

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



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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



J. F. Motte, L. Abbassi, T. Crozes : NEEL Grenoble



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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**

Outlines

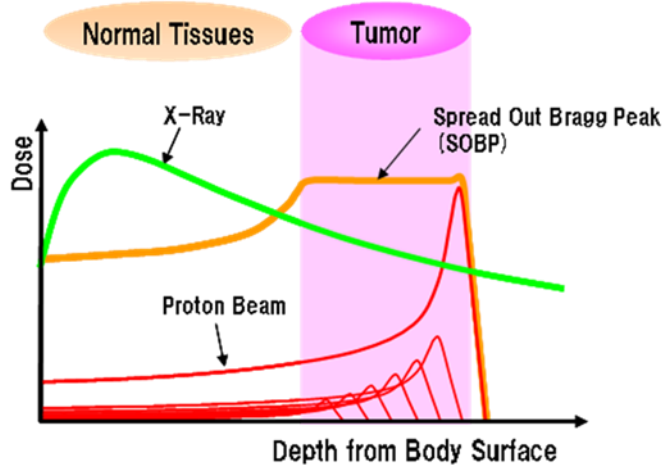
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Beam tagging hodoscope for online ion range verification in hadrontherapy

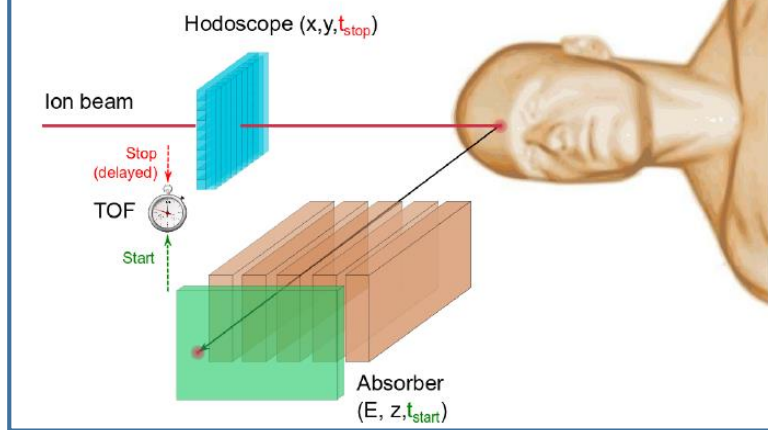
Prompt Gamma detection

Ion range monitoring in patient body : Bragg peak location

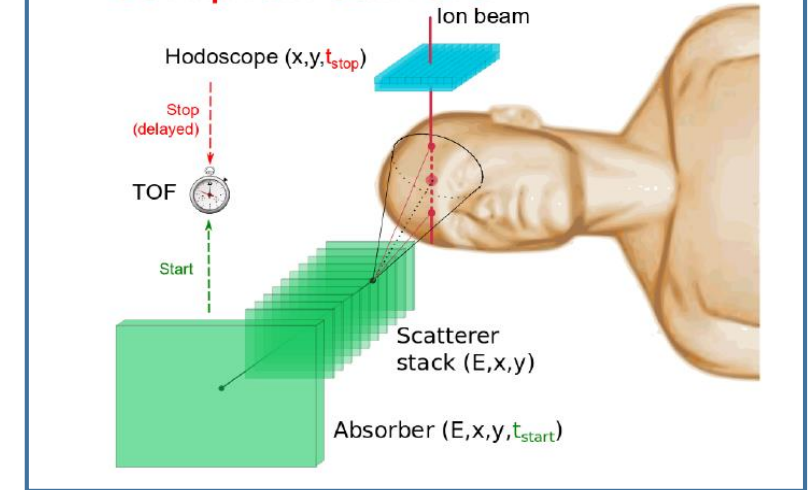
CLaRyS



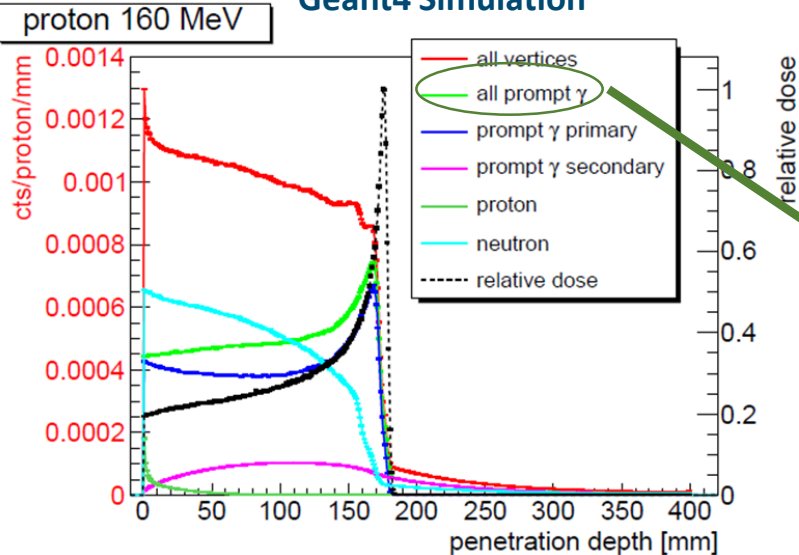
Multi-slit camera



Compton camera



Geant4 Simulation



Gamma Prompt Imaging

Beam tagging hodoscope for online ion range verification in hadrontherapy

Prompt Gamma detection

CLaRyS

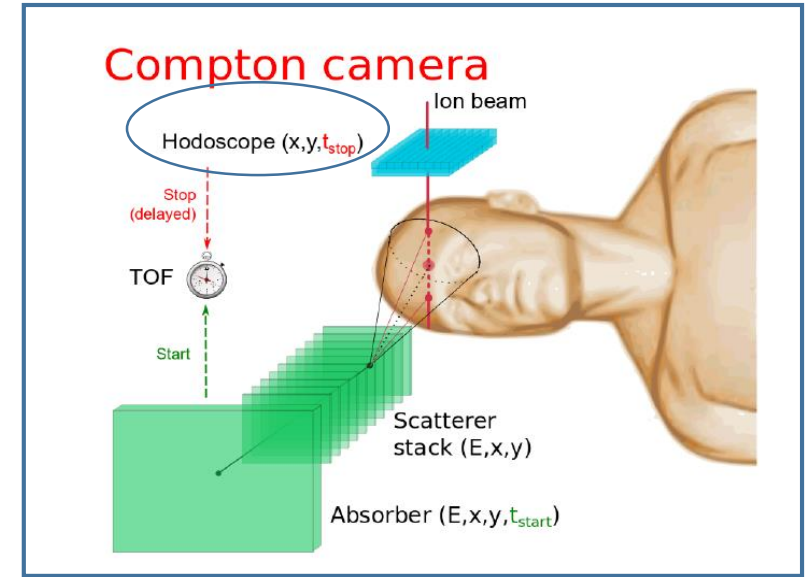
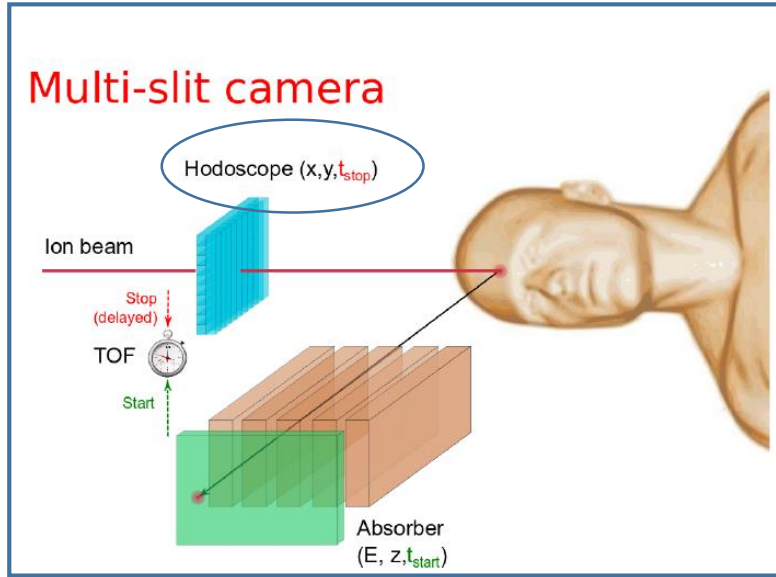
Gamma Prompt Imaging

Hodoscope Existing development :

