Single Particle Detection

Denis Dauvergne – LPSC Grenoble

2 topics

- Beam tagging hodoscope for particle therapy

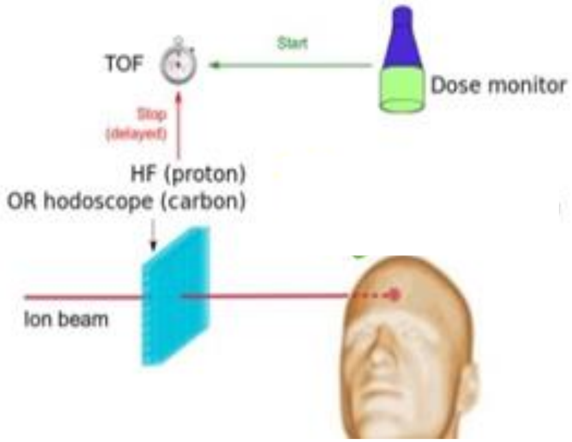
Collaboration LPSC-IP2I-CREATIS-ARRONAX-CAL-Nice (ML Gallin-Martel, L. Gallin-Martel, C. Hoarau, JF Muraz, P. Paris, M. Reynaud, J. Waquet, E. Testa, Y. Zoccaratto, H. Chen, J.M. Létang, C. Koumeir, J. Hérault, M. Vidal)

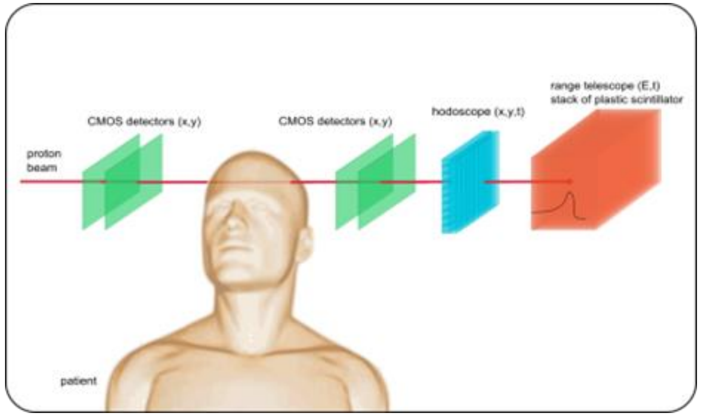
- Electron detection for the measurement of Zitterbewegung/Electron clock

Collaboration LPSC (D. Dauvergne), IJCLab (N. Delerue, H. Guler), IP2I (E. Testa)

Beam tagging hodoscope for particle therapy

- **Motivation**: online control of the ion range (reduce safety margins)
  - Detection of secondary radiation (prompt-gammas): ToF → background reduction+ transverse position
  - Proton radiography





Ion tagging in particle therapy

		synchrotron		cyclotron (IBA, Varian)	synchrocyclotron (S2C2, IBA)
		Carbon	Protons		
Intensité typique (ion·s^{-1})		10^7	10^9	10^{10}	$\sim 10^{10}$
Macrostructure	Période (s)	1 - 10		$\varnothing$	10^{-3}
Microstructure	Largeur de paquet (ns)	20 - 50		0.5 - 2	8
	Période (ns)	100 - 200		10	16 (variable)
	Ions/paquet	2 - 5	200 - 500	200	4000

Krimmer et al, NIMA, **878** (2018)

- **Challenges**:

  Protons: $\langle I \rangle_{clinics} \sim 10^{10}$ p/s → pulse tagging (cyclo)

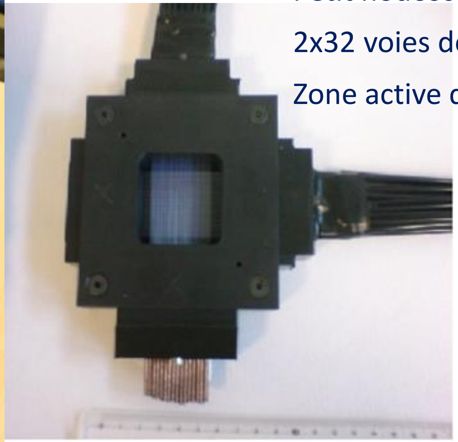
  → no ToF with synchrotron or synchro-cyclotron

  Improved performance at reduced intensity (ToF at ~100 ps resolution)

  Carbon: $\langle I \rangle \sim 10^{8}$ part/s max → single ion counting if segmented detector

Système CLaRyS : Hodoscope à fibres scintillantes

(Slide O. Allegrini)



Petit hodoscope:

2x32 voies de lecture

Zone active de 3.2 x 3.2 cm

- **2 plans** de fibres **perpendiculaires** pour un repérage 2D 12,8x12,8 cm^2
- **128 fibres** scintillantes en polystyrène BCF-12 **par plan**
- **Section** carrée de **1 mm²**
- Couplage par fibre optiques
- **8 PMT** multi-anodes H8500 pour assurer une lecture des deux cotés

❑ **Rôle de l’hodoscope :**

Fournir un **étiquetage en temps et spatial** par paquet d’ions ou par ion

Spécifications

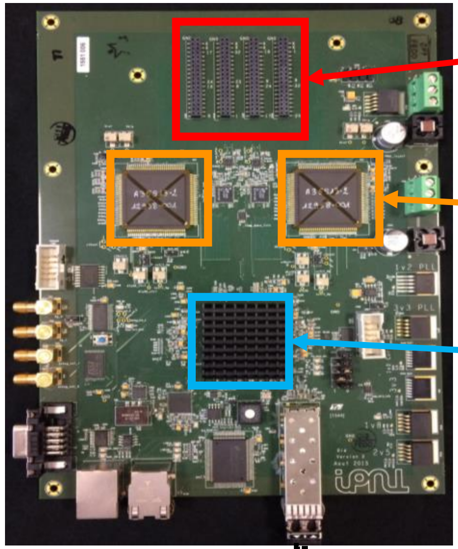
- **Efficacité de détection** avec un ET logique entre chaque plan : ~ **90 %**
- **Résolution temporelle** : **< 2 ns**
- **Taux de comptage** : jusqu’à **100 MHz**
- **Résistance aux radiations** : opérationnel pour au moins **1000 traitements**

Système CLaRyS : Hodoscope à fibres scintillantes

(Slide O. Allegrini)

