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<https://hal.science/hal-04694008v1>

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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



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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 μA .

Context

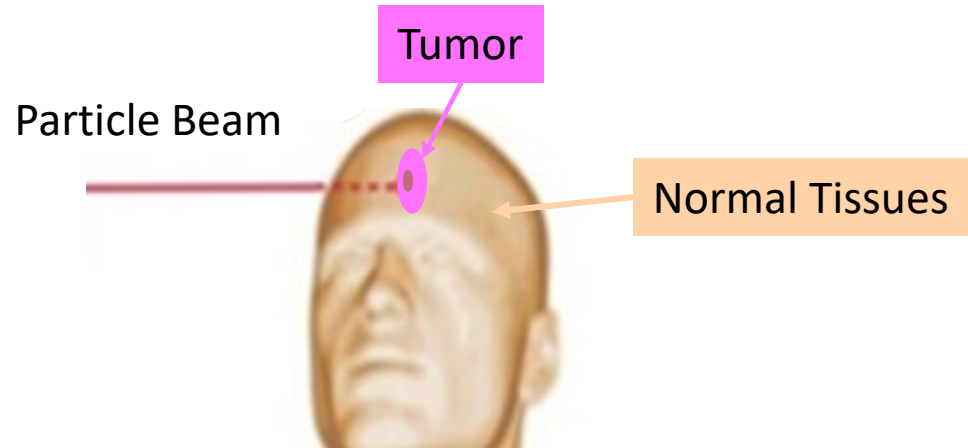
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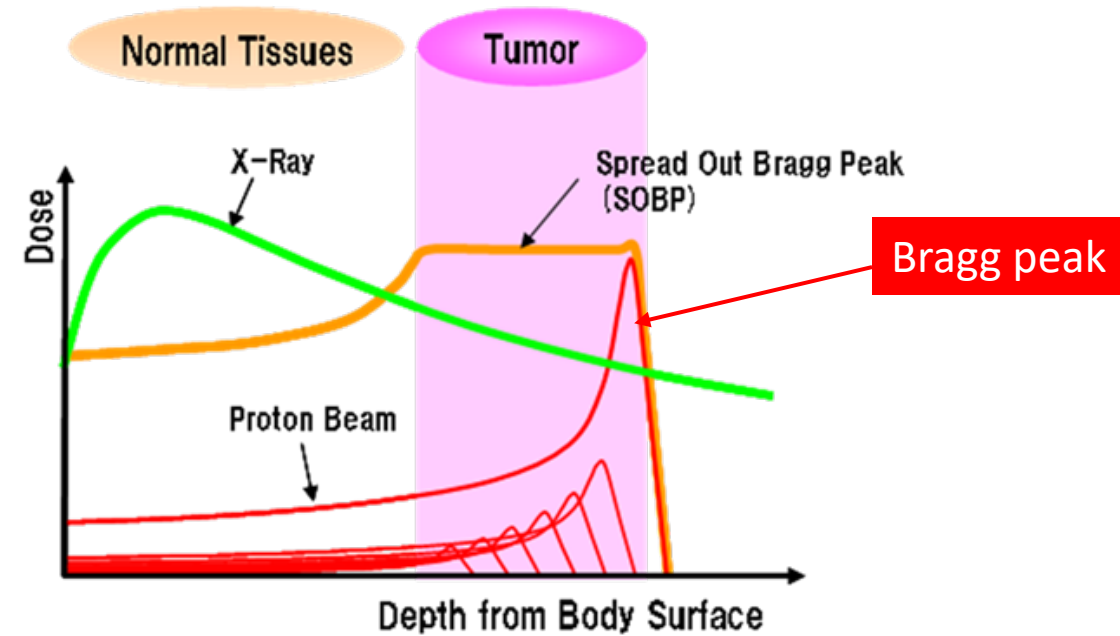
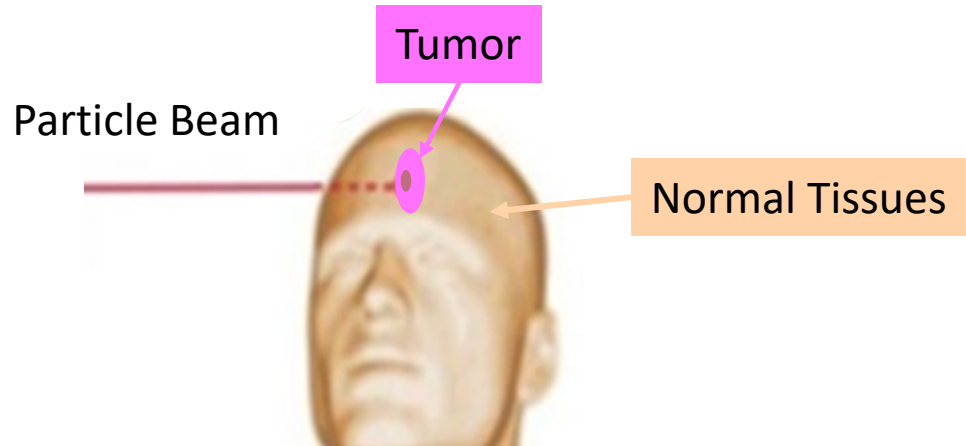
➤ The intrinsic qualities of diamond:

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What is hadrontherapy in cancer treatment ?



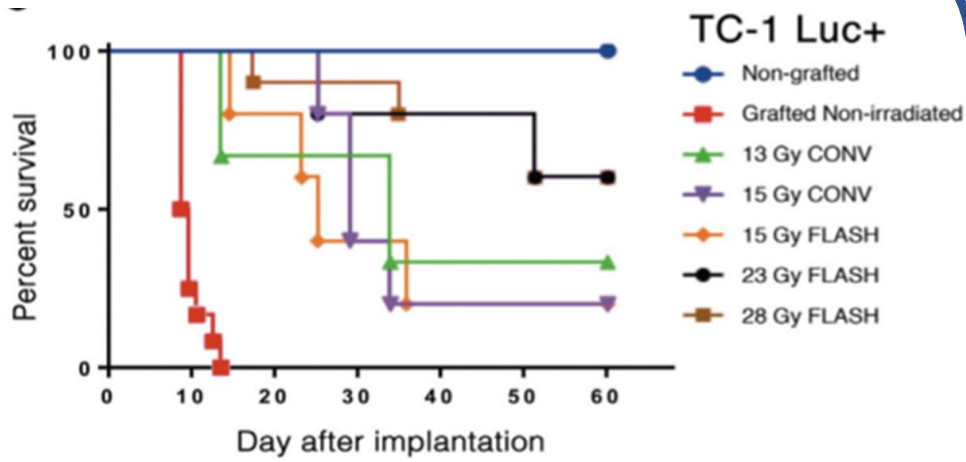
Hadrontherapy in cancer treatment



- 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 !



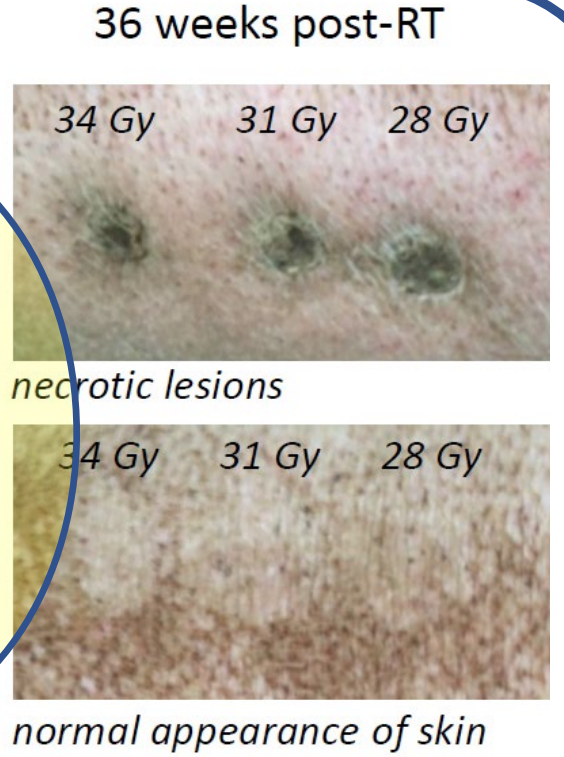
Favaudon et al (2015)
<https://www.sciencedirect.com/science/article/abs/pii/S1278321815001201?via%3Dihub>



1 Gy = 1 J/kg

Conventional
(5 Gy/min)

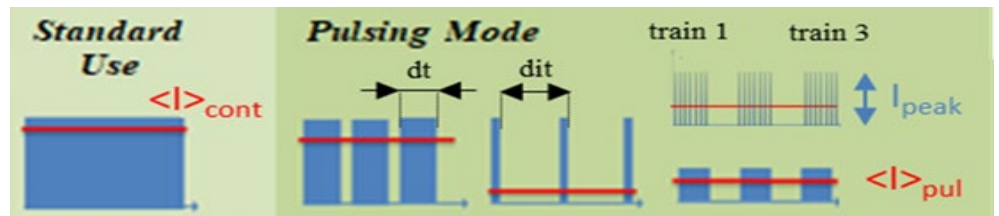
FLASH
(300 Gy/s)
3 Gy/pulse



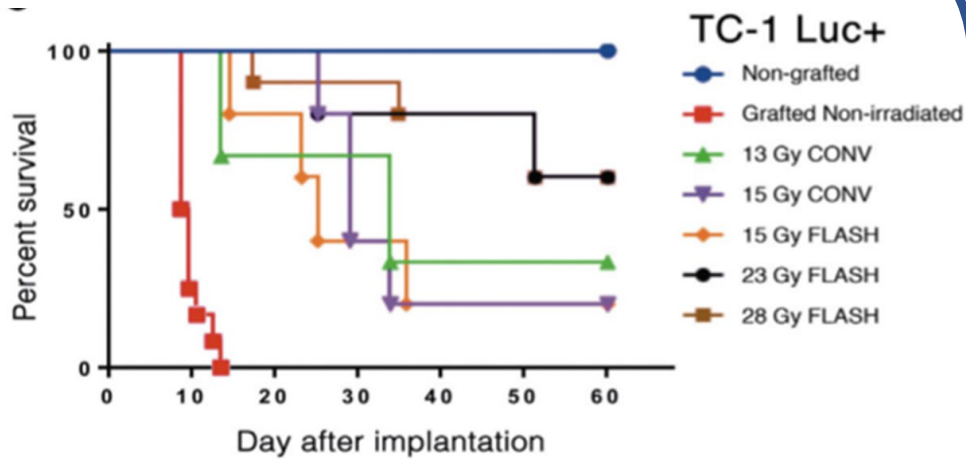
Vozenin et al., Clin Cancer Res 25 (2019) 35
<http://dx.doi.org/10.1158/1078-0432.CCR-17-3375>

