

Diamond : a suitable material for detecting particles in a highly radiative environment



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Context

➤ New challenges at accelerators:

- Nuclear fragment detection at high flux
- Materials under irradiation: pulsed-radiolysis applications
- Medical applications: hadrontherapy, flash therapies and X-ray or synchrotron radiation therapy

⇒ Precise beam monitoring with fast counting at high dose rate in a highly radiative environment.

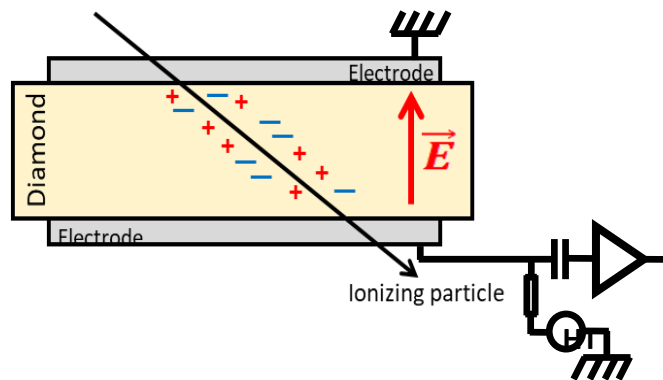
➤ The intrinsic qualities of diamond:

- speed, low leakage current, excellent SNR, resistance to radiation, high thermal conductivity

⇒ 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



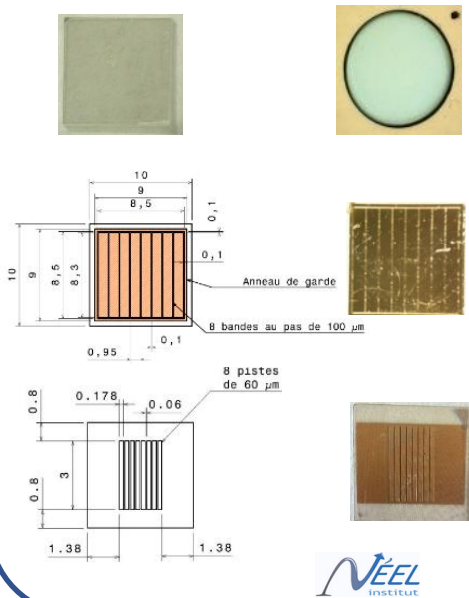
Read-out electronics

- Fast current preamplifier
- Charge preamplifier
- QDC

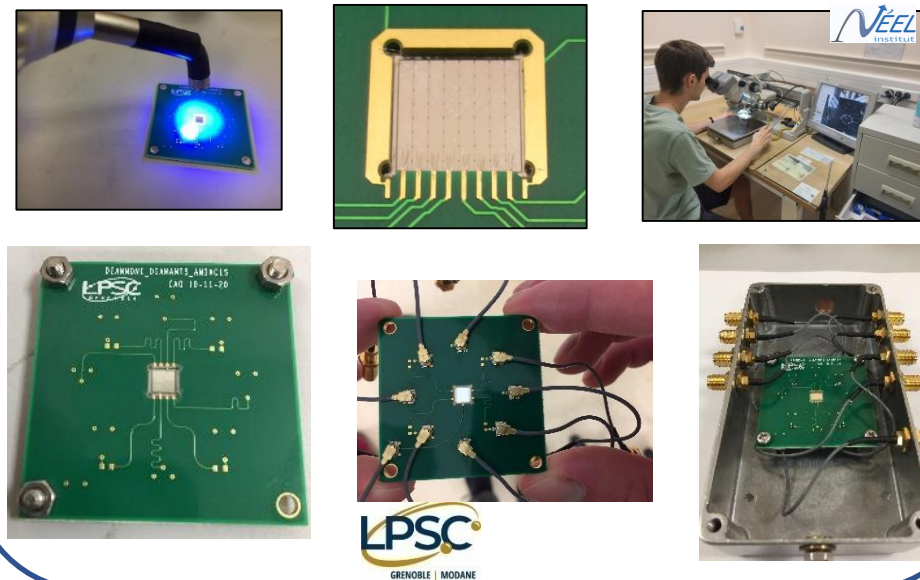


Band Width:	2 GHz
Gain:	40 dB
Impedance:	50 Ω
Dynamic range:	$\sim \pm 1$ V
Power Supply:	12 V / 100 mA