❑ Électronique de lecture

- Chaque PMT est lu par une carte frontale « HODOPIC »

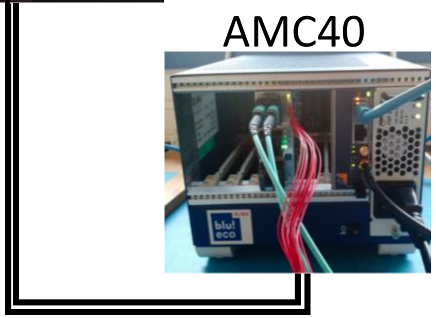


Connexion du PMT multi-anodes avec 64 voies d'entrée

ASICs

FPGA

AMC40



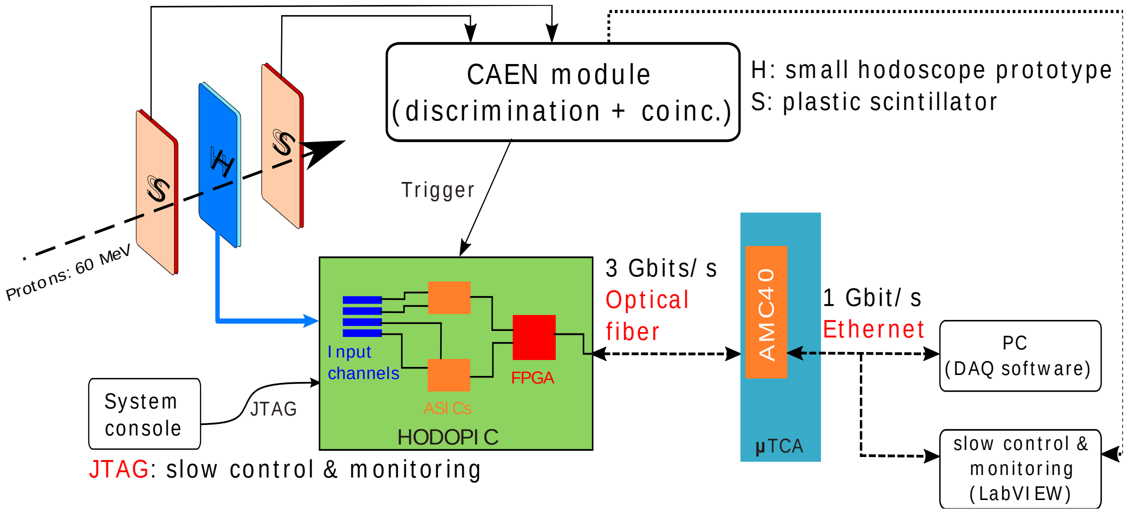
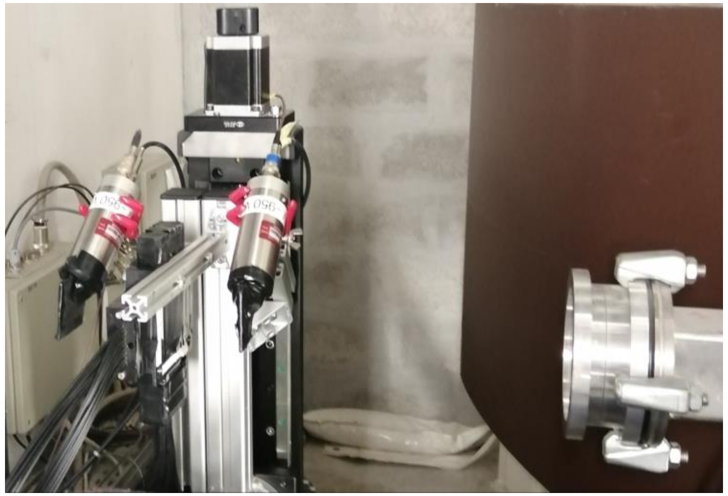


Schéma du dispositif expérimental et de la chaîne d'acquisition
(O. Allegrini et al. 2021 JINST)

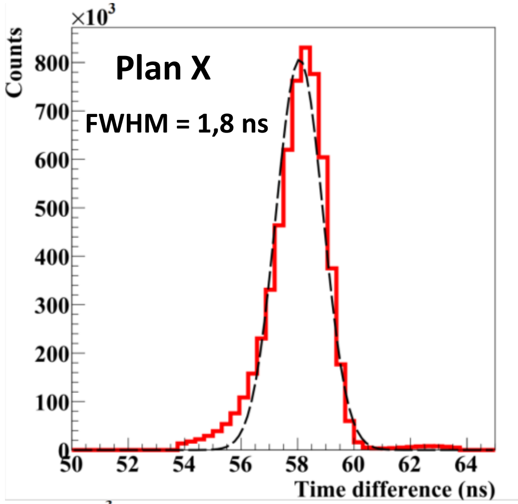
Dispositif expérimental ***Centre Antoine Lacassagne***
(65 MeV protons, HF 40,25 MHz)
Performances de l'hodoscope de taille réduite
(efficacité, résolution temporelle, multiplicité)

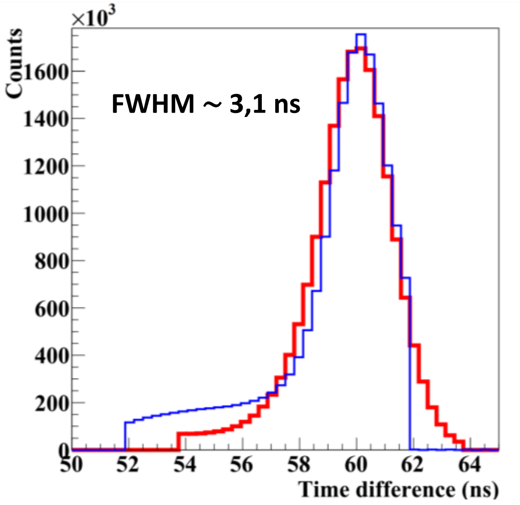


Hodoscope CLaRyS : Résultats

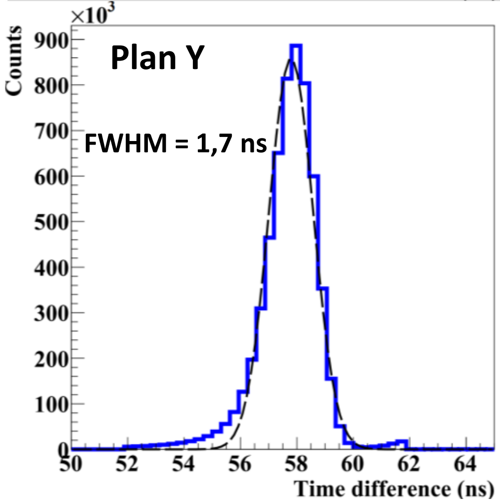
(Slide O. Allegrini)

