Diamond-based detector development for beam monitoring in the context of medical applications

ML. Gallin-Martel, A. Bes, G. Bosson, J. Bouvier, J. Collot, S. Curtoni, D. Dauvergne, P. Everaere, L. Gallin-Martel, A. Ghimouz, Ch. Hoareau, A. Lacoste, S. Marcatili, JF. Muraz, F. Rarbi, O. Rossetto, N. Rosuel, L. Tribouilloy, M. Yamouni : LPSC Grenoble

J-F Adam
STROBE, Grenoble

A. Guertin, F. Haddad, C. Koumeir, F. Poirier, V. Métivier, N. Servagent : ARRONAX et Subatech Nantes

E. Testa
IP2I Lyon

J-M Letang
CREATIS Lyon

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Context

- **Development of new generations of ion accelerators:**
  - medical applications: hadrontherapy, X-ray or synchrotron radiation therapy and flash 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.

Outlines

- **Beam tagging hodoscope for online ion range verification in hadrontherapy**
- **Diamond for beam monitor development**
  - **Material intrinsic qualities**
  - **Detector instrumentation**
  - **Performances in beam tests**
- **Development of a diamond beam monitor for innovative radiotherapies using spatially segmented photon beams at ESRF on ID17 medical beam line – IDSYNCHRO R&T Transverse IN2P3**
- **Diamond application to Flash Therapy : ANR – DIAMMONI**
- **Conclusion**

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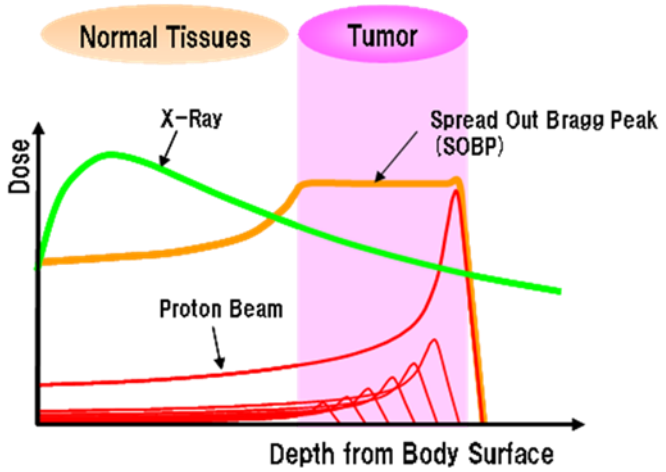
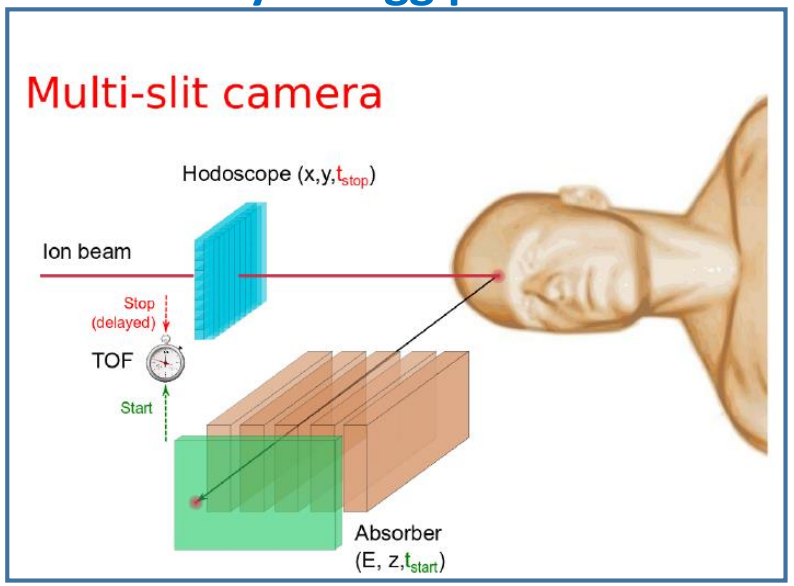
Beam tagging hodoscope for online ion range verification in hadrontherapy

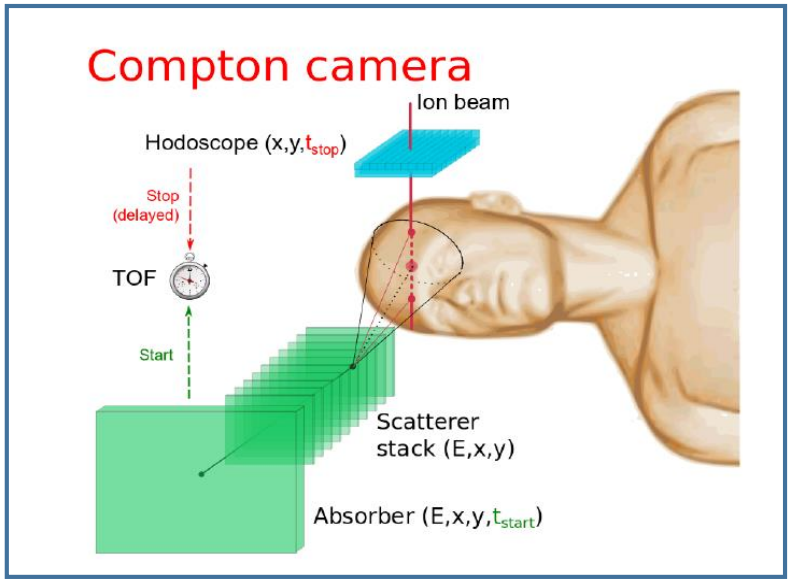
Prompt Gamma detection

CLaRyS

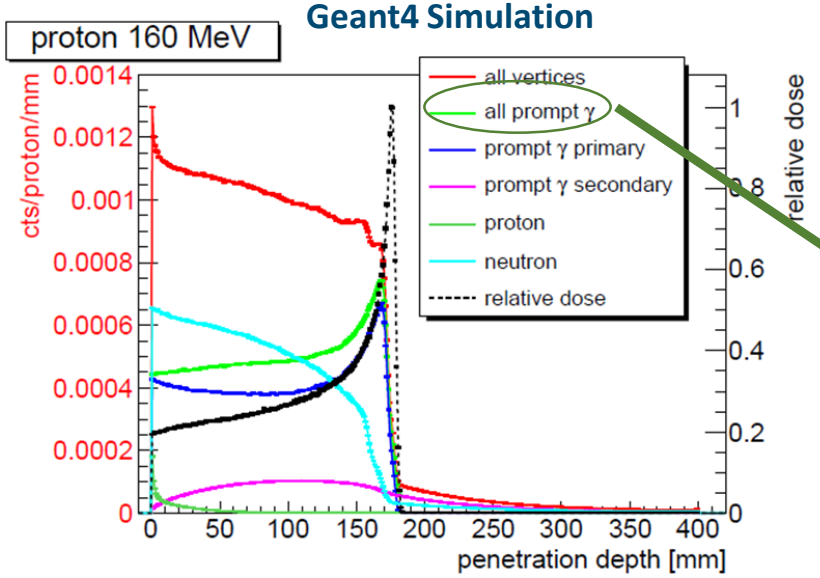
Ion range monitoring in patient body : Bragg peak location







Geant4 Simulation



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

Gamma Prompt Imaging

Beam tagging hodoscope for online ion range verification in hadrontherapy

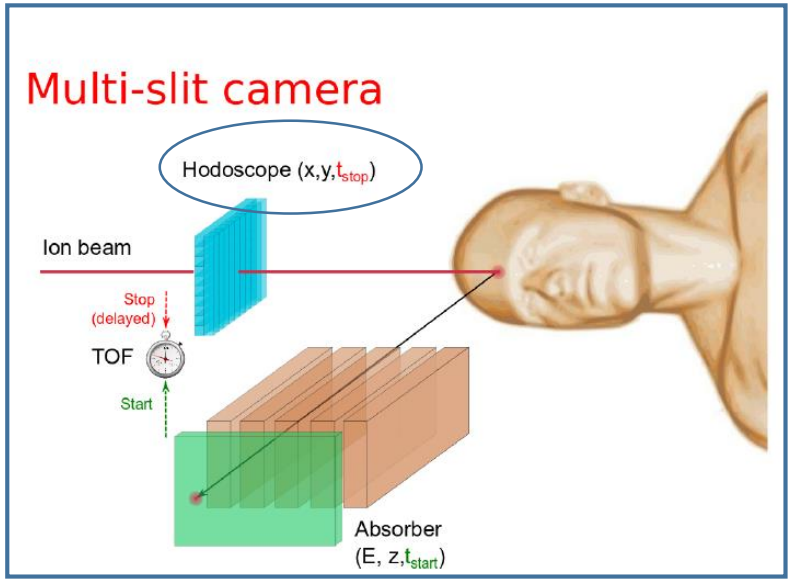
Prompt Gamma detection

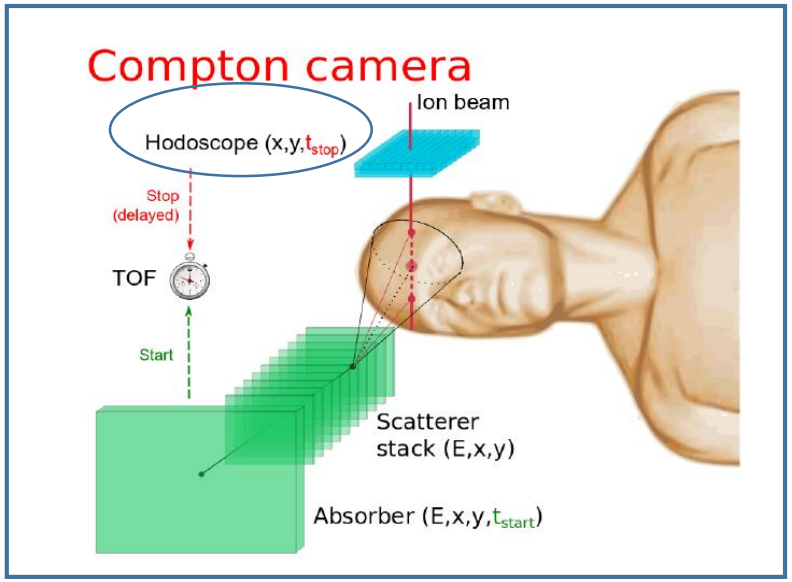
CLaRyS — **Gamma Prompt Imaging**

Hodoscope Existing development :

Array of scintillating fibres
+ multichannel PMT

Hodoscope : Background reduction + position and time stamp for the ion beam





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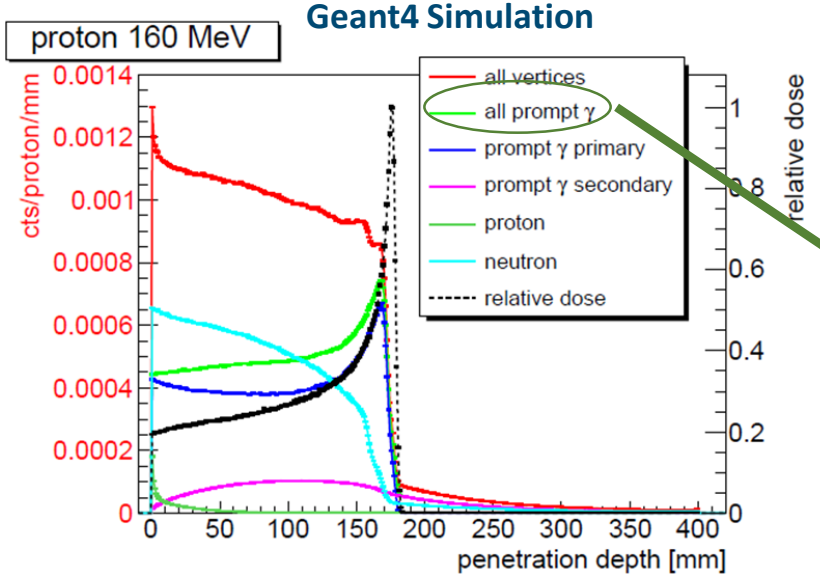

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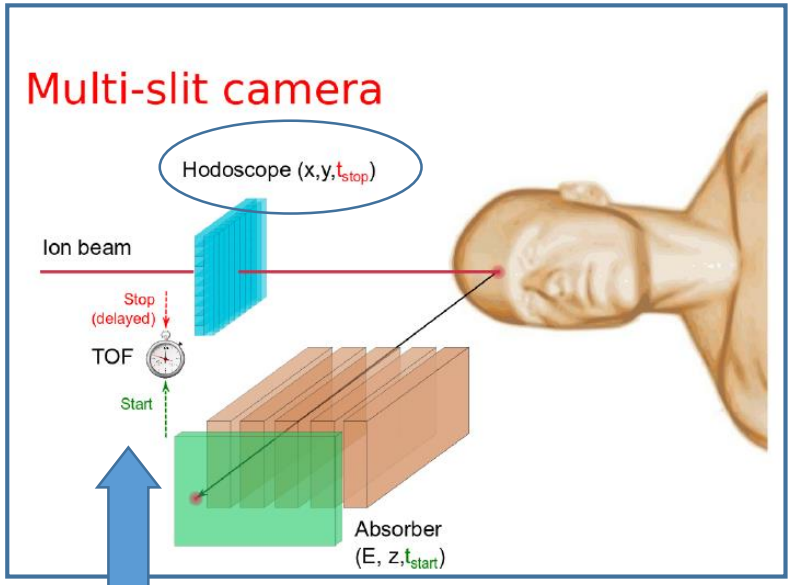

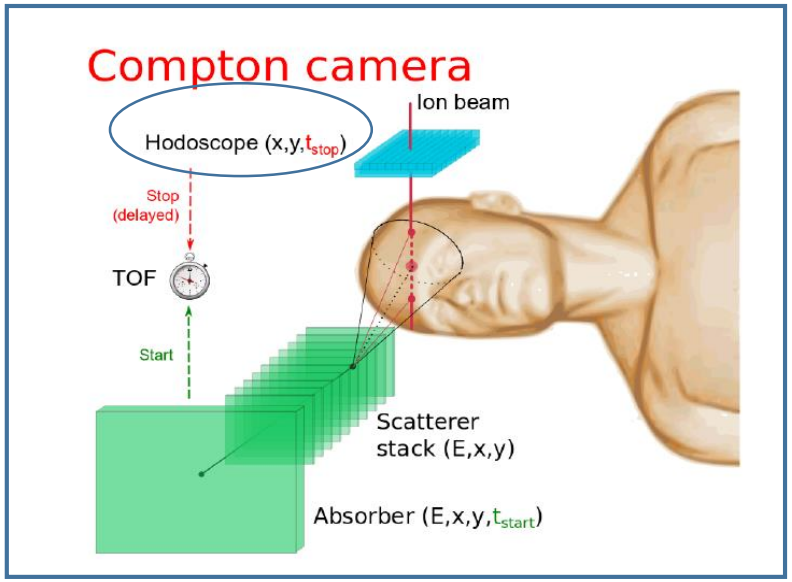

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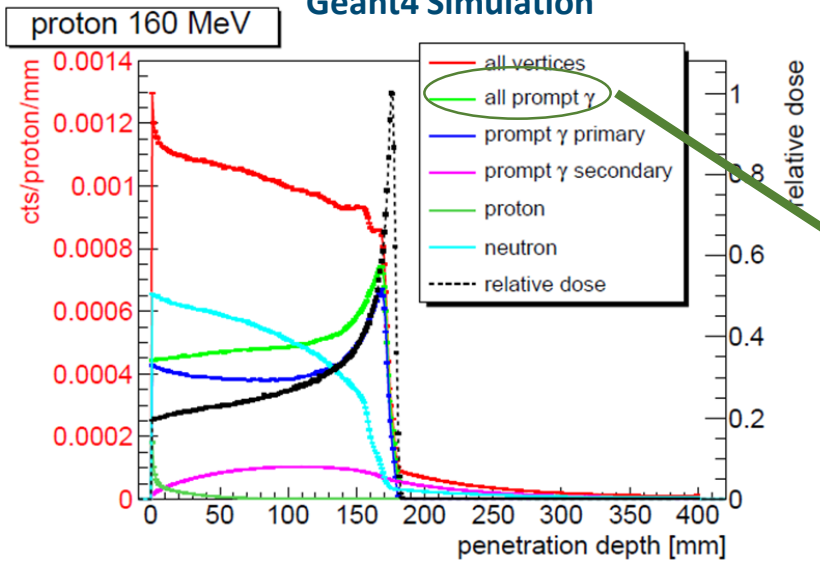
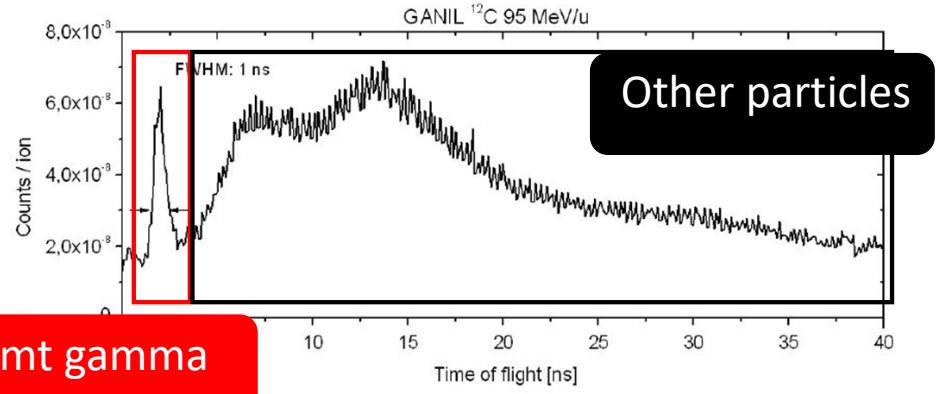


