# Fast diamond beam monitors for online control of the treatment and application with TIARA project: prompt-gamma time imaging

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on behalf of the CLARYS, DIAMMONI, DIAMTECH and TIARA French National Collaborations

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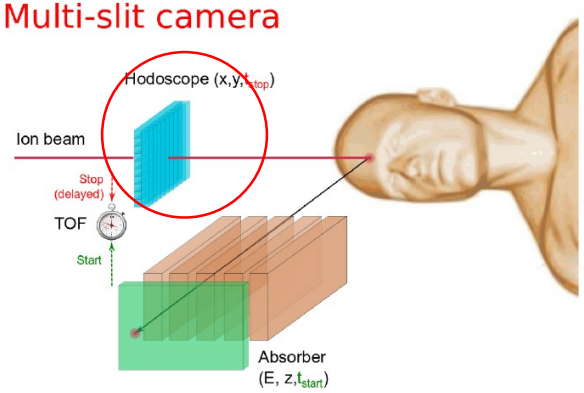
# Context

*In vivo* monitoring from the use of secondary emissions

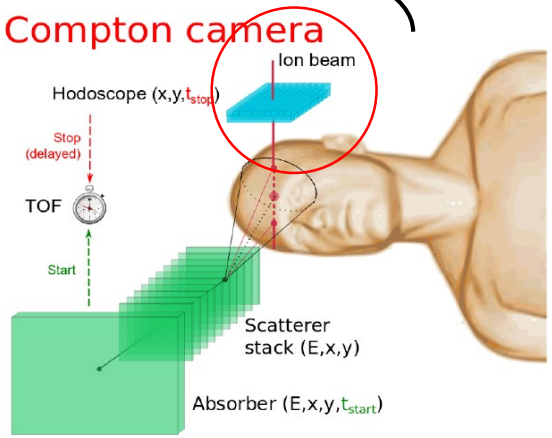
Improvement of treatment planning

## Prompt Gamma Imaging

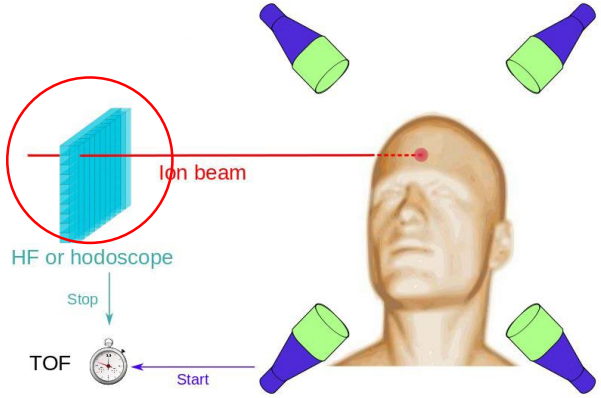
### Multi-slit camera



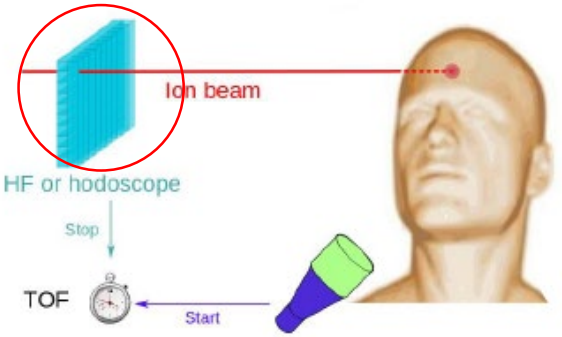

### Compton camera



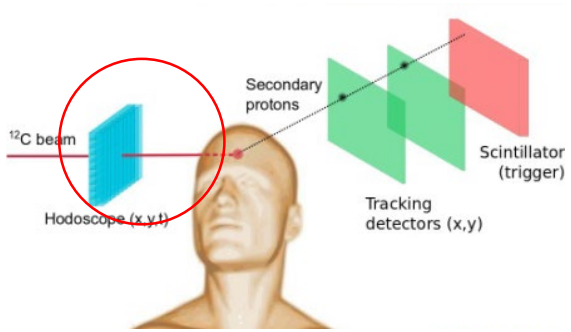

## Prompt Gamma Peak Integral



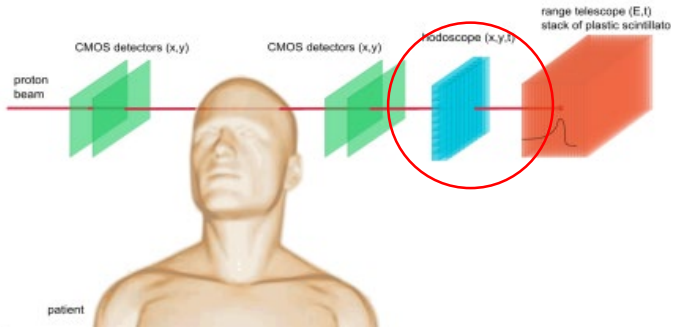

## Prompt Gamma Time Imaging




## Secondary proton vertex imaging in carbon therapy

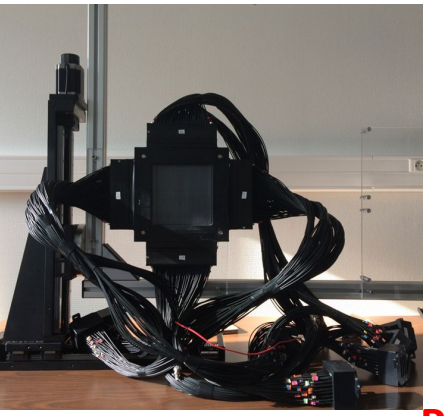



## Proton radiography




# Beam tagging hodoscope development

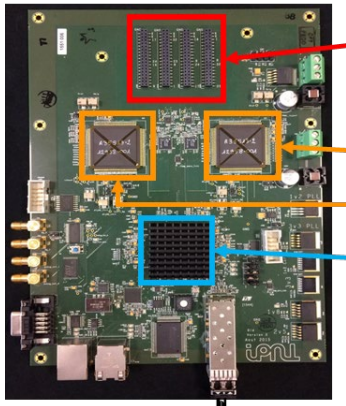
# The scintillating fibres hodoscope



## CLARYS collaboration

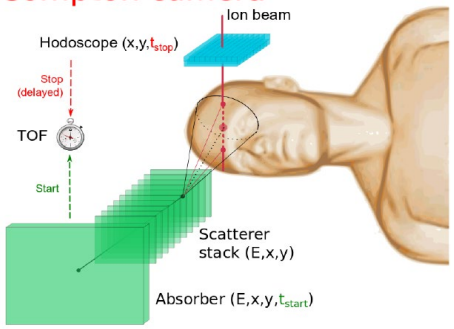
### Characteristics

- 2 perpendicular planes for a 2D mapping