Diamond metallisation

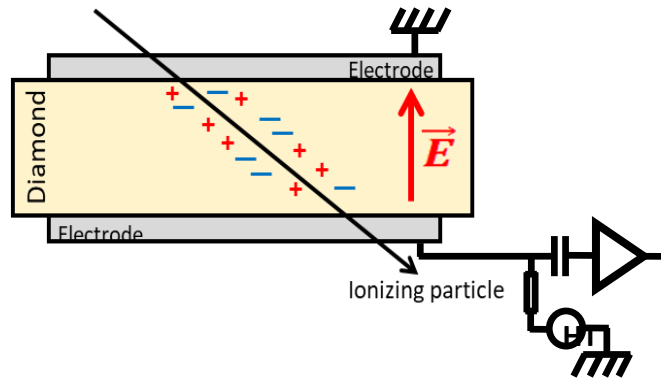


Detector assembly

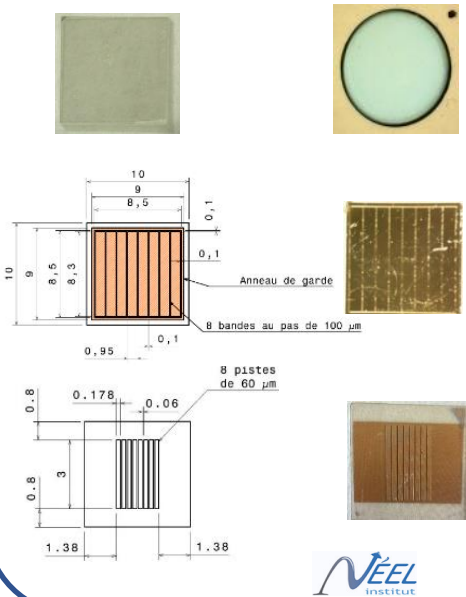


Diamond as beam monitors

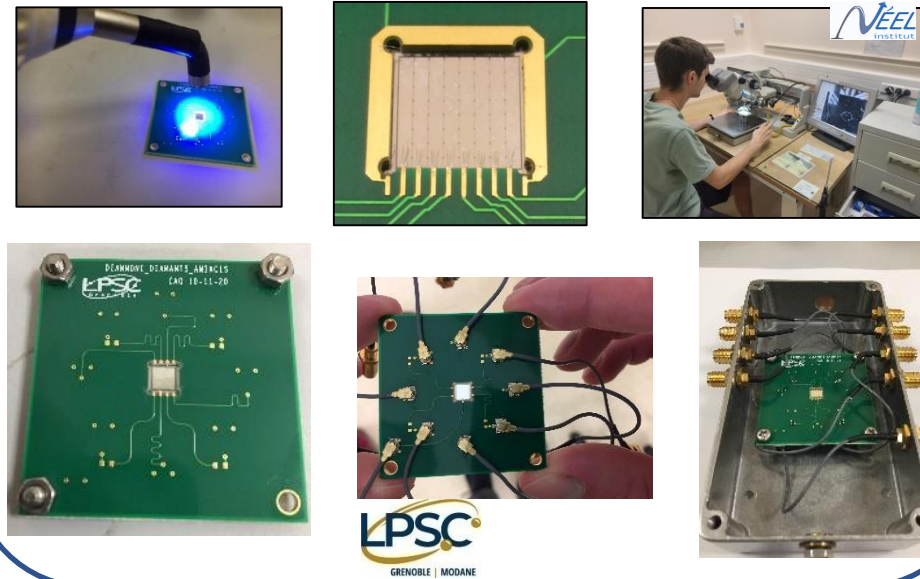
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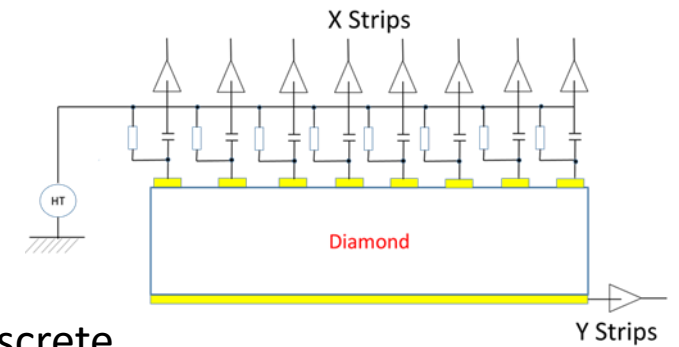
Detector assembly



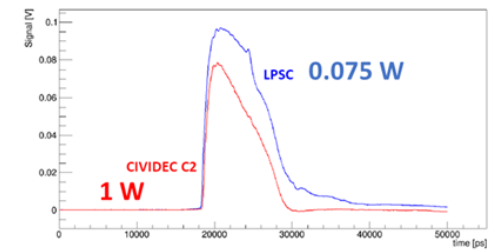
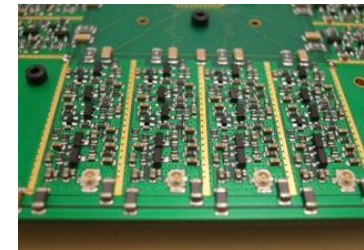
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Read out electronics @ LPSC