Krimmer et al., Nucl. Instr. Meth. A, **878** (2017) 58-73

Prompt gamma detection : experiment using 12C @95 MeV/u on PMMA
Time of Flight Spectrum



Promt gamma

Mauro Testa, Thèse, Univ. Lyon, 2010

Beam tagging hodoscope for online ion range verification in hadrontherapy

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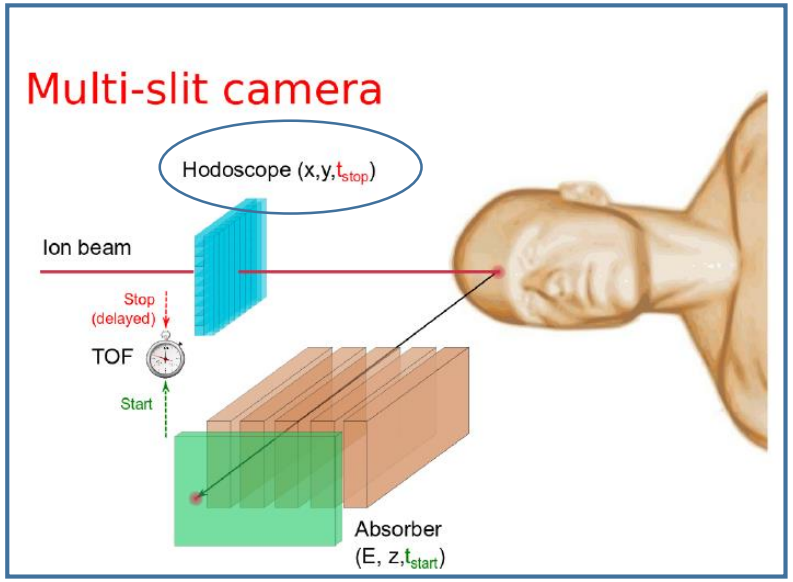

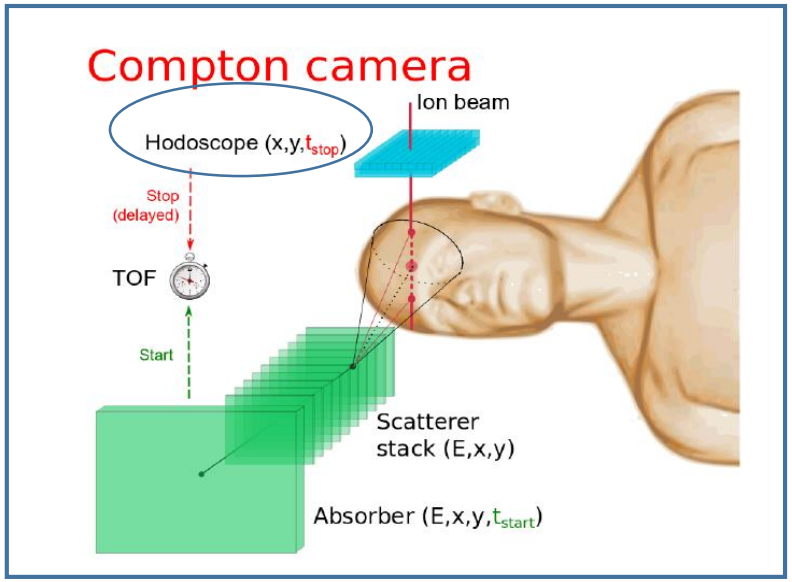

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Array of scintillating fibres + multichannel PMT

Limitations :

- ❑ Radiation hardness
- ❑ PMT count rate capability (10^7 cps per PMT)
- ❑ Time resolution 500 ps – 1 ns

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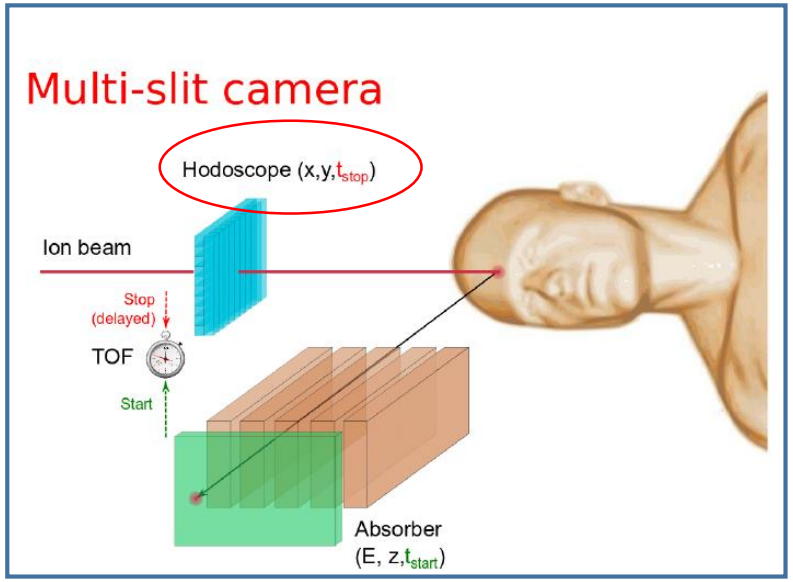

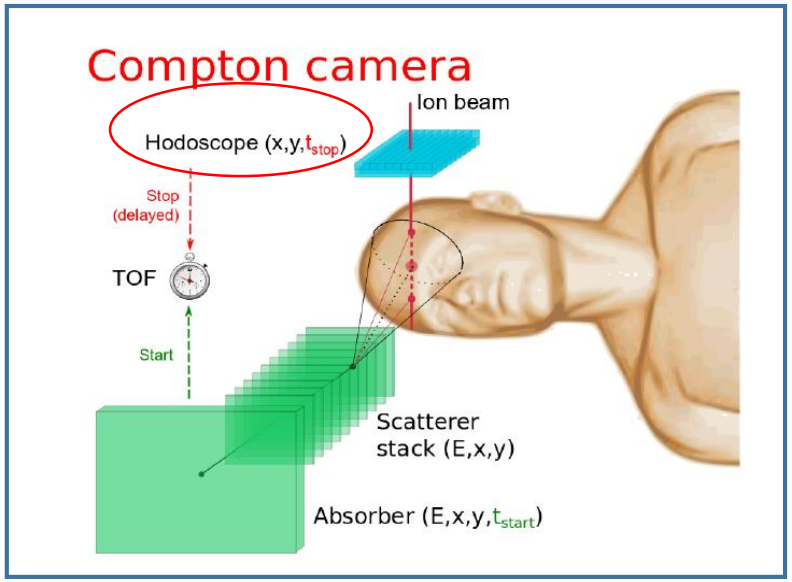

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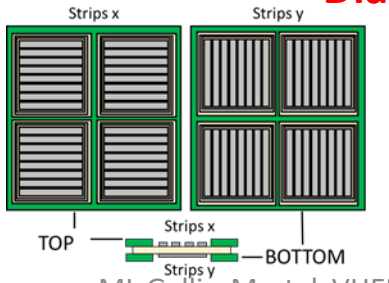
CLaRyS-Ultra-Fast Timing : 100 ps resolution using diamond

Diamond hodoscope

CLaRyS-UFT : S. Curtoni 2017-2020 PhD

→ **Imaging based on Time of Flight**



FE electronics

Beam tagging hodoscope for online ion range verification in hadrontherapy

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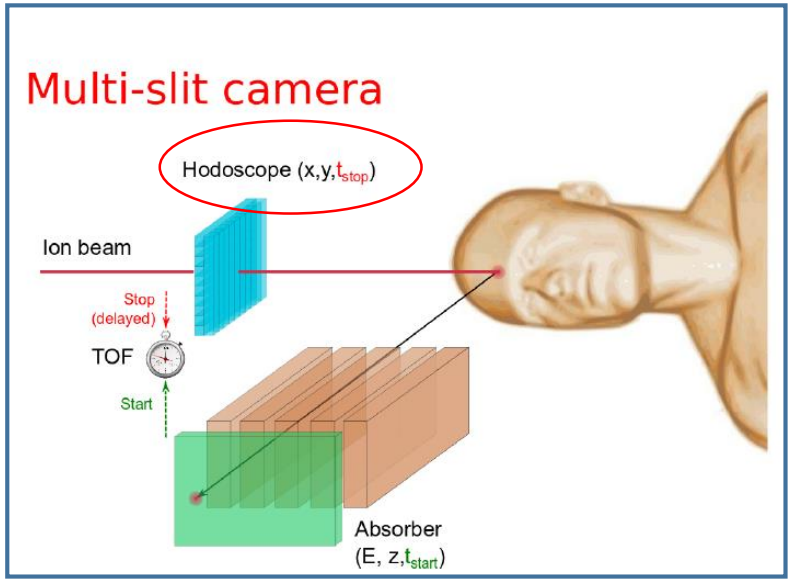

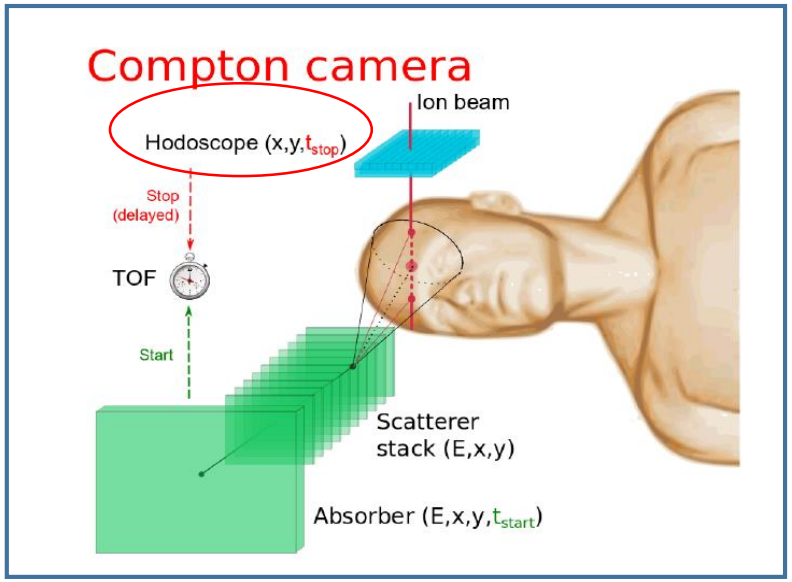

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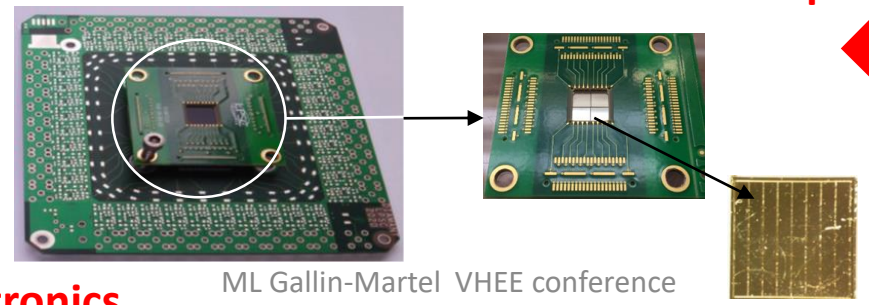

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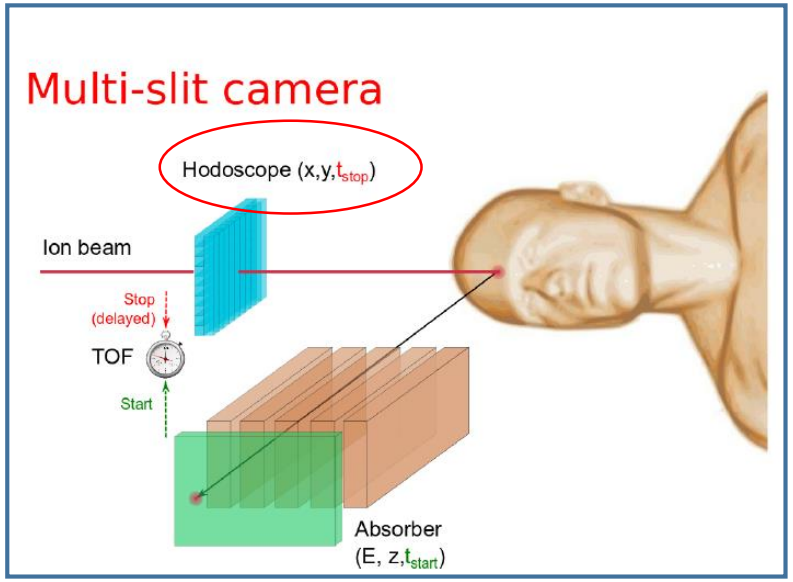

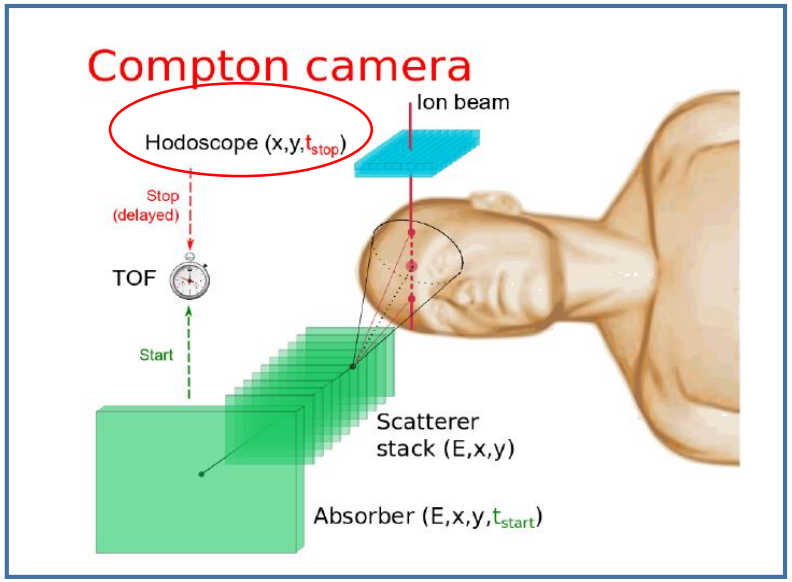

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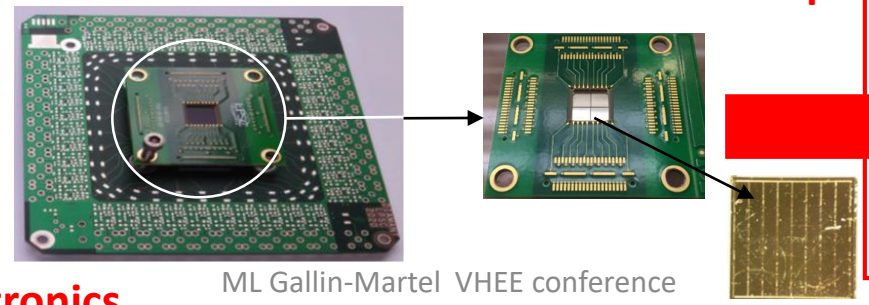

