Large area diamond detectors for fast beam tagging applications in particle therapy

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MediNet Task 1

Motivation (1/5)

Need for in vivo ballistic control in particle therapy

Uncertainty sources :

Dose calculation: Planification (from CT images, RBE), patient positionning, anatomic variations during treatment, moving organs/tumor

→ Margins

→ Beam incidences avoid OARs located straight behind PTV

Strategies:

Planification: dual-energy or proton CT, Monte Carlo simulations

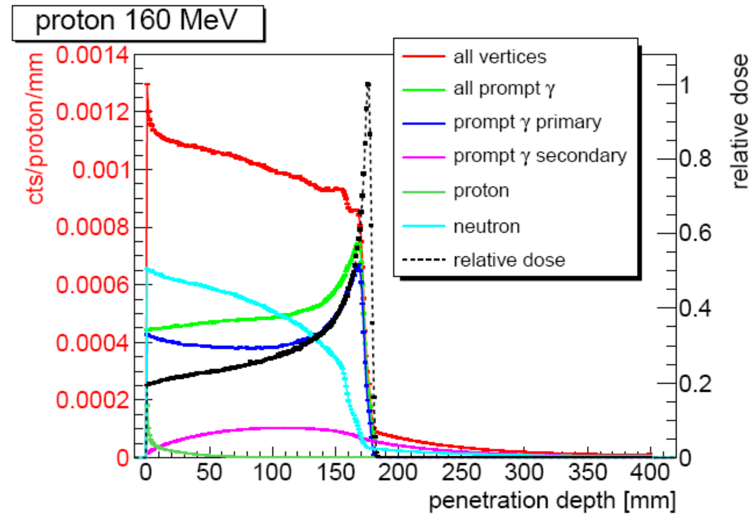
Online control: nuclear fragmentation products

- PET: a posteriori
- Prompt radiation:
  - Gamma (Review: [Krimmer et al, NIMA 878 (2018) 58-73])
  - protons (ions heavier than protons)

Motivation (2/5)
Time of Flight prompt-gamma imaging with 1D collimated camera

Prompt–γ emission is correlated to ion range

[Krimmer NIMA 2017]

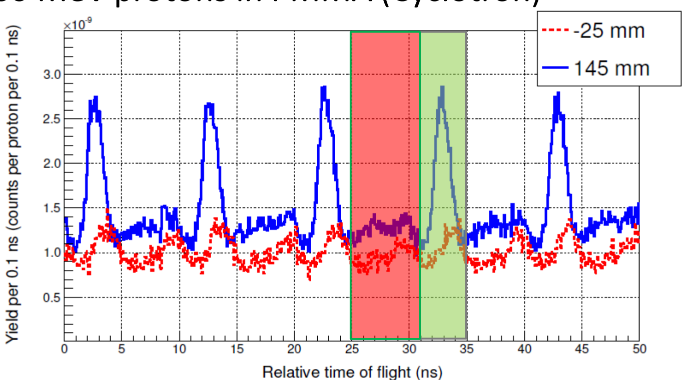


TOF: reduction of neutron-induced background

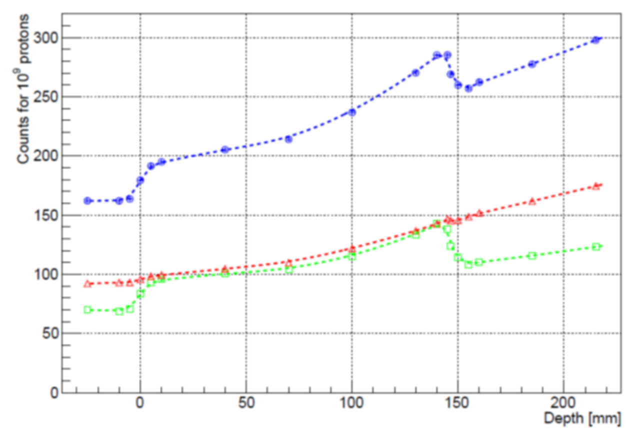
- **Synchronization with beam HF**

  Possible with Cyclotron proton beams (IBA-C230)

  160 MeV protons in PMMA (Cyclotron)



[Roellinghoff PMB 2014]



However :

Phase changes with beam energy

Limitations by bunch length (0.5 – 4 ns)

- **Ion per ion tagging at 10^7- 10^8 Hz**

  Carbon ions from synchrotrons (HIT, CNAO…): Microbunch duration >20 ns

  Synchro-cyclotron proton beams (IBA S2C2): Nanobunch duration ~8 ns (10^4 p/bunch)

  TOF $\Rightarrow$ reduction to 1 proton/bunch necessary

Motivation (3/5)

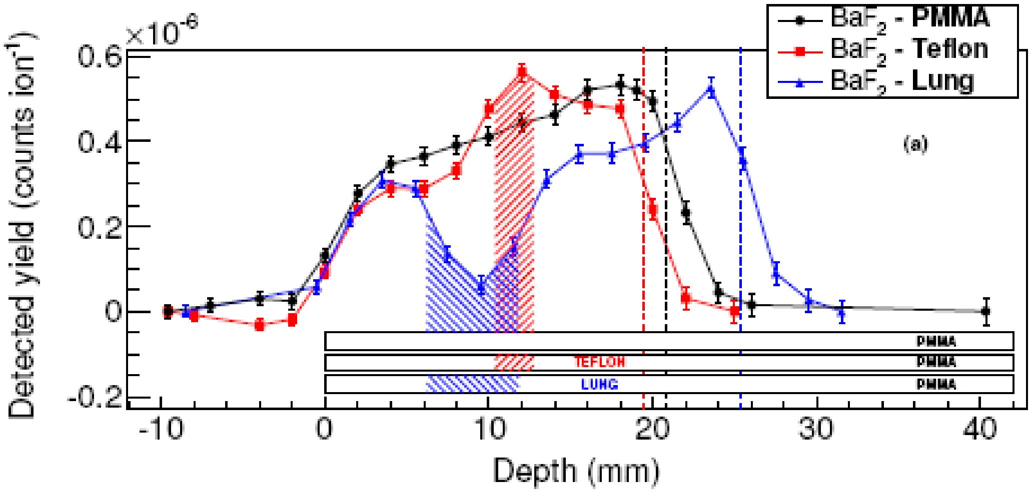
Spatial resolution issue

- Heterogeneities influence ion range and prompt-gamma yield

95 MeV/u carbon ions in PMMA

2 mm collimation slit

[Pinto Med Phys 2015]



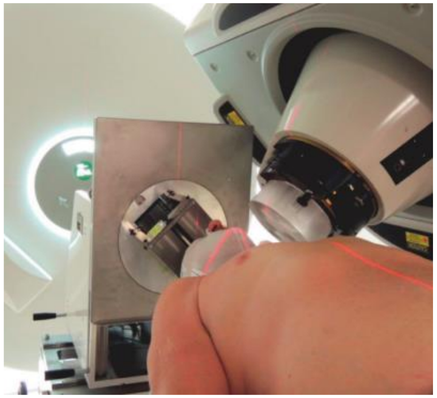
- Gamma imaging: compromise between spatial resolution and efficiency (statistics issue)