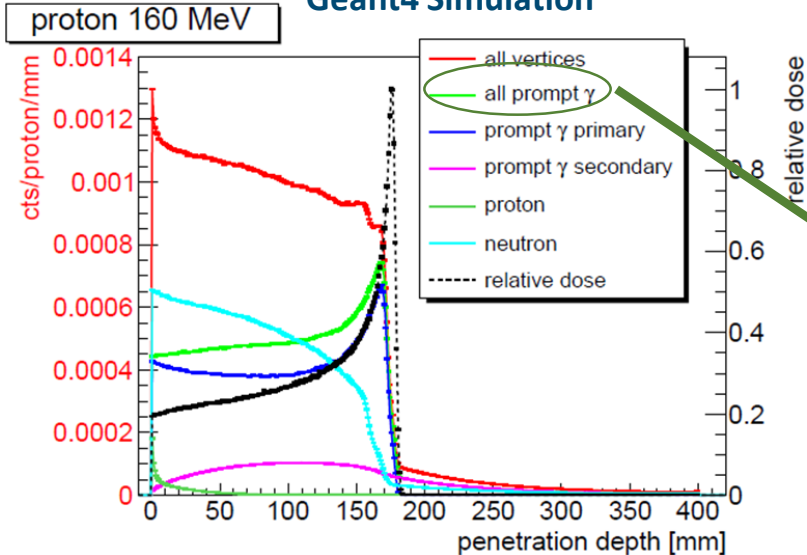


← Array of scintillating fibres + multichannel PMT

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



Geant4 Simulation



Gamma Prompt Imaging

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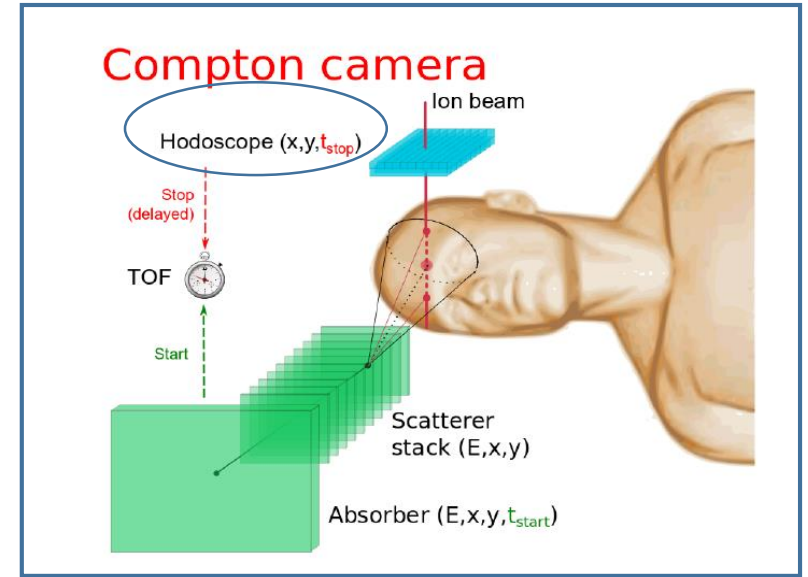
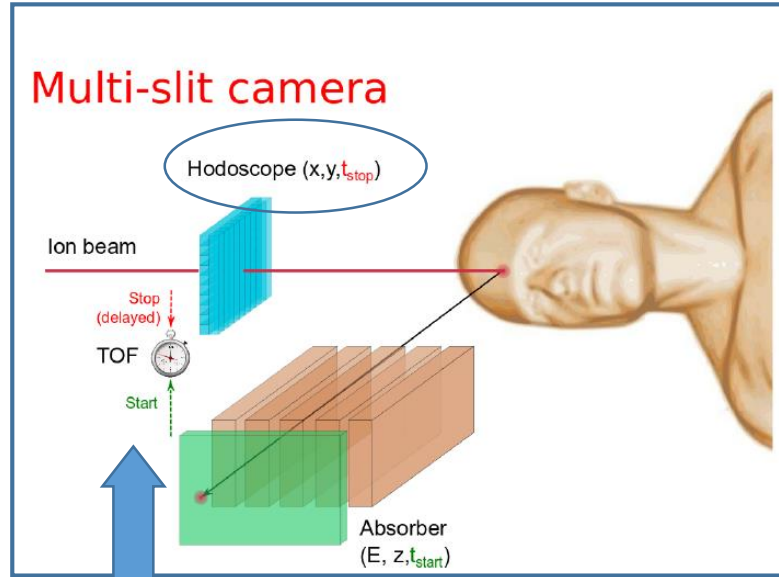
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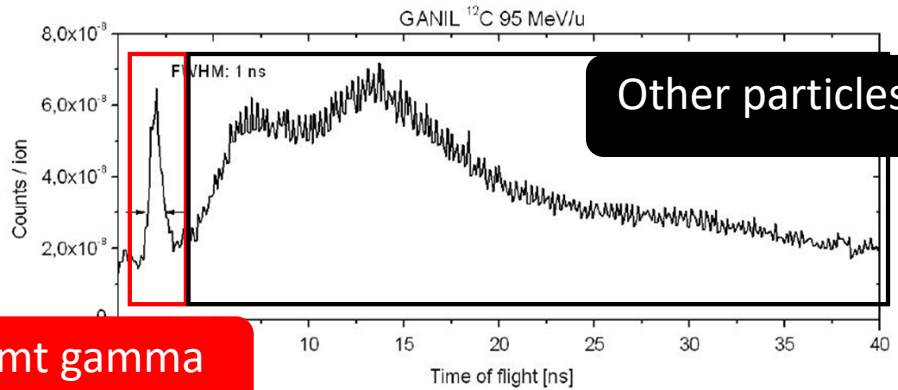
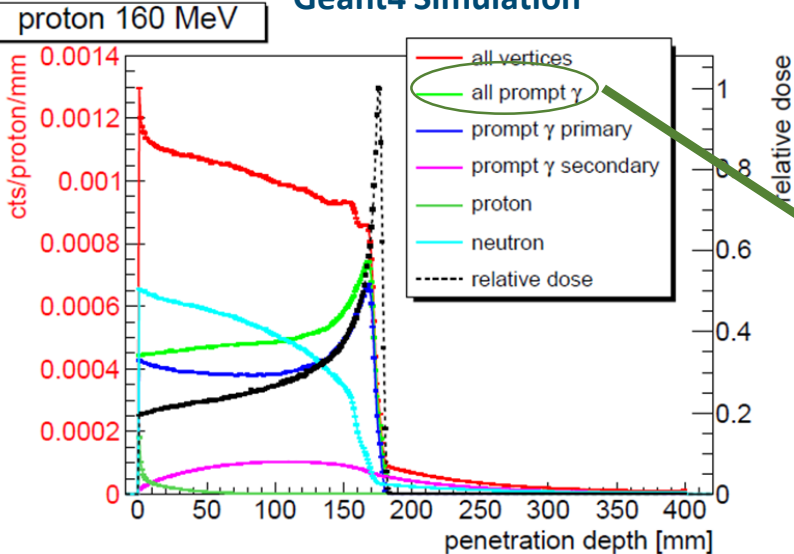
Array of scintillating fibres + multichannel PMT