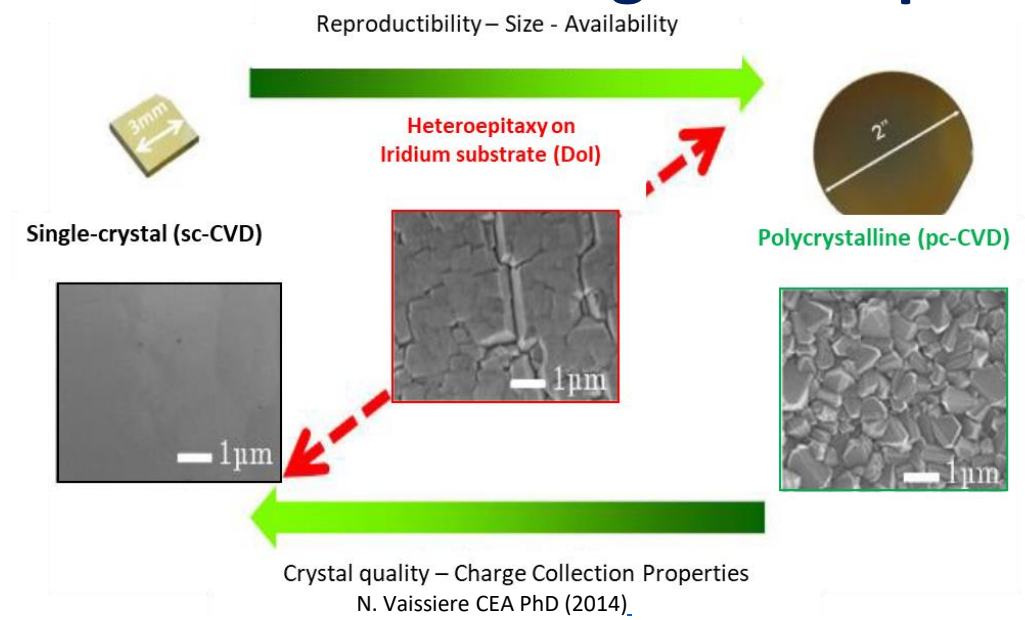
Discrete



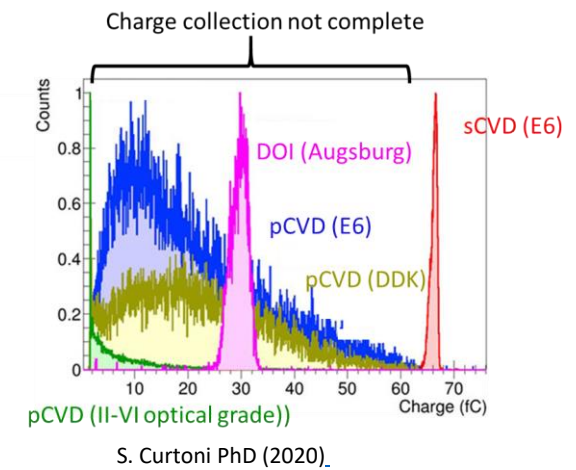
C. Hoarau *et al* 2021 *JINST* **16** T04005

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

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



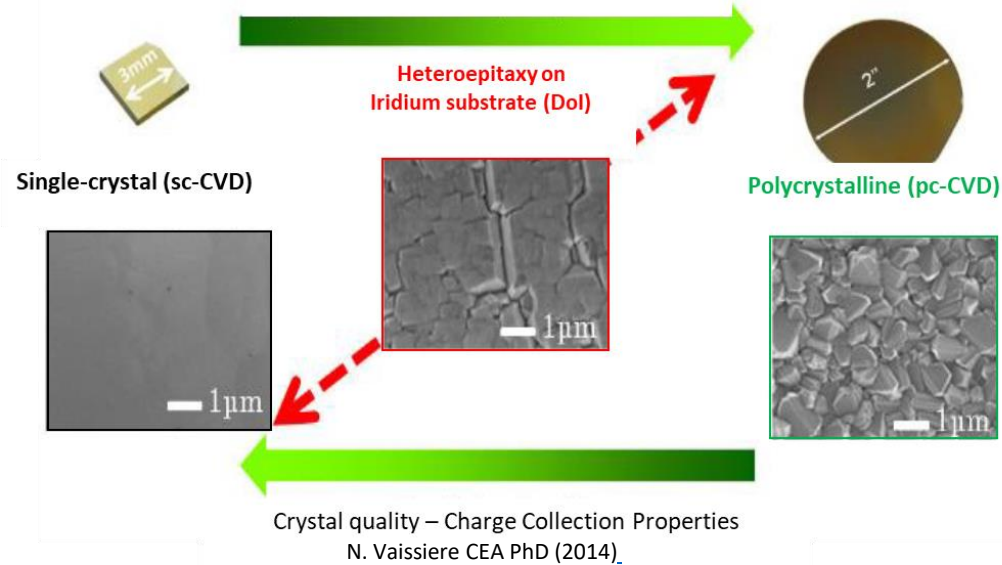
Spectroscopic measurement done at laboratory with diamond samples using an alpha source



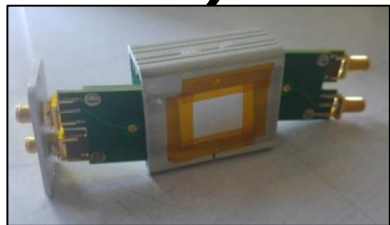
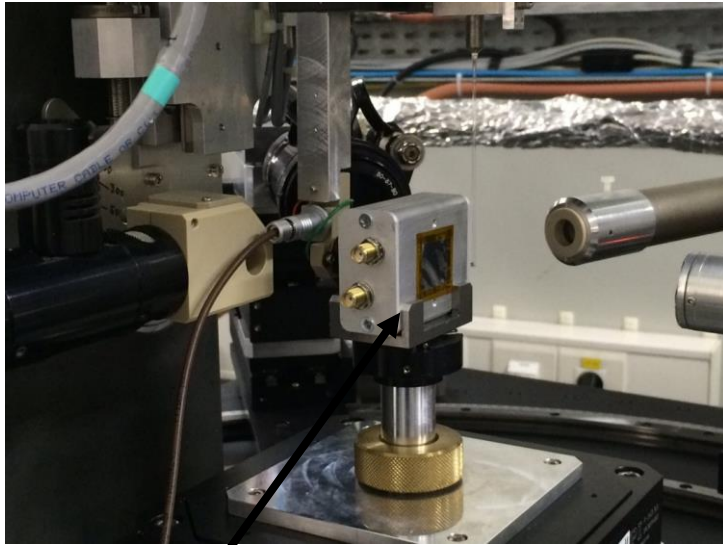
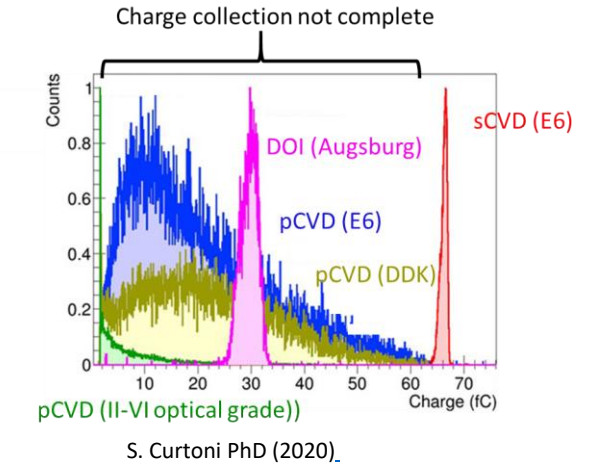
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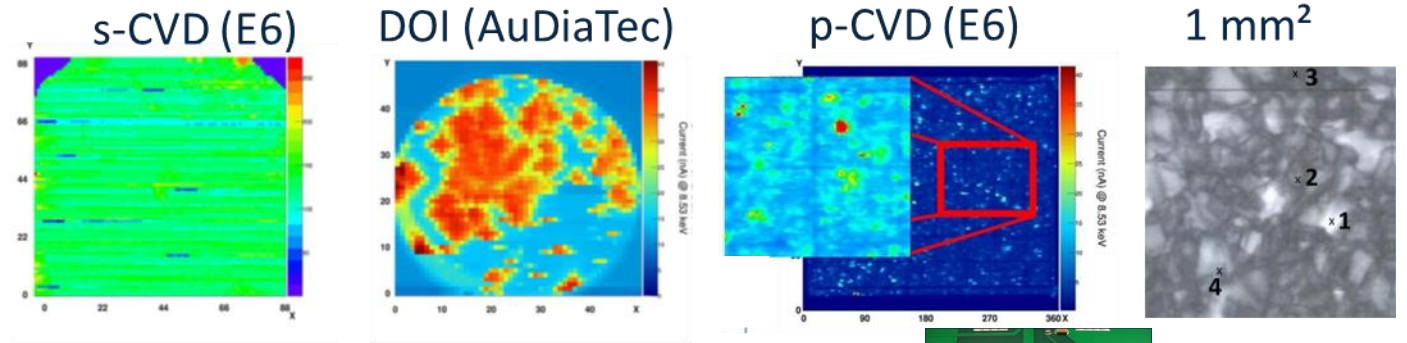
Reproducibility – Size - Availability



