



**HAL**  
open science

## Design of innovative diamond detectors for beam monitoring in highly radiative environment for applications in nuclear and medical physics

M.-L. Gallin-Martel, J.-L. Bouly, J. Collot, D. Dauvergne, P. Everaere, L. Gallin-Martel, C. Hoarau, F. Lafont, E. Lagorio, S. Marcatili, et al.

### ► To cite this version:

M.-L. Gallin-Martel, J.-L. Bouly, J. Collot, D. Dauvergne, P. Everaere, et al.. Design of innovative diamond detectors for beam monitoring in highly radiative environment for applications in nuclear and medical physics. MRS 2023 Spring Meeting, May 2023, Strasbourg, France. hal-04694008

**HAL Id: hal-04694008**

**<https://hal.science/hal-04694008>**

Submitted on 11 Sep 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

# Design of innovative diamond detectors for beam monitoring in highly radiative environment for applications in nuclear and medical physics



**M.-L. Gallin-Martel\***, J.-L. Bouly, J. Collot, D. Dauvergne, P. Everaere, L. Gallin-Martel, C. Hoarau, F. Lafont, E. Lagorio, S. Marcatili, R. Molle, J.-F. Muraz, N. Ponchant, F. Rarbi, M. Reynaud, O. Rossetto, J. Waquet, M. Yamouni



A. Guertin, F. Haddad, C. Koumeir,



V. Métivier, R. Molle, F. Poirier, N. Servagent



L. Abbassi, T. Crozes, J.-F. Motte



F. Lafont, T-N Tran - Thi



\*mlgallin@lpsc.in2p3.fr

# Context

## ➤ **Development of new generations of ion accelerators:**

- medical applications: hadrontherapy, flash therapies and X-ray or synchrotron radiation therapy  
⇒ very precise monitoring of the beam with rapid counting in a highly radiative environment.

## ➤ **The intrinsic qualities of diamond:**

- speed, low leakage current, excellent SNR, resistance to radiation  
⇒ an excellent candidate to meet such monitoring requirements over a wide dynamic range from a fraction of pA (single particle) up to  $\mu\text{A}$ .

# Context

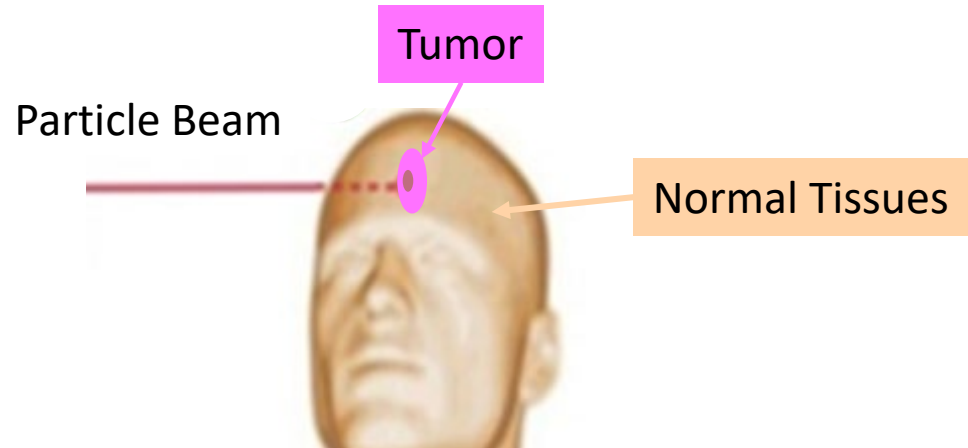
## ➤ Development of new generations of ion accelerators:

- medical applications: **hadrontherapy, flash therapies** and X-ray or synchrotron radiation therapy  
⇒ very precise monitoring of the beam with rapid counting in a highly radiative environment.

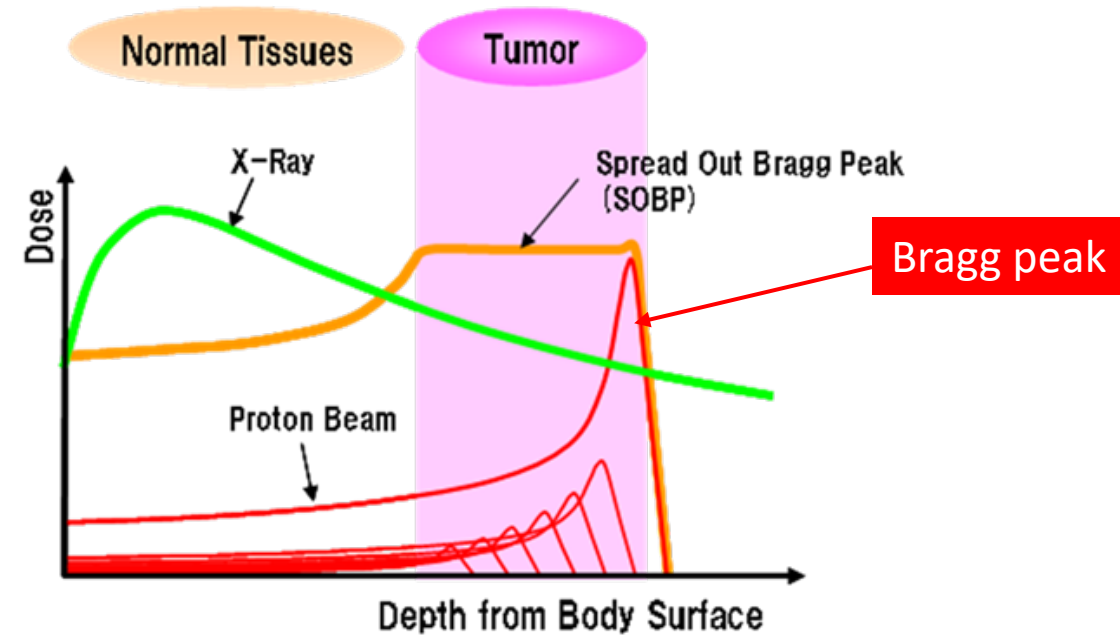
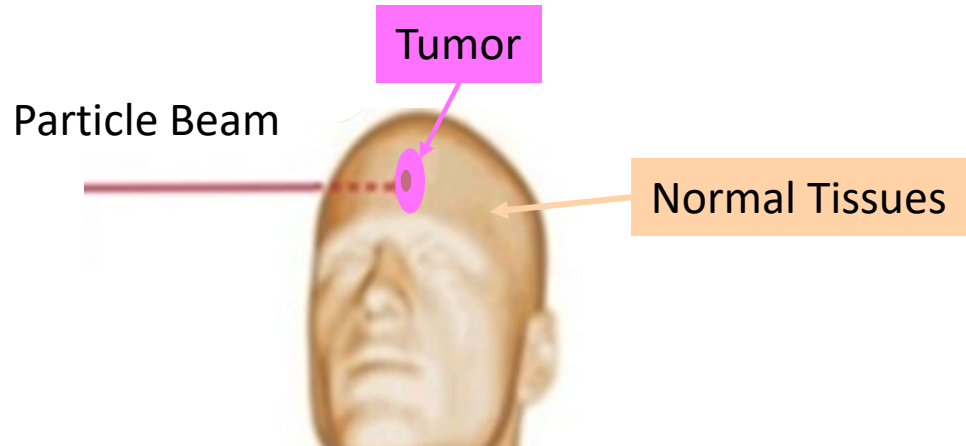
## ➤ The intrinsic qualities of diamond:

- speed, low leakage current, excellent SNR, resistance to radiation  
⇒ an excellent candidate to meet such monitoring requirements over a wide dynamic range from a fraction of pA (single particle) up to  $\mu\text{A}$ .

# What is hadrontherapy in cancer treatment ?



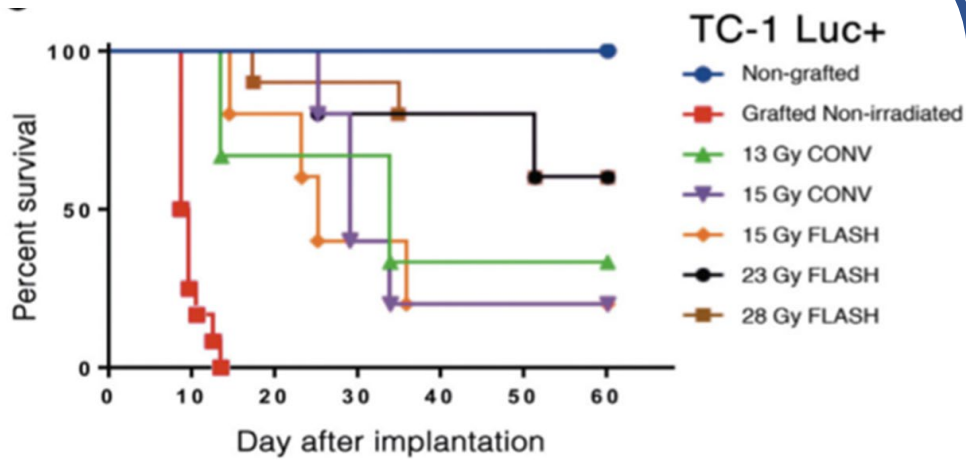
# Hadrontherapy in cancer treatment



- Energy deposition at the end of ion path in the Bragg peak = dose deposition (Gy) very locally in the tumor volume

$$1 \text{ Gy} = 1 \text{ J/kg}$$

# Towards Flash therapies in cancer treatment: the new challenges for beam monitoring !



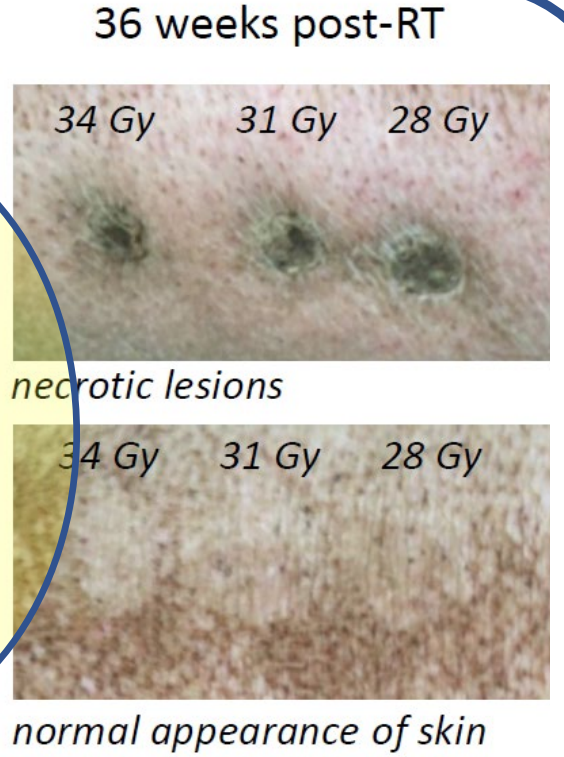
Favaudon et al (2015)  
<https://www.sciencedirect.com/science/article/abs/pii/S1278321815001201?via%3Dihub>



**1 Gy = 1 J/kg**

Conventional  
(5 Gy/min)

