# Fast diamond beam monitors for online control of the treatment in proton and carbon therapies

ML Gallin-Martel[1], et al.

on behalf of the CLARYS, DIAMANT - IN2P3 collaborations

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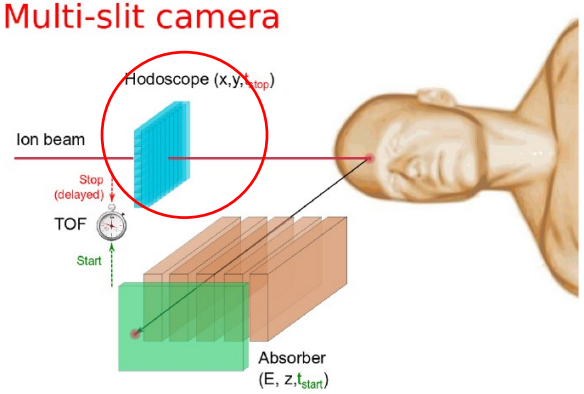
# Context

*In vivo* monitoring from the use of secondary emissions

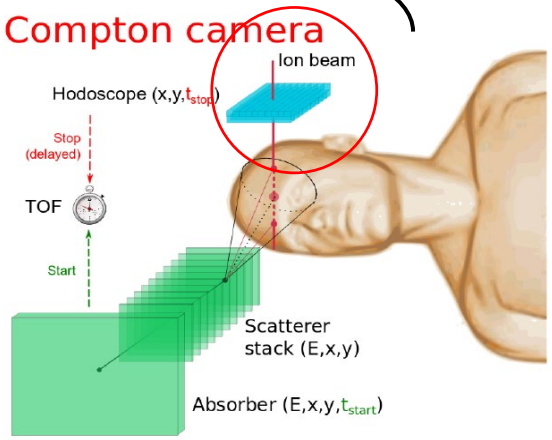
Improvement of treatment planning

## Prompt Gamma Imaging

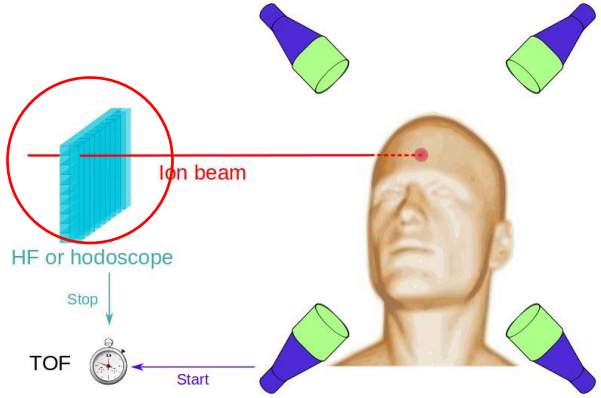
### Multi-slit camera



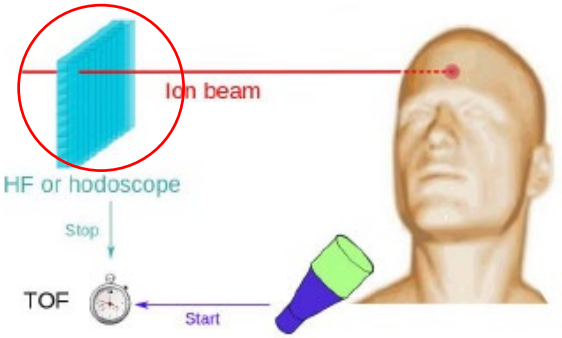

### Compton camera



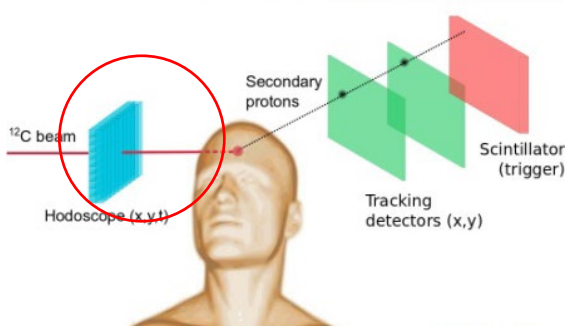

## Prompt Gamma Peak Integral



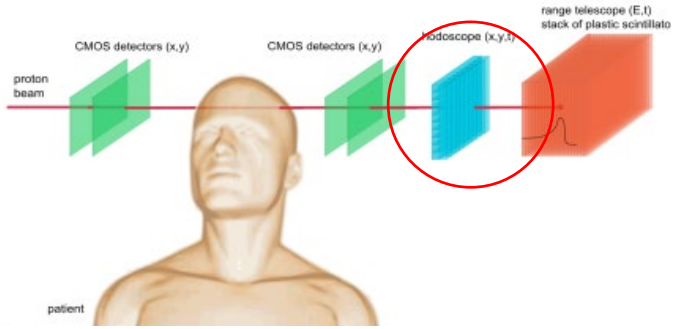

## Prompt Gamma Time Imaging




## Secondary proton vertex imaging in carbon therapy




## Proton radiography




# Beam tagging hodoscope development

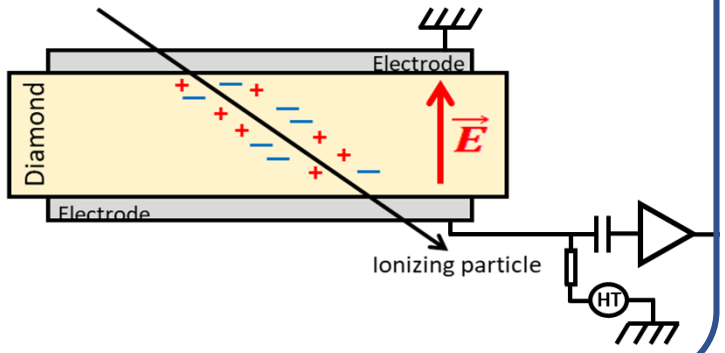
# Diamond as beam tagging monitors

## Diamond a wide-bandgap semiconductor

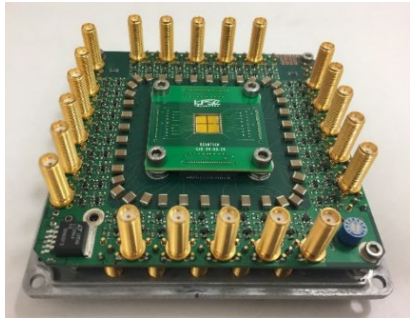
| | Diamond | Silicon | SiC |
|---|---|---|---|
| Undoped material resistivity (Ω.cm) | $> 10^{13}$ | $2.3 \cdot 10^{5}$ | $> 10^{5}$ |
| Bandgap (eV) | 5.5 | 1.1 | 3.26 |
| Pair creation energy $e^-/h^+$ (eV) | 13.1 | 3.6 | 7.8 |
| Displacement energy (eV) | 43 | 25 | 20 - 35 |
| Carrier mobility ($cm^2.V^{-1}.s^{-1}$) | > 2000 | 800 – 1400 | 115 - 1000 |
| Thermal conductivity ($W.cm^{-1}.K^{-1}$) | 20 | 1.5 | 1.2 |