Spectroscopic measurement done at laboratory with diamond samples using an alpha source



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



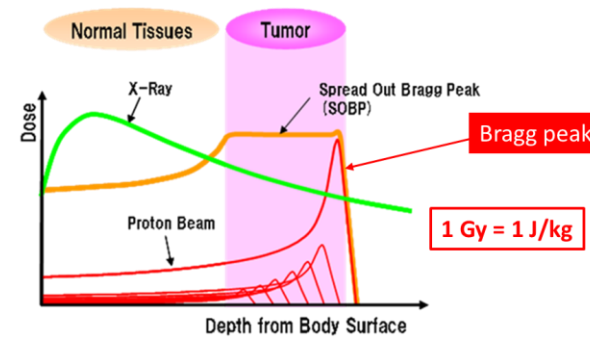
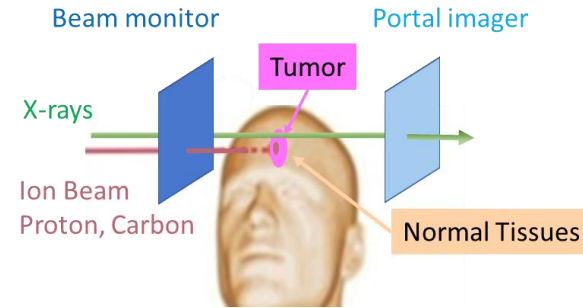
ML Gallin-Martel *Diamond and related materials* 112 (2021) 108236

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



Beam monitors for on-line control of innovative radiotherapies

X-rays vs hadrontherapy



Beam intensities

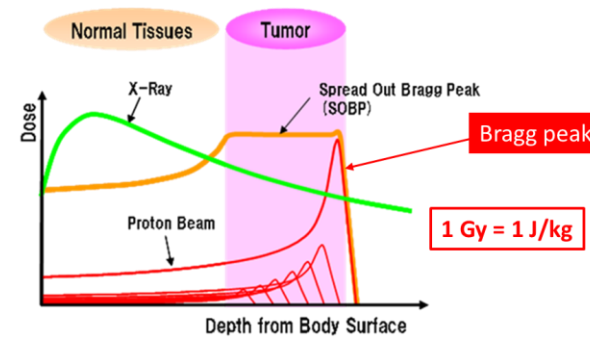
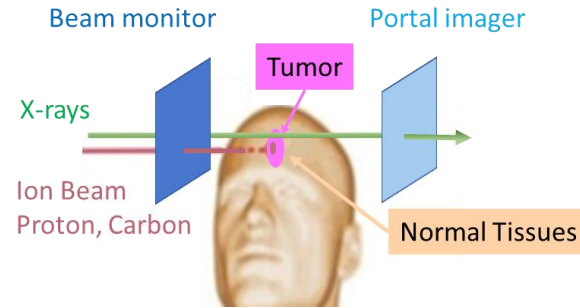
Proton-therapy $\sim 10^9\text{-}10^{10}$ p/s

Carbon-therapy $\sim 10^7\text{-}8$ C/s

⇒ Challenge for ion counting at clinical intensity

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Flash therapy vs conventional ⇒ high doses in a very short time

Conventional X-rays

or hadrontherapy → Gy/mn

Flash therapies → > 100 Gy/s for ions

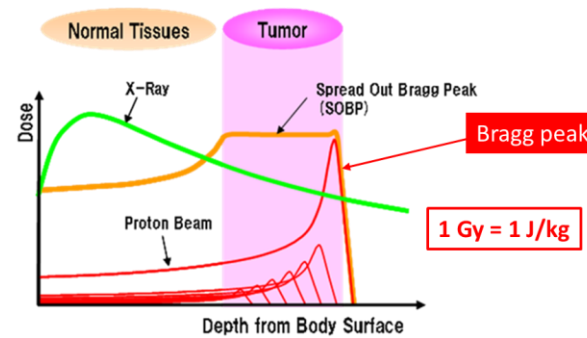
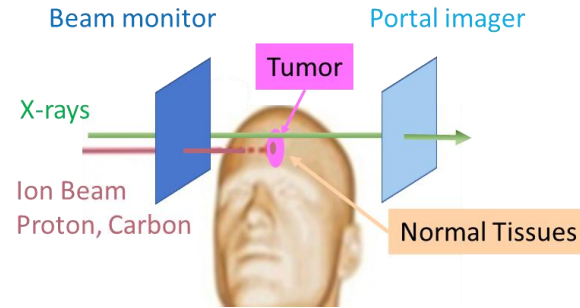
⇒ Short pulses to be monitored at high beam intensity !