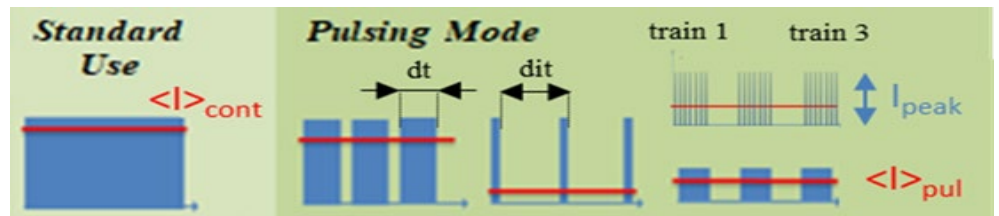
FLASH  
(300 Gy/s)  
3 Gy/pulse



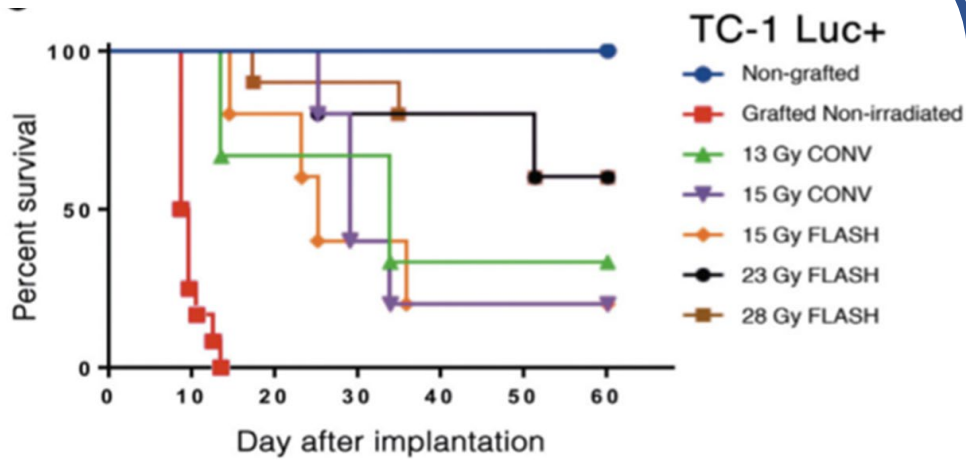
Vozenin et al., Clin Cancer Res 25 (2019) 35  
<http://dx.doi.org/10.1158/1078-0432.CCR-17-3375>

## Flash therapy vs conventional = high doses in a very short time

- ⇒ Short pulses to be monitored at **high beam intensity** !
- ⇒ **High particle counting rate capabilities** to be demonstrated
- ⇒ **Bunch or train of bunches time stamps**



# Towards Flash therapies in cancer treatment: the new challenges for beam monitoring !



Favaudon et al (2015)

<https://www.sciencedirect.com/science/article/abs/pii/S1278321815001201?via%3Dihub>



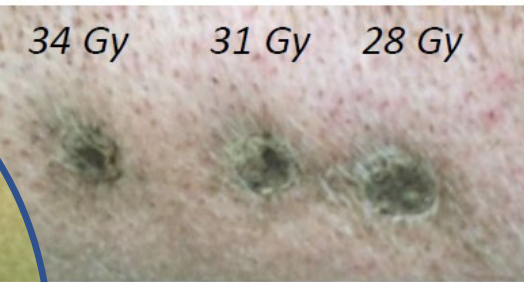
**1 Gy = 1 J/kg**

Conventional  
(5 Gy/min)

FLASH  
(300 Gy/s)

3 Gy/pulse

36 weeks post-RT



necrotic lesions



normal appearance of skin

Vozeninet *et al.*, Clin Cancer Res 25 (2019) 35

<http://dx.doi.org/10.1158/1078-0432.CCR-17-3375>

## Flash therapy vs conventionnal = high doses in a very short time

- ⇒ Short pulses to be monitored at high beam intensity !
- ⇒ High particle counting rate capabilities to be demonstrated
- ⇒ Bunch or train of bunches time stamps



**Diamond beam monitors to be instrumented + FE electronics = QDC**



**ANR DIAMMONI 2020-2024**





# Diamond as beam monitors

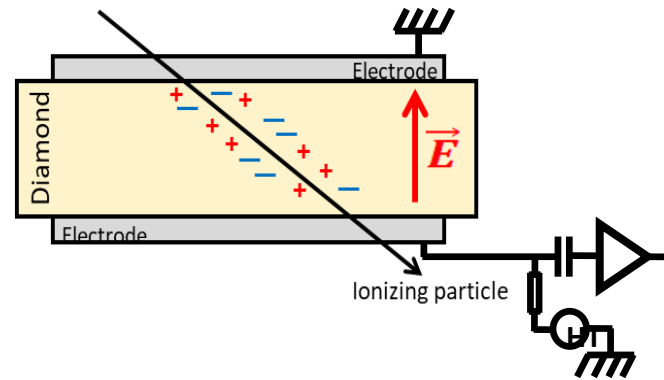
## Solid state ionization chamber

### 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



# Diamond as beam monitors

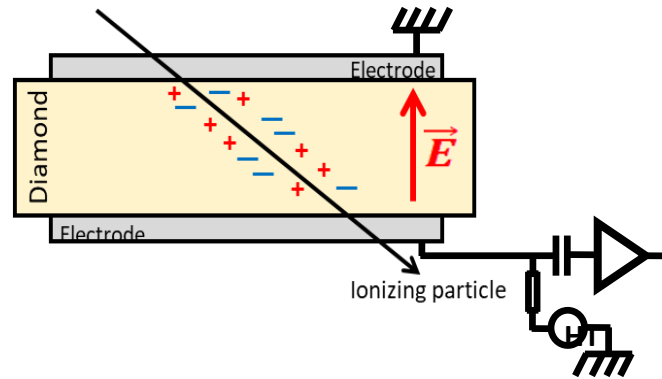
## Solid state ionization chamber

### Diamond Assets :

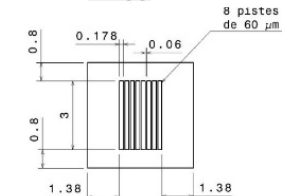
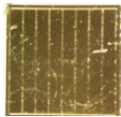
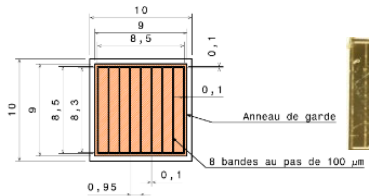
- ❑ Intrinsic radiation hardness
- ❑ Fast signal risetime enables timing precision of a few tens of ps
- ❑ Low noise

### Issues :

- ❑ Cost
- ❑ Availability of large area



## Diamond metallisation



# Diamond as beam monitors

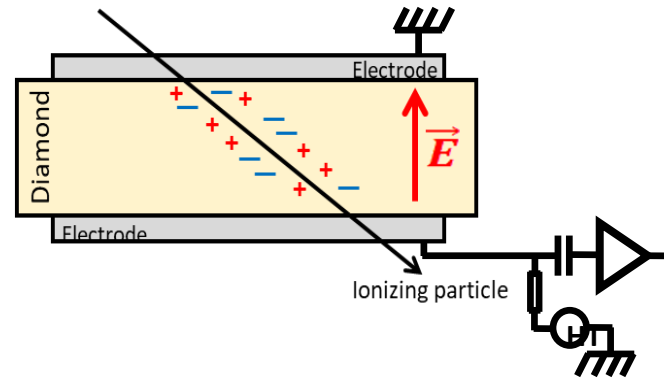
## Solid state ionization chamber

### Diamond Assets :

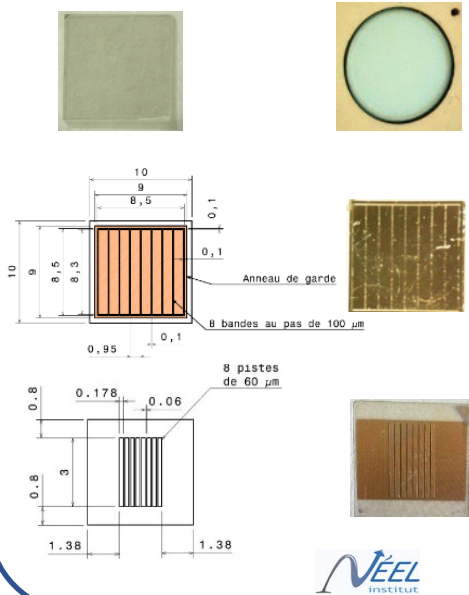
- Intrinsic radiation hardness
- Fast signal risetime enables timing precision of a few tens of ps
- Low noise