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>



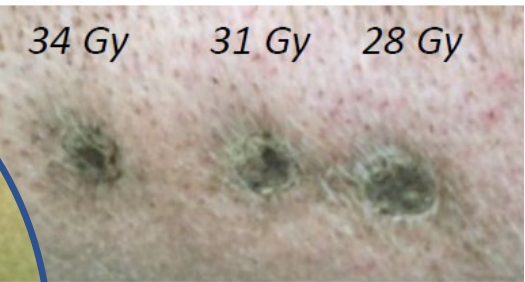
1 Gy = 1 J/kg

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

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Diamond beam monitors to be instrumented + FE electronics = QDC



ANR DIAMMONI 2020-2024



Diamond as beam monitors

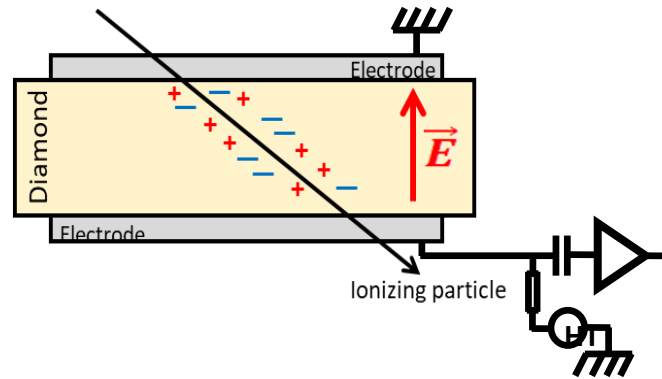
Solid state ionization chamber

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

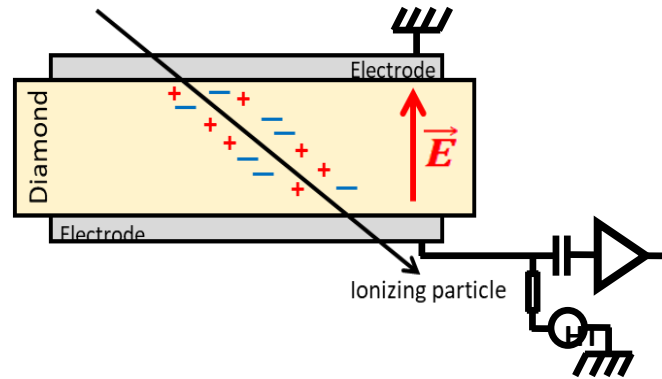
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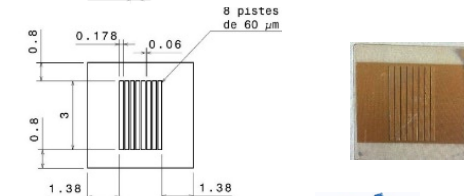
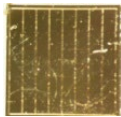
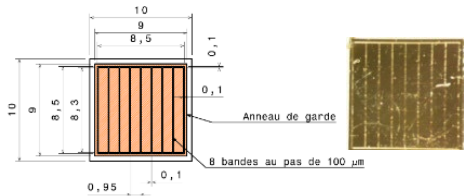
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Diamond metallisation



Diamond as beam monitors

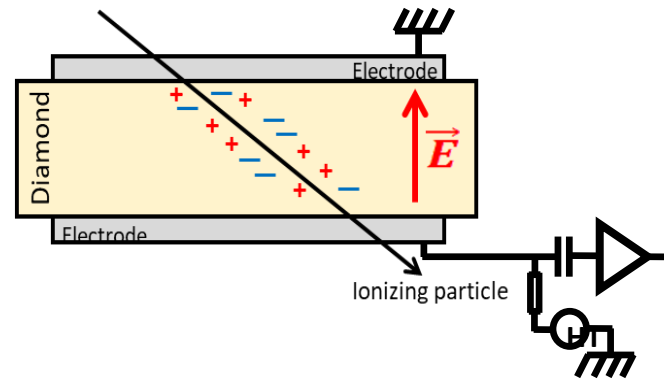
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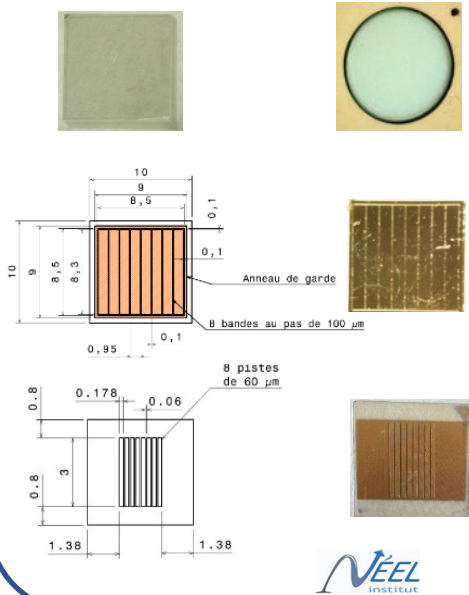
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Issues :

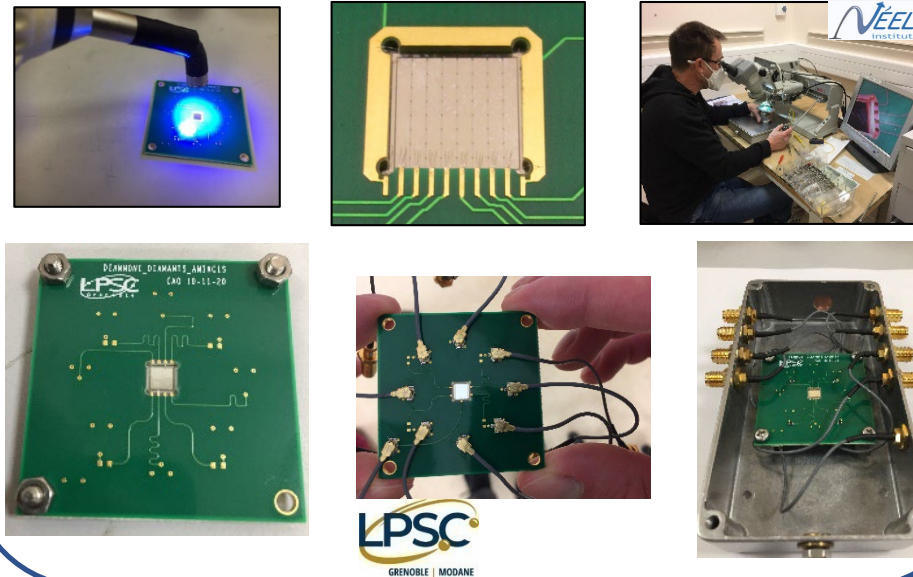
- Cost
- Availability of large area



Diamond metallisation



Detector assembly



Diamond as beam monitors

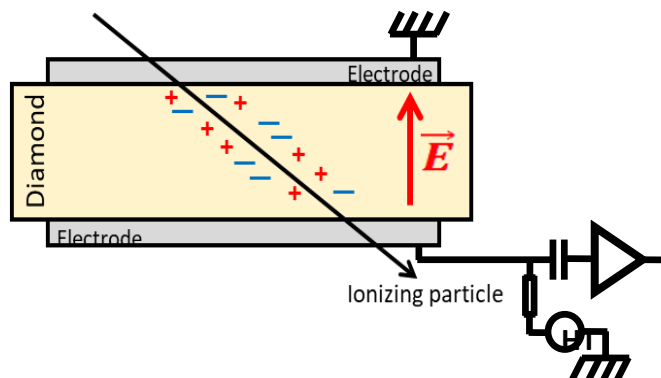
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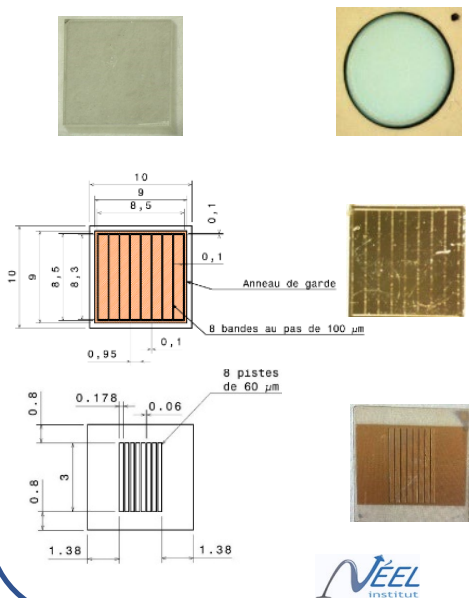
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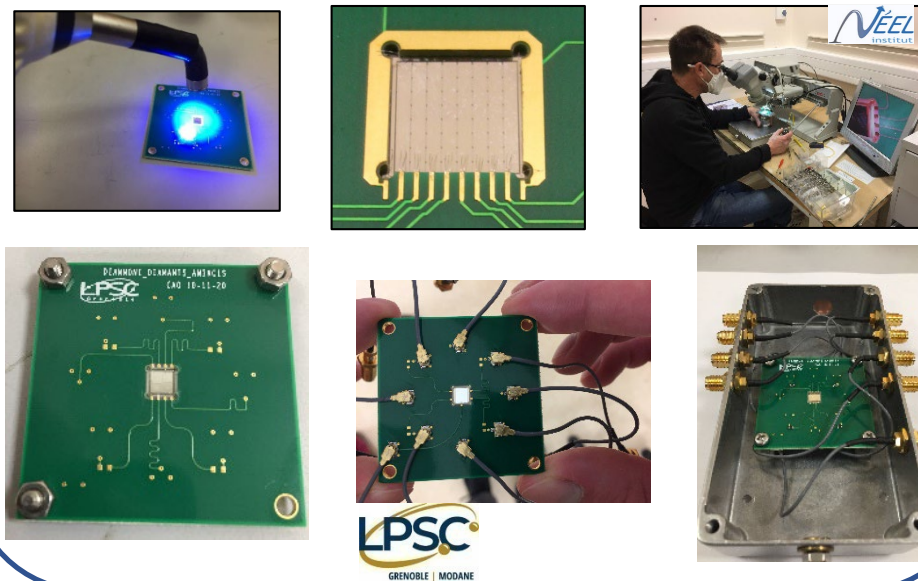
Read-out electronics