- 128 polystyrene scintillating fibers BCF-12 per plane
- 1 $mm^2$ squared section
- 8 multi-anode PM tubes for a two side read-out

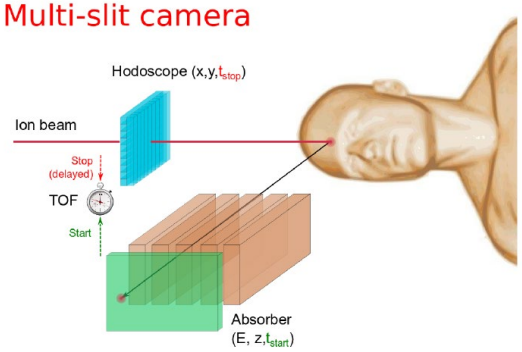



## Prompt Gamma (PG) Imaging

Compton camera

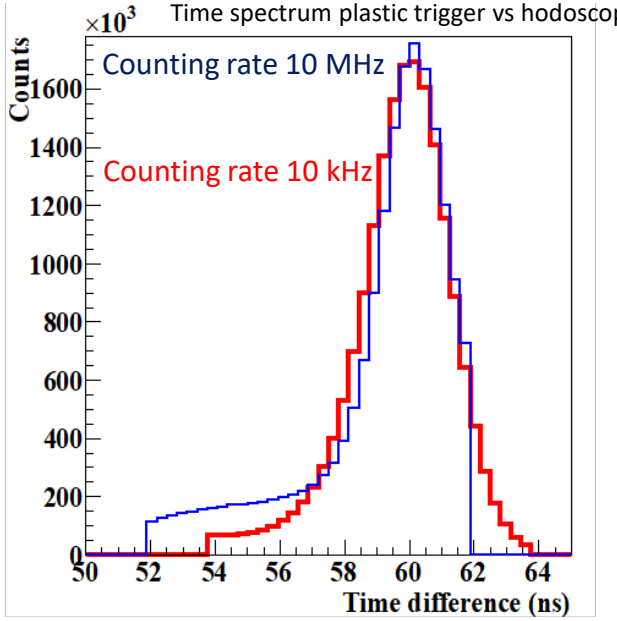



Multi-slit camera




### The read-out electronics

Each PM tube is readout by an ASIC "HODOPIC" FE board




| | Specifications | Measured performance |
|---|---|---|
| **Detection efficiency** | ~ 90 % (logical AND) at 100 MHz | 66 % (logical AND) at 20 MHz<br>97 % (logical OR) at 20 MHz |
| **Time resolution** | < 2 ns | 1.8 ns (10 MHz) |
| **Radiation hardness** | Operationnal for 1000 clinical irradiations | < 10 % loss of detection efficiency after an equivalent of 1000 clinical irradiations |

O. Allegrini et al., Journal of Instrumentation, IOP Publishing, 2021, 16, pp.P02028. 10.1088/1748−0221/16/02/P02028t

# The diamond sCVD beam hodoscope

**Objective: fast timing with 100 ps time resolution !**

**Diamond a wide-bandgap semiconductor**

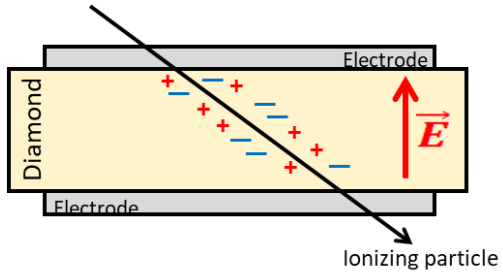
- → Very low leakage current
- → Low noise
- → Radiation hard
- → Fast timing
- → Room temperature