### Issues :

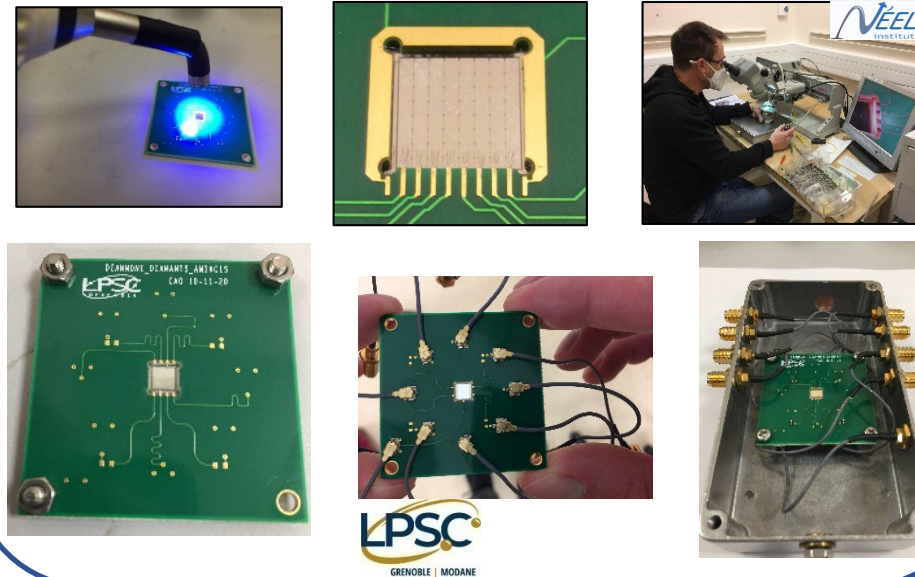
- Cost
- Availability of large area



## Diamond metallisation



## Detector assembly



# Diamond as beam monitors

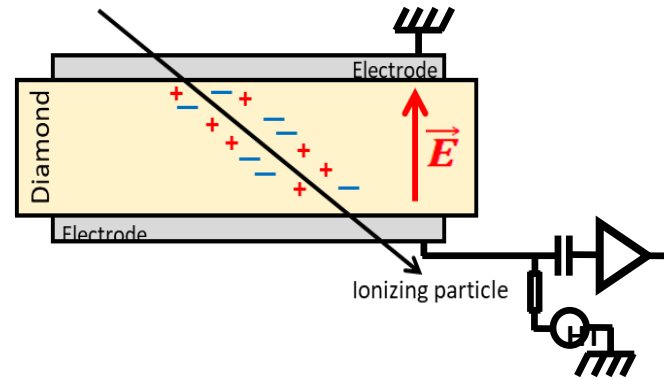
## Solid state ionization chamber

### Diamond Assets :

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

### Issues :

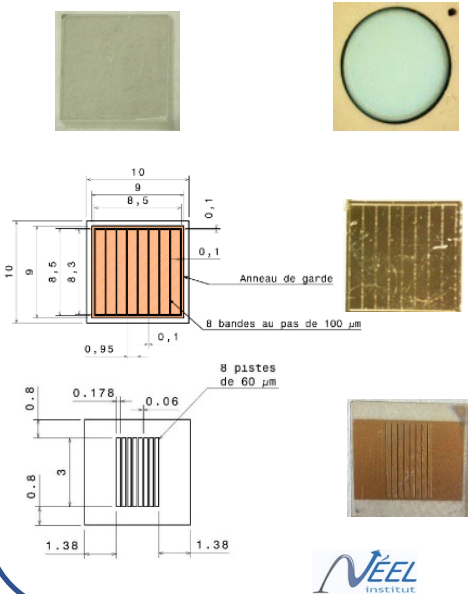
- Cost
- Availability of large area



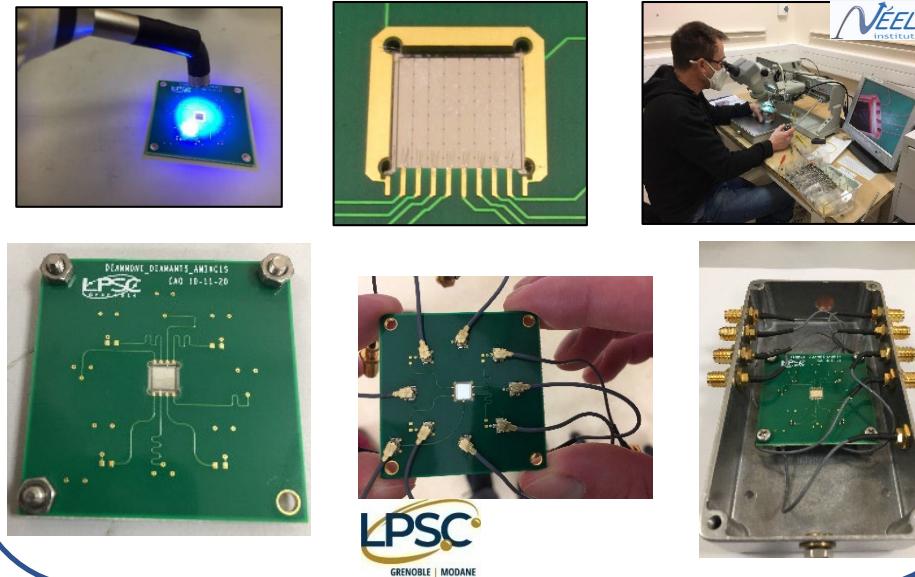
## Read-out electronics

- Fast current preamplifier
- Charge preamplifier
- Electrometer

## Diamond metallisation



## Detector assembly



# Diamond as beam monitors

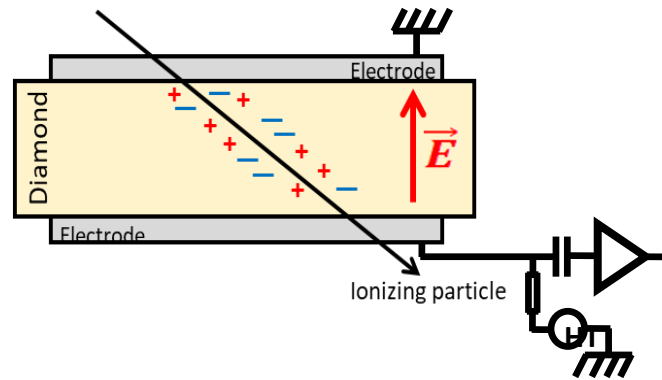
## Solid state ionization chamber

### 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



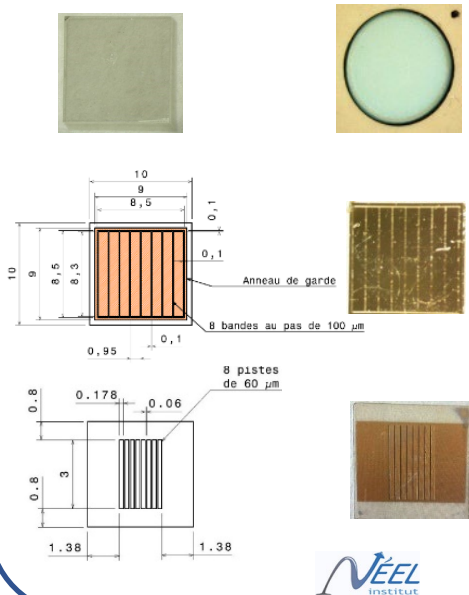
## Read-out electronics

- Fast current preamplifier
- Charge preamplifier
- Electrometer

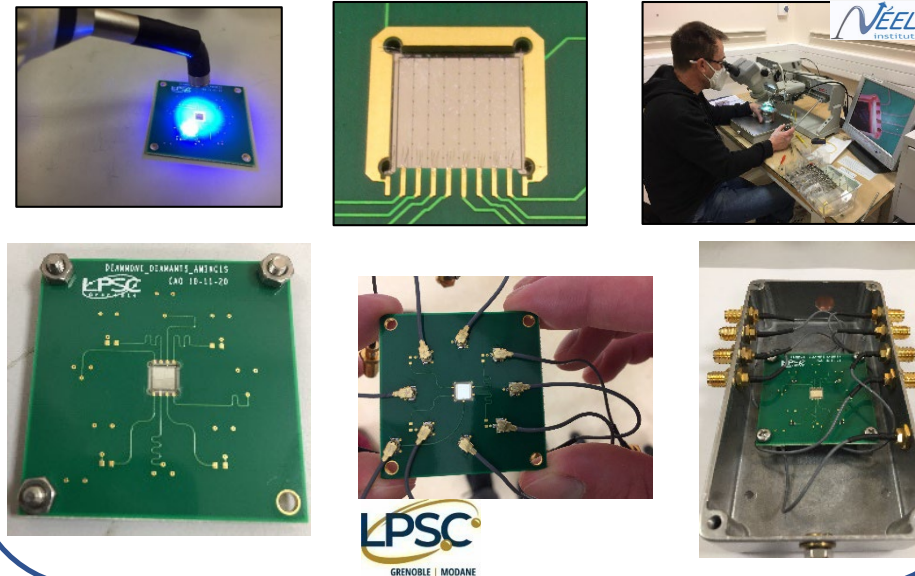


<b>Band Width:</b>	<b>2 GHz</b>
<b>Gain:</b>	<b>40 dB</b>
<b>Impedance:</b>	<b>50 Ω</b>
<b>Dynamic range:</b>	<b>~ +/- 1 V</b>
<b>Power Supply:</b>	<b>12 V / 100 mA</b>

## Diamond metallisation



## Detector assembly



# Diamond as beam monitors

## Solid state ionization chamber

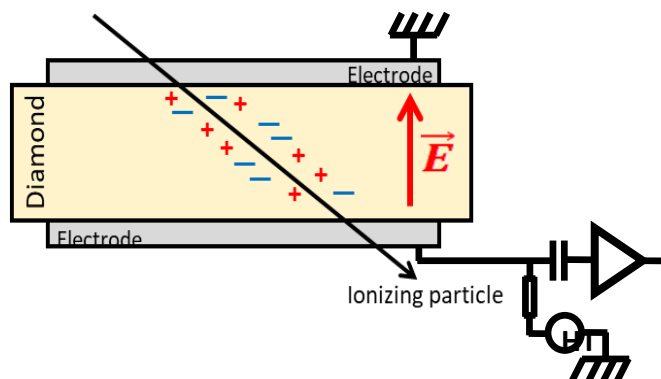
### Diamond Assets :

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

- ❑ Low noise

### Issues :

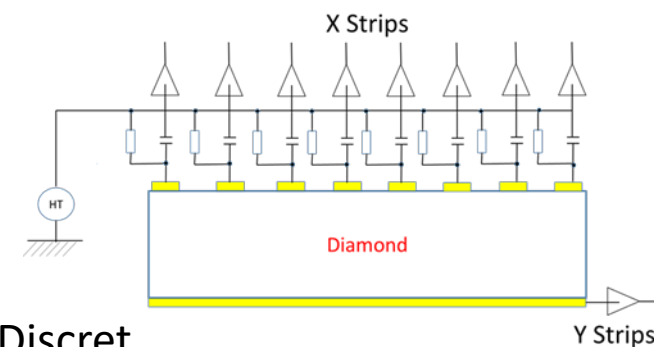
- ❑ Cost
- ❑ Availability of large area



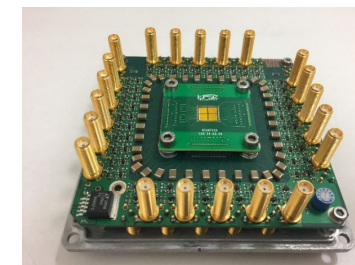
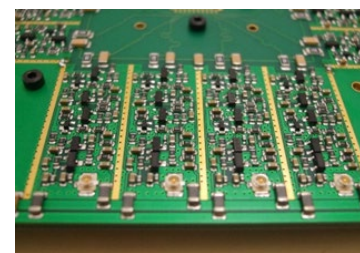
## Read-out electronics

- Fast current preamplifier
- Charge preamplifier
- Electrometer

## Read out electronics @ LPSC



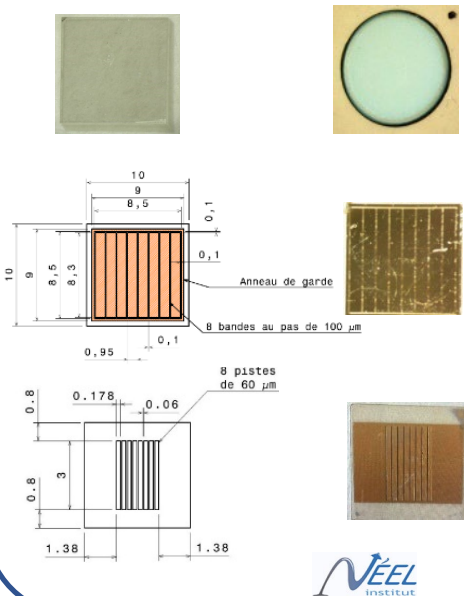
Discret



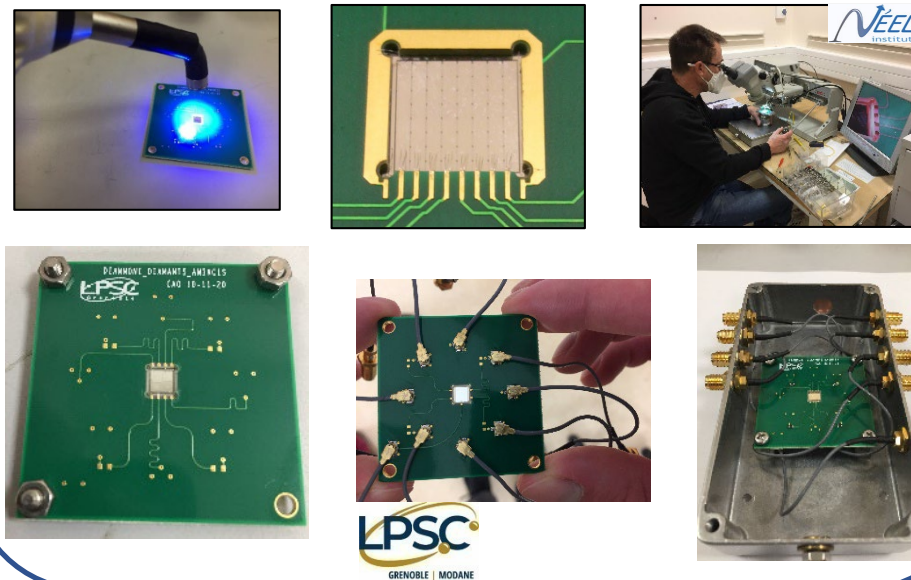
C. Hoarau *et al* 2021 *JINST* **16** T04005