- Fast current preamplifier
- Charge preamplifier
- Electrometer

Diamond metallisation



Detector assembly



Diamond as beam monitors

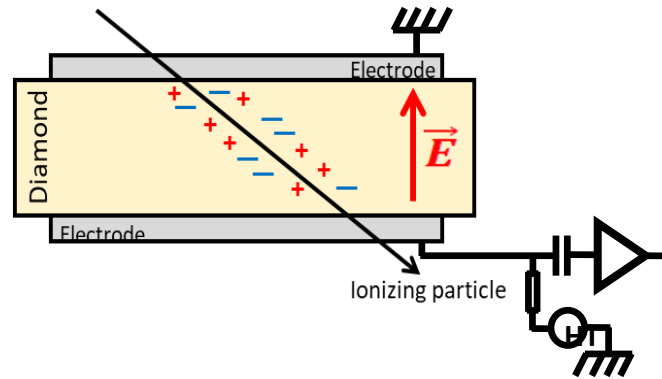
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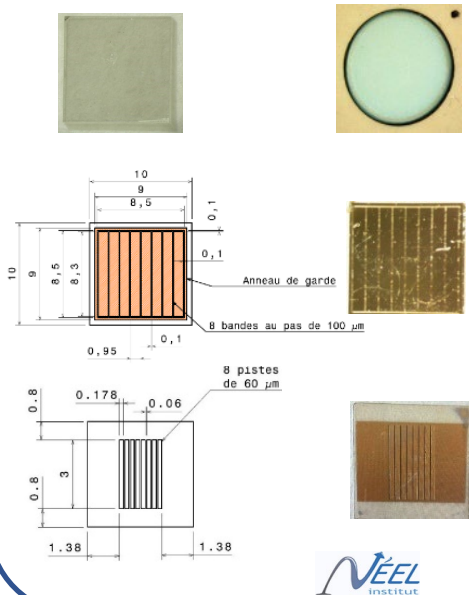
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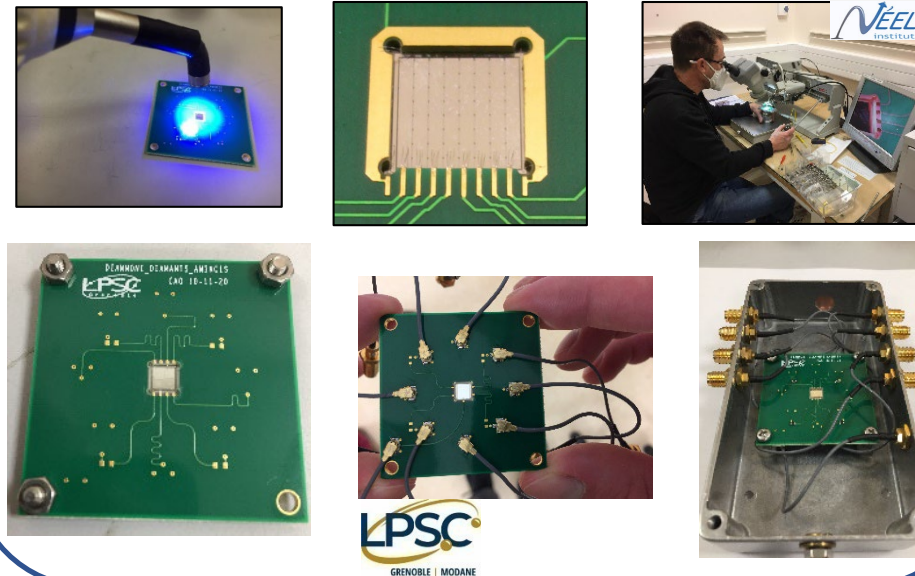


Band Width:	2 GHz
Gain:	40 dB
Impedance:	50 Ω
Dynamic range:	~ +/- 1 V
Power Supply:	12 V / 100 mA

Diamond metallisation



Detector assembly



Diamond as beam monitors

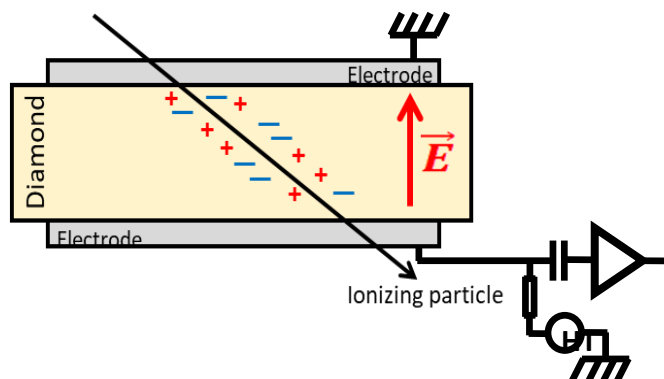
Solid state ionization chamber

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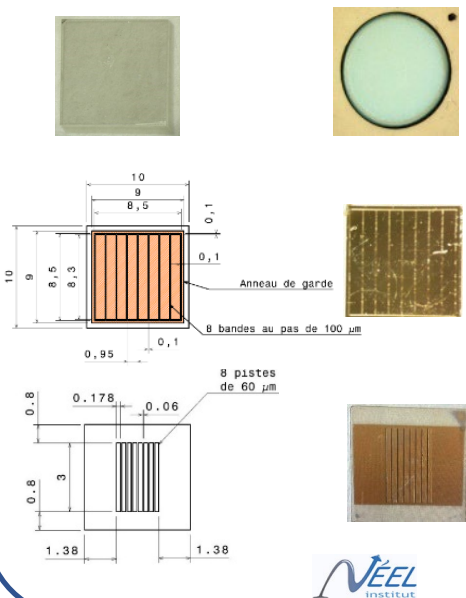
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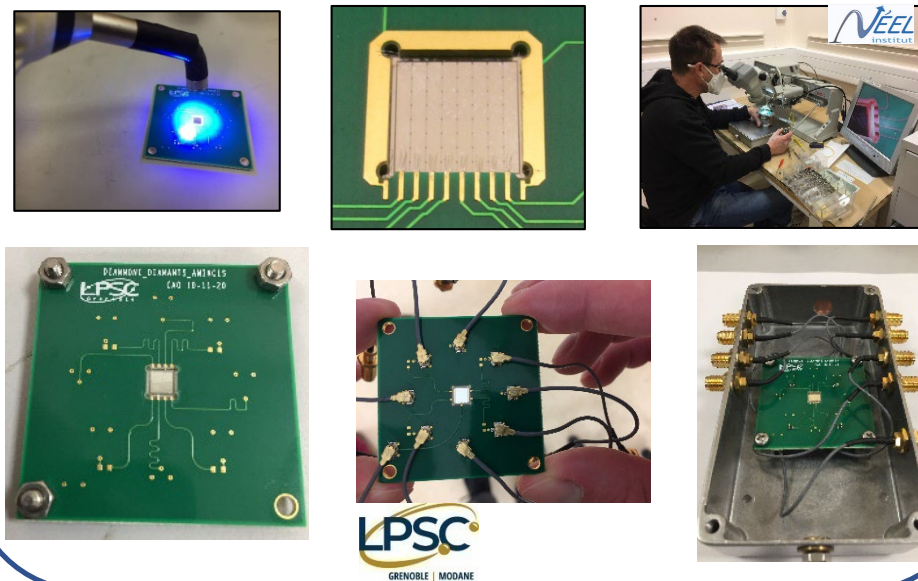
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Diamond metallisation



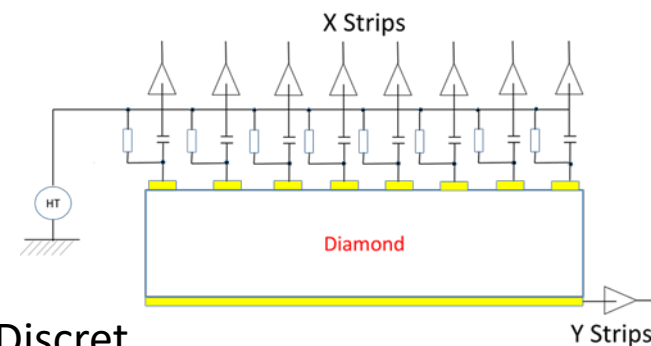
Detector assembly



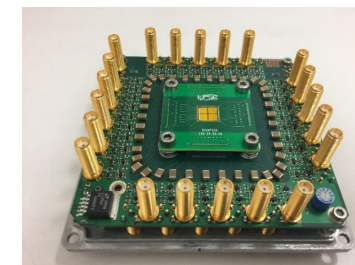
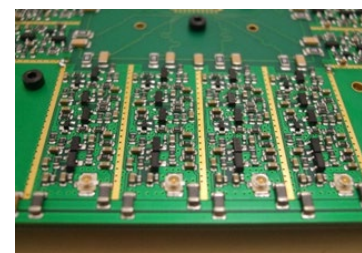
Read-out electronics

- Fast current preamplifier
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Read out electronics @ LPSC



