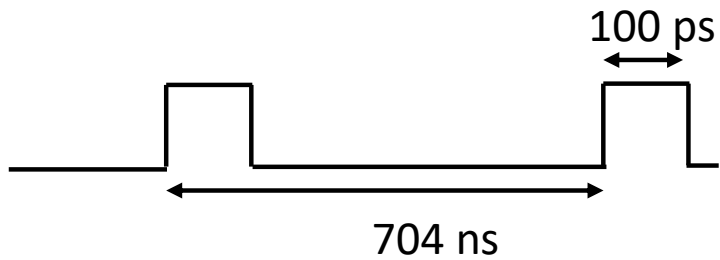
Characterization with X-ray micro-beam



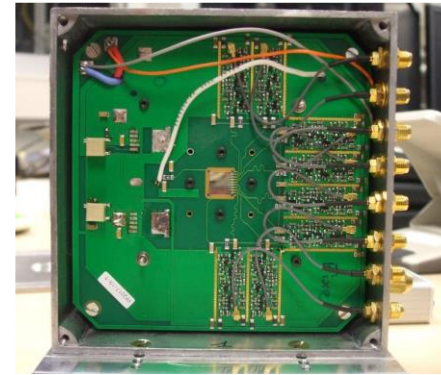
Pulsed X-ray micro-beam (8.5 keV)

~1500 photons / pulse

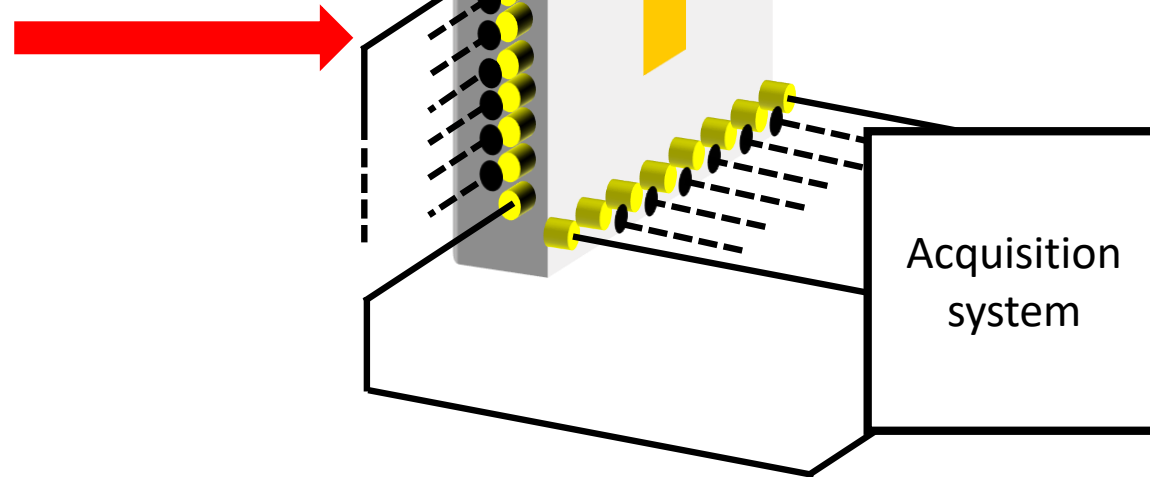
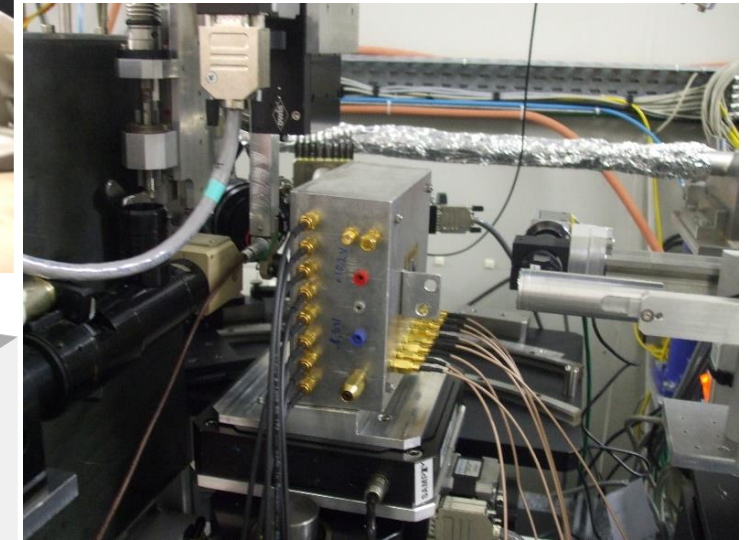
\varnothing spot : 1 μm



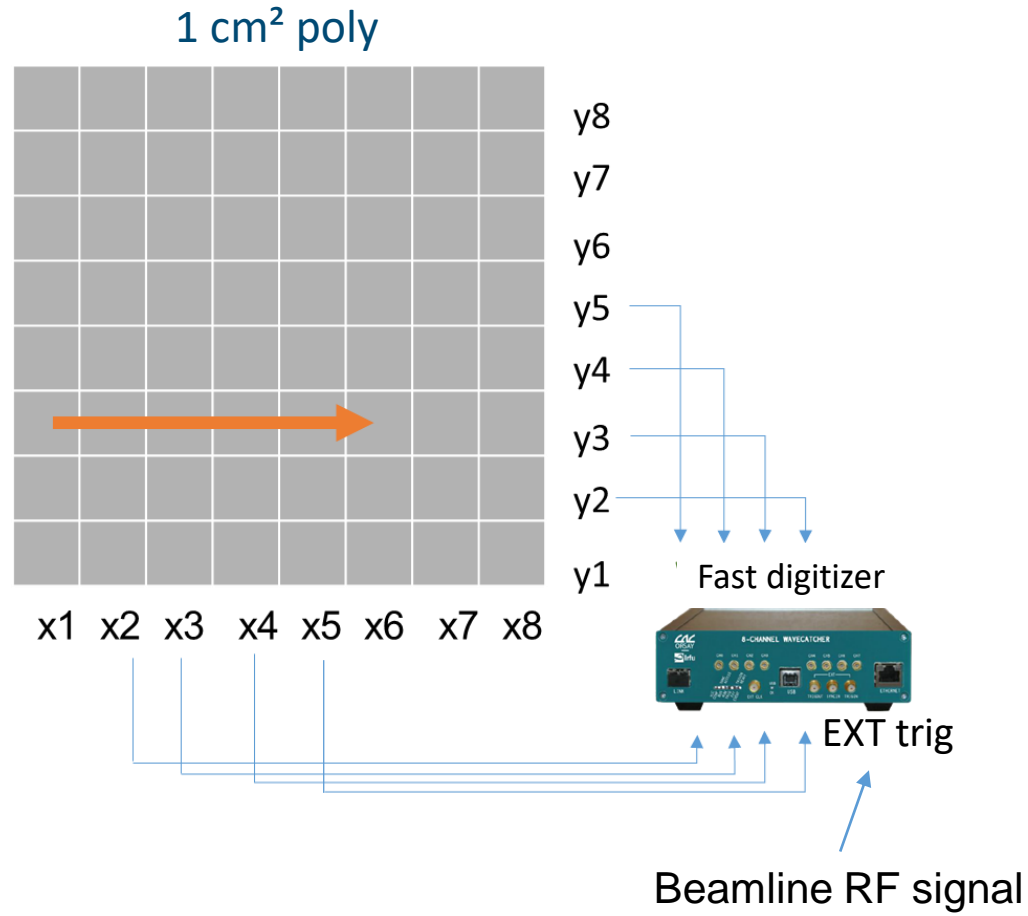
- Current mode: Surface scanning
- Pulse mode: Strip detectors performance