❑ Résolution temporelle :



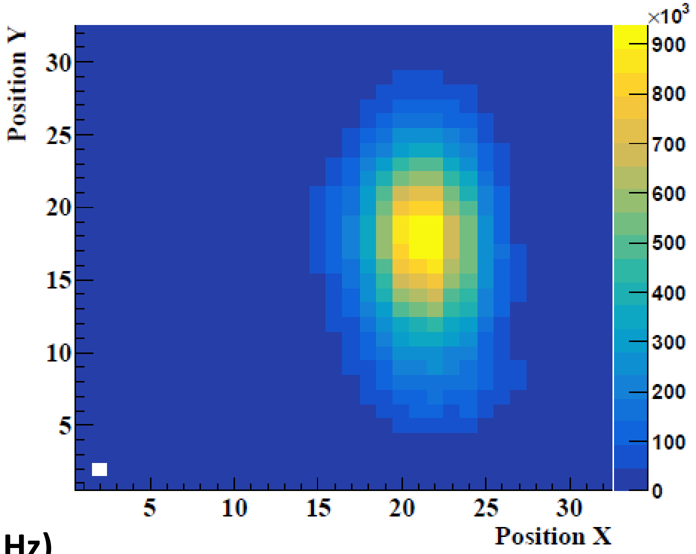


Intensité de faisceau élevée (~ 10^7 Hz)



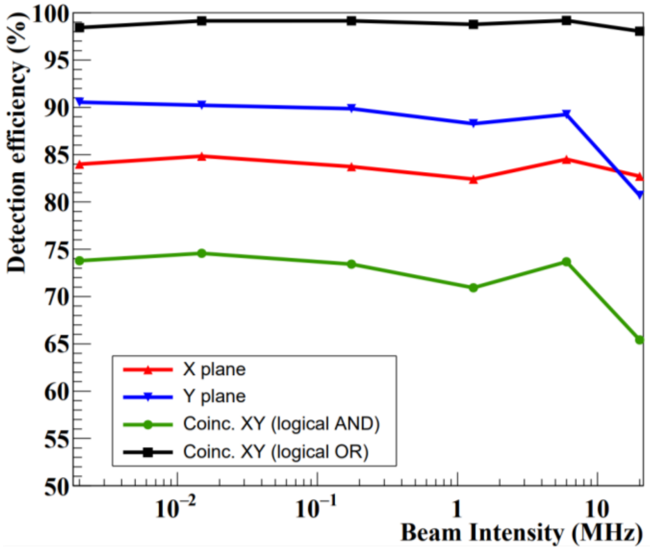
Intensité de faisceau faible (~ 10^5 Hz)

❑ Image 2D :



Intensité élevée (20 MHz)

❑ Efficacité de détection :



❑ Résistance aux radiations:

Mesures au GANIL (26 MeV déposés par ion C de 95 MeV/u)

L'efficacité passe de 94% à 86% après 3,6x10^{12} ions/cm^2 (> 1000 irradiations cliniques)

Récupération partielle après plusieurs jours

❑ Conclusions:

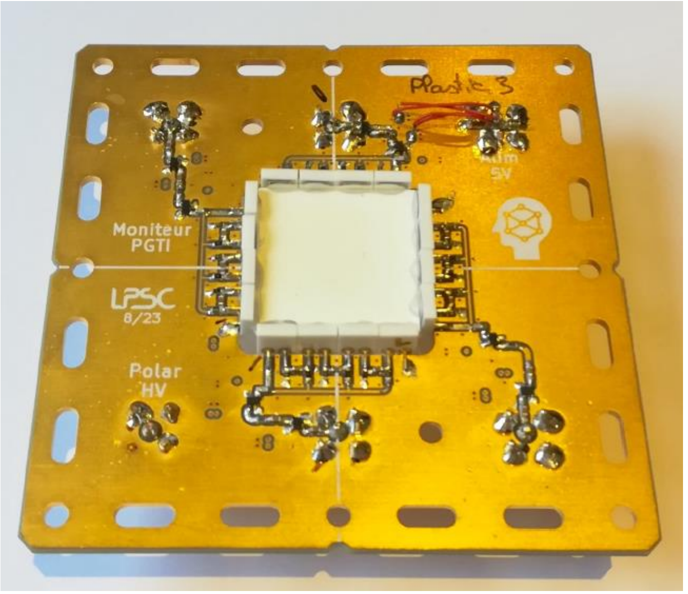
Problèmes de déclenchements multiples à haute intensité (ASIC)

Système complexe (512 voies de lecture), limité par taux de comptage des PMT

Single plastic monitor (TIARA project)

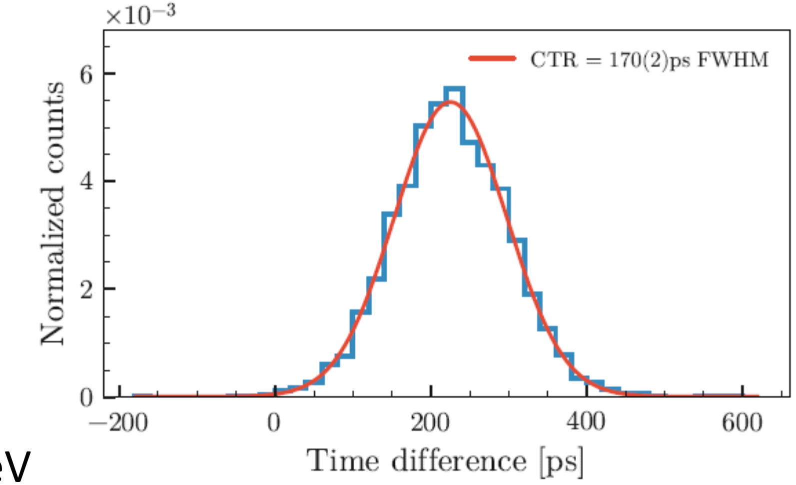
1 mm thick, 2,5x2,5 cm^2 plastic scintillator