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

## Diamond metallisation



## Detector assembly



# Diamond as beam monitors

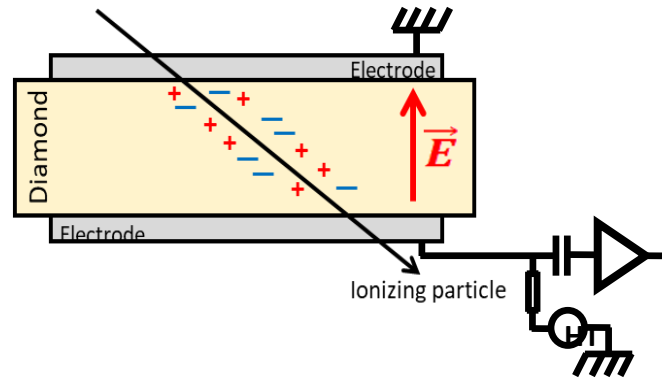
## Solid state ionization chamber

### Diamond Assets :

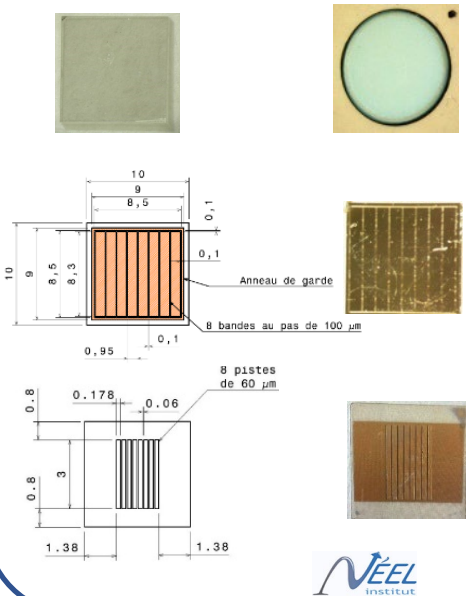
- Intrinsic radiation hardness
- Fast signal risetime enables timing precision of a few tens of ps
- Low noise

### Issues :

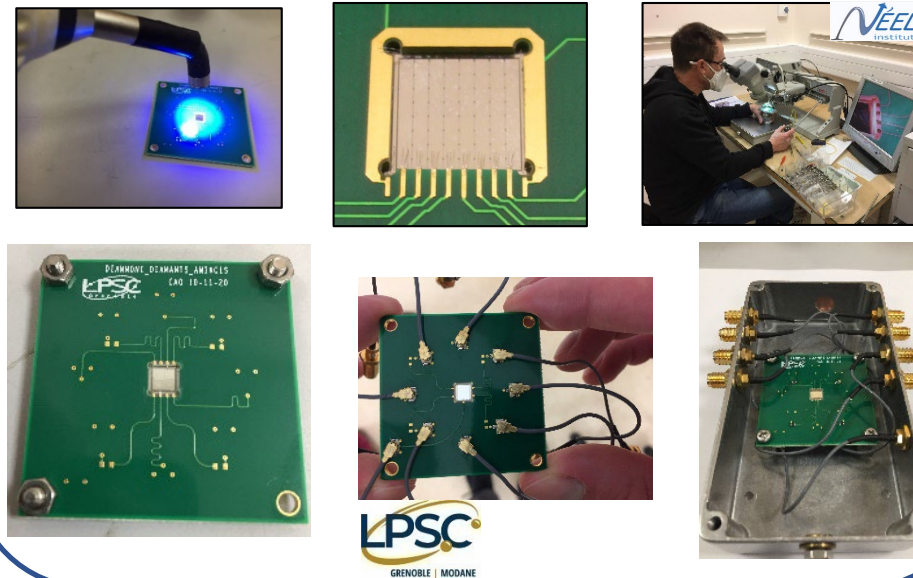
- Cost
- Availability of large area



## Diamond metallisation



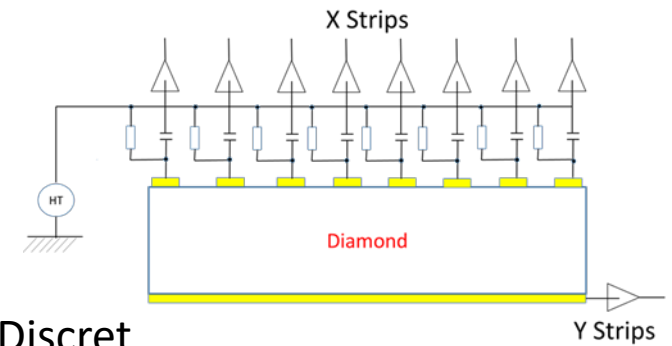
## Detector assembly



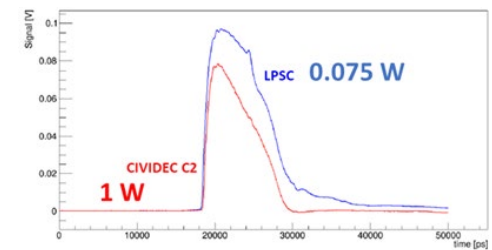
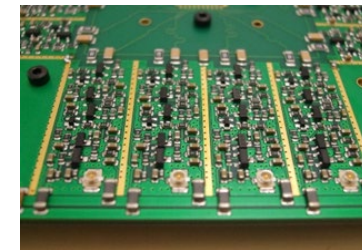
## Read-out electronics

- Fast current preamplifier
- Charge preamplifier
- Electrometer

## Read out electronics @ LPSC



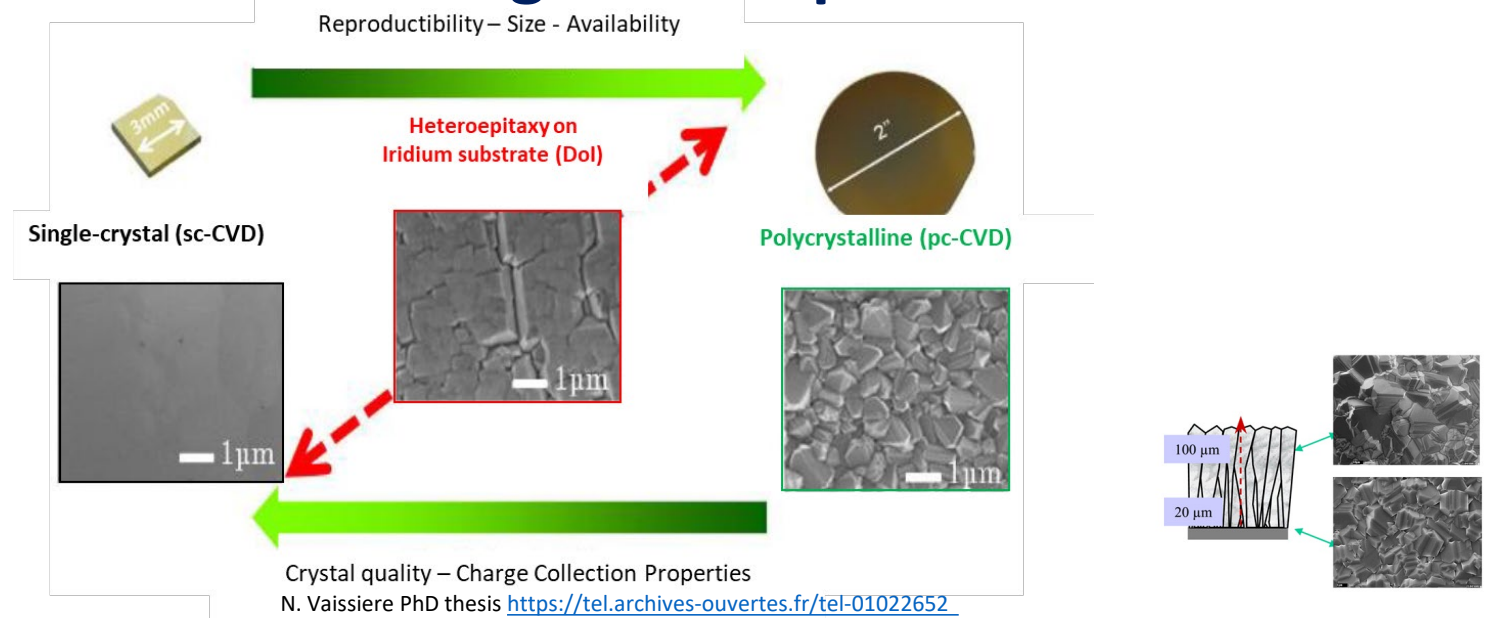
Discret



C. Hoarau *et al* 2021 *JINST* **16** T04005

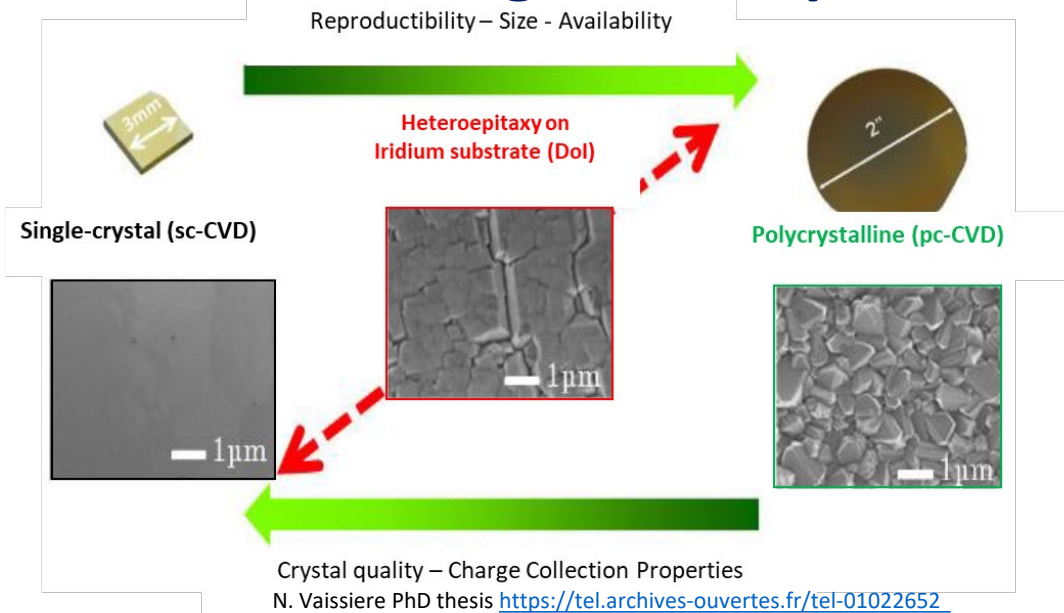
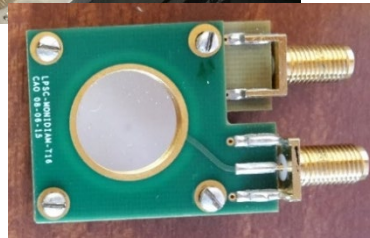
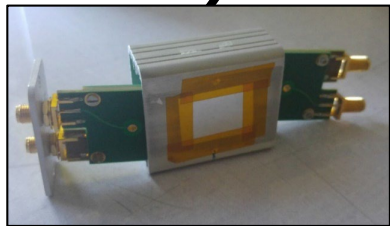
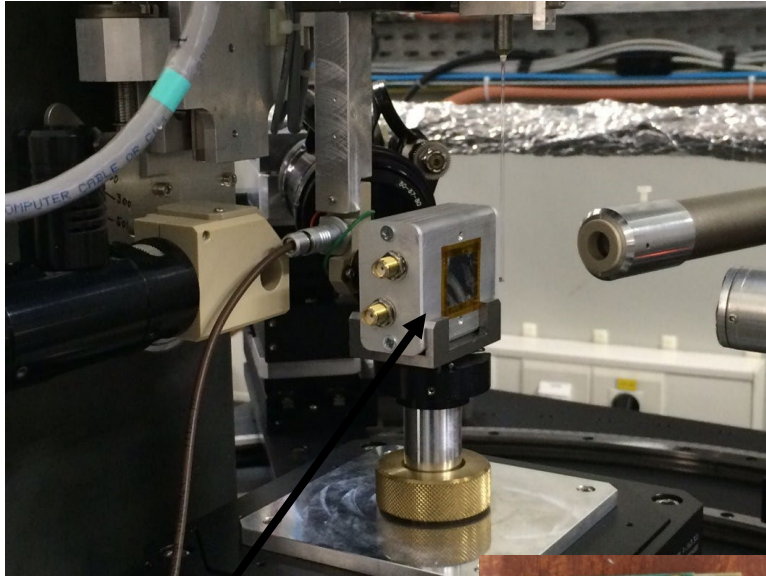
<https://doi.org/10.1088/1748-0221/16/04/T04005>