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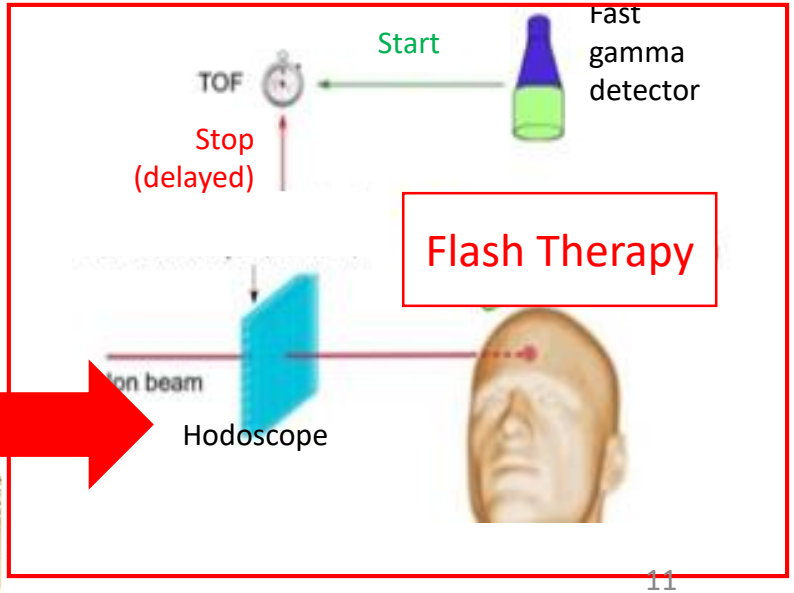
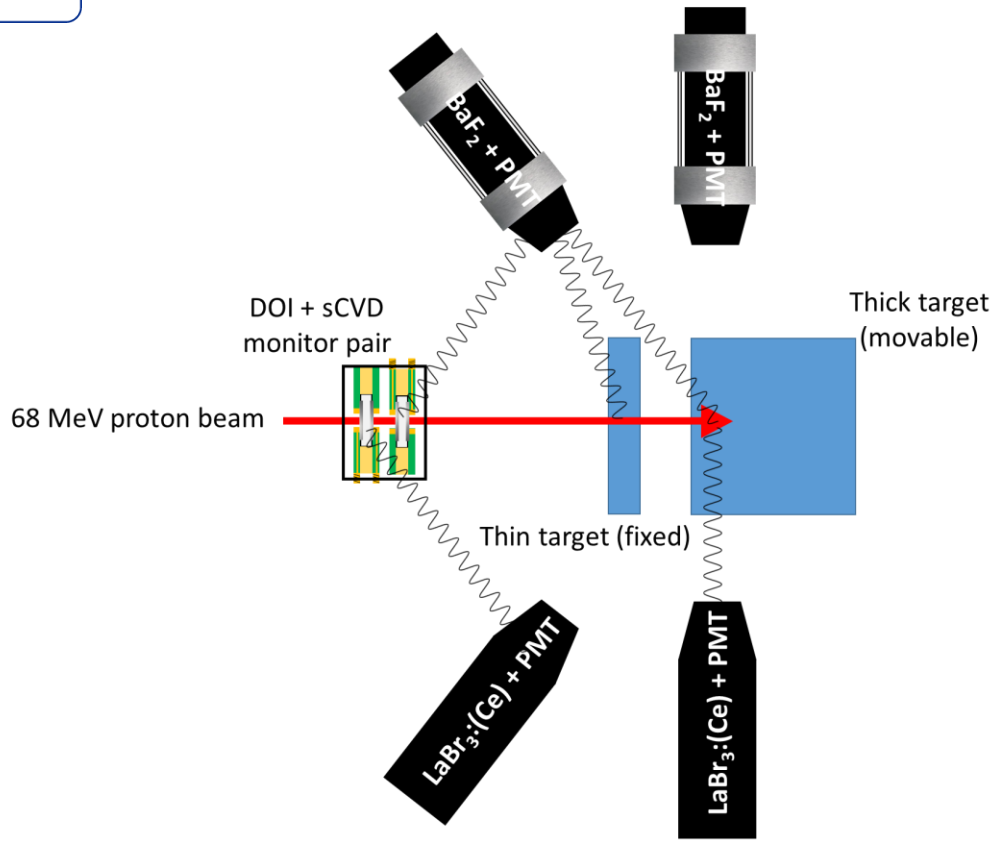
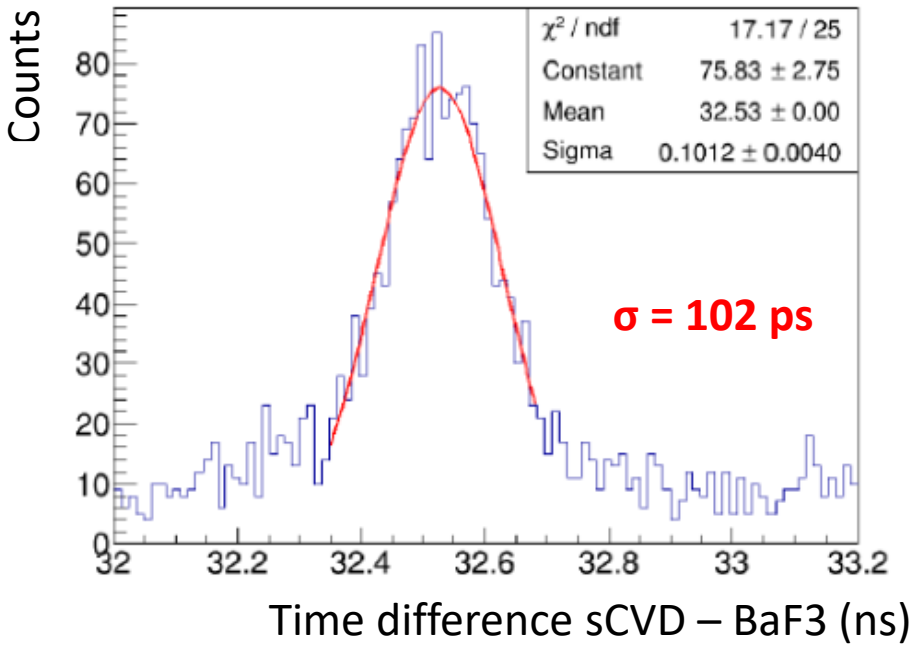


Beam tagging hodoscope for online ion range verification in hadrontherapy

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

S. Marcatili et al, PMB 2020

Outlines

- Beam tagging hodoscope for online ion range verification in hadrontherapy
- **Diamond for beam monitor development**
  - **Material intrinsic qualities**
  - **Detector instrumentation**
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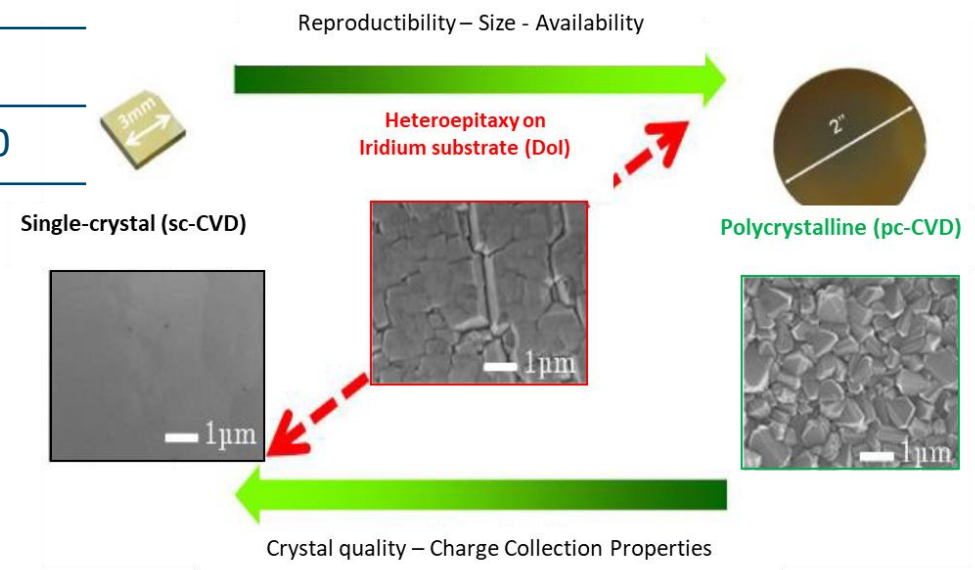
- Conclusion

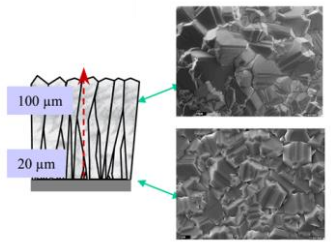
Diamond a wide-bandgap semiconductor

Characteristics @ 300 K

	Diamond	Silicon
Resistivity (Ω.m)	$> 10^{13}$	$2.3 \cdot 10^{7}$
Gap (eV)	5.5	1.1
e^-/h creation energy (eV)	13.1	3.6
Displacement energy (eV)	43	25
Charge carriers mobility ($cm^2.V^{-1}.s^{-1}$)	> 2000	800 – 1400
Thermal conductivity ($W.cm^{-1}.K^{-1}$)	18	2

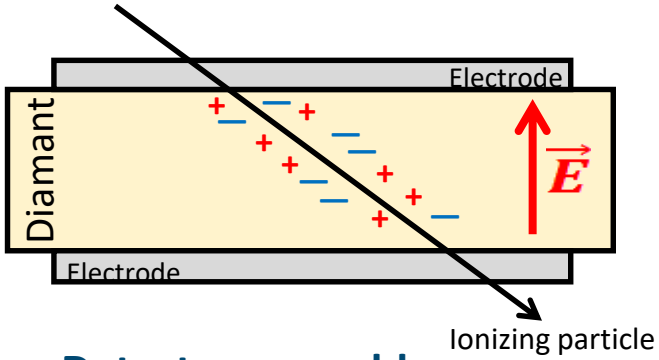
→ **Very low leakage current**
→ **Low noise**
→ **Radiation hard**
→ **Fast timing**
→ **Room temperature**



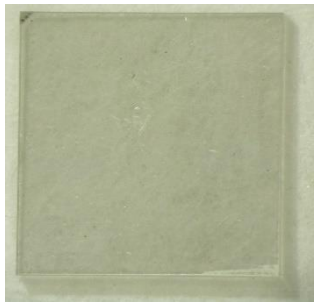


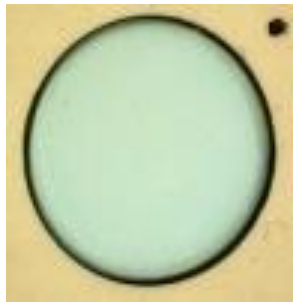
Diamond Sensor Instrumentation for test @ lab or in beam

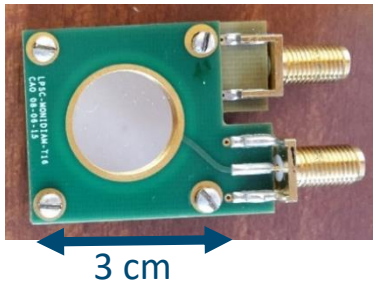
Solid state ionization chamber



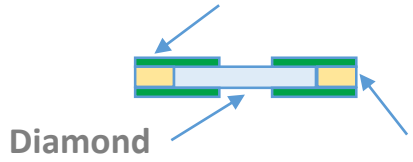
Detector assembly







PCB 50Ω adapted



Read-out electronics

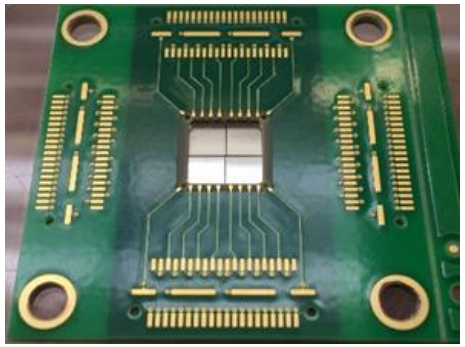
- Fast current preamplifier

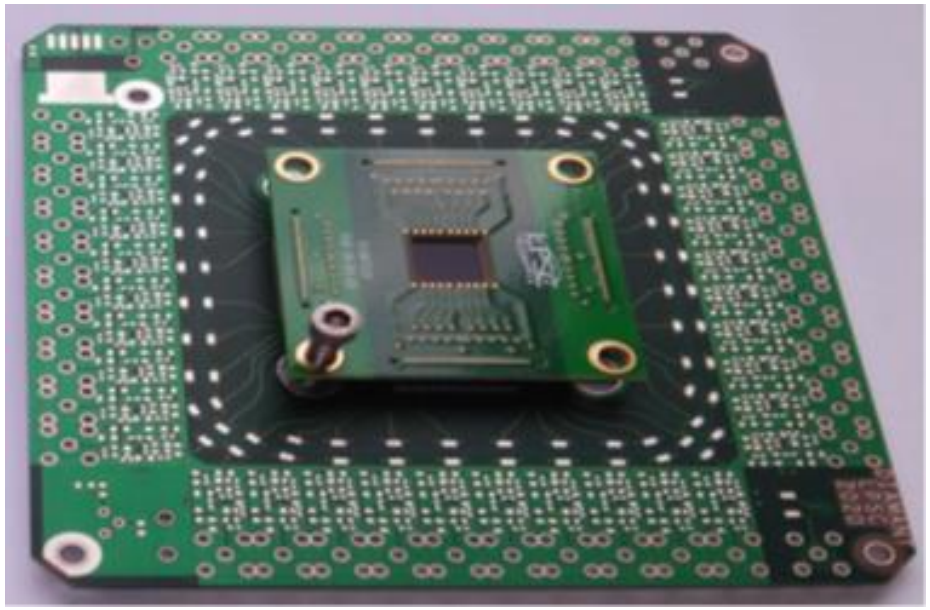
Band Width:	**2 GHz**
Gain:	**40 dB**
Impedance:	**50 Ω**
Dynamic range:	**~ +/- 1 V**
Power Supply:	**12 V / 100 mA**

+ for other application :

- Charge preamplifier
- Electrometer

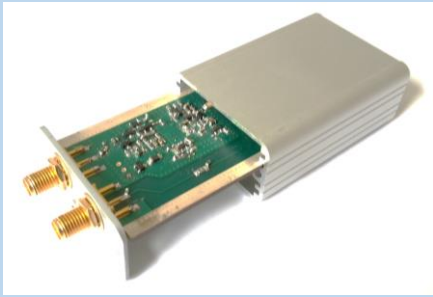
Diamond hodoscope Instrumentation

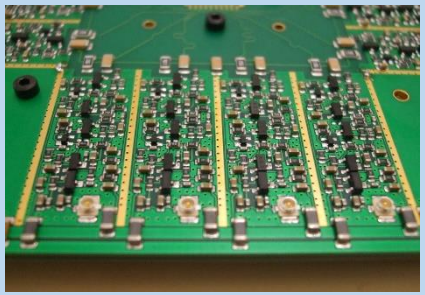




R&T IN2P3 DIAMTECH + ANR DIAMMONI 2020

Fast preamps + QDC in discrete electronics



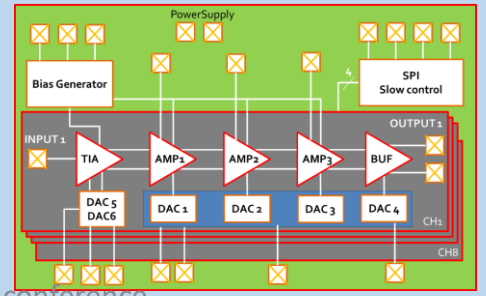


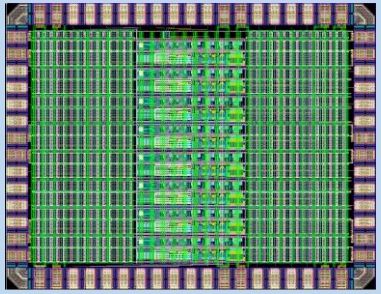
R&T IN2P3 DIAMASIC

LPSC - LPC Caen

ASIC Preamps +TDC+ QDC

- CMOS 130 nm (CERN)
- Radiation tolerant

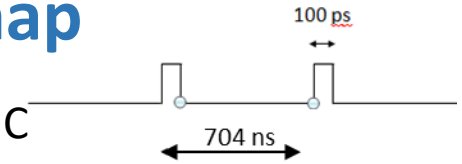




Beam tests XBIC @ESRF – 2D current response map

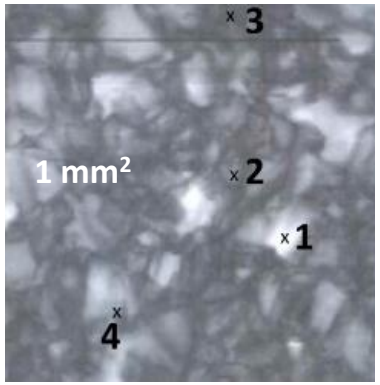
Tests at ESRF with 8.5 keV photons = XBIC source