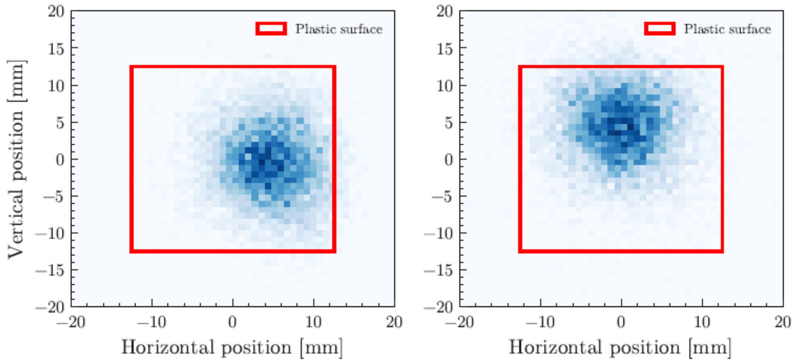
Readout by SiPM (4 arrays multiplexed)



Timing resolution ~100 ps rms
Efficiency 100% for single protons 230 MeV
Spatial resolution ~2mm rms

Performance for large areas?

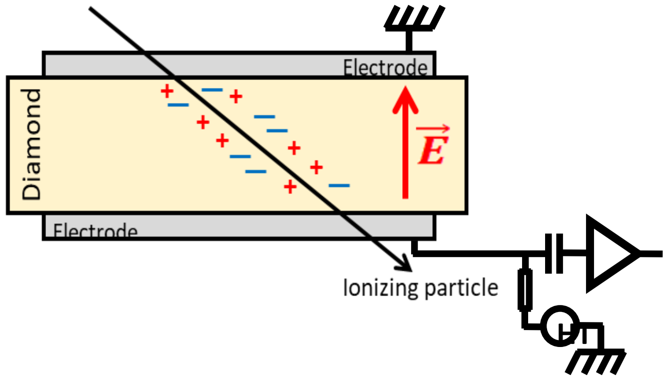




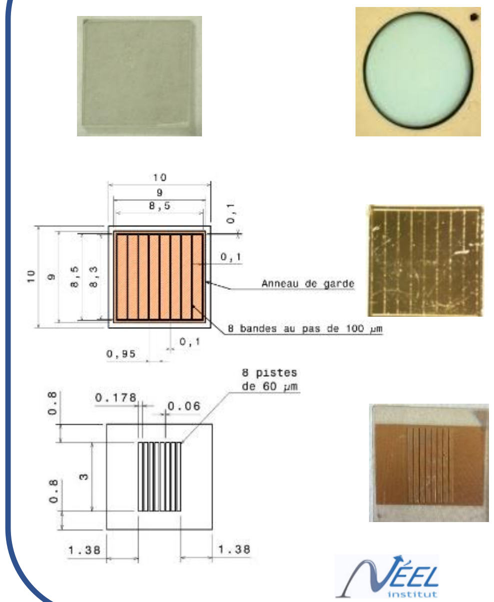
A. André et al, IEEE TRPMS 2025

Diamond as beam monitors

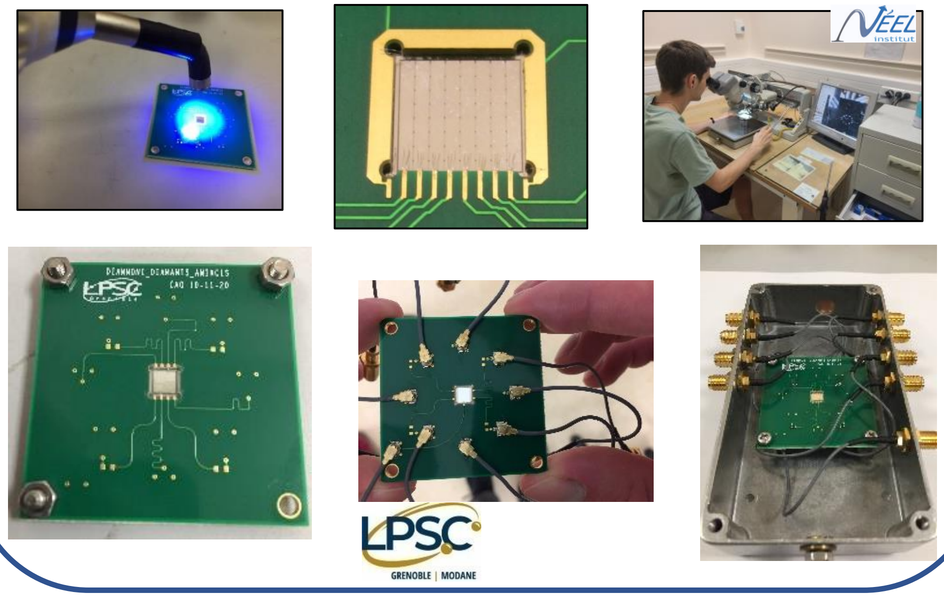
Solid state ionization chamber



Diamond metallisation



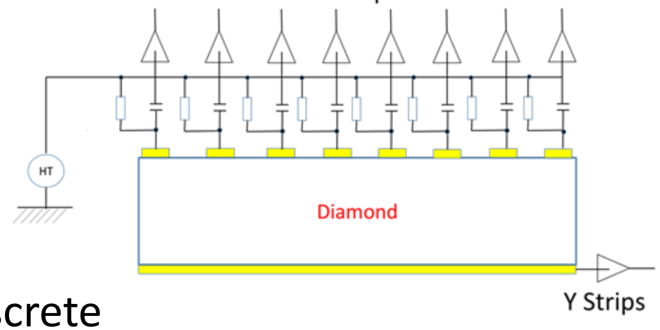
Detector assembly



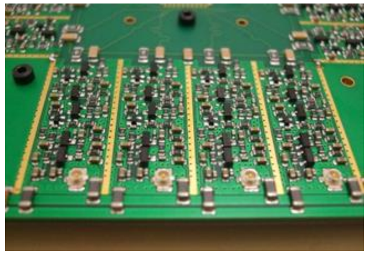
Read-out electronics

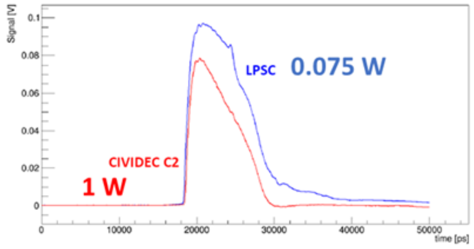
- Fast current preamplifier
- Charge preamplifier
- QDC