⇒ High particle counting rate capabilities to be demonstrated

⇒ Bunch or train of bunches time stamps

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X-rays vs hadrontherapy



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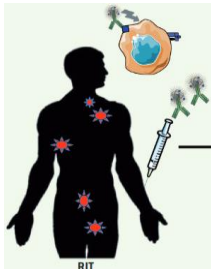
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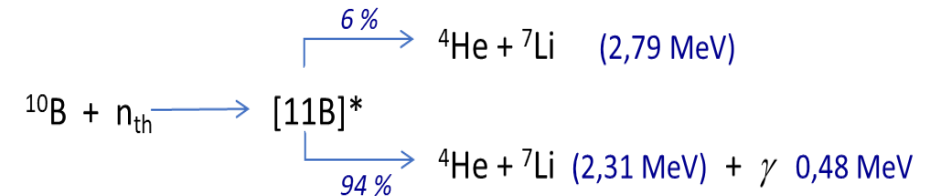
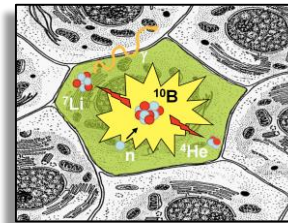
⇒ Bunch or train of bunches time stamps

Targeted Alpha Therapy (TAT) and Boron Neutron Capture Therapy (BNCT)



Radionuclides α : ^{223}Ra ,
 ^{225}Ac , $^{212}\text{Bi}/^{213}\text{Bi}$, ^{211}At ...

Energy α : 5 – 9 MeV



Objectives: improve dose predictions and biological effects for targeted radiotherapy

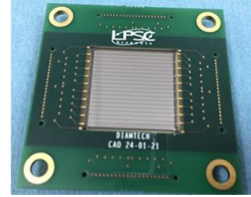
⇒ monitor low-energy ion beams for in vitro biology experiments

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

40 preamps + DFC + TDC



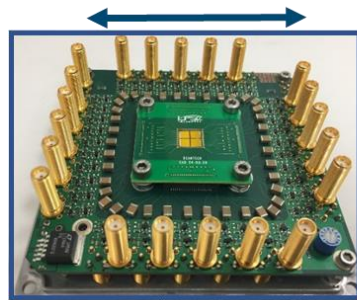
4 diamond sCVD in mosaic or 1 pCVD



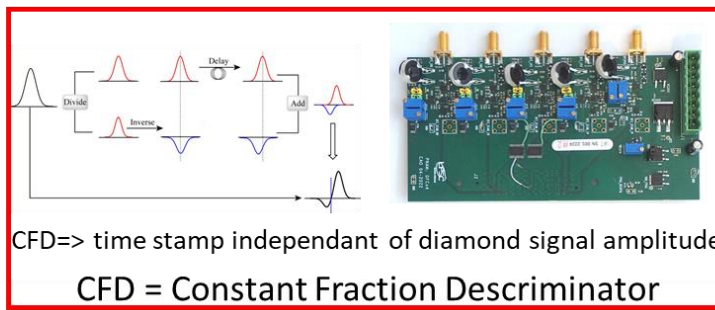
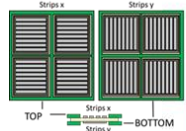
Proton beam monitoring in hadrontherapy (CAL)

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

- Single particle
 - XY spatial resolution ~ 1 mm
 - Time resolution ~ 100 ps
- Beam monitor and ToF**



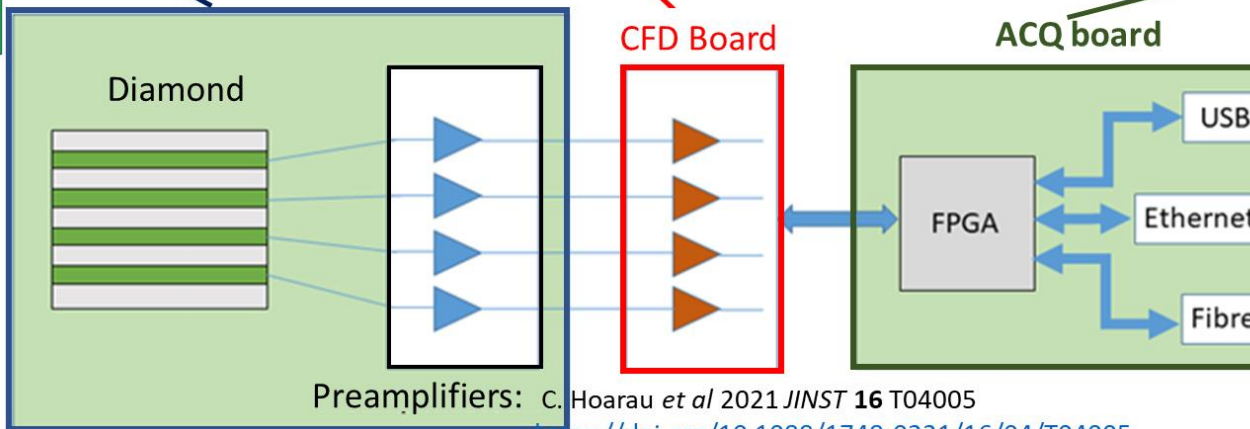
42 channels



Beam Monitor

CFD Board

ACQ board

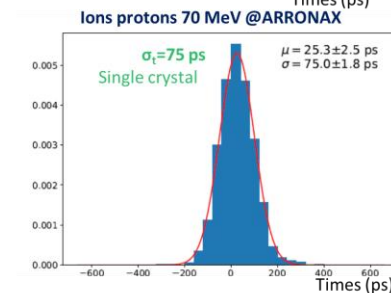
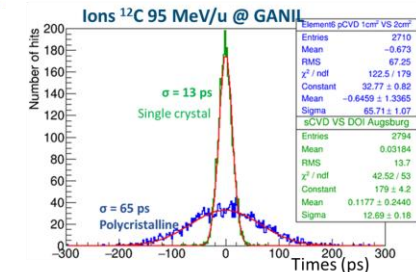


S. Curtoni PhD thesis <http://www.theses.fr/2020GRALY045> UGA / CLARYS-UFT INSERM 2020

Intel Cyclone 10
FPGA
2020
LPSC Grenoble
25 ps RMS

2021 CMOS 130 nm
12,5 ps RMS

TDC = Time Digital Converter



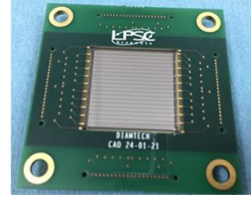
Need for large area sCVD to cover the beam surface !