Xray Beam Induced Current = XBIC

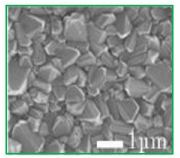


Poly-crystalline E6

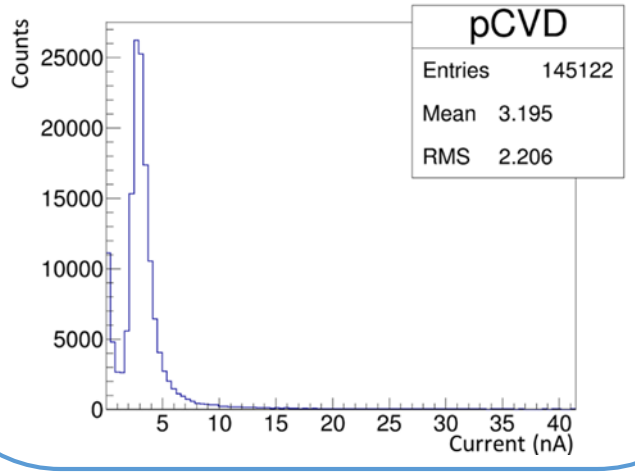
10 x 10 mm² x 500 µm pc-CVD



Polycrystalline (pc-CVD)



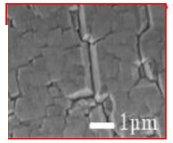
Reflects spatial distribution of grain boundaries

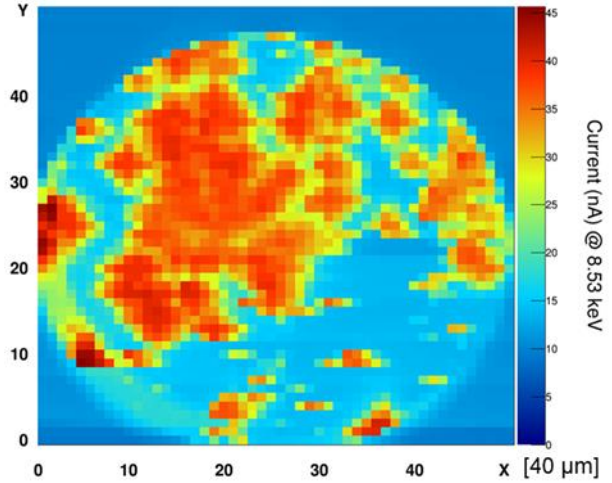


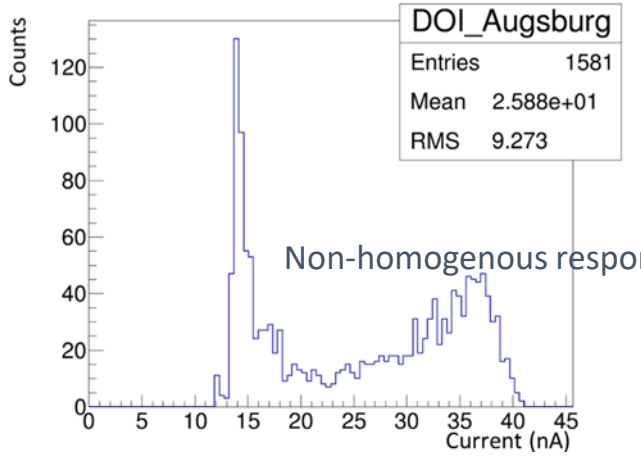
DOI AuDiaTec

5 × 5 mm² × 300 µm DOI-CVD

Heteroepitaxy on Iridium substrate (DoI)





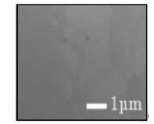


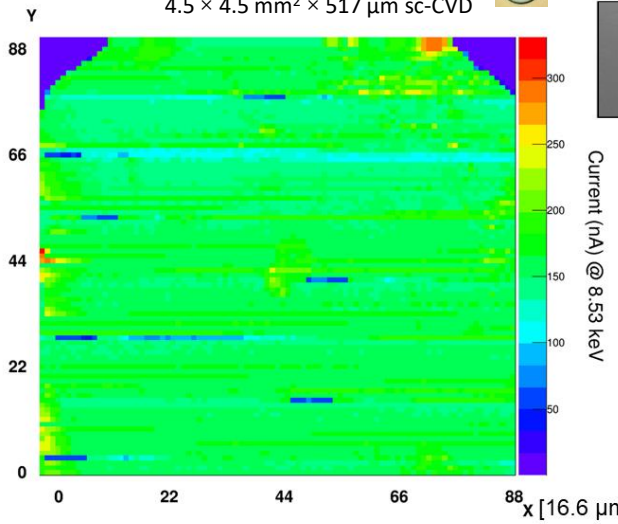
Non-homogenous response map

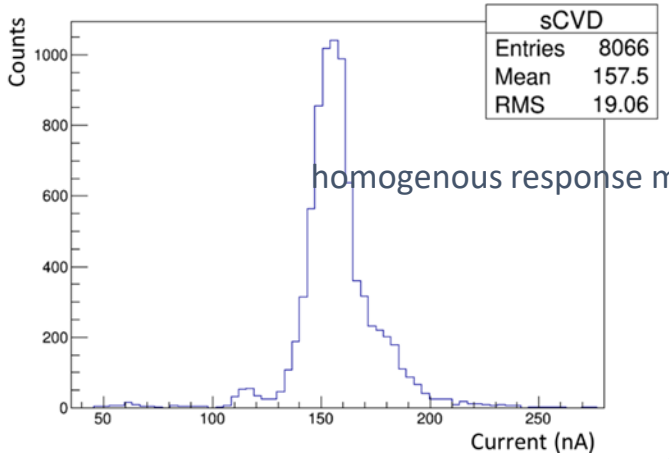
Single-crystal E6

4.5 × 4.5 mm² × 517 µm sc-CVD

Single-crystal (sc-CVD)





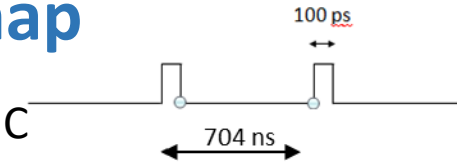


homogenous response map

Beam tests XBIC @ESRF – 2D current response map

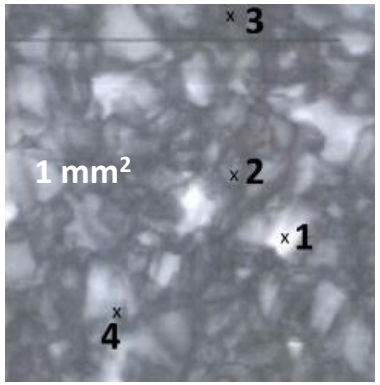
Tests at ESRF with 8.5 keV photons = XBIC source

Xray Beam Induced Current = XBIC

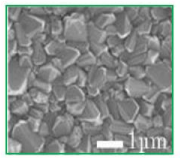


Poly-crystalline E6

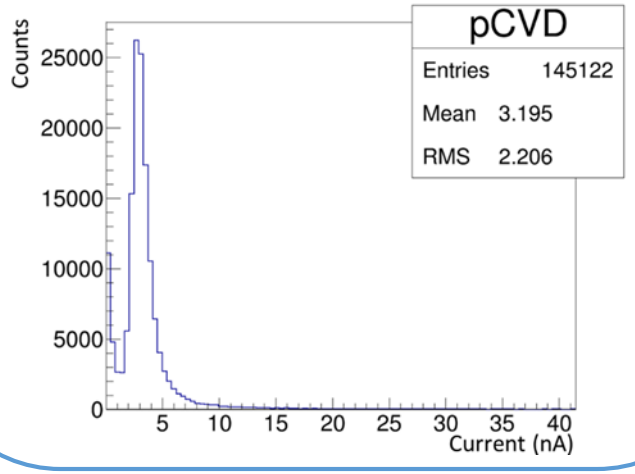
10 x 10 mm² x 500 µm pc-CVD



Polycrystalline (pc-CVD)



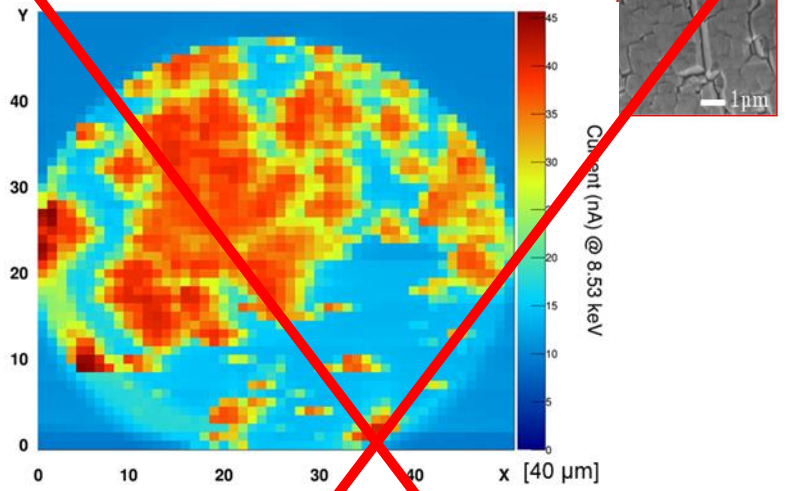
Reflects spatial distribution of grain boundaries

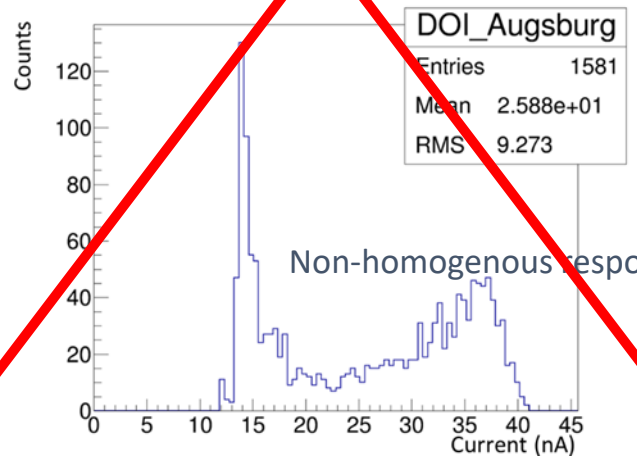


DOI AuDiaTec

5 × 5 mm² × 300 µm DOI-CVD

Heteroepitaxy on Iridium substrate (Dc)





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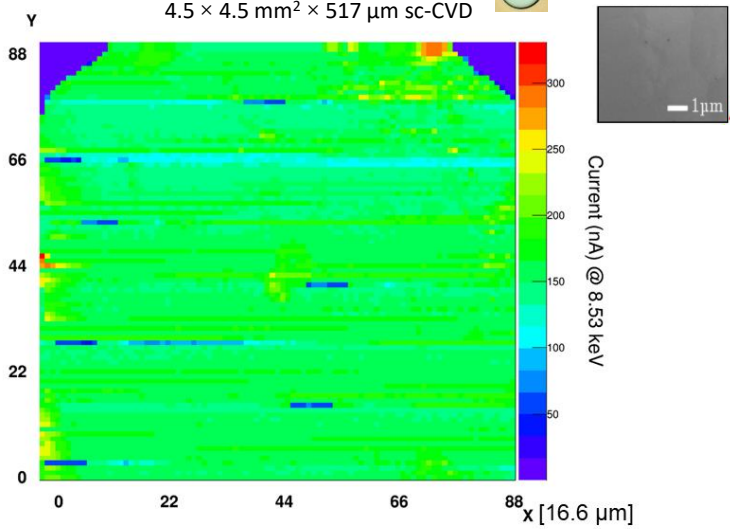

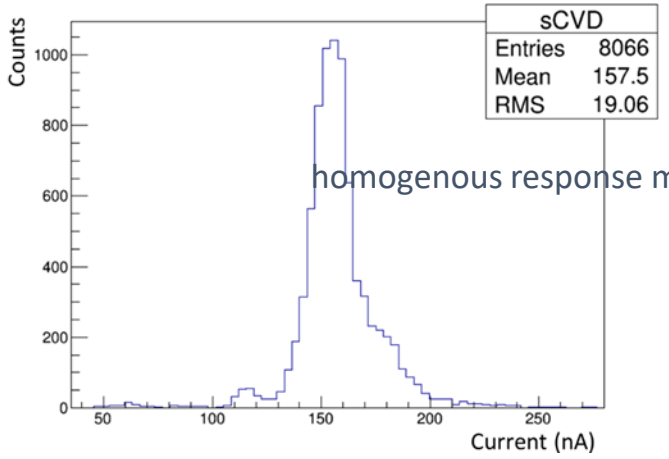

homogenous response map

Outlines

- Beam tagging hodoscope for online ion range verification in hadrontherapy
- Diamond for beam monitor development
  - Material intrinsic qualities
  - Detector instrumentation
  - Performances in beam tests
- **Development of a diamond beam monitor for innovative radiotherapies using spatially segmented photon beams at ESRF on ID17 medical beam line – IDSYNCHRO R&T Transverse IN2P3**
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- Conclusion

IDSYNCHRO 2020-2023 (R&T IN2P3 DIAMTECH)

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

R&T IN2P3 DIAMTECH

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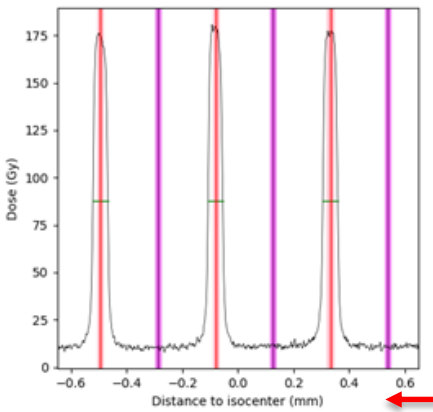
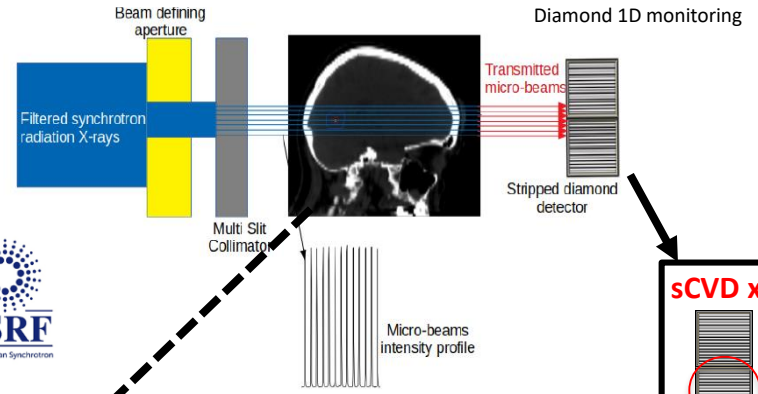
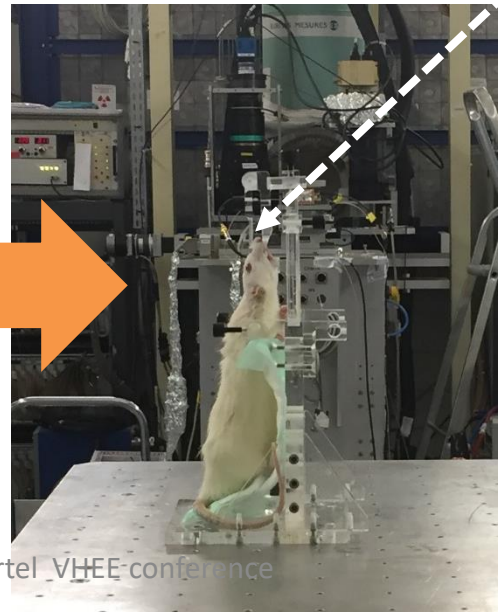
→ *X-Rays detection*
→ *Spatial (micro beams)*
→ *Huge dynamique (High dose rate)*