# Diamond detector for beam monitoring: sCVD ? pCVD ? DOI ?



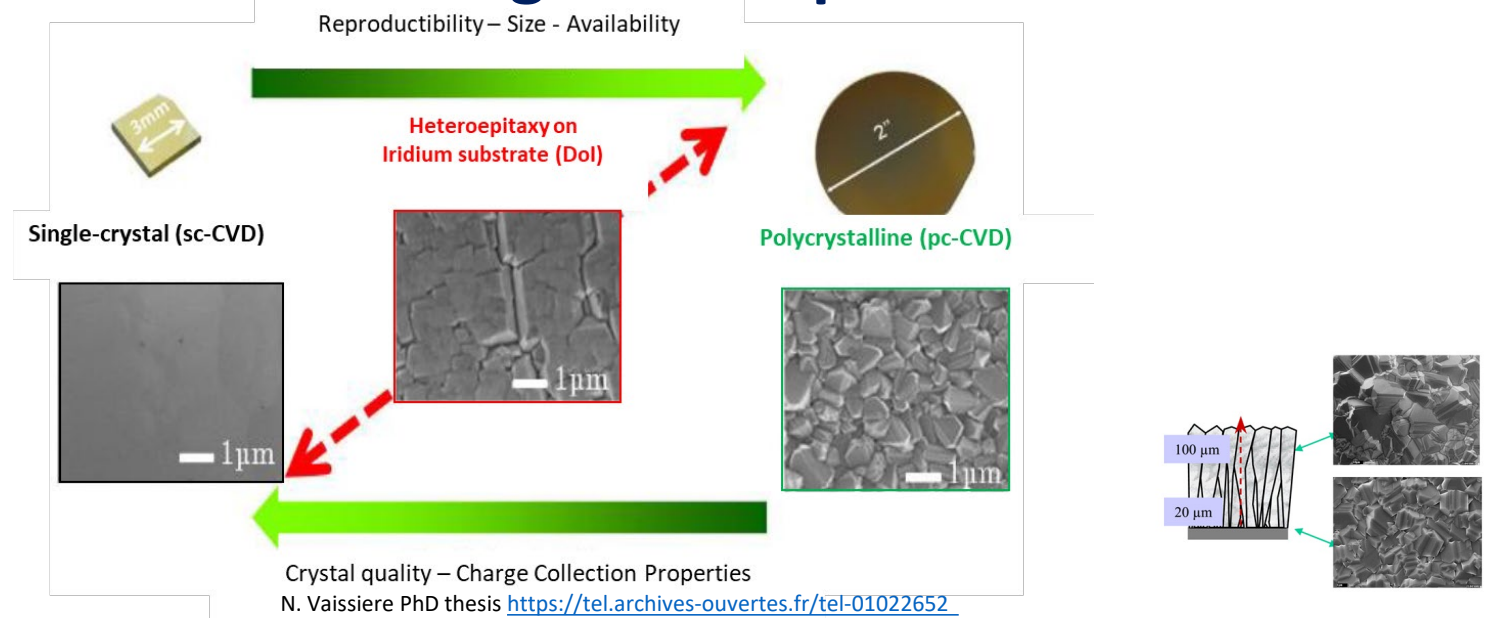
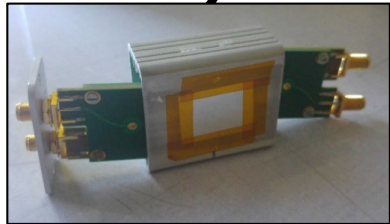
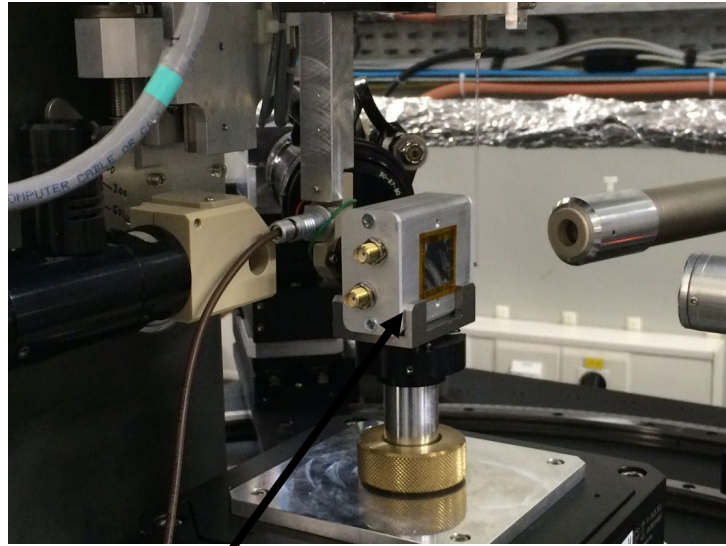


# Diamond detector for beam monitoring: sCVD ? pCVD ? DOI ?

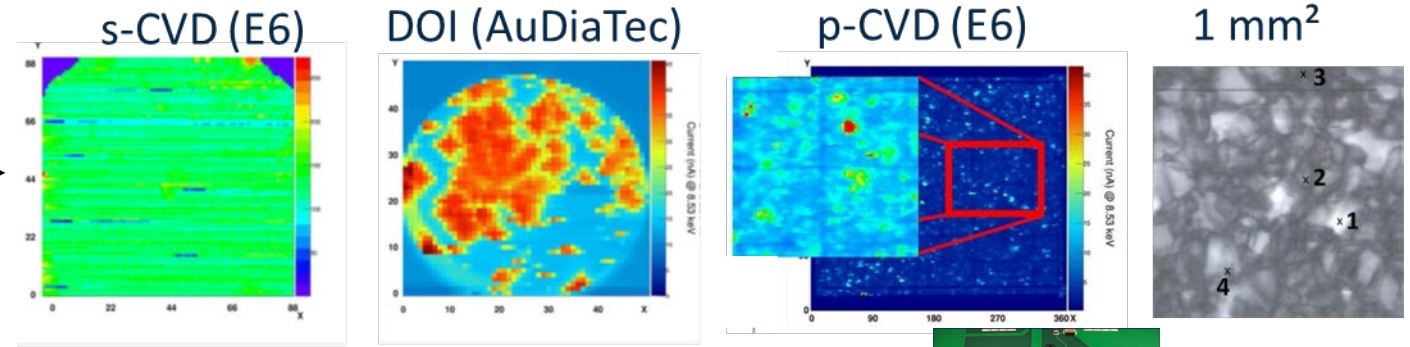


**XBIC = X rays Beam Induced Current  
@ ESRF (France) : Photons 8.5 keV**

# Diamond detector for beam monitoring: sCVD ? pCVD ? DOI ?

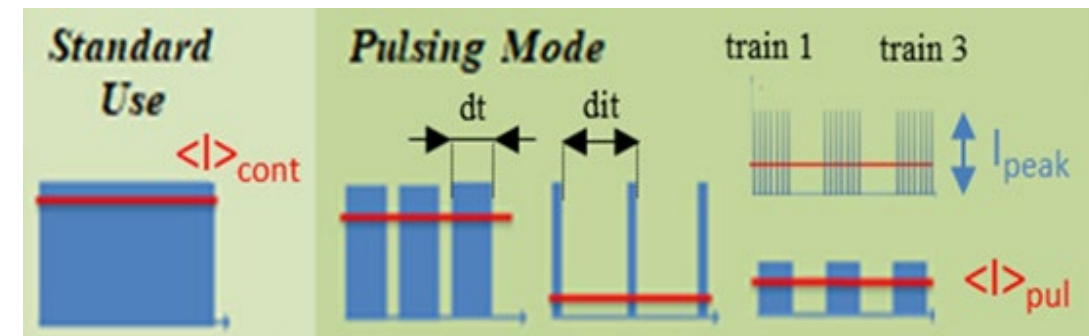
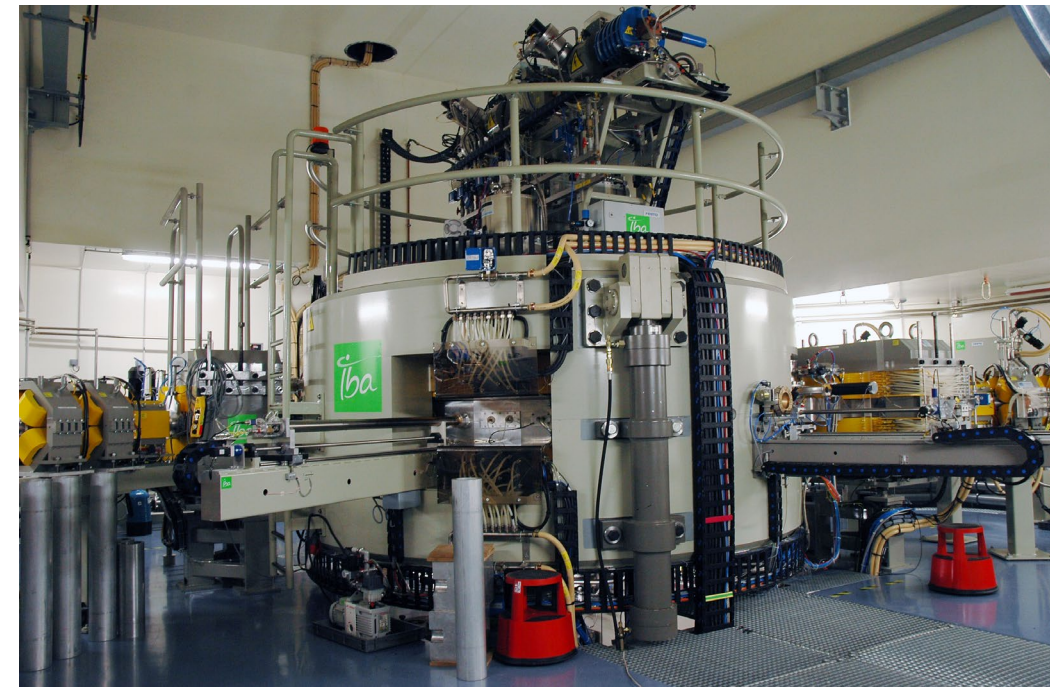