→ **Very low leakage current**
→ **Low noise**
→ **Radiation hard**
→ **Fast timing**
→ **Room temperature**

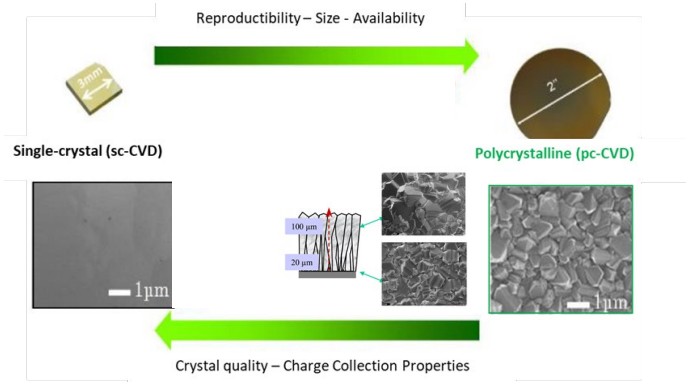
## Solid-state ionizing chamber



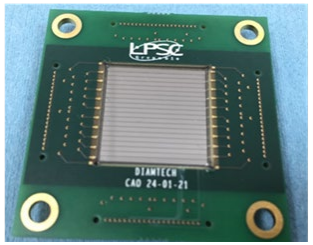

## Diamond beam monitor for hadrontherapy



4 sCVD = 1cm²
32 channels




N. Vaissiere PhD thesis https://tel.archives-ouvertes.fr/tel-01022652



1 pCVD = 4cm²
40 channels

**LPSC Hodoscope prototype 42 channels + Front End electronic (fast preamplifiers) developped at LPSC**

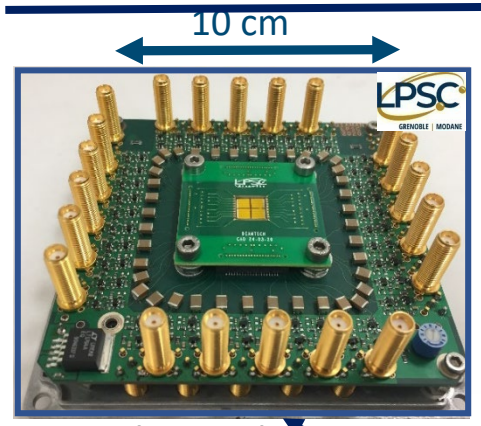
## Beams specifications

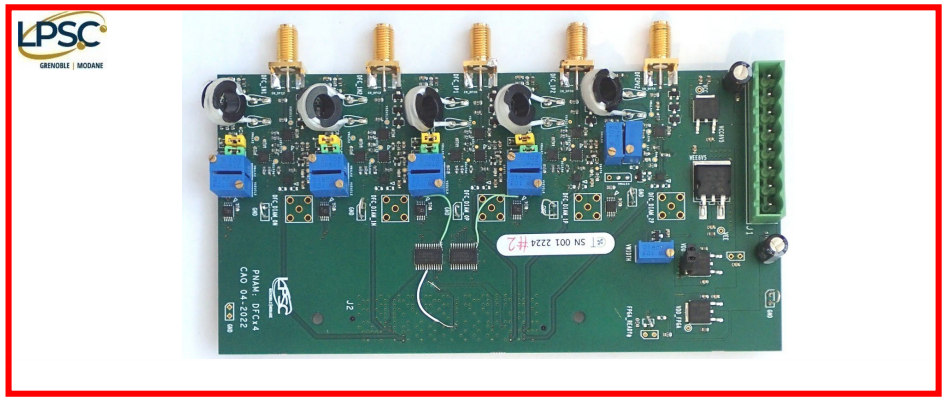
- **Proton therapy** (Cyclotron IBA/C230 Orsay, Dresden…):
  - Bunch: 1-2 ns
  - HF : 100 MHz
  - 200 protons/bunch
- **Proton therapy** (Synchro-cyclotron Nice S2C2):
  - Bunch: 7 ns (16 ns)
  - Train: 4 µs (1 ms)
  - $10^4$ protons/ micro-bunch
- **Carbone therapy** (HIT):
  - Bunch: 20-40 ns
  - Bunch interval: 200 ns
  - 10 ions/bunch

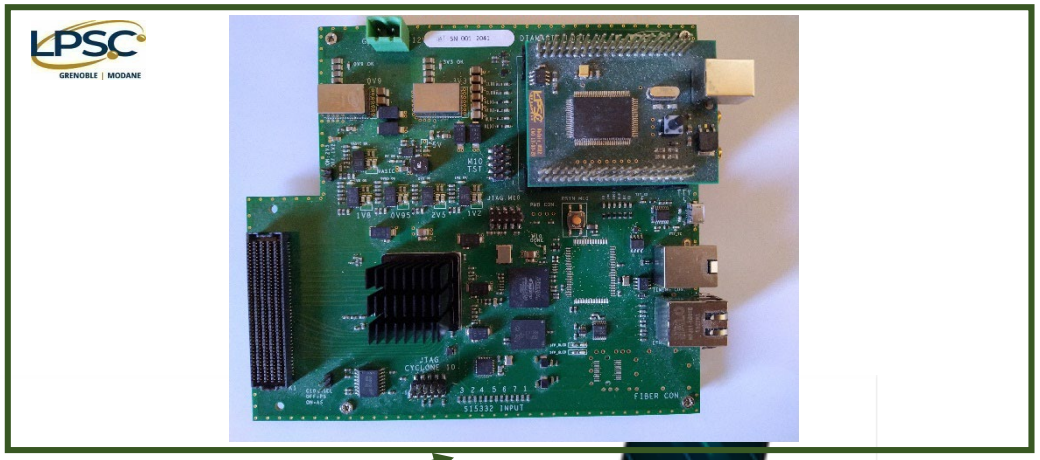
## Beam tagging hodosope specifications

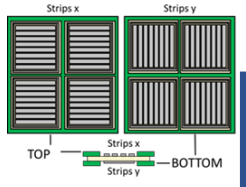
- **Counting rate:**
  - 100 MHz for the whole detector
  - ~10 MHz per channel
- **Time resolution:**
  - At the level of 100 ps
- **Spatial resolution:**
  - 1mm (readout strip)
- **Radiation hardness:**
  - $10^{11}$ protons/cm²/treatment, about 20 treatments a day =>$10^{14}$ protons/cm²/year