N. Rosuel PhD thesis (2018-2021)

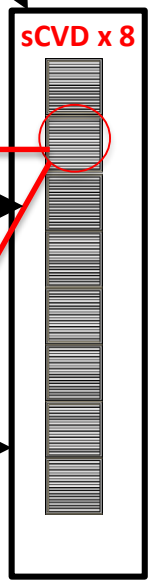




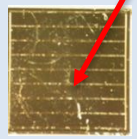
MRT: 50 µm
Micro Beam Radiation Therapy



Strips on diamond to satisfy MRT beam structure

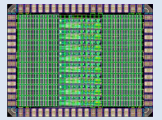


Detector = 8 x sCVD (4.5 × 4.5 mm²) strip metallized



+

elec FE = QDC ASIC LPSC



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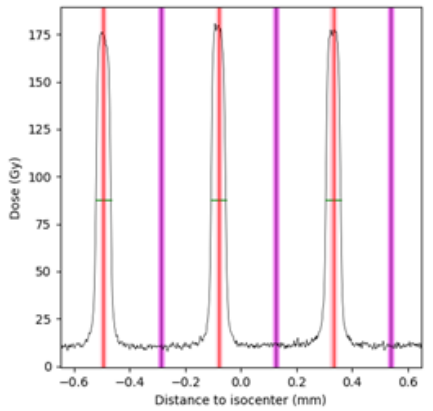
N. Rosuel PhD thesis (2018-2021)



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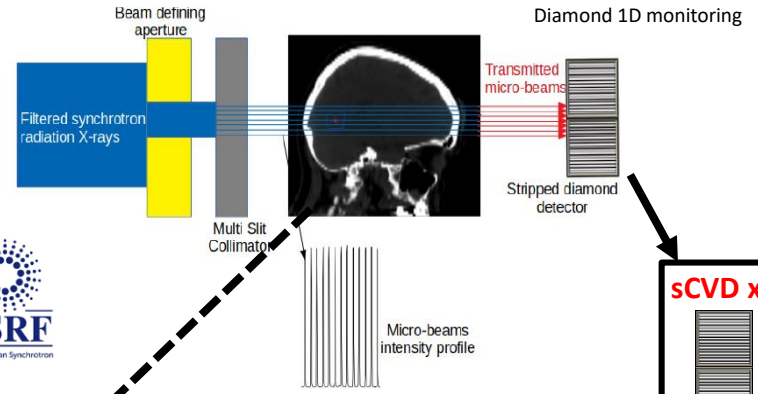
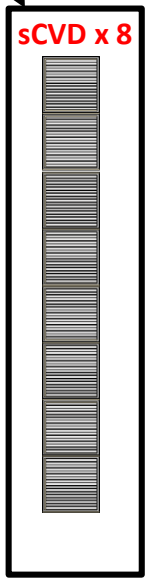
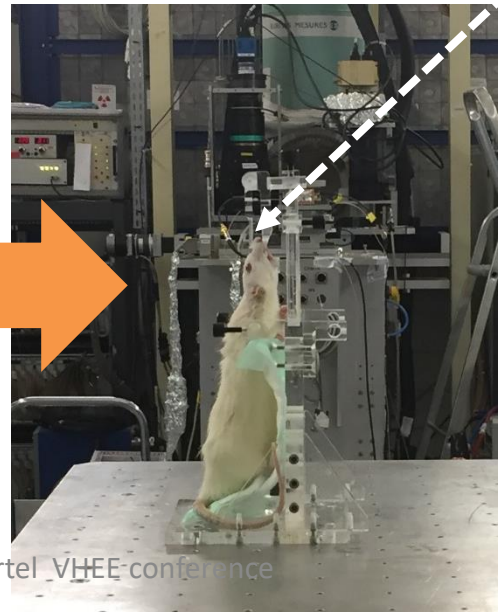
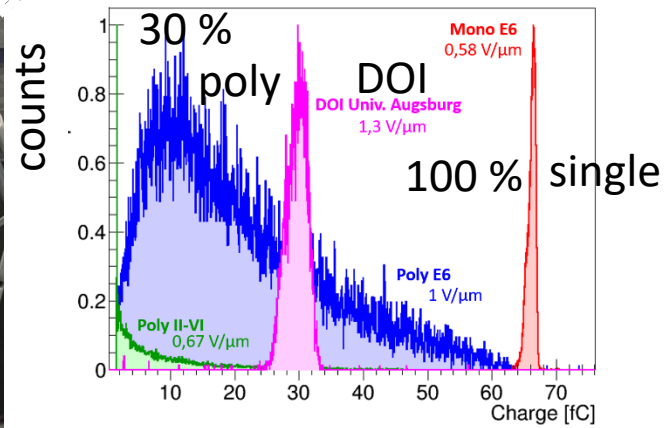
Micro Beam Radiation Therapy







Why sCVD ?



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

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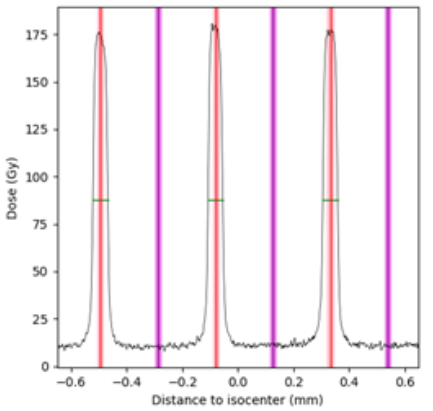

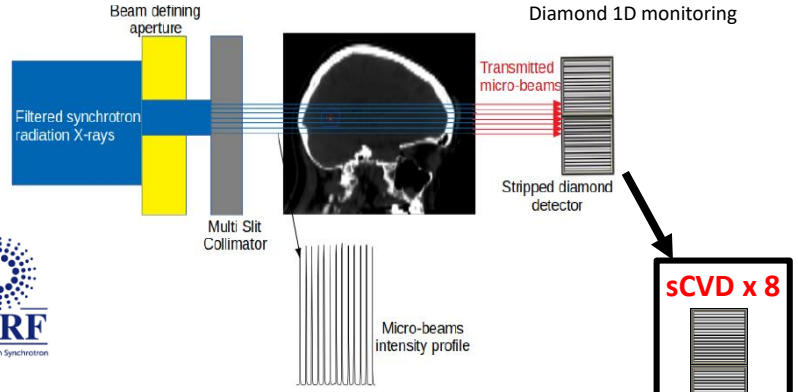

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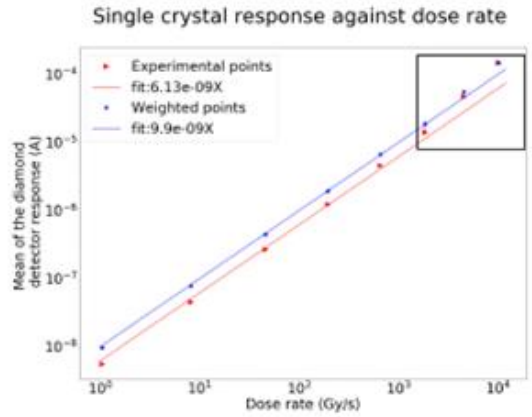
N. Rosuel PhD thesis (2018-2021)

- Slightly loss of linearity for the highest flow rates (2019 result)
- Simulation => thinner diamond to be used
- New tests currently in Oct. 2020 @ESRF



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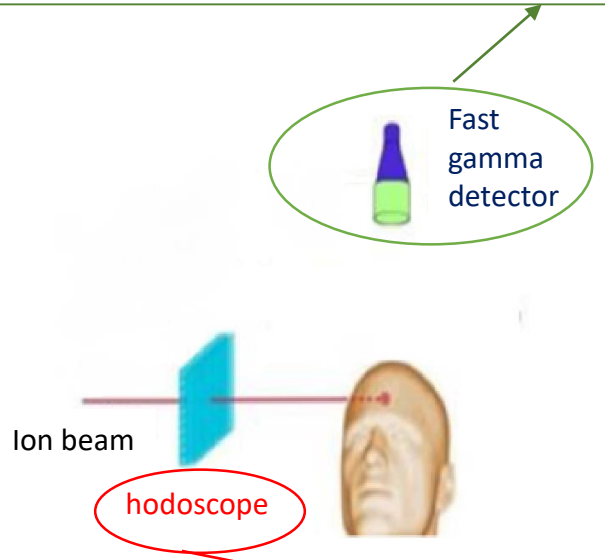
DIAMMONI 2020-2024 (ANR + R&T IN2P3 DIAMTECH)

Diamond beam monitoring + prompt gamma detection with the Prompt Gamma Peak Integral method

Collaboration LPSC IP2I CREATIS in the frame work of Labex Primes



Collaboration LPSC SUBATECH ARRONAX : ANR DIAMMONI + R&T transverse DIAMTECH

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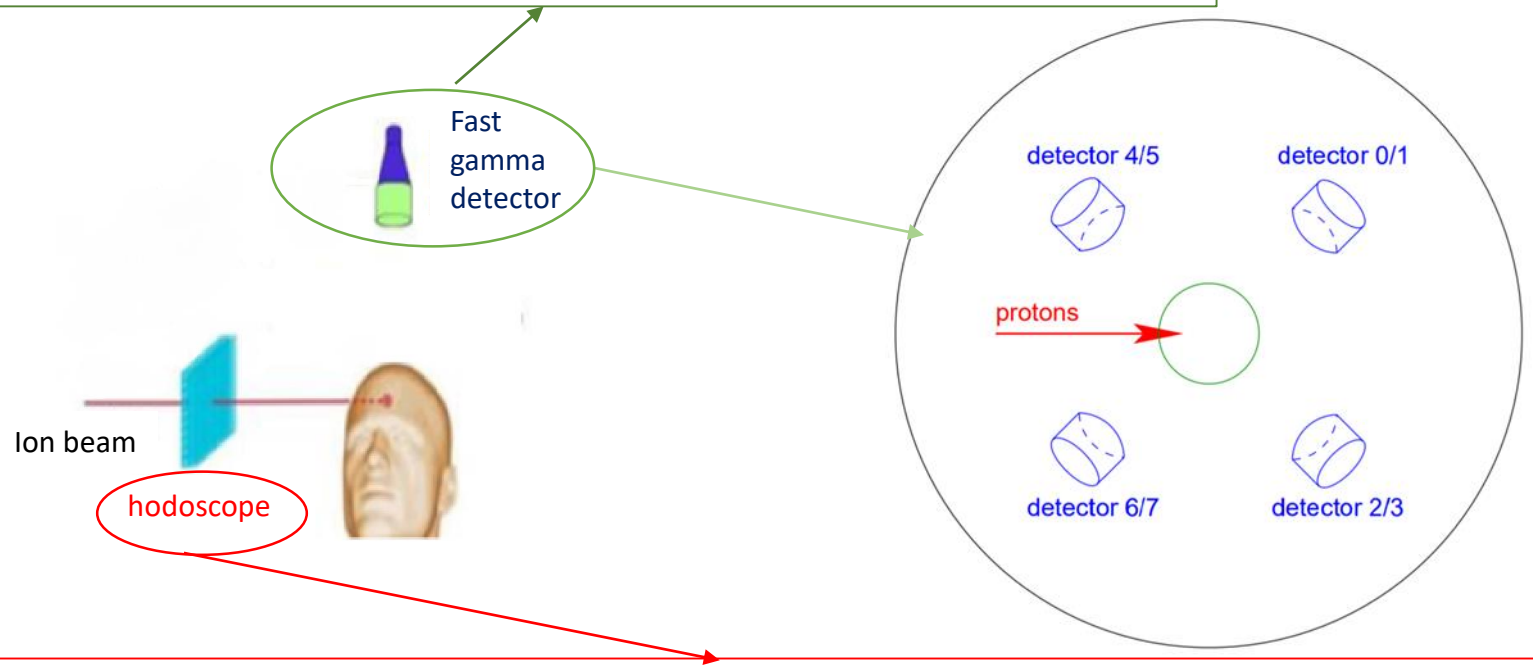
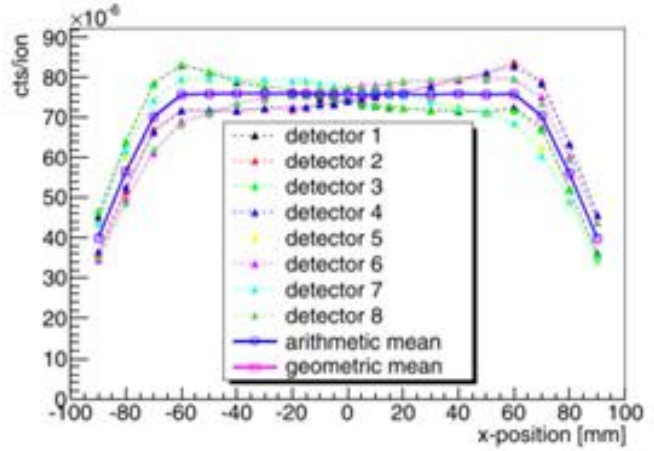
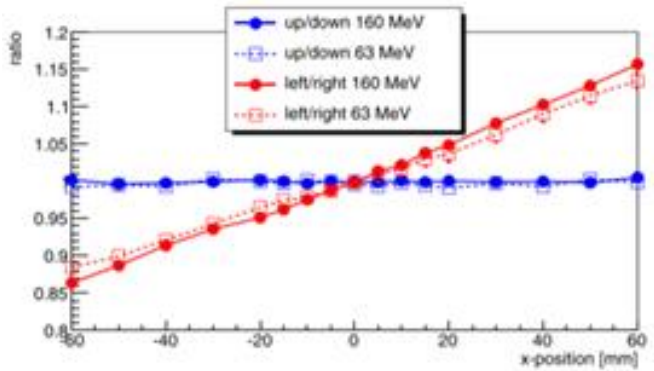


Collaboration LPSC SUBATECH ARRONAX : ANR DIAMMONI + R&T transverse DIAMTECH





Krimmer 2017

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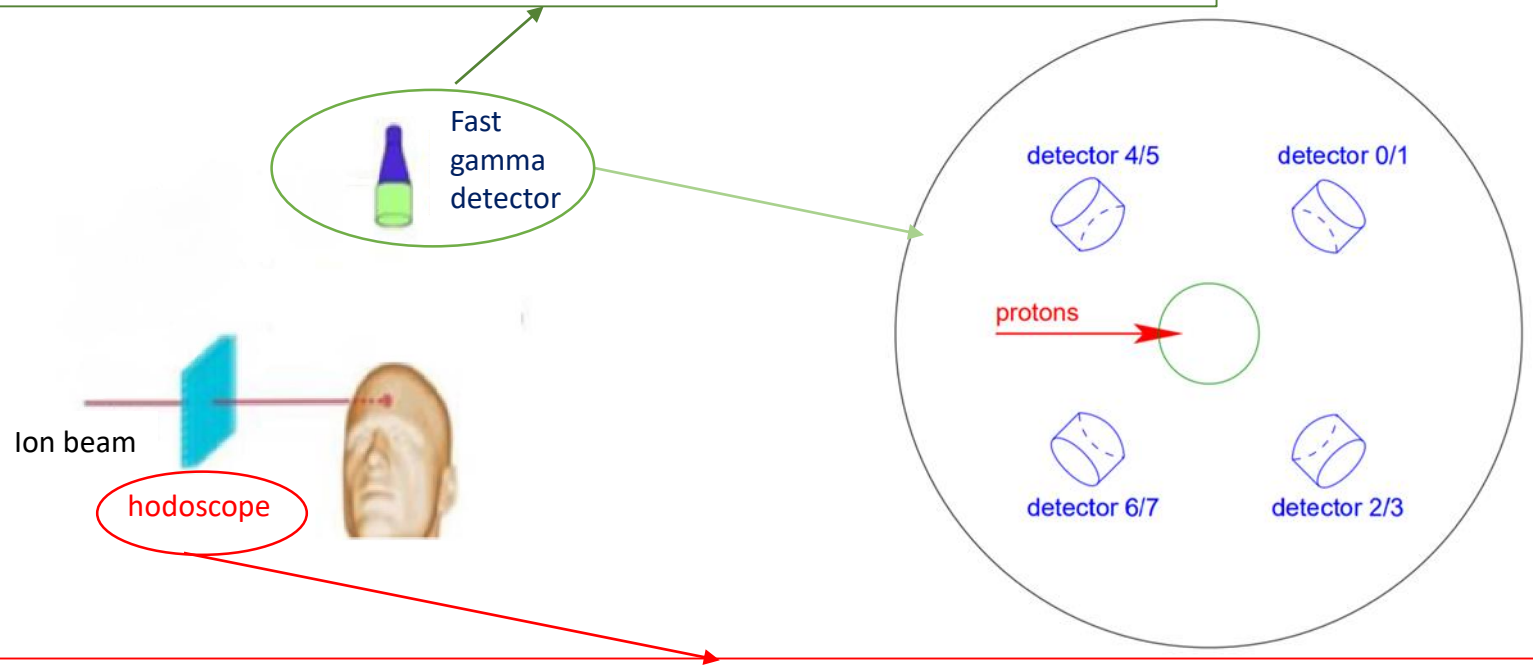
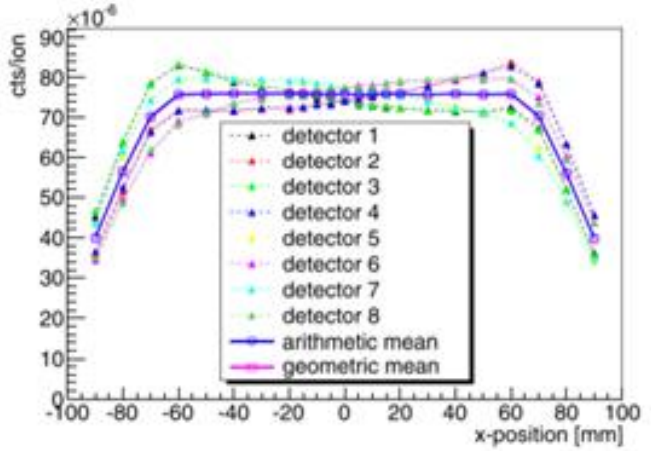
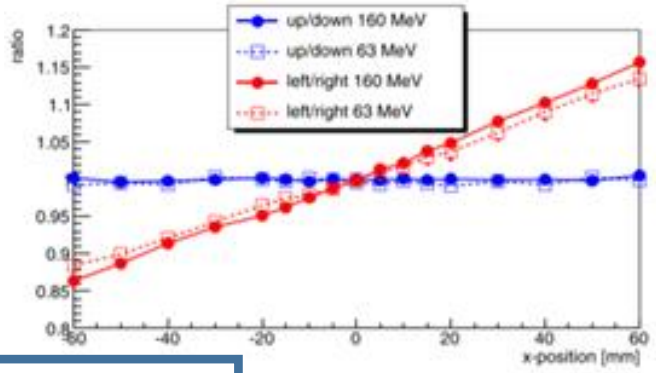