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4 diamond sCVD in mosaic or 1 pCVD



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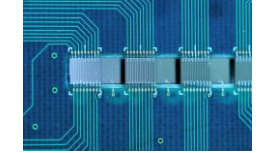
Micro-Xrays beam monitoring application to Microbeam Radiation Therapy (ESRF)

R&T DIAMTECH / IDSYNCHRO / PAIR TUMC - Coll. LPSC – STROBE (Inserm) (C. Milewski PhD thesis)

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

F. Di Franco et al. J Synchrotron Radiat. 2023 hal-04217250t

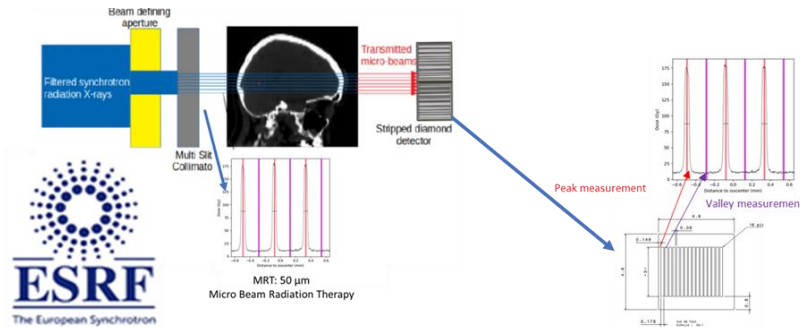
138 QDC channels : 20 ASIC + 8 Diamonds in 1 row



Micro Beam Radiation Therapy (MRT)

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

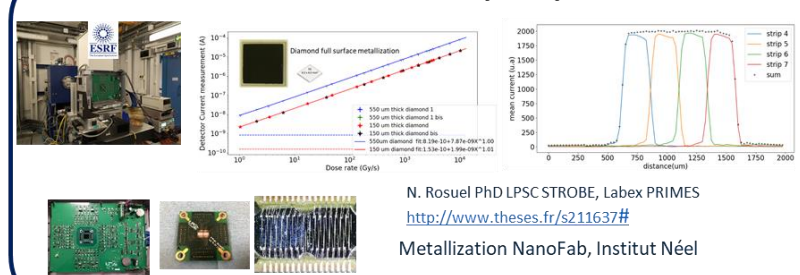
- Innovative radiotherapies using spatially segmented photon beams
- Energy 50-200 keV@ ESRF + very high dose rate 10^4 Gy/s



2nd Version: 8 channels with ASIC QDC

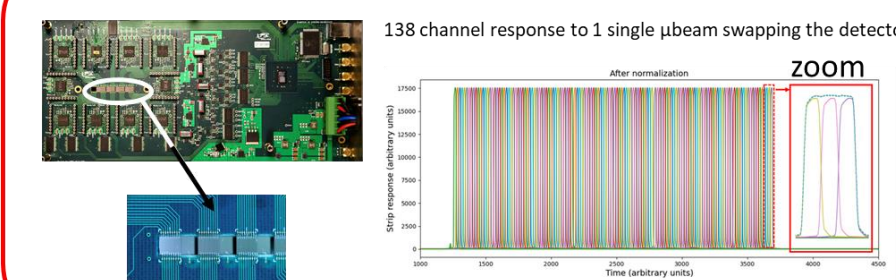
1st veterinary patients

1st 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

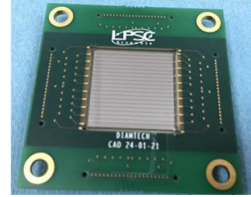


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4 diamond sCVD in mosaic or 1 pCVD



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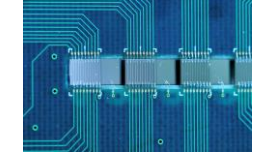
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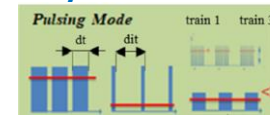


Pulsed proton beam monitoring – application to Flash Therapy (ARRONAX)

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

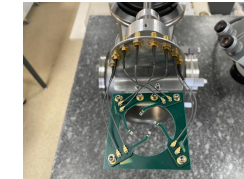
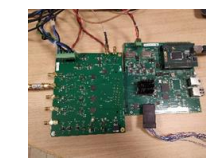
ANR DIAMMONI