Read out electronics @ LPSC



Discrete



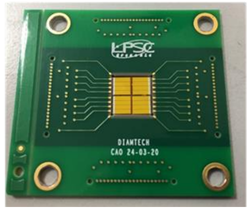


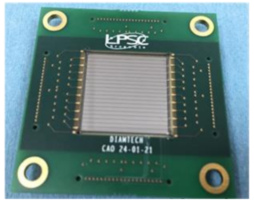
C. Hoarau *et al* 2021 *JINST* **16** T04005
https://doi.org/10.1088/1748-0221/16/04/T04005

DIAMOND – Beam monitoring @IN2P3 and for medical application : various specification lists!

40 preamps + DFC + TDC

4 diamond sCVD in mosaic or 1 pCVD

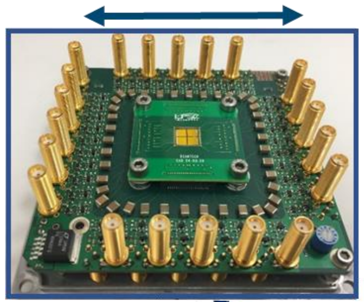




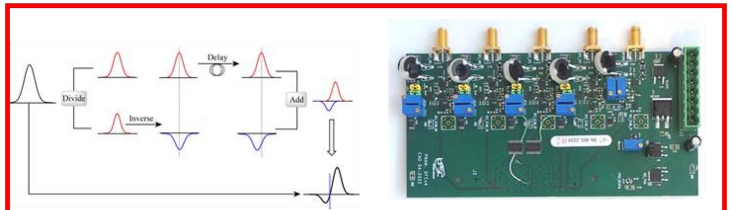
Proton beam monitoring in hadrontherapy (CAL)

Coll. Clarys UFT / Coll. ClaRyS - LaBeX PRIMES (P. Everaere PhD thesis)

- Single particle
- XY spatial resolution ~1 mm **Beam monitor and ToF**
- Time resolution ~100 ps

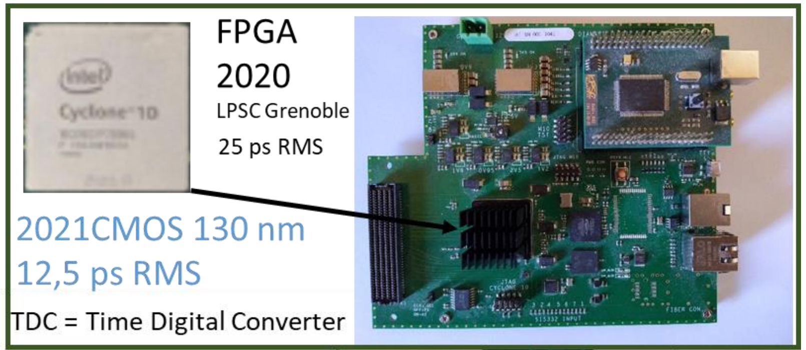


42 channels

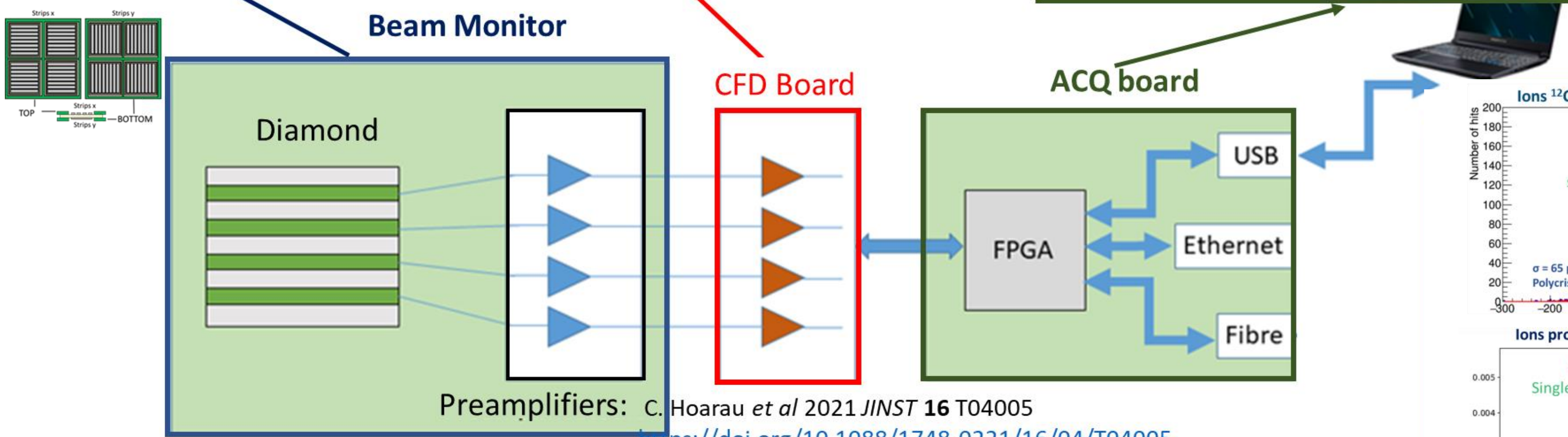


CFD=> time stamp independant of diamond signal amplitude

CFD = Constant Fraction Descriminator

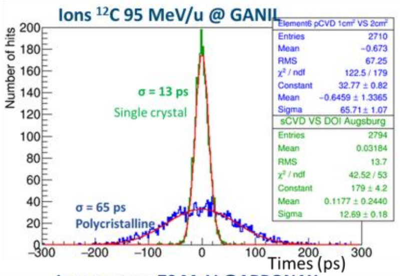


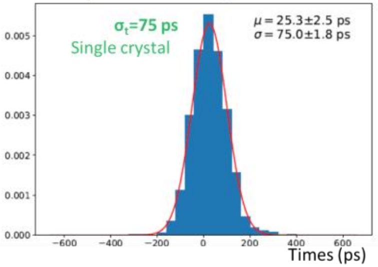
TDC = Time Digital Converter



C. Hoarau *et al* 2021 *JINST* **16** T04005
https://doi.org/10.1088/1748-0221/16/04/T04005

S. Curtoni PhD thesis http://www.theses.fr/2020GRALY045 UGA / CLARYS-UFT INSERM 2020





Need for large area CVDs to cover the beam scanning area !