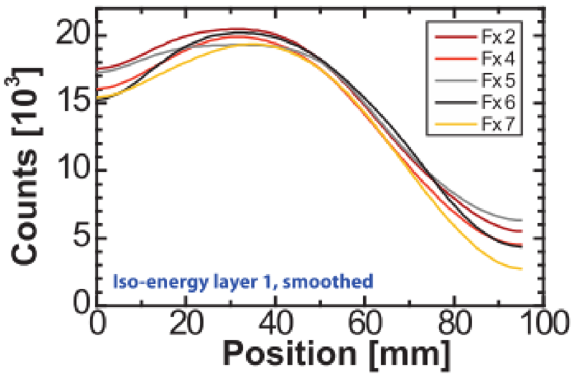
Proposed solution by IBA:

Knife-edge camera

(~2 cm spatial resolution)

[Richter, RaOn 2016]





- Ultra-fast timing resolution will improve spatial resolution

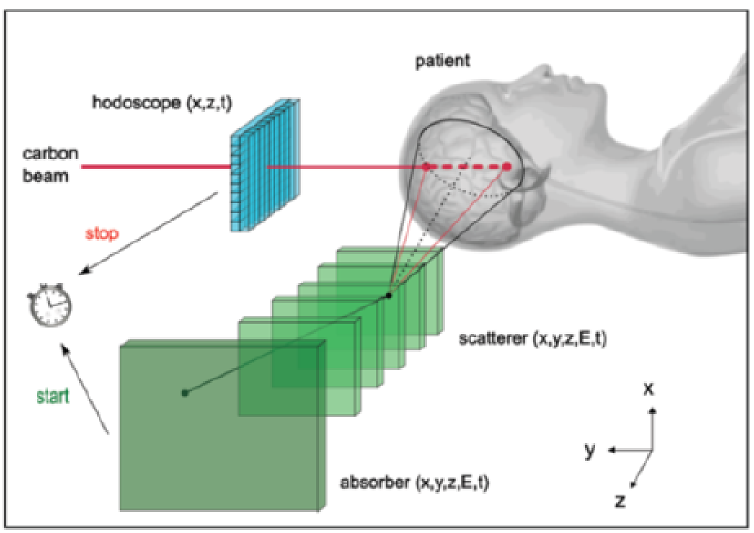
Motivation (4/5)

Compton imaging with beam hodoscope

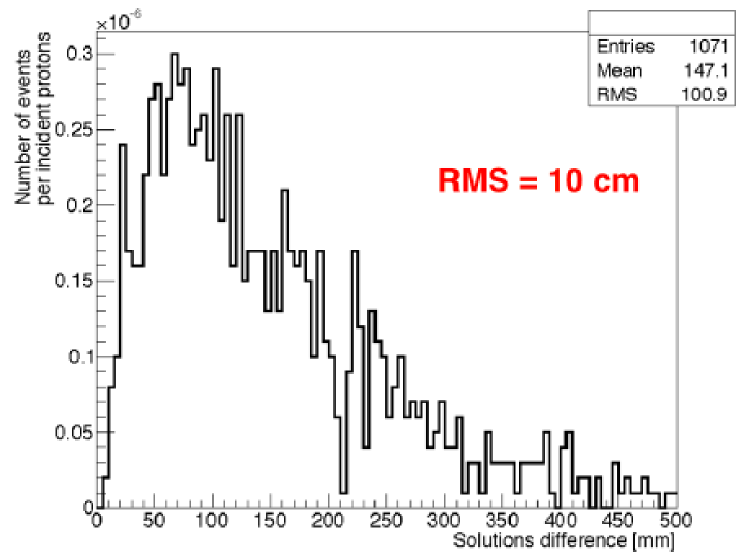
CLaRyS collaboration (IPN Lyon, CPPM Marseille, LPC Clermont, LPSC Grenoble)

Potentially higher detection efficiency than collimated devices

- Beam hodoscope: line-cone intersection



Distance between cone intersections

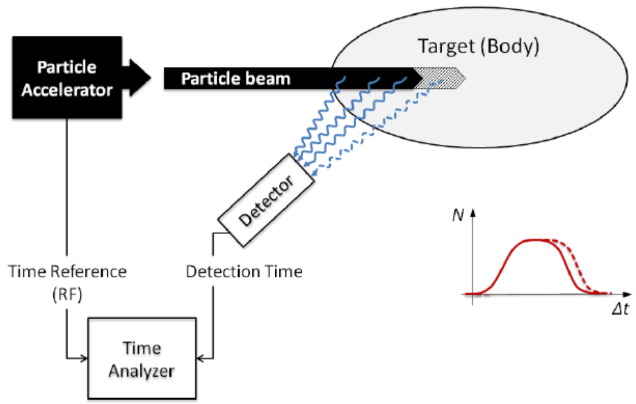


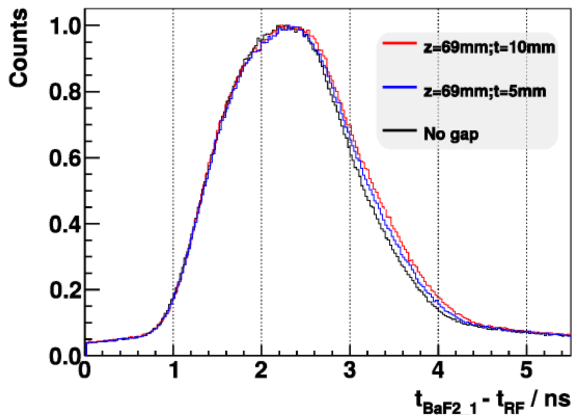
[Ley PhD 2015]

- TOF resolution < 500 ps → real time Compton imaging

Motivation (5/5)
Prompt-gamma counting solutions

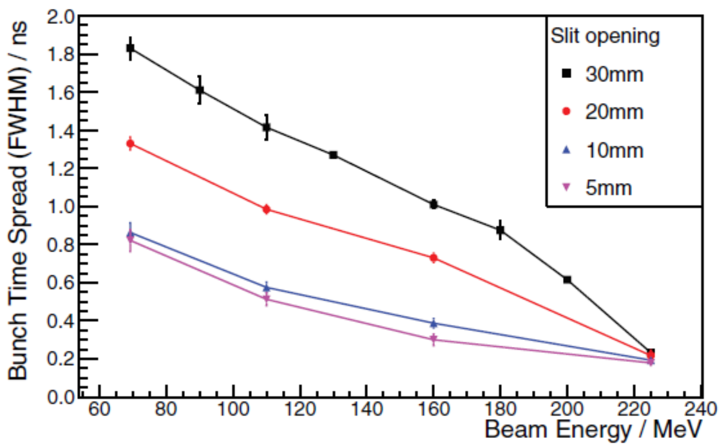
- Prompt-γ timing





[Hueso-Gonsalez PMB 2015]

- Average time and shape related to proton range
- 5mm range shift measurable with single spot
- Requires high timing resolution (< 1ns)
- Limitations:
  - Cyclotrons
  - Bunch time spread



[Petzoldt PMB 2016]

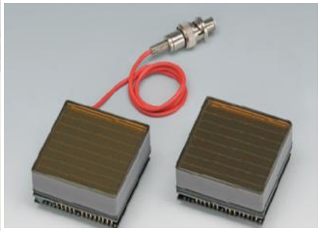
- Prompt-γ Peak Integral **[Krimmer APL 2017]**
  - 2-4 ns time window selection: PG issued from patient
  - Yield depends on energy deposited, beam position

- Both methods would benefit from fast and high-resolution beam-tagging system

Beam tagging hodoscope development : LPSC MoniDiam project (within CLaRyS collaboration)

Existing development (CLaRyS) :

Array of scintillating fibres coupled to multichannel photomultiplier tubes (PMT). Fast readout with μTCA acquisition under test.