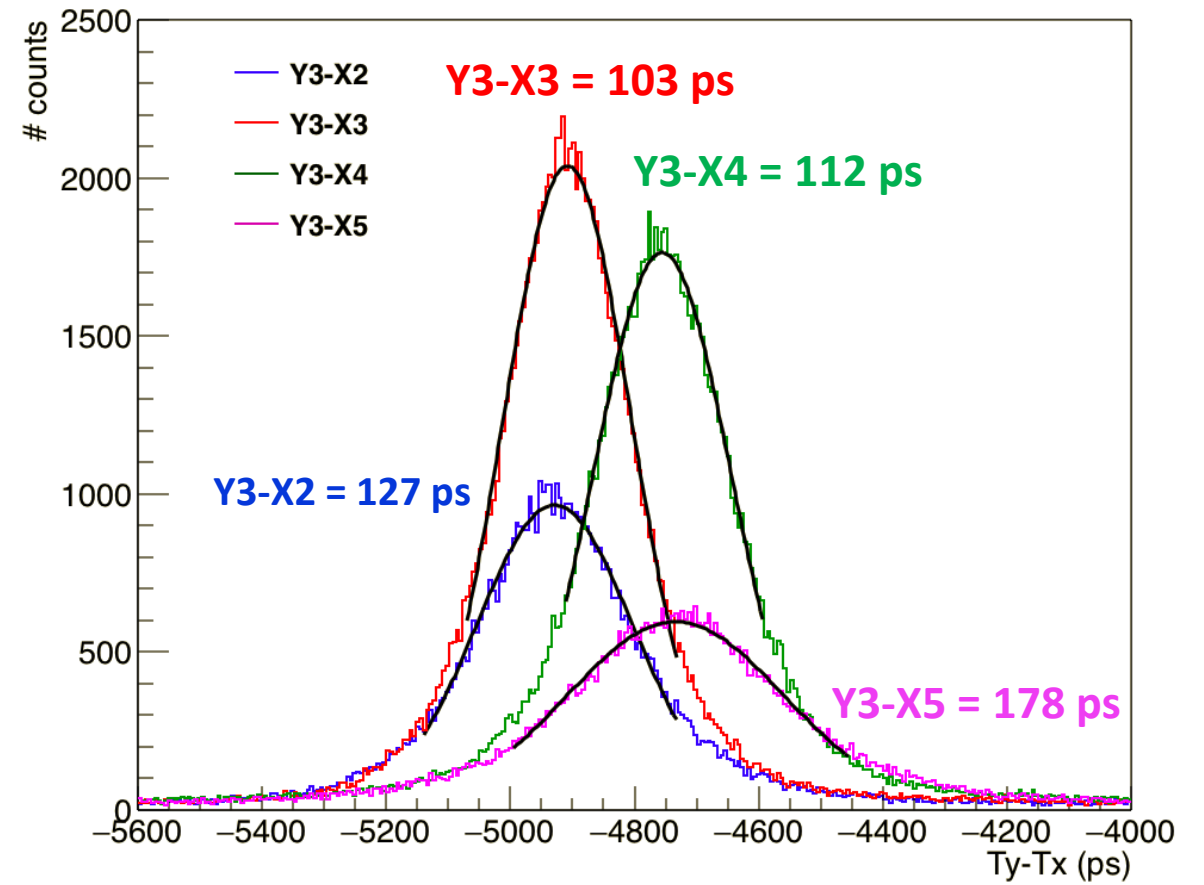
1 cm² poly



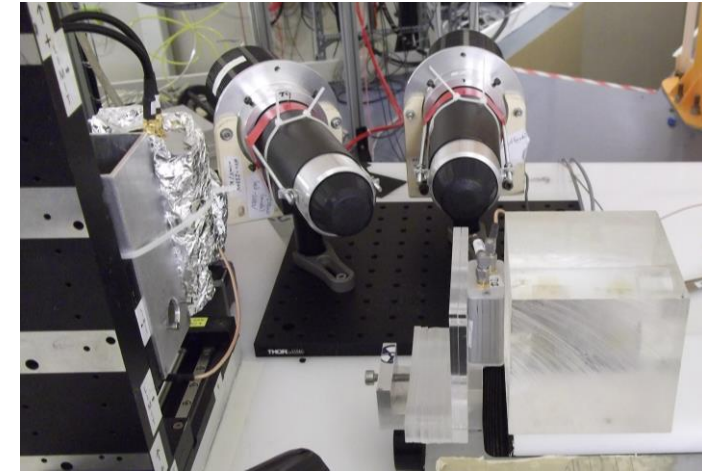
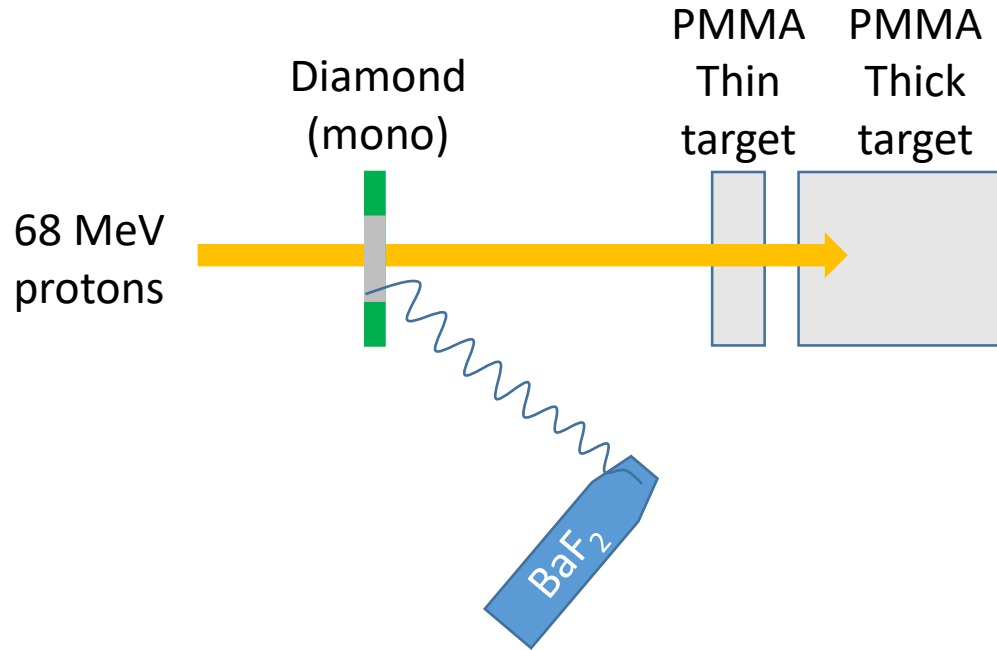
Strip detector time resolution



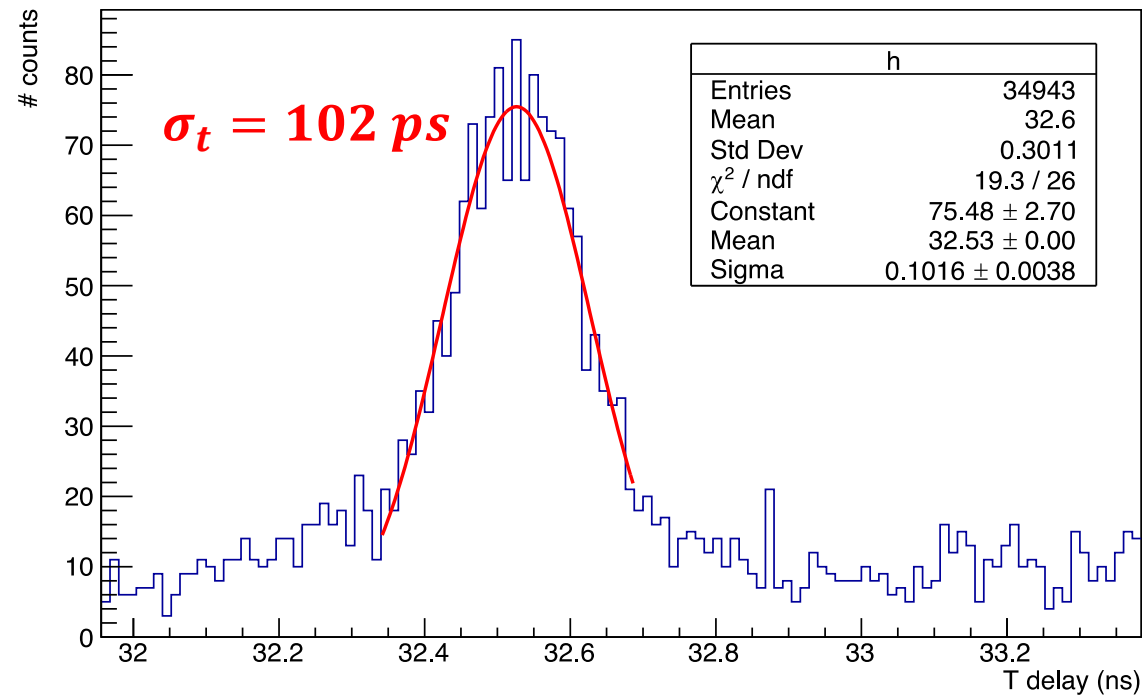
Intrinsic time resolution (rms)



