Faisceaulogie – dosimétrie
Développements de détecteurs diamant innovants

11/06/2021

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The scientific context

Nuclear Physics

Spectroscopy

- Alpha particles
- Short range particles detection
- Neutrons

Particle Physics

Beam monitoring

- LHC
- KEK
- J-PARC ….

Medical Physics

Beam monitoring

- position, time stamp

Dosimetry

- charge counting

The objectives of our projects

Innovative diamond detectors development from :

diamond growth + ion implantation + electronic development (fast preamplifier, QDC, TDC, ASIC and discrete FE readout electronics) + detector assembly + access to radiation facilities

⇒ ΔE – E diamond monolithic detector

⇒ *PN junction development*

Measurement of beam line activation for new generation of accelerators

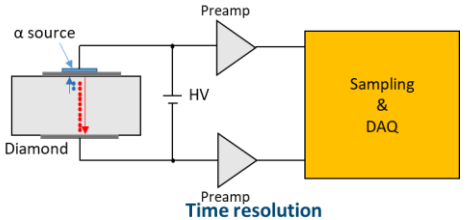
⇒ Need for high quality, pure, affordable, reliable, large area diamond single-crystal detectors

⇒ Compact multi stripped diamond detector associated to a multi-channel readout electronics (fast preamplifier, QDC, TDC)

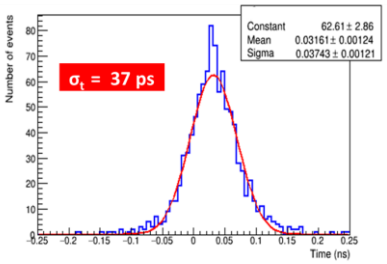
Diamond a solution for very innovative detectors with remarkable properties

Properties	Diamond	Silicon
Density [g.cm^3]	3.52	2.33
Gap [eV]	5.48	1.12
Energy required to produce e-h [eV]	13.1	3.62
Mean signal MIP [e-/µm]	36	89
Resistivity [Ω.cm]	$10^{13} – 10^{16}$	$10^5 – 10^6$
Thermal conductivity [W.cm^{-1}.K^{-1}]	>1800	1.48
Displacement energy [eV]	43	25
Electron mobility [cm^2.V^{-1}.s^{-1}]	1900	1450
Hole mobility [cm^2.V^{-1}.s^{-1}]	2300	505

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

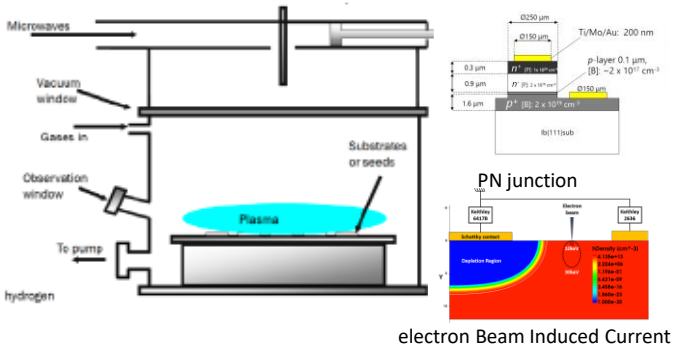


Time resolution
(offline Constant Fraction Discrimination)



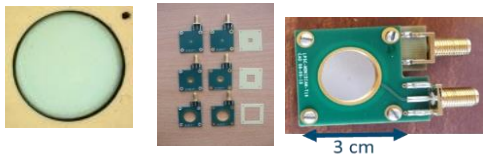
R&D with diamond detectors and complementarity of the consortium

CVD Diamond growth, doping, characterization



NIMS -AIST- Institut Néel – LSPM-DiamFab

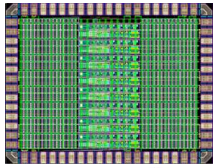
Metallized diamond detector assembly

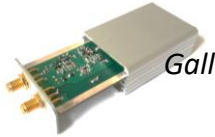


KEK – LPSC – NANOFAB Néel

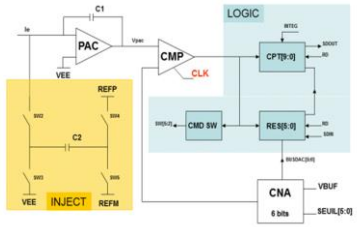
Diamond detector electronic read-out development

Fast preamp.





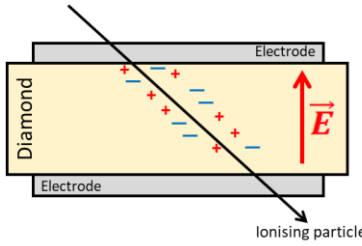
QDC



Gallin-Martel, IEEE NSS-MIC 2016

LPSC - LPCcaen

Diamond detector performances evaluation with radiation facilities



KEK - LPSC – IJCLab- SUBATECH

Diamond = solid state ionization chamber

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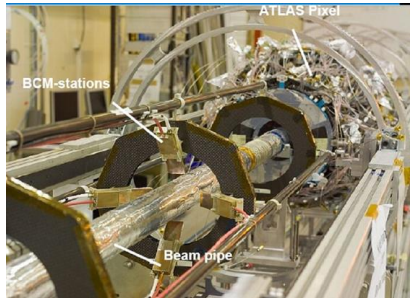
Present experience with on-line beam monitors

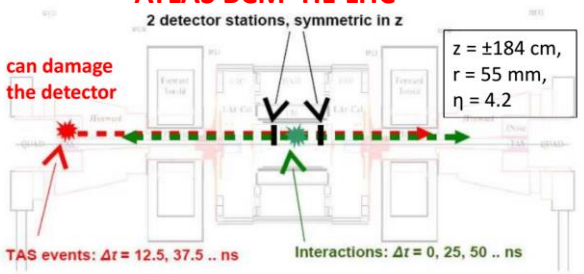
LHC ATLAS and CMS

ATLAS BCM



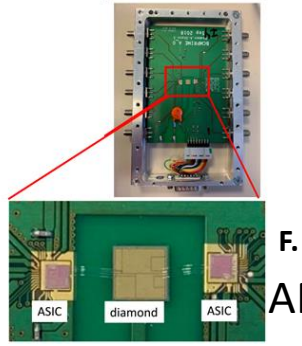
RD42 collaboration @ CERN https://rd42.web.cern.ch/rd42/

ATLAS BCM' HL-LHC



Robust solution for HL-LHC→ BCM' (BCM Prime)

ATLAS BCM' HL-LHC



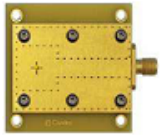
F. Rarbi, J Collot (LPSC)

ANR MONODIAM

SUPERKEK B

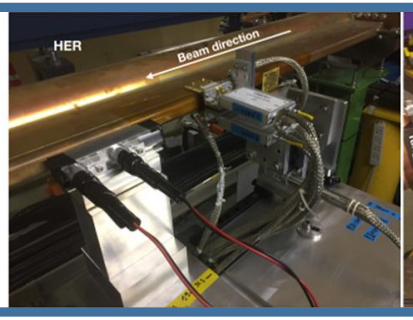
A fast luminosity monitor based on diamond detectors for the SuperKEKB collider

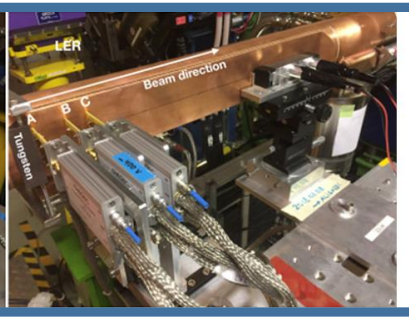
Diamond detector



Ph. Bambade (IJCLab), C. G. Pang et al.: Nucl. Instrum. Meth. A931 (2019) 225-235

https://doi.org/10.1016/j.nima.2019.03.071

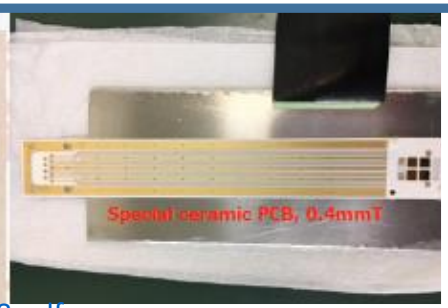


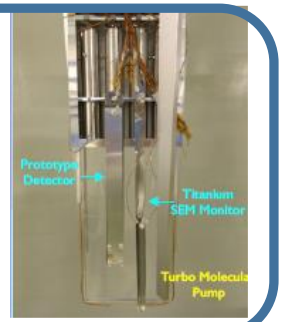


COMET experiment

Search for the muon to electron (μ- e) conversion in nuclei with the sensitivity below 10^{-16} => development of a diamond based proton beam monitor

Y. Fujii, **H Nishiguchi**, S. Mihara, Y Hashimoto (KEK Tsukuba)
14th Pisa meeting On Advanced Detectors
Labiodola, Isola d'Elba, Italy, 2018
https://agenda.infn.it/event/17834/contributions/83592/attachments/60425/71543/276-Poster-fujii-yuki_Pisameet18.pdf





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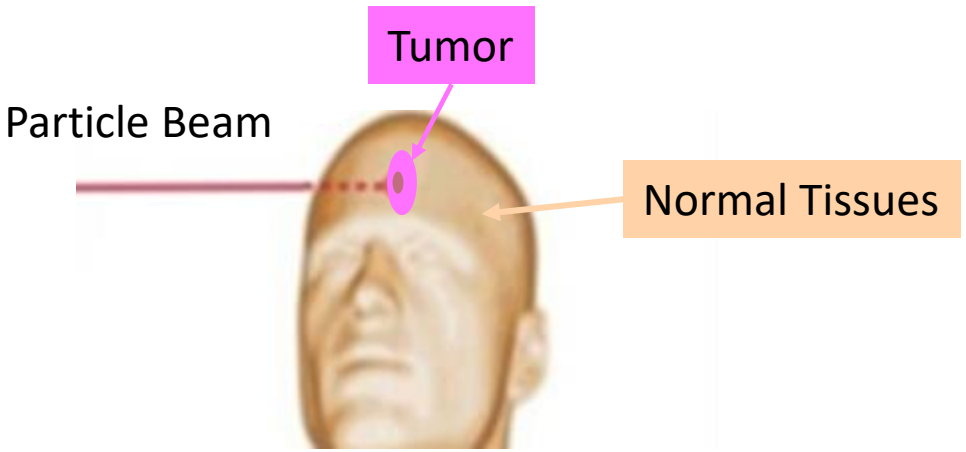
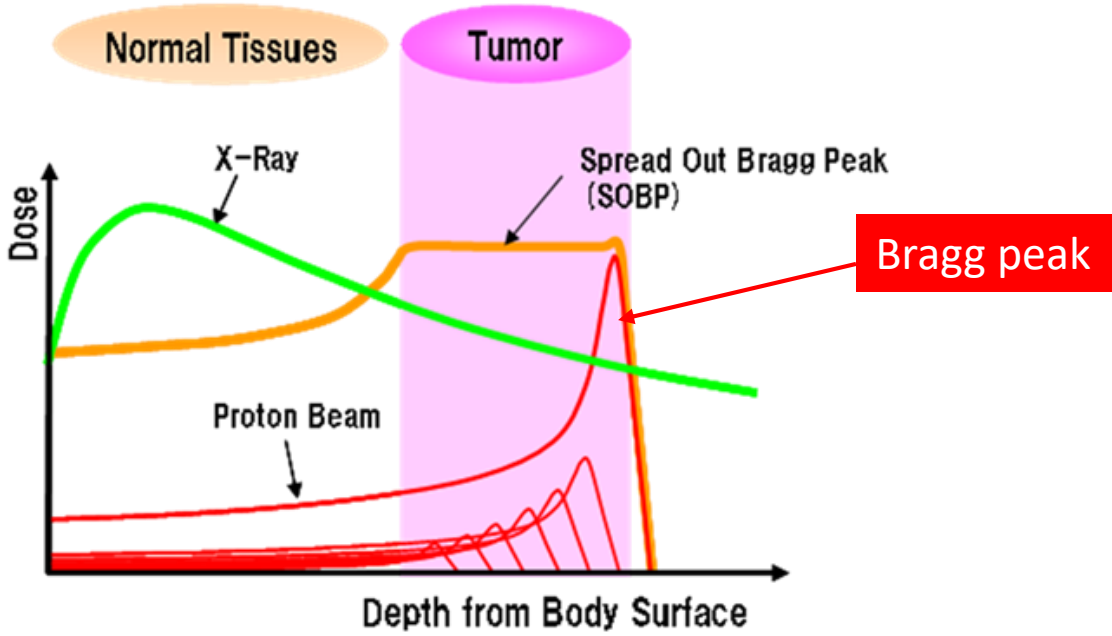
Beam tagging hodoscope for online ion range verification in hadrontherapy

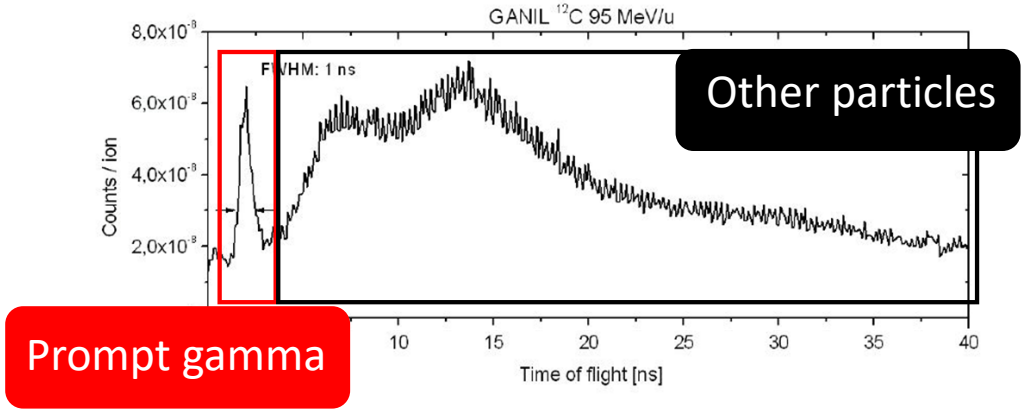
Prompt Gamma detection





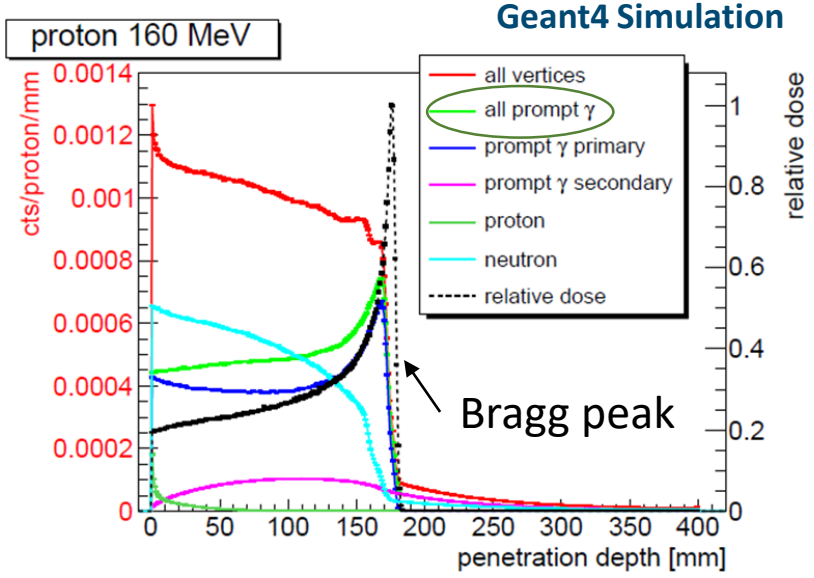
Ion range monitoring in patient body : Bragg peak location

Prompt gamma detection : experiment using 12C @95 MeV/u on PMMA (human body phantom)
Time of Flight Spectrum