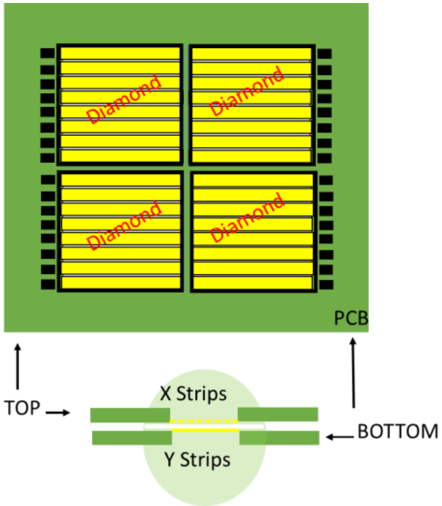


Limitations :

- ❑ Radiation hardness
- ❑ PMT count rate capability (10^7 cps per PMT)
- ❑ Time resolution 500 ps – 1 ns

Foreseen development :

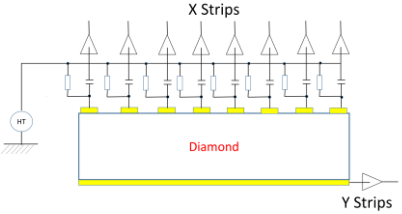
MoniDiam : diamond based hodoscope and its dedicated integrated fast read-out electronics for 100 ps resolution



Diamond Assets :

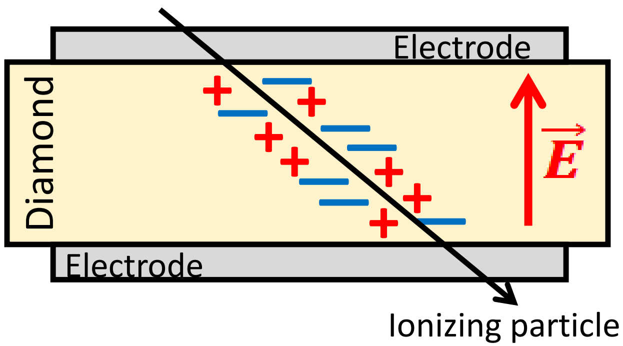
- ❑ Intrinsic radiation hardness
- ❑ Fast signal risetime enables timing precision of a few tens of ps
- ❑ Low noise

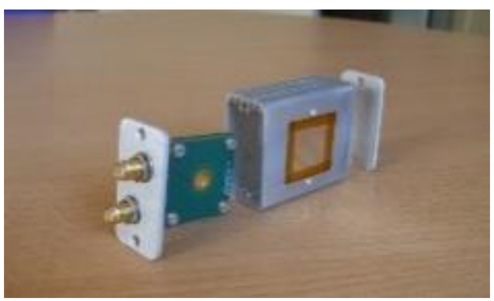
Issues :
- ❑ Cost
- ❑ Availability of large area

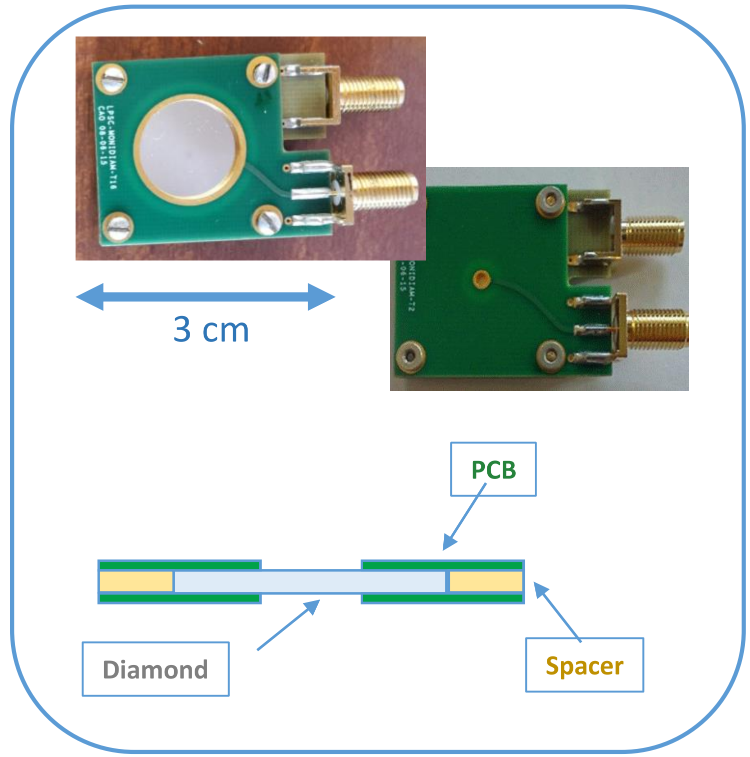


Solution : Assembly of double-side stripped diamond, polycrystalline or DOI

First tests: single disk-shape metallized diamonds

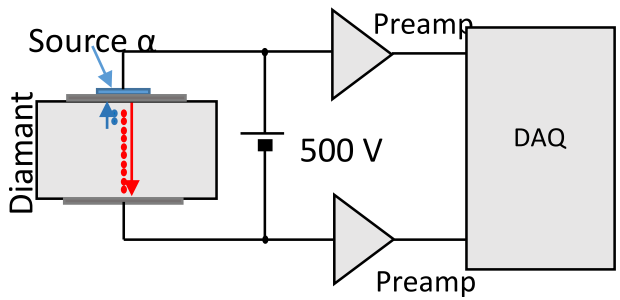


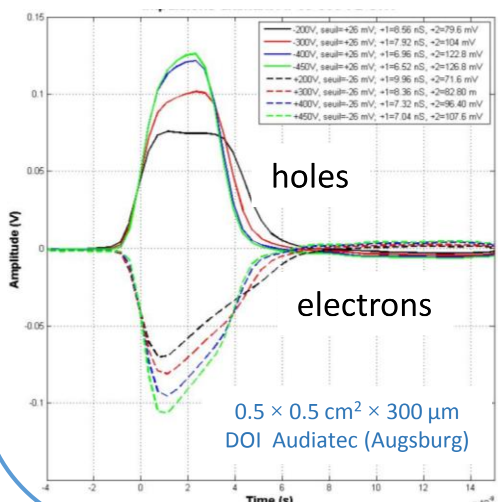




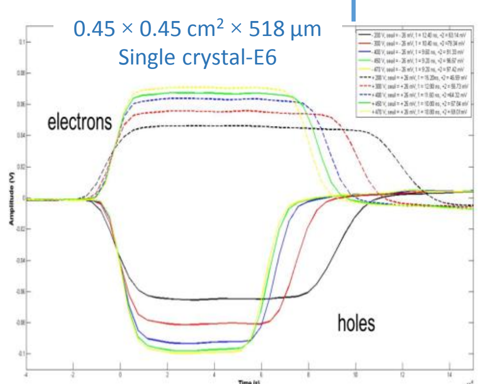
Diamond detector characterization: test benches at LPSC