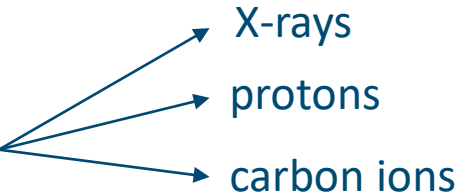
Prompt Gamma Timing @ ARRONAX



Diamond vs BaF₂ Time-of-Flight resolution



Conclusions

- Detectors characterized under various irradiation conditions 
- Comparison of performances obtained with different crystal qualities (mono, poly and DOI)
- Time resolution in good agreement with project specifications
- First strip sensors : satisfactory results

Perspectives

- Analysis to assess single proton detection efficiency is ongoing
- Assembling of a 4-diamond hodoscope demonstrator
- Both custom integrated and discrete electronics are currently developed and tested at LPSC
- Characterization with protons and carbon ions
- Integration to the CLaRyS μ TCA data acquisition system

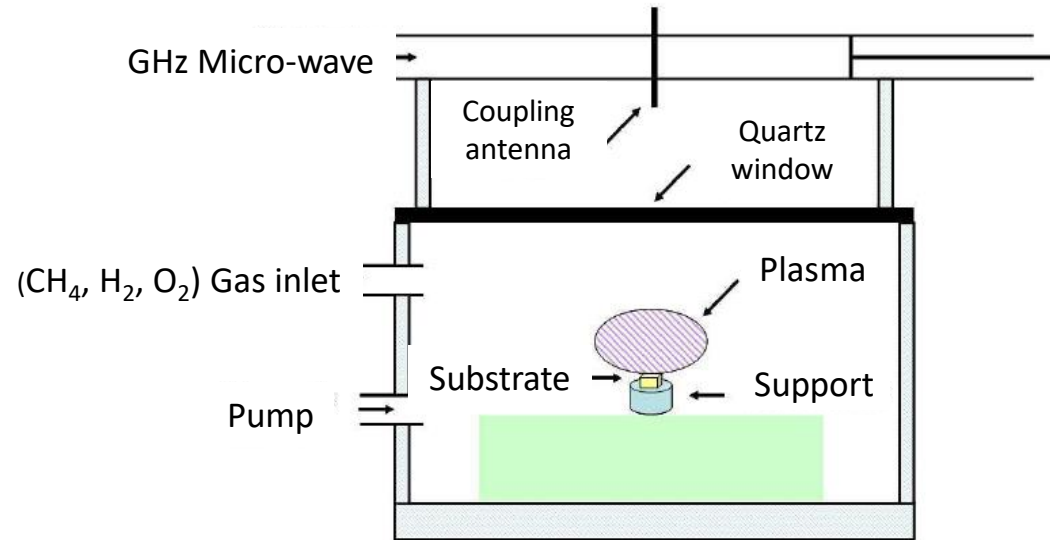
Thank you for your kind attention

This work has been financially supported by:

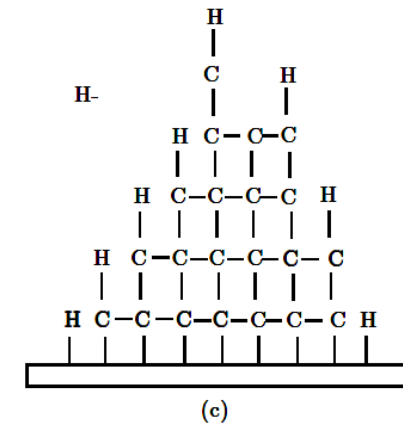
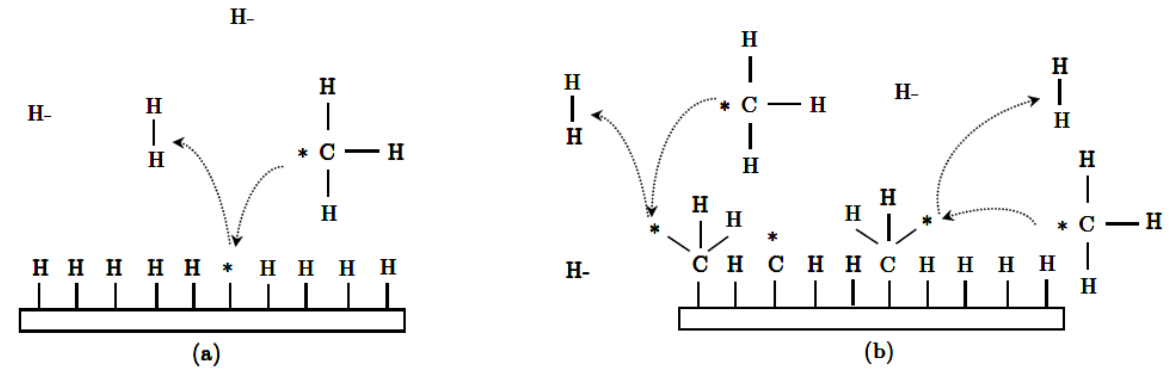


Chemical Vapor Deposition

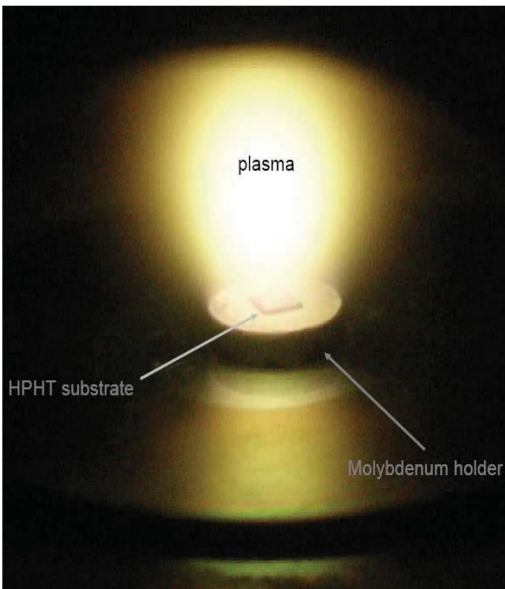
Plasma reactor



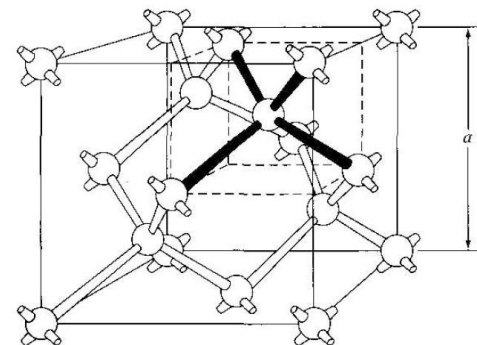
[F Marsolat PhD thesis, CEA-LIST 2013]



[D Tromson, PhD thesis, Univ. Paris 7 2000]



[M Pomorski, PhD thesis, Univ. Frankfurt 2008]






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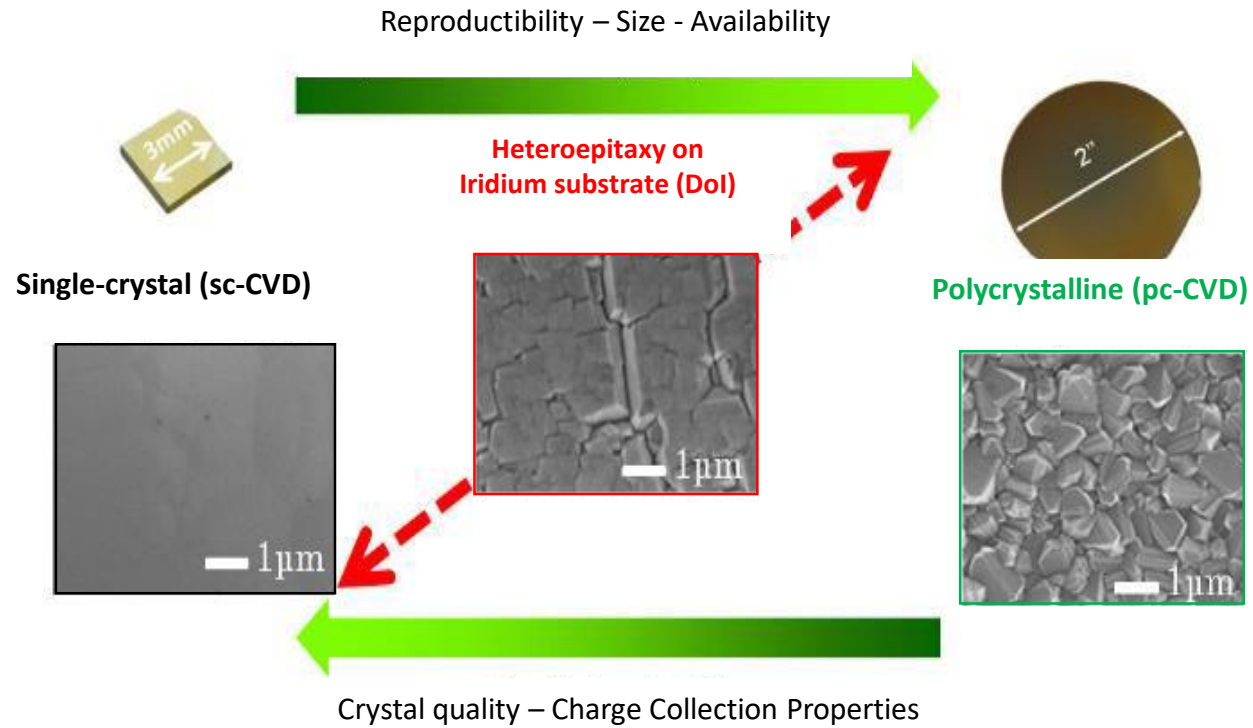
Different crystal qualities