Mauro Testa, Thèse, Univ. Lyon, 2010

Geant4 Simulation

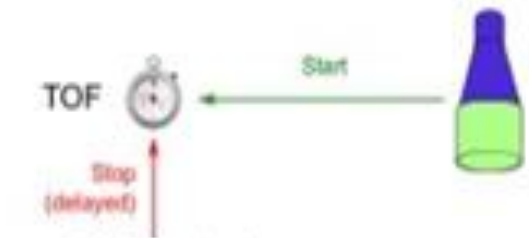


Krimmer et al., Nucl. Instr. Meth. A, **878** (2017) 58-73

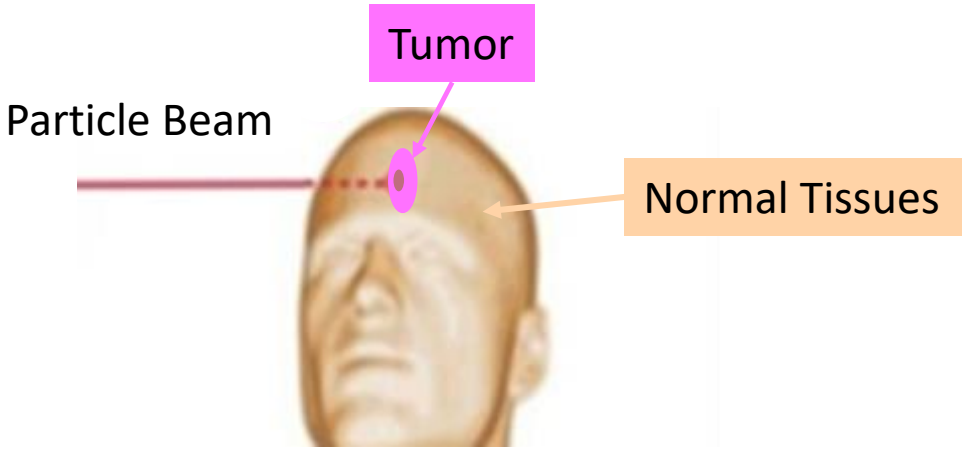
Beam tagging hodoscope for online ion range verification in hadrontherapy

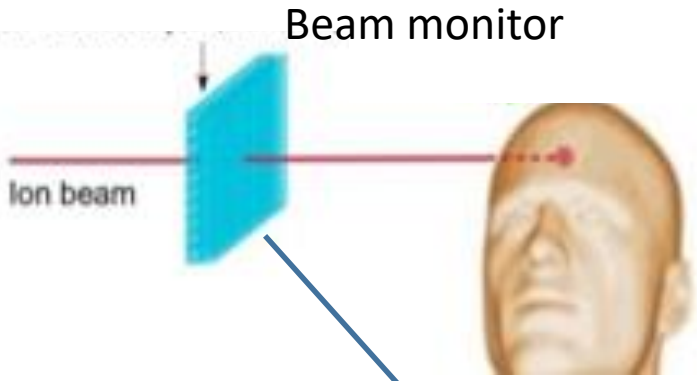
Prompt Gamma detection

Time of Flight : gamma detector vs beam monitor => prompt gamma selection



Gamma detector

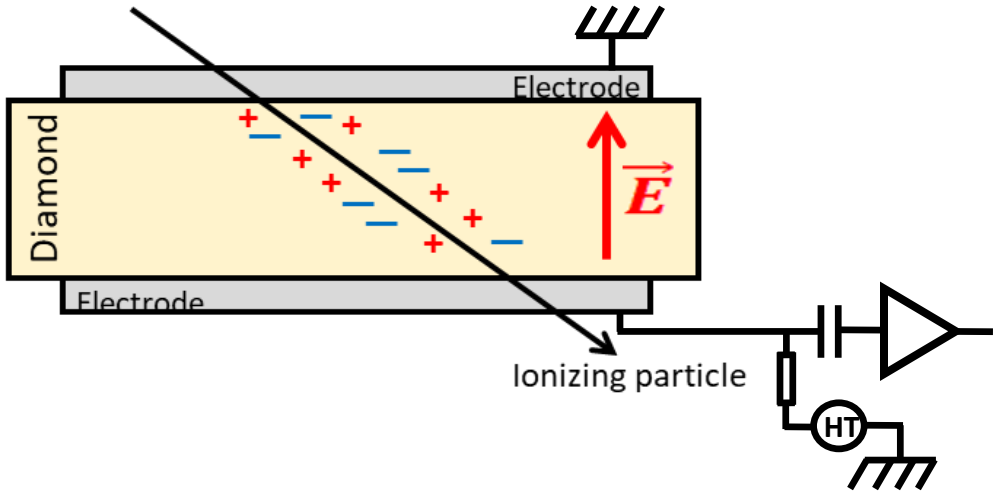




Beam monitor : background reduction + position and time stamps for the ion beam

Diamond Sensor Instrumentation for test @ laboratory or in beam

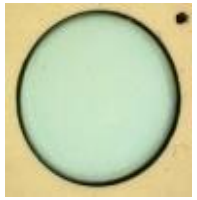
Solid state ionization chamber



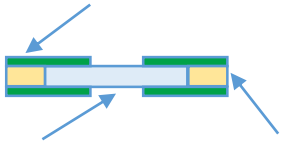
Read-out electronics

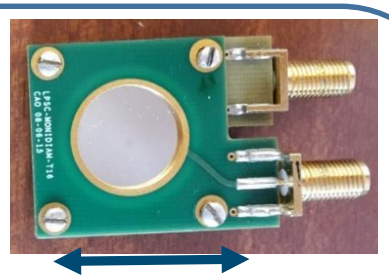
- Fast current preamplifier
- Charge preamplifier
- Electrometer

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



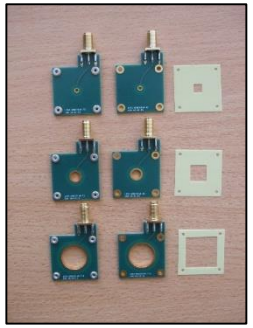
PCB 50Ω adapted

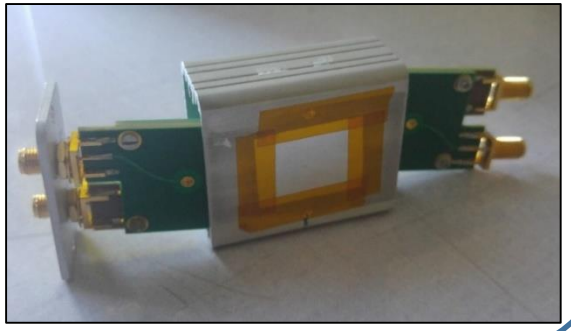




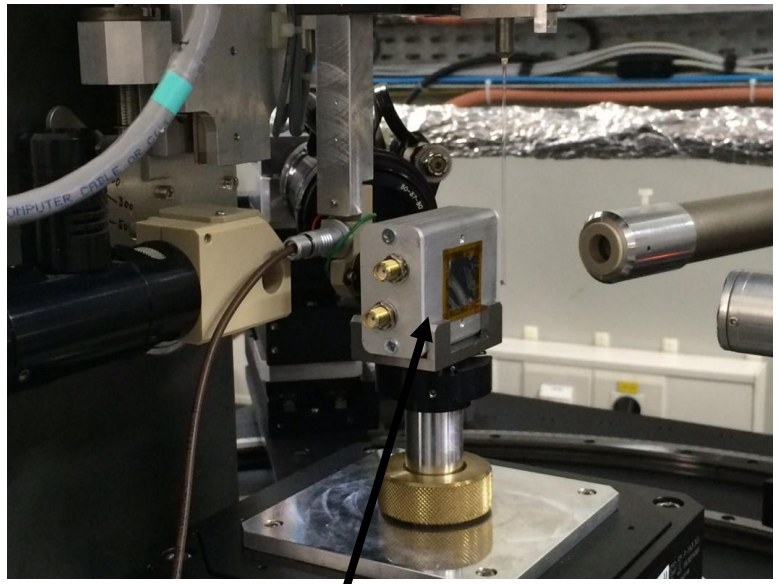
3 cm

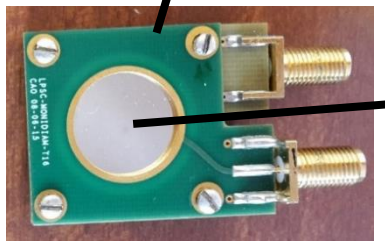
Detector assembly

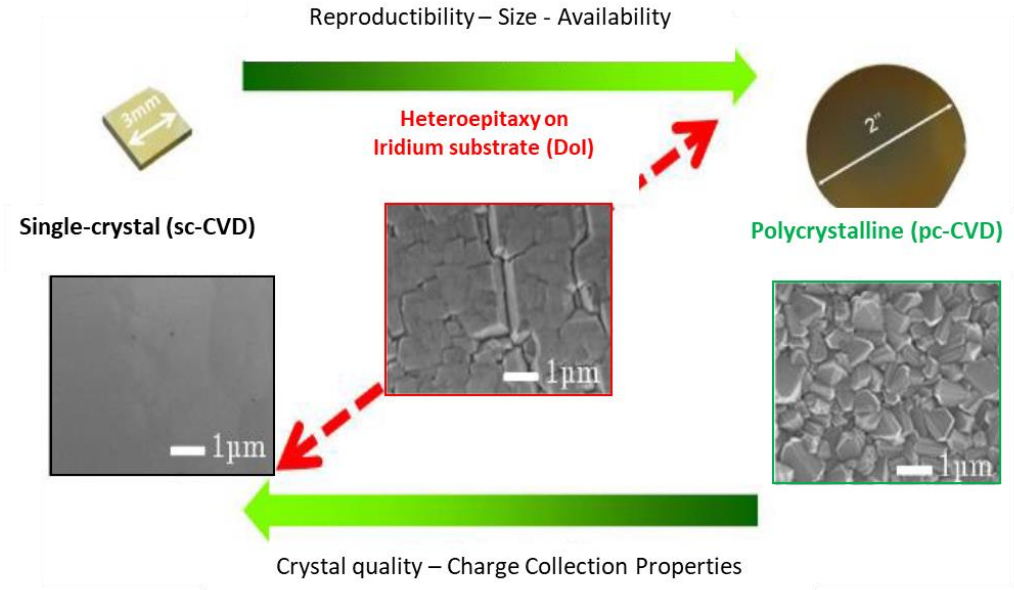




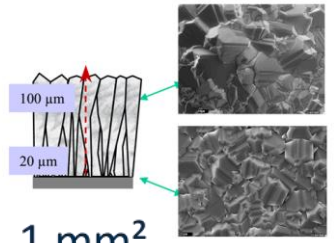
Diamond detector for beam monitoring: sCVD ? pCVD ? DOI ?

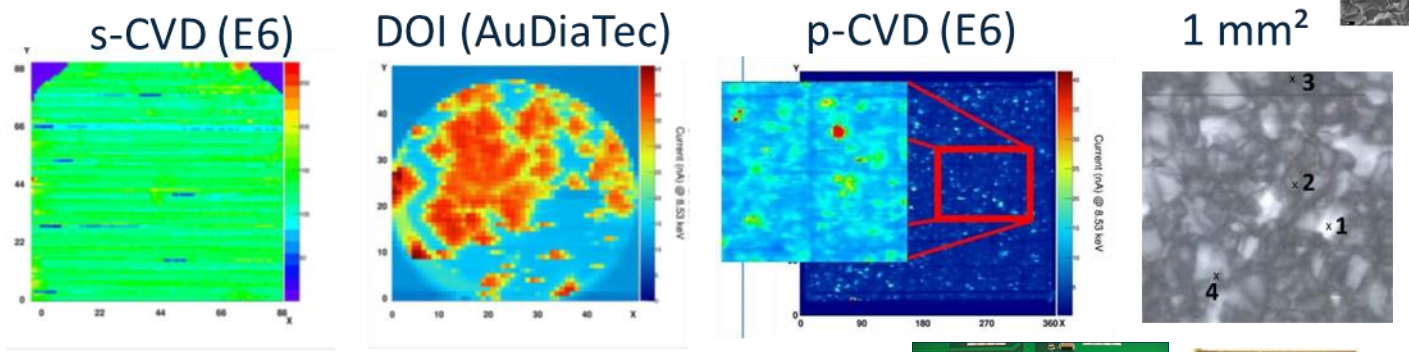




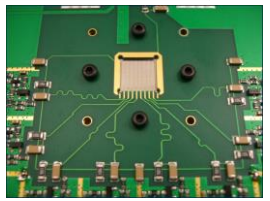


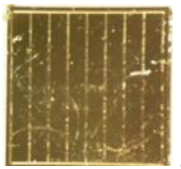
@ ESRF (France) : Photons 8.5 keV (XBIC) => 2D map





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





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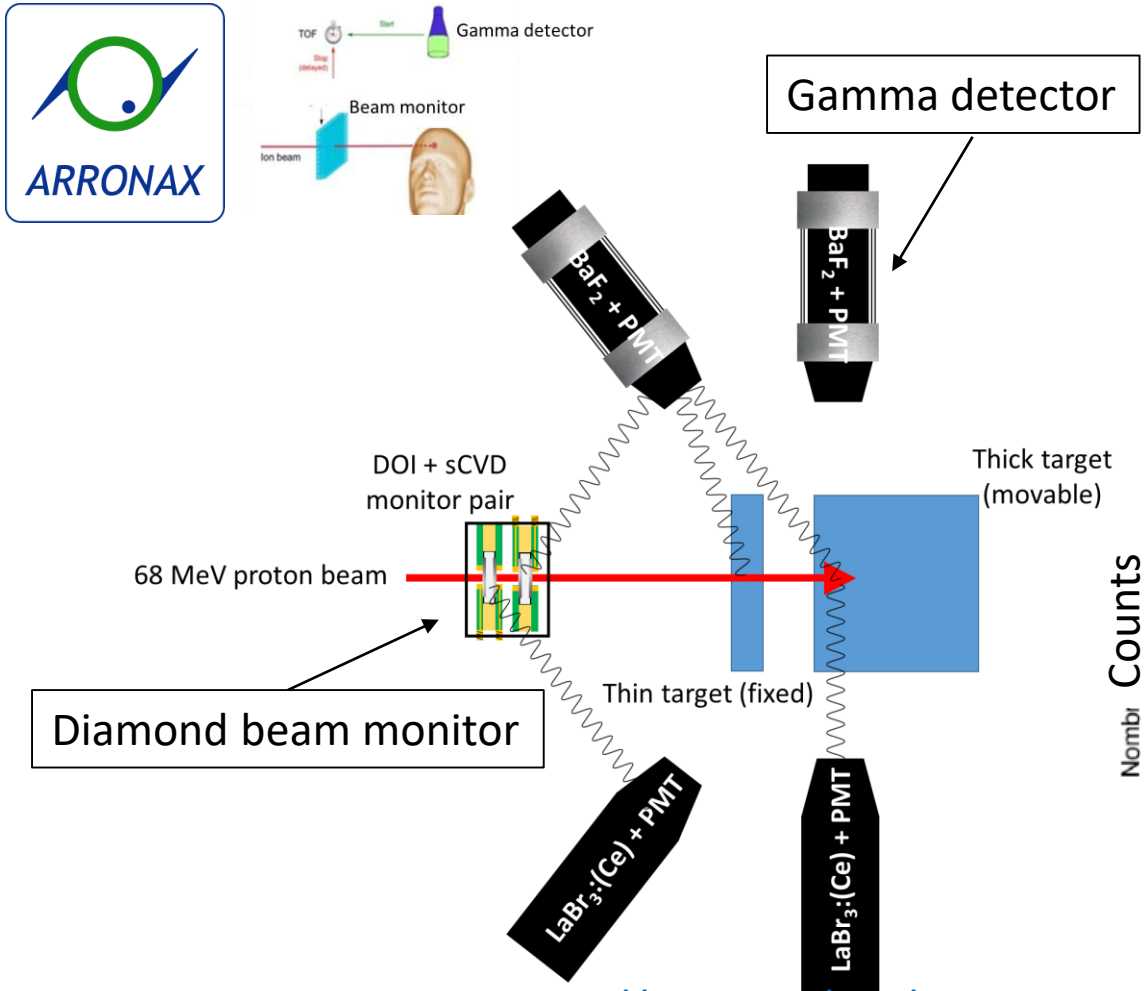
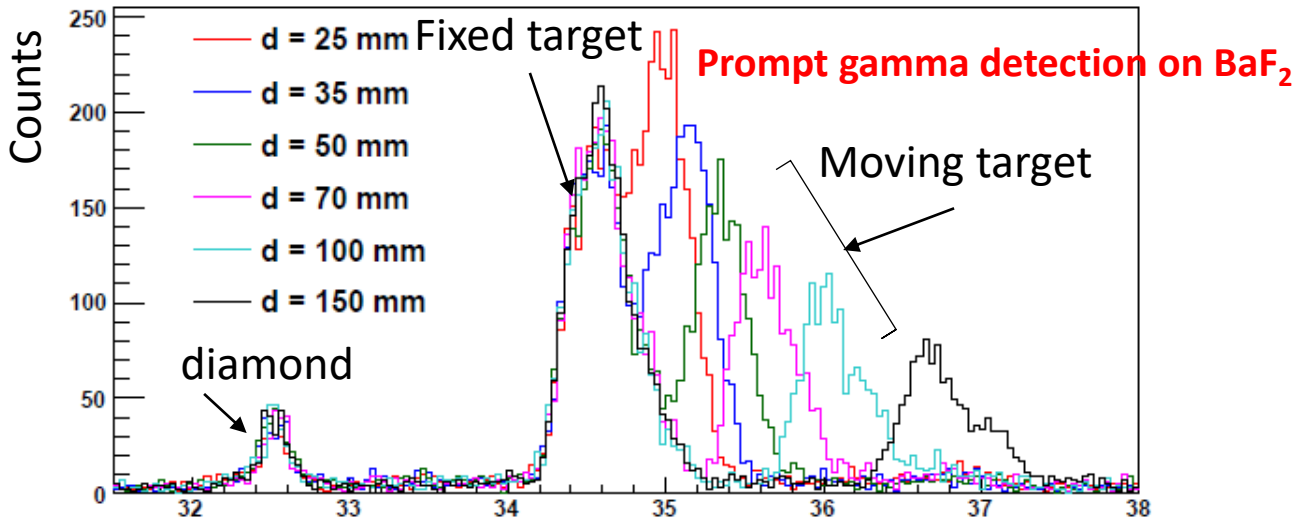
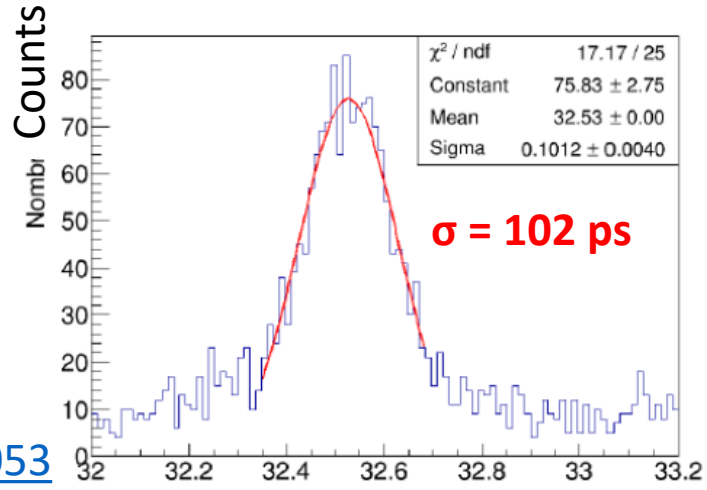
Prompt Gamma detection

