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

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J. Bousquet, E. Corne, J. Letellier, D. Nusimovici.

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Context

- **Development of new generations of ion accelerators:**
  - Nuclear applications: the production of radical species for radiolysis applications
  - 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.

Diamond as beam monitors

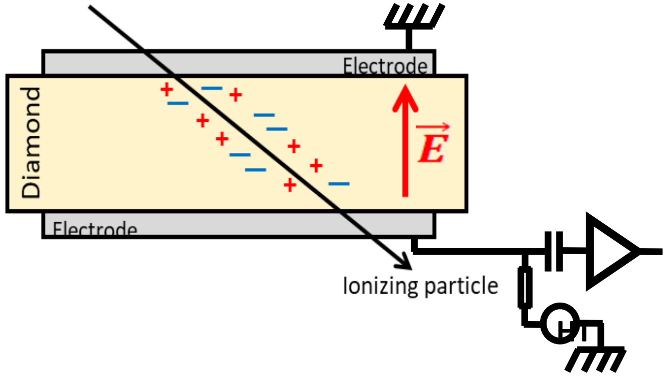
Solid state ionization chamber

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

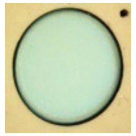


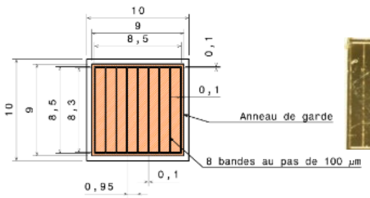
Read-out electronics

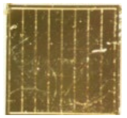
- Fast current preamplifier
- Charge preamplifier
- QDC

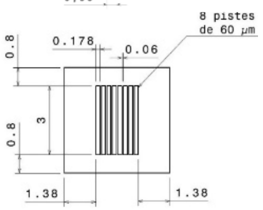
Band Width:	2 GHz
Gain:	40 dB
Impedance:	50 Ω
Dynamic range:	~ +/- 1 V
Power Supply:	12 V / 100 mA

Diamond metallisation

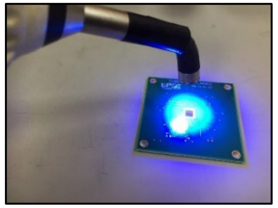


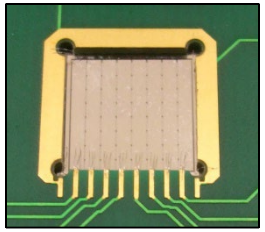


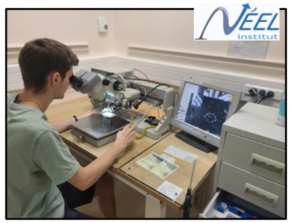


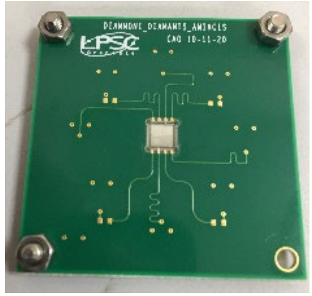


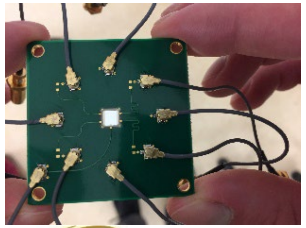
Detector assembly

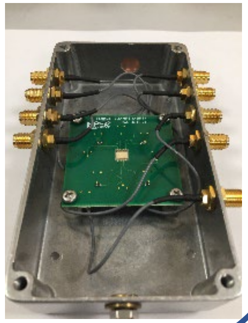












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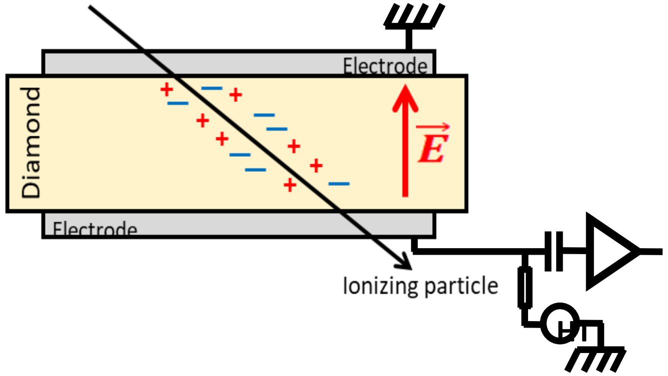

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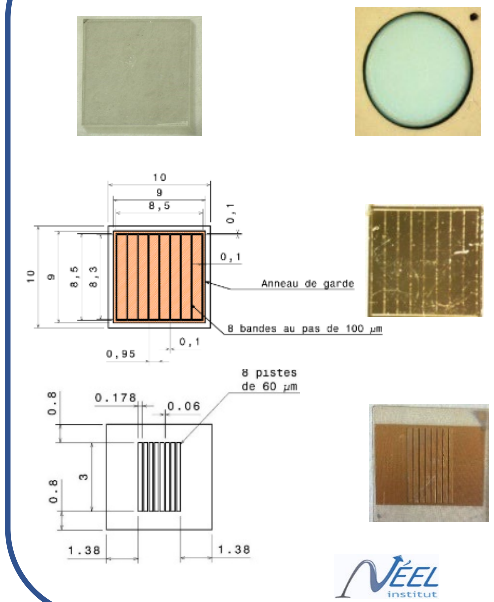

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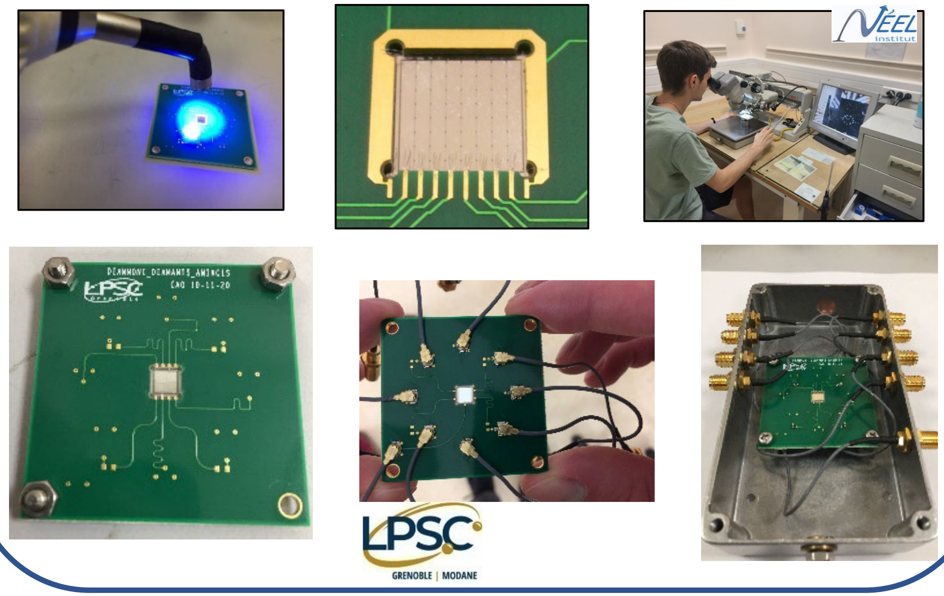

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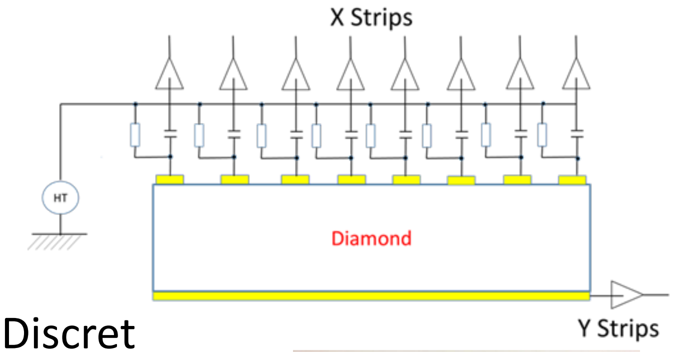
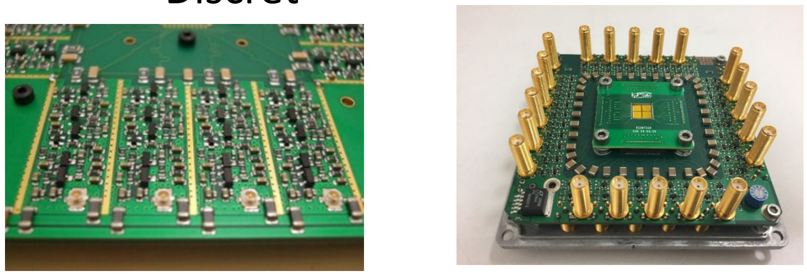
- Charge preamplifier
- QDC

Read out electronics @ LPSC



Discret



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

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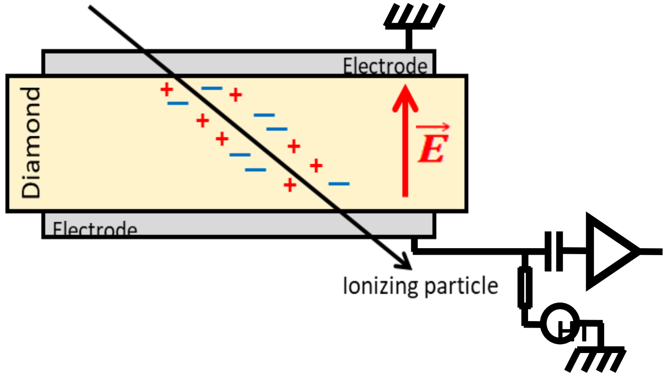