**XBIC = X rays Beam Induced Current**  
**@ ESRF (France) : Photons 8.5 keV => 2D « current maps » with CVD diamonds**



*ML Gallin-Martel Diamond and related materials 112 (2021) 108236*  
<https://doi.org/10.1016/j.diamond.2020.108236>



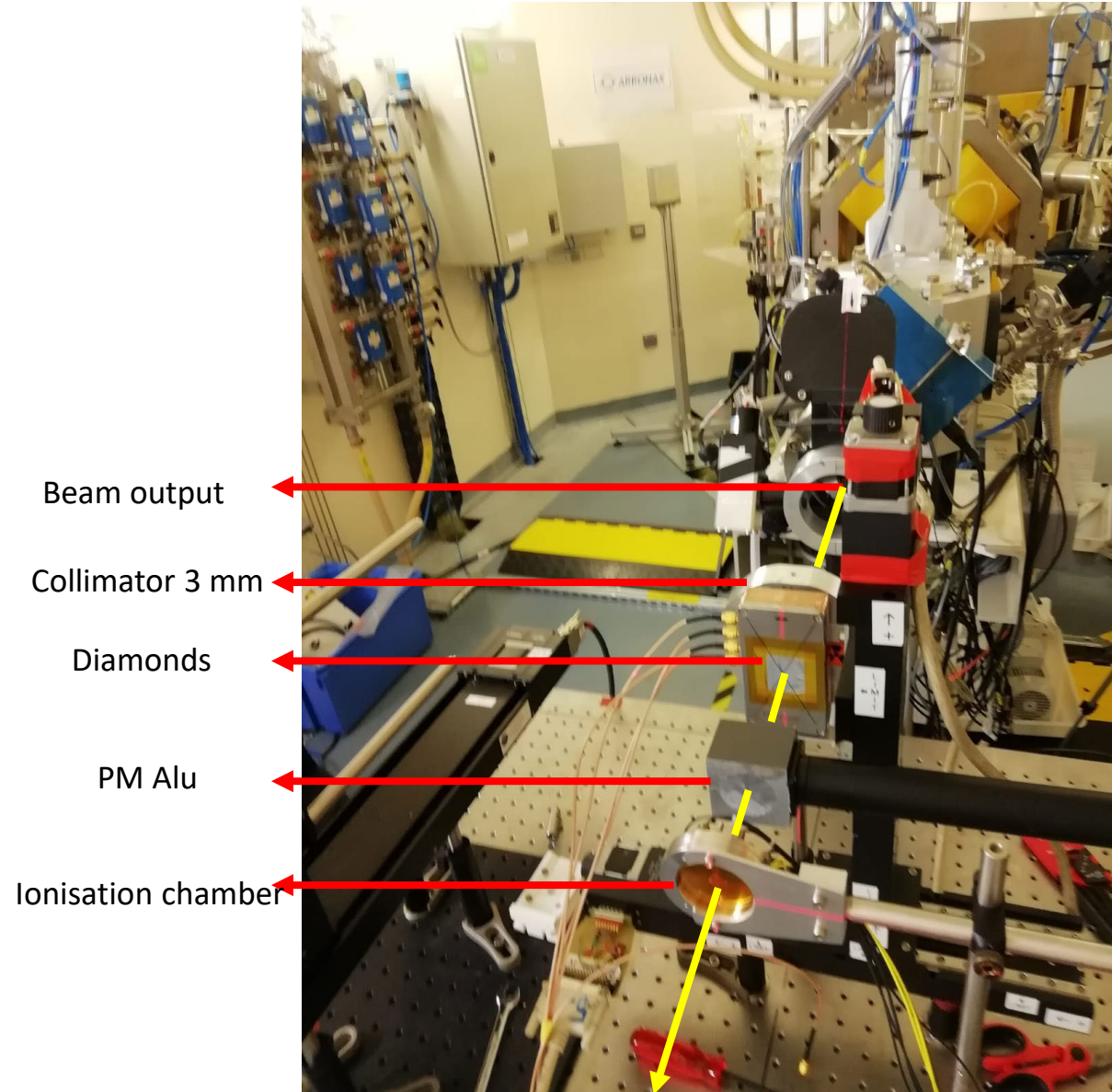


- 68 MeV proton / 70 MeV alpha particles cyclotron
- Beam intensity up to  $20\mu\text{A}$
- Continuous or pulse mode beam delivery with tunable dt and dit time duration
- Bunch : 4ns ON, 29ns OFF ( $f = 30,45\text{ MHz}$ )

Source: The pulsing chopper-based system of the ARRONAX C70XP Cyclotron, Poirier et al., International Particle Accelerator Conference, 2019. URL

<https://doi.org/10.18429/JACoW-IPAC2019-TUPTS008>

# Beam test set-up in ARRONAX with 68 MeV proton beams



Beam output

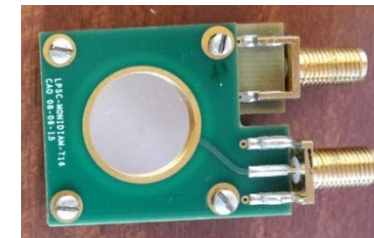
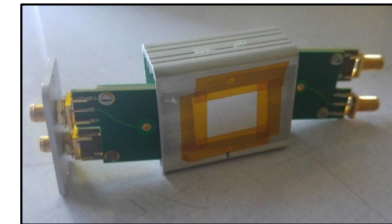
Collimator 3 mm

Diamonds

PM Alu

Ionisation chamber

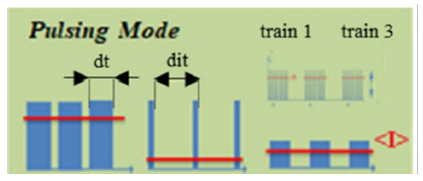
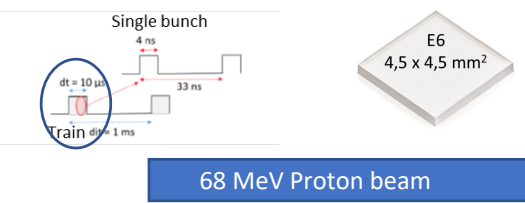
### Diamond set-up



# Train Counting Mode

Beam intensity up to 300 nA measured on diamond

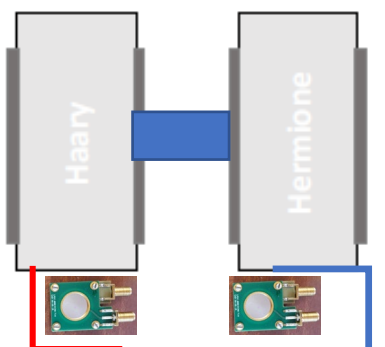
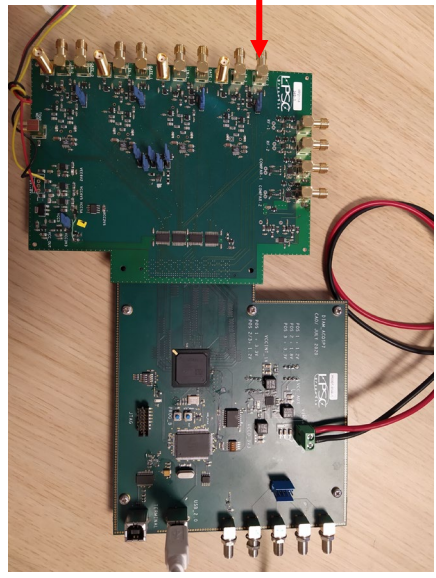
R. Molle  
PhD Thesis  
LPSC ARRONAX SUBATECH