Alpha source (^{241}Am – 5.4 MeV)



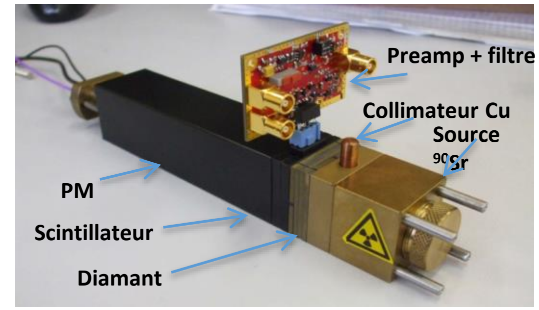


0.5 × 0.5 cm² × 300 µm
DOI Audiatec (Augsburg)

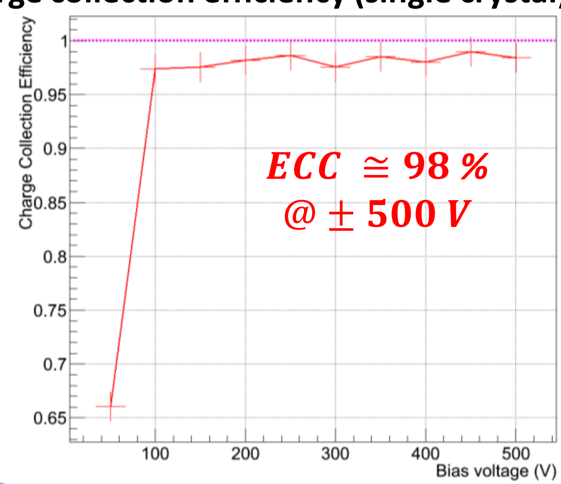


0.45 × 0.45 cm² × 518 µm
Single crystal-E6

Beta source (^{90}Sr)



Charge collection efficiency (single crystal)

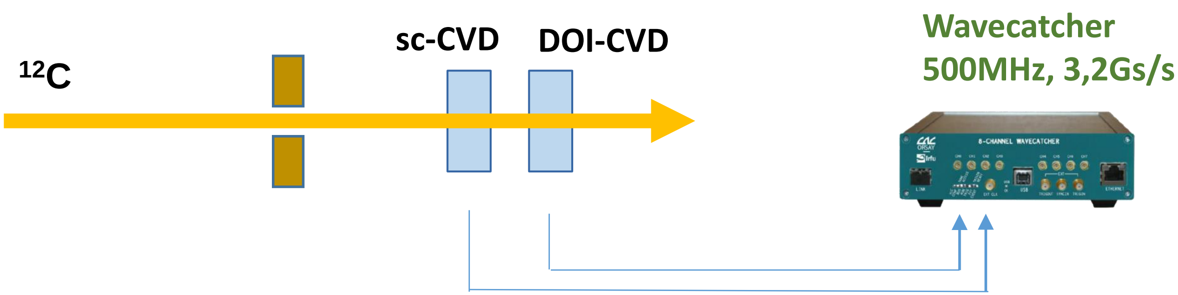


Data acquisition:

Wave catcher 500 MHz
3.2 Gs/s, 8 channels

Wave-runner Lecroy 4GHz
40Gs/s

Beam test at GANIL : 95 MeV/u ^{12}C

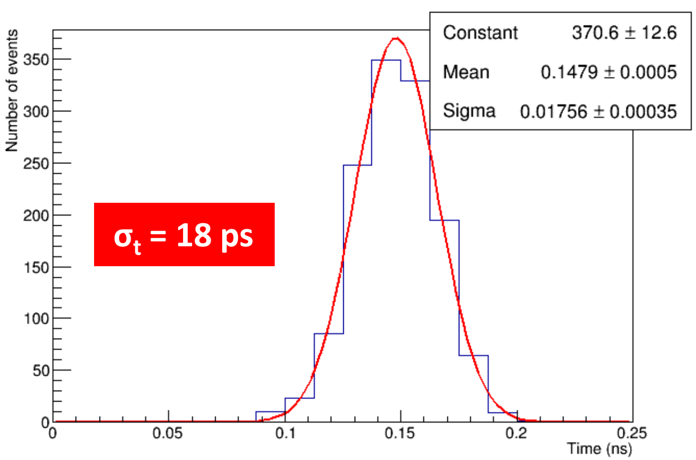


Monocrystalline :
sc-CVD E6 + DBA III
0.45 x 0.45 cm^2 x 518 µm

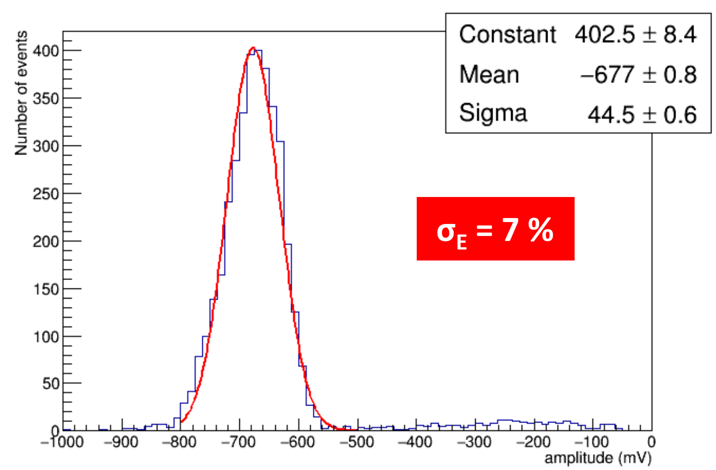
Hetero-epitaxial :
DOI-CVD Audiatec + Cividec C2
0.5 x 0.5 cm^2 x 300 µm