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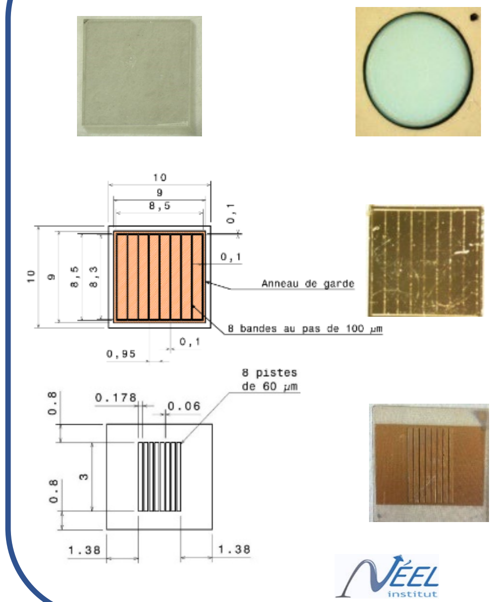
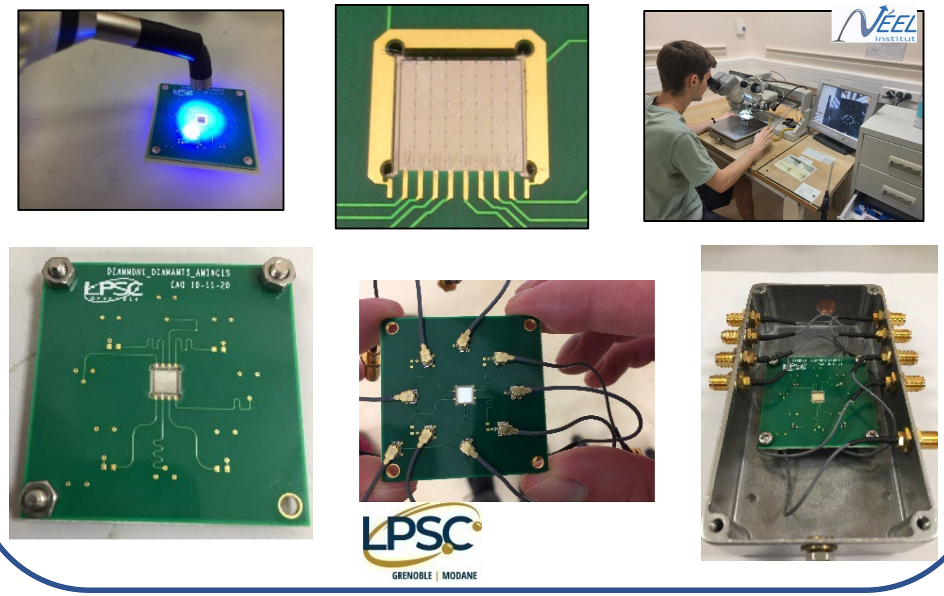


Detector assembly



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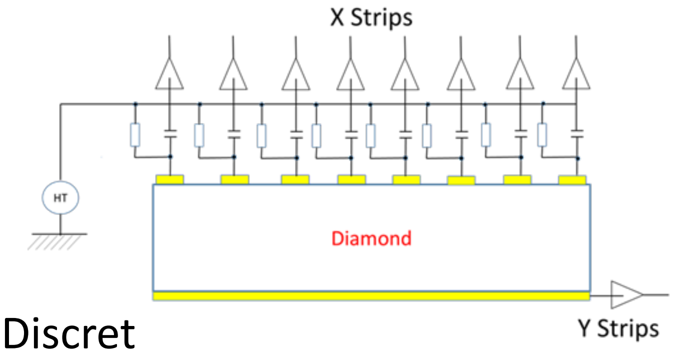

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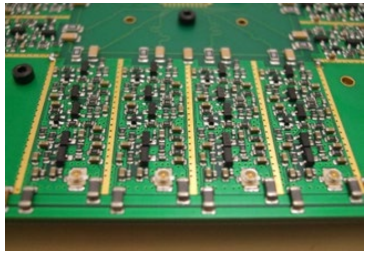

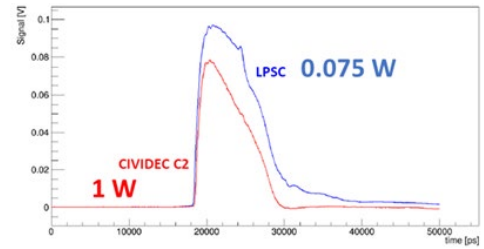

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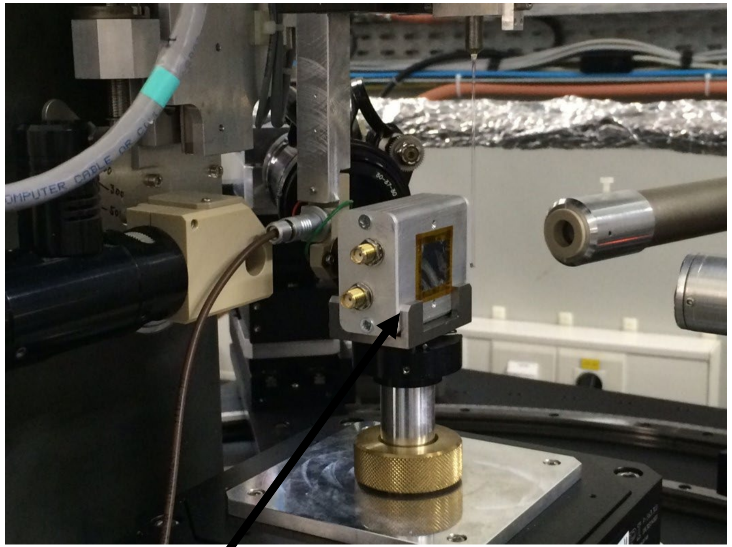
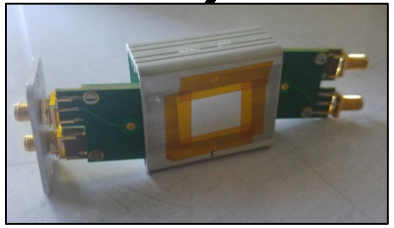
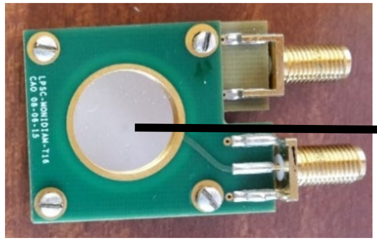
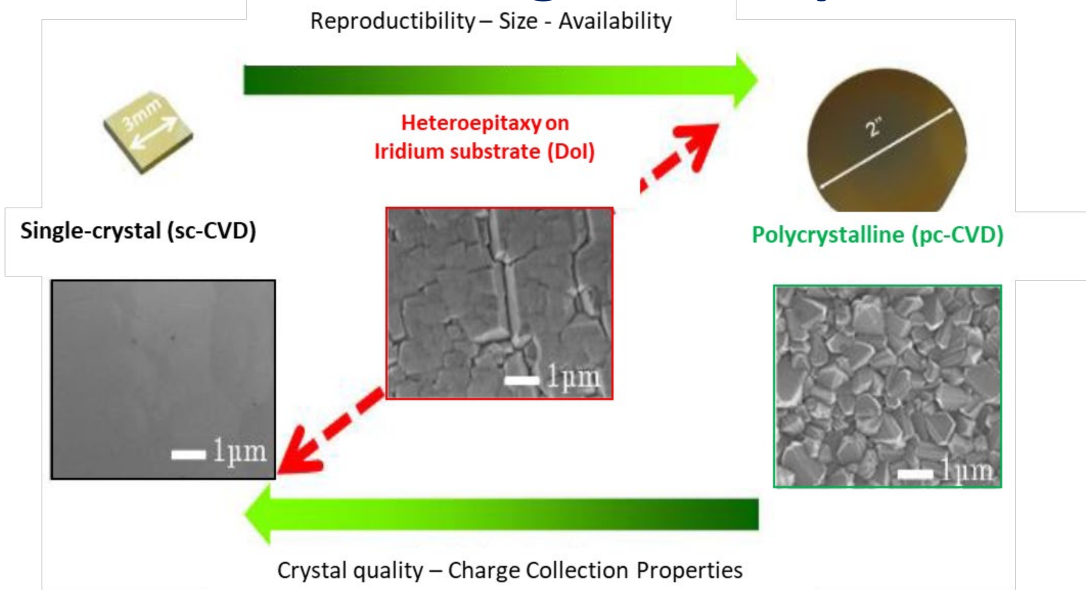
Diamond detector for beam monitoring: sCVD? pCVD? DOI?