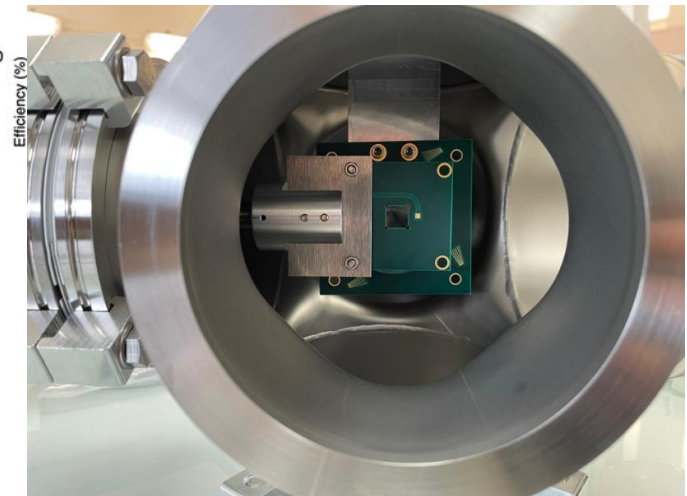
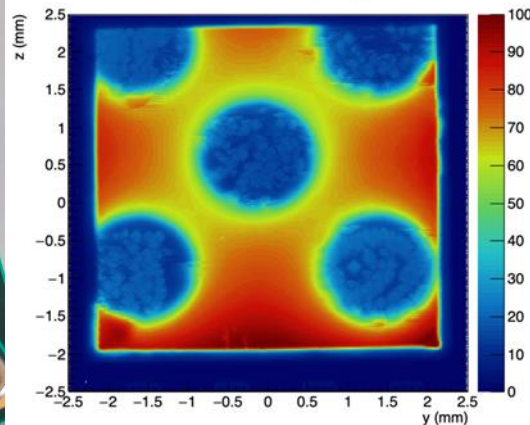
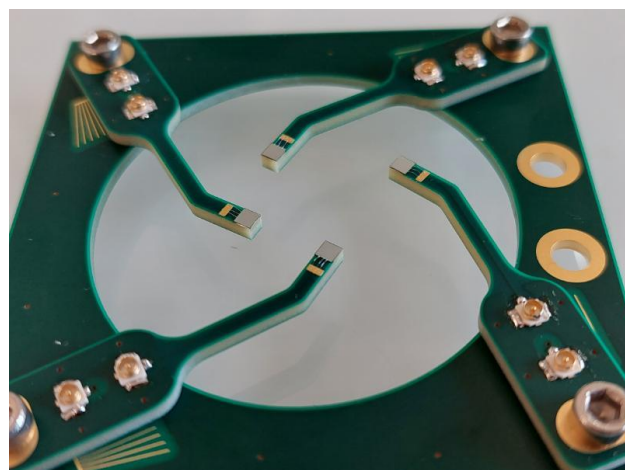
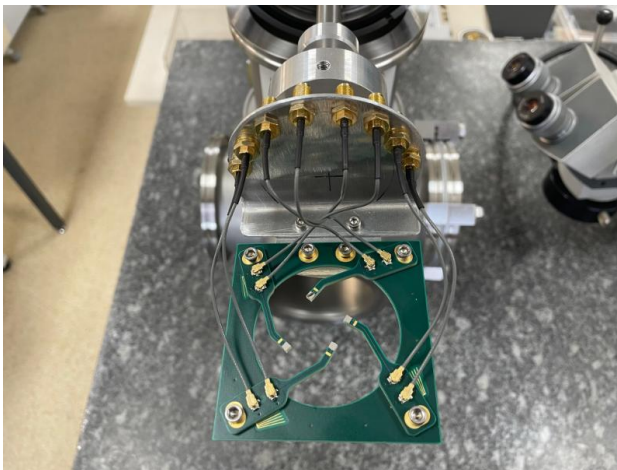
QDC : Train counting



4 sCVD + 1 sCVD diamond



Fast preamp + 500 MHz ADC : Bunch counting



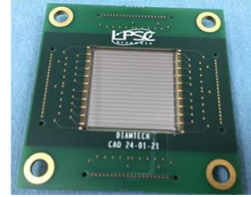
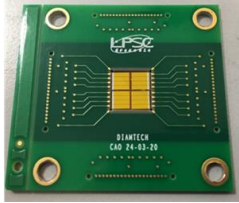
The challenge is to cope with diamond radiation hardness when bombarded with ions cumulating huge fluences (nb particles/surface unit)

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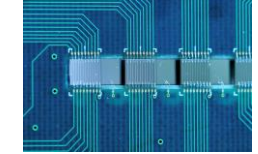
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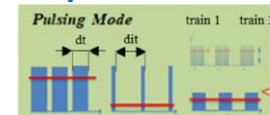
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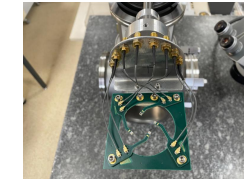
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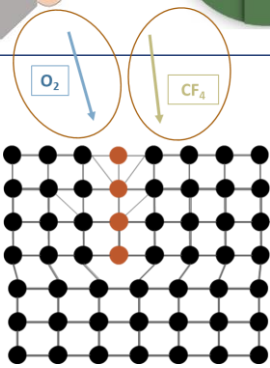
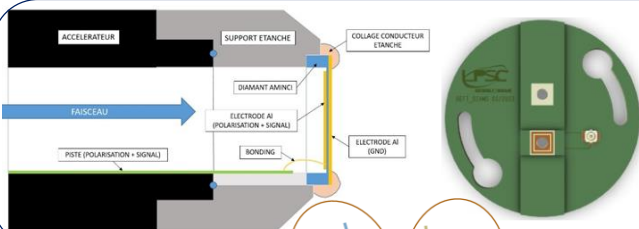


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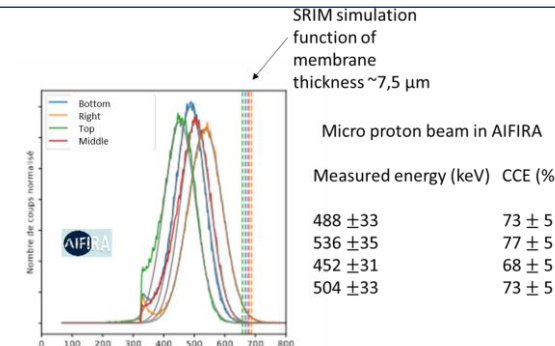
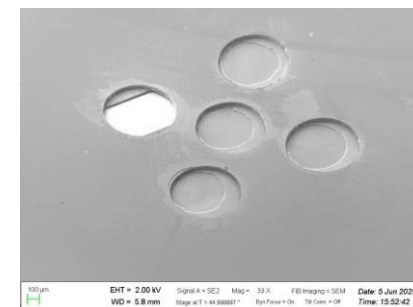