Deposited energy ~40 MeV

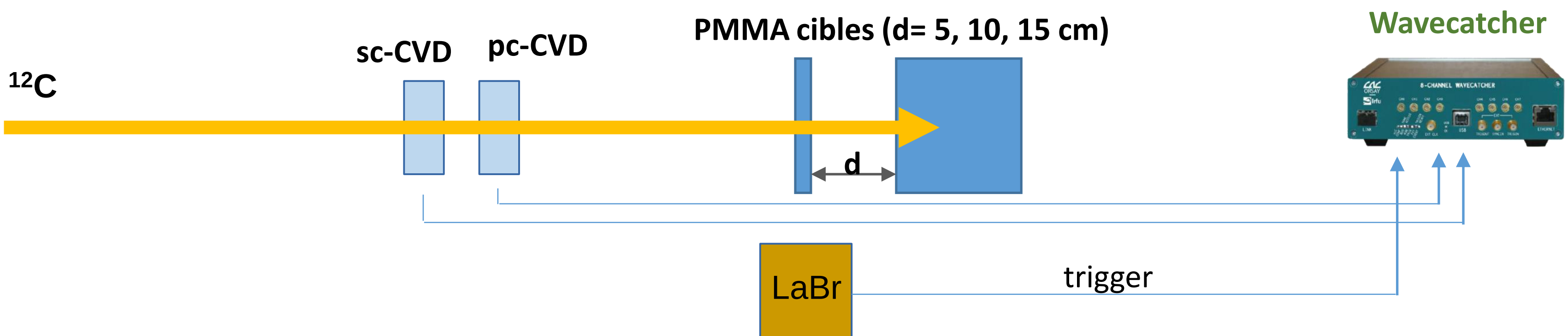
Timing resolution Mono vs DOI



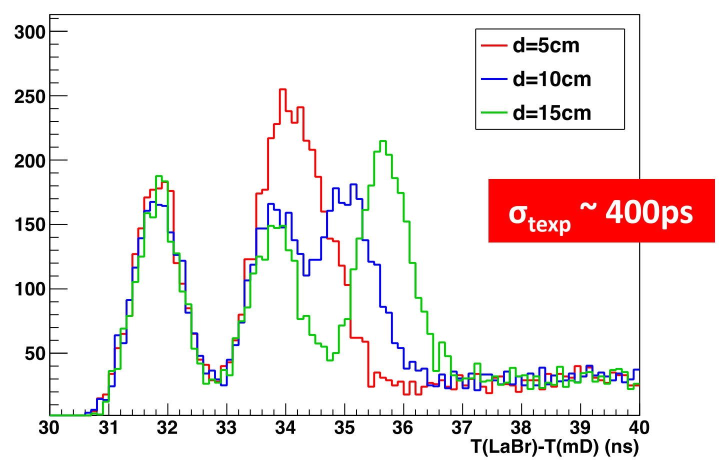
Energy resolution DOI

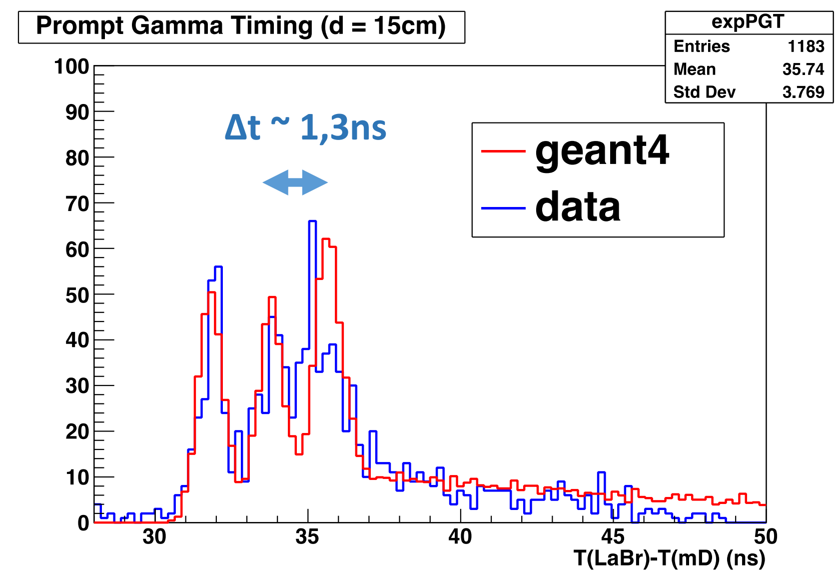


Beam test at GANIL : Time of flight measurements



Simulation G4 :
TOF distribution LaBr vs. sc-CVD E6

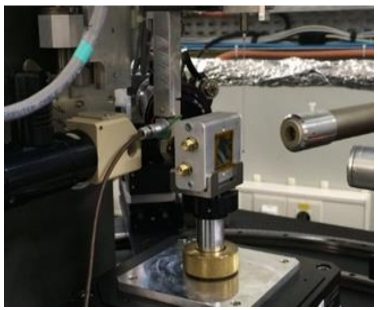




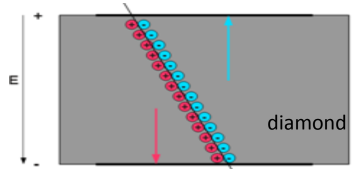
Beam test at ESRF : XBIC source at 8.5 keV

ESRF The European Synchrotron

Continuous energy deposit (0 to 4 MeV)

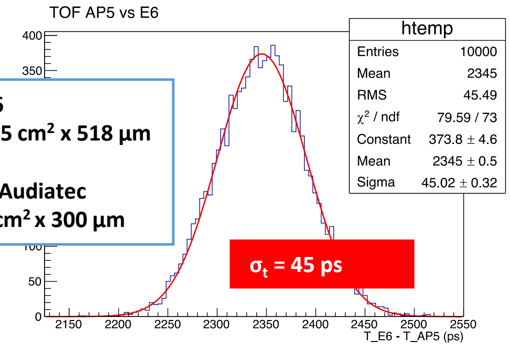


Spot ~ 1 um
~ 1500 photons/bunch
Bunch width = 100ps



Ionizing particle

Timing resolution



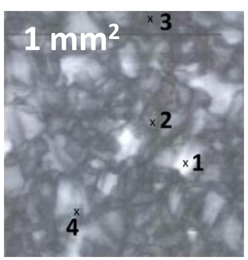
sc-CVD E6
0.45 x 0.45 cm² x 518 µm

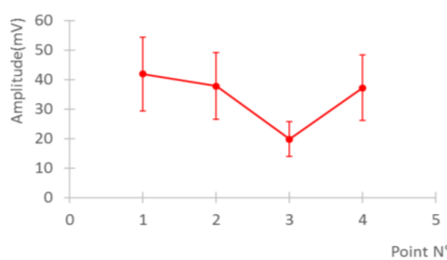
DOI-CVD Audiatec
0.5 x 0.5 cm² x 300 µm

σ_t = 45 ps

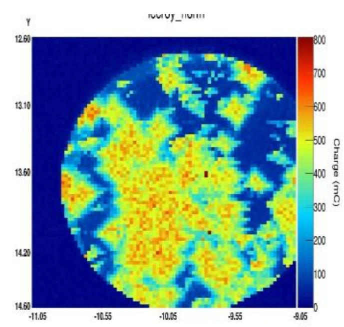
Current response map

Poly-crystalline





10 x 10 mm² x 500 µm pc-CVD



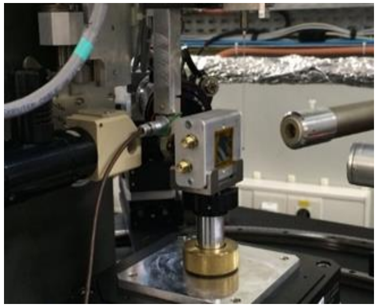
DOI

Non-homogenous response

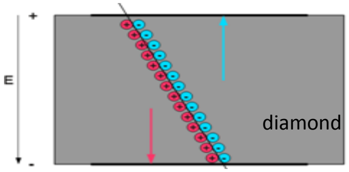
5 × 5 mm² × 300 µm DOI-CVD

Beam test at ESRF : XBIC source at 8.5 keV

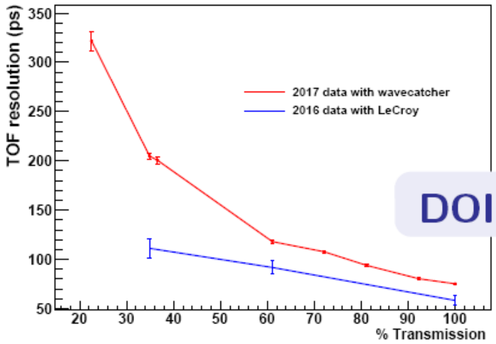
Continuous energy deposit (0 to 4 MeV)