$I = 10\text{ nA}$ ,  $dt = 10\mu\text{s}$ ,  $dit = 1\text{ s}$

QDC board  
developped @ LPSC

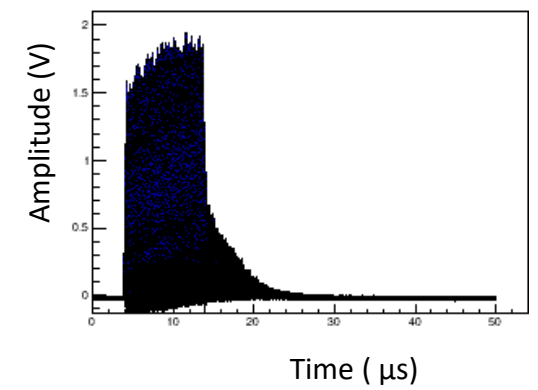
DAQ  
developped @ LPSC



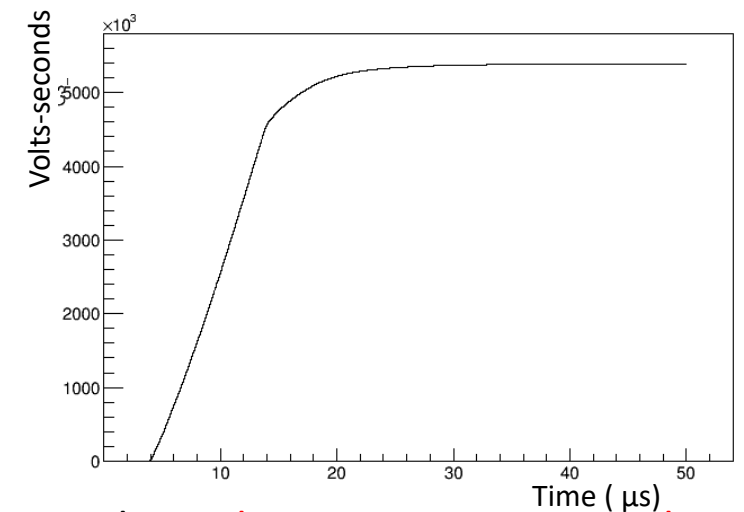
DSO Lecroy  
2 GHz; 10 or 20 GS/s



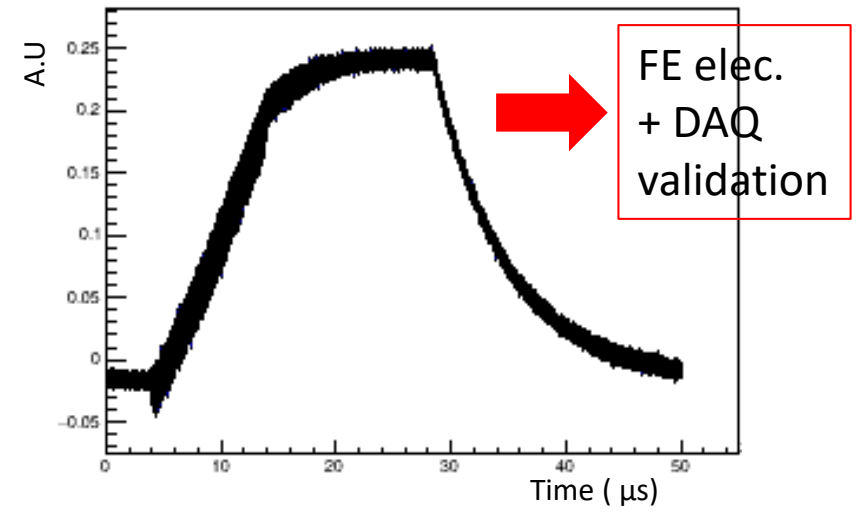
Train - Diamond signal



Train integral = DSO post analysis

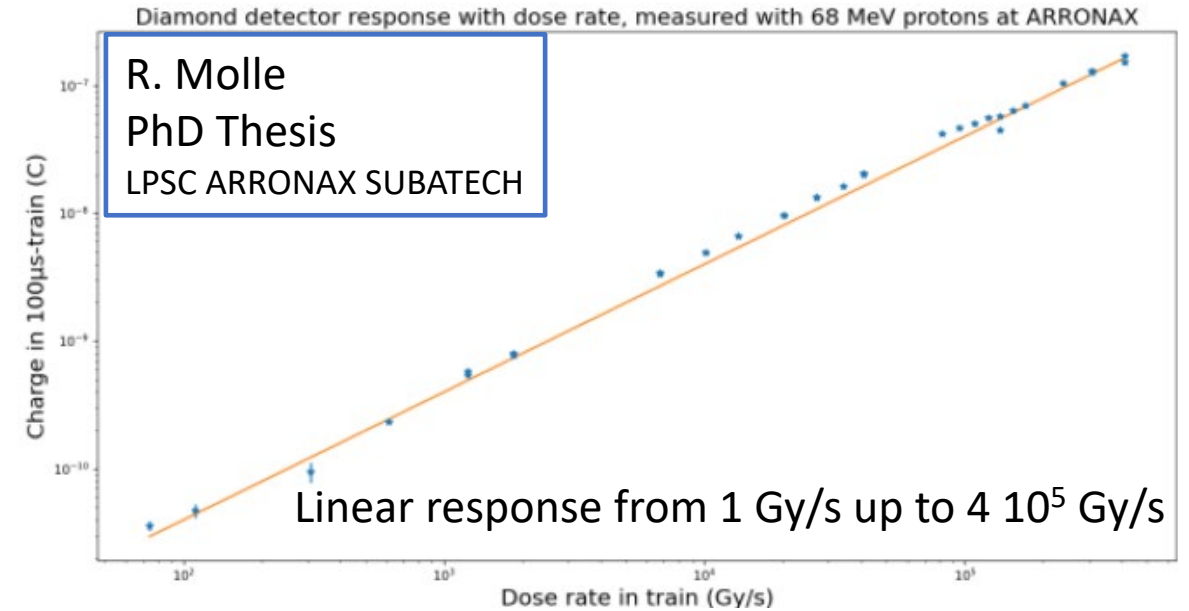
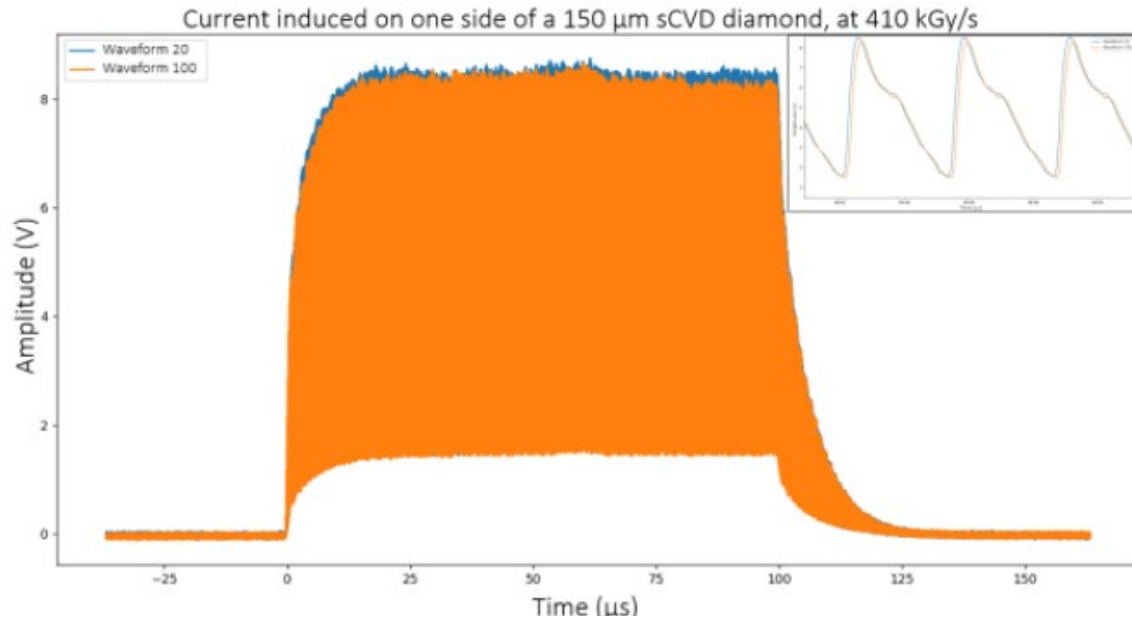


Train integral = on line measurement with LPSC QDC



## Study of linearity as a function of beam intensity

E6  
4,5 x 4,5 mm<sup>2</sup>

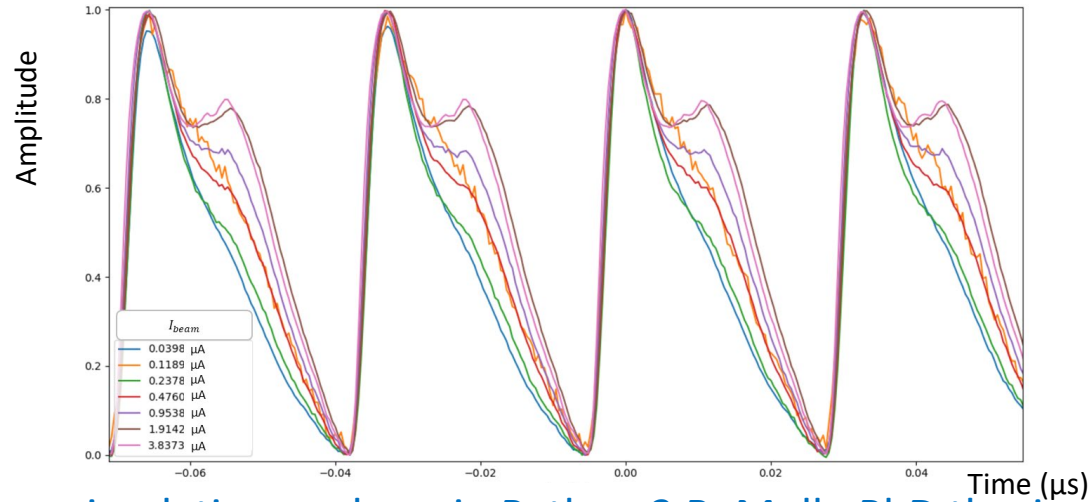


DIAMMONI equipped with :  
150 μm thick sCVD diamonds mounted on PCB  
+ QDC FE  
+ DAQ

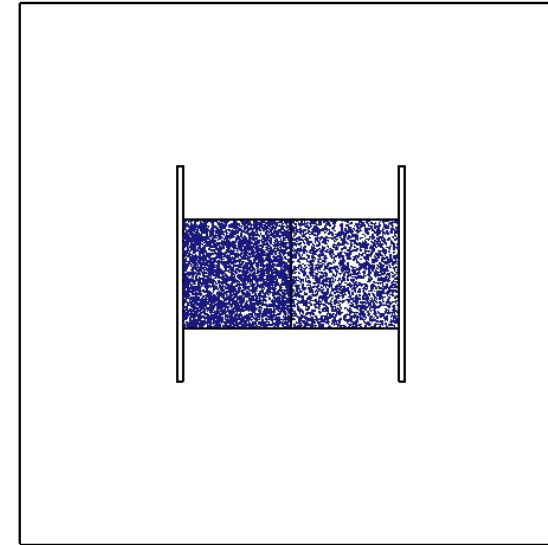


for monitoring proton beams in FLASH conditions

150  $\mu\text{m}$  sCVD diamond signal for different beam intensities  
(amplitude normalized)

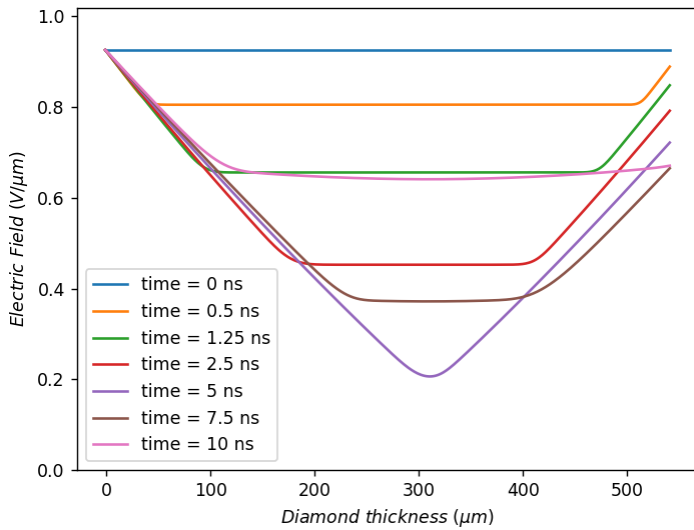


Simulation with a gaseous ionisation chamber

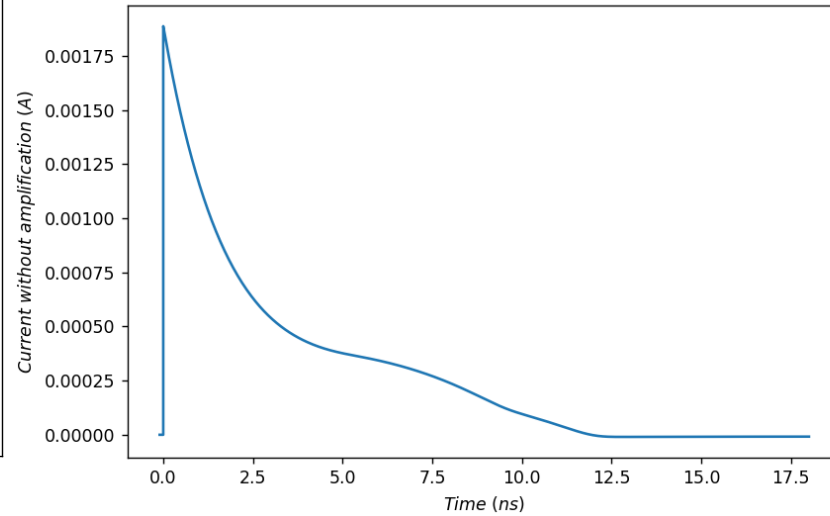


PyDiam simulation package in Python 3 R. Molle PhD thesis

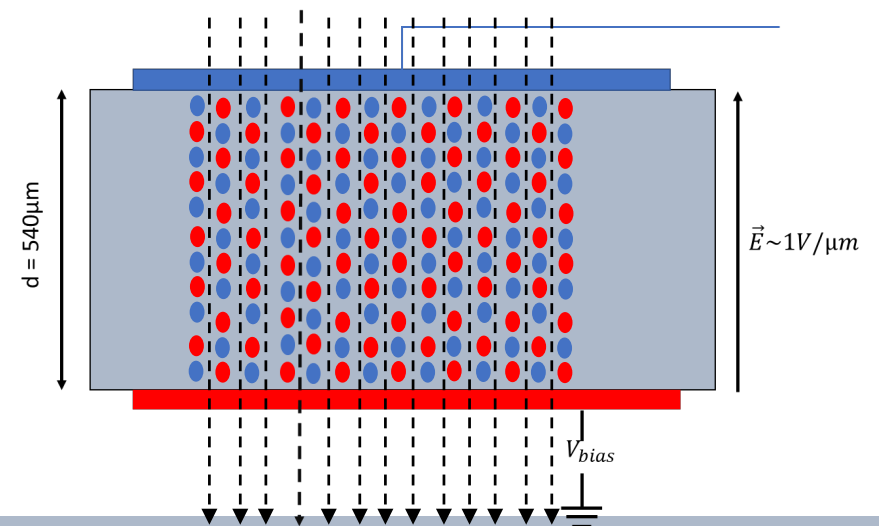
Electric Field



Measurable signal on diamond - 68MeV protons - Flux = 8.9E9 protons/cm<sup>2</sup>/s