Proof of concept : beam tests in ARRONAX with 68 MeV proton beam







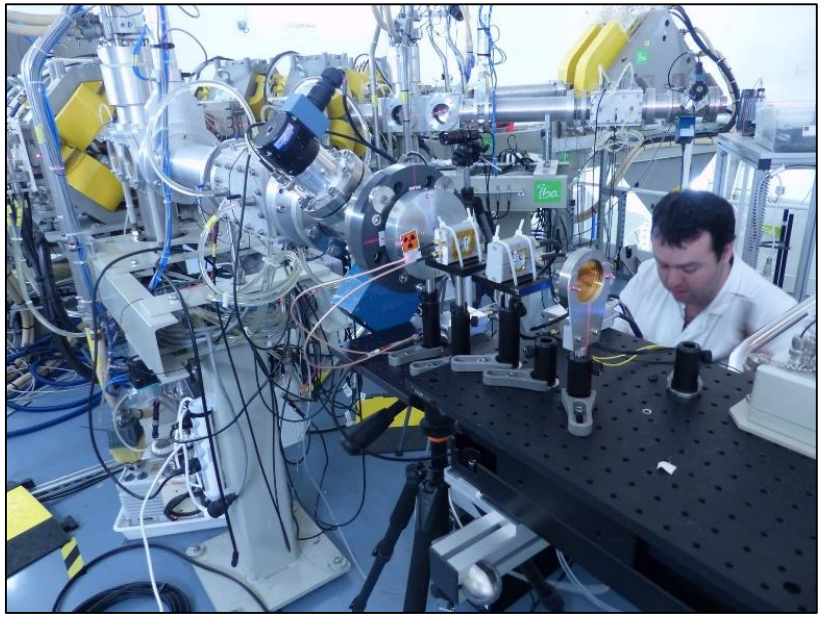
Time resolution single crystal diamond vs scintillator

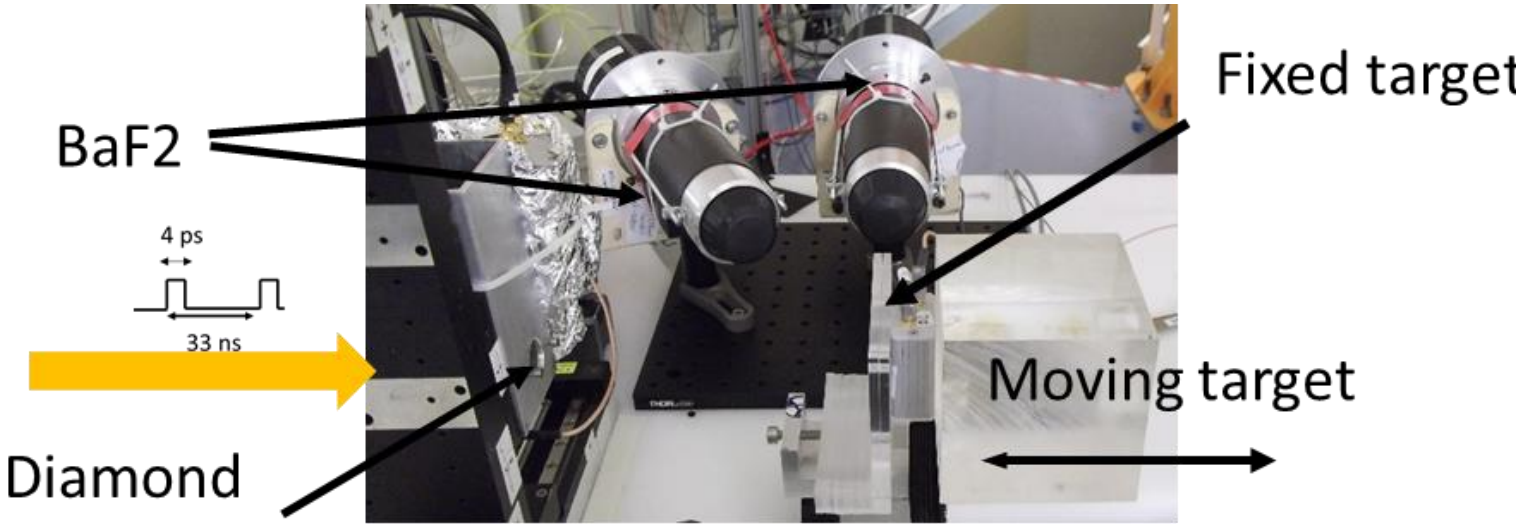
S. Curtoni PhD thesis and https://arxiv.org/abs/2105.05053

S. Marcatili et al. Phys Med Biol 65 (2020) 245033

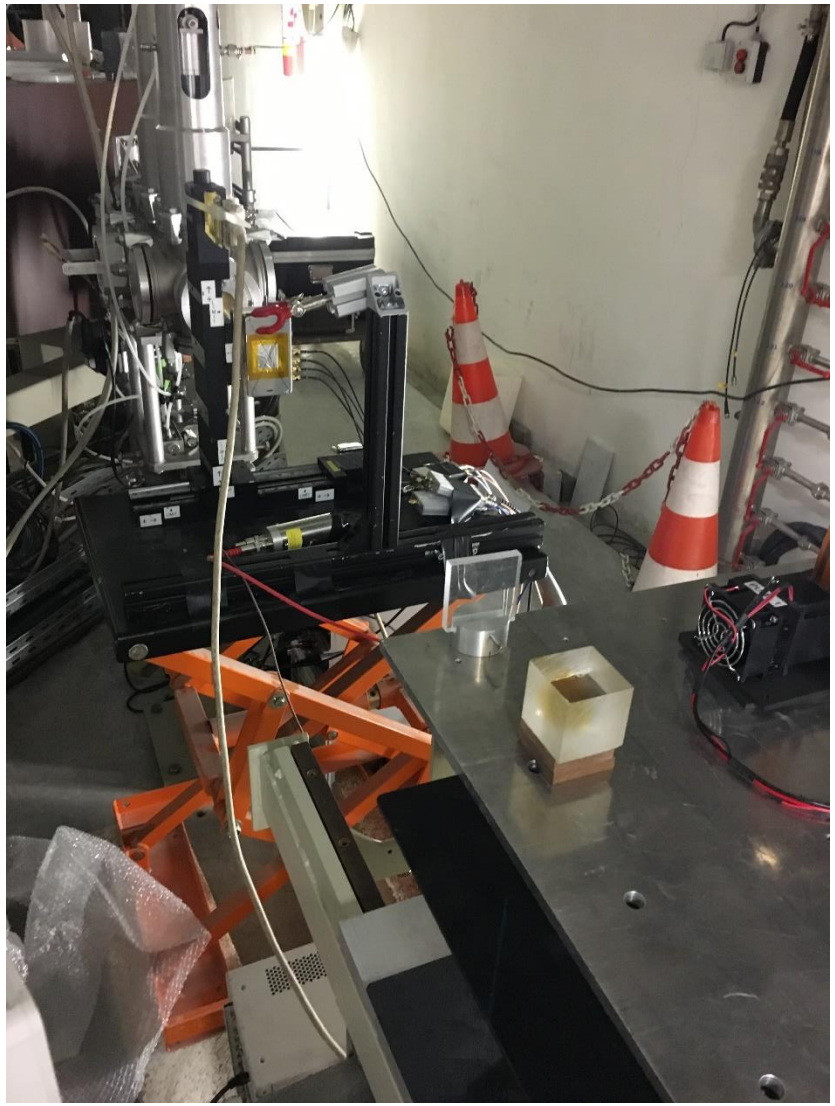
@ ARRONAX: Protons (68 MeV)

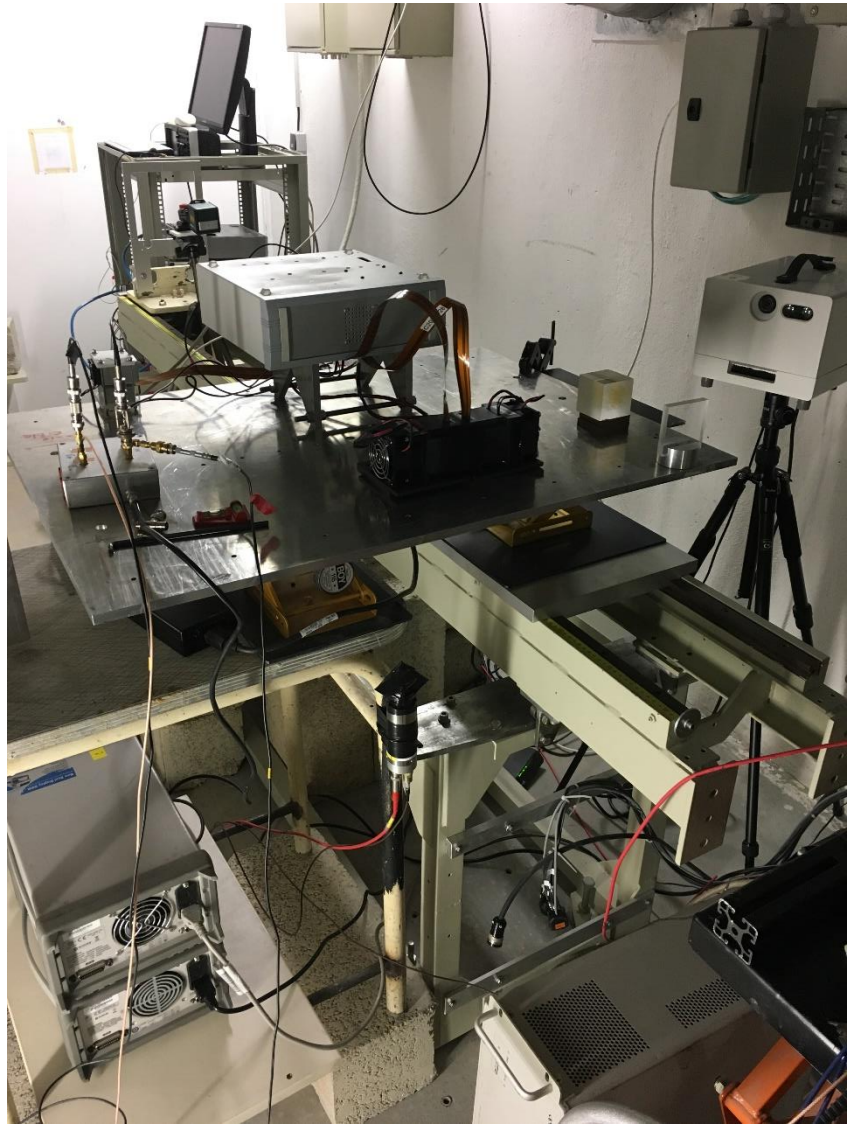
Charbel Koumeir (ARRONAX)



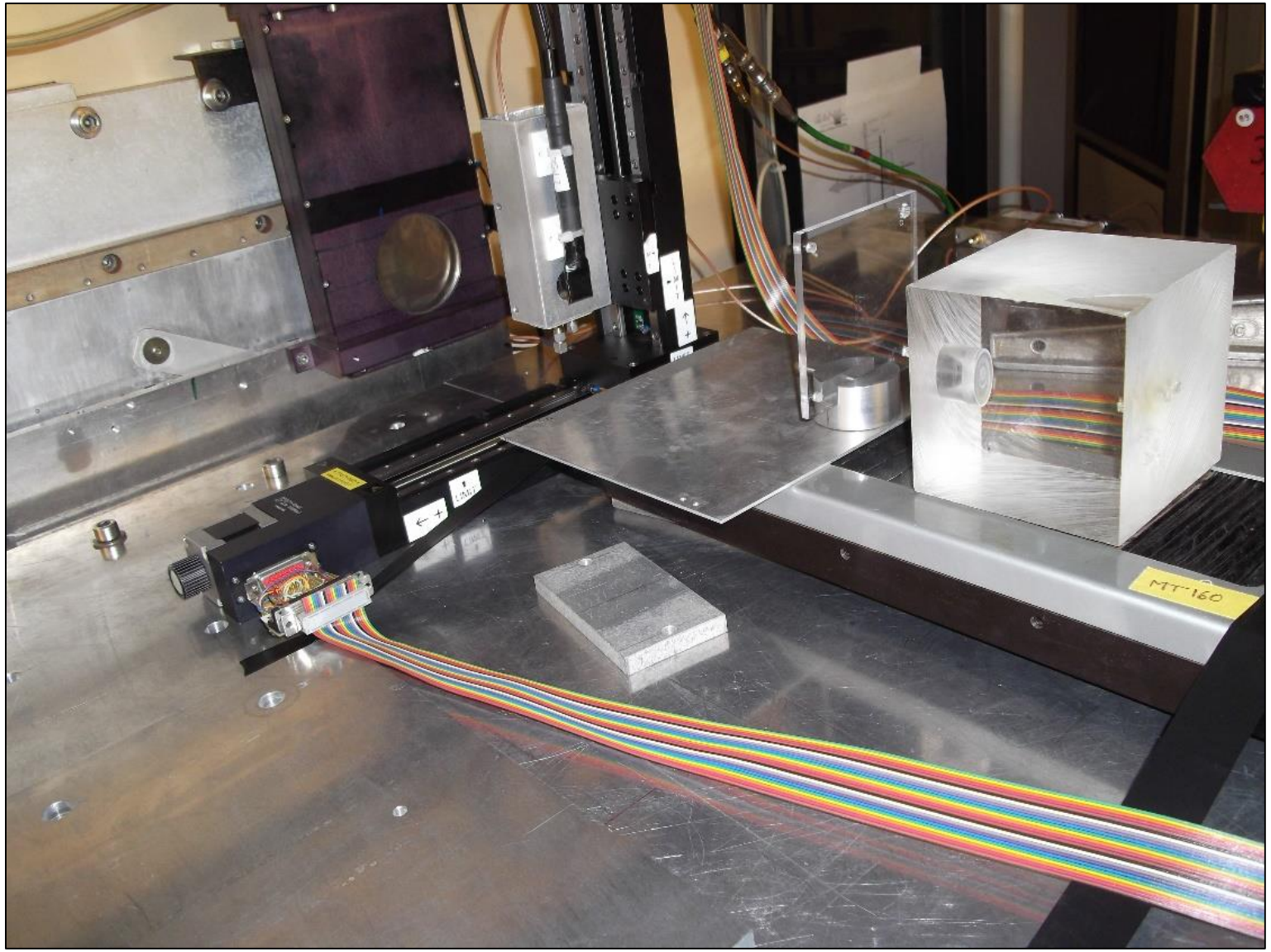


@ CAL : Protons (Hadronthérapie)