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



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

Geant4 Simulation



Prompt gamma

Mauro Testa, Thèse, Univ. Lyon, 2010

ML Gallin-Martel VHEE conference

Beam tagging hodoscope for online ion range verification in hadrontherapy

Prompt Gamma detection

CLaRyS

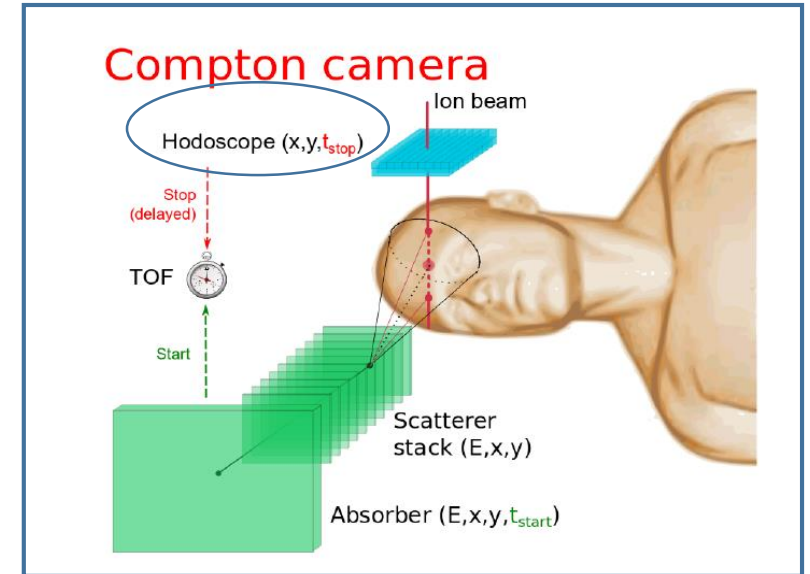
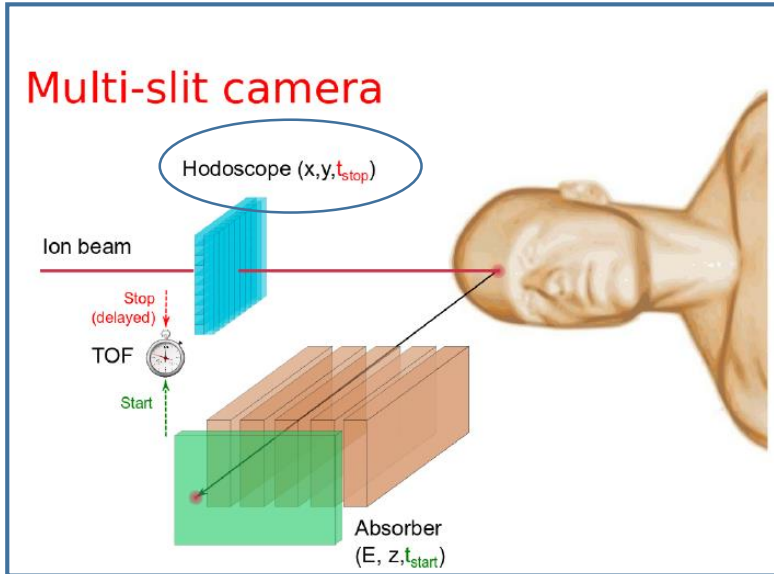
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Limitations :

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

Beam tagging hodoscope for online ion range verification in hadrontherapy

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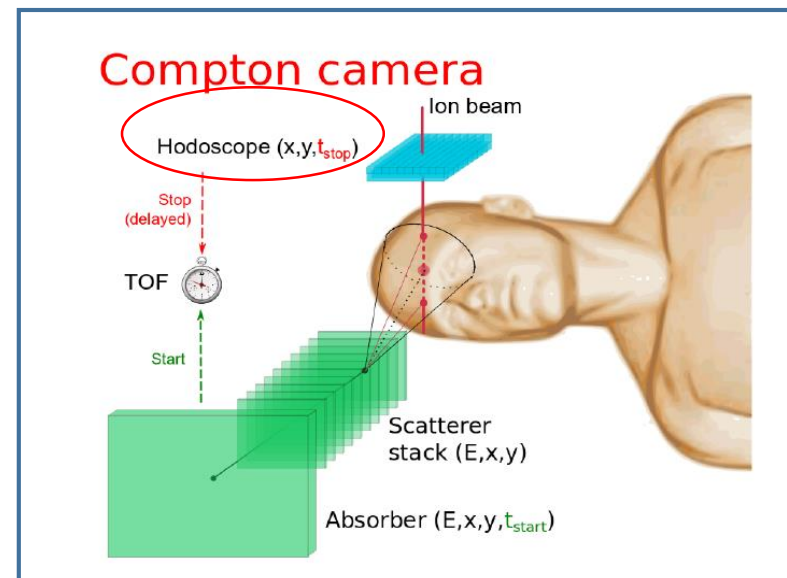
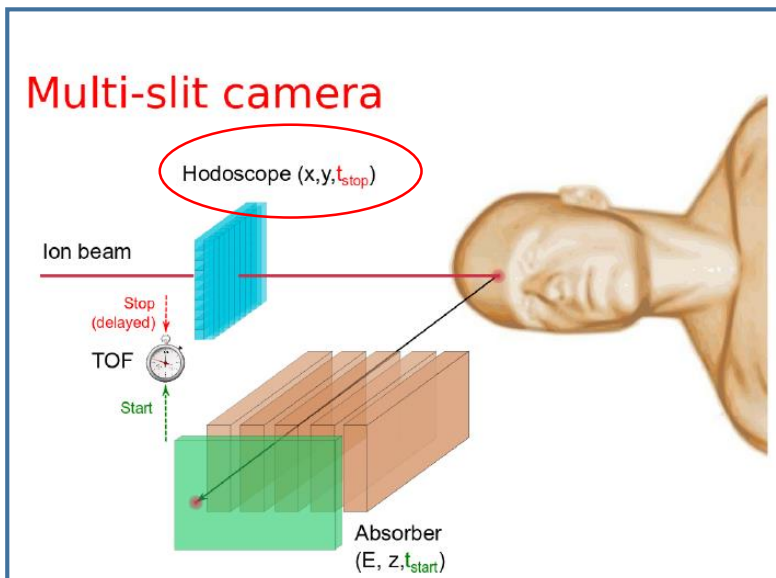
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CLaRyS-Ultra-Fast Timing : 100 ps resolution using diamond