Discret



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

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

Diamond as beam monitors

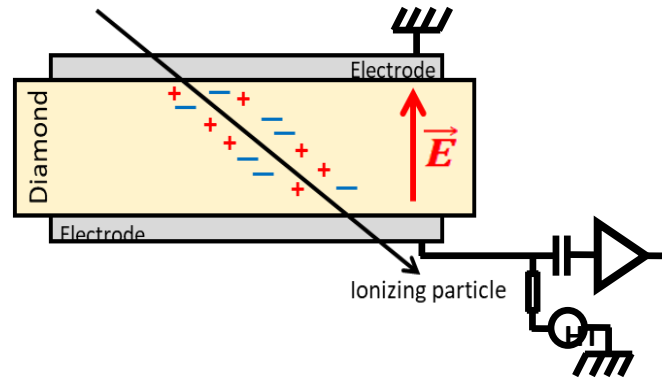
Solid state ionization chamber

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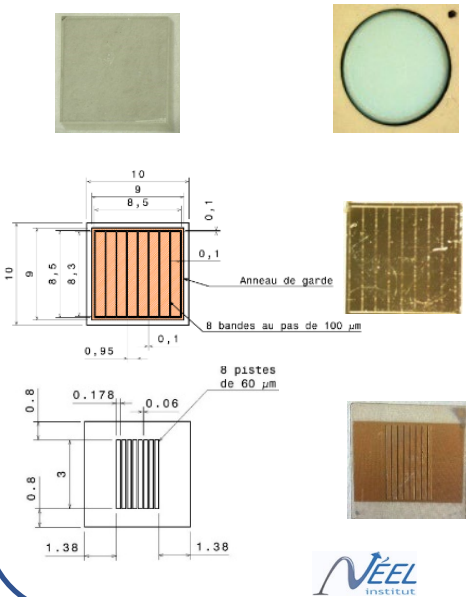
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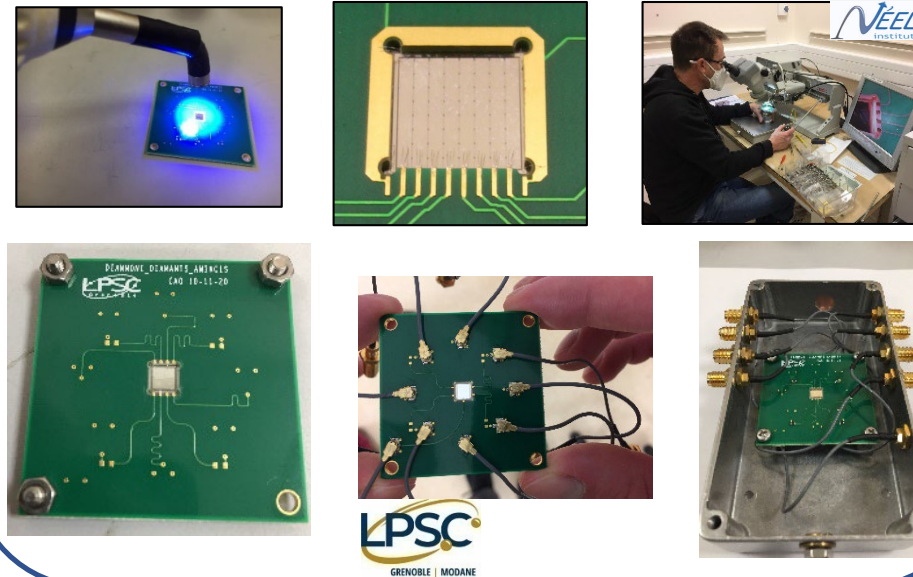
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Diamond metallisation



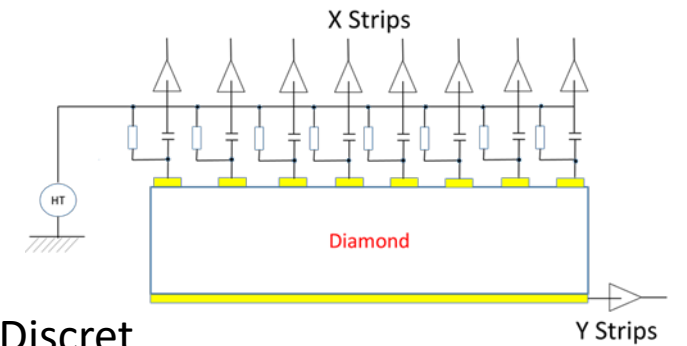
Detector assembly



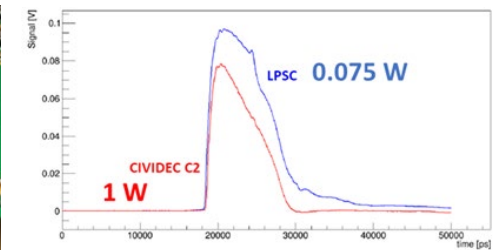
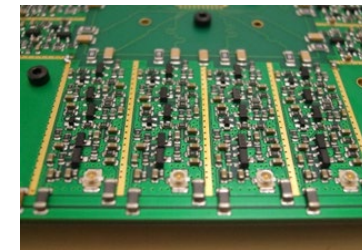
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- Electrometer

Read out electronics @ LPSC



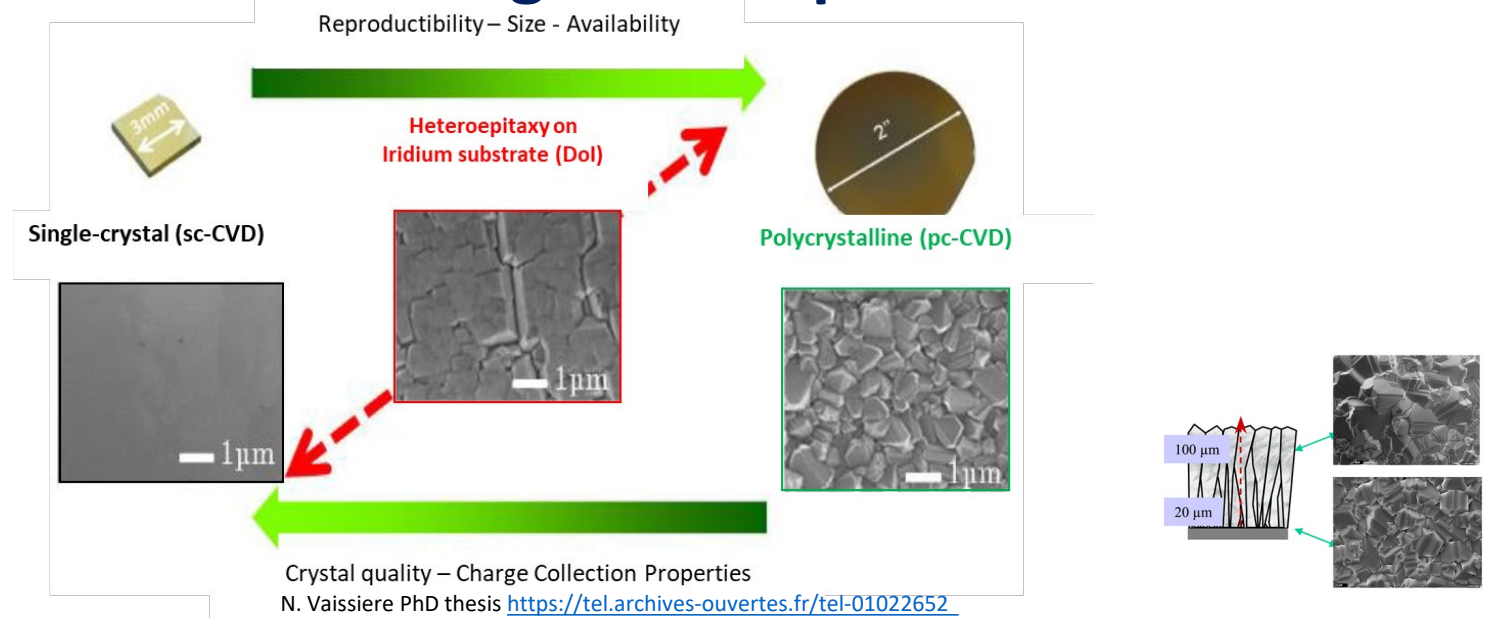
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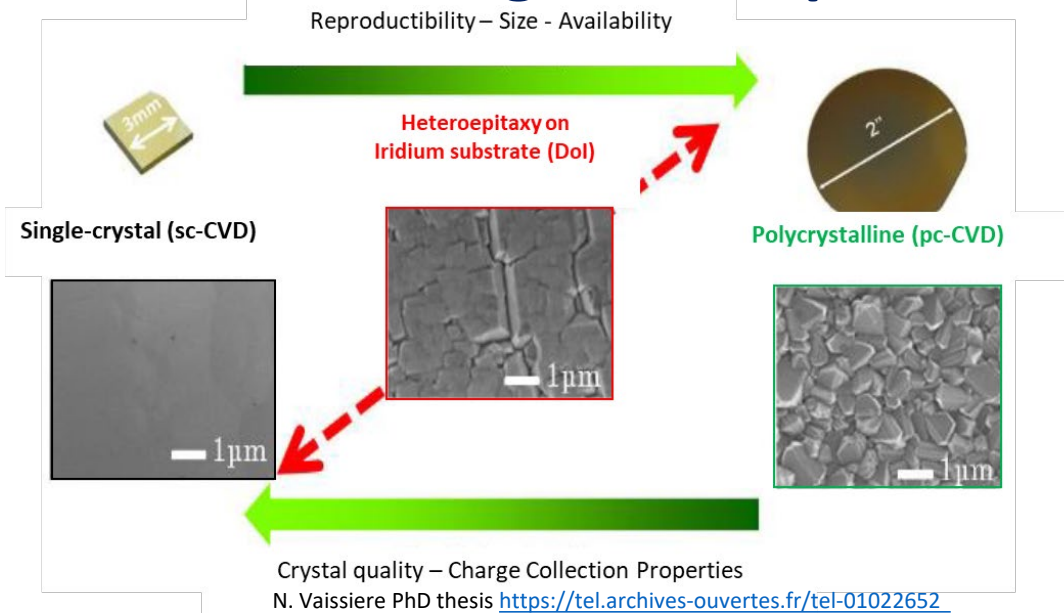
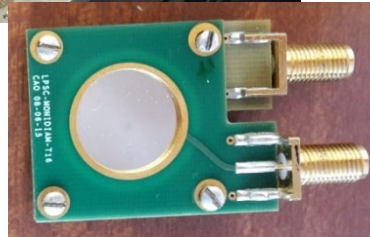
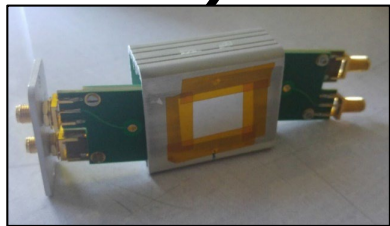
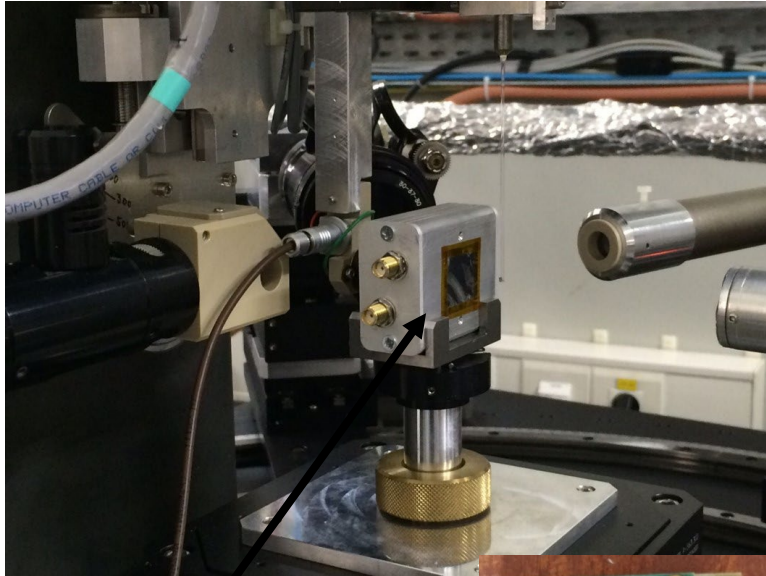
C. Hoarau *et al* 2021 *JINST* **16** T04005