**CLARYS-UFT**

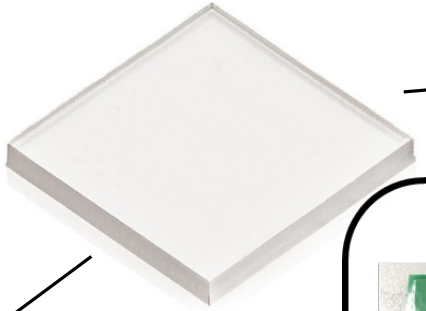
**DIAMTECH**

**ANR DIAMMONI collaborations**

## Solid state ionization chamber



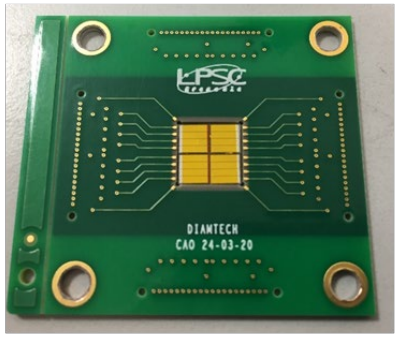

## Detector assembly



Diamond strip metallized

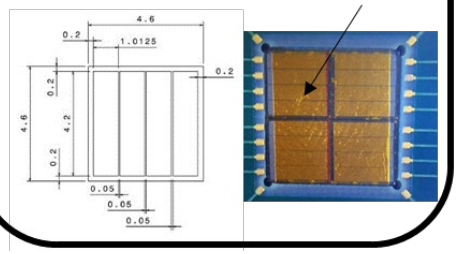
sCVD = Single crystal

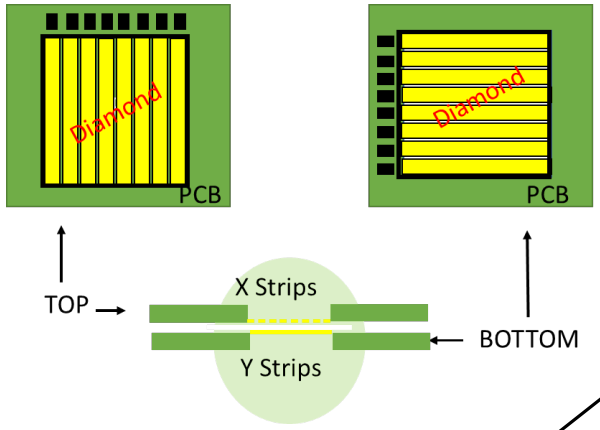
4 sCVD = 1 cm²

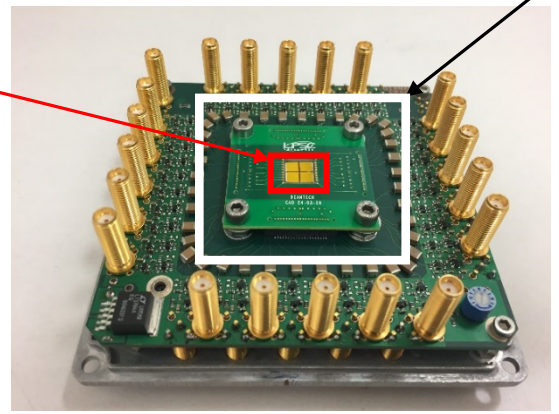



32 strips

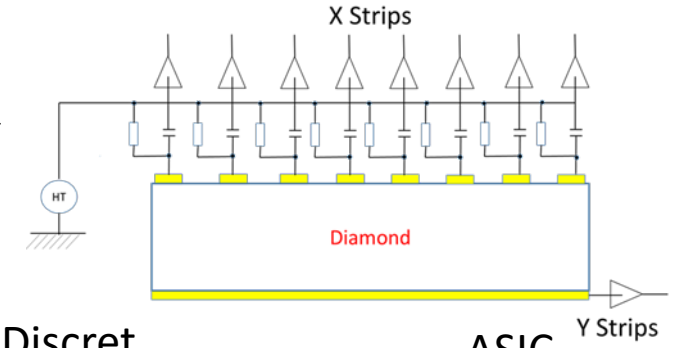
Film Kapton 60 µm



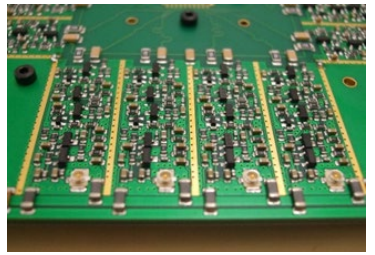


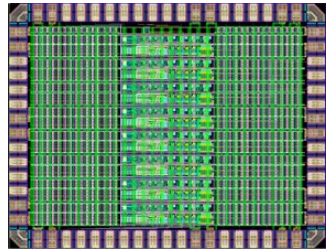
## Read out electronics




Discret



ASIC

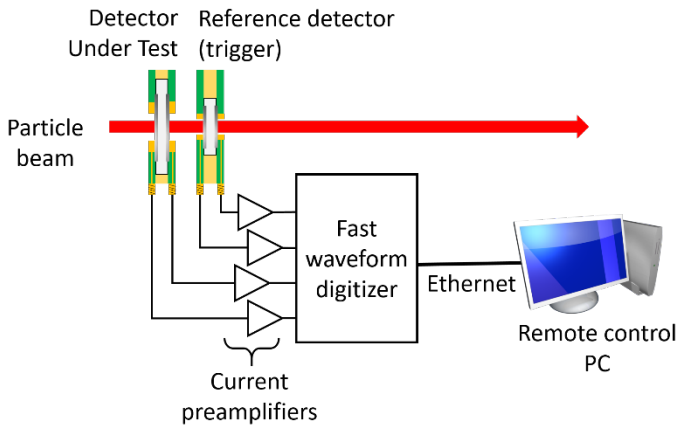


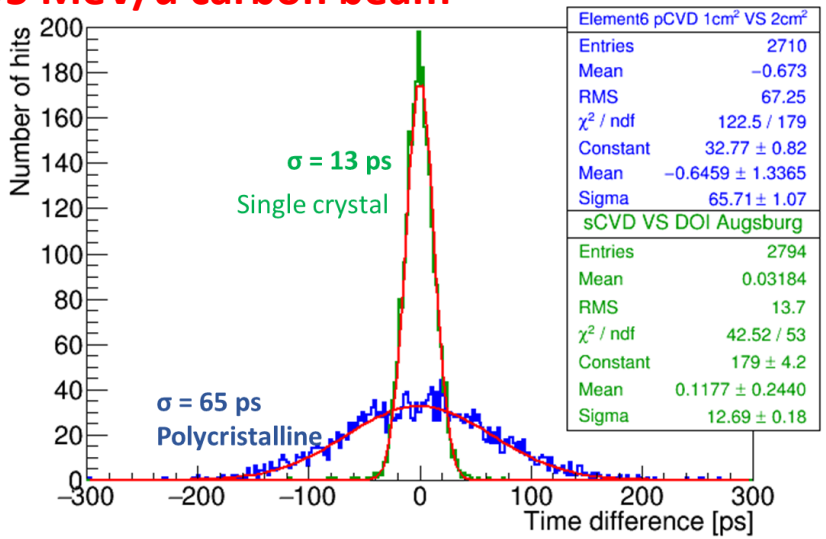
C. Hoarau *et al* 2021 *JINST* **16** T04005
https://doi.org/10.1088/1748-0221/16/04/T04005