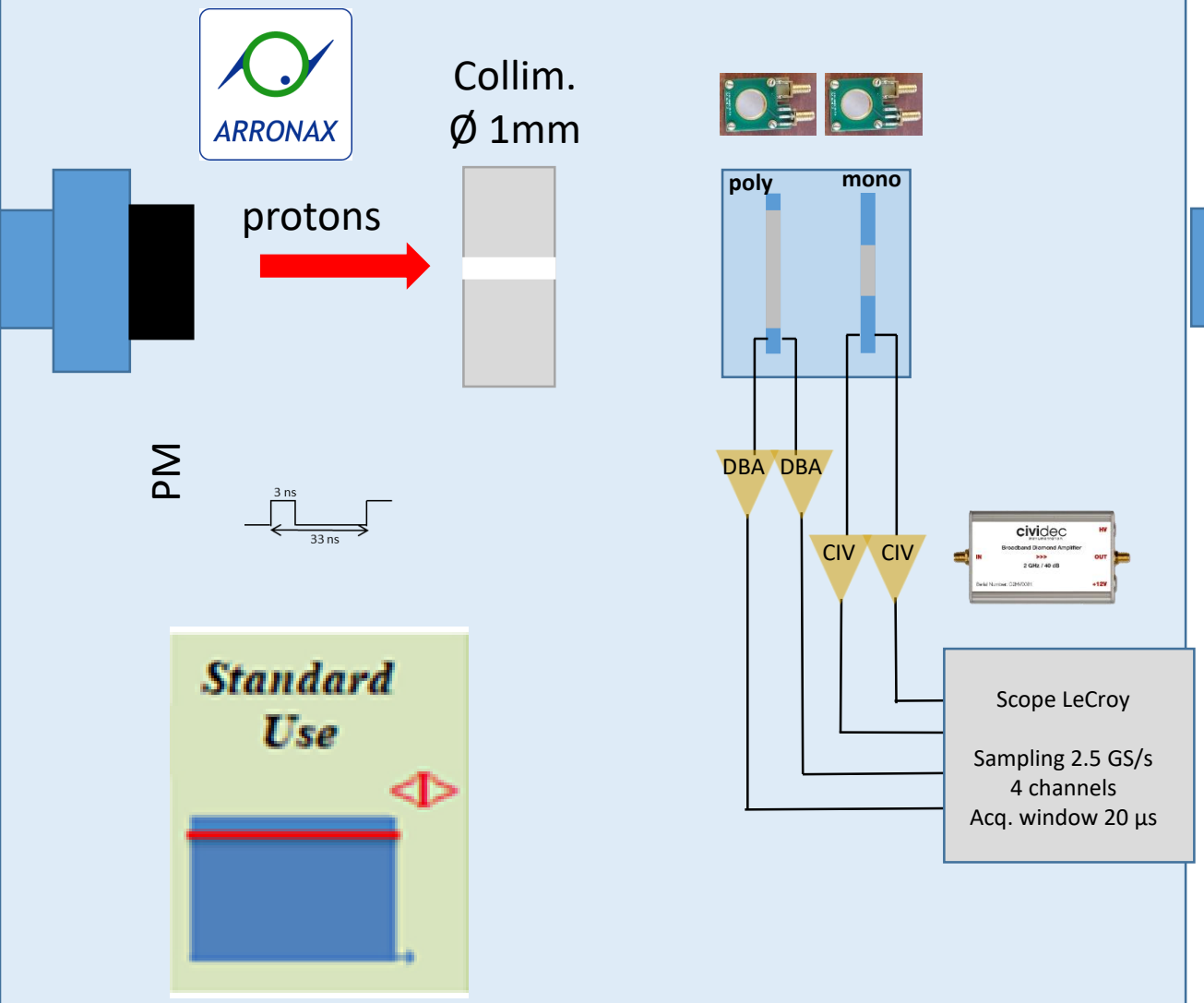
Krimmer 2017

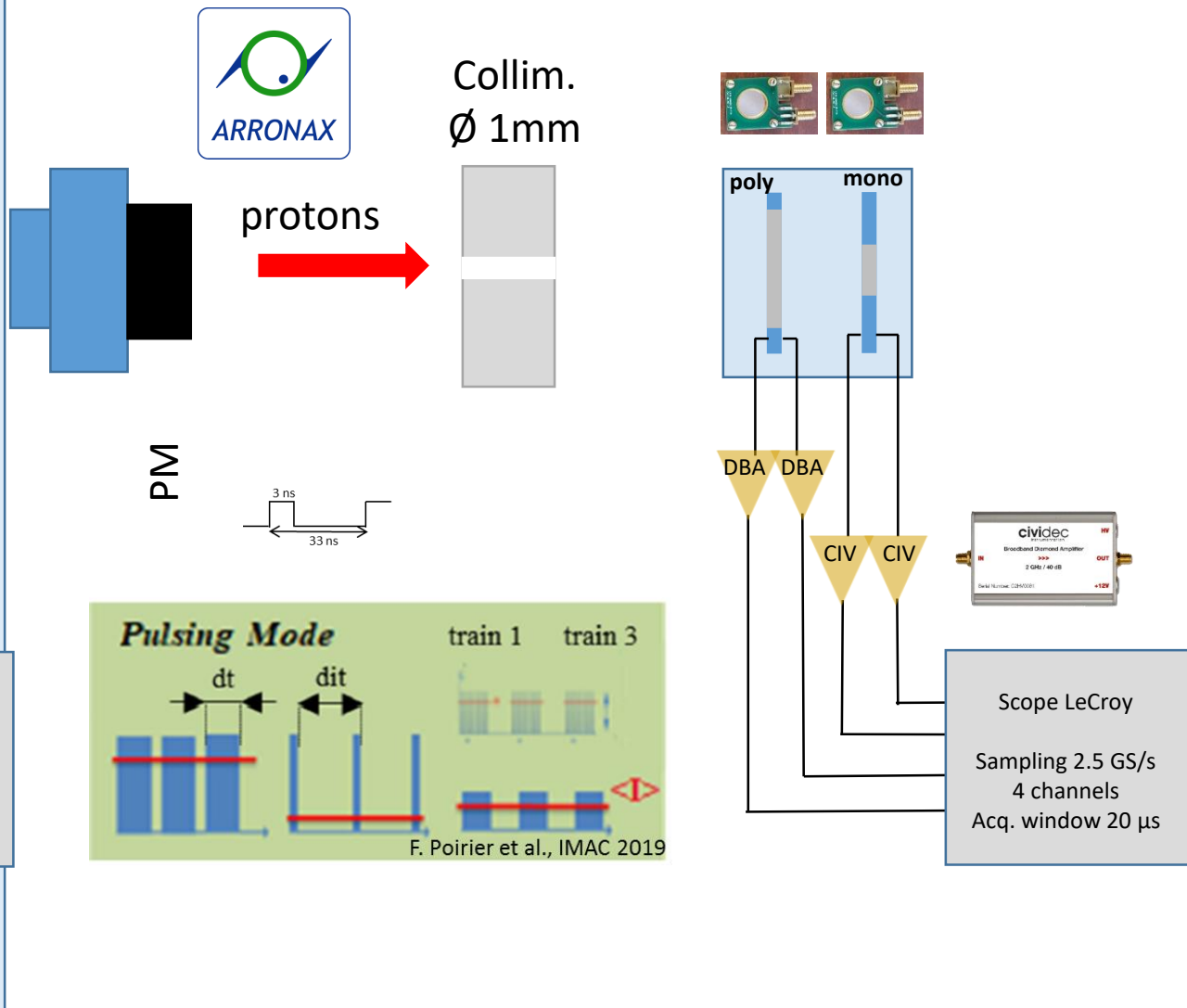
Collaboration LPSC SUBATECH ARRONAX : ANR DIAMMONI + R&T transverse DIAMTECH

P. Everaere PhD thesis (Labex Primes 2020-2023) : simulation + experiment in FLASH condition both in ARRONAX and in CAL (Centre Antoine Lacassagne de Nice)

X PhD thesis (ANR 2021-2024) : diamond hodoscope for pulsed beam monitoring

DIAMMONI 2020-2024 (ANR + R&T IN2P3 DIAMTECH)

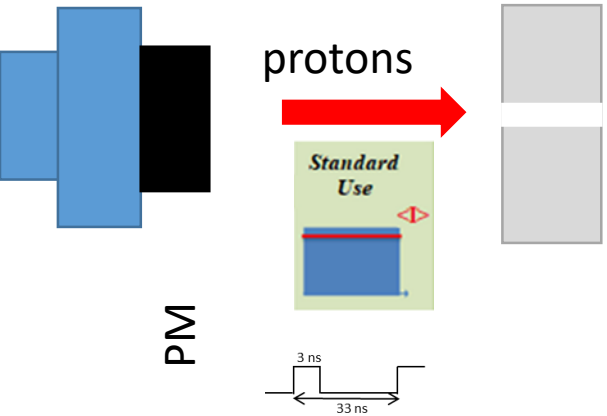


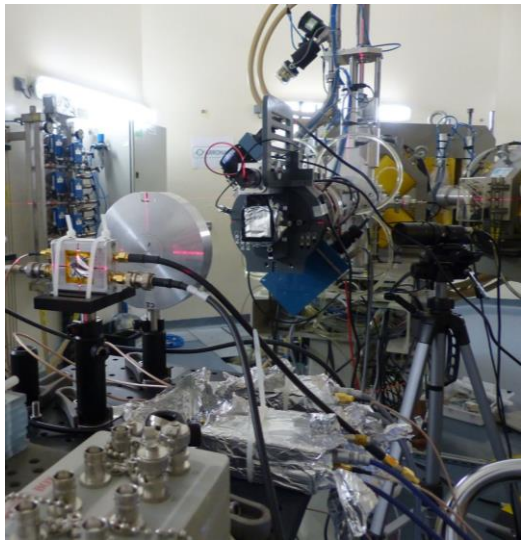


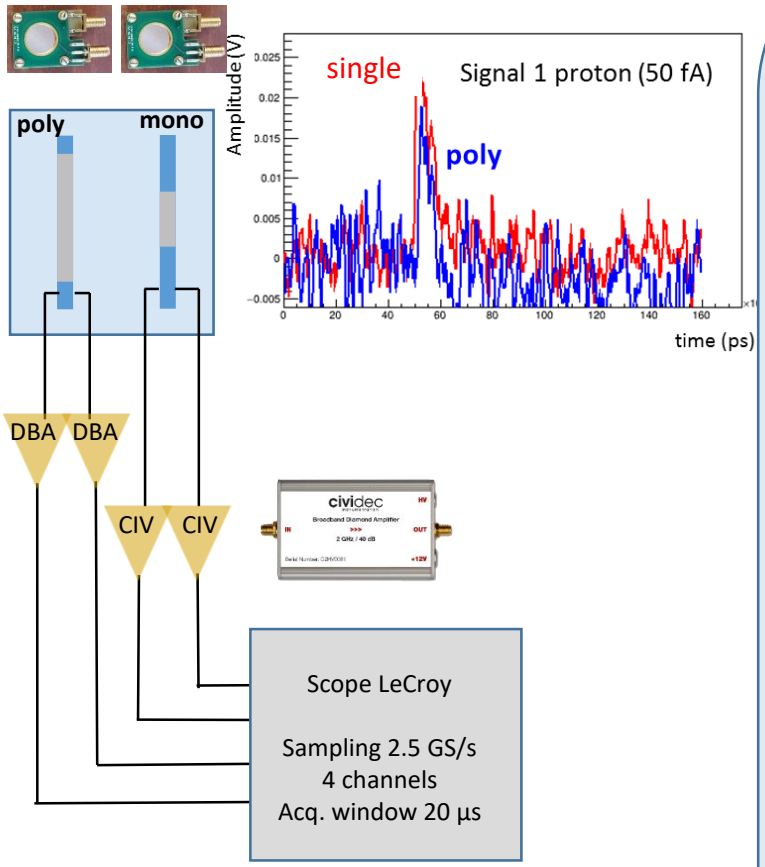
Pulsed mode => Flash Thérapy !