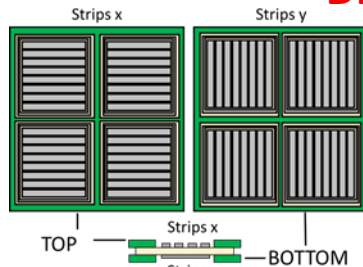
CLaRyS-UFT : S. Curtoni 2017-2020 PhD

→ Imaging based on Time of Flight

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



Diamond hodoscope



ML Gallin-Martel VHEE conference

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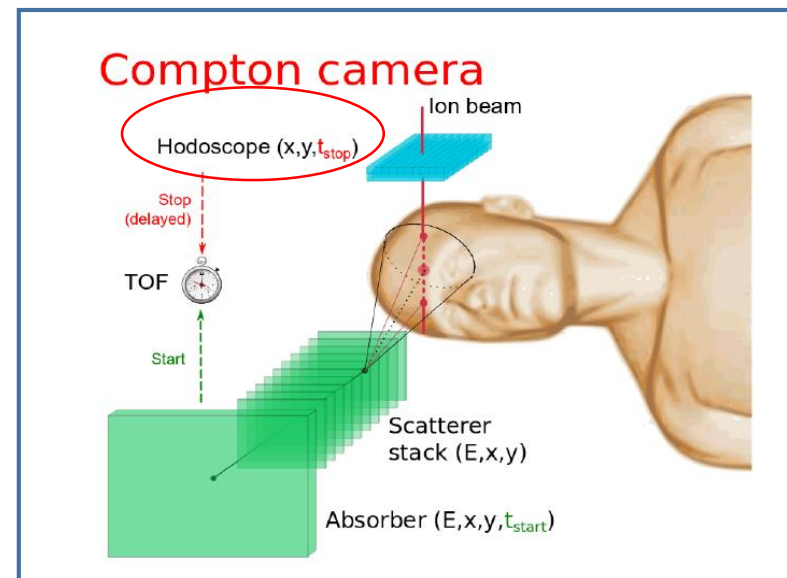
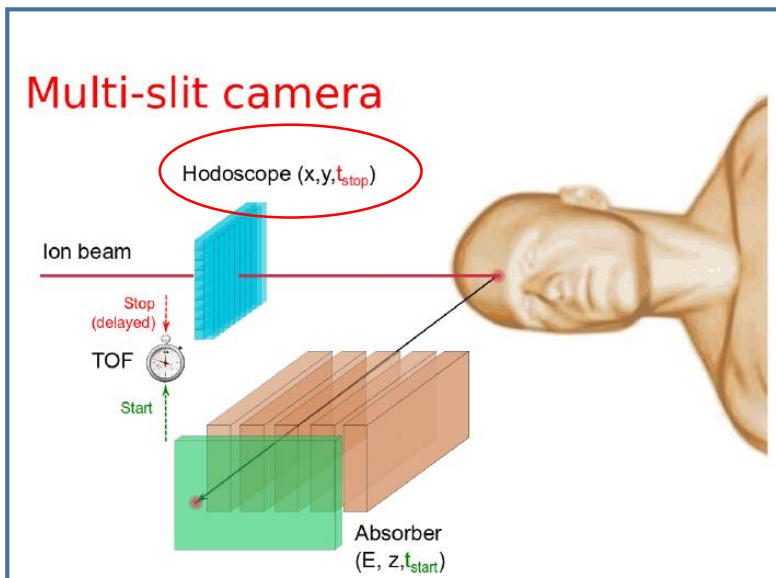
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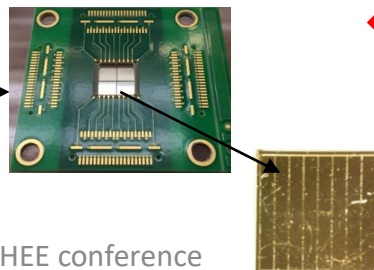
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Diamond hodoscope