Front – end electronic developed at laboratory

# The diamond pCVD beam hodoscope

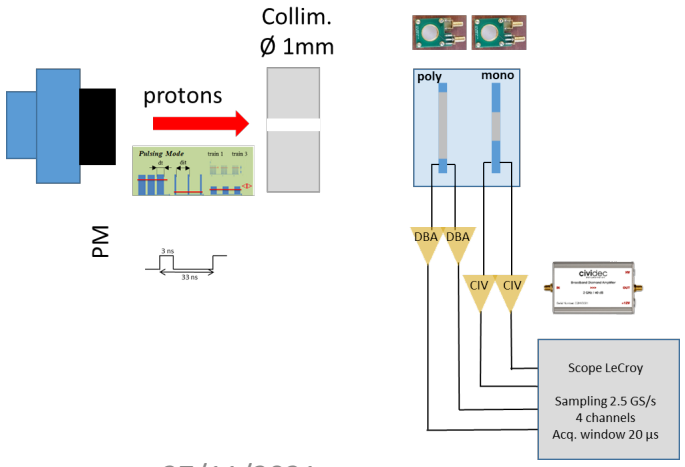
## Beam tests in GANIL with 95 MeV/u carbon beam

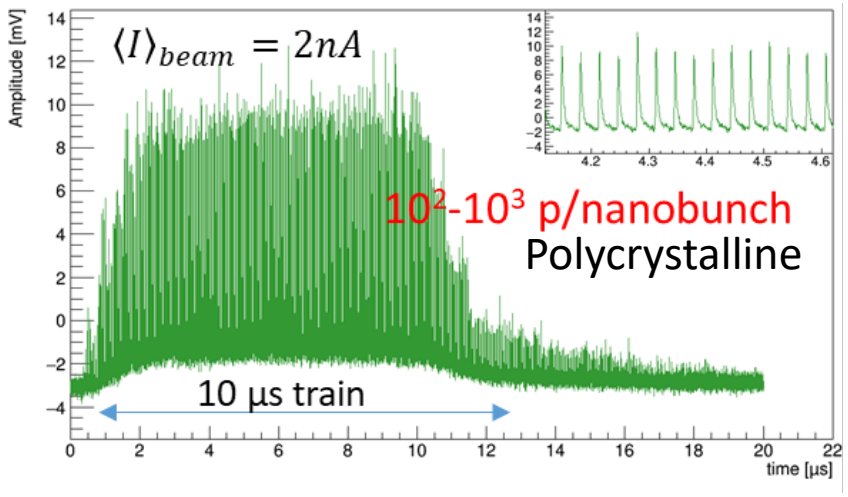



S. Curtoni et al, NIM A, Elsevier,2021, 1015, pp.165757. ;10.1016/j.nima.2021.165757

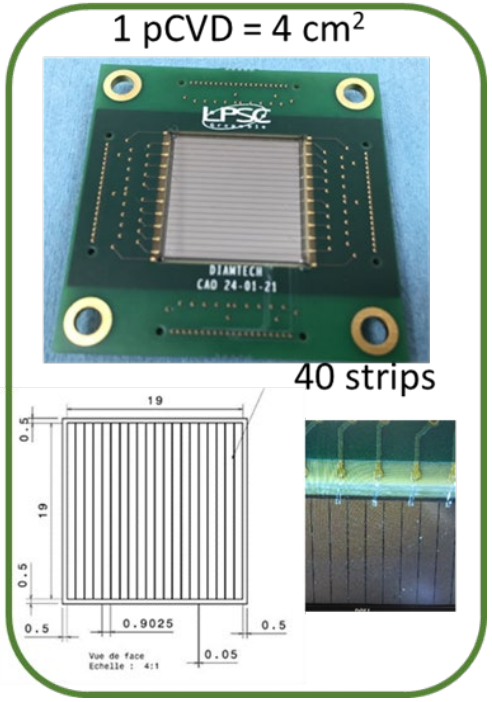
## Beam tests in ARRONAX with 68 MeV proton beam