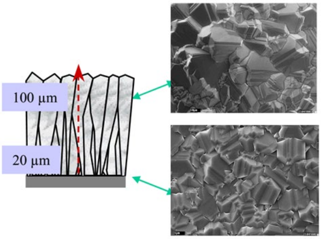








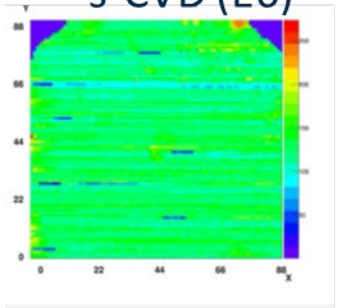
N. Vaissiere PhD thesis https://tel.archives-ouvertes.fr/tel-01022652

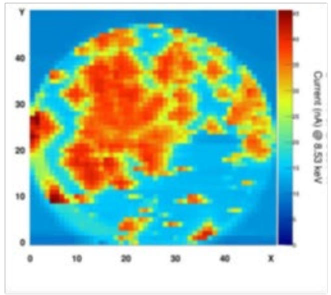


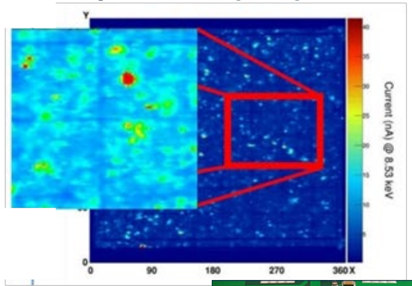
XBIC = X rays Beam Induced Current

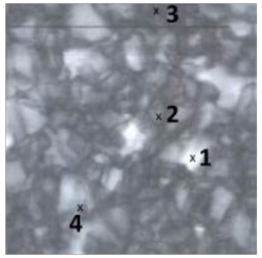
@ ESRF (France) : Photons 8.5 keV=> 2D « current maps » with CVD diamonds

s-CVD (E6) | DOI (AuDiaTec) | p-CVD (E6) | 1 mm²



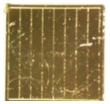


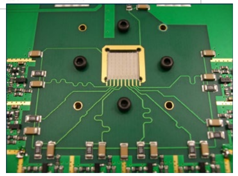




ML Gallin-Martel Diamond and related materials 112 (2021) 108236

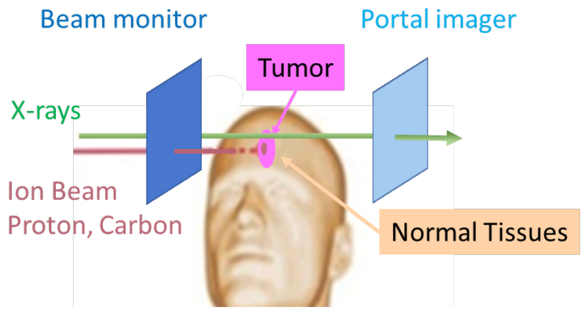
https://doi.org/10.1016/j.diamond.2020.108236

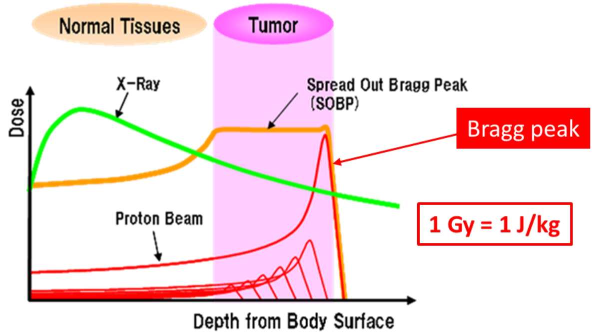




Beam monitors for on-line control of radiotherapies in cancer treatment

X-rays vs hadrontherapy



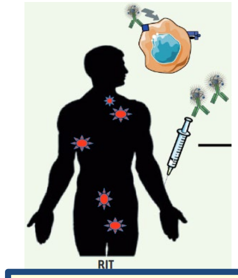


Flash therapy vs conventionnal => high doses in a very short time

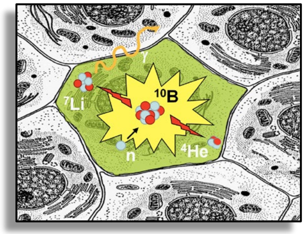
Conventional X-rays
or hadrontherapy → **Gy/mn**
Flash therapies → **100 Gy/s**

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

Vectorized Internal Radiotherapy and Boron Neutron Capture Therapy (BNCT)



Radionuclides α : 223Ra, 225Ac, 212/213Bi, 211At…
Energy α : 5 – 9 MeV



$^{10}B + n_{th} \rightarrow [11B]^*$

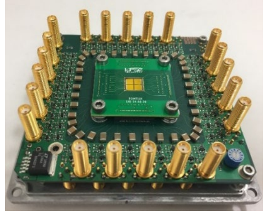
- 6 % → $^4He + ^7Li$ (2,79 MeV)
- 94 % → $^4He + ^7Li$ (2,31 MeV) + γ 0,48 MeV

Objectives: improved dose predictions and biological effects for targeted radiotherapy

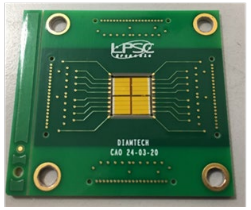
⇒ **monitor low-energy ion beams** for radiobiology experiments

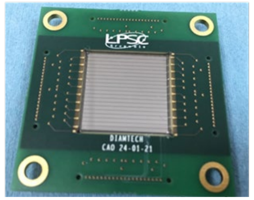
DIAMANT – Beam monitoring @IN2P3 and for medical application : various specification lists!

40 preamps + DFC + TDC



4 diamond sCVD in mosaic or 1 pCVD





Proton beam monitoring in hadrontherapy (CAL)

Coll. Clarys UFT / Coll. TIARA / Coll. ClaRyS - LaBeX PRIMES (P. Everaere PhD thesis)

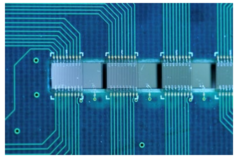
- Single particle
- XY spatial resolution ~1 mm
- Time resolution ~100 ps

Micro-Xrays beam monitoring application to Microbeam Radiation Therapy (ESRF)

R&T DIAMTECH / IDSYNCHRO / PAIR TUMC - Coll. LPSC – STROBE (INSERM) (N. Rosuel PhD thesis)

- Current integration (dynamic=10^6)
- Integration from 10 ms up to 100 ms

138 QDC channels : 20 ASIC + 8 Diamonds in 1 row

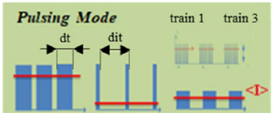


Pulsed proton beam monitoring – application to Flash Therapy (ARRONAX)

R&T DIAMTECH / ANR – DIAMMONI Coll. LPSC SUBATECH ARRONAX (R. Molle PhD thesis)

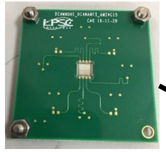
- Current integration (dynamic=10^5)
- Train Counting => Time stamps ~3 ns
- Bunch Counting

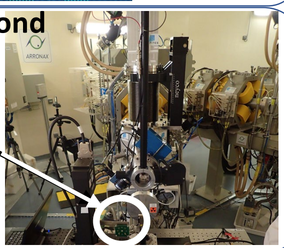
DIAMMONI



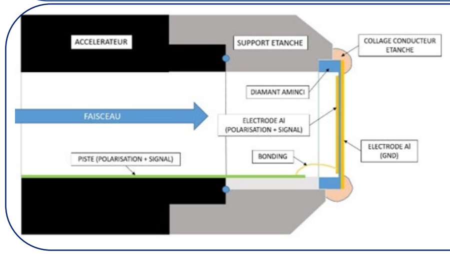
QDC : Train counting

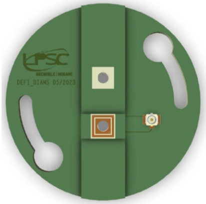
1 sCVD / 1 pCVD diamond





Fast preamp + 500 MHz ADC : Bunch counting





Micro - ion beam monitoring (LP2I Bordeaux/AIFIRA - IRSN/ MIRCOM)

Coll. LPSC Institut Néel-Grenoble LP2I-Bordeaux IRSN (C. Léonhart PhD thesis)

- To be crossed by protons with energy up to 4 MeV, alpha particles up 6 MeV and B, C, O, … ions up to 8 - 10 MeV.
- Diamond deep etching => diamond menbrane of ~1 µm (Institut Néel)
- Integration on the µ beam line = extraction window

DéFI DiaMs

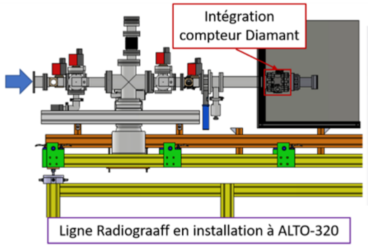
Mission pour les Initiatives Transverses et Interdisciplinaires

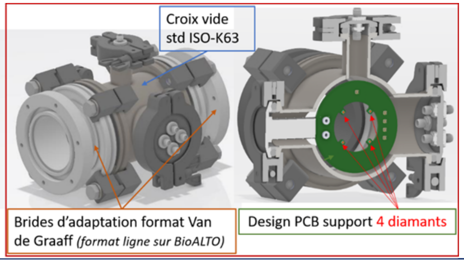
PRIME 80

Monitoring low energy ion beam (ALTO)

Coll. LPSC IP2I Lyon IJC lab via PICTURE *(MP Diamant & BioALTO)*

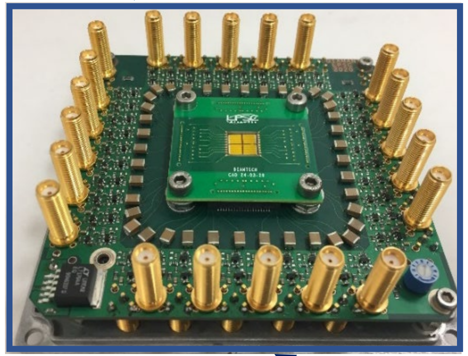
- Counter with 4 diamonds (2x2x0.1mm^3) placed in the halo of the beam for irradiation monitoring and beam alignment.