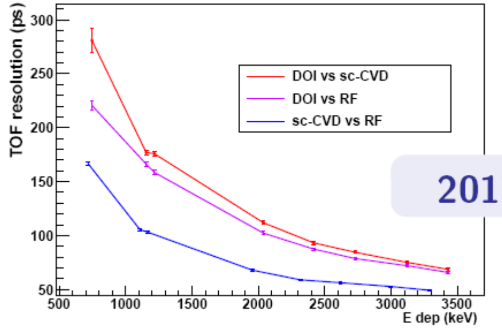
Spot ~ 1 um
~ 1500 photons/bunch
Bunch width = 100ps



Time resolution

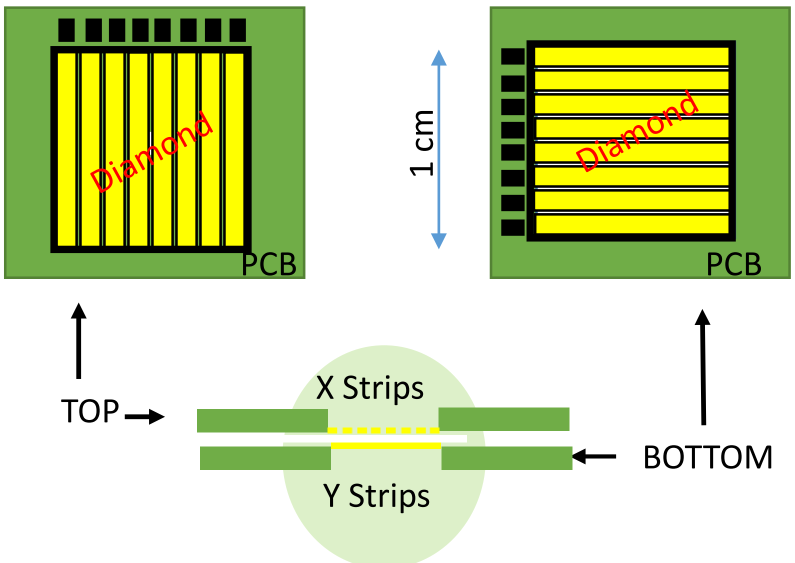


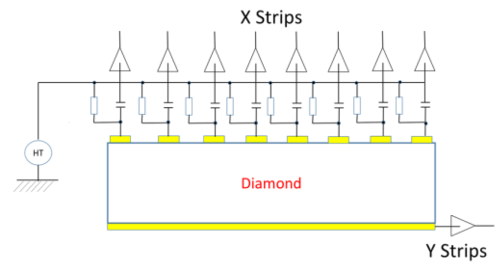
TOF resolution: DOI vs sc-CVD

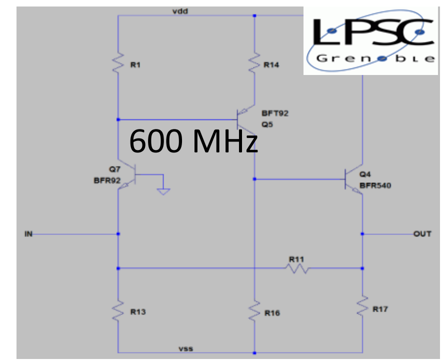


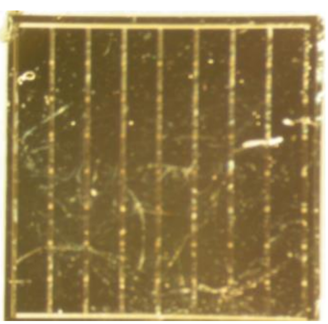
Although noisy conditions in 2017
100 ps resolution reasonable

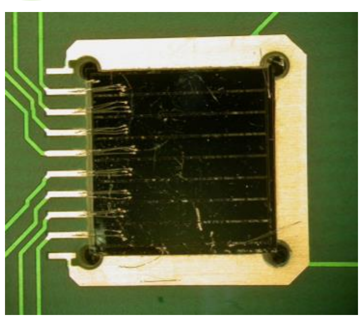
Stripped diamond characterization

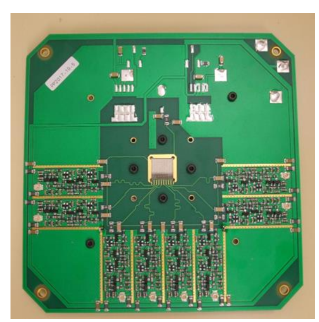


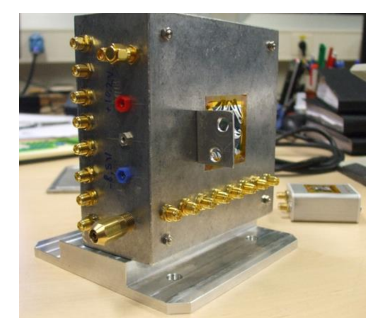












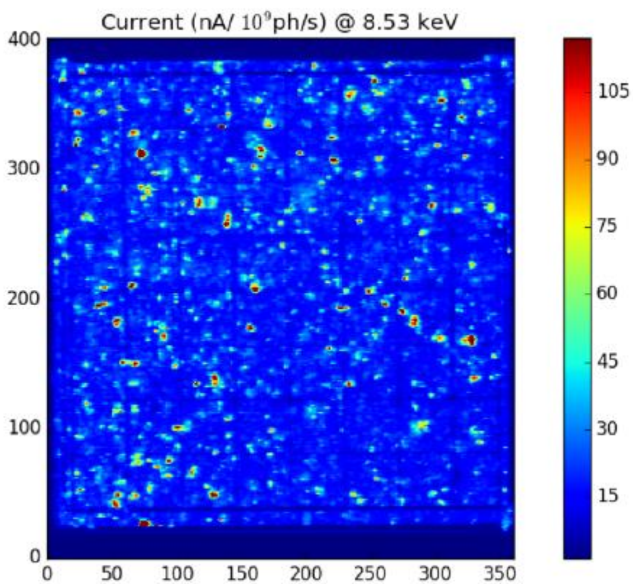
NANOFAB Neel Institut Grenoble
100 nm Al deposition by UV lithography
Wire bonding