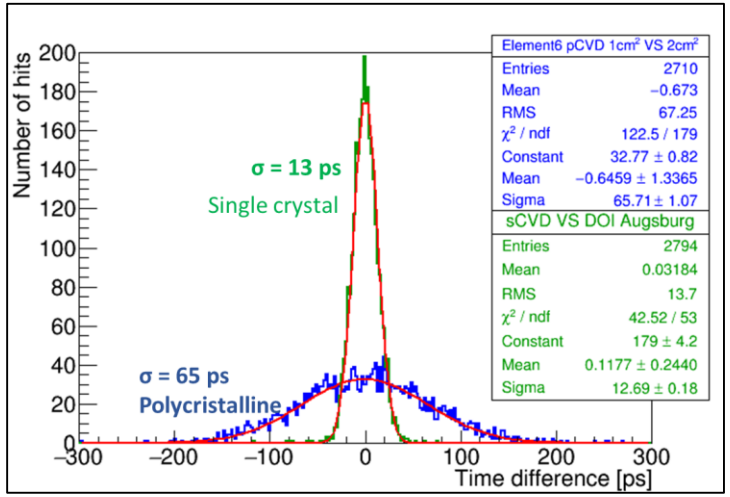




@ GANIL : C



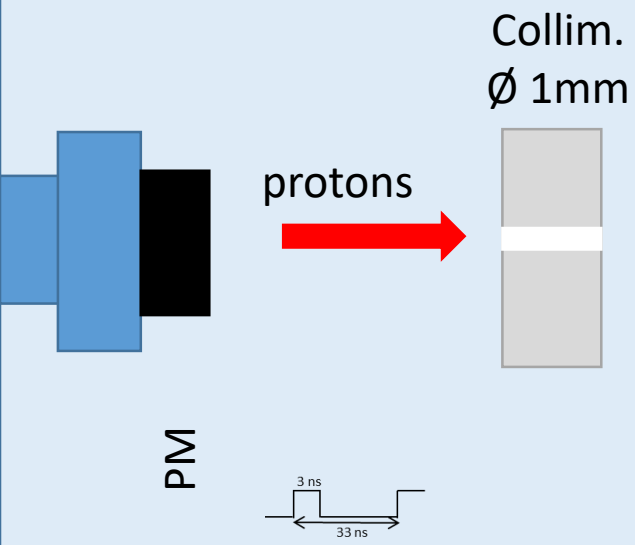
Carbon beam in GANIL (95 MeV/u)

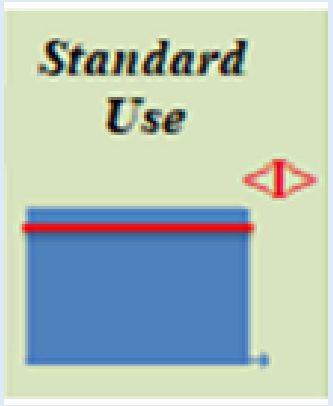


S. Curtoni, LPSC, Thèse, Novembre 2020

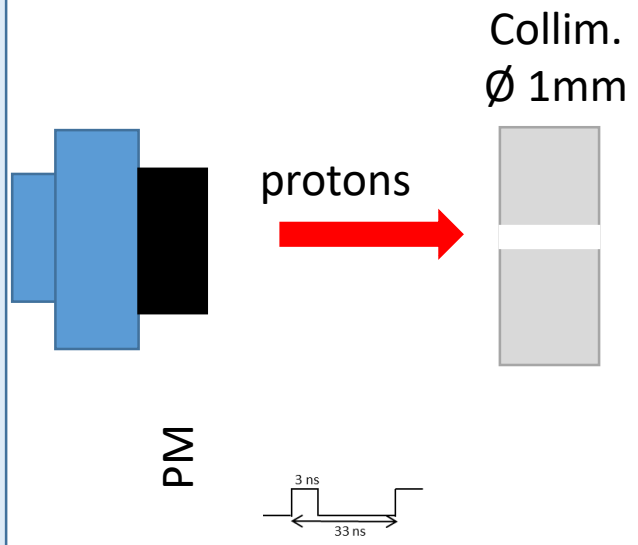
S. Curtoni et al., arXiv:2105.05053, 2021

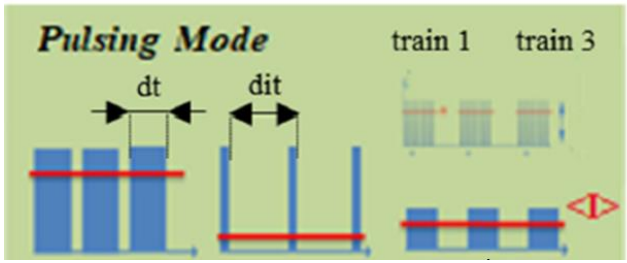
Continuous mode





Pulsed mode



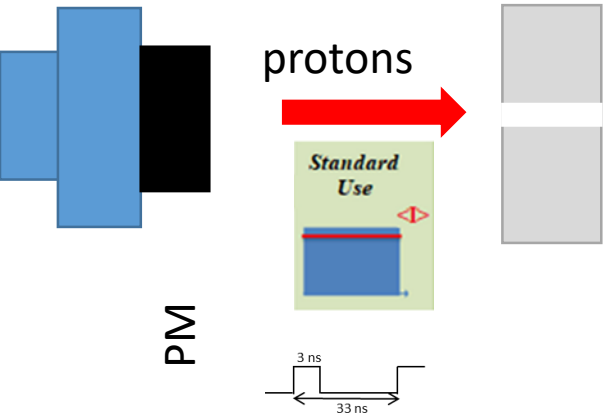


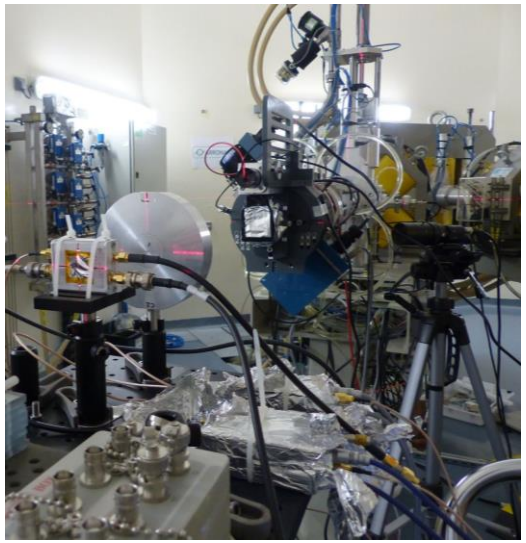
F. Poirier et al. IPAC 2019

Continuous mode

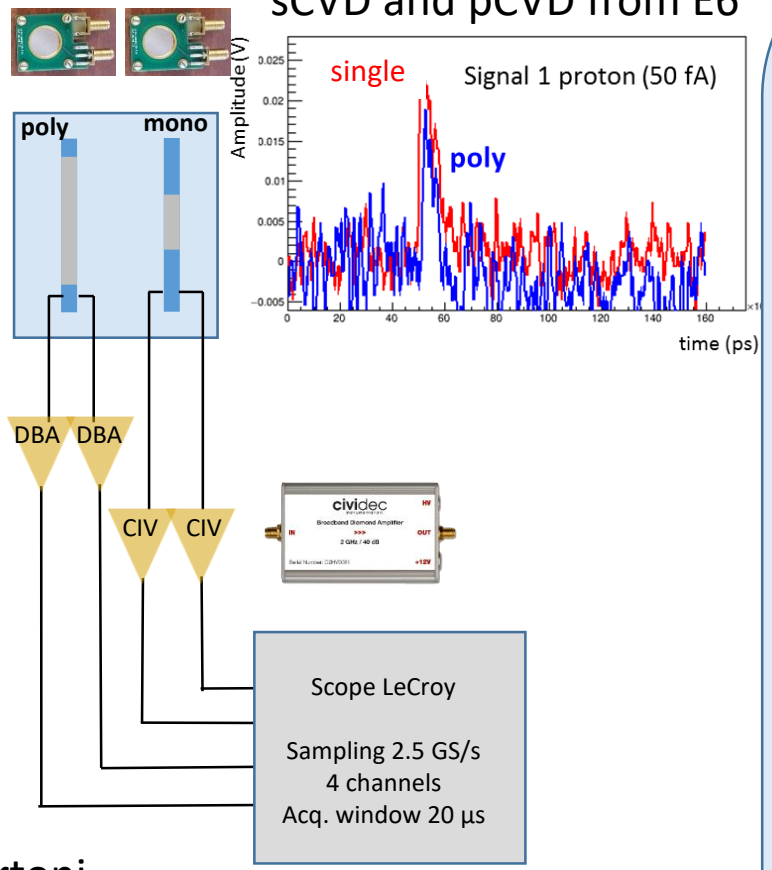
Particle counting vs I_{beam}: preliminary measurement

Collim.
Ø 1mm



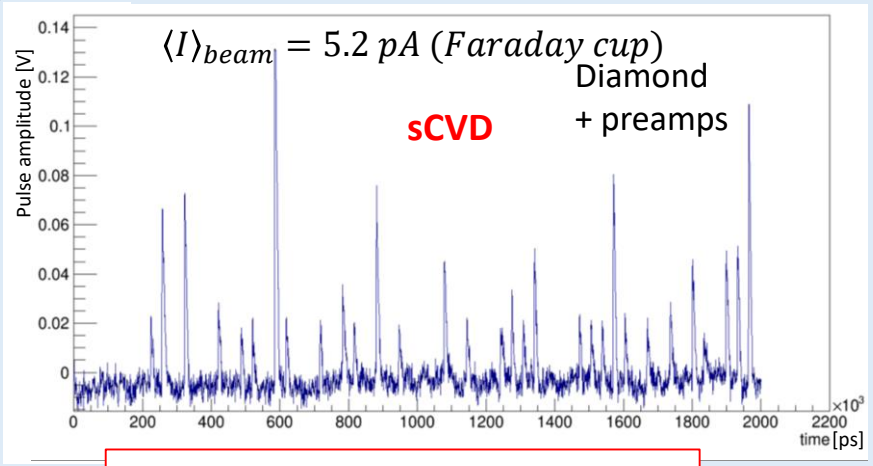


sCVD and pCVD from E6

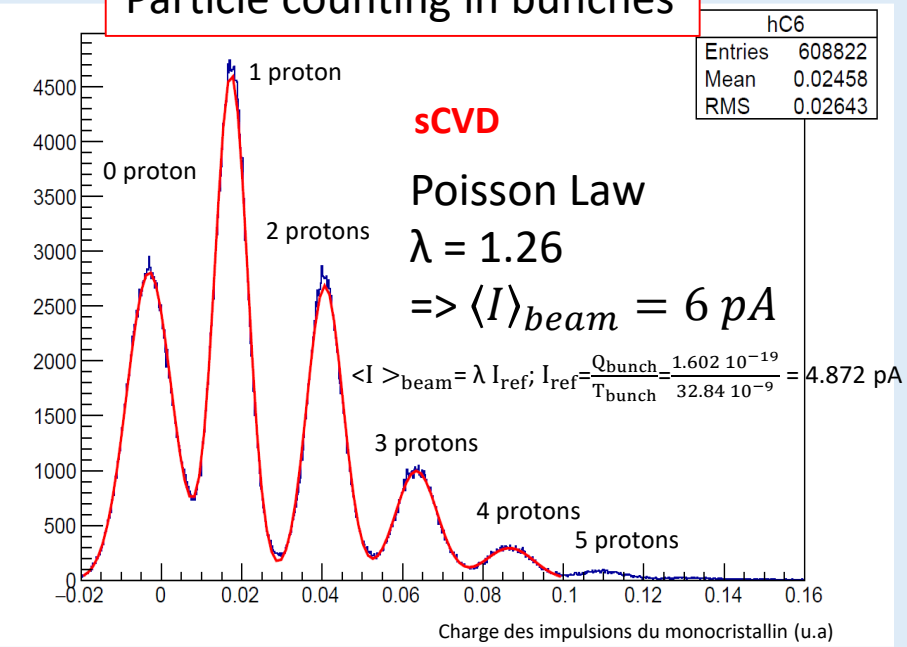


S. Curtoni
https://arxiv.org/abs/2105.05053

Continuous mode and reduced intensity

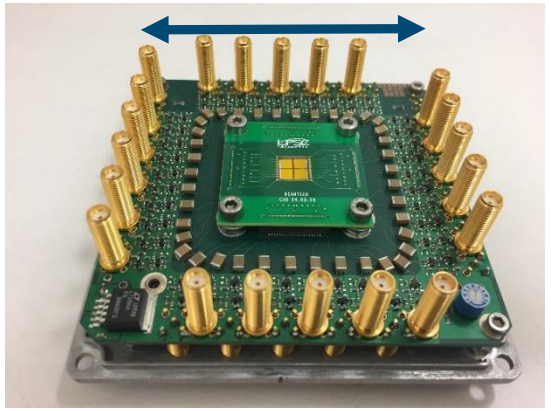


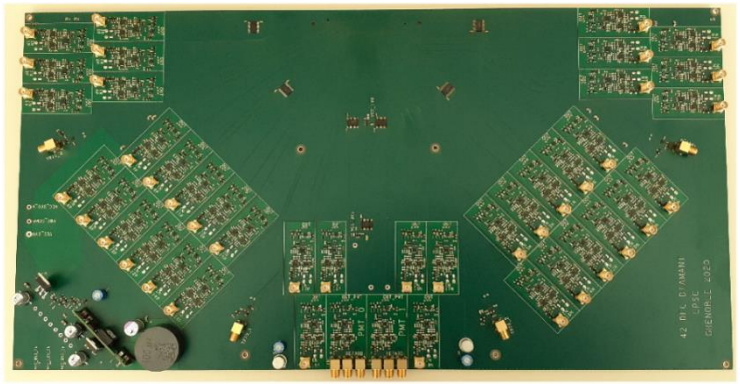
Particle counting in bunches



Proton counting in nano pulse

First prototype of diamond beam monitor + FE electronic + Data acquisition

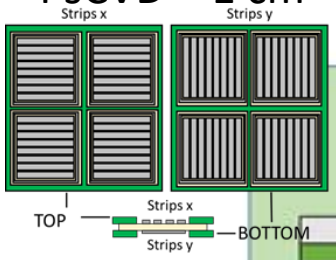




FPGA
2020
LPSC Grenoble

2021 CMOS 130 nm
TDC

4 sCVD = 1 cm²

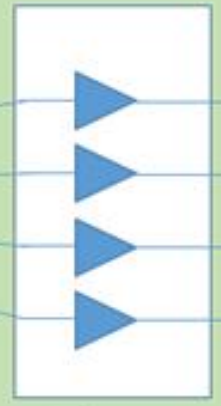


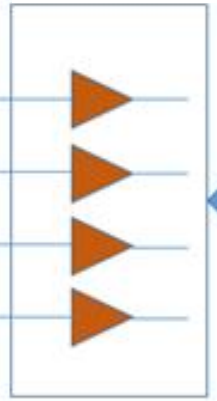
Beam Monitor

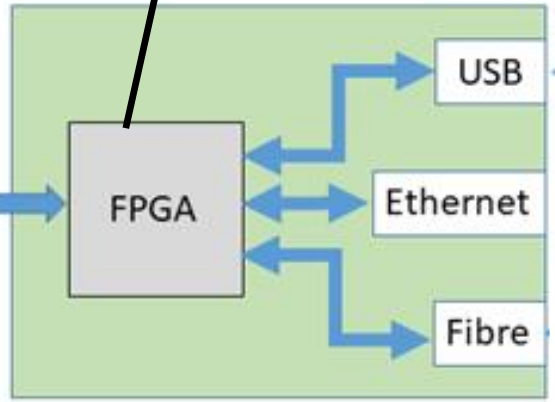
CFD Board

ACQ board

Diamant







S. Curtoni
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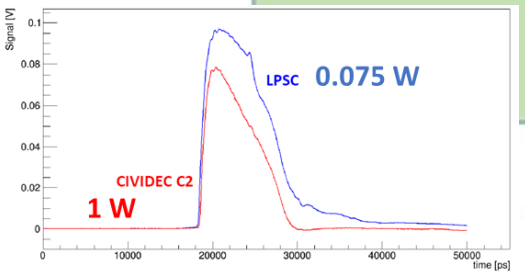
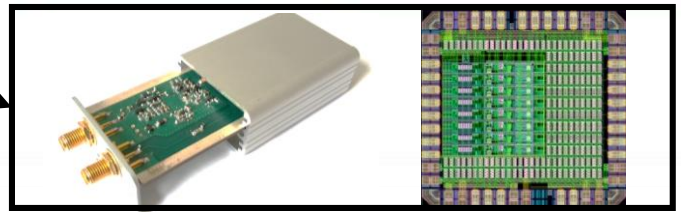