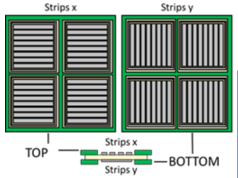


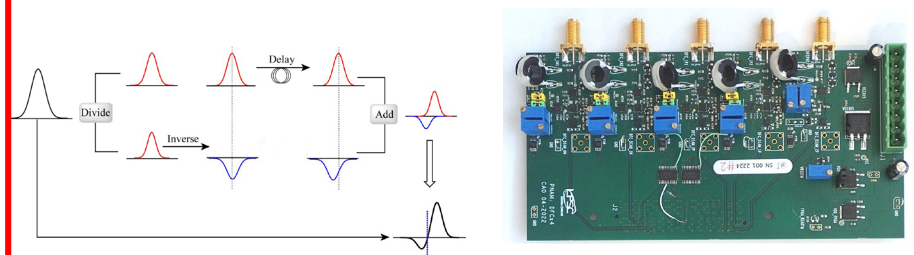
Diamond beam hodoscope in single proton regime (hadrontherapy monitoring): the 100 ps time resolution challenge

10 cm



42 channels





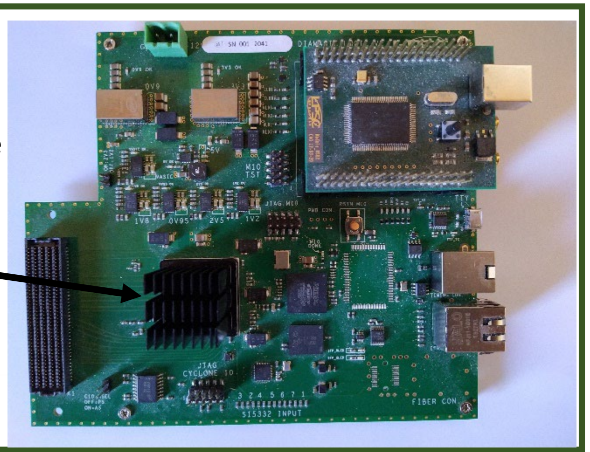
CFD=> time stamp independant of diamond signal amplitude

CFD = Constant Fraction Descriminator

FPGA 2020

LPSC Grenoble

25 ps RMS

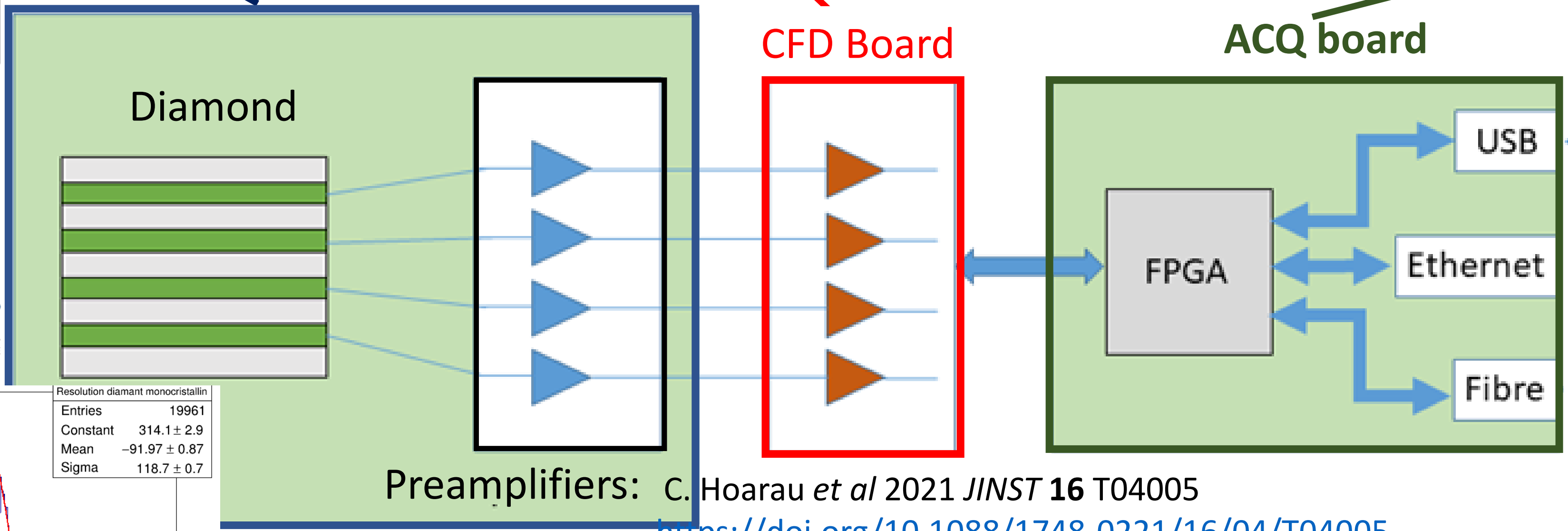


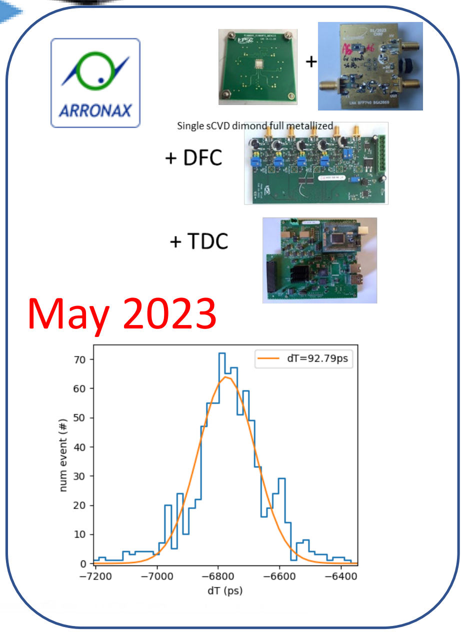
2021CMOS 130 nm

12,5 ps RMS

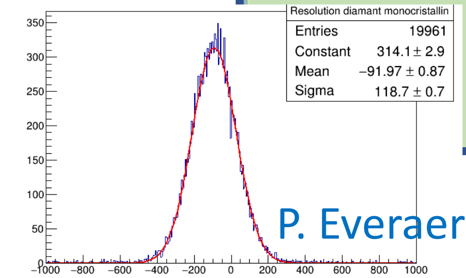
TDC = Time Digital Converter

Beam Monitor





Antoine Lacassagne CENTRE DE LUTTE CONTRE LE CANCER unicancer NICE



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P. Everaere PhD thesis, Labex PRIMES

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

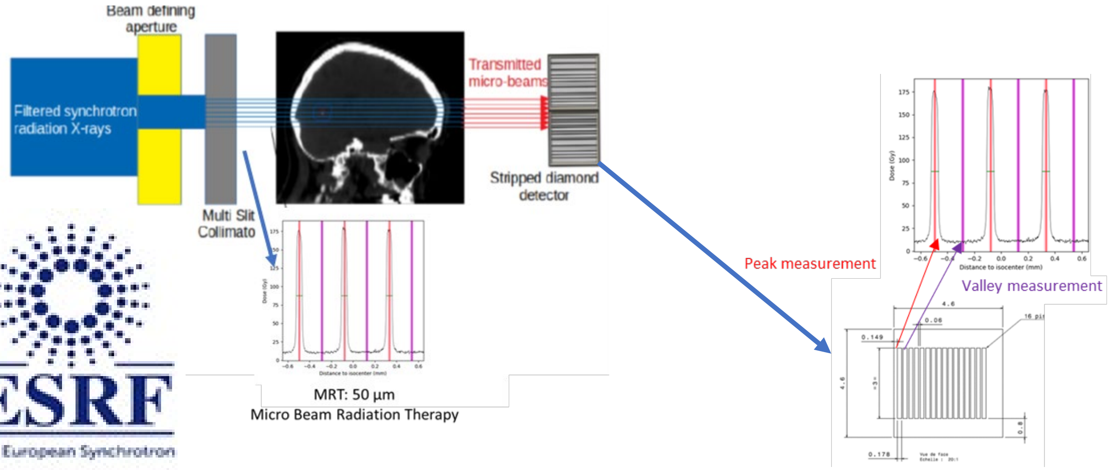
Time resolution between two orthogonal X and Y strips

Diamond for X-rays µ-beams: charge integration + linear response over a wide dynamic « Flash therapies »

Micro Beam Radiation Therapy (MRT)

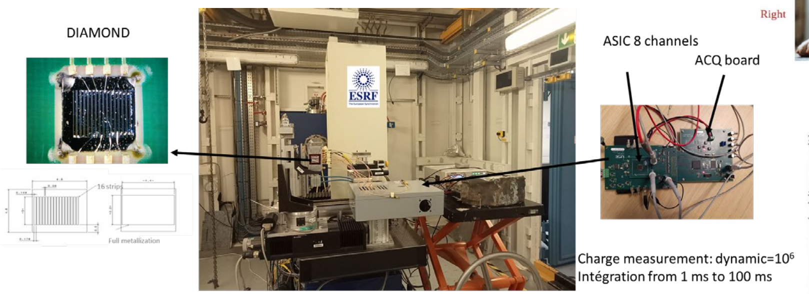
R&T DIAMTECH/ IDSYNCHRO UGA / PAIR TUMC MRT-CLINTRA INSERM

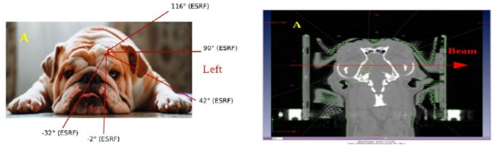
- Innovative radiotherapies using spatially segmented photon beams
- Energy 50-200 keV@ ESRF + very high dose rate 10^4 Gy/s

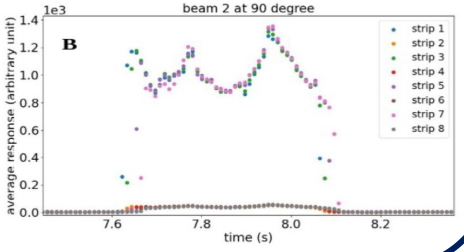


2nd Version: 8 channels with ASIC QDC

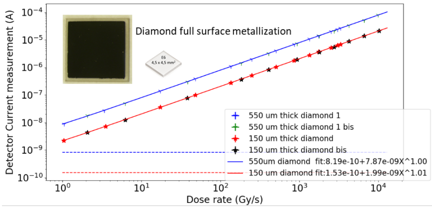
1st veterinary patients

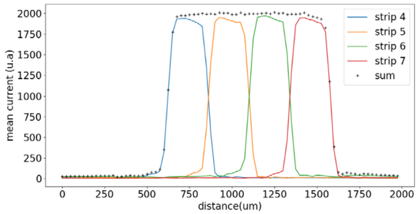


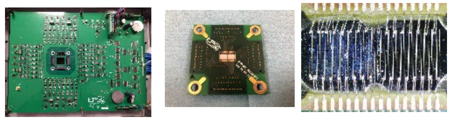




1rst version: 32 channels (QDC) in discrete elec.