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

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

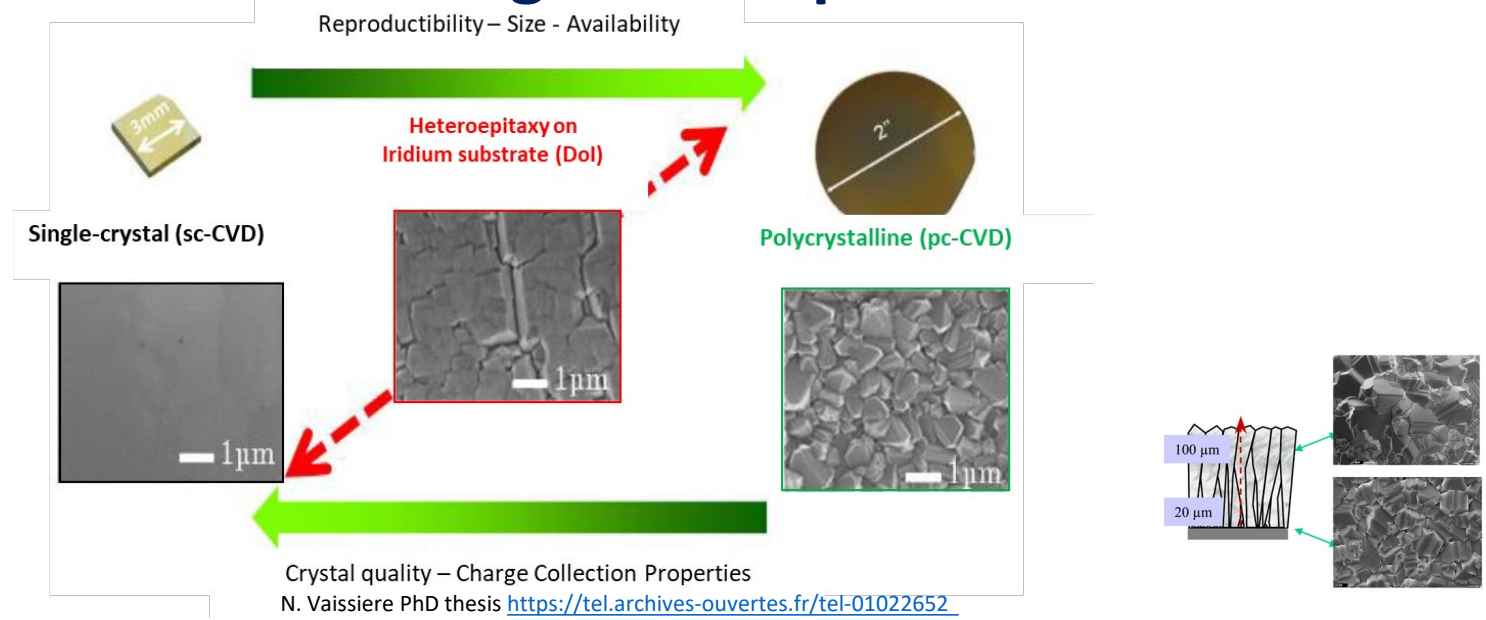
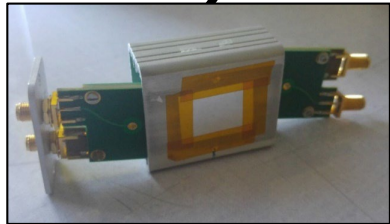
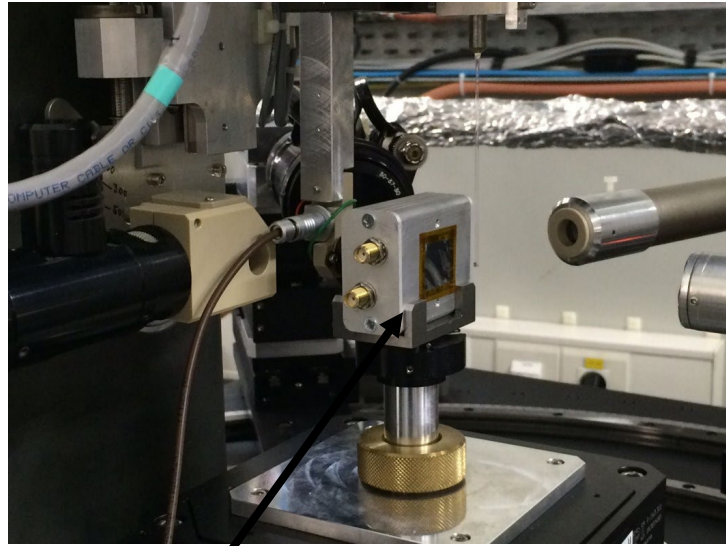


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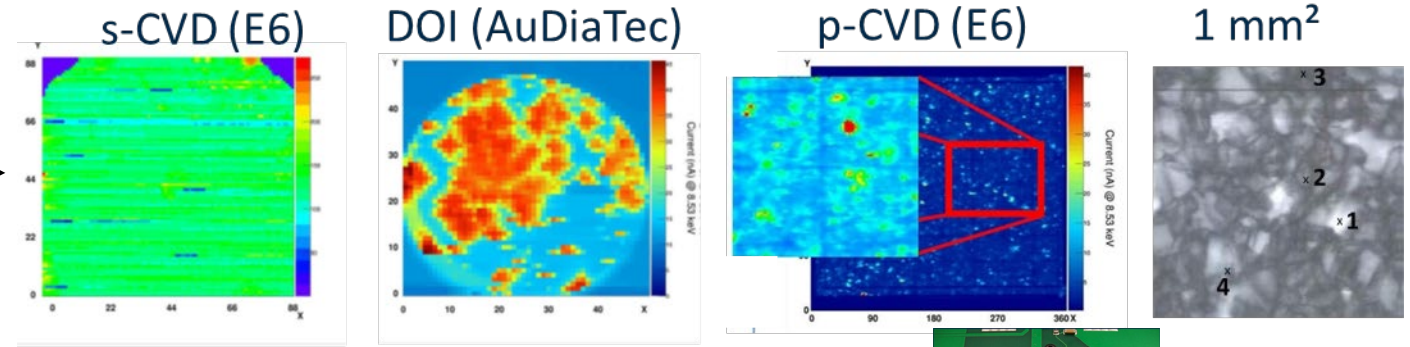


**XBIC = X rays Beam Induced Current
@ ESRF (France) : Photons 8.5 keV**

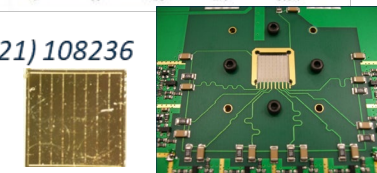
Diamond detector for beam monitoring: sCVD ? pCVD ? DOI ?



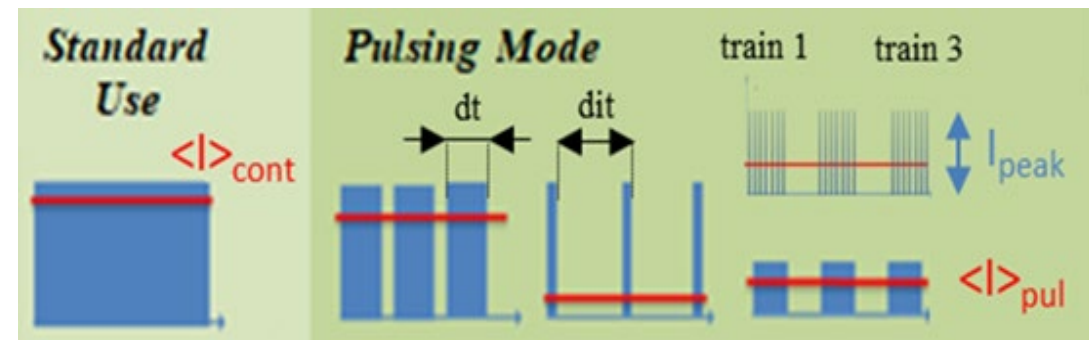
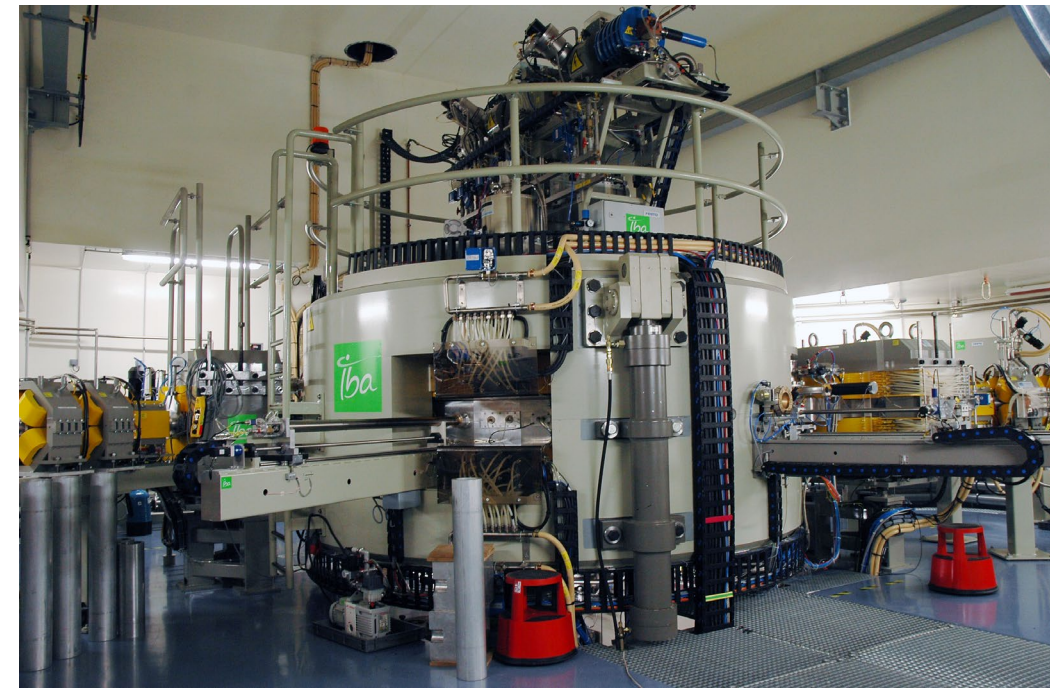
XBIC = X rays Beam Induced Current
@ ESRF (France) : Photons 8.5 keV => 2D « current maps » with CVD diamonds