2 growth processes:

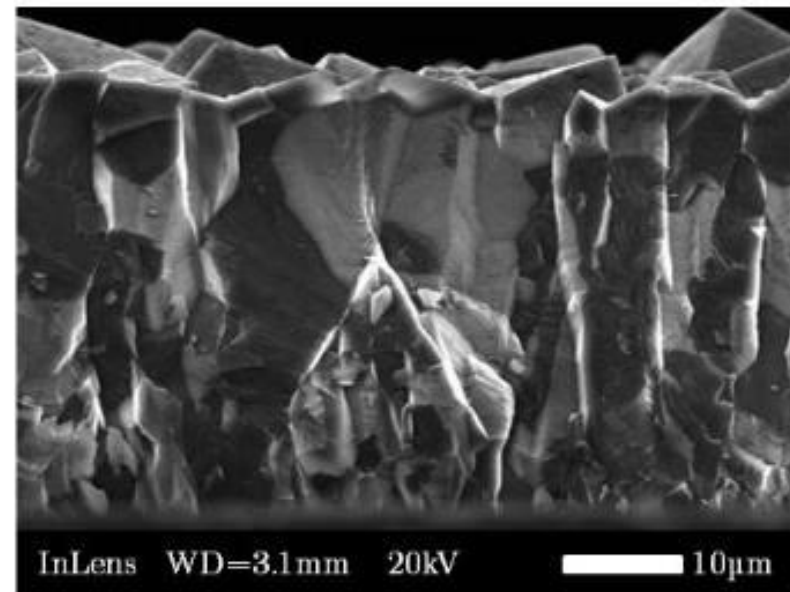
- High Pressure High Temperature (boron and nitrogen contamination)
- **Chemical Vapor Deposition (CVD)**

	Single crystal (mono)	Polycrystalline (poly)	Heteroepitaxy on Iridium (DOI)
Max size.	4.5 x 4.5 mm ²	20 x 20 mm ²	10 x 10 mm ²
Fast response	+++	++	++
Sensitivity	++	+	?
Homogeneity	++	?	?
Availability			
Price	€€€	€	€€

Chemical Vapor Deposition



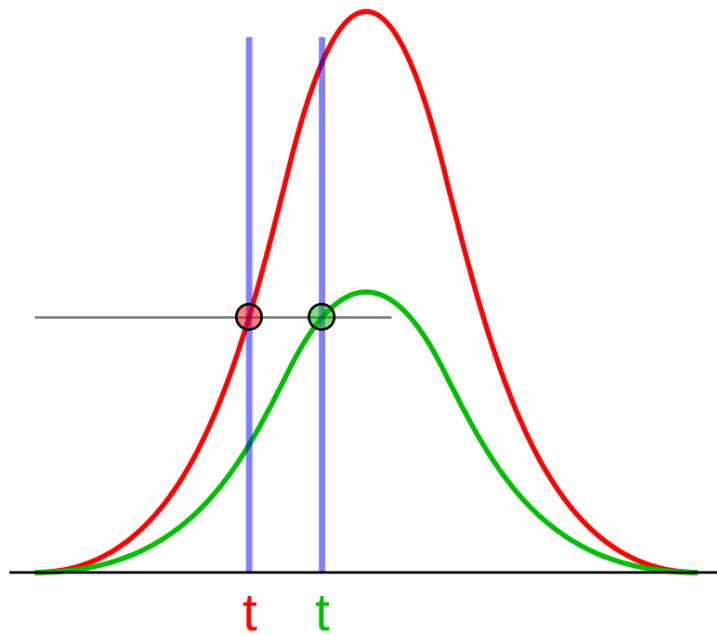
[N Vaissière PhD thesis, CEA-LIST 2014]



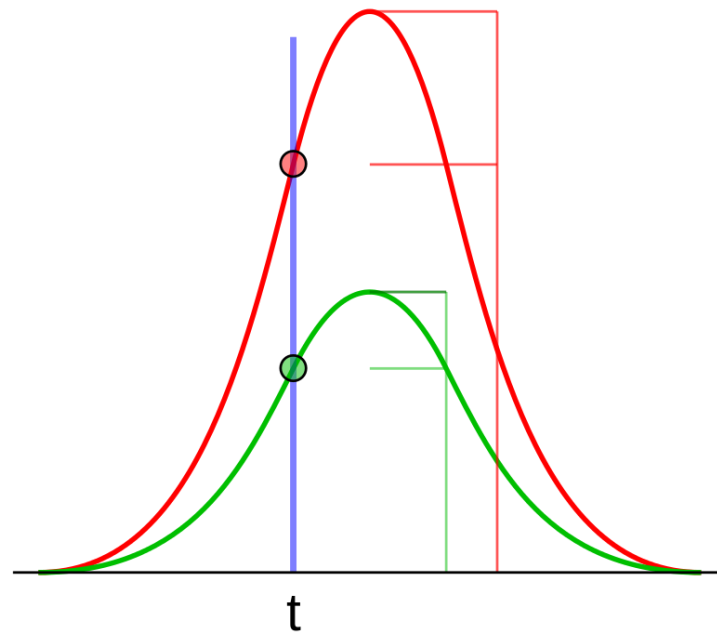
[N Vaissière PhD thesis, CEA-LIST 2014]

Normalised threshold discrimination

Leading edge threshold



Normalised threshold



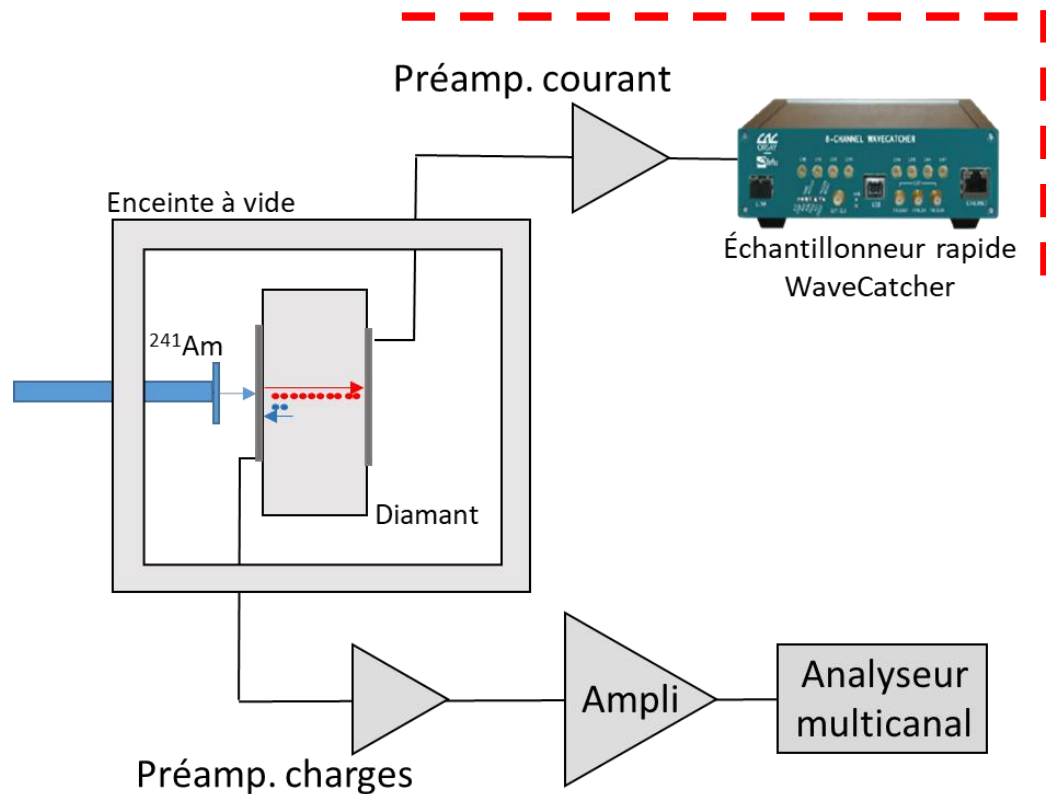
Limits the walk effect

Caractérisation en laboratoire

Source $\alpha = {}^{241}\text{Am}$ (~ 5.5 MeV, 6.38 kBq)