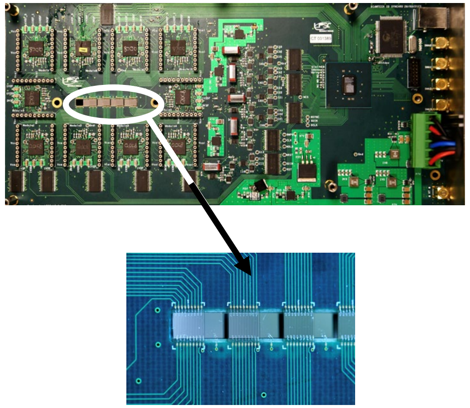


N. Rosuel PhD LPSC STROBE, Labex PRIMES

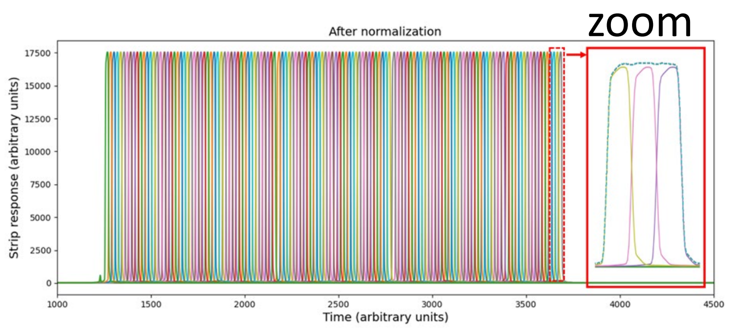
http://www.theses.fr/s211637#

Metallization NanoFab, Institut Néel

Final version : 158 channels 20 QDC ASIC 8 diamonds in a row



138 channel response to 1 single µbeam swapping the detector



Train Counting Mode

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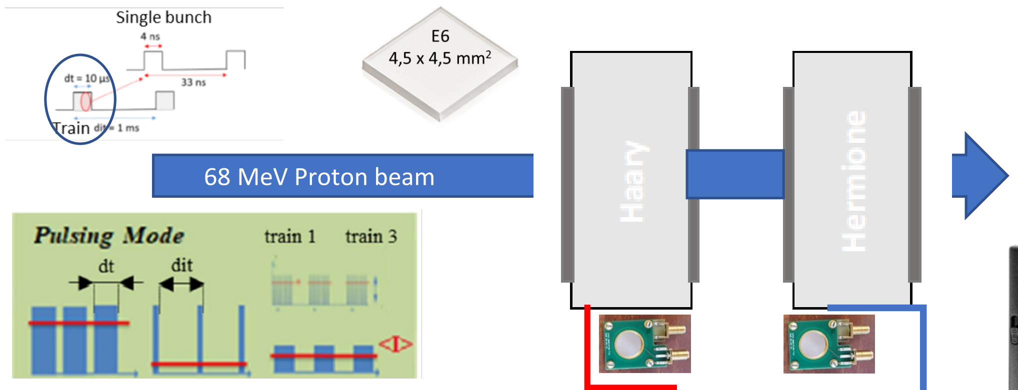
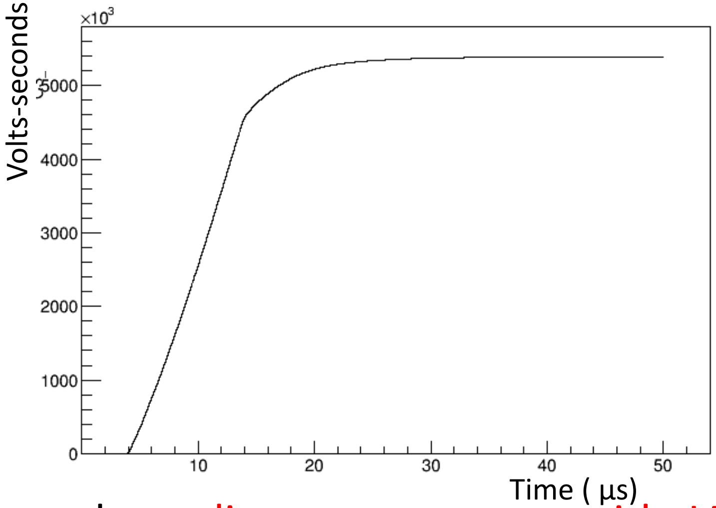
Beam intensity up to 300 nA measured on diamond