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



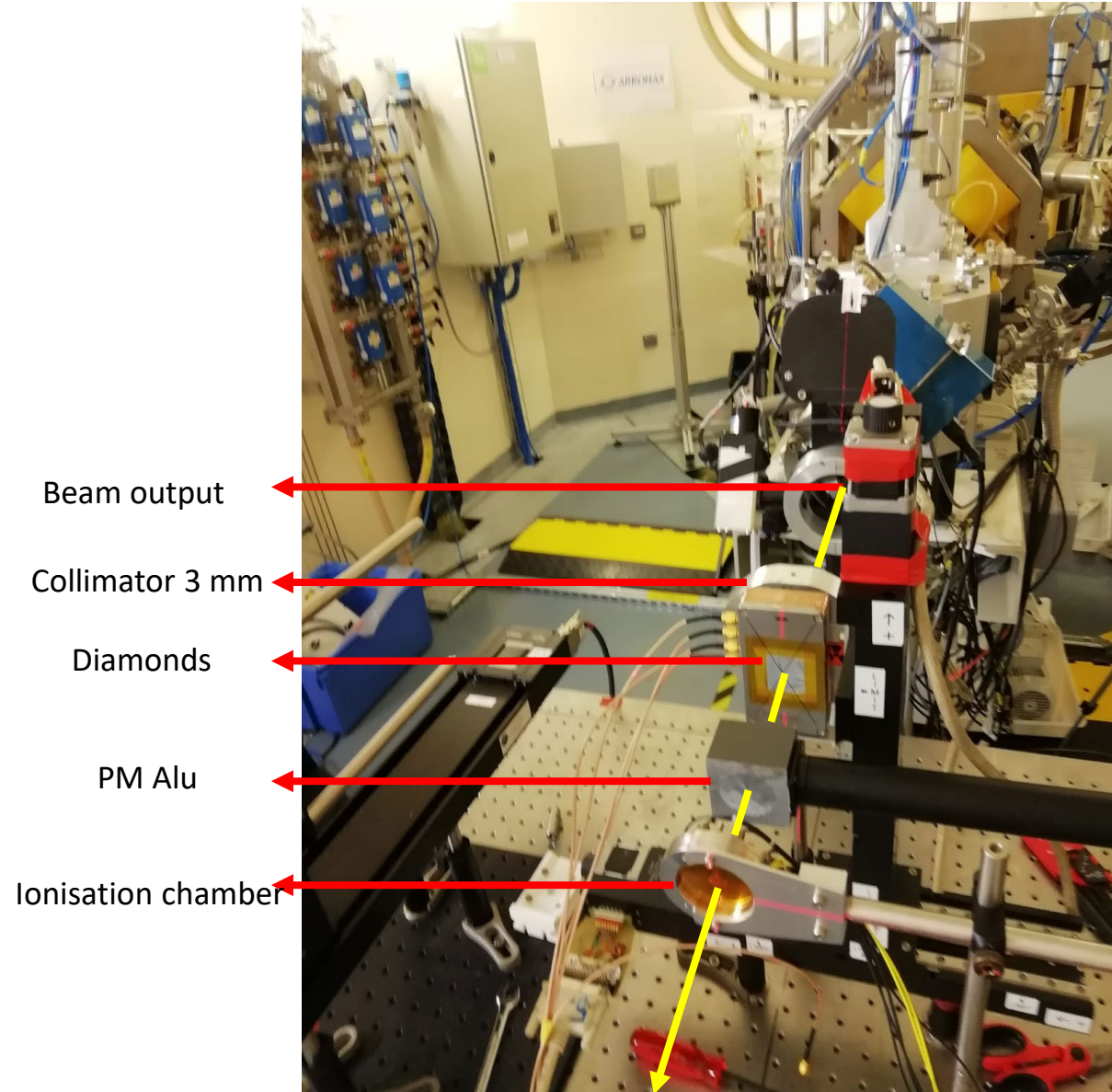
ARRONAX in Nantes (France)



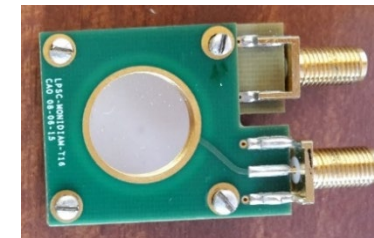
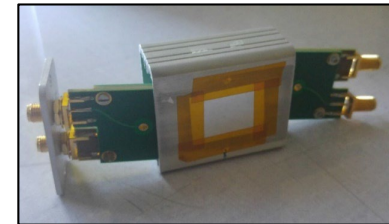
- 68 MeV proton / 70 MeV alpha particles cyclotron
- Beam intensity up to 20 μ A
- Continuous or pulse mode beam delivery with tunable dt and dit time duration
- Bunch : 4ns ON, 29ns OFF (f = 30,45 MHz)

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

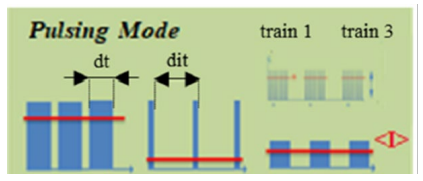
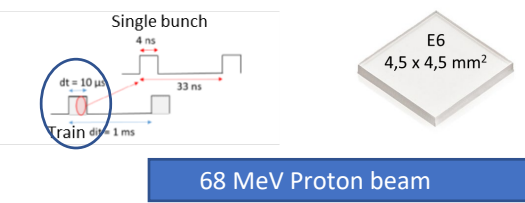