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CLaRyS

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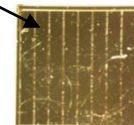
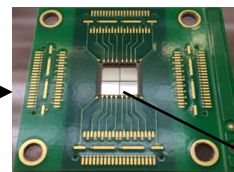
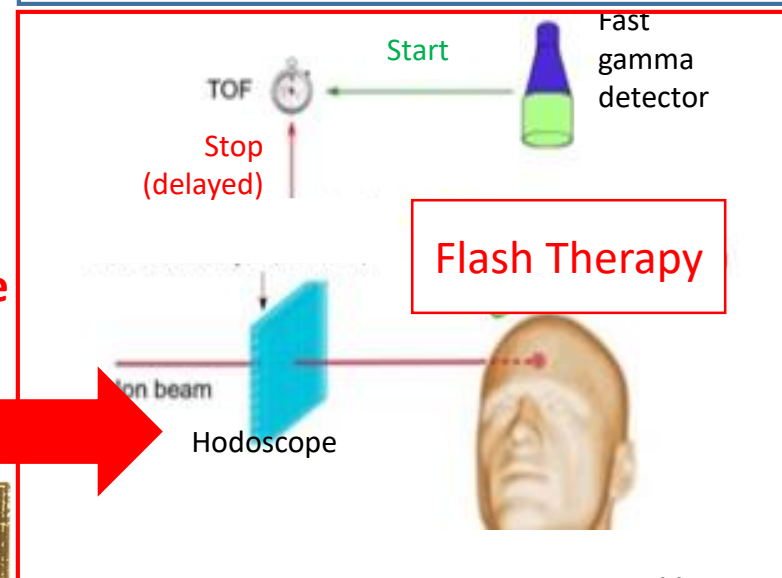
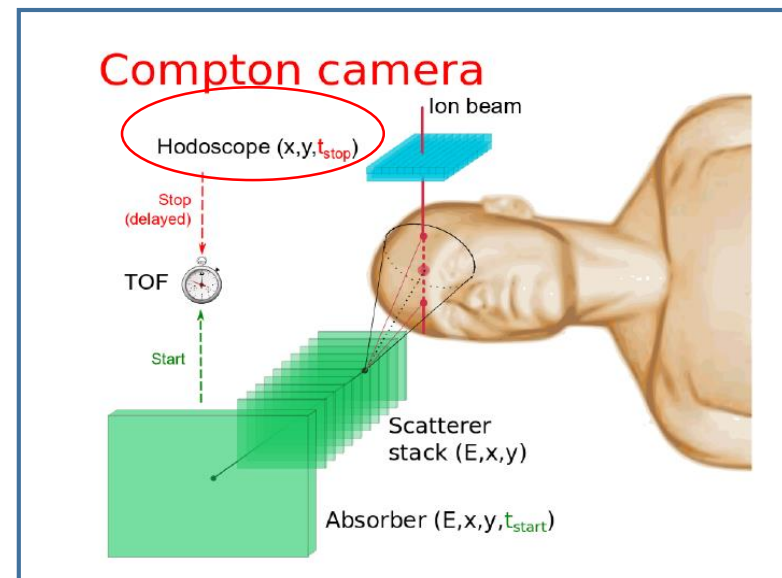
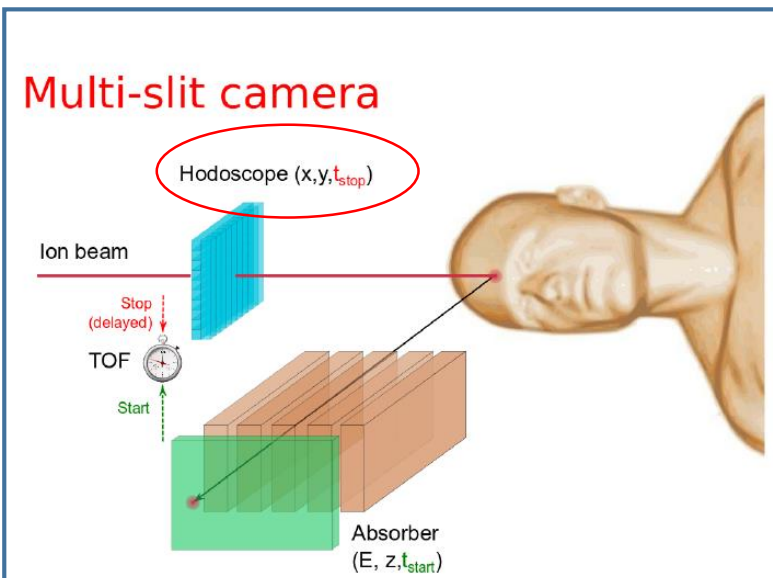
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→ Imaging based on Time of Flight