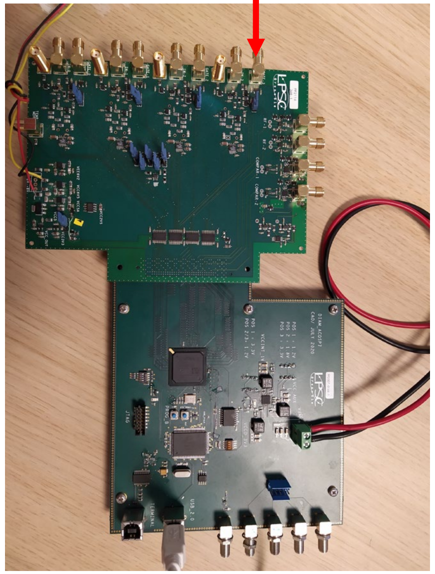
DSO Lecroy
2 GHz; 10 or 20 GS/s

Train integral = DSO post analysis



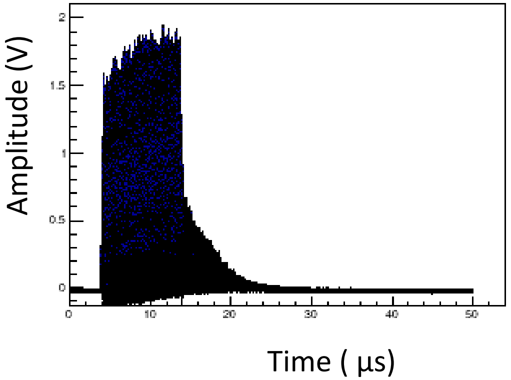
I = 10nA, dt = 10µs, dit = 1s

QDC board
developped @ LPSC

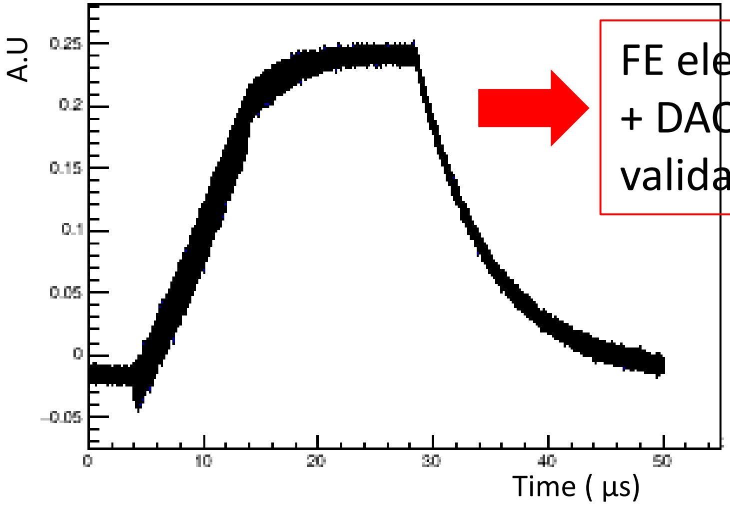


DAQ
developped @ LPSC

Train - Diamond signal



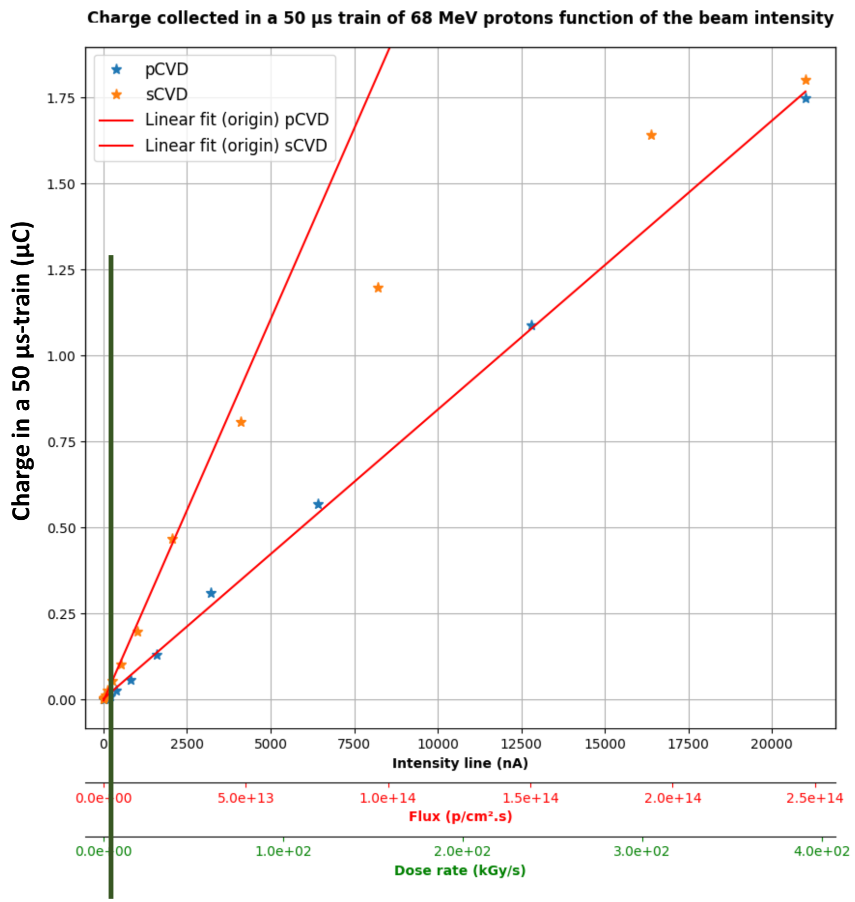
Train integral = on line measurement with LPSC QDC



FE elec.
+ DAQ
validation

Diamond beam monitor : the challenge of a linear response on a wide dynamic with ion beams

Study of linearity as a function of beam intensity: sCVD versus pCVD

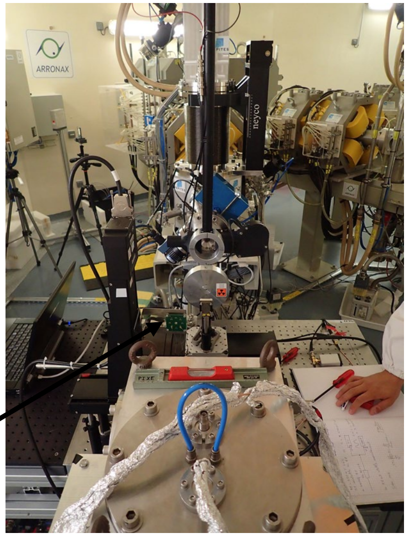


~300 Gy/s

Each point = ACQ on a single train to avoid any influence of the fluence

R. Molle, PhD Thesis LPSC ARRONAX SUBATECH, ANR DIAMMONI

Diamond



DSO Lecroy
2 GHz; 10 or 20 GS/s

ARRONAX

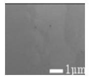
sCVD: Linear response from 1 Gy/s up to 10^2 kGy/s

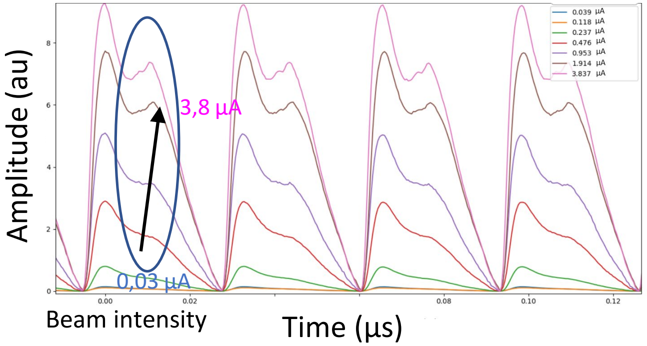
pCVD: Linear response from 1 Gy/s up to 4 10^2 kGy/s

☺ **for monitoring proton beams in FLASH conditions with typical dose rate : ~ 300 Gy/s**

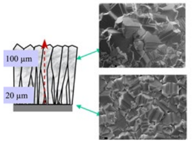
High proton flux : diamond signal analysis and simulation towards a better understanding of charge collection mechanism

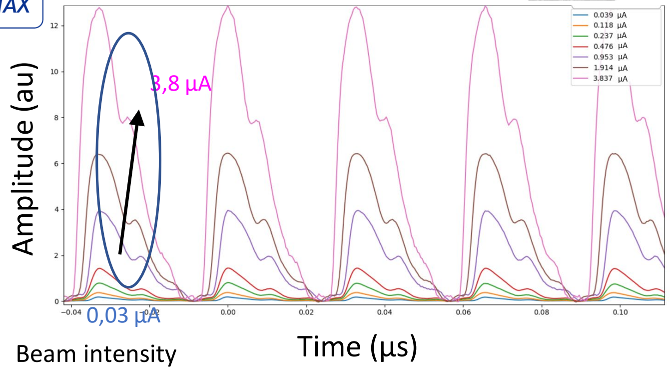
sCVD and pCVD diamond signals for different beam intensities in ARRONAX

sCVD 



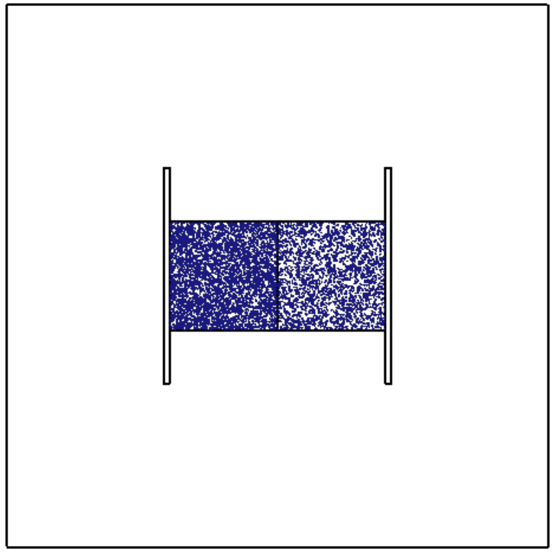
ARRONAX

pCVD 

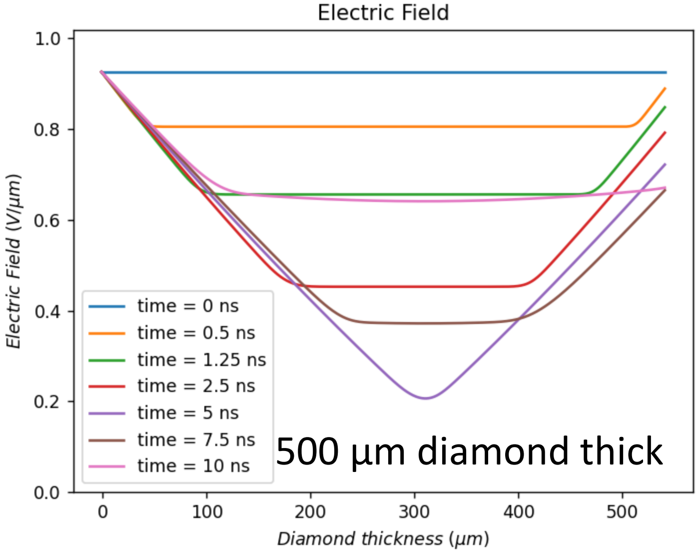


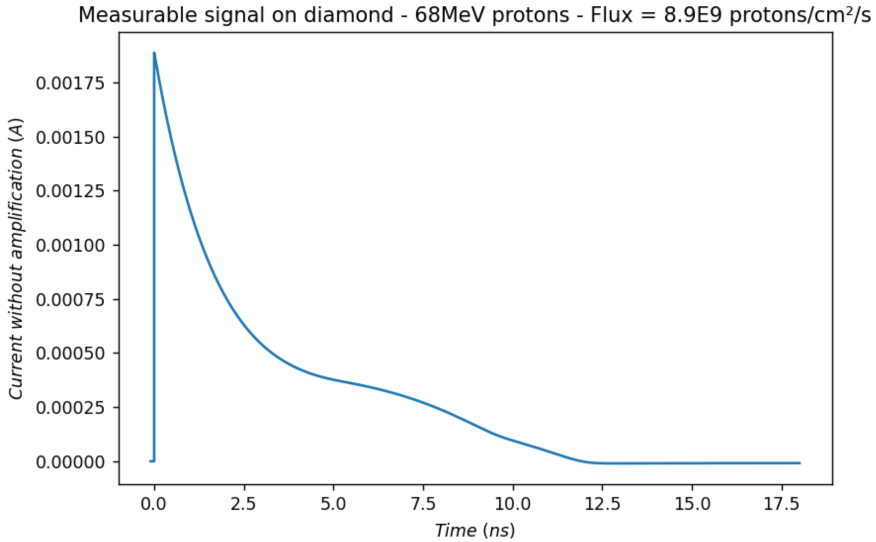
X µA = beam intensity measured on diamond

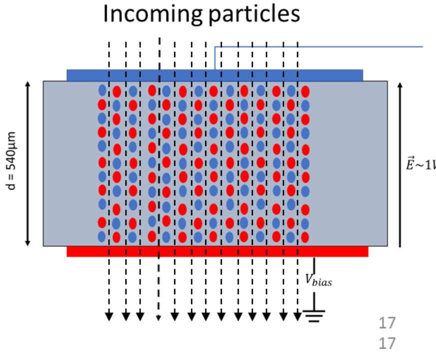
Y. Arnoud simulation of a gas ionization chamber



PyDiam simulation package in Python 3 (R. Molle PhD thesis, ANR DIAMMONI)







DIAMMONI needs to be
- → **Thin: 50 µm**
- → **Biased > 1V/µm (= « normal » bias): 200 V = 4 V/µm**

High fluences : what's the limit for diamond continuous exposure in a ion beam?