\leftrightarrow 14 μm dans diamant (\ll épaisseur)

➔ Polarisation sélectionne le porteur de charges étudié



Electronique rapide

Conserve la forme originelle du signal généré dans le diamant

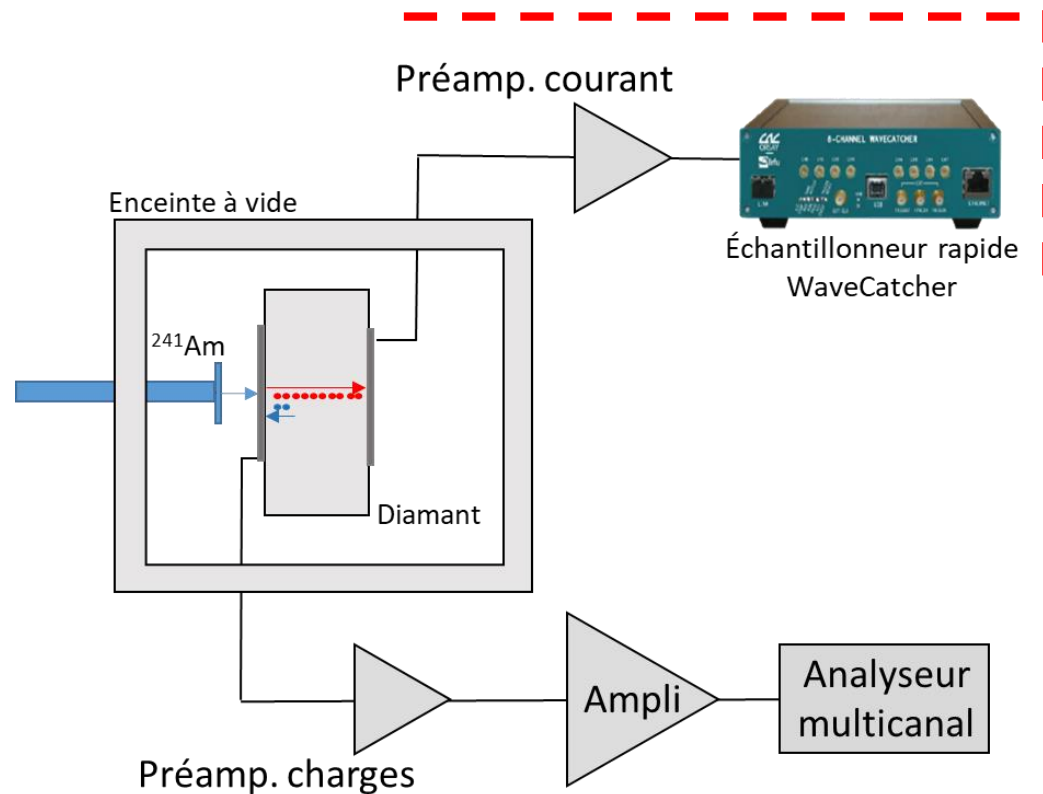
- Analyse de forme \rightarrow qualité de l'échantillon
- Propriétés porteurs de charges (vitesses de dérive, mobilités, temps de vie effectif...)

Caractérisation en laboratoire

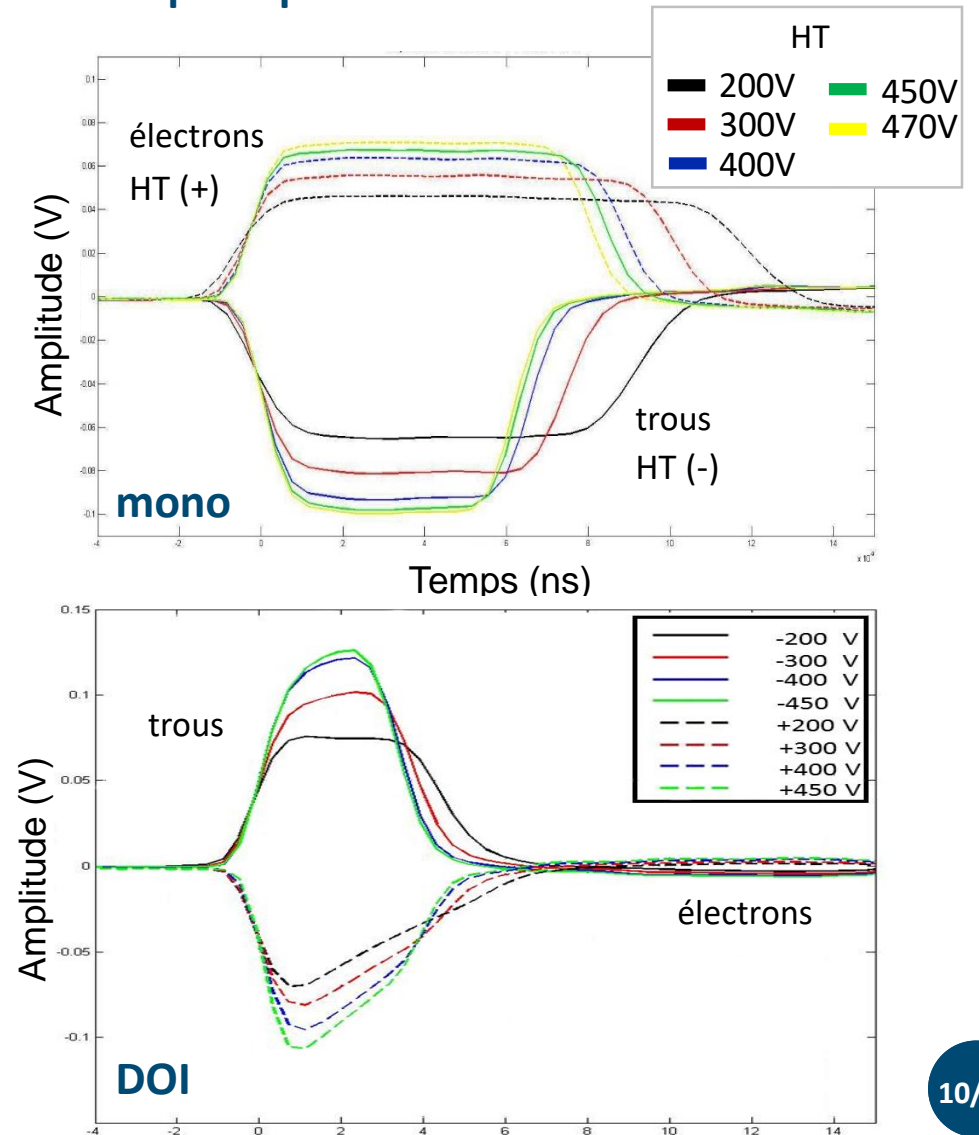
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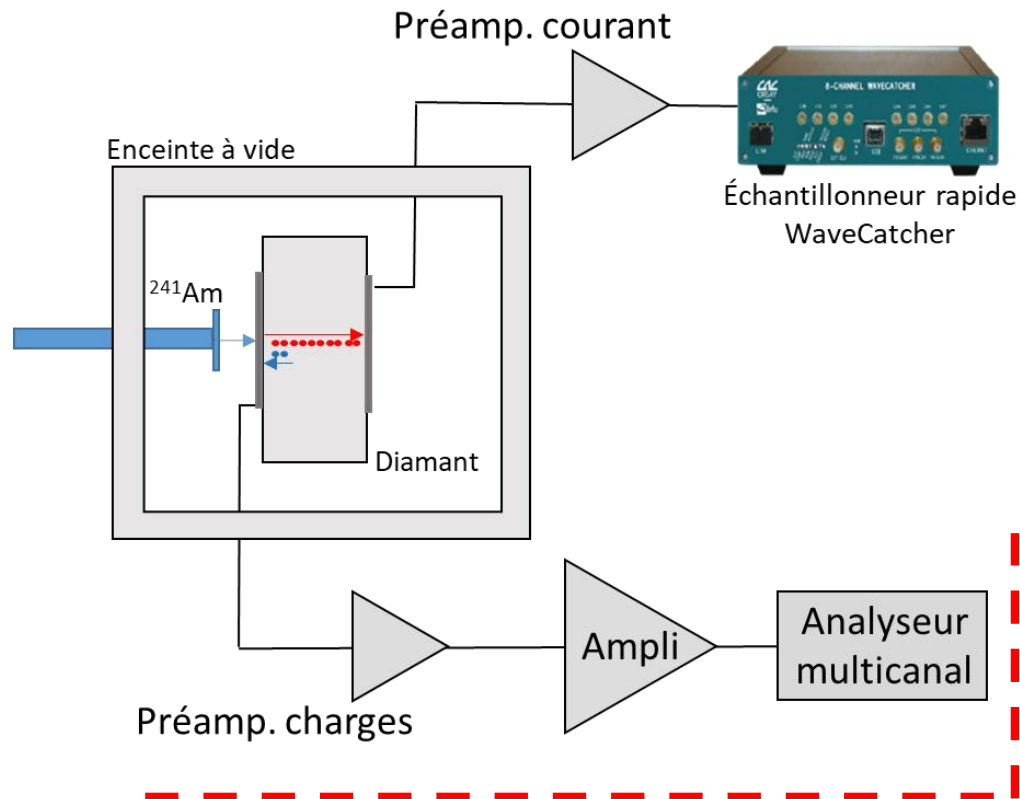