LPSC Grenoble
PCB design
Current preamplifier
Detector assembly

Beam test at ESRF : XBIC source at 8.5 keV

Surface Analysis

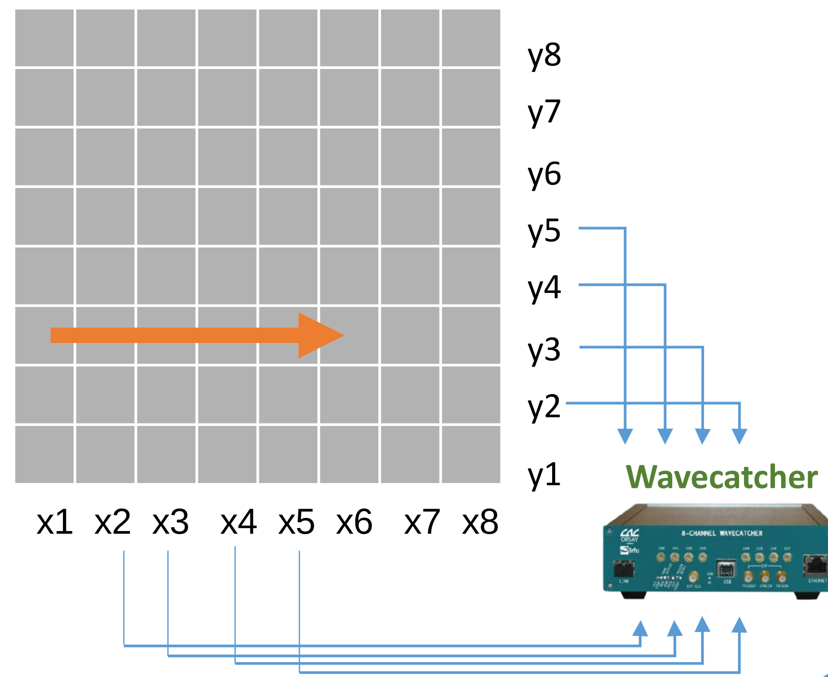
Current-integration mode



$1 \times 1\ \mathrm{cm}^2 \times 300\ \mu\mathrm{m}$

pc-CVD from Element 6

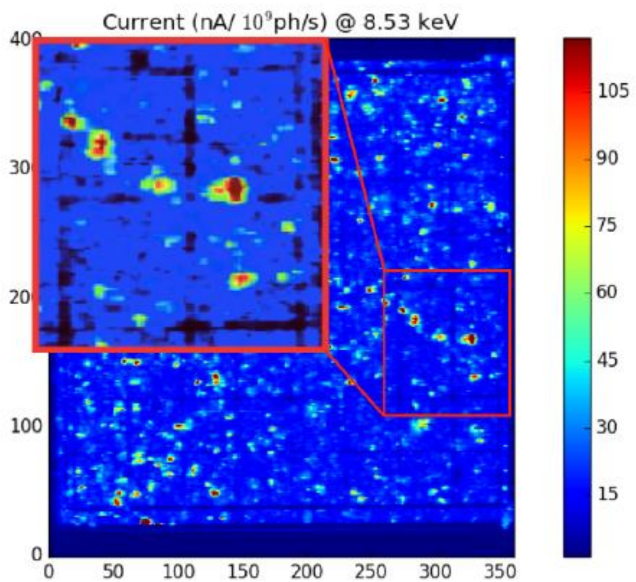
XBIC detecteur scan (100 µm step)



Beam test at ESRF : XBIC source at 8.5 keV

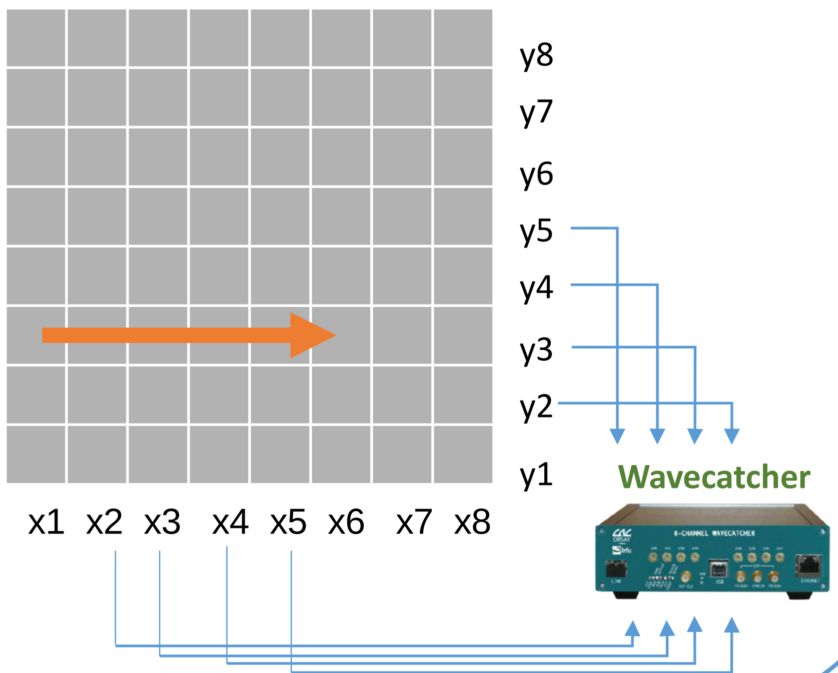
Surface Analysis

Current-integration mode



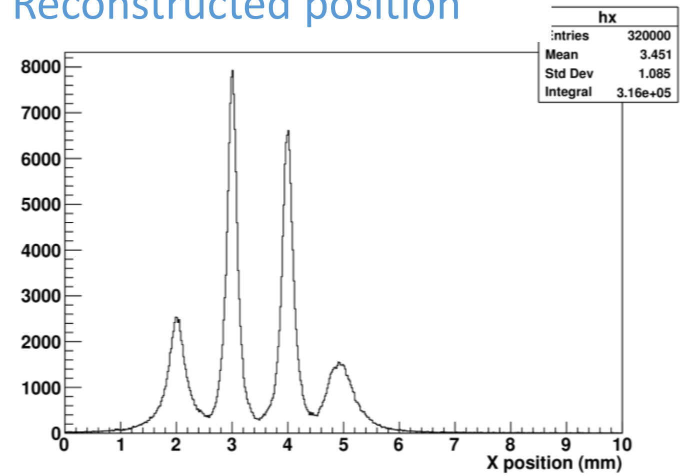
$1 \times 1\ cm^2 \times 300\ \mu m$
pc-CVD from Element 6

XBIC detecteur scan (100 µm step)