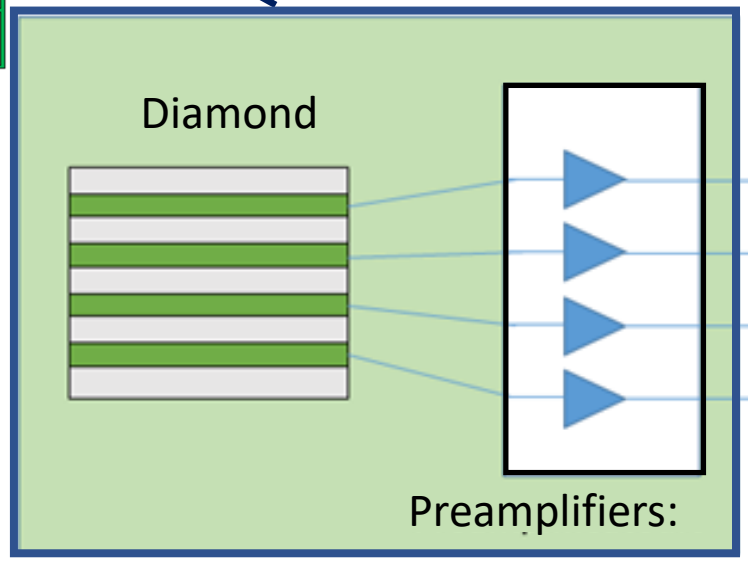
# Diamond Beam Tagging monitor





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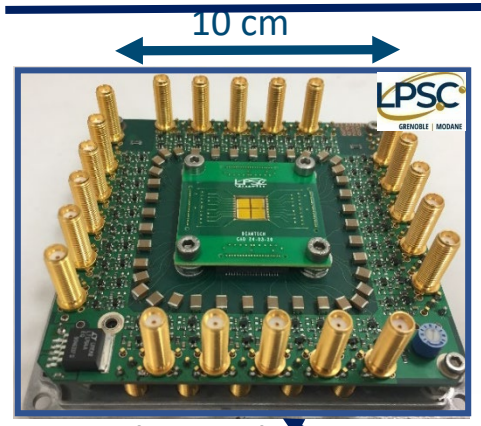
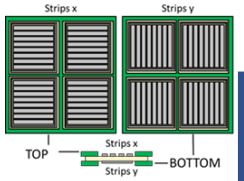
https://doi.org/10.1088/1748-0221/16/04/T04005

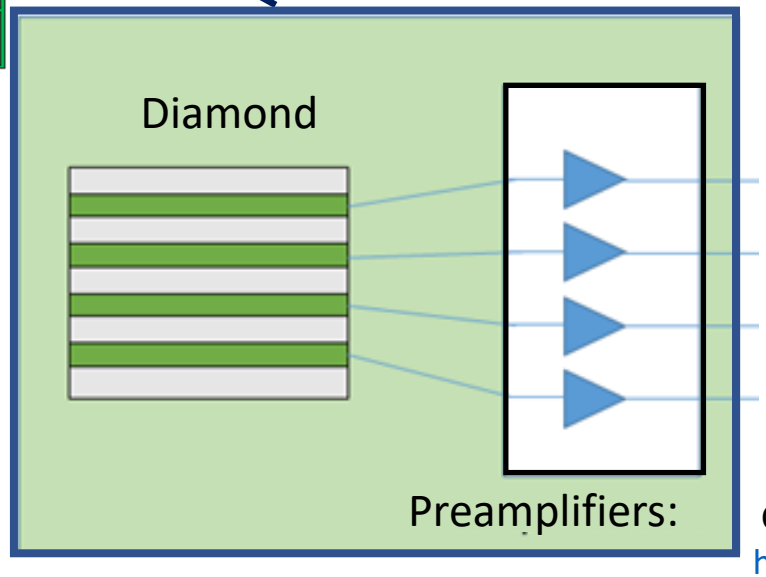
P. Everaere PhD thesis, Labex PRIMES

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

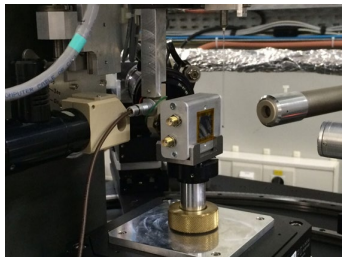
# The active volumes and the Front End (FE) electronic

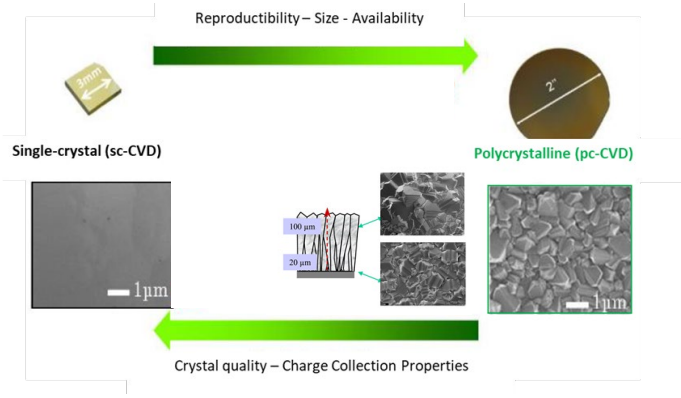


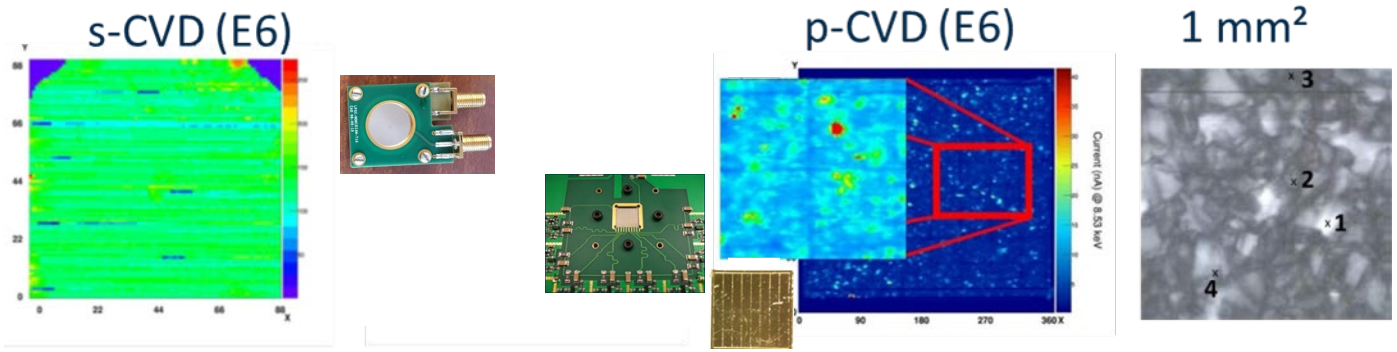










**XBIC = X rays Beam Induced Current**
**@ ESRF (France) : Photons 8.5 keV** **=> 2D « current maps » with CVD diamonds**




*ML Gallin-Martel Diamond and related materials 112 (2021) 108236*

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P. Everaere PhD thesis, Labex PRIMES