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$\leftrightarrow 14 \mu\text{m}$ dans diamant (\ll épaisseur)

➔ Polarisation sélectionne le porteur de charges étudié



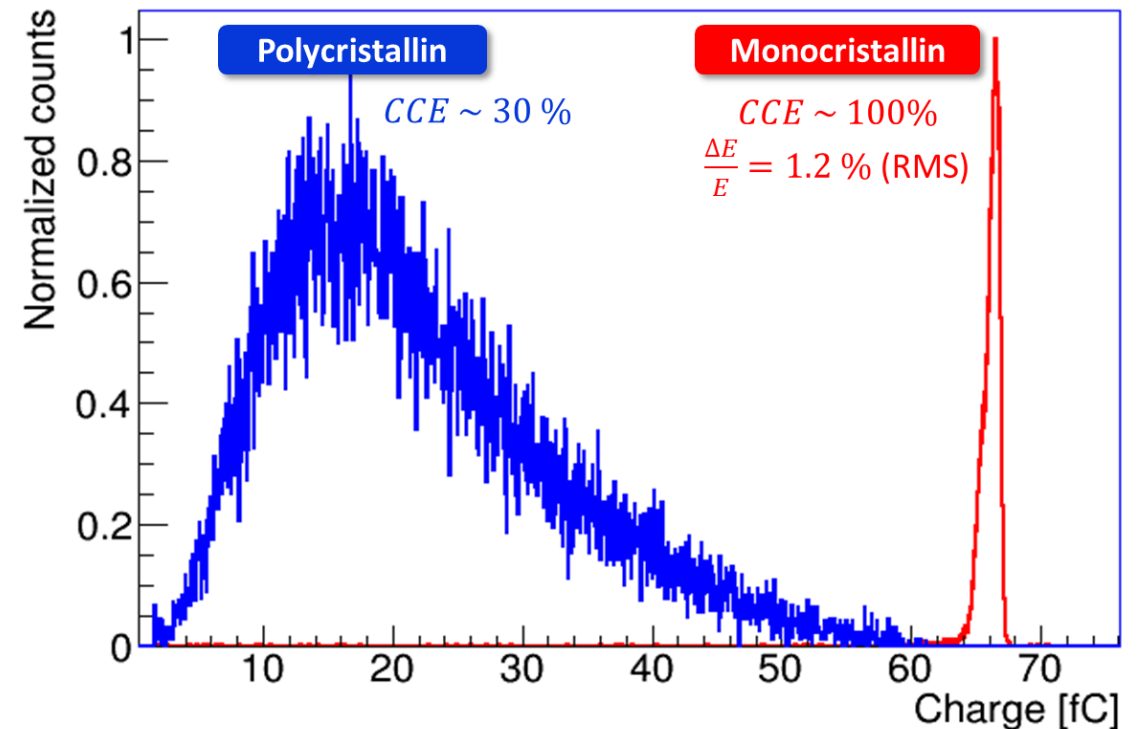
Electronique de spectroscopie

Intègre/filtre le signal

→ Augmente le rapport Signal/Bruit

- Résolution en énergie
- Efficacité de Collection de Charges (CCE)