Electron per electron measurement for internal clock observation

Internal clock (L. De Broglie thesis, 1924)

A particle is surrounded by a wave Ψ

In its rest frame $\Psi = a_0 \exp(2\pi i \nu_0 t)$

$$E = m_0 c^2 = h\nu_0 \quad \rightarrow \quad \nu_0 = m_0 c^2/h$$

Internal Clock frequency: $\nu_0 = 0{,}78\ \mathrm{ZHz}$

“A Clock Directly Linking Time to a Particle's Mass”,
Shau-Yu Lan et al. Science 339, 554 (2013);

Zitterbewegung

Dirac (1957) and Schrödinger (1930):

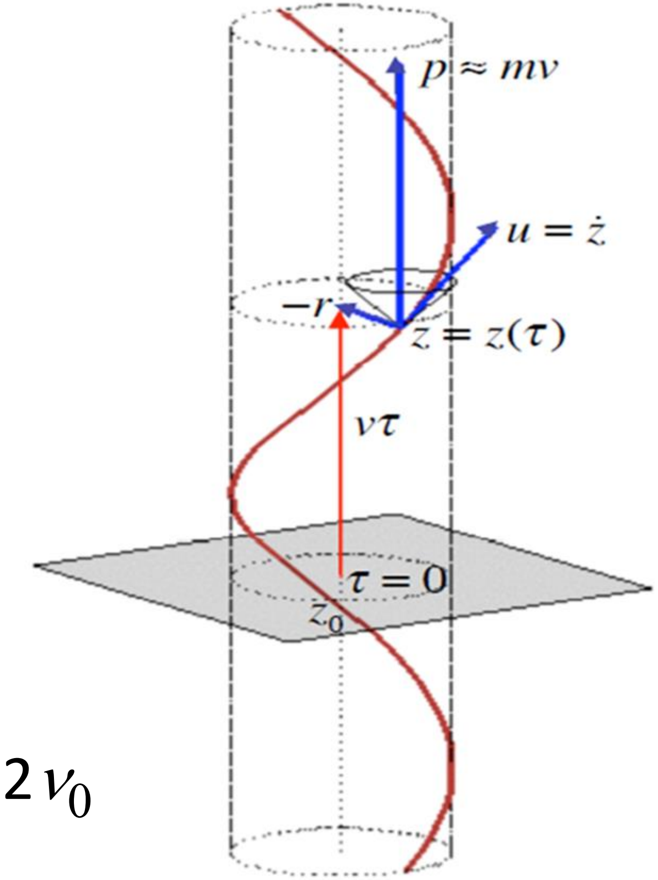
x(t)= *v.t* + "Zitterbewegung"

- *v.t* is the classical motion of a particle.
- the "Zitterbewegung" term is roughly:

$o(\lambda_c)\cos(\omega_z t/\gamma)$

λ_c = ~10^{-10} cm for e- .

$\omega_z = 2\, m_0 c^2/\hbar$.



Zitterbewegung frequency: ν_Z = 1.55 ZHz =2 ν_0

D.Hestenes. Zitterbewegung in Quantum Mechanics. *Found. Phys.*, 40 (2010)1
D. Hestenes, Gyromagnetics of the electron clock, IEEE Access 13 (2025) 53772
M.M. Asif, Eur. Phys. J. Plus 131 (2016) 37
M.J.J. Fleury, O. Rousselle, Critical Review of Zitterbewegung Electron Models, Symmetry 2025, 17, 360
W.Zawadzki and T.M. Rusin, J. Phys.: Condens. Matter 23 (2011) 143201
R. Gerritsma et al, Nature 463 (2010) 68

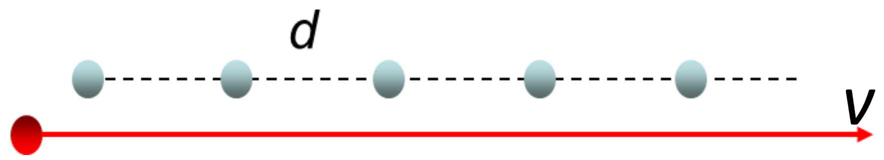
Experimental observation of Zitterbewegung?

- No direct observation so far

- Idea: could the trajectory be perturbed by its internal clock, when its velocity v is adjusted in order to fit the resonant condition $\nu_n = n\nu_0 = n\,\gamma\, v/d$ by a spatial periodic excitation?

- 10^{21} Hz ~ collision frequency along atomic string in a crystal by relativistic particles (γ ~10^2, d ~ few Å):

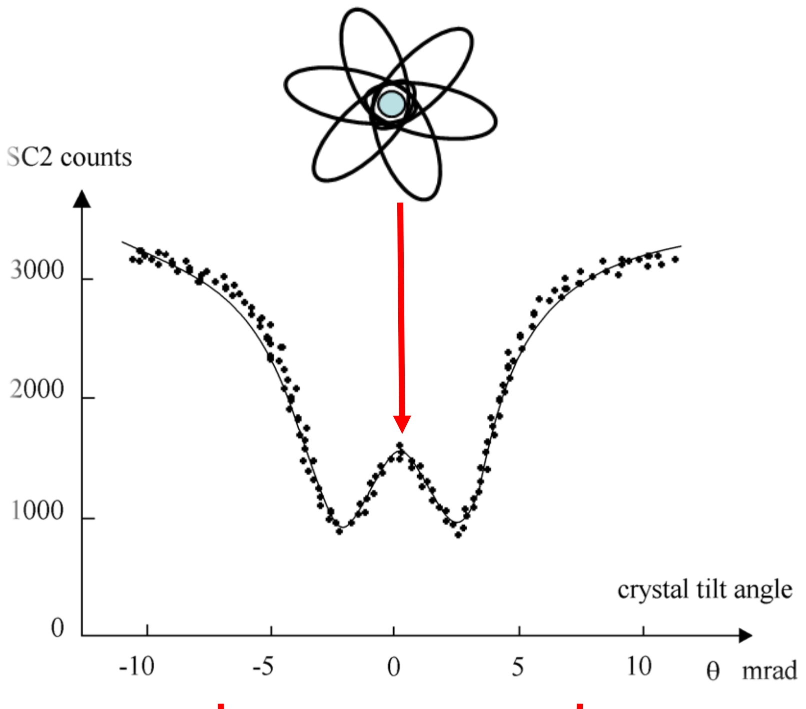
$$\nu = \gamma\, v/d$$



Electron channeling along <110> axis of silicon
Energy scan: first signature of IC at ALS