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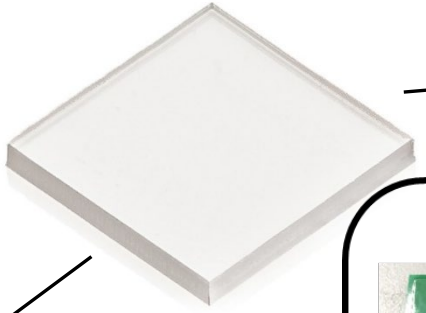
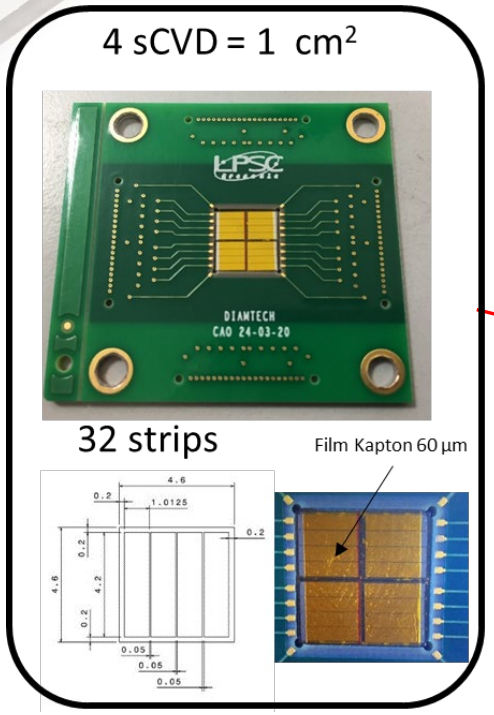
# 1rst Active volume: sCVD diamond

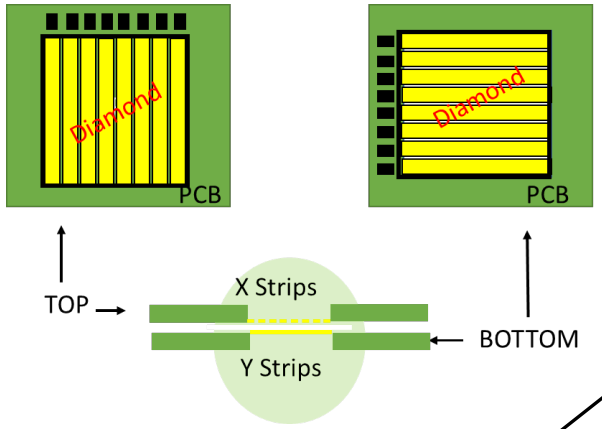
## Detector assembly

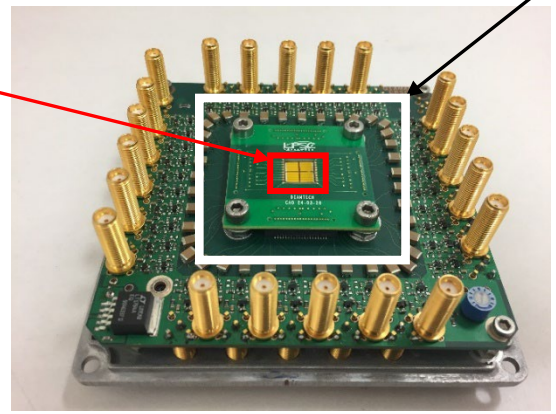


Diamond strip metallized

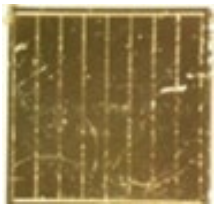
sCVD = Single crystal



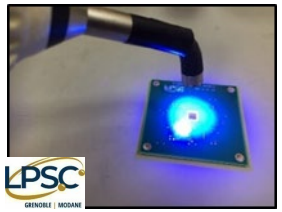



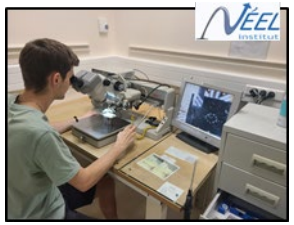
Strip metallisation Laser Lithography



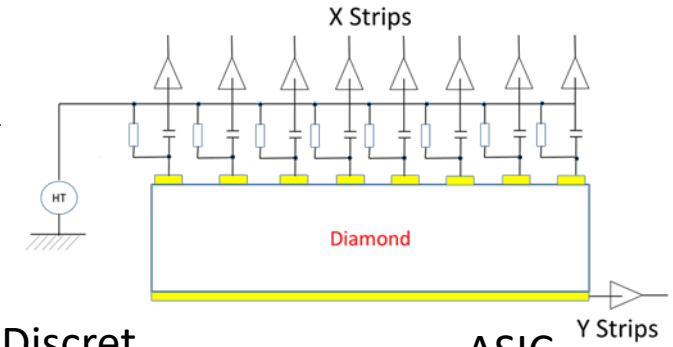
Diamond on PCB



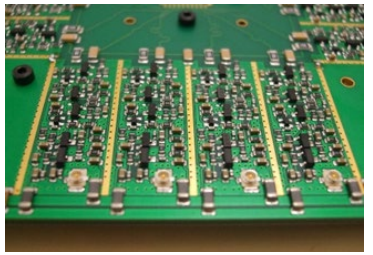
Wire bonding



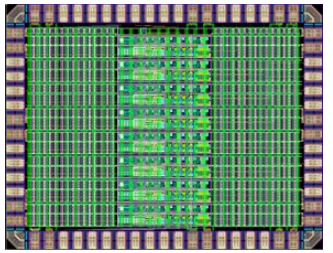
## Read out electronics (ROE)




Discret



ASIC



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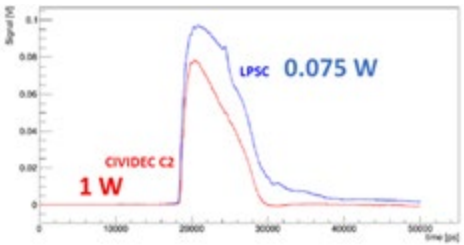
https://doi.org/10.1088/1748-0221/16/04/T04005