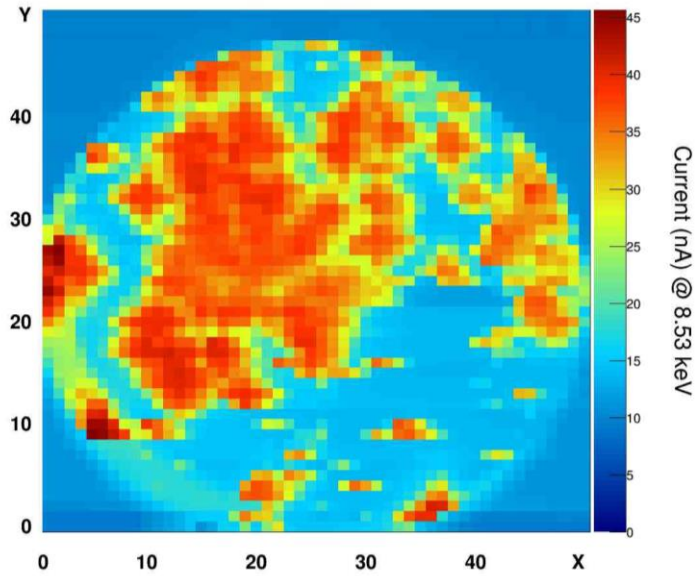
$$CCE = Q_{collectée} / Q_{générée}$$



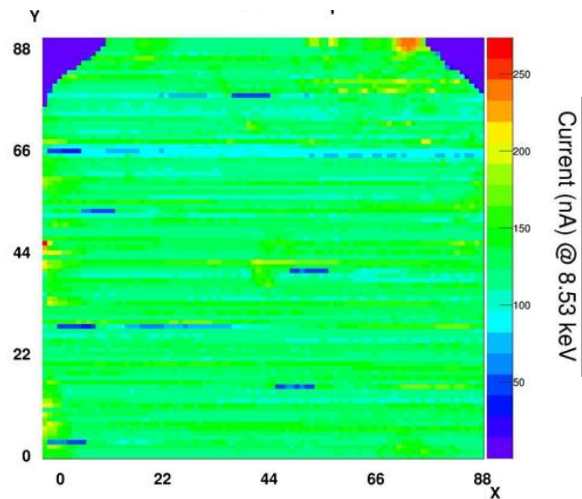
Current mode response

X-ray induced current mapping

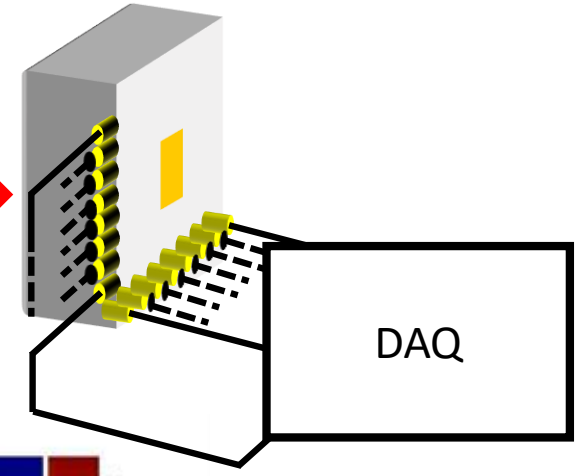
DOI



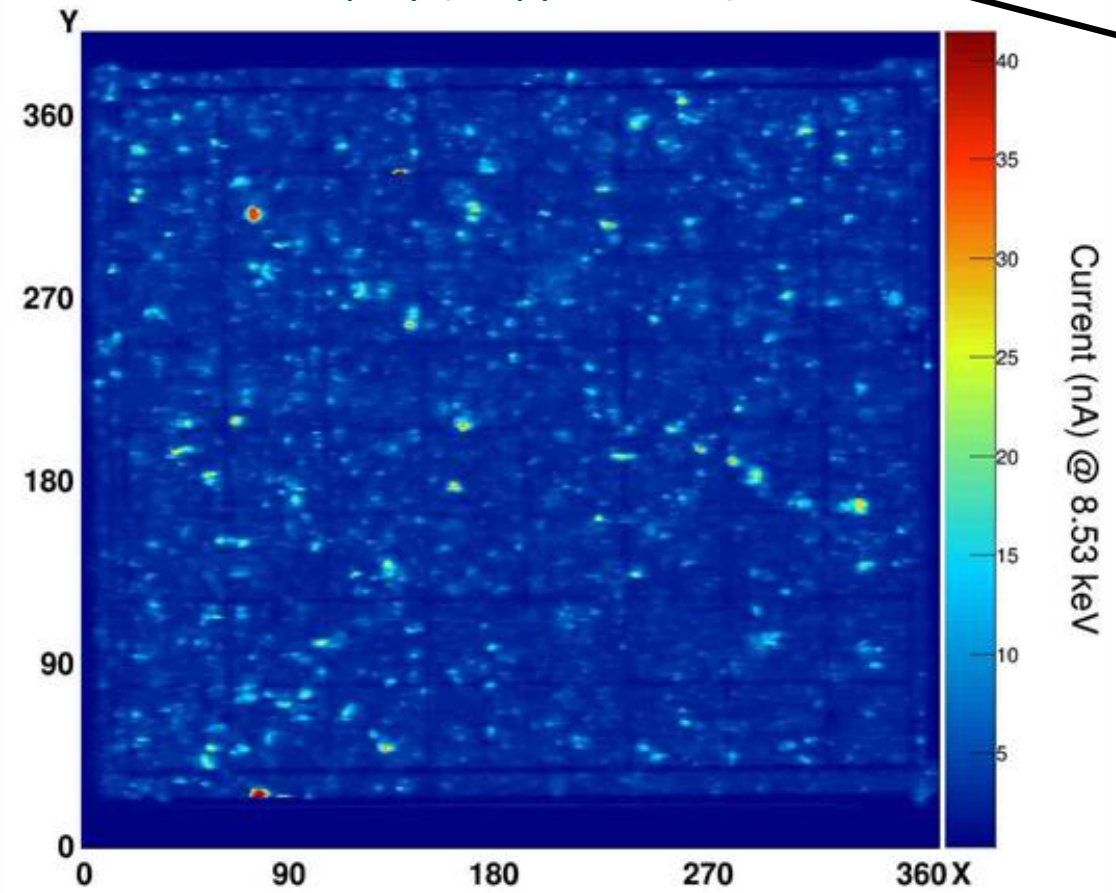
mono



8.5 keV X-rays



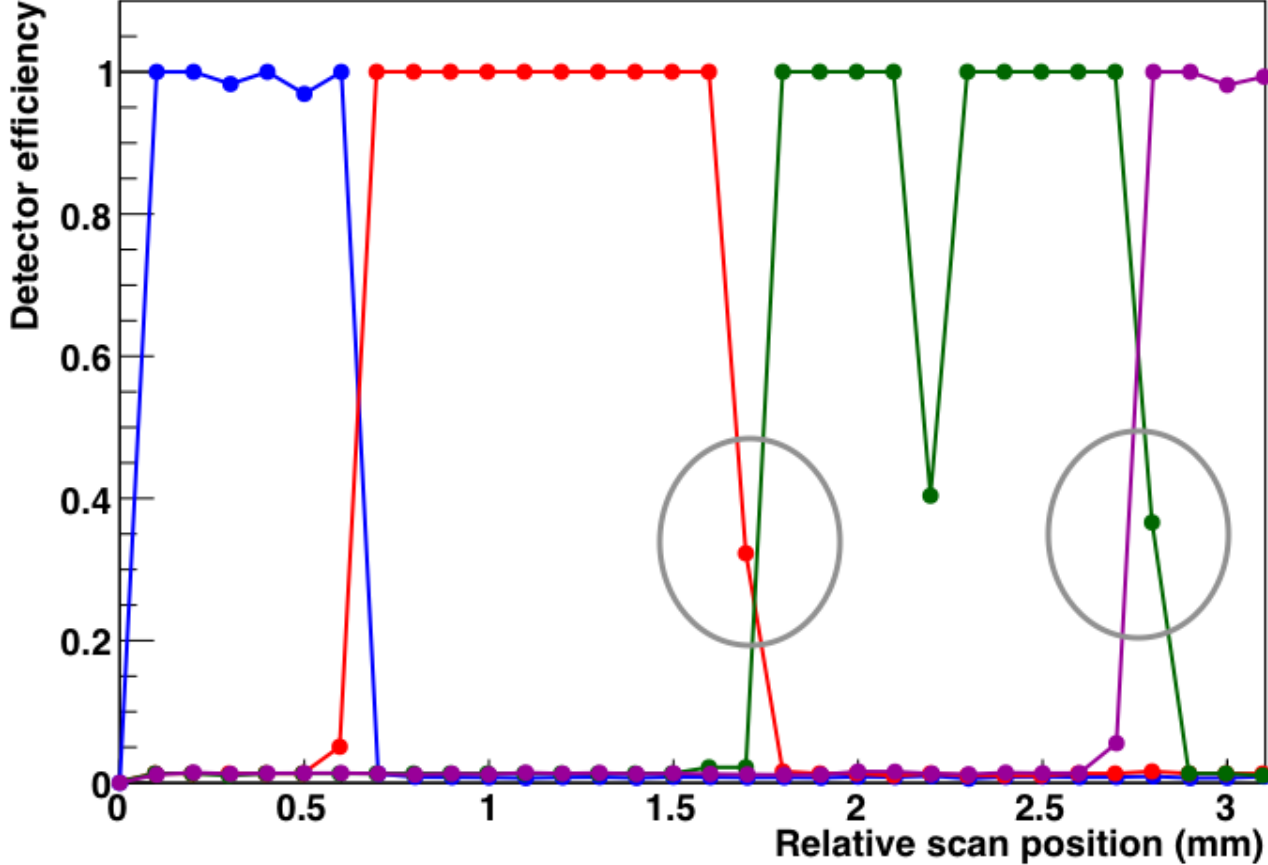
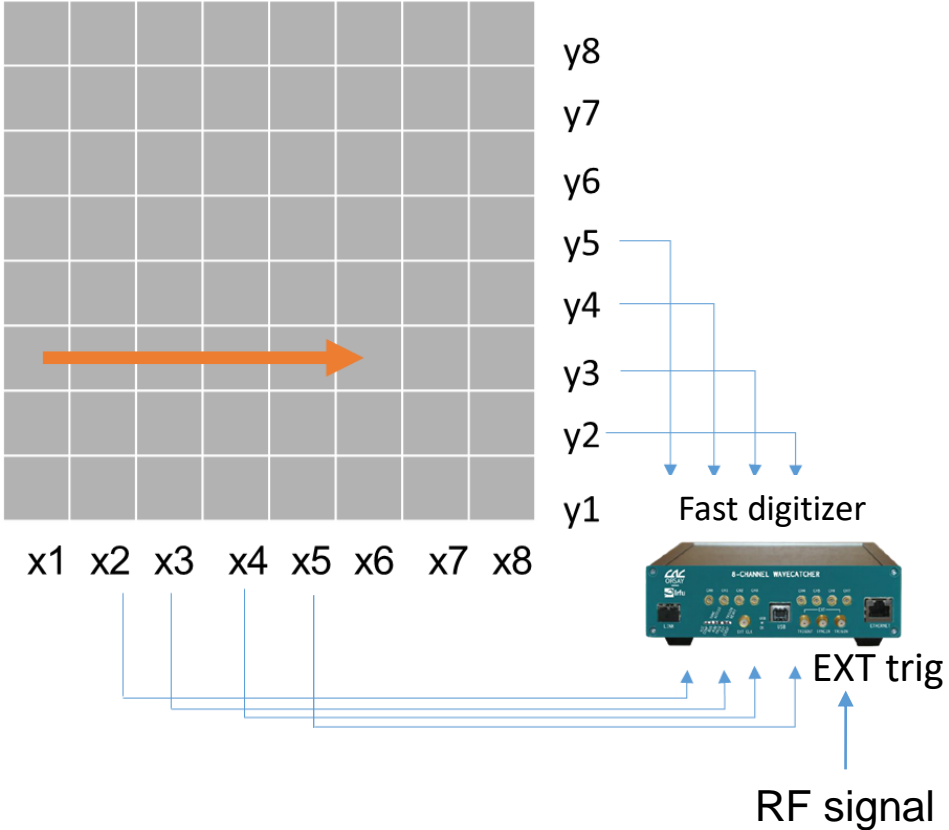
poly (stripped 1cm²)