- Rosette motion

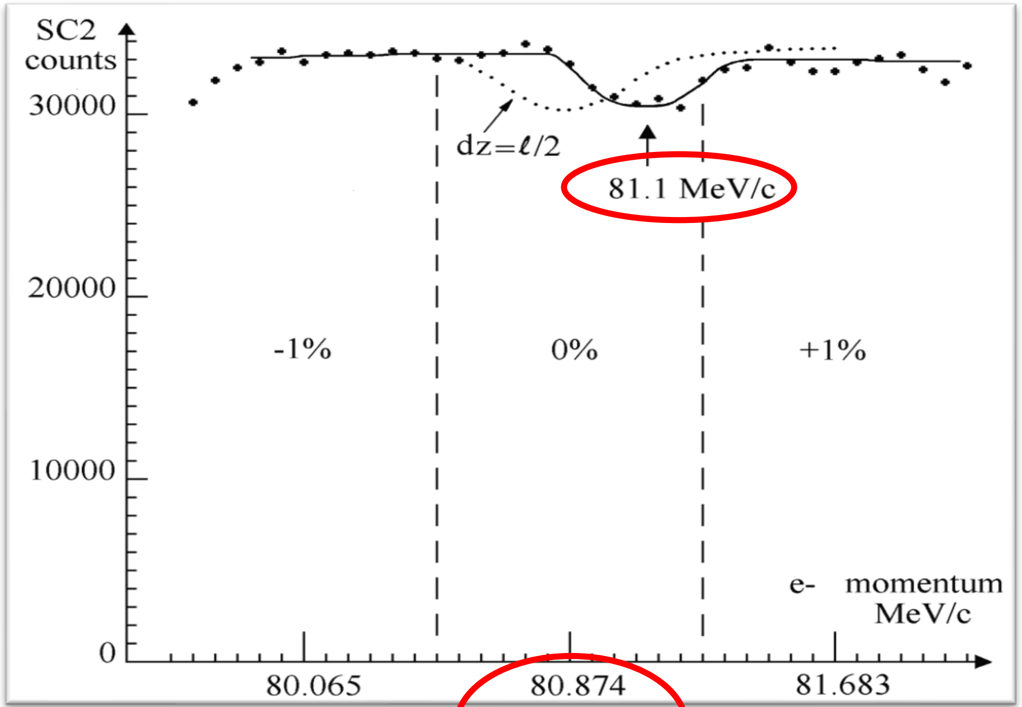
in a 1µm thick Si crystal



Enhanced scattering
(rainbow effect)

- Expected resonance

at ≈ 80,9 MeV/c



$= m_e d\nu_0$

Catillon et al, 2008

Confirmation is needed !

Resonance energy

Zitterbewegung
ΔE=1022 keV
$= n\ hp/m_e d$

p (MeV/c)

	Diamond <110>	Si <110>
n=1	106,21	161,76
2	53,11	80,88
3	35,40	53,92
4	26,55	40,44

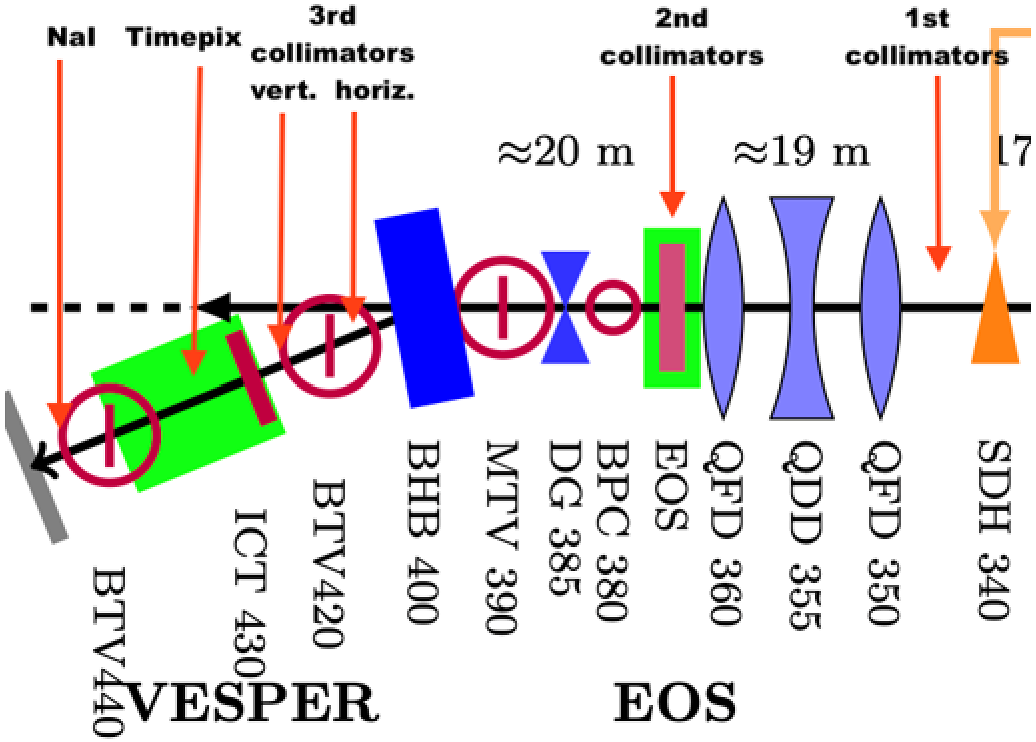
Internal clock (DB)
ΔE=511 keV

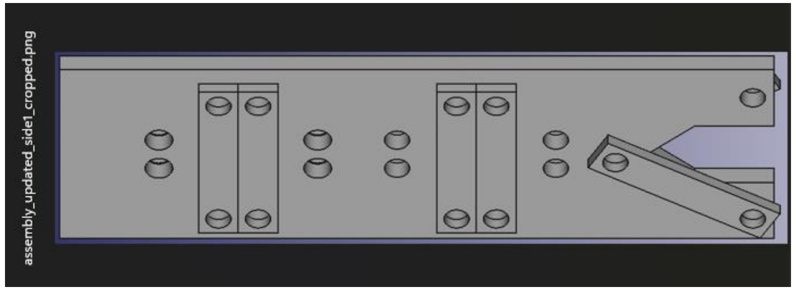
p (MeV/c)