Front – end electronic developed at laboratory

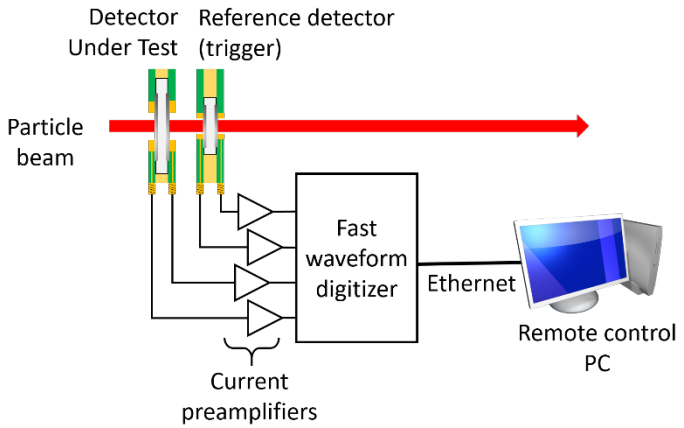


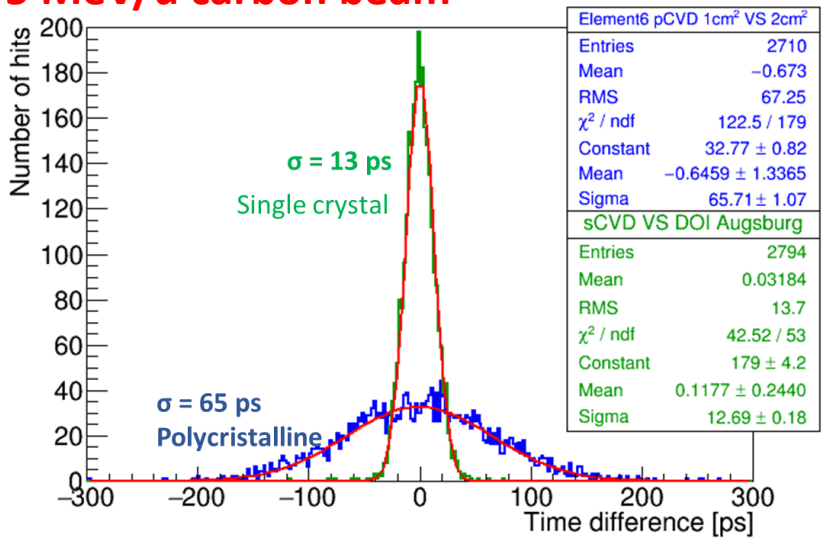


| | |
|---|---|
| Band Width: | 2 GHz |
| Gain: | 40 dB |
| Impedance: | 50 Ω |
| Dynamic range: | ~ +/- 1 V |
| Power Supply: | 12 V / 100 mA |

# 2nd Active volume: pCVD diamond

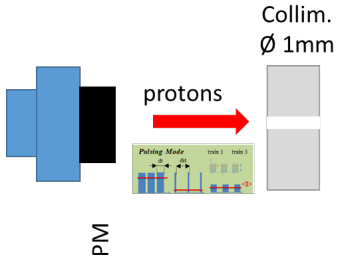
## Beam tests in GANIL with 95 MeV/u carbon beam

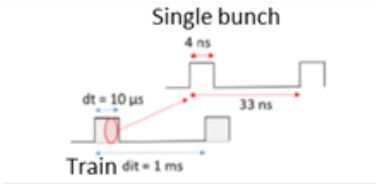


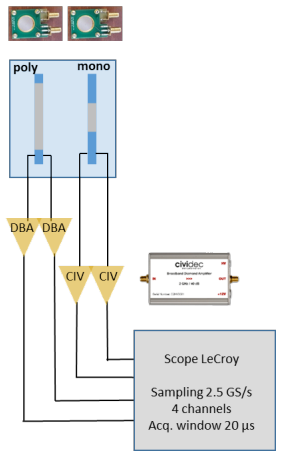



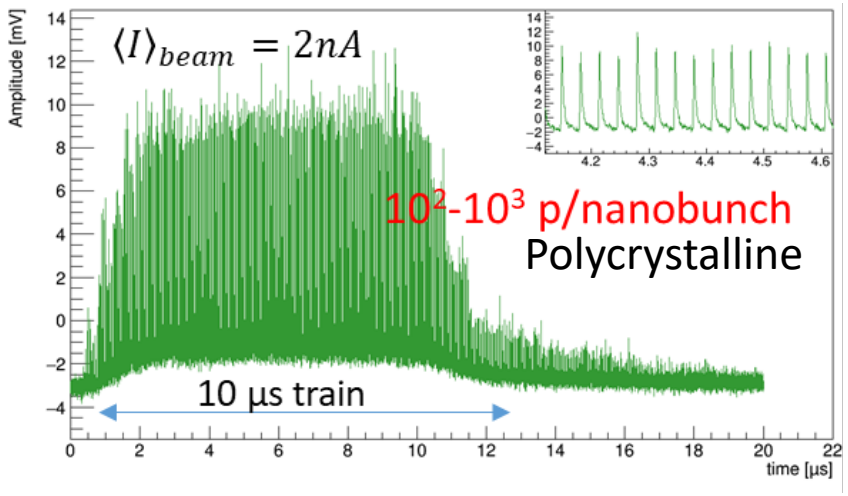

S. Curtoni et al, NIM A, Elsevier,2021, 1015, pp.165757. ;10.1016/j.nima.2021.165757

## Beam tests in ARRONAX with 70 MeV proton beam



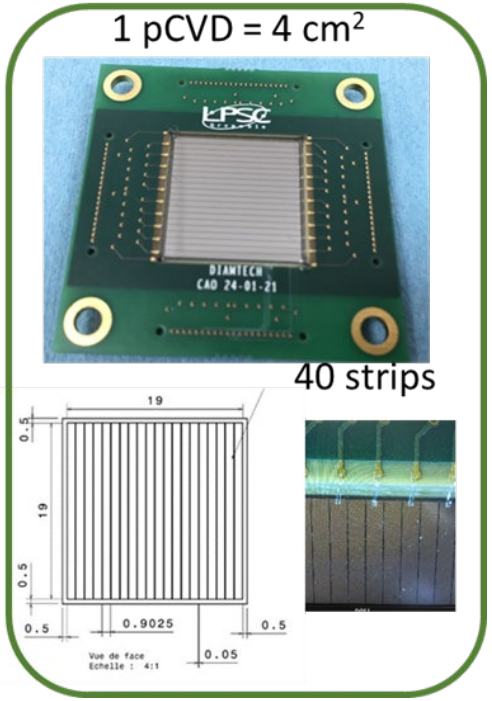



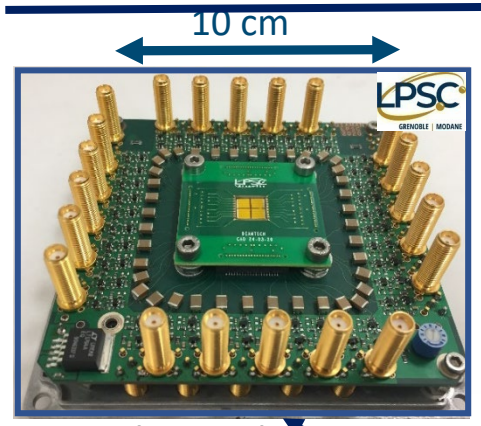

Polycrystalline diamond (pCVD)

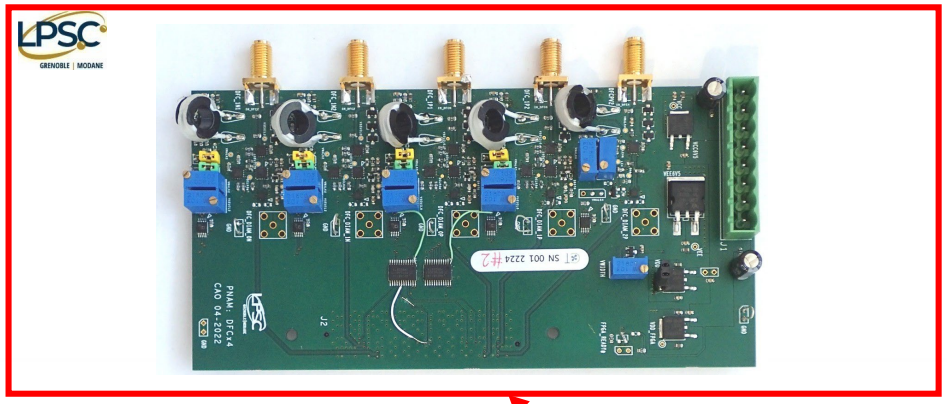
- Large available surface 20 x 20 mm²
- Intrinsic radiation hardness
- Time resolution <100 ps
- High rate particle counting capabilities up to clinical intensity