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

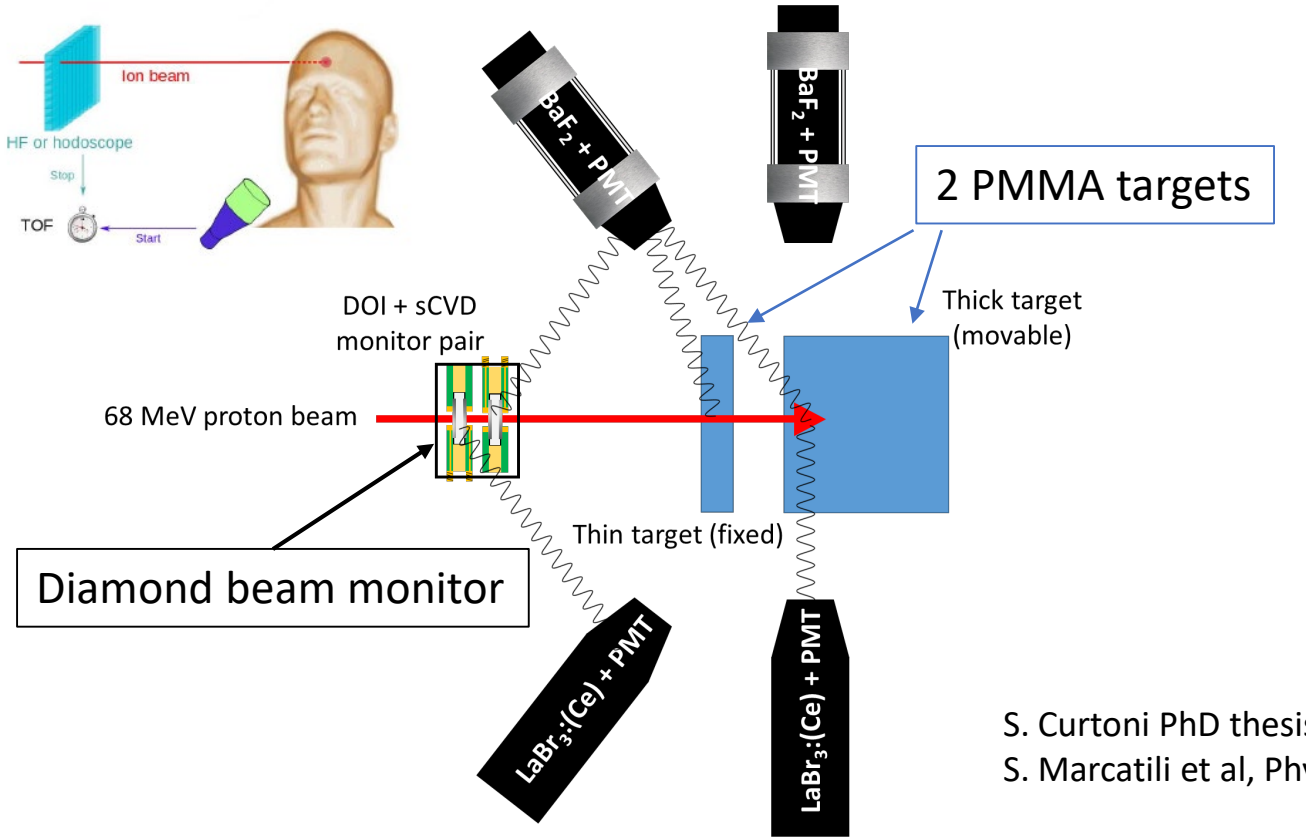



**Designed to be used right now with carbon ions**

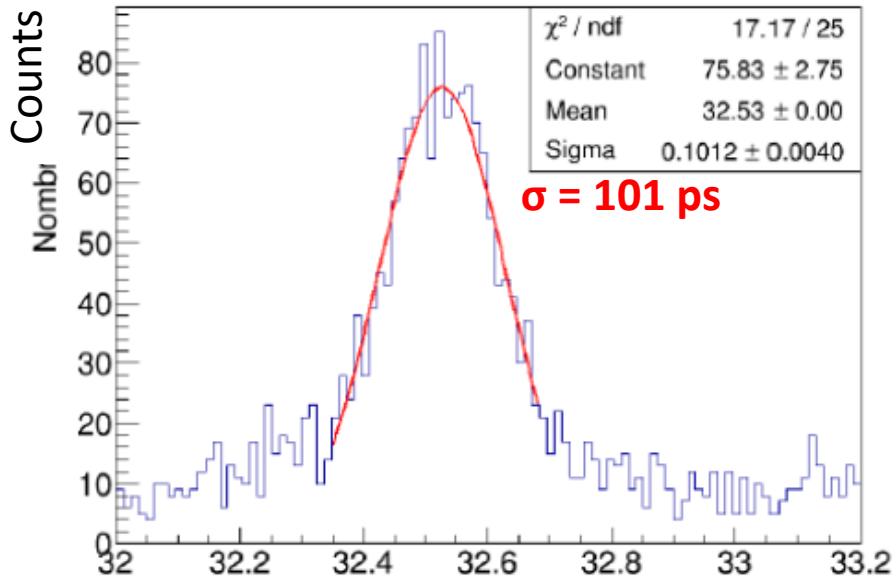
# Fast timing using diamond beam monitoring: proof of concept

## Beam tests in ARRONAX with 68 MeV proton beam

Fast scintillators for PG detection




**Time resolution single crystal diamond vs scintillator**




Time difference sCVD diamond – BaF3 scintillator (ns)

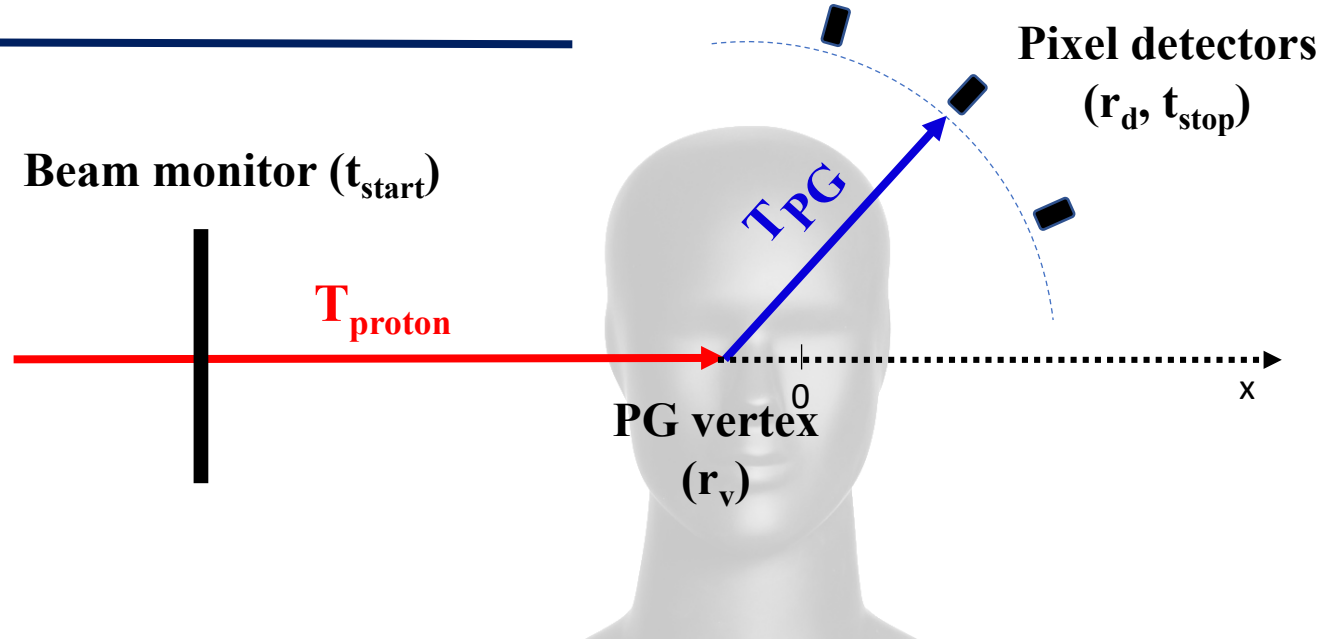
S. Curtoni PhD thesis http://www.theses.fr/2020GRALY045