Incoming particles

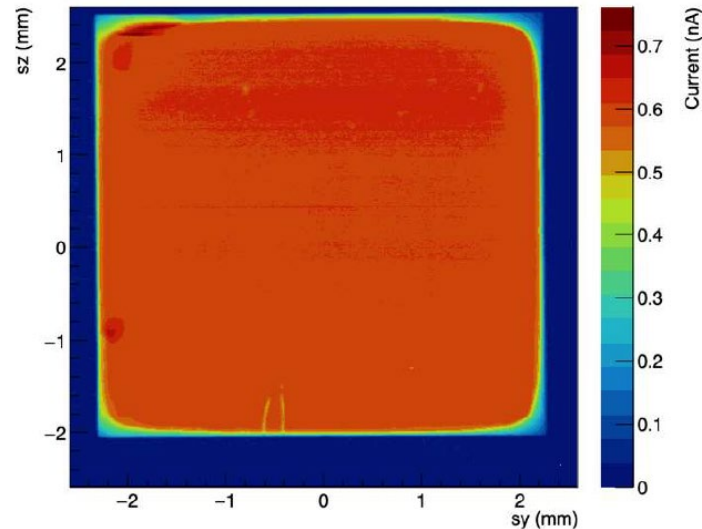


## Objectives of the “aging” experimental set-up:

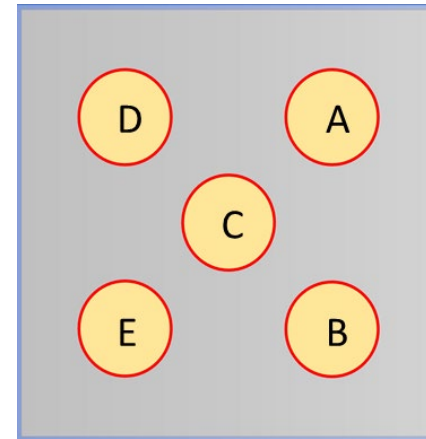
- each area corresponds to a beam intensity (= flux =  $\varphi$ )
- Irradiation of each zone until obtaining an identical cumulative fluence ( $=\phi$ ) between the zones at the end of the experiment

Before irradiation

sCVD 500 $\mu$ m E6



XBIC mapping at ESRF



Targeting objective



## See session M04, talk 526 F. Lafont

This diamond was irradiated with 68-MeV alpha particles at ARRONAX with a fluence of approximately  $10^{15}$  ions/cm<sup>2</sup>

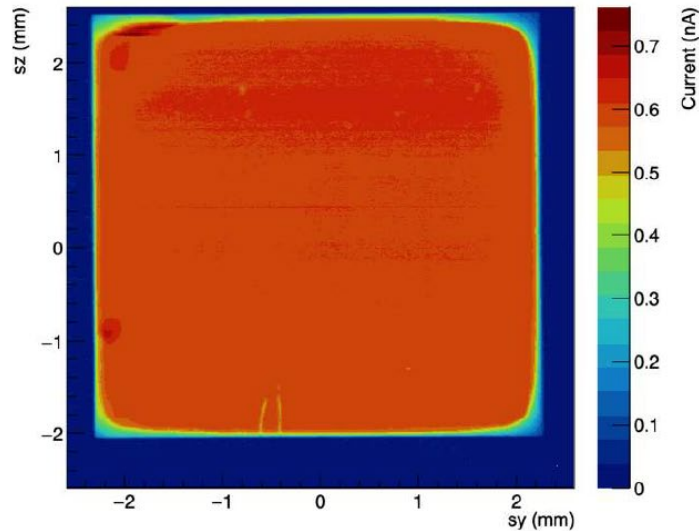
The absolute values cannot be compared since the beam intensity is not the same

The current scales are in relation to the X-beam intensities in the two experiments (before vs after irradiation)

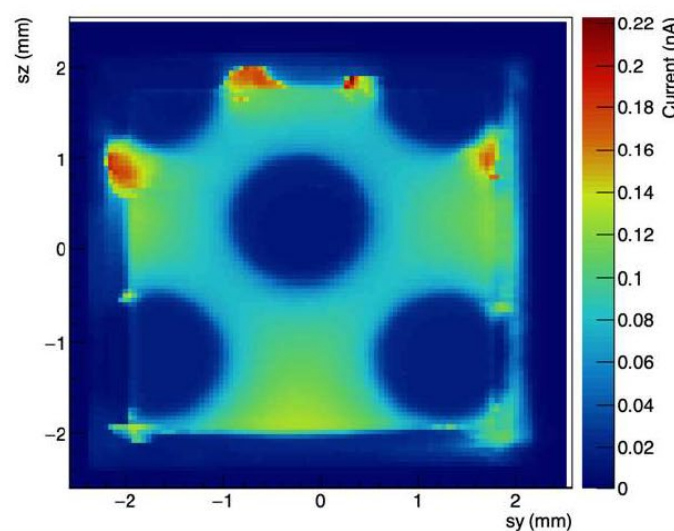
=> The main observation is that the XBIC is close to the leakage current in the irradiated areas which means that the charges are no longer collected.

Before irradiation

sCVD 500 $\mu$ m E6



XBIC mapping at ESRF



XBIC mapping at ESRF

*In blue the areas of less effective charge collection*

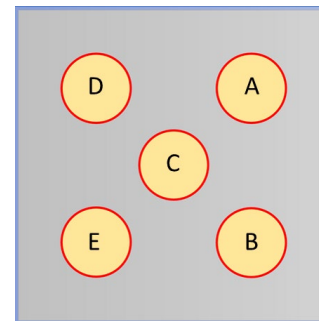
After irradiation

To understand if the origin of this degradation, Bragg diffraction imaging was performed.

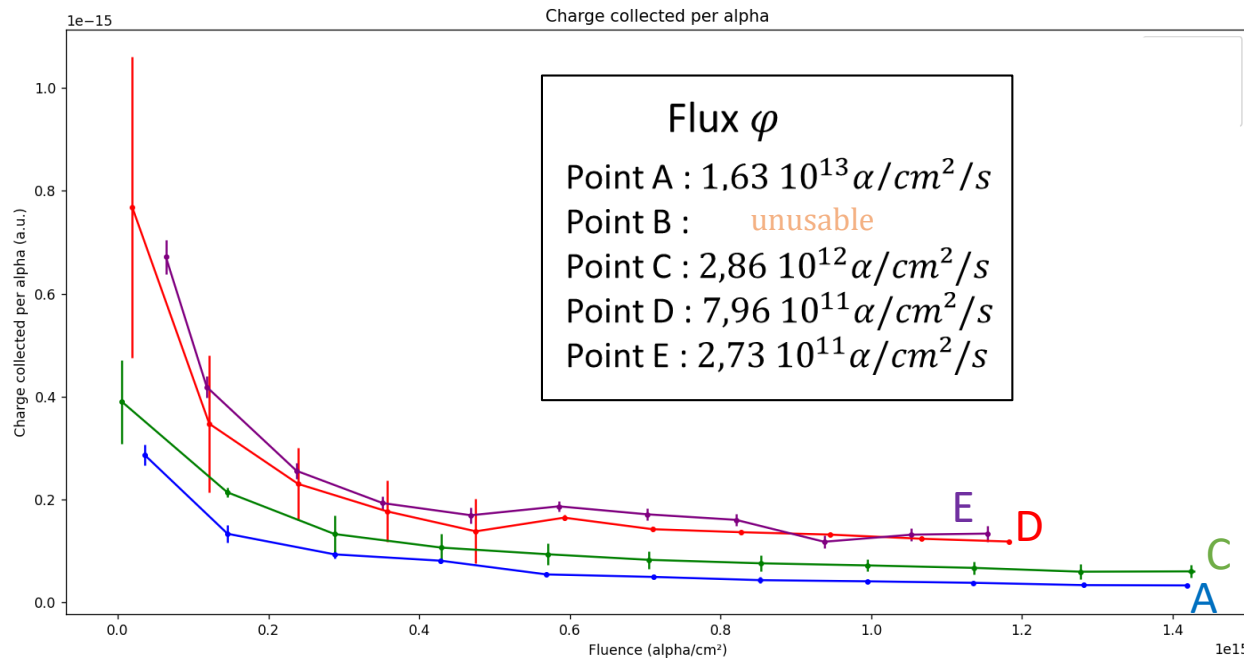
No irradiation-related structural defects are visible => the vacancies created by the irradiation are too far from one another to induce a significant deformation of the crystalline mesh.

From simple calculations, we estimated the displacements per atom to be of the order of few p.p.m

## Impact of flux on charge collection efficiency



CCE : Charge Collection Efficiency



Charge normalized by alpha particle

With increasing flux, charge collection decreases.

The fluence creates damage in the detector.

→ It results in the creation of traps that disrupt the collection of charges.

Possibly reversible phenomenon: annealing?

Annealing studies are on going ! Results soon ...

# Conclusion

- **The development are in connection with collaborations established at CNRS and ESRF**
- **It has been done in the context of interdisciplinary research IN2P3 INP skills exchanges take place between**
  - characterization: sources (labs) + accelerator beams @ IN2P3 GIP - ARRONAX, XBIC @ ESRF +...
  - Instrumentation (IN2P3 labs, Institut Néel, etc.)
- **A diamond beam monitor + FE electronics and DAQ has been developed in the context of ANR-DIAMMONI :**
  - it satisfies beam monitoring in the FLASH therapy condition (linear response in the range 1 to 4  $10^5$  Gy/s)
  - the proposed detection systems will bring significant added value to the transfer of high dose rate flash radiotherapy to clinical trials
- **Aging studies are on going for a better understanding of the impact of very high fluences (up to  $10^{15}$  ions/cm<sup>2</sup>) on charge collection**



# THANKS FOR YOUR ATTENTION !