Objectives of the "aging" experimental set-up:

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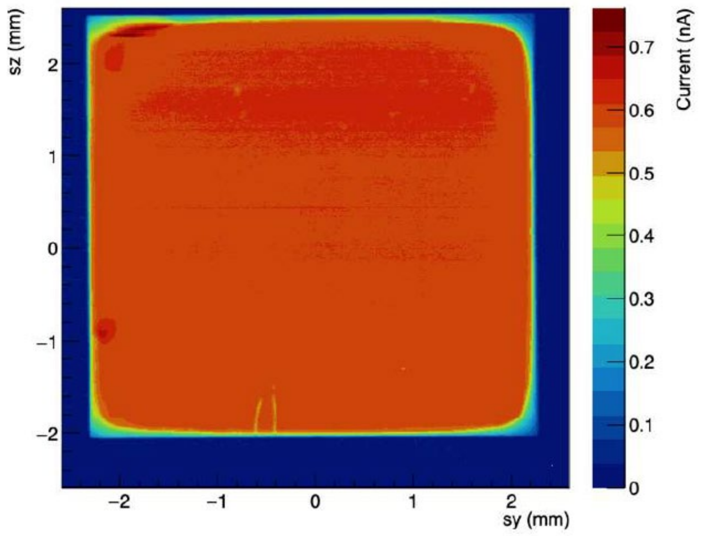
- each area corresponds to a beam intensity (= flux = φ)
- Irradiation of each zone until obtaining an identical cumulative fluence (=ϕ) between the zones at the end of the experiment

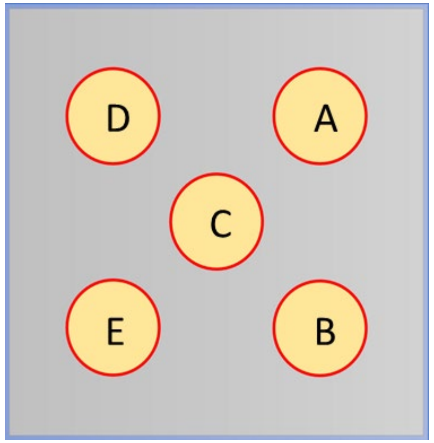
Before irradiation

sCVD 550µm E6

ESRF
The European Synchrotron



XBIC mapping at ESRF



Targeting objective

High fluences : diamond aging studies with 68 MeV alpha particles

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

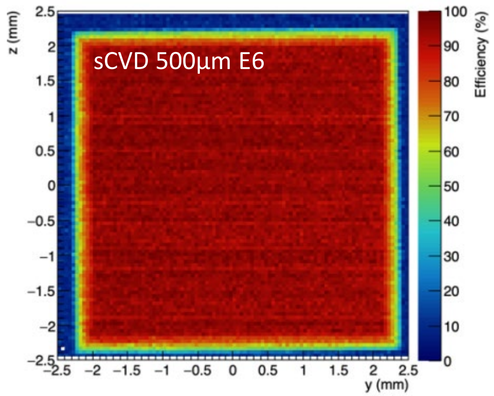
The absolute values cannot be compared since the beam intensity is not the same

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

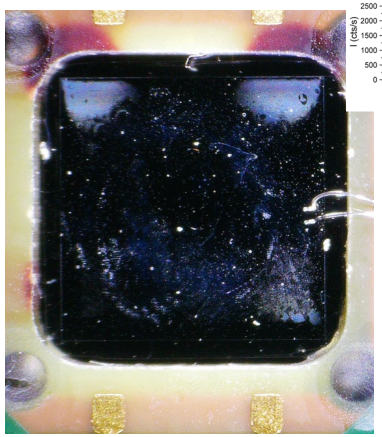
=> The main observation is that the XBIC is close to the leakage current in the irradiated areas which means that the charges are no longer collected.

Photoluminescence spectra

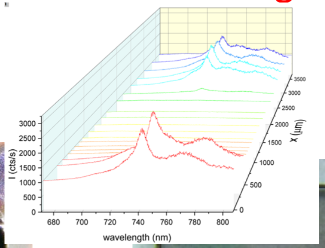
F. Laffont, TN , Tran – Thi XBIC setup BM05 ESRF

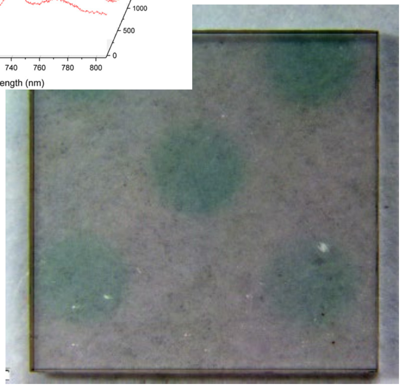


XBIC mapping at ESRF
Before irradiation

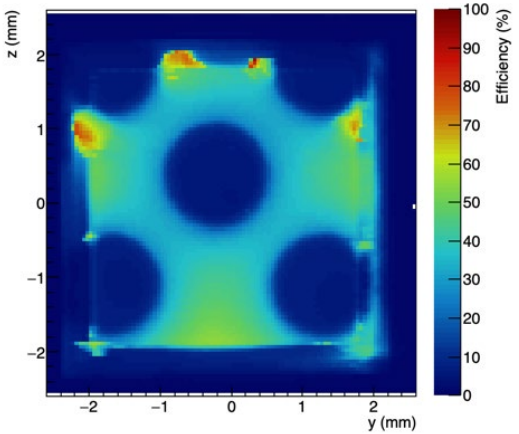


Binocular observation
Black traces of irradiation on the PCB

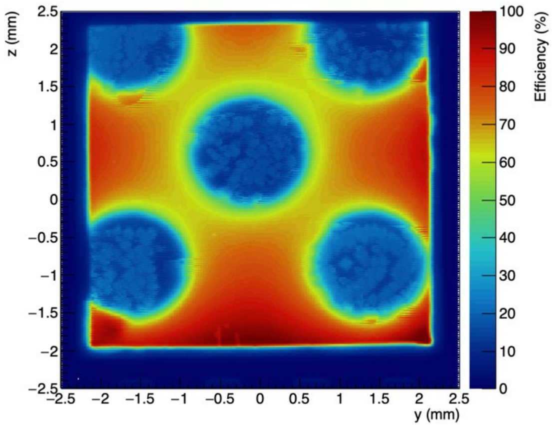




The diamond is colored in green typical of GR1 type defects



XBIC mapping at ESRF
After irradiation
In blue the areas of less effective charge collection



XBIC mapping at ESRF
After annealing (1000 °C for 6 hours)
Diamond has recovered

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

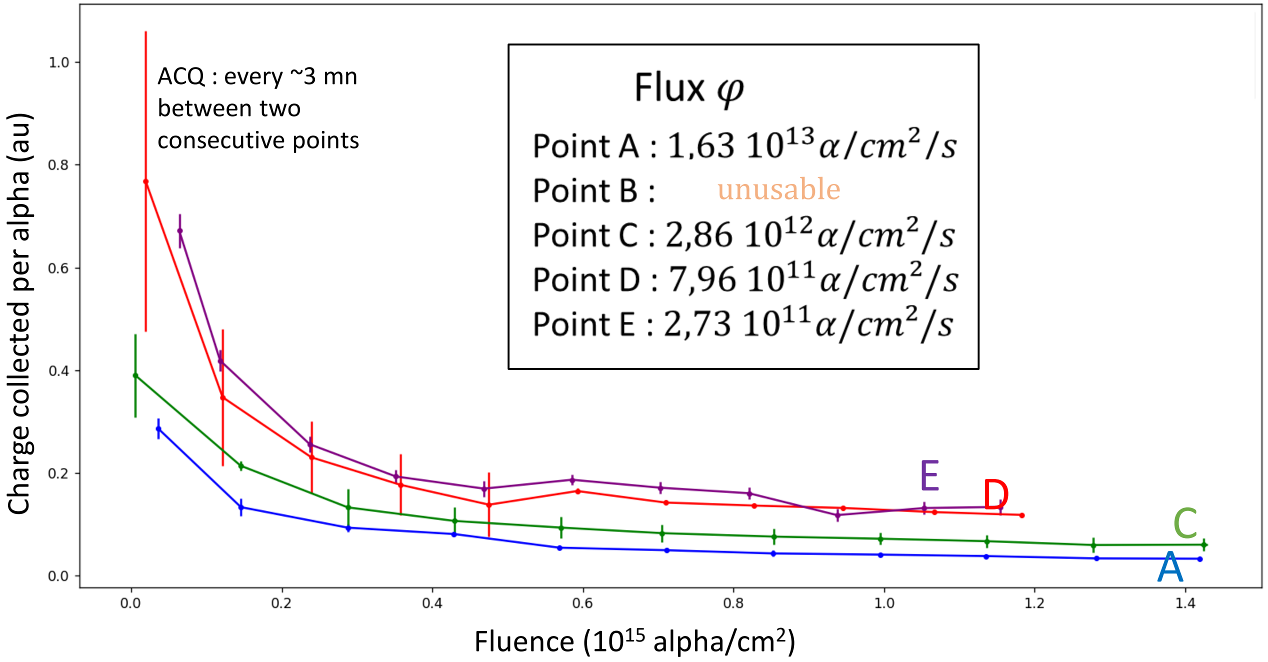
No irradiation-related structural defects are visible => the vacancies created by the irradiation are too far from one another to induce a significant deformation of the crystalline mesh.