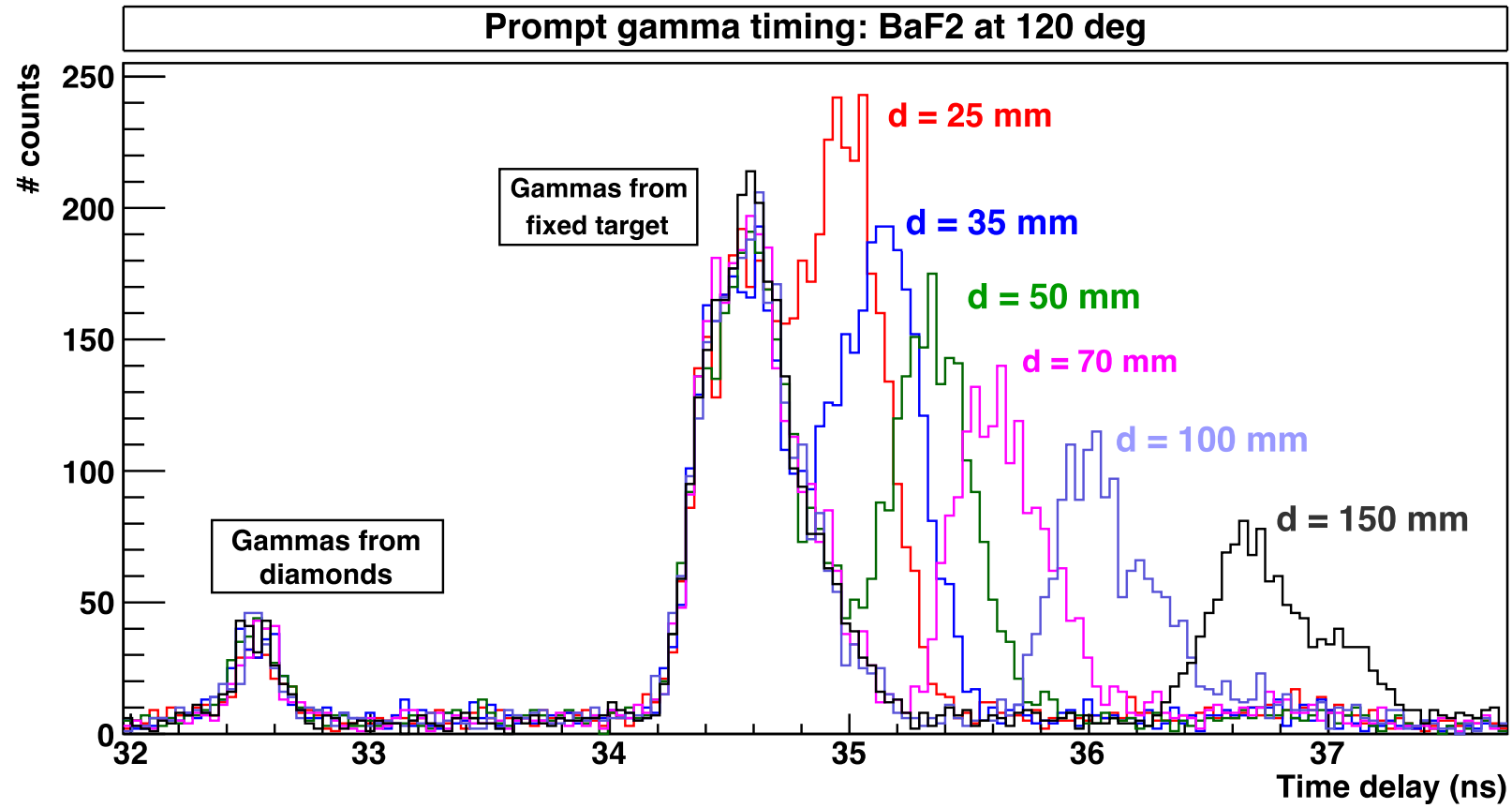


Strip detector detection efficiency

Detection efficiency
(with respect to the
beamline RF signal)

- Y3-X2
- Y3-X3
- Y3-X4
- Y3-X5

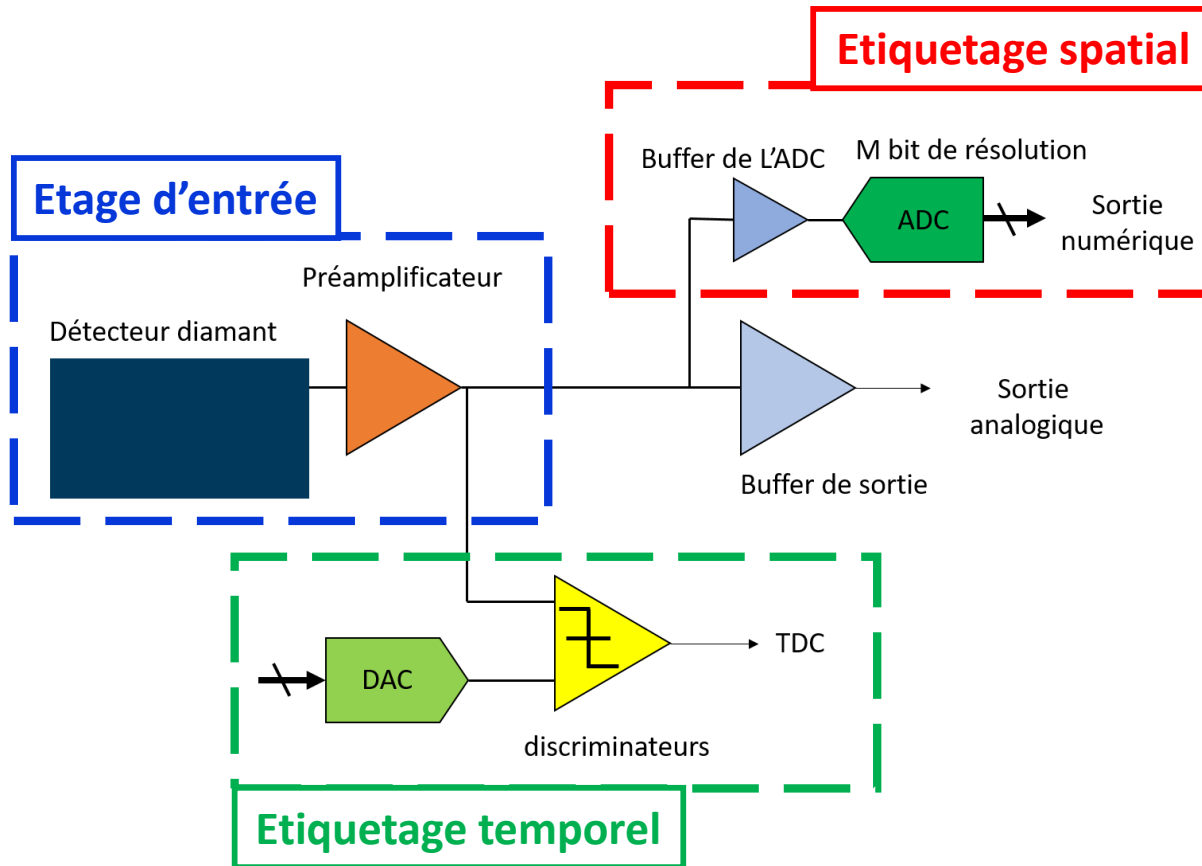




Développements en électronique

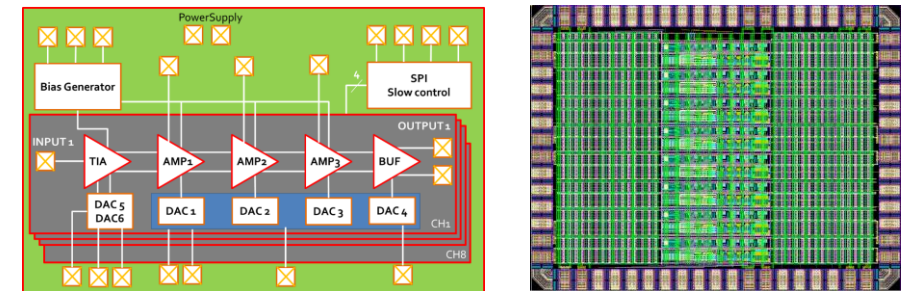
G. BOSSON, J. BOUVIER, L. GALLIN-MARTEL, A. GHIMOUZ, C. HOARAU, F. RARBI, O. ROSSETTO

- Conception de circuits intégrés spécifiques (ASIC)



ASIC 8 voies

- Technologie CMOS 130 nm (CERN)
- Résistant aux radiations
- Soumis en Décembre 2018



Préamplificateurs courant discrets

- En boîtier ou monté sur carte
- Solution alternative