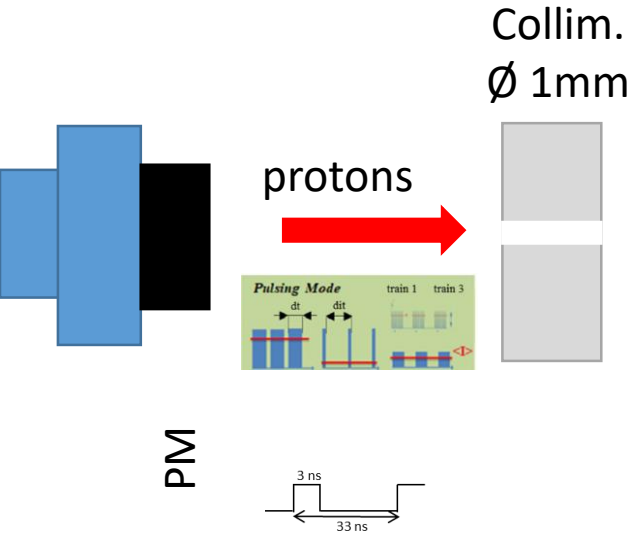
Preamplifiers

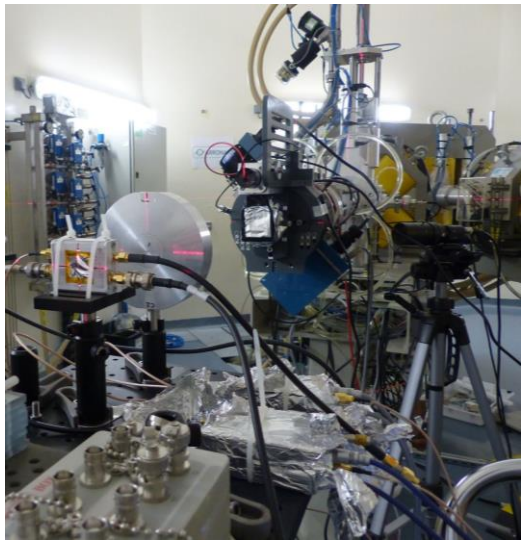


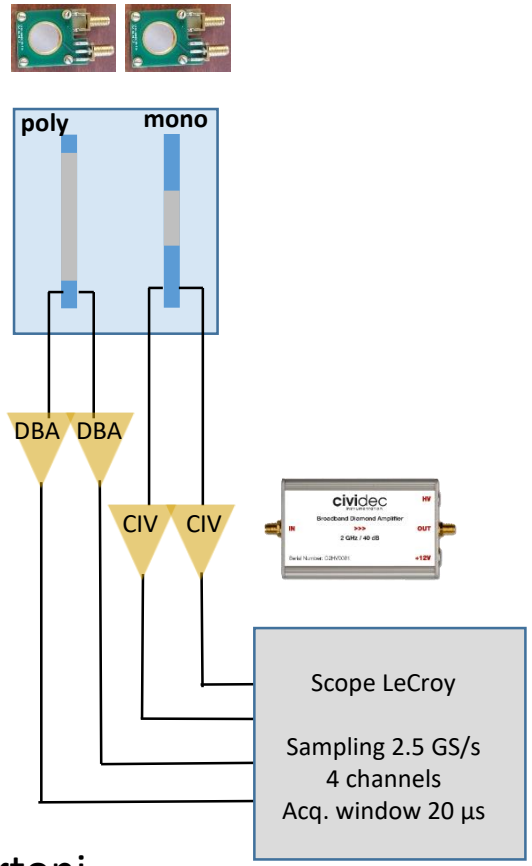
ASIC, CMOS 130 nm

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

Pulsed mode : flash therapy ?

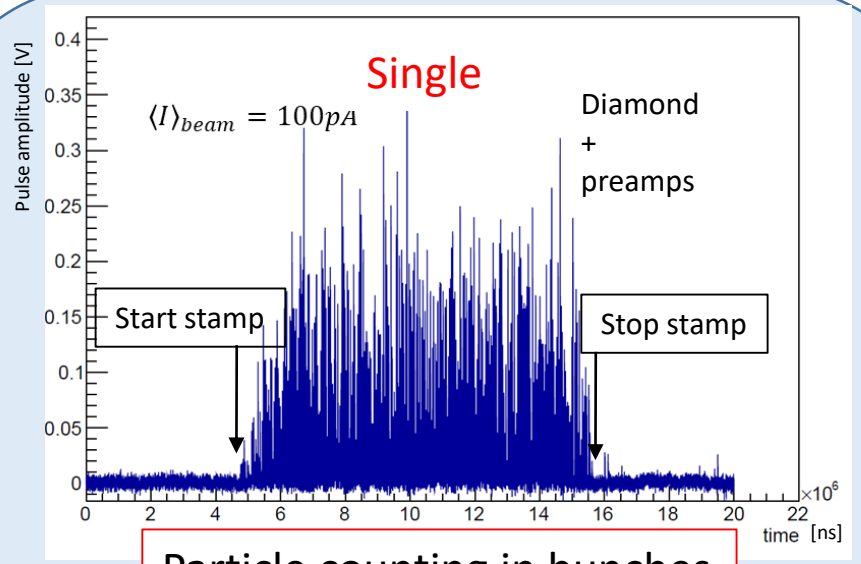




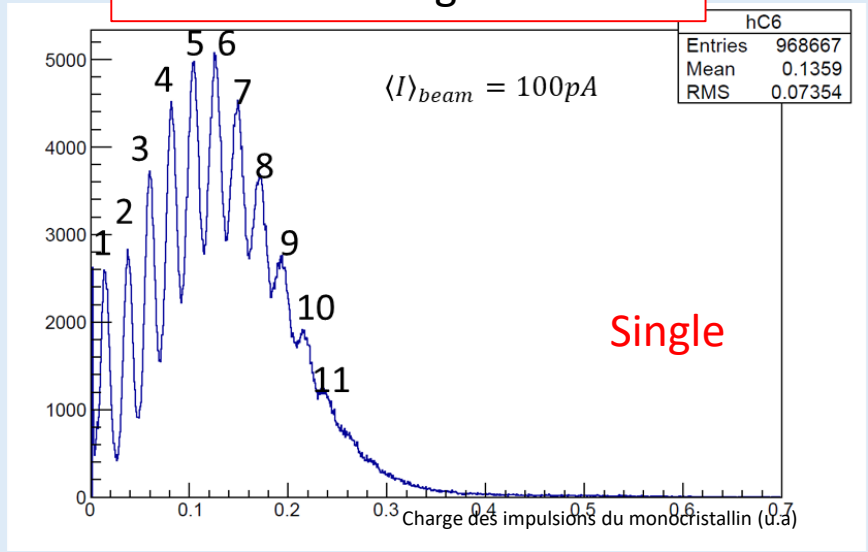


S. Curtoni
https://arxiv.org/abs/2105.05053

Pulsed mode and $\langle I \rangle_{beam} = 100\ pA$

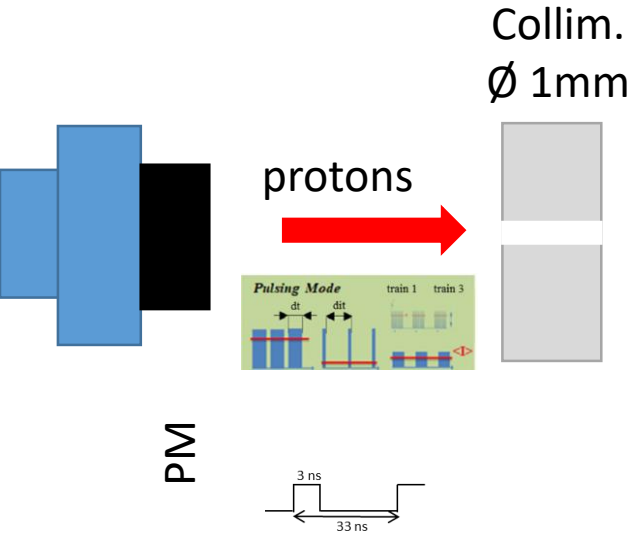


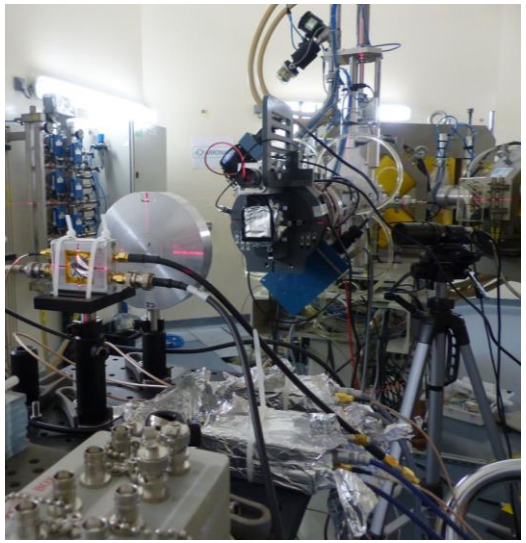
Particle counting in bunches

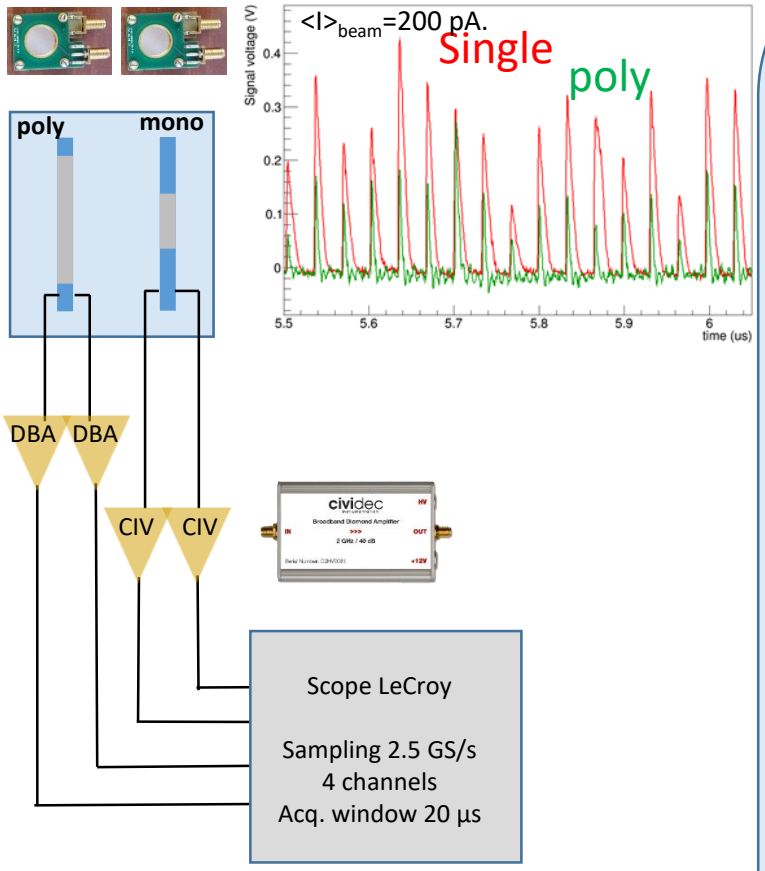


Proton counting in pulses !

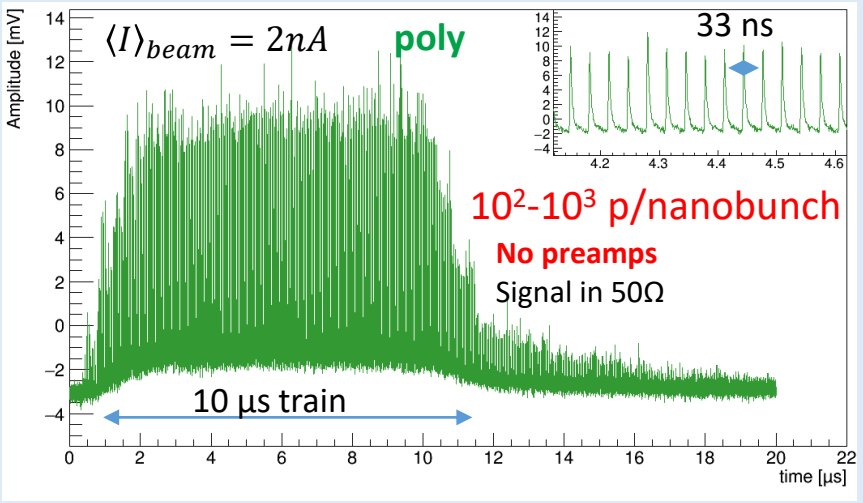
Pulsed mode : flash therapy ?

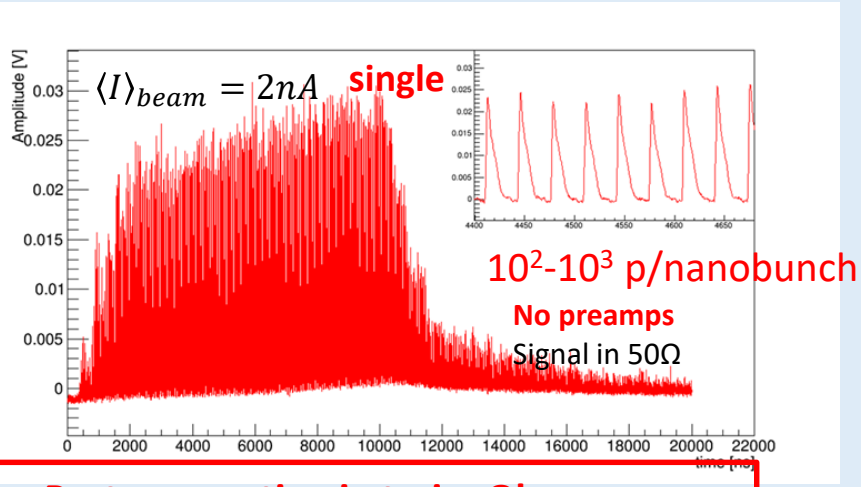






ANR –DIAMMONI (2020 -2024)





=> Proton counting in train: Ok
=>« start » and « stop » train stamp: Ok !

The scientific context

Nuclear Physics

Spectroscopy

- Alpha particles
- Short range particles detection
- Neutrons

Particle Physics

Beam monitoring

- LHC
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- J-PARC ….

Medical Physics

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Xrays @ESRF Micro Beam Radiation Therapy (MRT)

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

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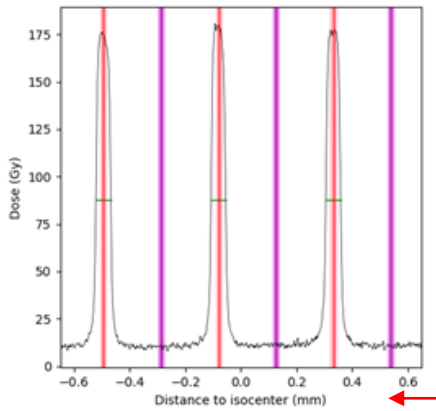
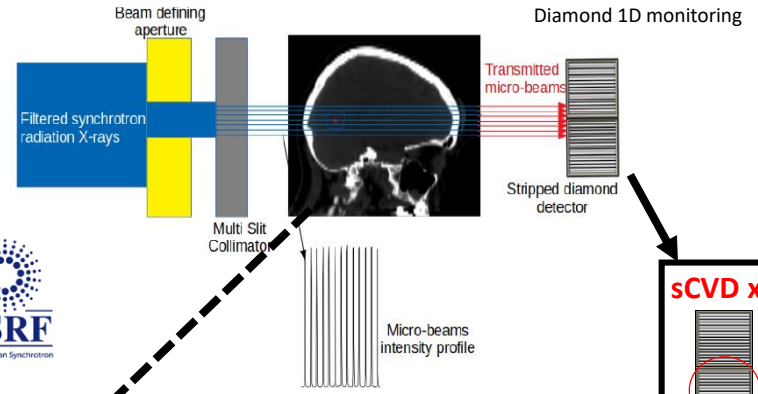
Synchrotron radiation on-line monitoring

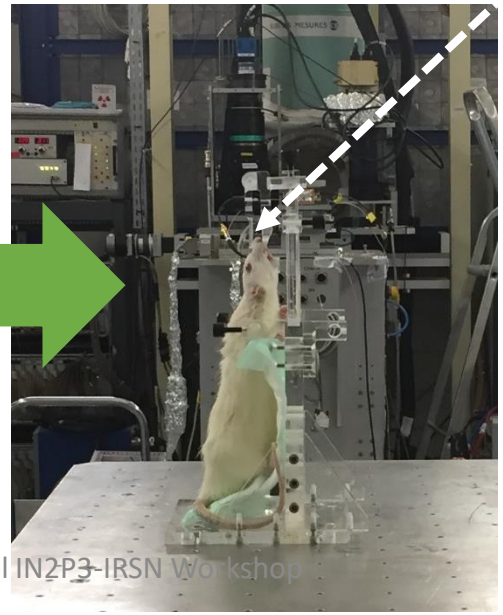
→ *X-Rays detection*
→ *Spatial fractionation (micro beams)*
→ *Huge dynamics (High dose rate)*