Diamond set-up



Train Counting Mode

Beam intensity up to 300 nA measured on diamond



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

QDC board developed @ LPSC

DAQ developed @ LPSC

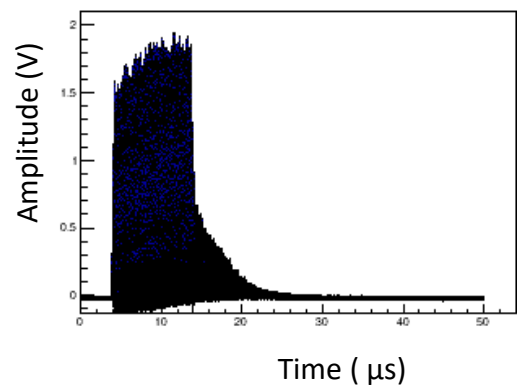


R. Molle
PhD Thesis
LPSC ARRONAX SUBATECH

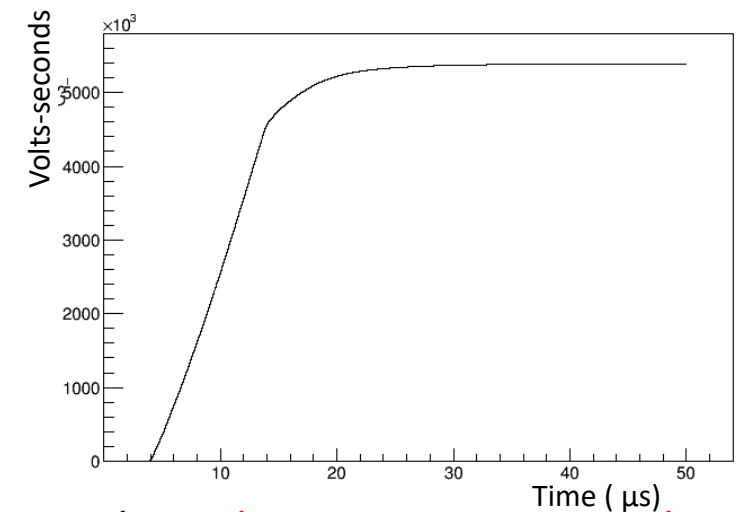
DSO Lecroy
2 GHz; 10 or 20 GS/s



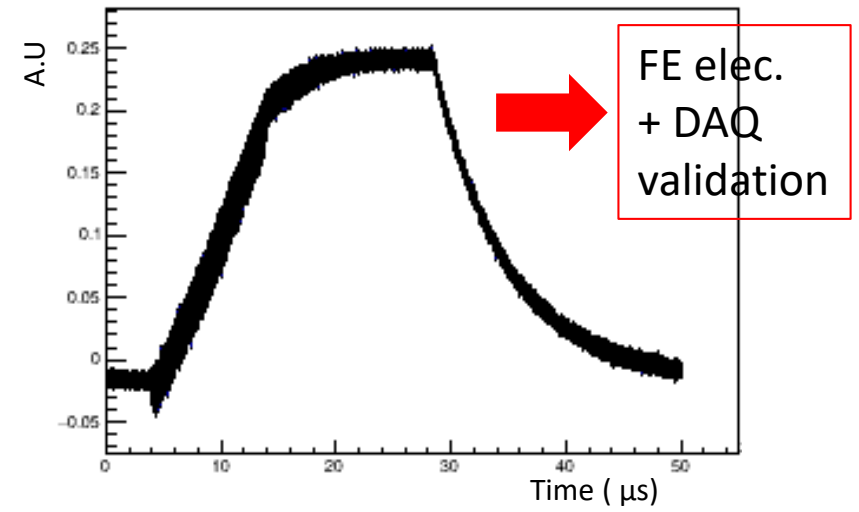
Train - Diamond signal



Train integral = DSO post analysis

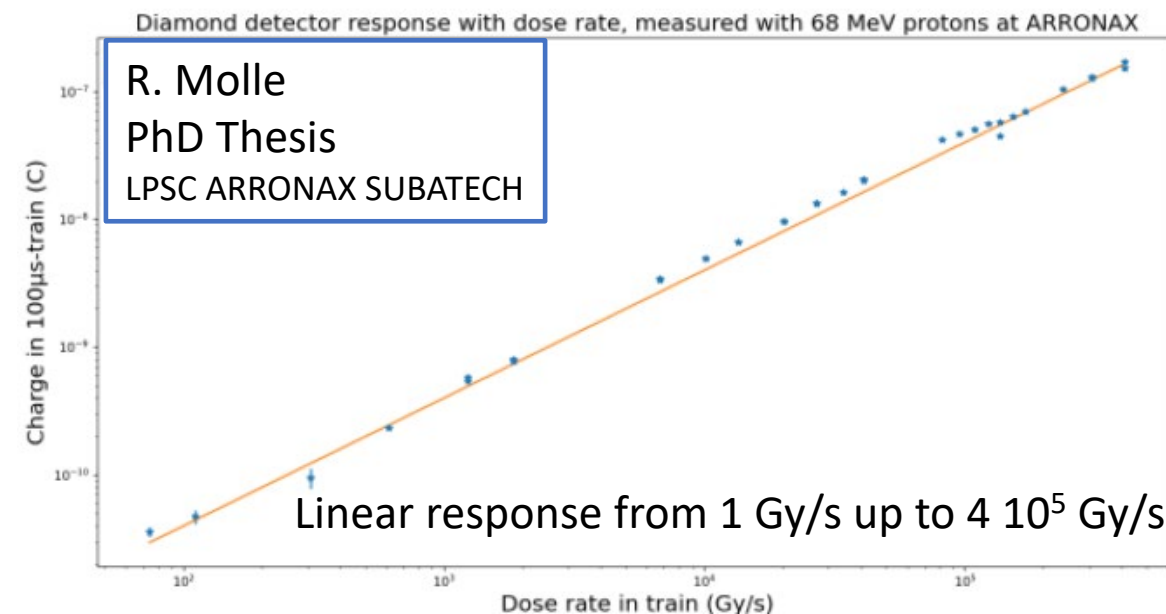
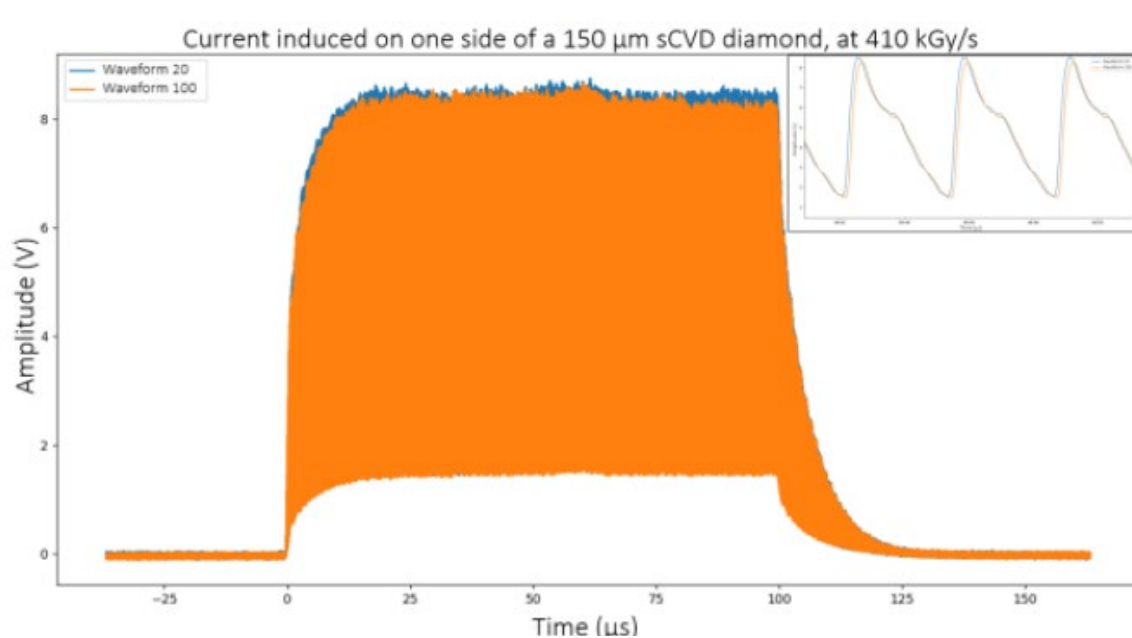


Train integral = on line measurement with LPSC QDC



Study of linearity as a function of beam intensity

E6
4,5 x 4,5 mm²

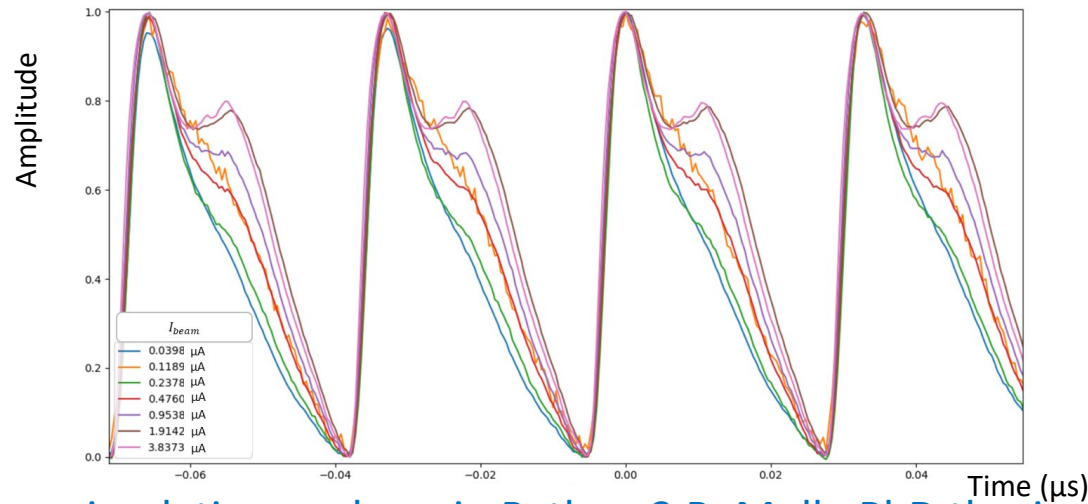


DIAMMONI equipped with :
 150 μm thick sCVD diamonds mounted on PCB
 + QDC FE
 + DAQ

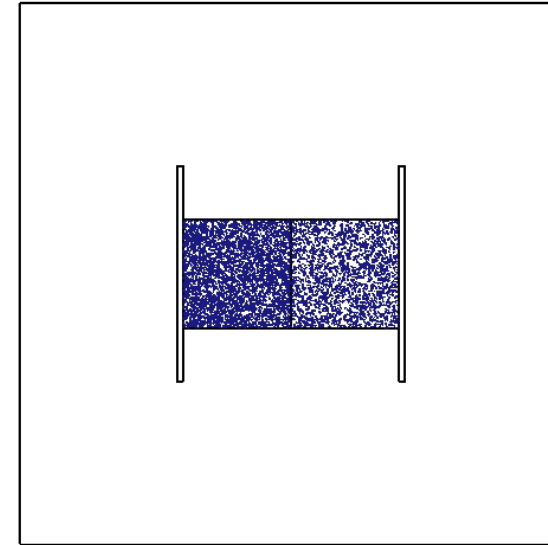


for monitoring proton beams in FLASH conditions

150 μm sCVD diamond signal for different beam intensities
(amplitude normalized)