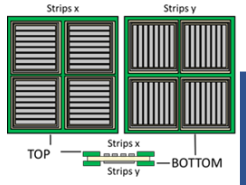



**Designed to be used right now with carbon ions**

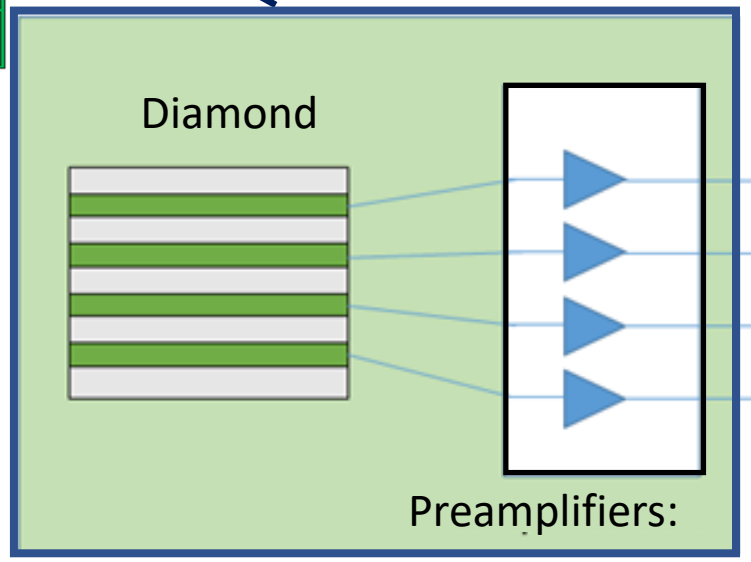
# Diamond Beam Tagging monitor and the Read Out Elec.



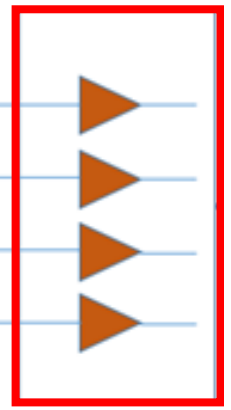






**Beam Monitor**

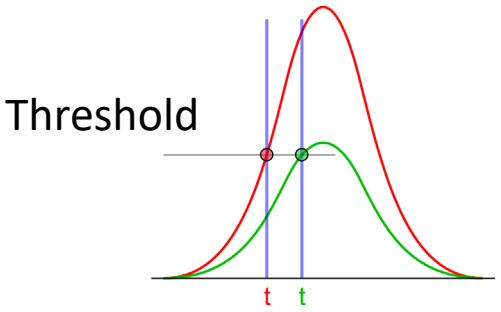



CFD Board

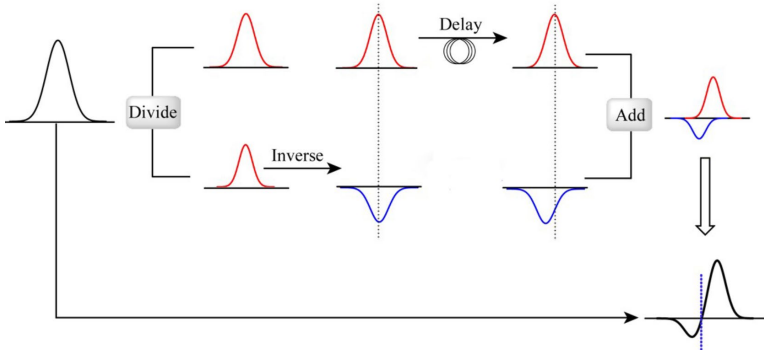


**CFD = Constant Fraction Descriminator**

Preamplified diamond signal




**Principle**




**=> time stamp independant of diamond signal amplitude**

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https://doi.org/10.1088/1748-0221/16/04/T04005

P. Everaere PhD thesis, Labex PRIMES

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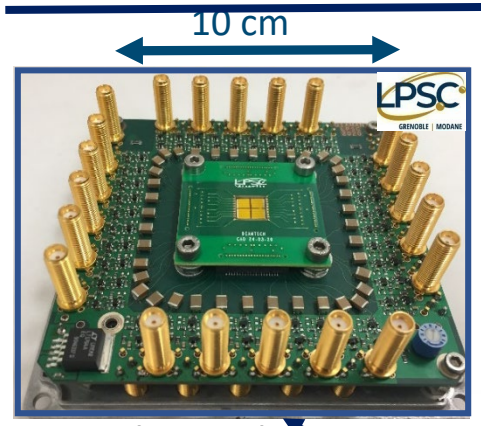
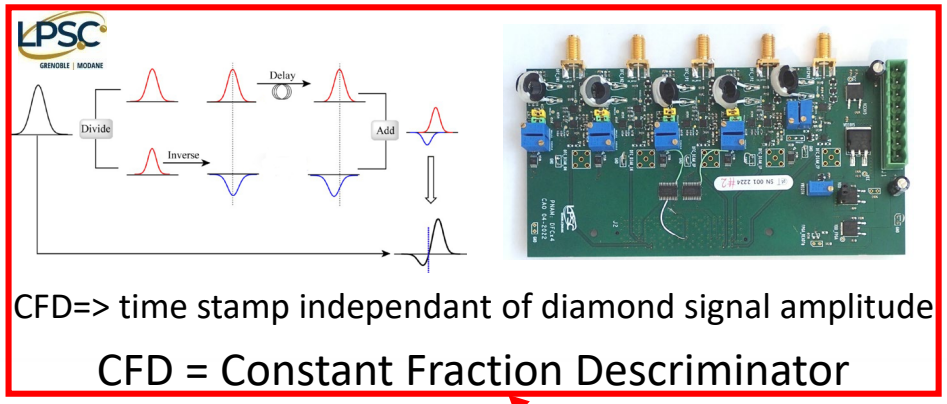
# Diamond Beam Tagging monitor ROE and DAQ