N. Rosuel PhD thesis (2018-2021)

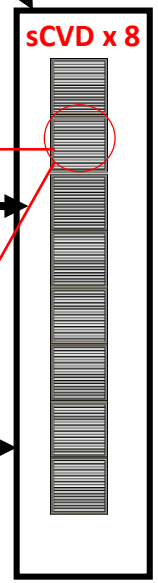




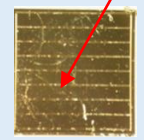
MRT: 50 µm
Micro Beam Radiation Therapy



Strips on diamond to satisfy MRT beam structure

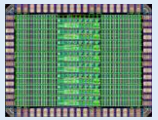


Detector = 8 x sCVD (4.5 × 4.5 mm²) strip metallized



+

elec FE = QDC
Discret + ASIC @ LPSC



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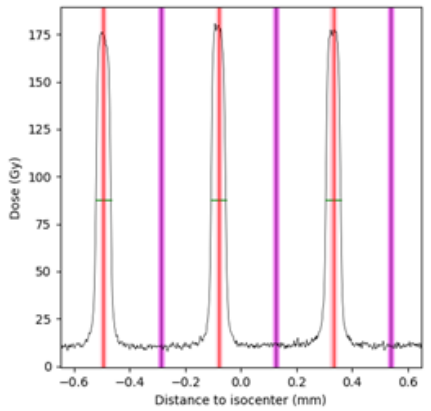

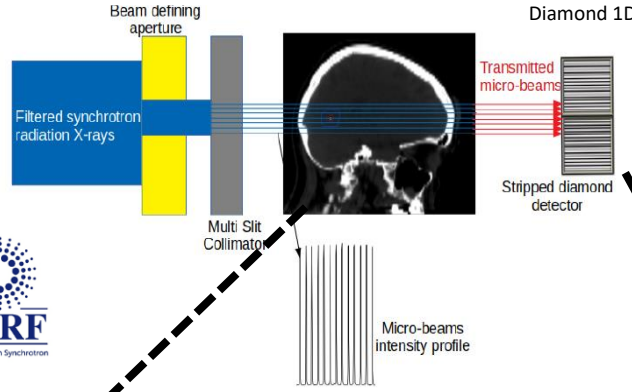

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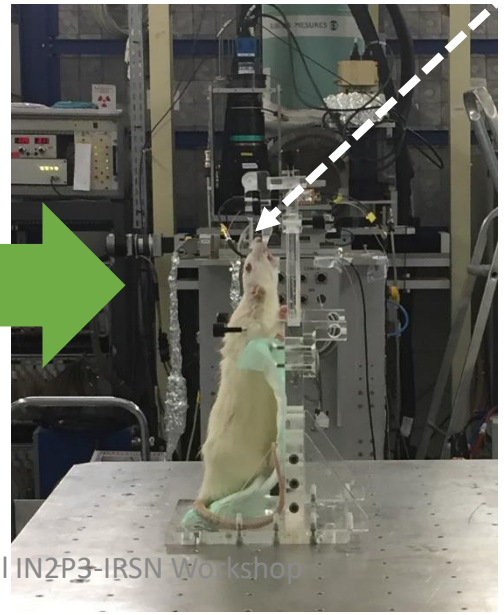
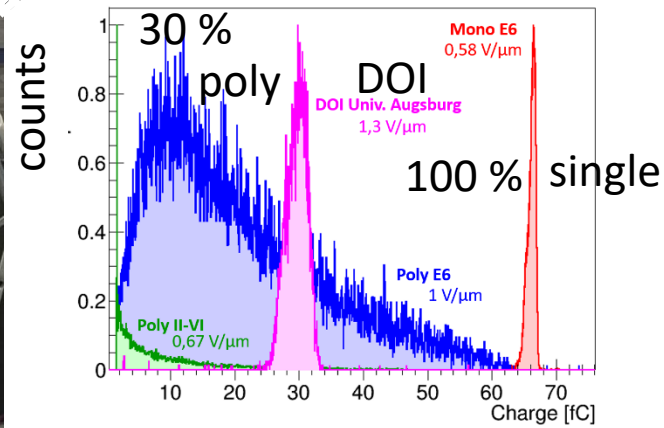


sCVD x 8

Why sCVD ?



Am α source test resuls @lab
5.5 MeV => 67 fC charge deposition
S. Curtoni PhD thesis

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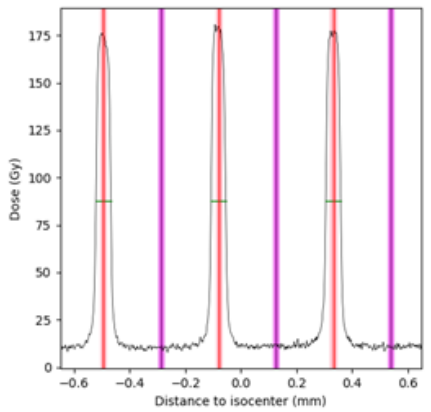
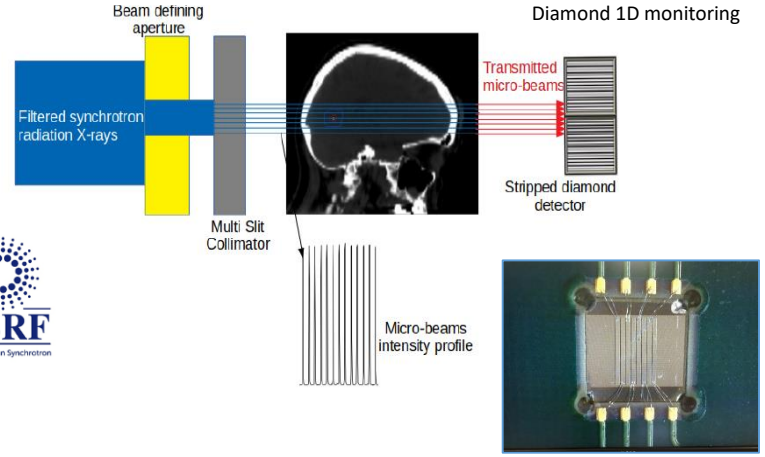
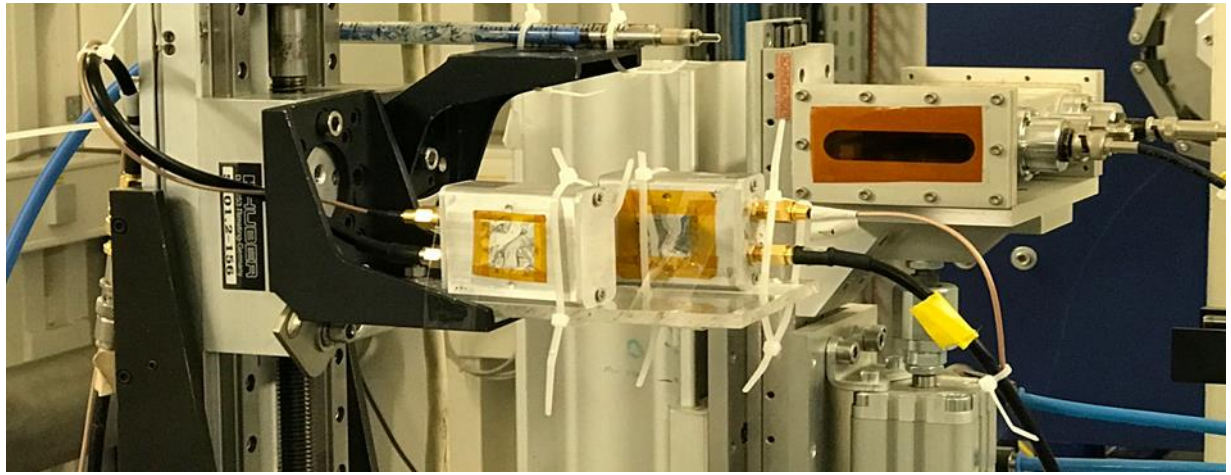


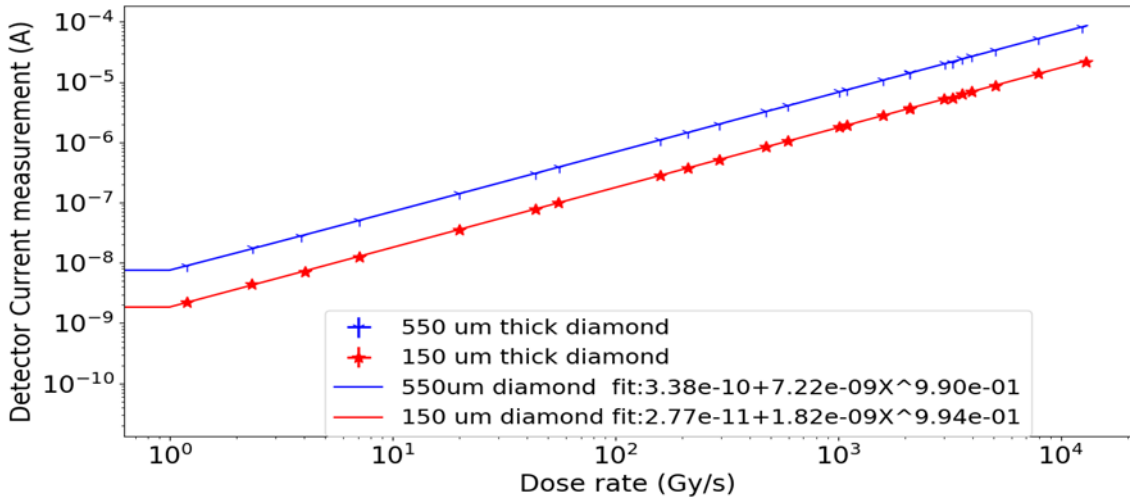


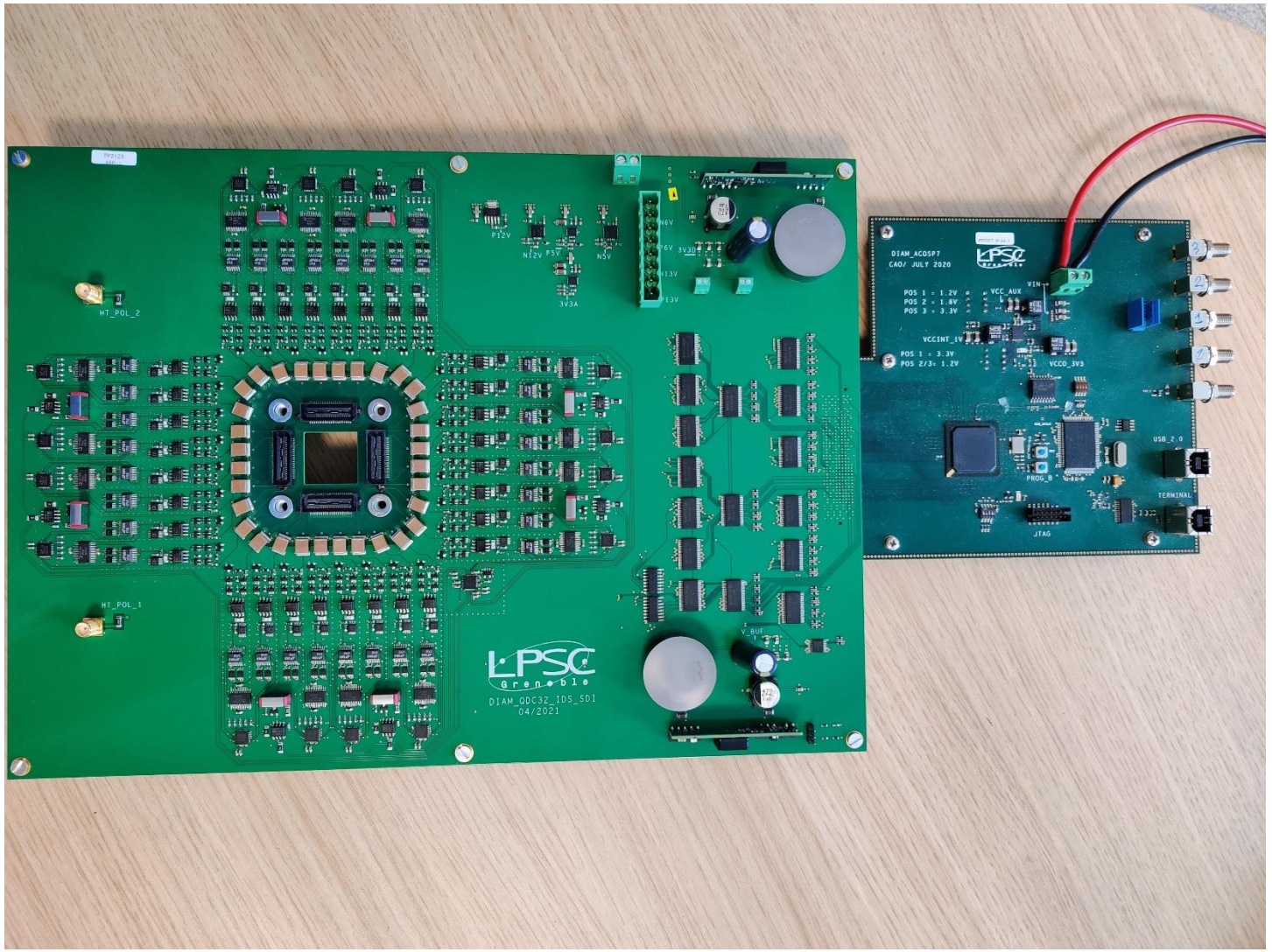
MRT: 50 µm

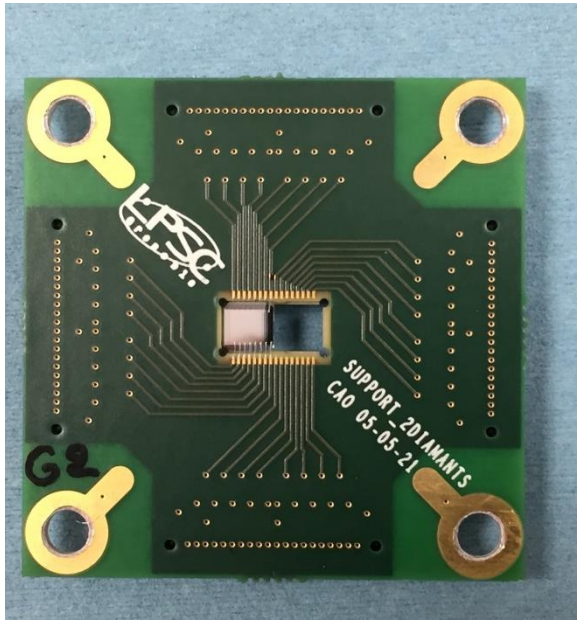
Micro Beam Radiation Therapy

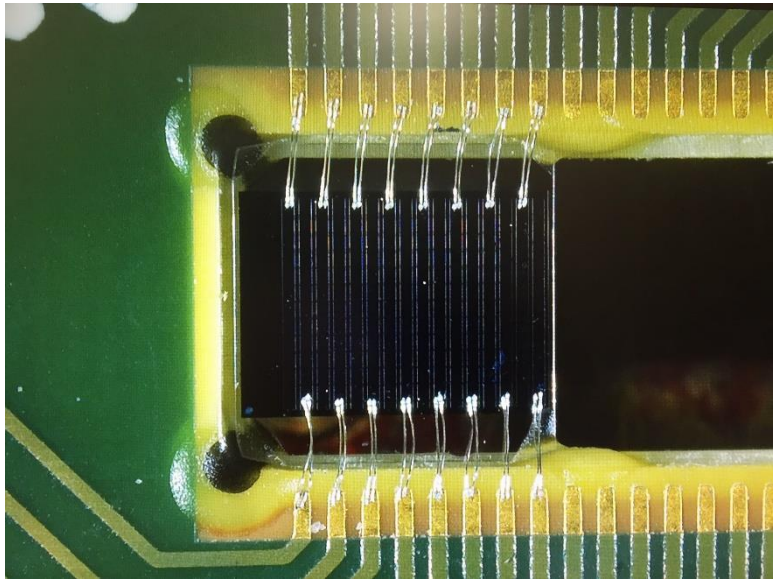
Integration on beam line ID17 at ESRF (Xrays up to 10 000 Gy/s)






LPSC
Grenoble
DIAM_QDC32_IDS_SD1
04/2021
DIAM_ACQSP7
CAO/ JULY 2020
POS 1 : 1.2V
POS 2 : 1.8V
POS 3 : 3.3V
VCC_AUX
VCCINT_1V
VCCO_3V3
USB_2.0
PROG_B
TERMINAL
JTAG