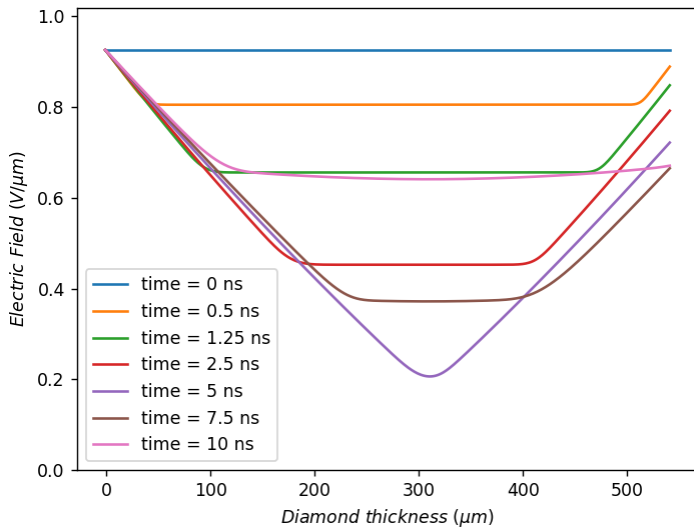


Simulation with a gaseous ionisation chamber

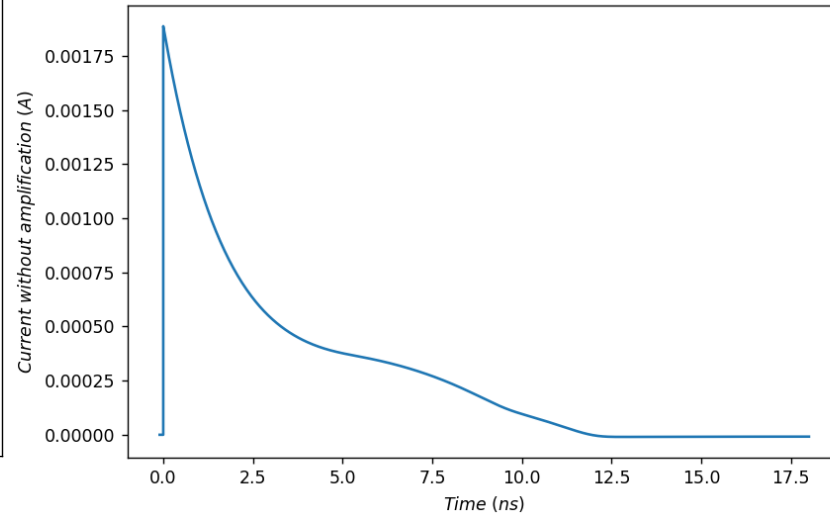


PyDiam simulation package in Python 3 R. Molle PhD thesis

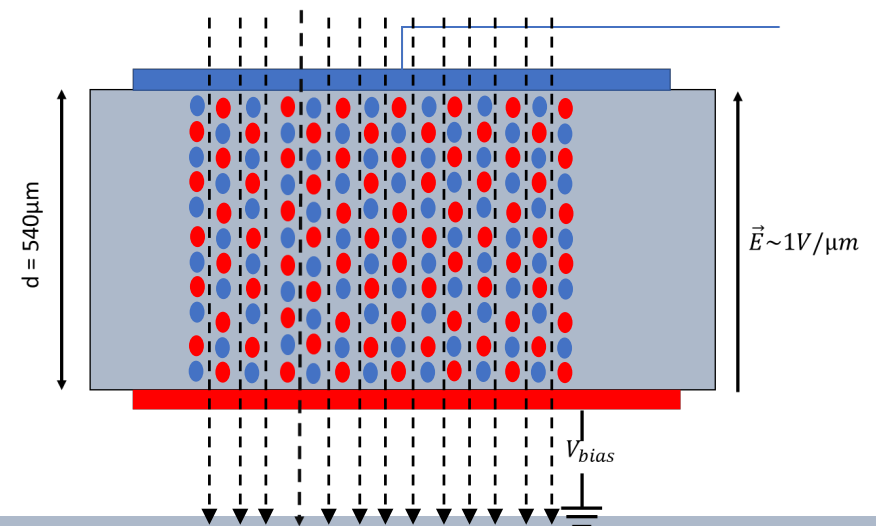
Electric Field



Measurable signal on diamond - 68MeV protons - Flux = 8.9E9 protons/cm²/s



Incoming particles

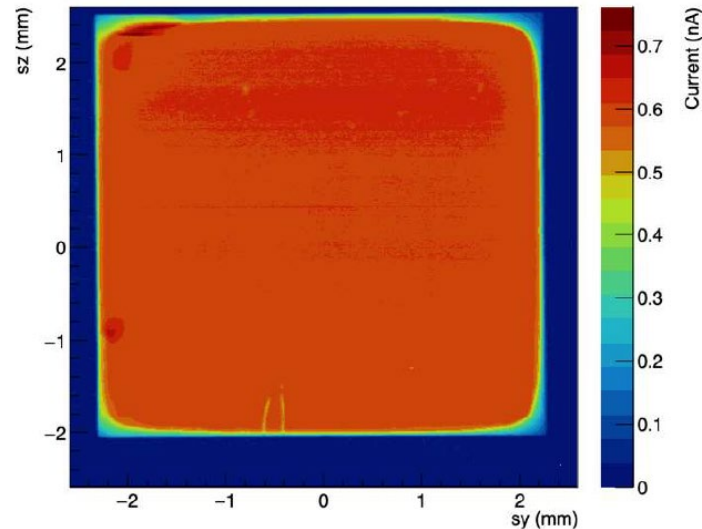


Objectives of the “aging” experimental set-up:

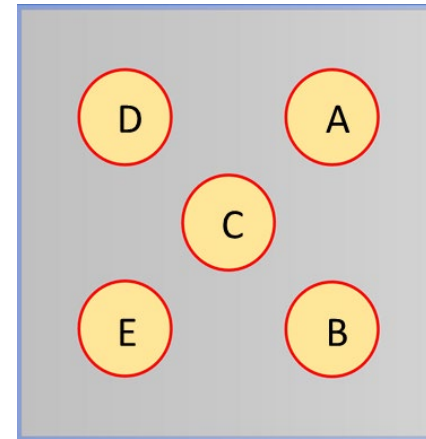
- each area corresponds to a beam intensity (= flux = φ)
- Irradiation of each zone until obtaining an identical cumulative fluence ($=\phi$) between the zones at the end of the experiment

Before irradiation

sCVD 500 μ 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/cm²

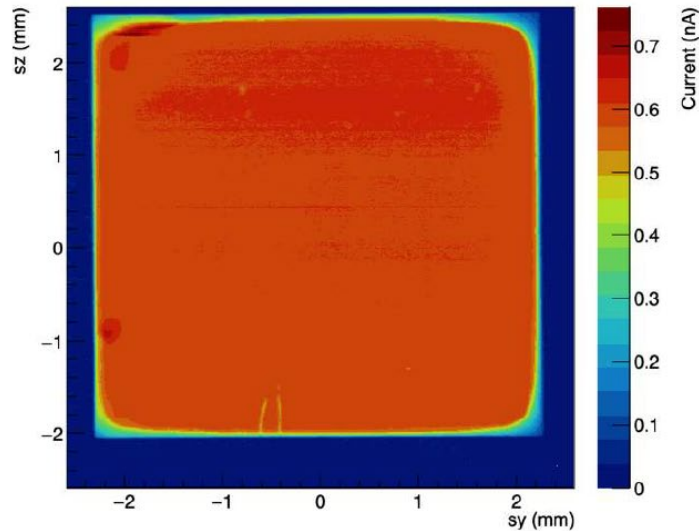
The absolute values cannot be compared since the beam intensity is not the same

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

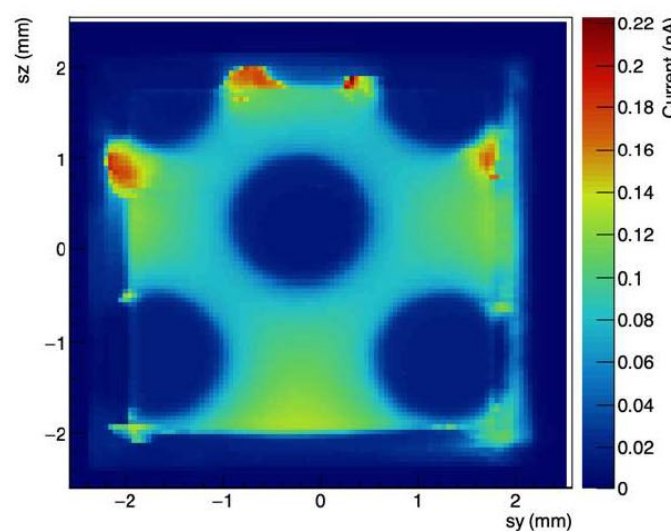
=> The main observation is that the XBIC is close to the leakage current in the irradiated areas which means that the charges are no longer collected.

Before irradiation

sCVD 500 μ m E6



XBIC mapping at ESRF



XBIC mapping at ESRF

In blue the areas of less effective charge collection

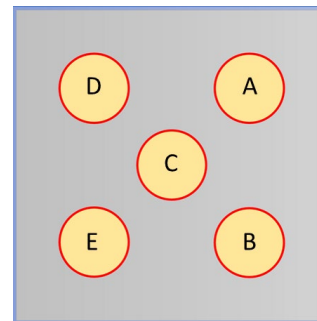
After irradiation

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

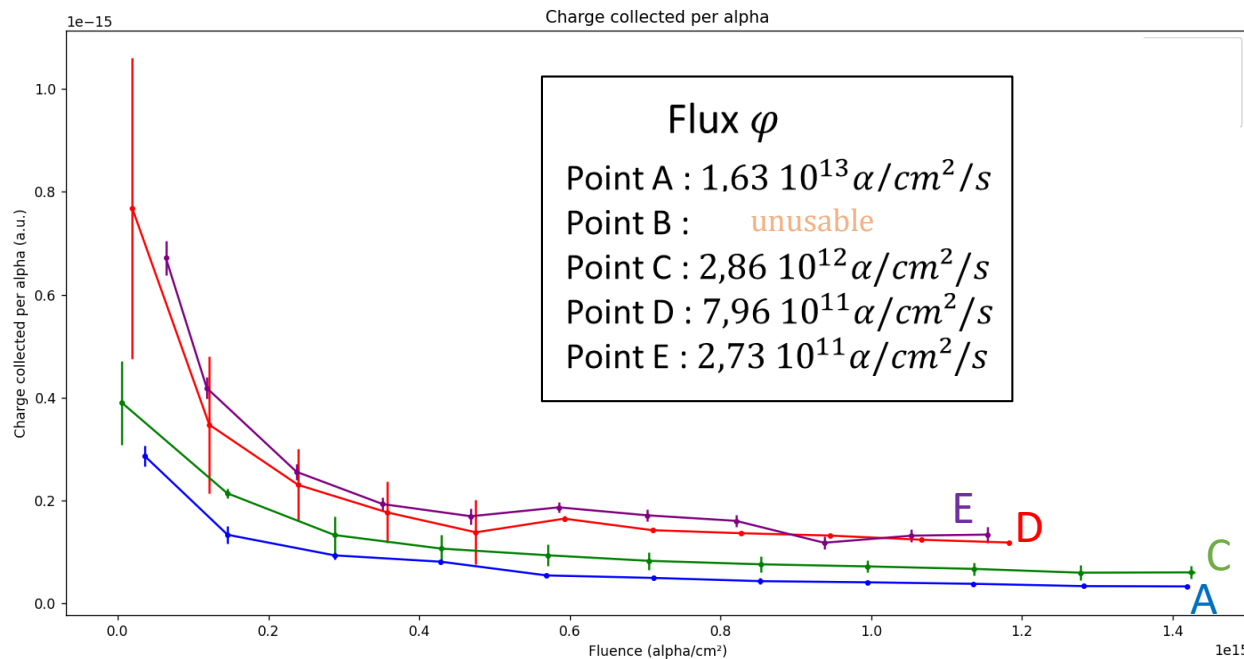
No irradiation-related structural defects are visible => the vacancies created by the irradiation are too far from one another to induce a significant deformation of the crystalline mesh.

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/cm²) on charge collection**



THANKS FOR YOUR ATTENTION !