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

High fluences : diamond aging studies with 68 MeV alpha particles

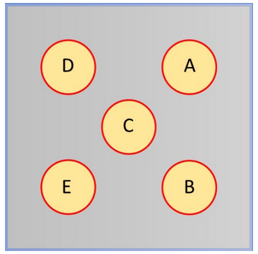
R. Molle PhD thesis ANR DIAMMONI

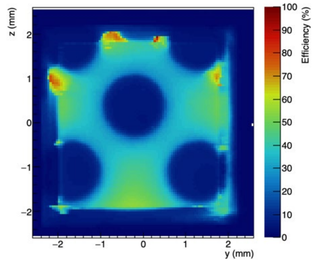
Impact of flux on Charge Collection Efficiency (CCE)

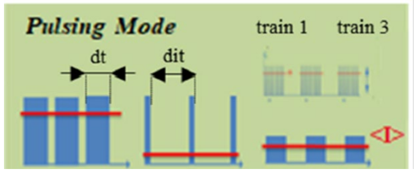


Normalized charge collection per alpha particle

68-MeV alpha particles







dt = 50µs
dit : variable => <I> = cste
Duration : ~30 mn for each A to E point

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.**

→ **CCE drops faster with fluence at higher flux.**
10^{13} alphas/cm^2/s = 0.1 alpha/nm^2/s: interplay between vacancy creation and stable electronic defects (charge carrier traps)?

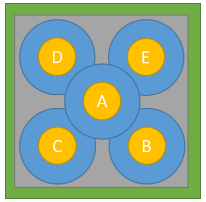
sCVD and pCVD diamond response to 70 MeV protons: aging studies

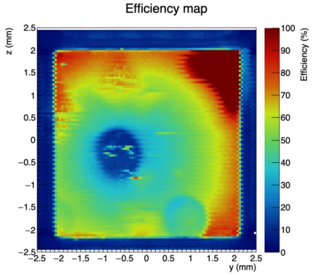
R. Molle PhD thesis ANR DIAMMONI

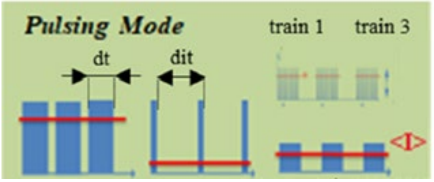
70-MeV protons

Point	Fluence	Flux
A	~10^{15}	2,5 10^{14}
B	~10^{14}	9,9 10^{13}
C	~10^{13}	4 10^{13}
D	~10^{12}	1,6 10^{13}
E	~10^{11}	6,3 10^{12}

sCVD results





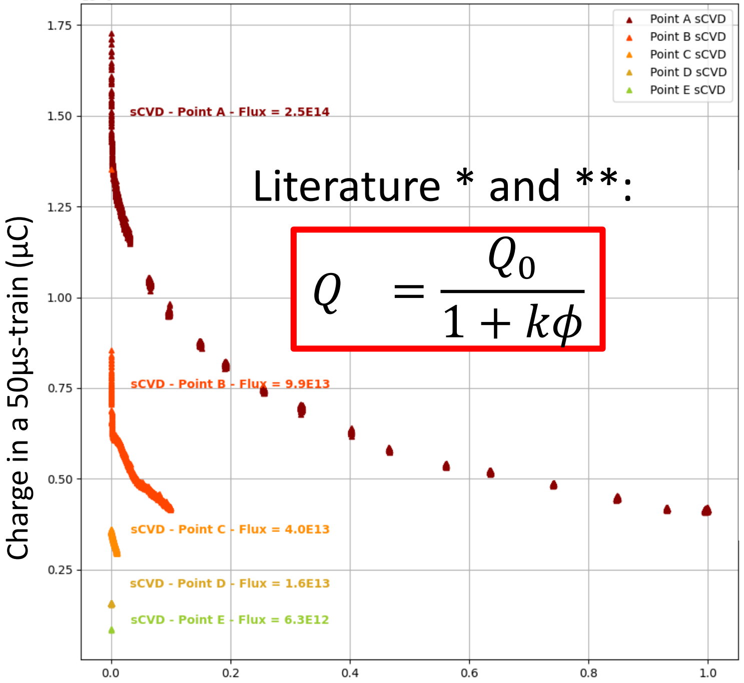


dt = 50µs

dit : variable => <I> = cste

PRELIMINARY

Charge in a 50µs-train of 70 MeV protons as a function of fluence



Literature * and **:

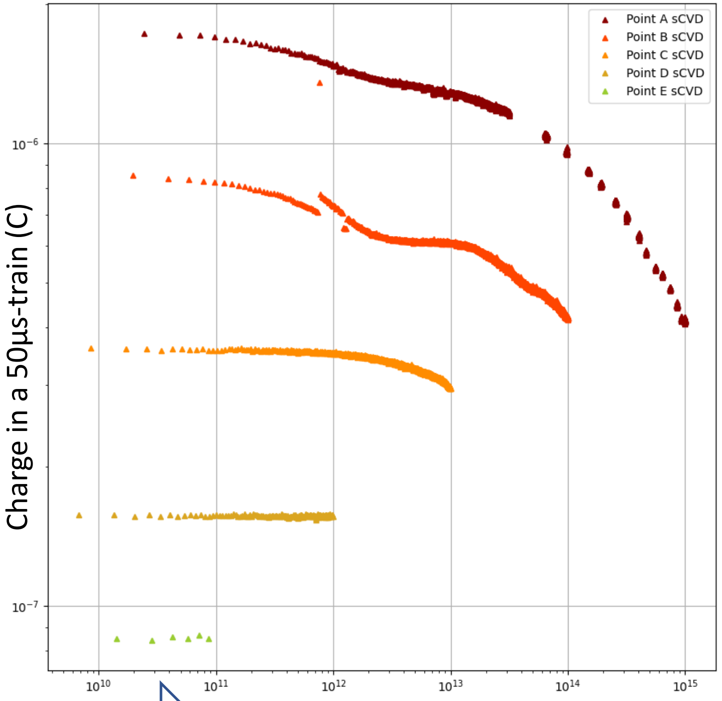
$$Q = \frac{Q_0}{1 + k\phi}$$

Fluence (10^{15} p/cm²)

log. scales on the both axes

Q = *charge* ϕ = fluence Q_0, k = Cste = fit parameters

Flux in p/cm²/s



Fluence (p/cm²)

RD42 CERN coll. results:**

→k is decreasing with proton energy

Question to be answered:

→k = k (φ) with φ = flux?

Ongoing studies!

Ref.	Proton energy (MeV)	k cm²/p/µm
RD42 coll.	25	4,4 10^{-18}
RD42 coll.	70	2,6 10^{-18}
This work	70 (A point)	3,1 10^{-18}
RD42 coll.	800	1,67 10^{-18}
RD42 coll.	24000	1,0 10^{-18}

* A. Bhattacharya et al, « Degradation of single crystal diamond detectors in swift heavy ion beams », Diamond and related Materials 70 (2016) 124-131

**L. Bäni et al, RD42 coll. , « A study of the radiation tolerance of CVD diamond to 70 MeV protons, fast neutrons and 300 MeV pions », Sensors 2020, 20, 6648

Proton therapy:

~10^{10} protons/cm²/treatment

~20 patient/day

~10^{13} proton/cm²/year

Conclusion

- **The development are in connection with collaborations established at IN2P3, CNRS (INP), CAL, IRSN 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 AIFIRA / GIP - ARRONAX, XBIC @ ESRF
  - Instrumentation (IN2P3 labs, Institut Néel, etc.)

- **Diamond beam monitors + FE electronics and DAQ have been developed**

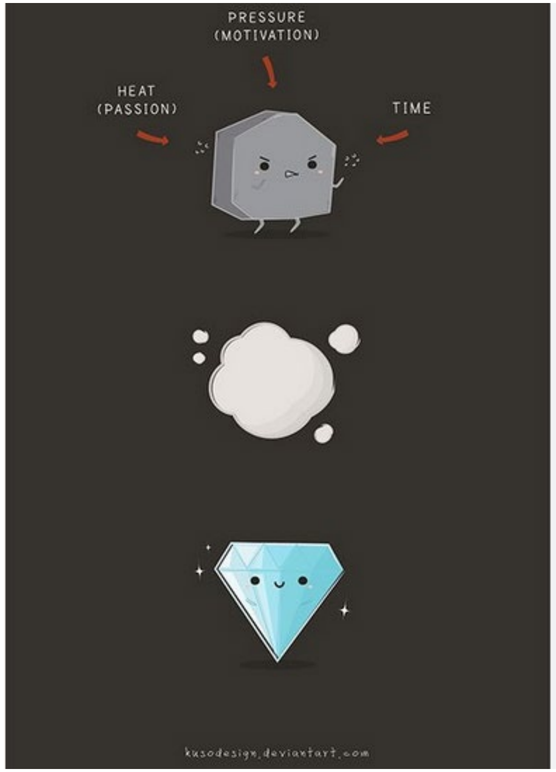
  - Various specifications (time resolution, continuous or pulsed beams, single particle counting up to 10^6 particle in a bunch)
  - Diamond beam monitoring satisfies the FLASH therapy condition (linear response in the range 1 to 4 10^5 Gy/s with X-rays and proton beams)

  => the proposed detection systems will bring significant added value to the transfer of high dose rate flash radiotherapy to clinical trials

- **Simulation + aging studies are on going for a better understanding of the signal formation and the impact of very high fluences on charge collection**

THANKS FOR YOUR ATTENTION !

LPSC GRENOBLE | MODANE
Subatech
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis
LP2i Bordeaux
AIFIRA
ARRONAX
STROBE
IRSN
NÉEL institut
DIAMFAB
ESRF
Antoine Lacassagne CENTRE DE LUTTE CONTRE LE CANCER unicancer NICE



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