Micro - ion beam monitoring (LP2I Bordeaux/AIFIRA - IRSN/ MIRCOM)

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 to 6 MeV and B, C, O, ... ions up to 8 - 10 MeV.
- Diamond deep etching => diamond membrane of ~ 1 μ m (Institut Néel)
- Integration on the μ beam line = extraction window

DéFI DiaMs

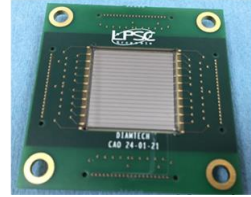
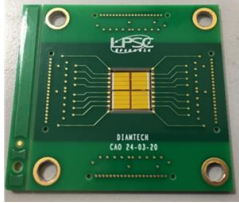


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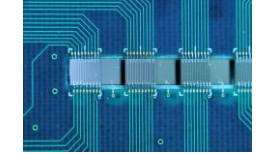
Micro-Xrays beam monitoring application to Microbeam Radiation Therapy (ESRF)

R&T DIAMTECH / IDSYNCHRO / PAIR TUMC - Coll. LPSC – STROBE (Inserm) (C. Milewski PhD thesis)

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

F. Di Franco et al. J Synchrotron Radiat. 2023 hal-04217250t

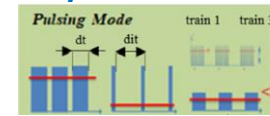
138 QDC channels : 20 ASIC + 8 Diamonds in 1 row



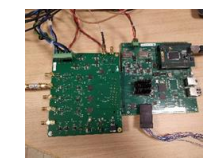
Pulsed proton beam monitoring – application to Flash Therapy (ARRONAX)

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

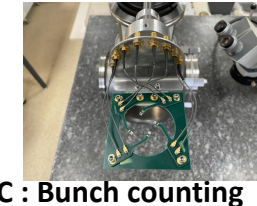
- Current integration (dynamic= 10^5)
- Train Counting => Time stamps ~ 3 ns
- Bunch Counting



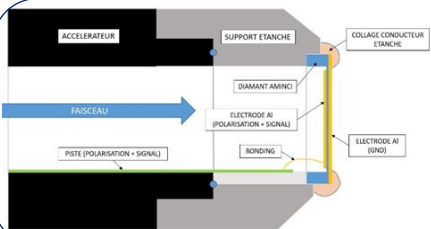
QDC : Train counting



4 sCVD +1 sCVD 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 membrane of ~ 1 μ m (Néel)
- Integration on the μ -beam line = extraction window

DéFI DiaMs



Monitoring low energy ion beam (ALTO)

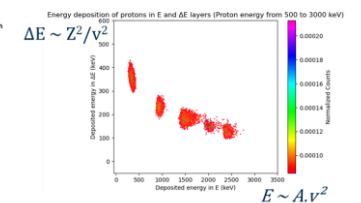
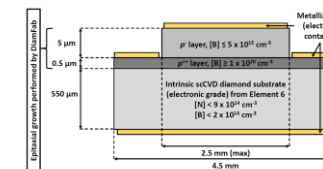
Coll. LPSC IP2I Lyon IJC lab via PICTURE (MP Diamant & BioALTO)

- 4 diamonds ($2 \times 2 \times 0.1 \text{ mm}^3$) placed in the halo of the beam for irradiation monitoring (beam energy) and beam alignment.



ΔE -E monolithic detector Coll. LPSC - Néel (C. Léonhart PhD thesis)

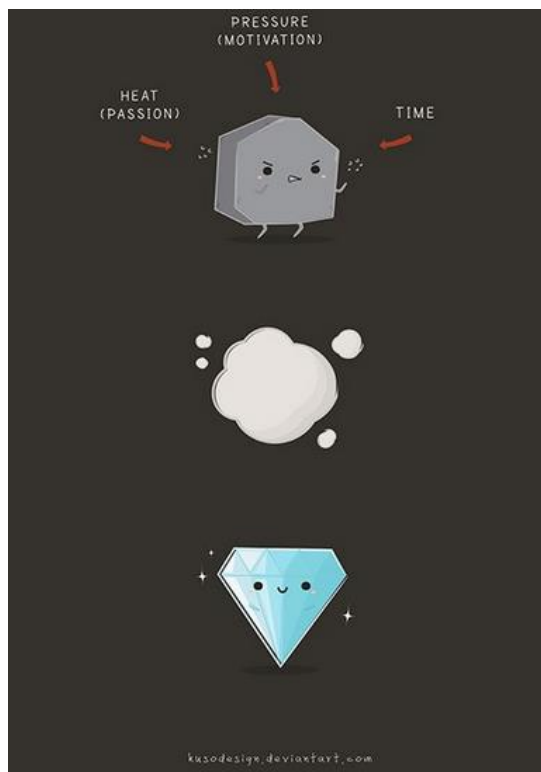
- P++ and P- layers
- Epitaxial on sCVD substrate



Conclusion

- **The developments are in connection with collaborations established at IN2P3 and INP, Inserm, CAL, IRSN and ESRF**
- **Interdisciplinary research: IN2P3 - INP skills exchanges**
 - 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/bunch)
 - Diamond beam monitoring satisfies the FLASH therapy conditions (linear response in the range $1 - 4 \times 10^5$ Gy/s with X-rays and proton beams)
 - => the proposed systems will bring significant added value to the transfer of FLASH radiotherapy to clinical trials
- **Simulation + aging studies are ongoing for a better understanding of the signal formation and the impact of very high fluxes and fluences on charge collection**

THANKS FOR YOUR ATTENTION !



© Diamond Jokes Quotes