LPSC
G2
SUPPORT_2DIAMANTS
CAO 05-05-21



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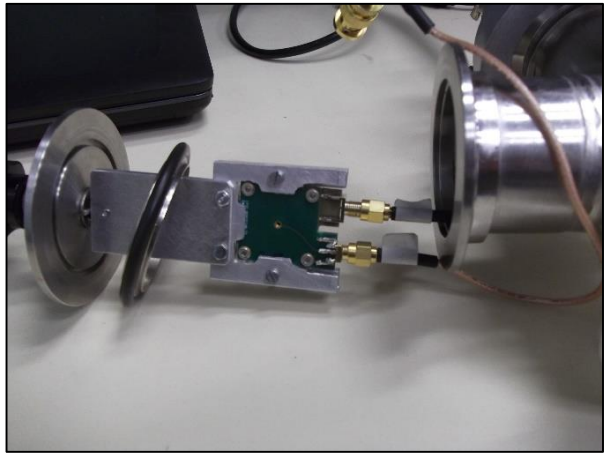
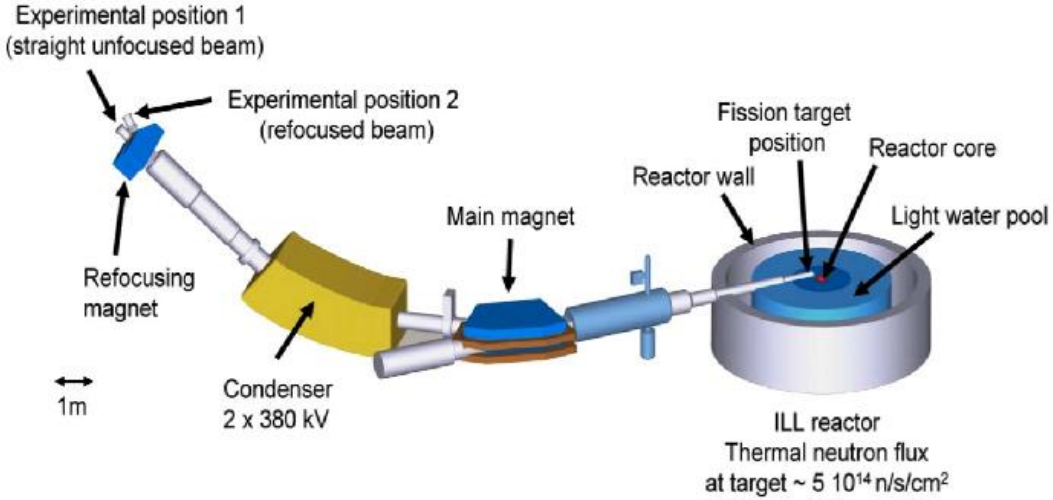
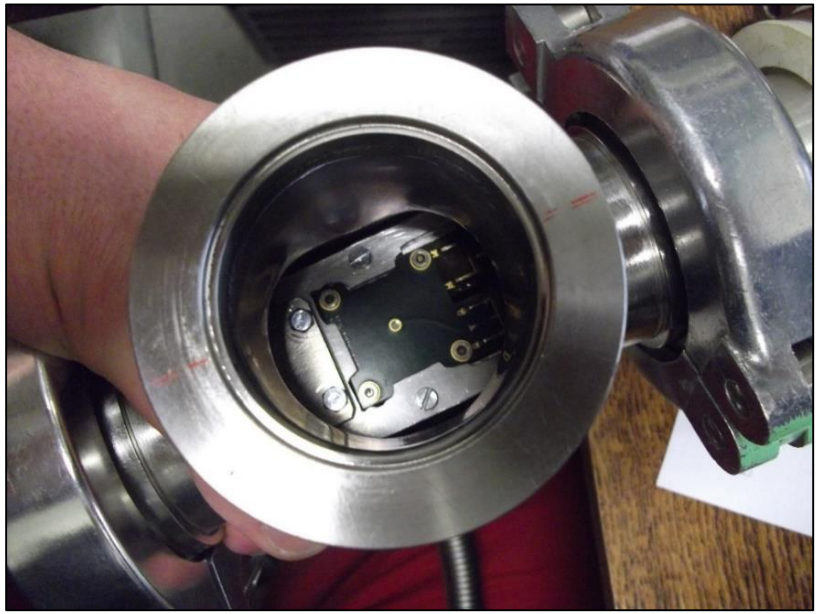
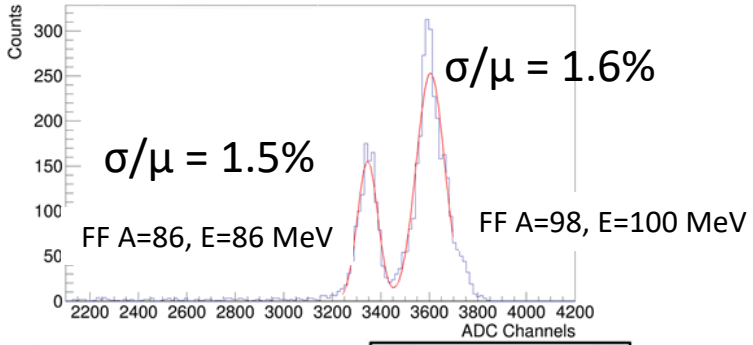
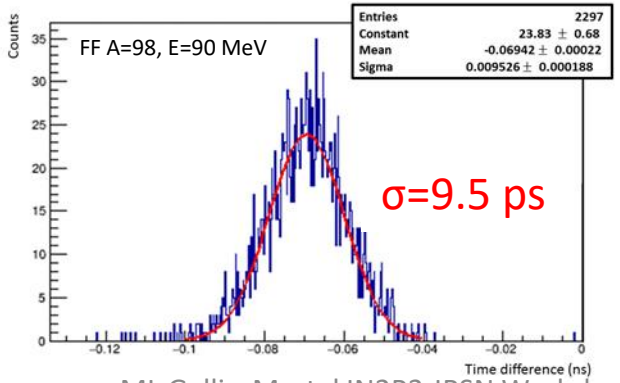
@ ILL Lohengrin: Ions (PF), Alpha

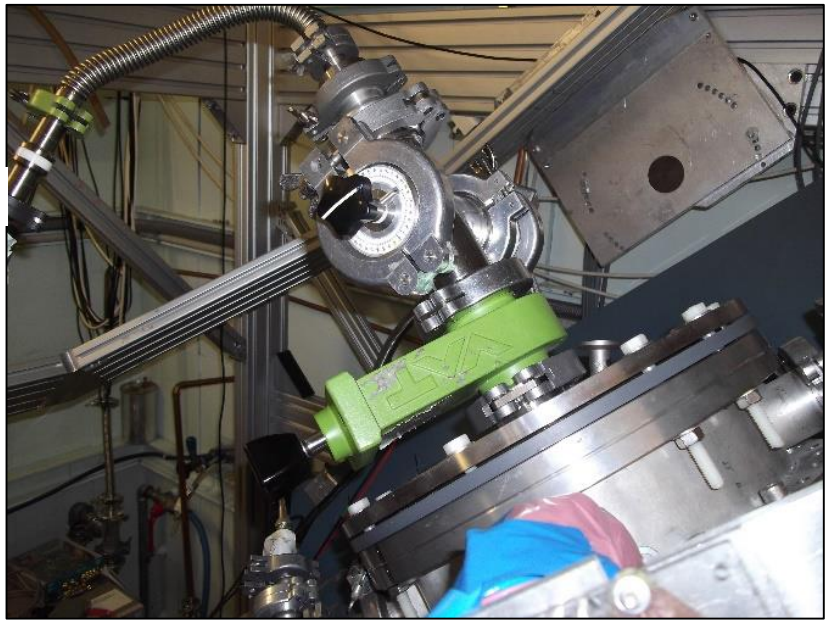




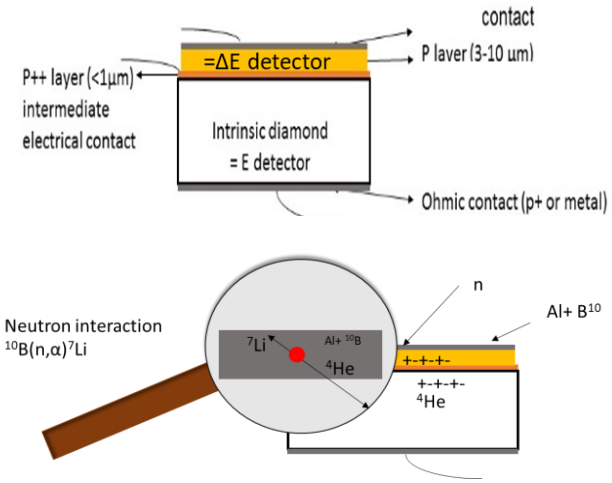






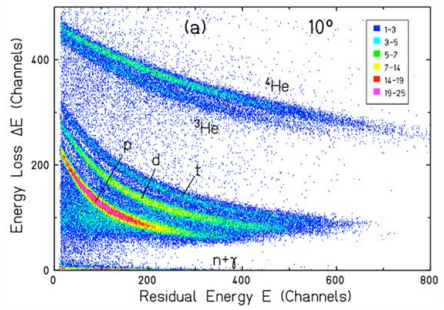


Design of a monolithic diamond ΔE-E telescope and PN junction for short range particle detection



^{12}C 200 MeV/u ions Gunzert-Marx 2008

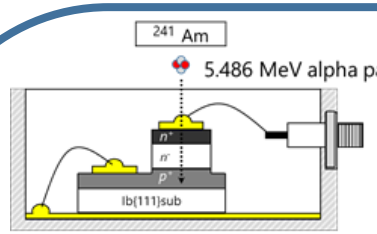
$\Delta E \sim Q^2/v^2$



$E \sim A.V^2$

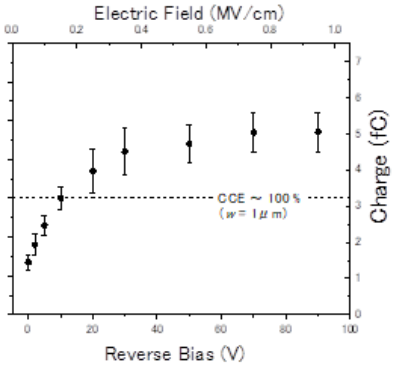
➡ Neutron detection + short range particle detection

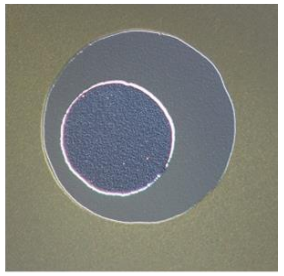
DiamFab Institut Néel ➔ CVD process of a high quality epitaxial diamond layer with a good-controlled boron doping concentration



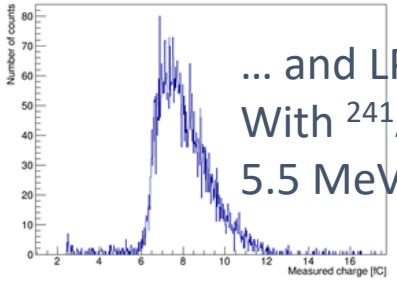
Charge collection efficiency (CCE)

$$CCE = \frac{Q_{collected}}{Q_{induced}} \times 100\ (\%)$$





Alpha particle detection done at KEK ….



… and LPSC With ^{241}Am 5.5 MeV

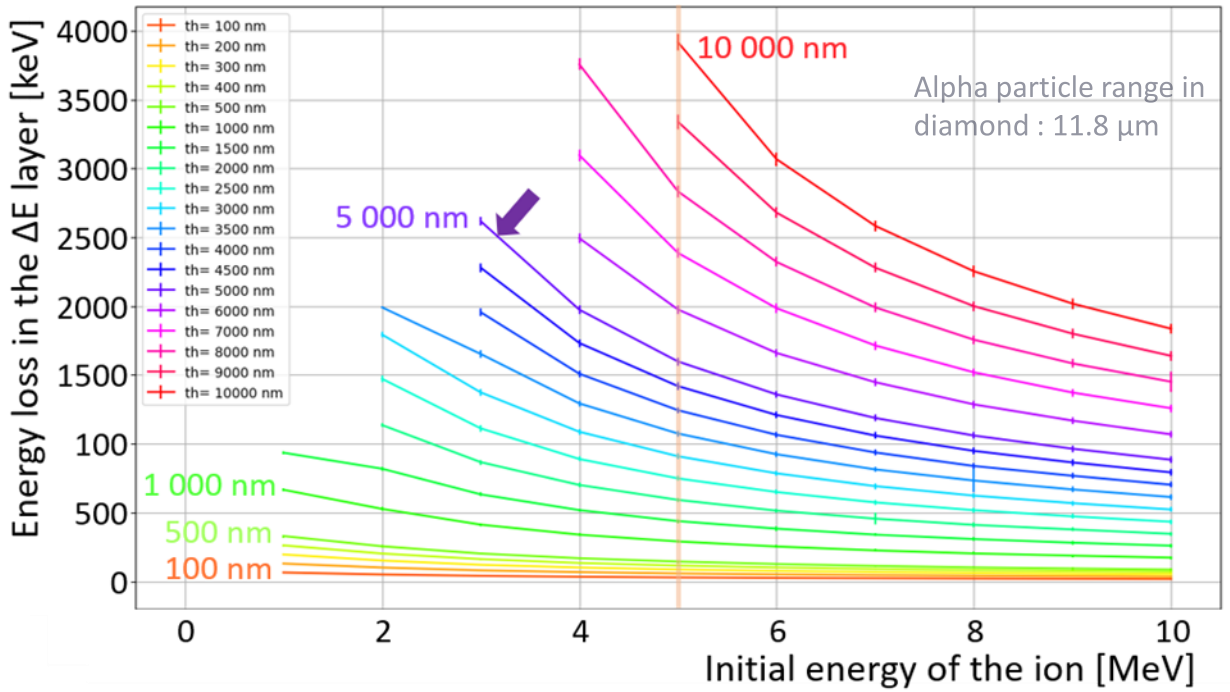
PN Junction from NIMS

NIMS, KEK ➔ pn (PIN) junction device formation by n- and p-type doping with high quality device processing combined with KEK radiation sensing technologies.

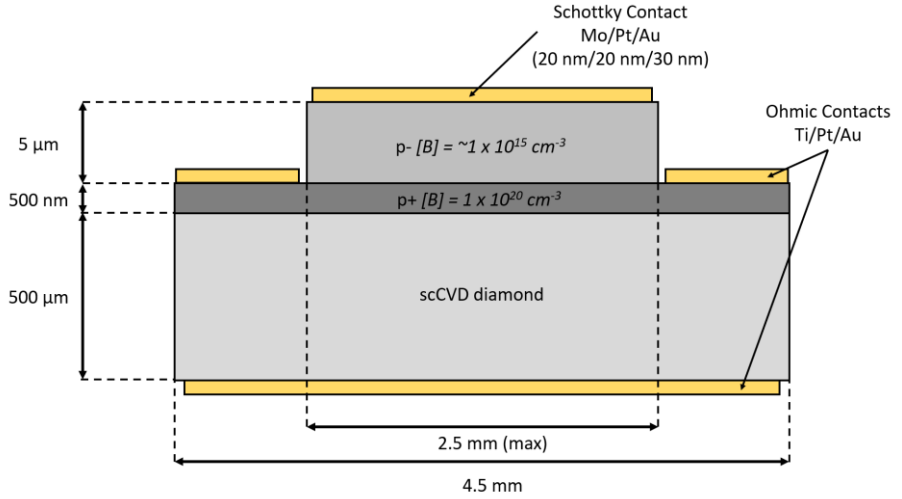
- High quality pin structure will be formed to detect alpha and beta particles with intrinsic electric field.