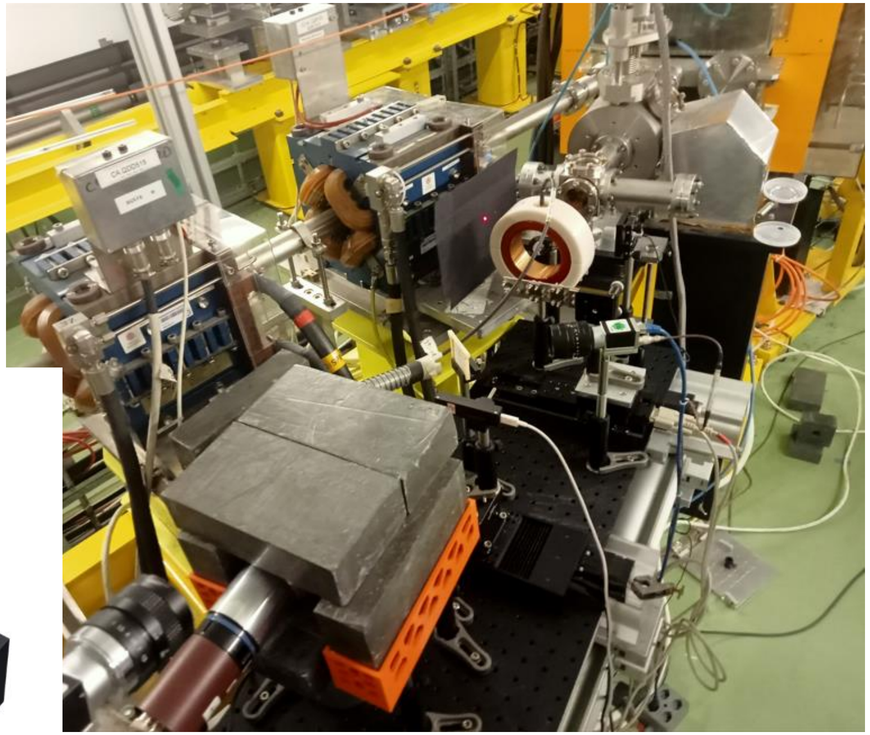
	Diamond <110>	Si <110>
n=1	53,11	80,88
2	26,55	40,44
3	17,70	26,96
4	13,28	20,22

E < 50 MeV: observable at ALTO

First test at CLEAR/CERN



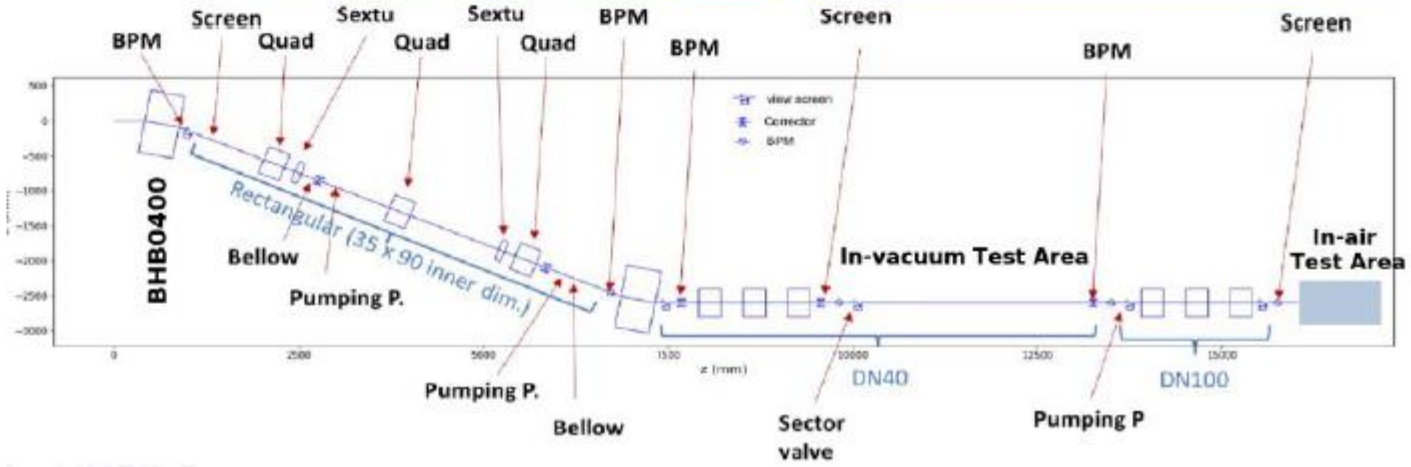




- 3 sets of collimators
  - 2 for emittance selection (0.1π.mm.mrad)
  - 1 for energy selection ($dp/p < 10^{-3}$)
- 2D TIMEPIX detector (100µm ⟷ 0,1 mrad)
- Calorimeter (multiplicity=pair creation signature)

New beamline at CLEAR Commissioning end 2025

In parallel, tests at ALTO? (50 MeV)



Conclusions

- Comptage ion par ion en hadronthérapie
  - Compromis entre résolution temporelle, taux de comptage, surface disponible, budget matière et complexité (nombre de voies)
- Détecteurs diamant
  - Augmentation de la surface (mosaïque de grands polycristaux)
  - Développement électronique pour timing pour les MIPS
- Expérience Zitterbewegung/horloge interne
  - Façonnage d'un faisceau électron/électron à faible émittance
  - Réalisation d'une expérience de channeling (alignement d'un cristal avec goniomètre): CLEAR (+ALTO)
  - Mesure 2D impact par impact avec Timepix
  - Variation de l'énergie par pas de $dp/p \sim 10^{-3}$ sans changer les paramètres faisceau