S. Marcatili et al, Phys.Med.Biol., 2020, 65 (24), pp.245033;10.1088/1361−6560/ab7a6c;

# Application with the TIARA project: PG monitoring through the exclusive measurement of TOF

$$TOF = t_{stop} - t_{start} =$$

$$= T_{proton}(\mathbf{r}_v) + T_{PG}(\mathbf{r}_v, \mathbf{r}_d)$$




## On going developments at IN2P3

1) Dedicated image reconstruction algorithm

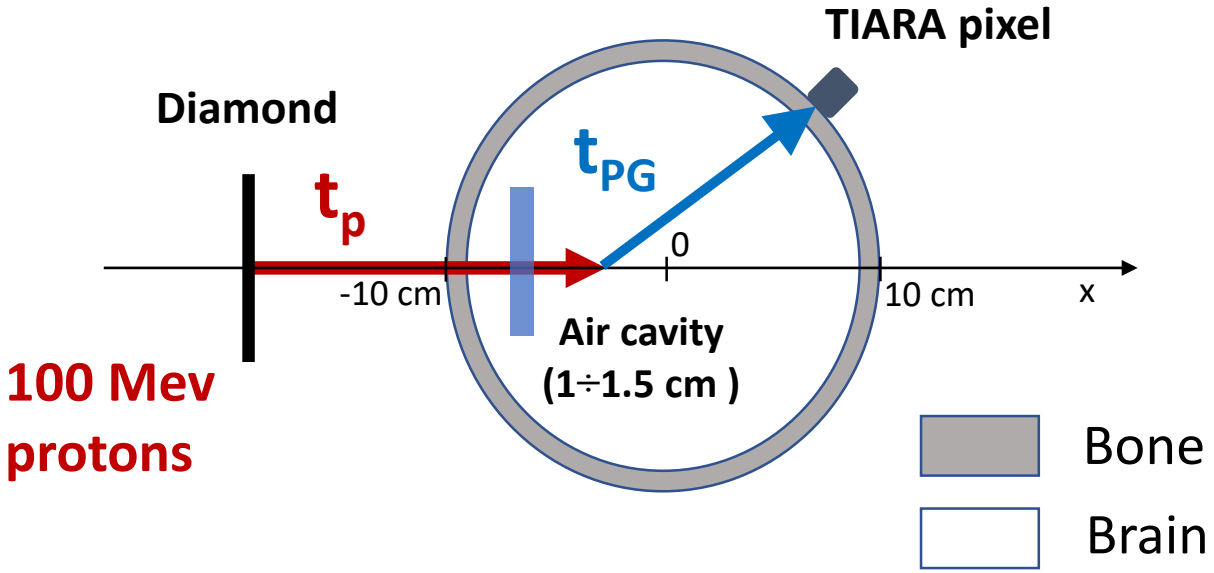
2) TIARA (Time-of-flight Imaging ARrAy) detector
   - ~30 pixel detectors (1 $cm^3$)
   - 100 ps (rms) coincidence time resolution

## Pixel detector:
## Cherenkov radiator (PbF2) + SiPM

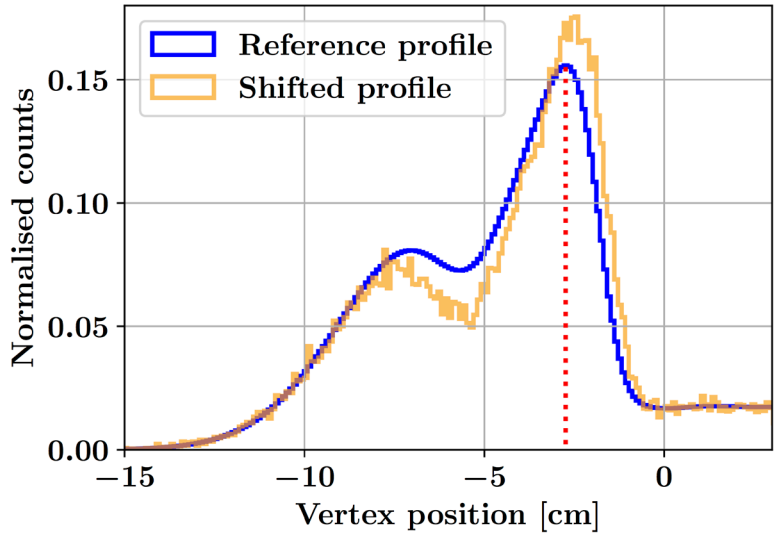
- Intrinsically faster than scintillation
- High Z
- Suppression of neutron background
- Natural threshold below 1 MeV