DIAMMONI 2020-2024 (ANR + R&T IN2P3 DIAMTECH)

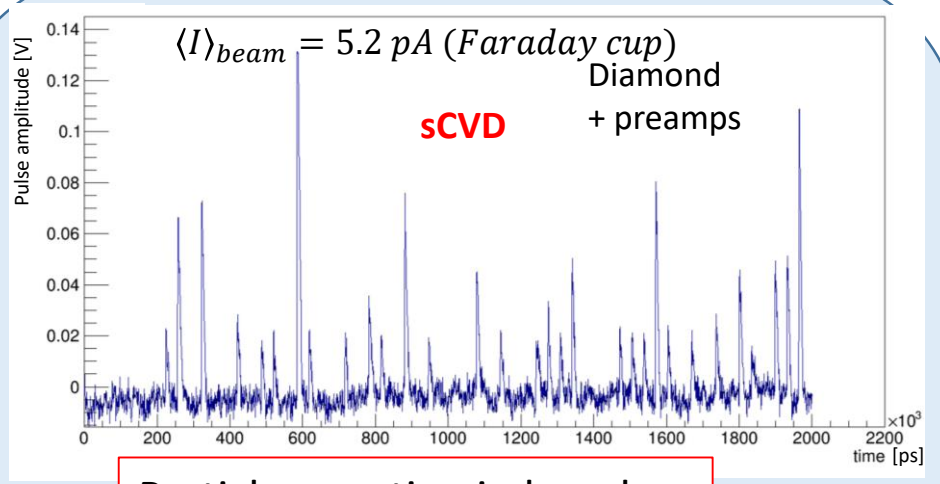
Particle counting vs I_{beam}: preliminary measurement



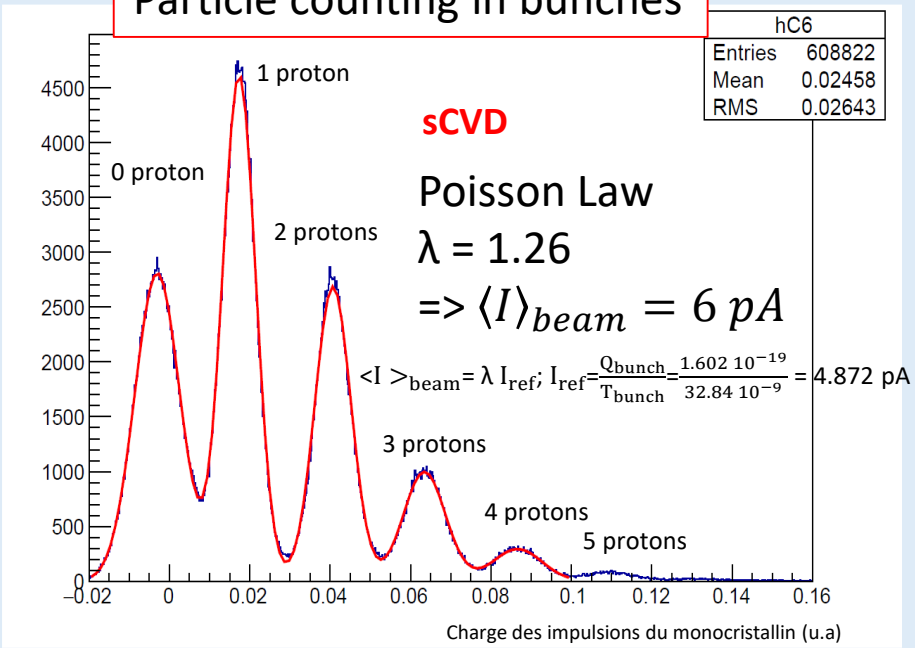




Continuous mode and reduced intensity



Particle counting in bunches



Proton counting in nano pulse

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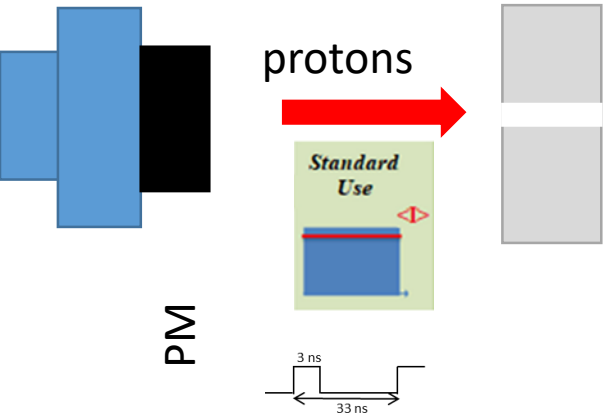
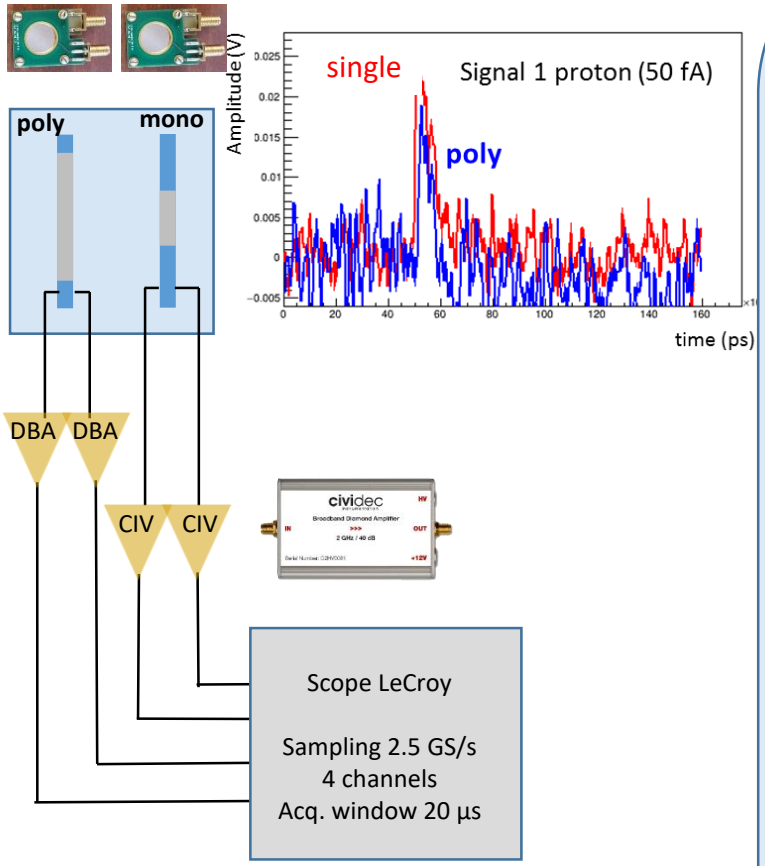
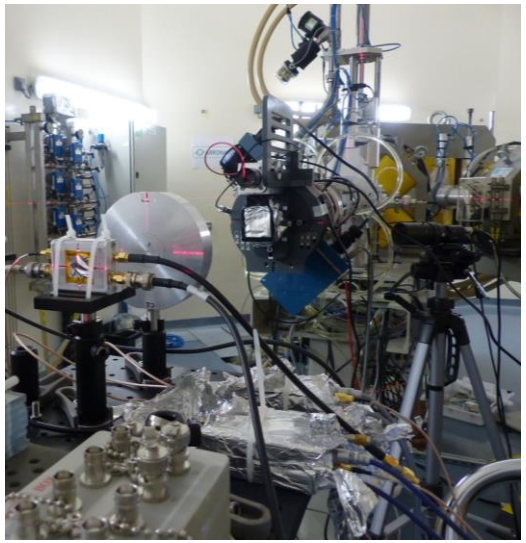
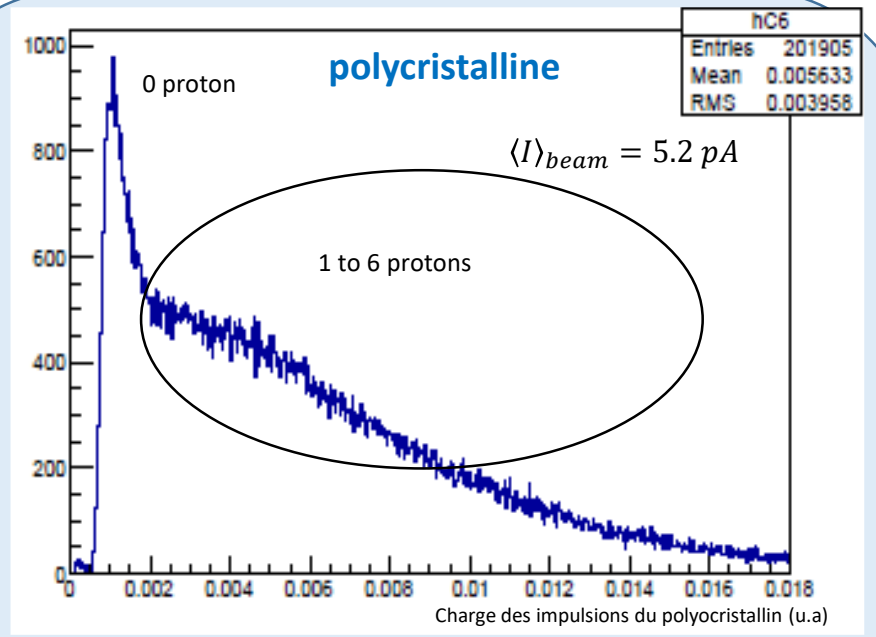
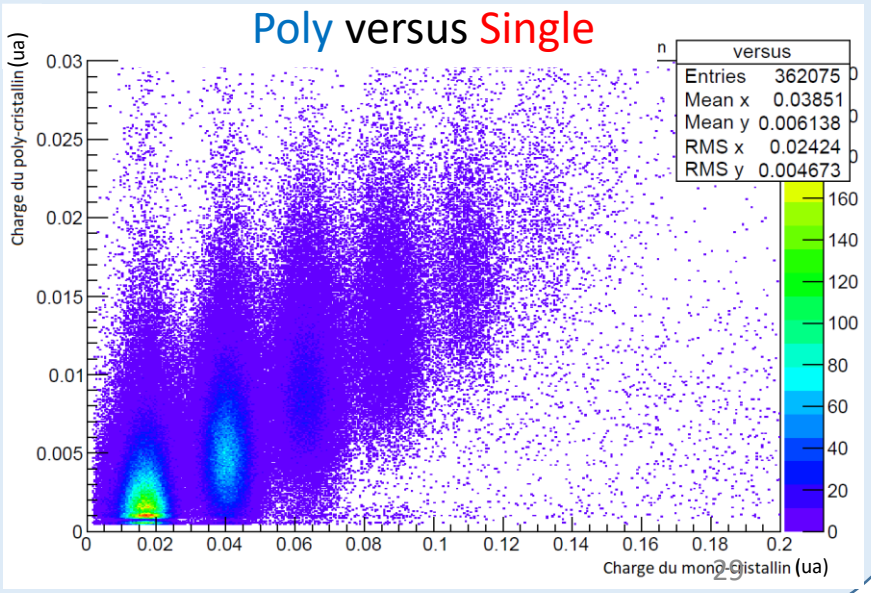






Continuous mode and reduced intensity





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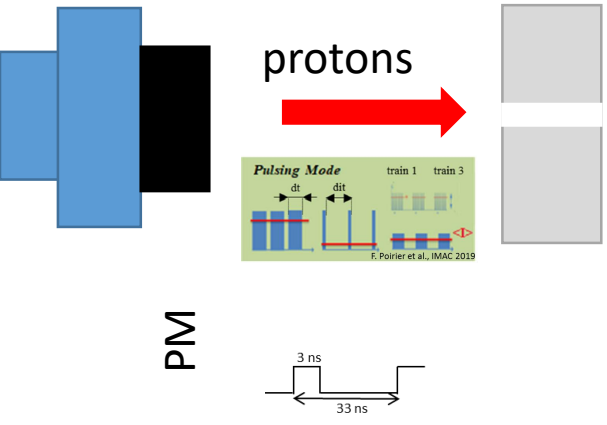
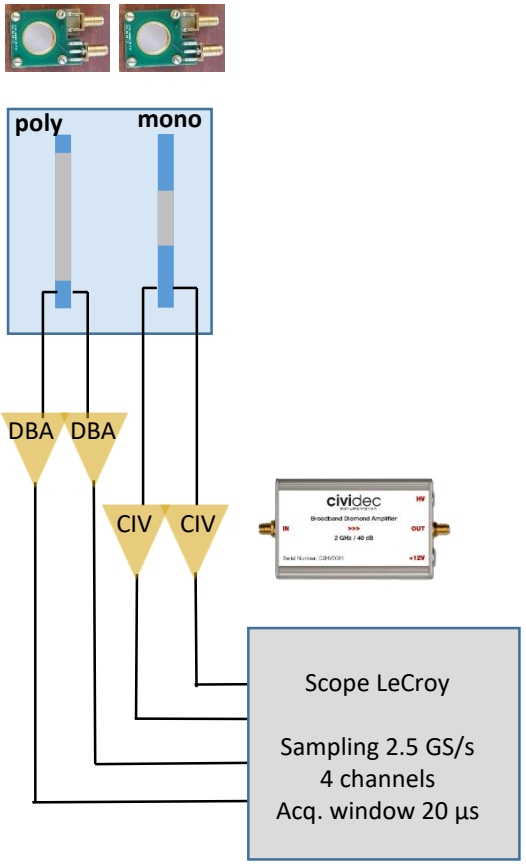
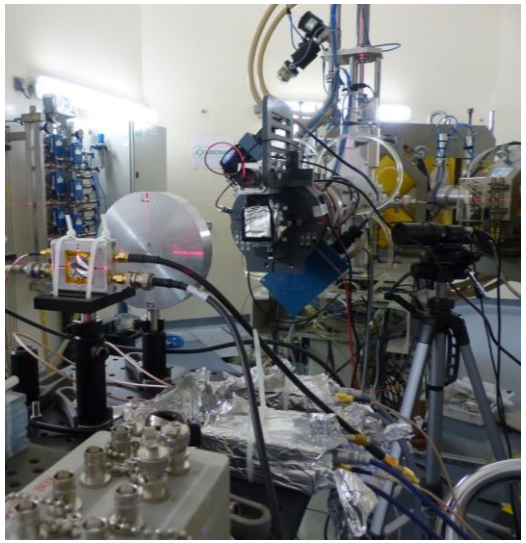
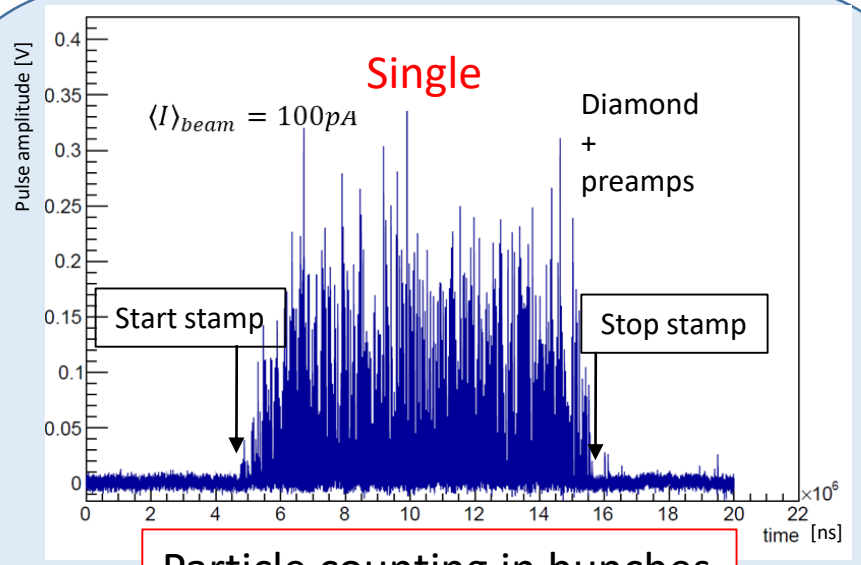


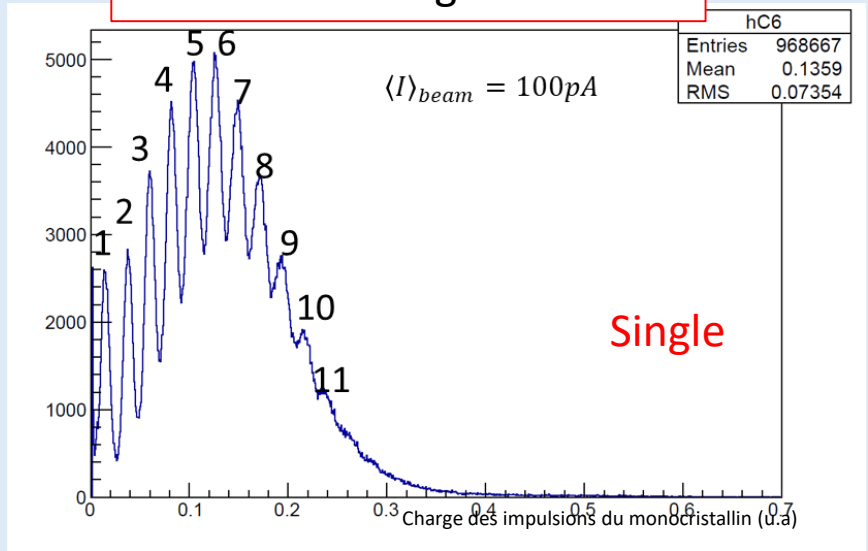




Pulsed mode and $\langle I \rangle_{beam} = 100\ pA$



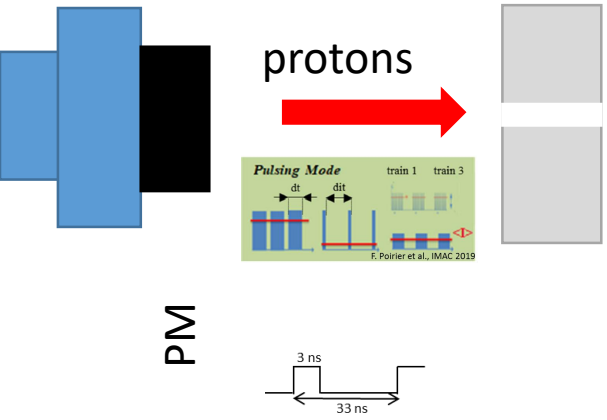
Particle counting in bunches

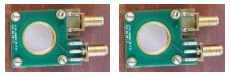


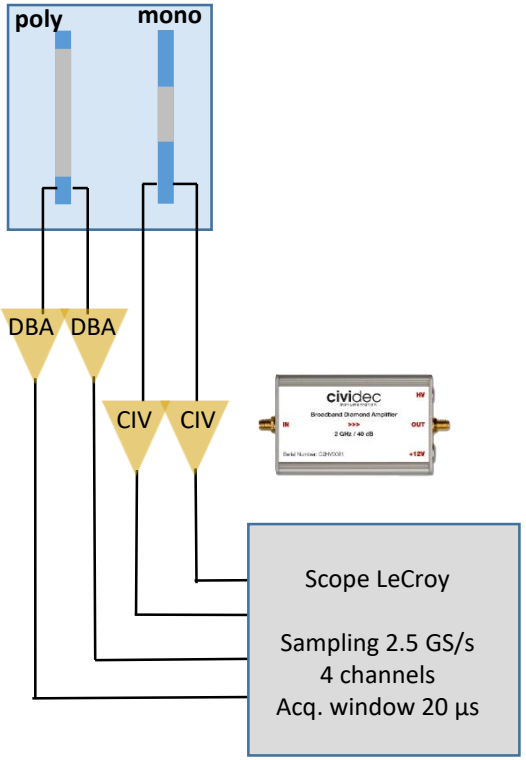
Proton counting in pulses !