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

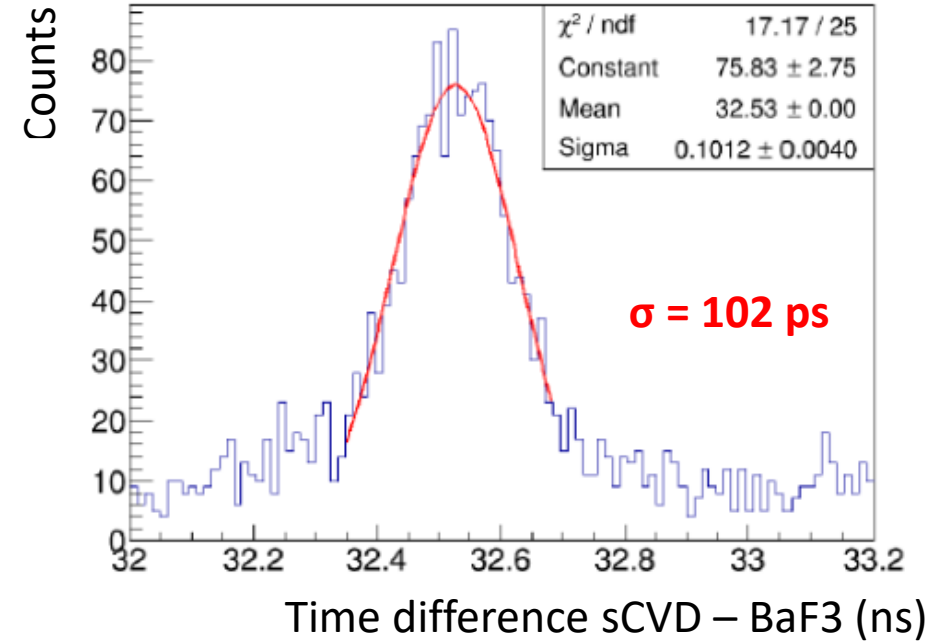
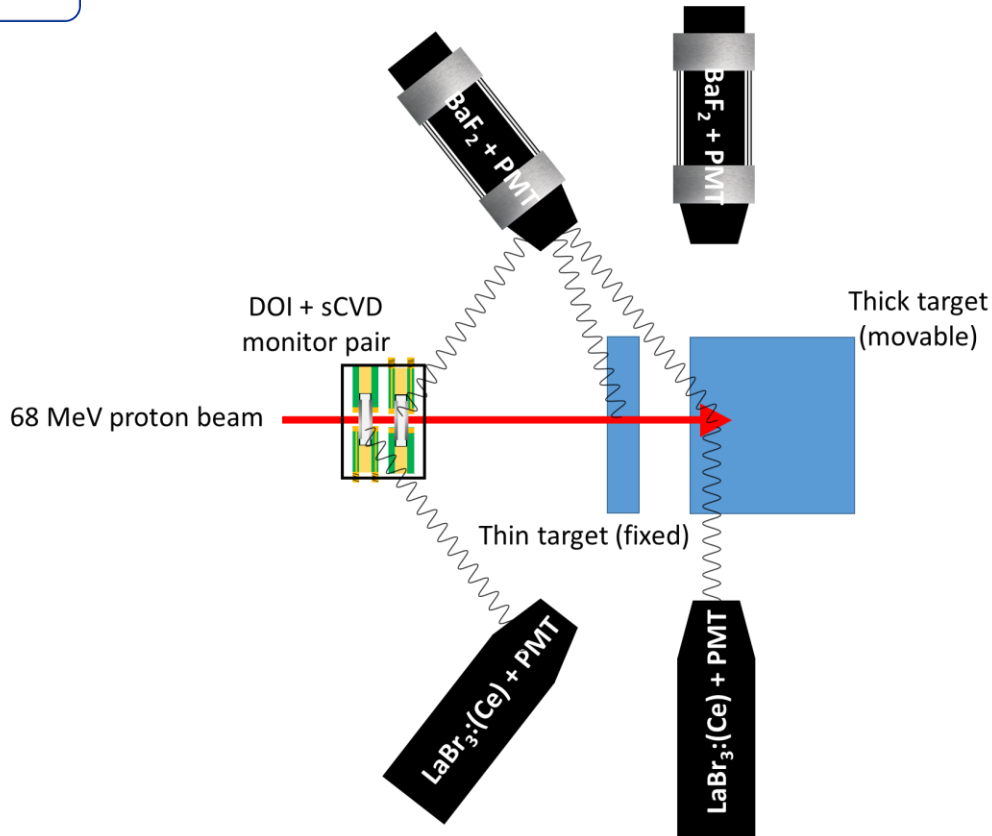