# Development of a simplified reconstruct algorithm (1D)

**Geant4** : head with variable thickness air cavity
+ 30 pixels TIARA detector




**Goal**: measure the induced proton range shift from the PG profile



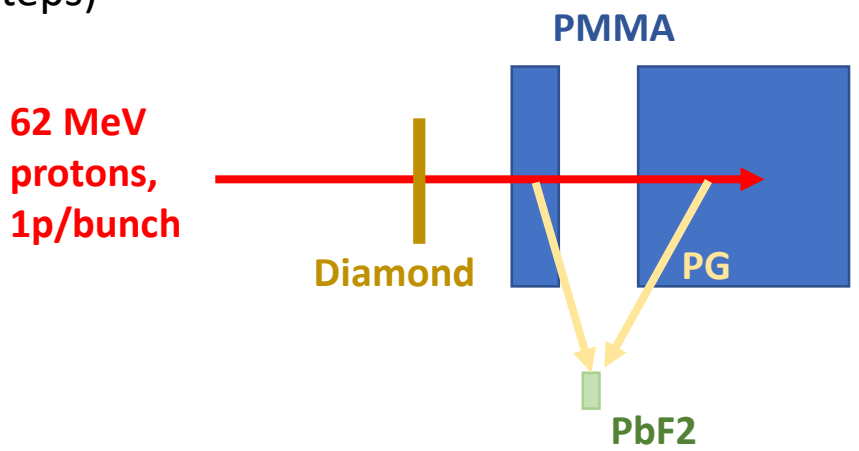

## Expected sensitivity

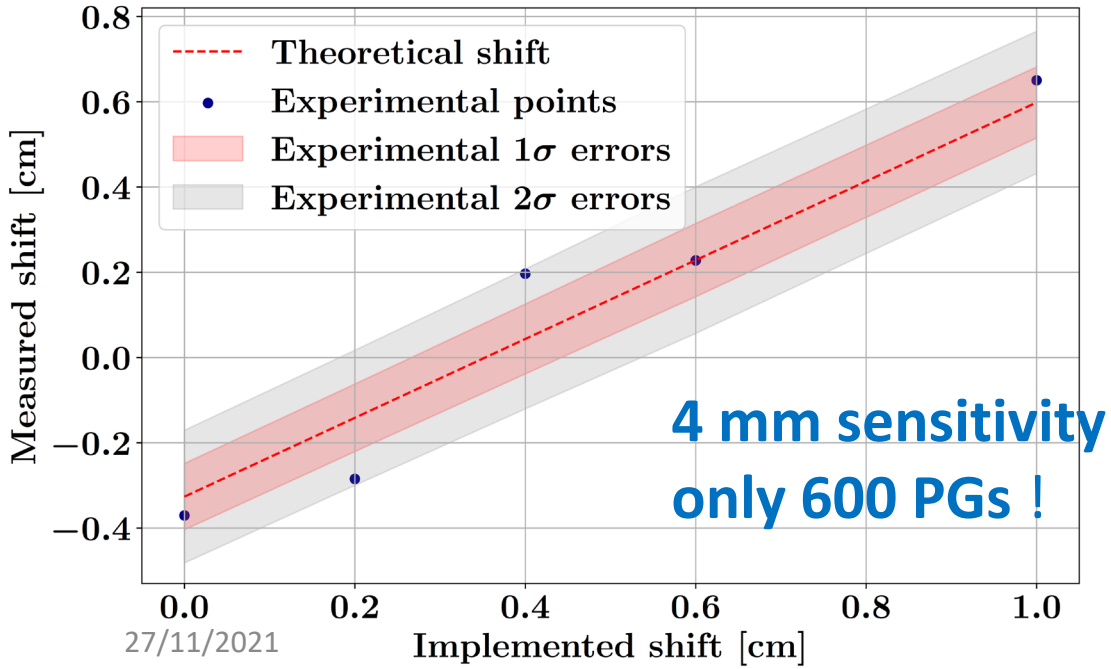
Jacquet *et al.* Phys. Med. Biol. 2021

| | TOF resolution | Number of protons | Sensitivity at 2σ |
|---|---|---|---|
| Single proton regime | 100 ps rms | $10^7$ | 3 mm |
| | | $10^8$ | 1 mm |
| Nominal intensity | 1 ns rms | $10^9$ | 2 mm |

# Experimental data with one pixel detector

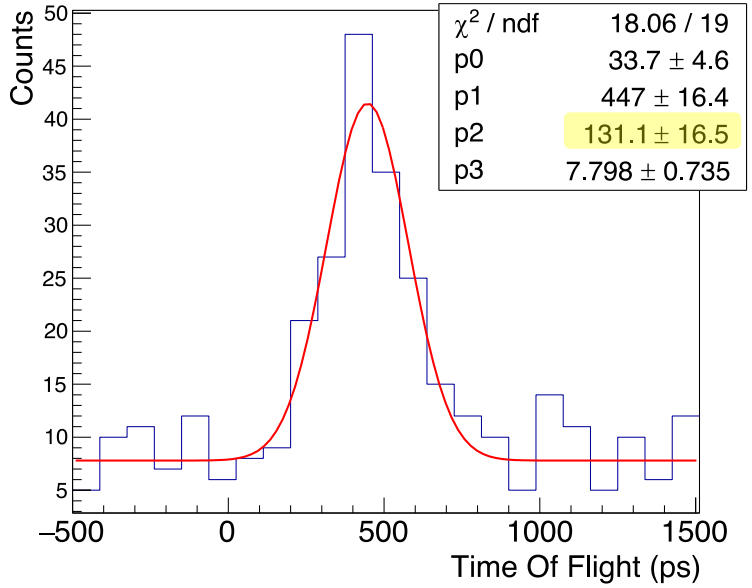
**Set up:** Variable thickness air cavity, from 1 to 2 cm (2 mm steps)