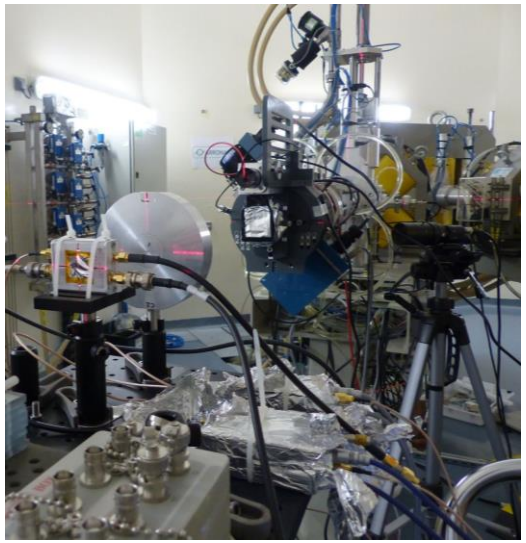
DIAMMONI 2020-2024 (ANR + R&T IN2P3 DIAMTECH)

Particle counting vs I_{beam}: preliminary measurement



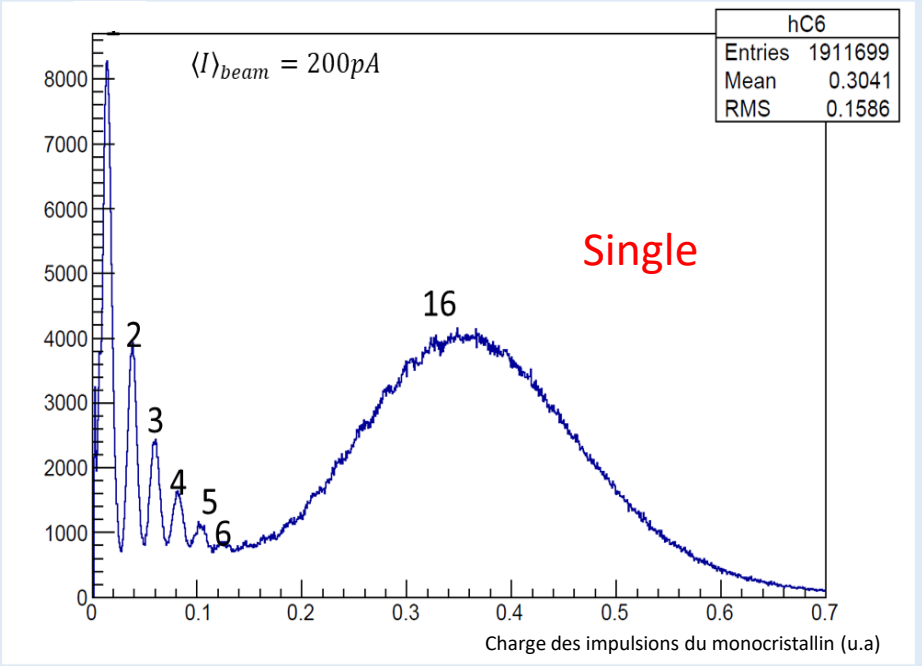






Pulsed mode and $\langle I \rangle_{beam} = 200\ pA$

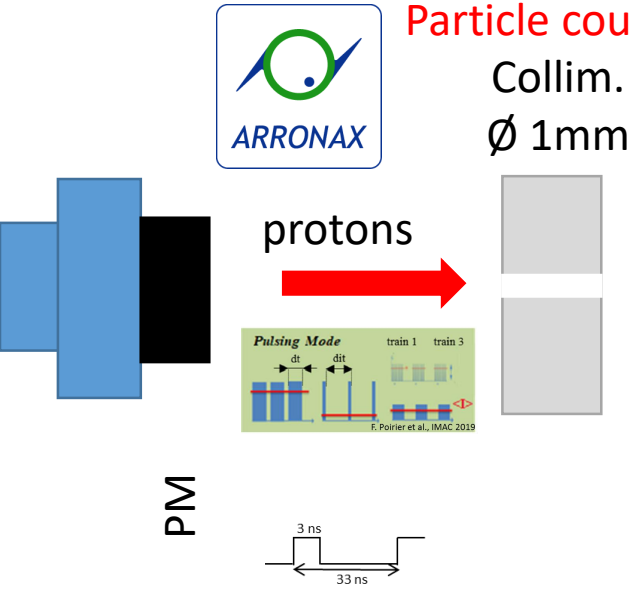
Particle counting in bunches

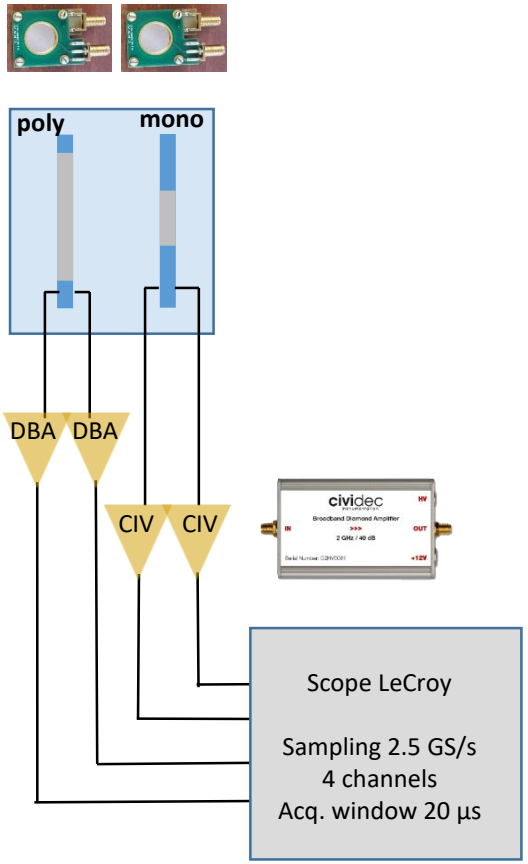


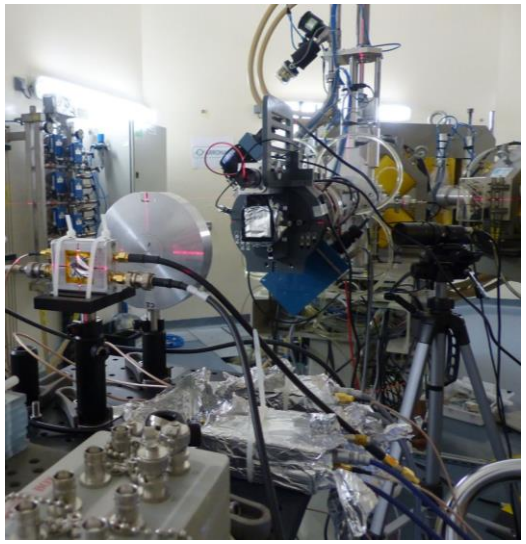
Preliminary Exp.
=> proton counting in bunches at 5.2 pA = calibration
=> proton counting in bunches at 200 pA !

DIAMMONI 2020-2024 (ANR + R&T IN2P3 DIAMTECH)

Particle counting vs I_{beam}: preliminary measurement

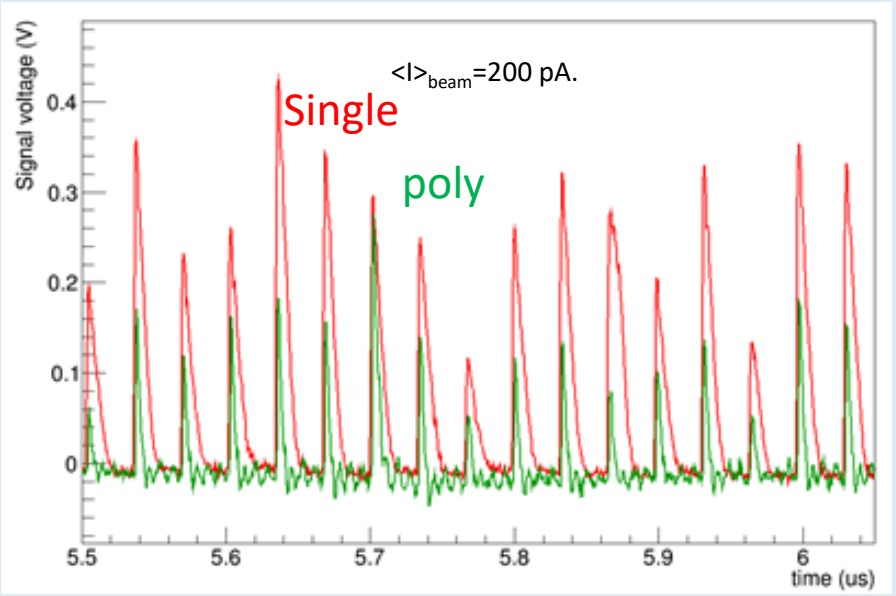




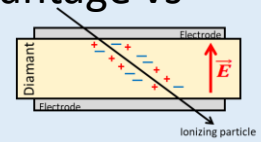


Pulsed mode and $\langle I \rangle_{beam} = 200\ pA$

Single vs Poly at higer beam intensity ?



Polycrystalline crystals (pCVD) advantage vs single-crystals (sCVD) !



Charge recombination on the path of the charge carriers to the electrode occurs

=> a narrower signal !

DIAMMONI 2020-2024 (ANR + R&T IN2P3 DIAMTECH)

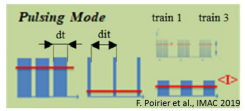
ARRONAX

Particle counting vs I_{beam}: preliminary measurement

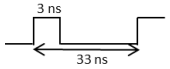
Collim.
Ø 1mm

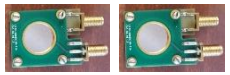
protons

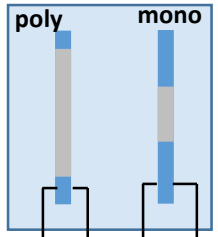
PM

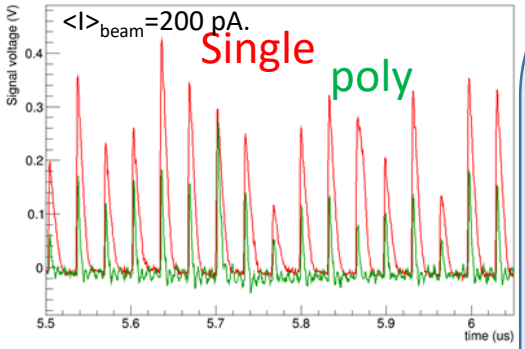


Pulsed mode





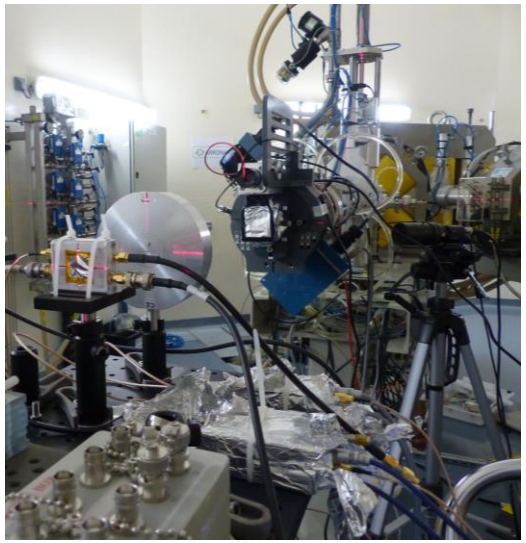




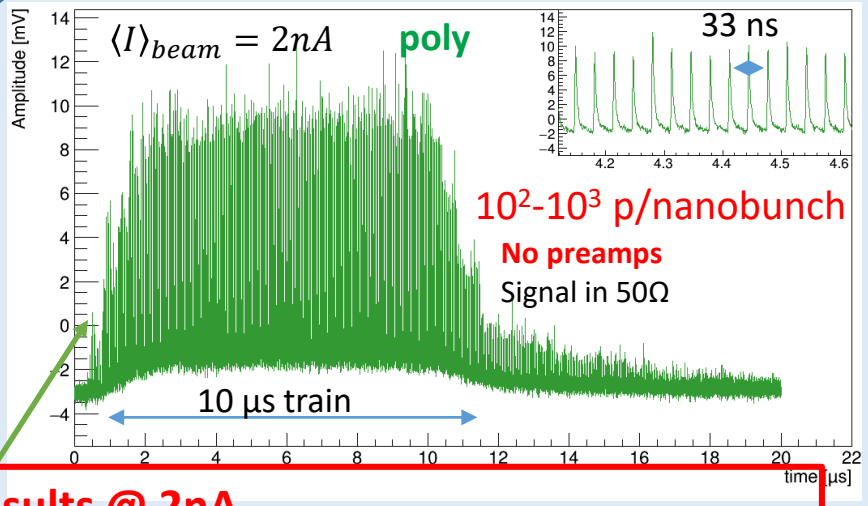
DBA DBA CIV CIV

Scope LeCroy

Sampling 2.5 GS/s
4 channels
Acq. window 20 µs

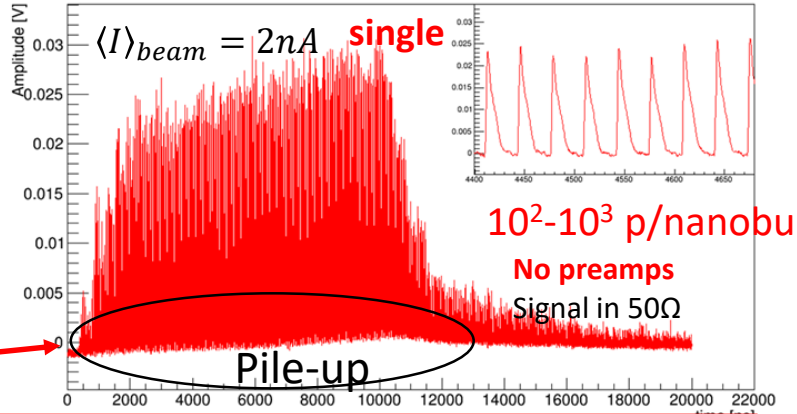


pCVD instead of sCVD
or
Single diamond to be thinned!
=> ANR-DIAMMONI be investigated in 2020-2024 !



10^2-10^3 p/nanobunch
No preamps
Signal in 50Ω

Preliminary results @ 2nA
Flash => $\langle I \rangle_{beam}$ up to µA to be done in Nov. 2020 !



10^2-10^3 p/nanobunch
No preamps
Signal in 50Ω

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

Outlines

- Beam tagging hodoscope for online ion range verification in hadrontherapy
- Diamond for beam monitor development
  - Material intrinsic qualities
  - Detector instrumentation
  - Performances in beam tests
- Development of a diamond beam monitor for innovative radiotherapies using spatially segmented photon beams at ESRF on ID17 medical beam line – IDSYNCHRO R&T Transverse IN2P3
- Diamond application to Flash Therapy : ANR – DIAMMONI
- **Conclusion**

Conclusion

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…), GIP - ARRONAX, ESRF +…
  - Instrumentation (IN2P3 labs, Institut Néel, etc.)

- **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).

=> 2020-2024 objectives: design of monitors for CLaRyS-UFT + DIAMTECH-IDSYNCHRO + DIAMTECH-DIAMMONI to perform beam diagnostics and radiotherapies monitoring

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The authors would like to acknowledge the **ESRF** for provision of synchrotron radiation facilities and would like to thank the ID21 beamline staff for their assistance with experiment MI-1243.

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