CFD=> time stamp independant of diamond signal amplitude

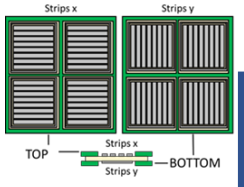
CFD = Constant Fraction Descriminator

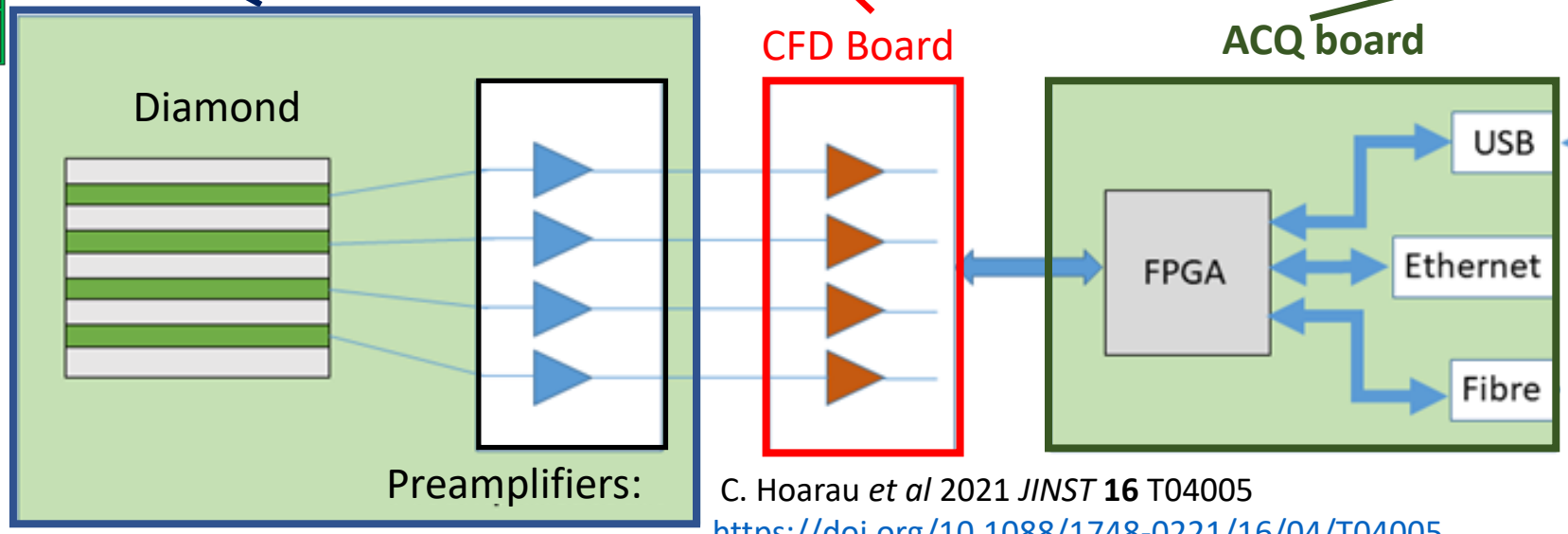

2021 ASIC CMOS 130 nm

12,5 ps RMS

R&T DIAMASIC

TDC = Time Digital Converter

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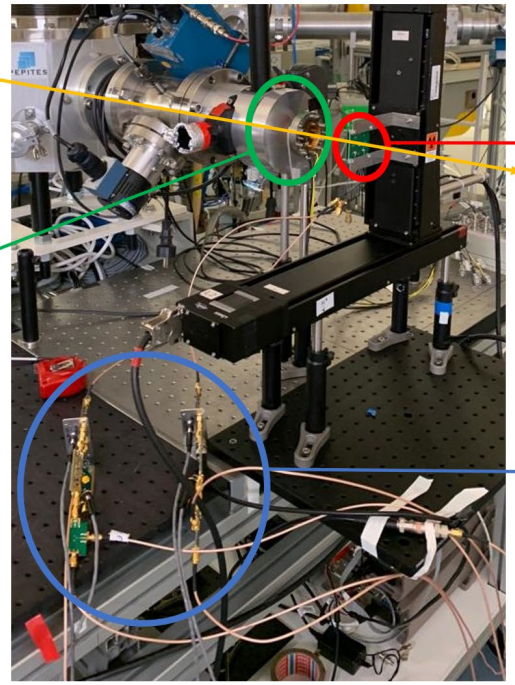
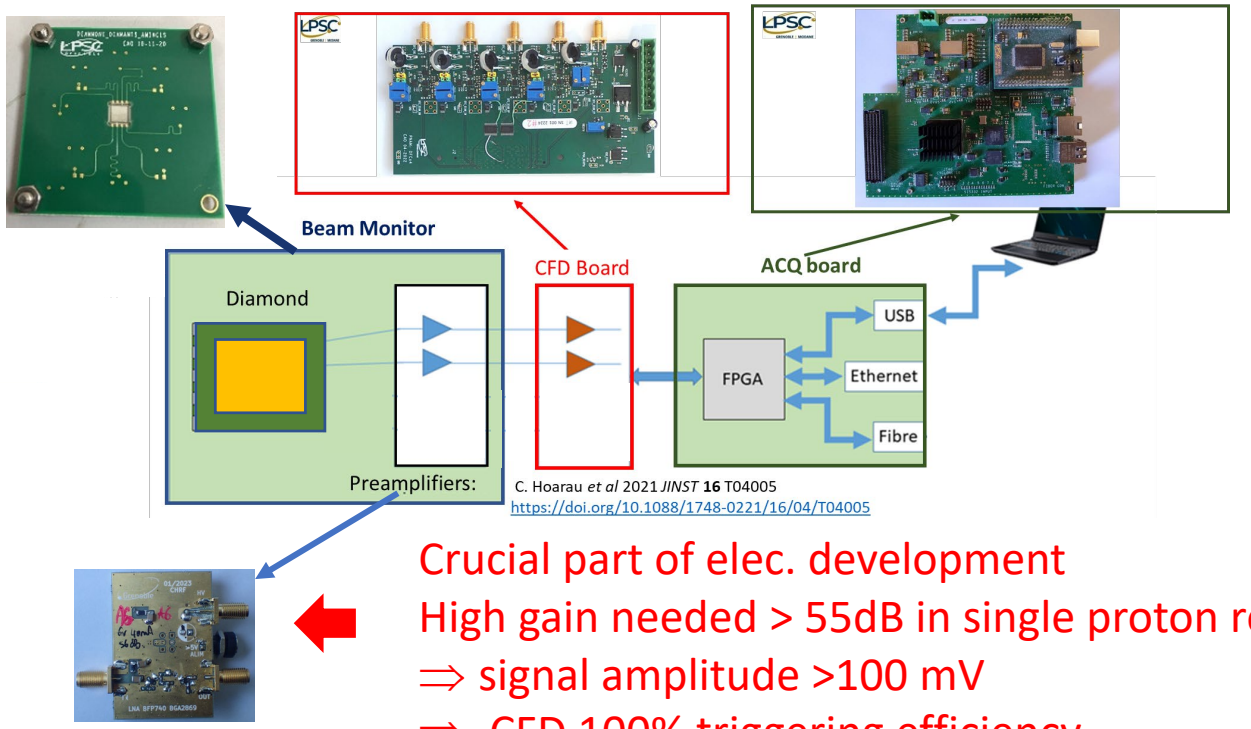
https://doi.org/10.1088/1748-0221/16/04/T04005