Work in progress since 2020: monolithic diamond ΔE-E telescope prototype

SRIM simulations for α particles

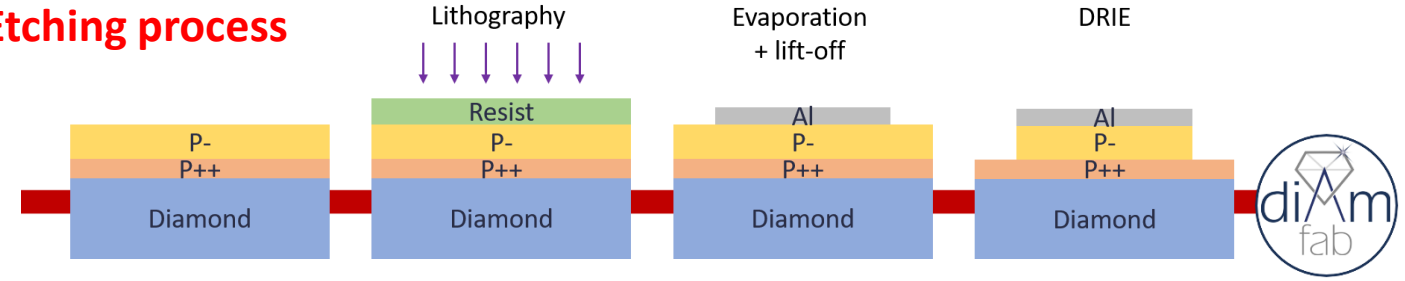


First simple design scheme

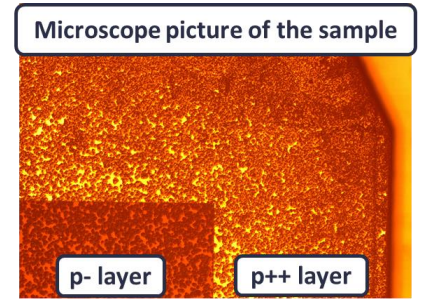


Requirements: (For E_{init} = 5MeV)		**Solution chosen:**
Energy deposited:	**Leakage current:**	
$E_{\Delta E} > 1$ MeV $E_{\Delta E} > E_{init}/2$	$I_{leak} < 1$ nA	Thickness: 5 µm Schottky Contact

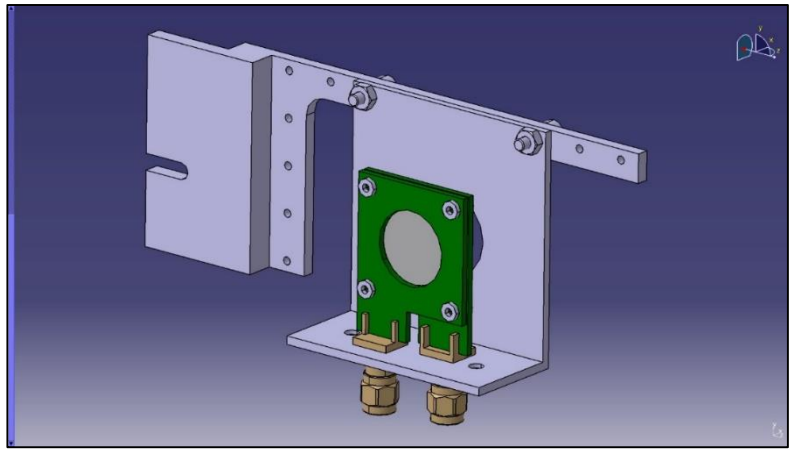
Etching process

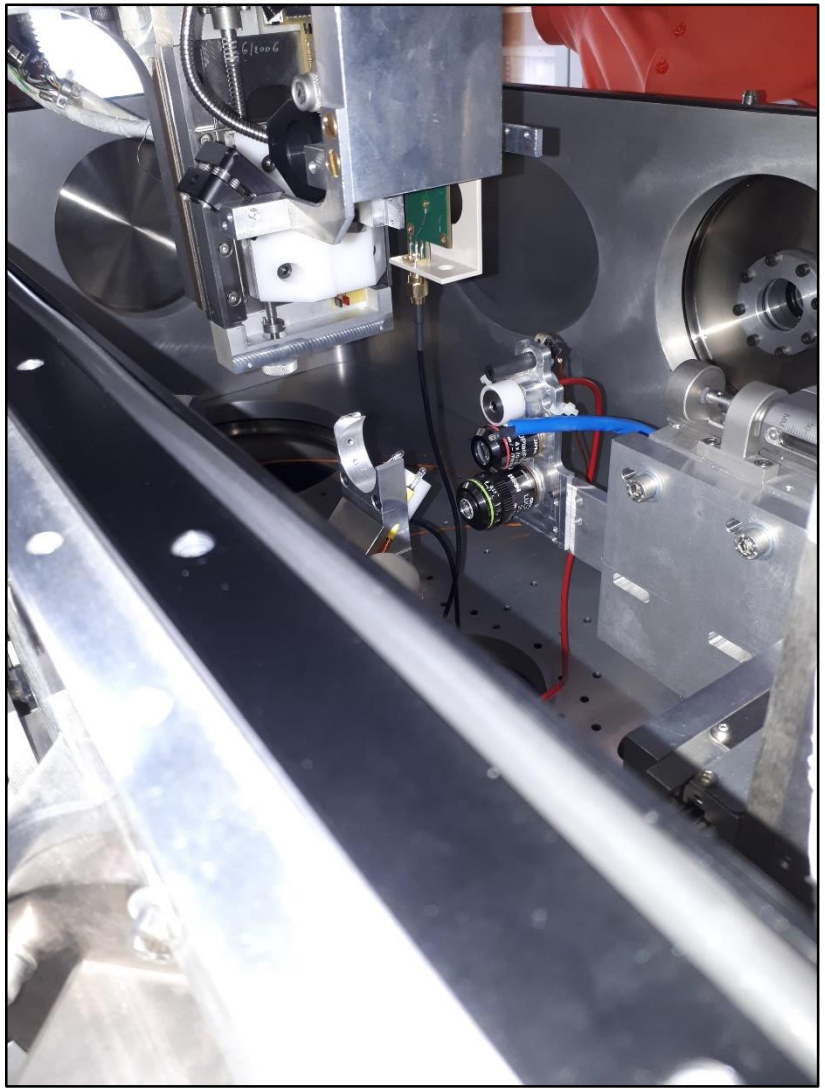


The start-up DiamFab from Institut Néel is in charge of the epitaxial growth.

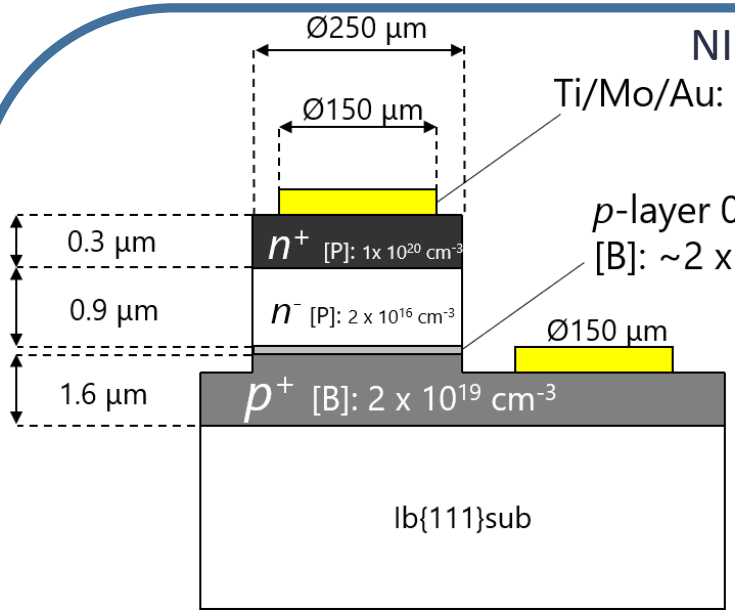


@ AIFIRA – CENBG: 3 MeV Ions

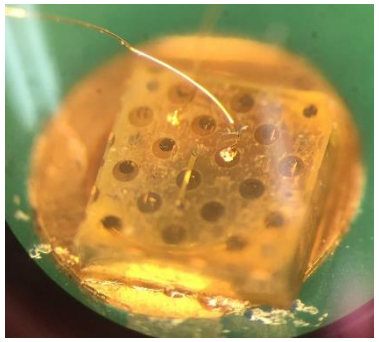


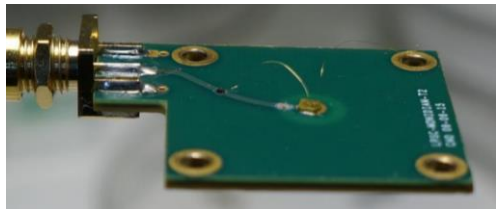


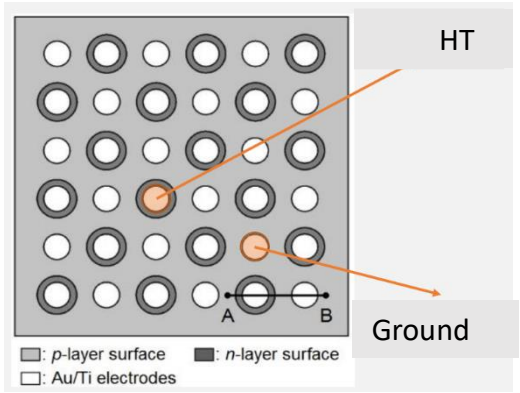
Work in progress since 2020 : japenese pn junction test in eBIC at Institut Néel + IBIC (Ion Beam Induced Current) at AIFIRA



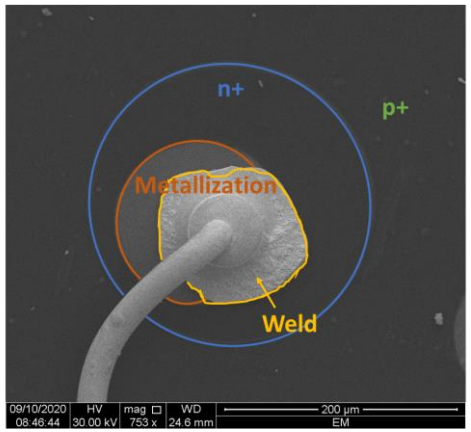
NIMS, AIST, U. Tsukuba, KEK





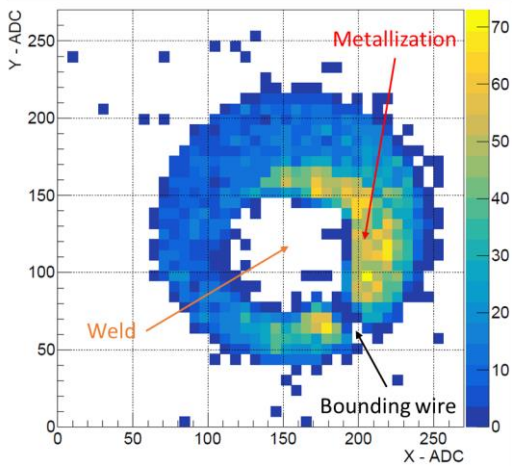


SEM image of the n+ contact



Electron beam at Institut Néel

Mapping of the hits for E – ADC ∈]130 ; 160[



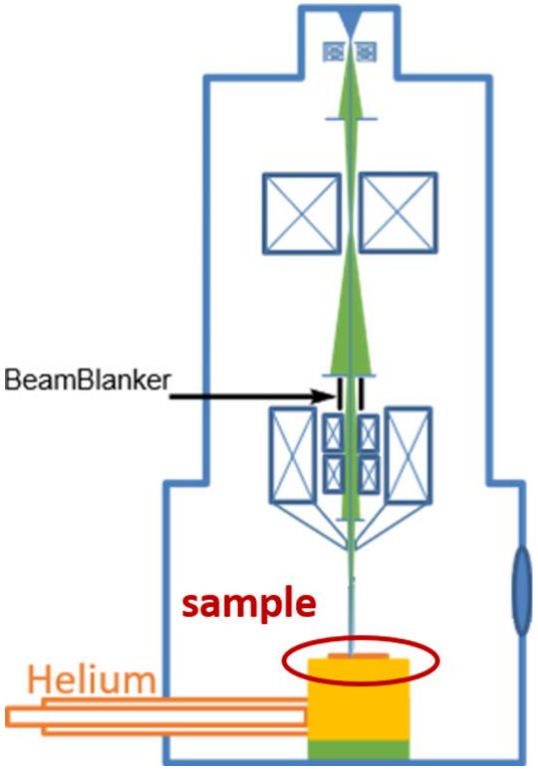
Alpha beam (3MeV) in AIFIRA-CENBG France

Active area of the junction : ~1 µm

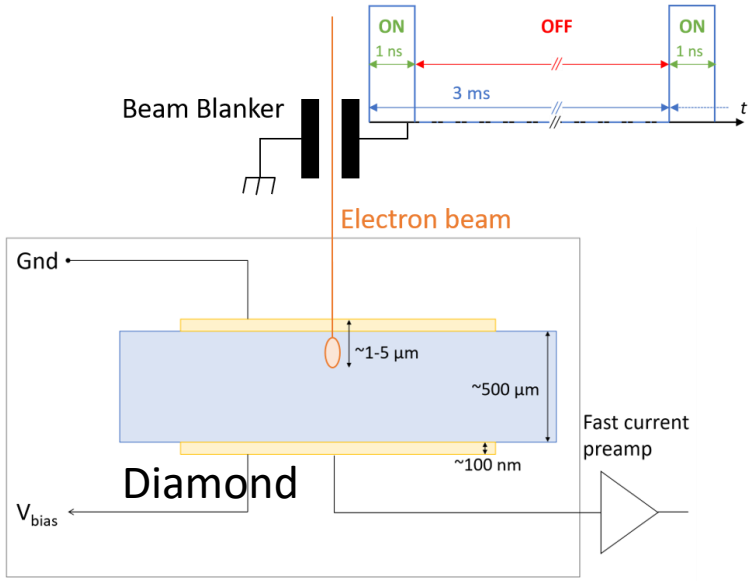
Bounding wires are used to read signals and polarized the junction.

The PN junction was set on a LPSC holder for tests

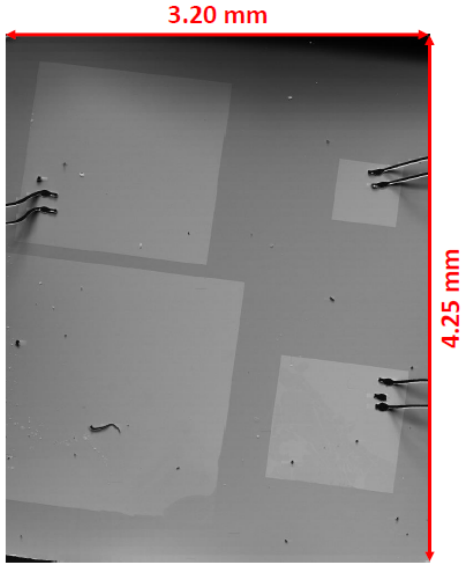
@ Institut Néel ToF electron Beam Induced Current (eBIC)



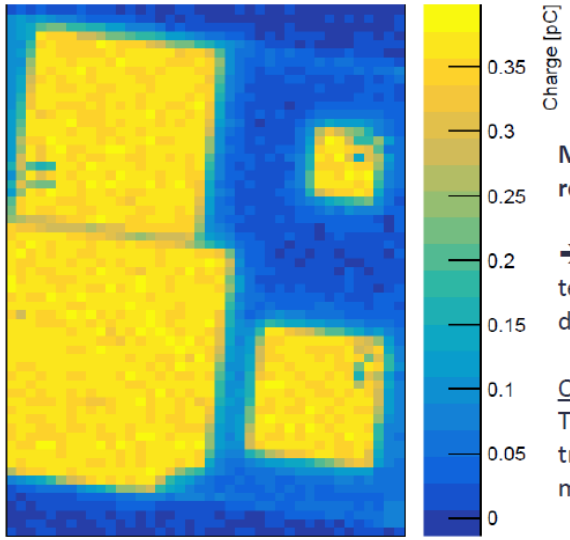
Sample = intrinsic sCVD commercial diamond from Element 6



SEM mapping picture



Mapping of detector charge response (10 h acquisition – Pixels size: 70x80 µm)



Micrometric spatial resolution

➔ Powerful technique to study detector homogeneity

<u>Ongoing</u>:
Time resolved transient current measurement

Conclusion 1/2

These developments are

- **in connection with collaborations established at IN2P3 (CLaRyS / ClaRyS-UFT– DIAMTECH – ANR DIAMMONI)**
- **in a context of interdisciplinary research at CNRS (IN2P3, INP, INC): skills exchanges take place between**
  - characterization: sources (labs) + eBIC (Institut Néel) + accelerator beams @ IN2P3 (IP2I GENESIS GANIL AIFIRA…), GIP - ARRONAX, ESRF +…
  - Instrumentation (IN2P3 labs, Institut Néel, etc.)

Beam monitoring

- **the proposed detection systems will bring significant added value to the transfer of high dose rate flash radiotherapy to clinical trials**
  - Microbeam Radiation Therapy: **IDSYNCHRO** @ ESRF on ID17 medical beam line : “flash effect” with a 10^4 Gy/s dose rate
  - Proton therapy : a monitoring system derived from the system studied for flash intensities in **DIAMMONI** can be easily implemented in a clinical environment (a few detectors located at ~ 1m from the patient).

Dosimetry

- **the proposed detection system will permit to make dosimetry with the Δ E- E development or the portal imaging system IDSYNCHRO**

Conclusion 2/2

- The **LPSC** has an expertise in detector development for particle physics (**ATLAS**) and medical physics (**beam hodoscope**).
- **LPSC** and **LPC Caen** collaborate for FE electronic development (ASIC)
- **SUBATECH, GIP-ARRONAX, GANIL, CENBG** are skilled with the problematic of physics with accelerators.
- The **IJCLab** is already involved in the lumiBELLE2 project and is used to the use of diamond for fast luminosity measurement at KEK.
- The **KEK** group is experimented by problematics linked to particle physics and beam accelerators. **KEK-NIMS-AIST-University of Tsukuba** has developed a new diamond-base beam monitor for J-PARC proton accelerator
- **NIMS, AIST, Tsukuba University** and **LSPM**, **DIAMFAB** has an expertise in diamond growth and doping.
- **Néel** has an international recognition in development of diamond high power electronic devices, diamond processing and eBIC.