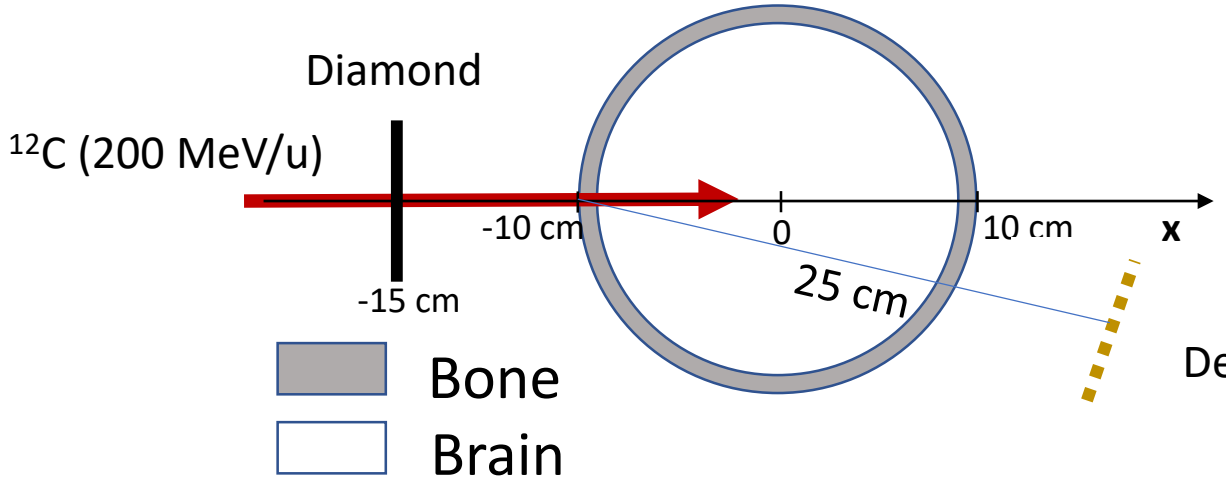

**4 mm sensitivity with only 600 PGs !**

## Coincidence Time resolution : 131 ps rms



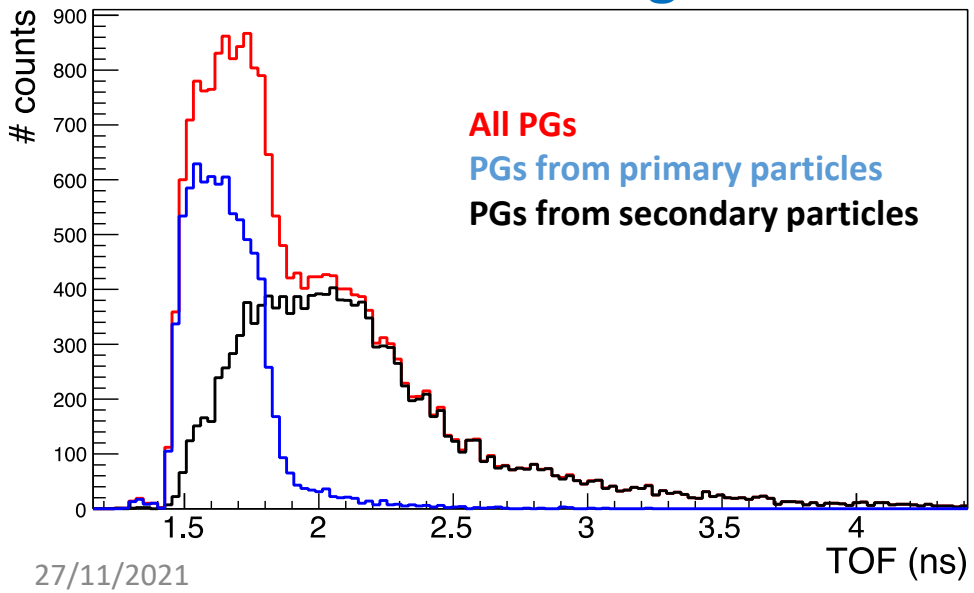

| | Experiment | Simulation |
|---|---|---|
| | 1 pixel | 30 pixels |
| **Nb. Of protons** | - | $10^7$ |
| **Nb. Of PG detected** | 600 | 3500 |
| **Time resolution (rms)** | 131 ps | 100 ps |
| **Sensitivity (2σ)** | 4 mm | 3 mm |

# PG TOF detection for Carbon ions (Monte Carlo)

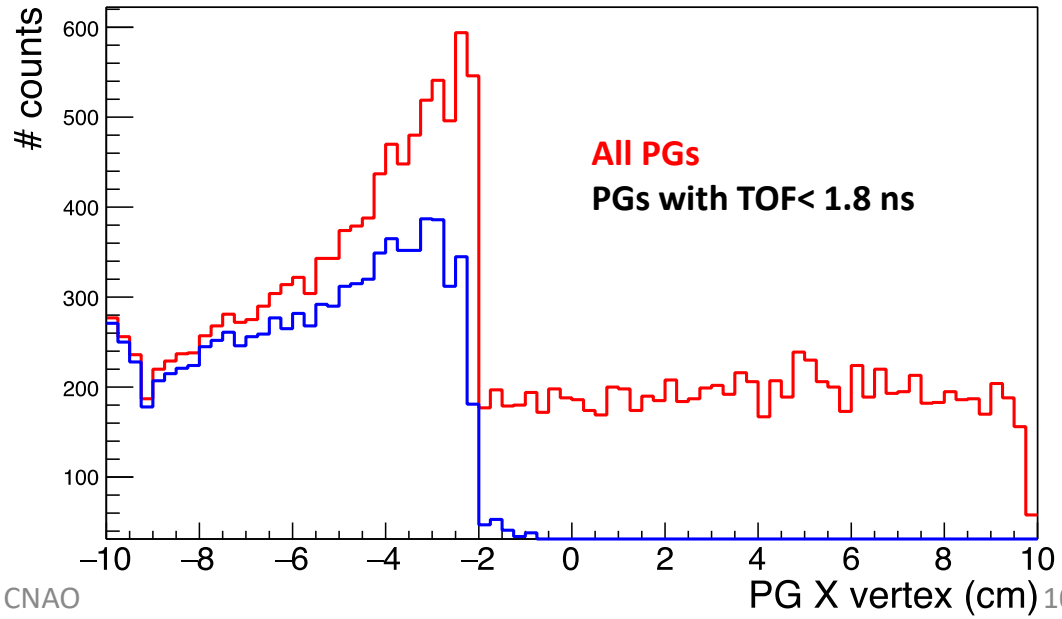



Very preliminary

## PG Time-Of-Flight




## PG profile



# Conclusions and perspectives

- **Scintillating fibres hodoscope:**
  - Can be used with ions to **provide clinical intensity mm and ns spatio-temporal labeling**

- **Diamond hodoscope:**
  - Can be used with ions to **provide clinical intensity mm and ~100 ps spatio-temporal labeling, 16 $cm^2$ sensitive surface can be reached using polycrystalline diamond sensors in a 2 x 2 mosaic arrangement**

- **TIARA prompt-gamma timing imaging**
  - feasibility **validated by experiments and simulation for proton irradiation**

**Perspective development in our collaborations: Time of Flight based monitoring for carbon irradiation**

# Thanks for your attention