P. Everaere PhD thesis, Labex PRIMES

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

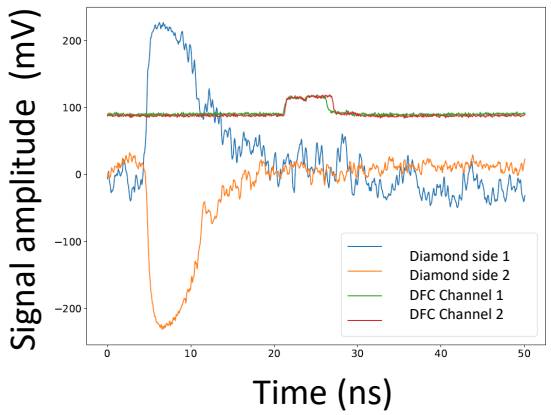
# Proof of concept: 70 MeV proton in single particle regime

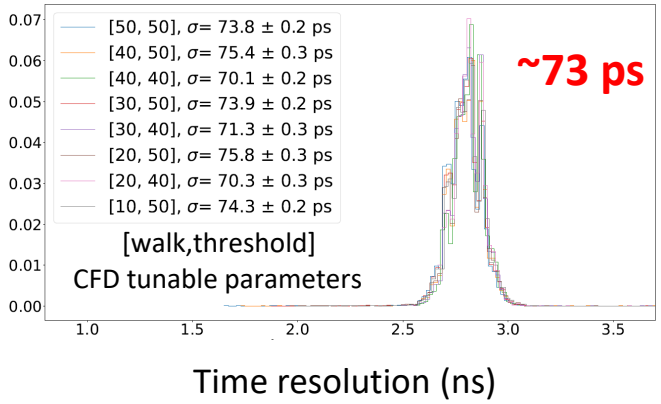



C. Hoarau *et al* 2021 *JINST* **16** T04005
https://doi.org/10.1088/1748-0221/16/04/T04005

Crucial part of elec. development
High gain needed > 55dB in single proton regime
⇒ signal amplitude >100 mV
⇒ CFD 100% triggering efficiency




**Time resolution ~73 ps diamond sCVD + whole ROE with 70 MeV protons in single particle regime**

# Conclusion

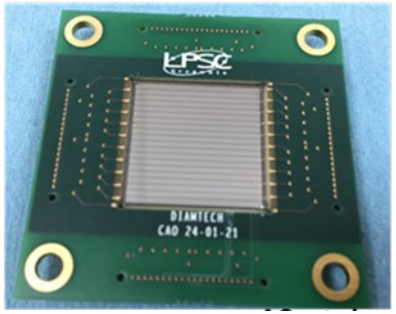
**Diamond board**

4 sCVD

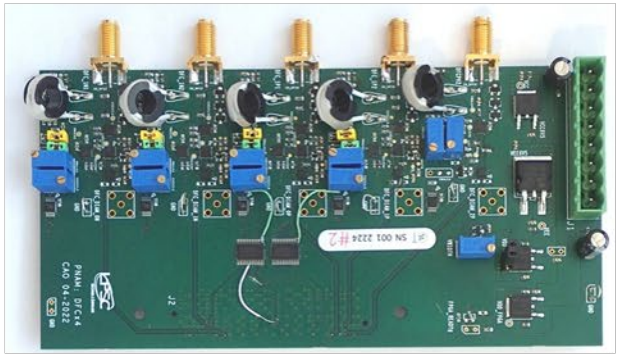
4,5 x 4,5 x 500 µm

1 pCVD

2,0 x 2,0 x 300 µm




**CFD board**



**TDC board**

⇒ Beam tagging monitor developed using diamond technology + ROE electronic developed at laboratory

⇒ Can be used with ions to **provide clinical mm and ~100 ps spatio-temporal labeling**

⇒ **16 cm² sensitive surface** can be reached using polycrystalline diamond sensors **in a 2 x 2 mosaic arrangement**

⇒ **First sCVD/pCVD prototypes to be ready in early 2024 to be tested with carbon ions**

# Groupe Thématique DOSADO

**DOS**imétrie, **A**pplications, **DO**nnées nucléaires

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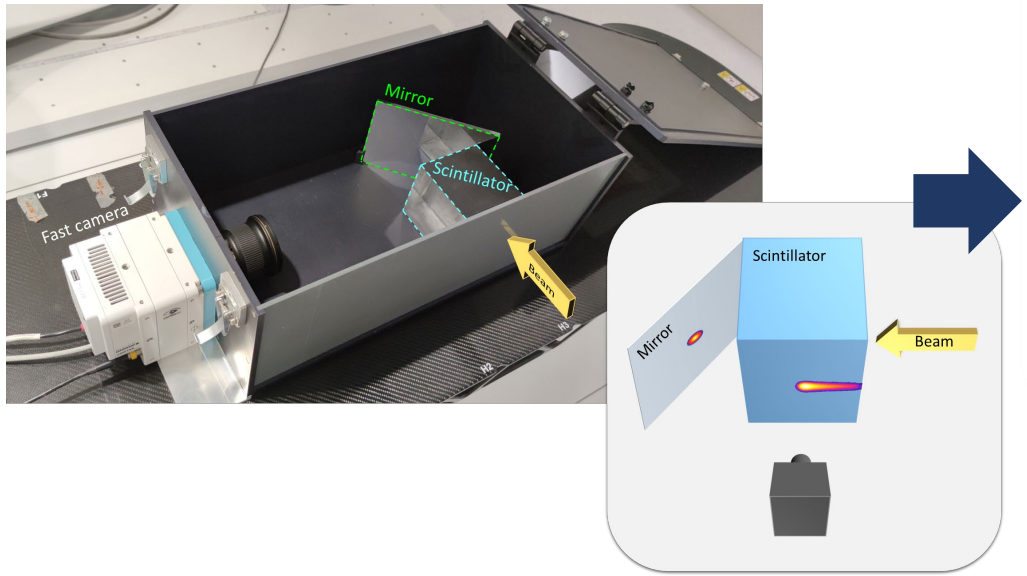
## DOSIMETRY IN PENCIL BEAM SCANNING PROTON THERAPY CASE OF THE SMALL IRRADIATION FIELDS (< 3 × 3 cm²)

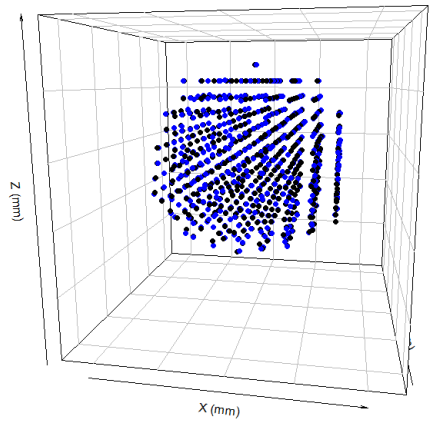
*Collab.: LPC Caen, CLCC Baclesse*

Le projet PMRT est financé par RÉGION NORMANDIE, UNION EUROPÉENNE Fonds européen de développement régional

Treatment limitations: Treatment Planning System uncertainties
→ Development of a high spatial resolution scintillation dosimeter

- Quality assurance of delivered beams characteristics
- 3D dose distributions reconstruction




**PMRT RIN Project (Normandy region)**
**→ New setup in 2022**
**PhD Thesis obtained in 2022**

→ Ongoing project. Possible extension to Carbon ion therapy or radiobiology

# Thanks for your attention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