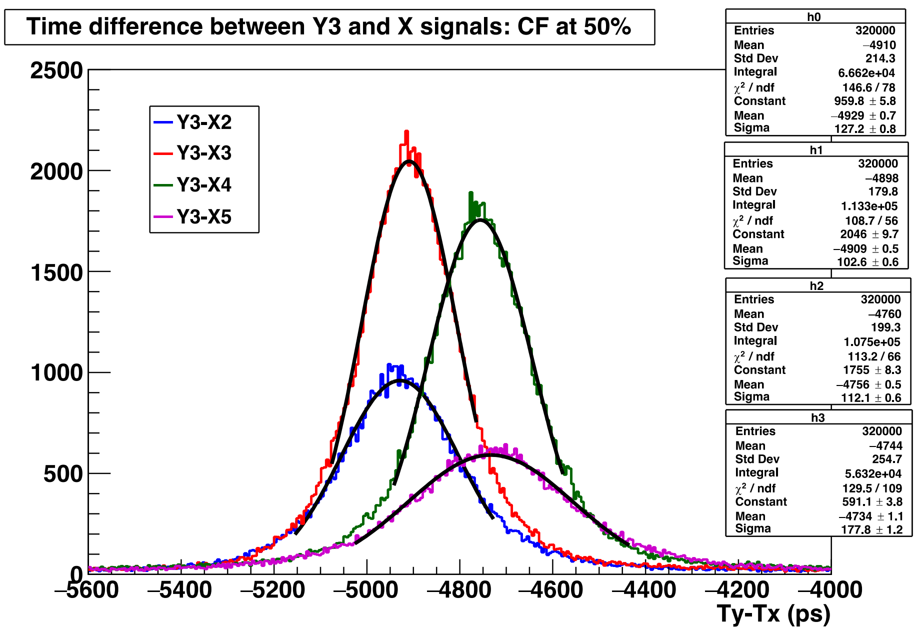


First results

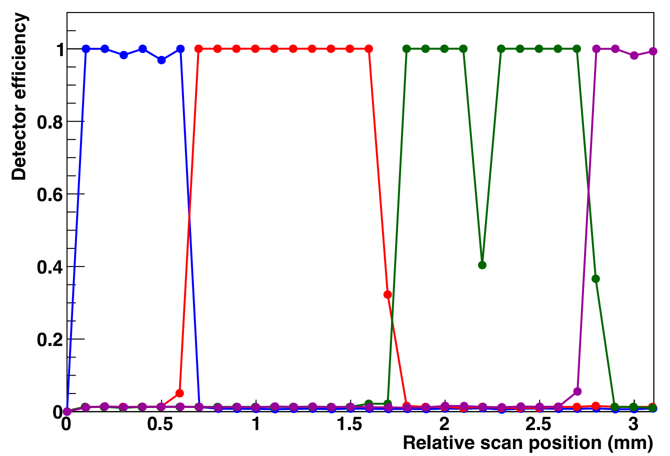
Reconstructed position



Timing resolution



Detection efficiency

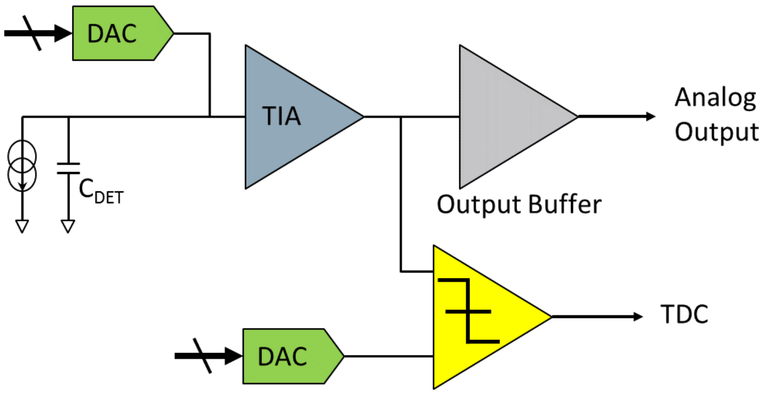


Best result: σ_t = 103 ps

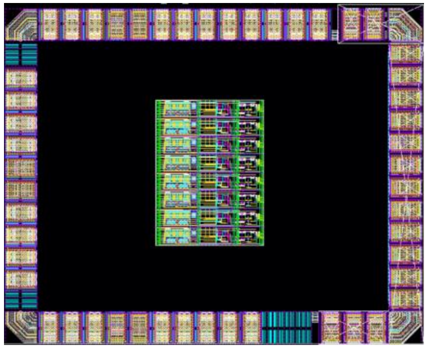
Front-End Electronics

- 130nm CMOS TIA + Fast Discriminator
  - Radhard technology
  - Wide bandwidth, Low noise TIA
  - 8 channels, submitted January 2018

TIA Parameters	Value
A_0	> 60 dB
F_{-3dB}	1.2 GHz
Z_{in}	20 – 50 Ω
$V_{n,out}$ (output noise)	< 1 mV_{RMS}
Input Dynamic range	3 µA – 120 µA (<1% linearity)



1 channel FEE



1.485 x 1.2 mm^2

Conclusion

- Characterization of the performances of small and medium size detectors with sources, ions, and synchrotron
- Multi-strip detectors: a first prototype of 1 cm^2 has been developed and tested with discrete electronics
- Micro-electronics readout under development (technical collab. with LPC-Caen)
- Framework:
  - Local: ESRF, NEEL, ILL:
    local pole for detector and electronic devices
    crystal processing and characterization
  - National: LSPM, IPHC, CEA-LIST and CLaRyS collaboration (+CAL-Nice, Arronax…)
  - International: RD42

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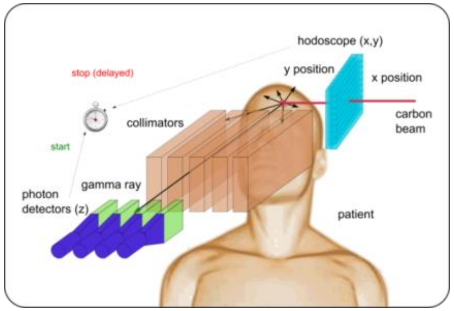
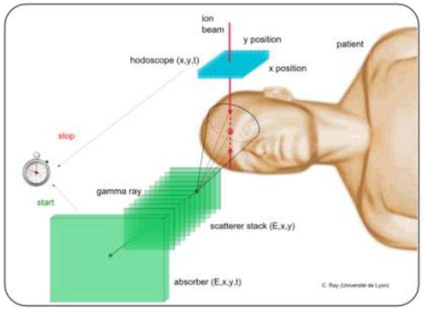
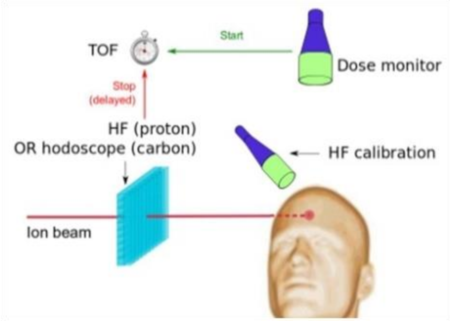
Spares

Hodoscope faisceau :
un outil commun d’étiquetage spatial et temporel

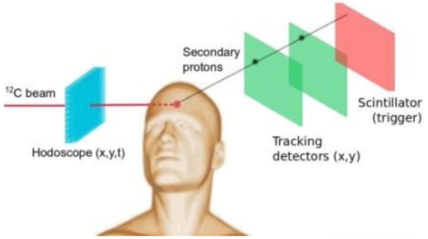
- Gamma prompts (détection avec temps de vol)







•Imagerie de vertex protons secondaires



•Radiographie protons