Diamond hodoscope

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. Curtioni PhD thesis

S. Marcatili et al, PMB 2020

Outlines

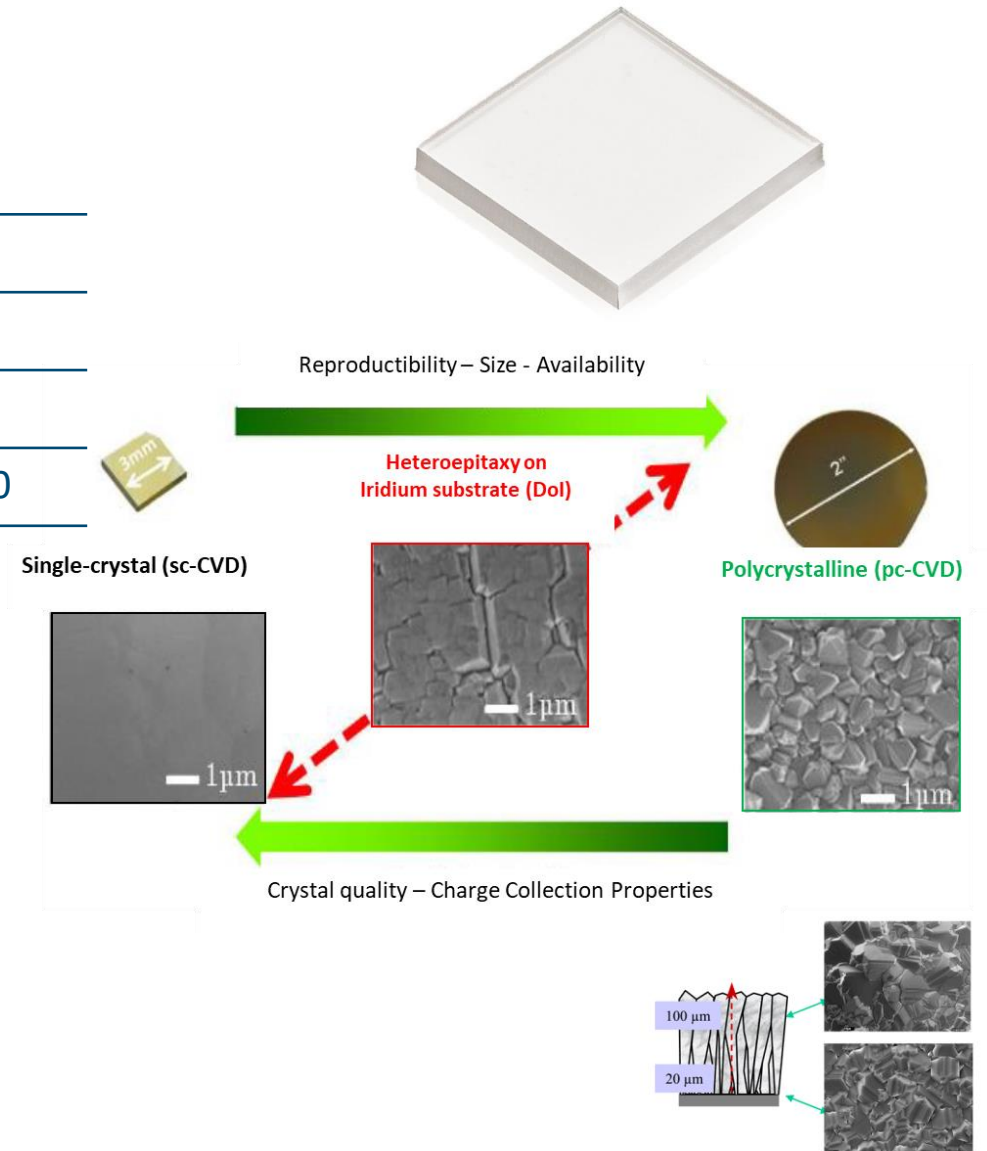
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Diamond a wide-bandgap semiconductor

Characteristics @ 300 K

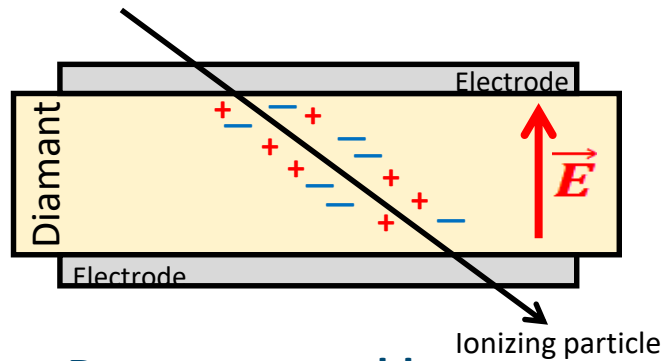
	Diamond	Silicon
Resistivity ($\Omega.m$)	$> 10^{13}$	$2.3 \cdot 10^7$
Gap (eV)	5.5	1.1
e ⁻ /h creation energy (eV)	13.1	3.6
Displacement energy (eV)	43	25
Charge carriers mobility ($cm^2.V^{-1}.s^{-1}$)	> 2000	800 – 1400
Thermal conductivity ($W.cm^{-1}.K^{-1}$)	18	2

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

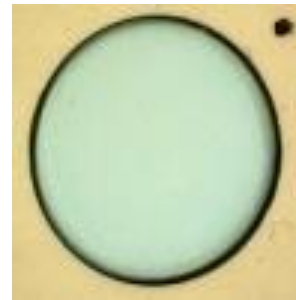
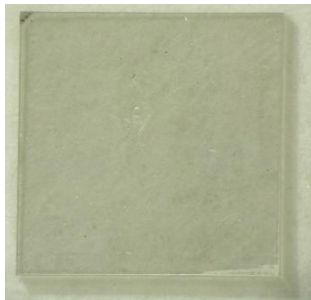


Diamond Sensor Instrumentation for test @ lab or in beam

Solid state ionization chamber

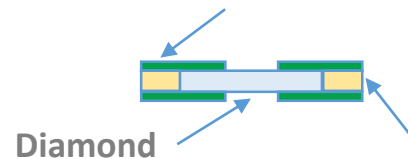


Detector assembly



3 cm

PCB 50Ω adapted



Diamond

Spacer

Read-out electronics

- Fast current preamplifier

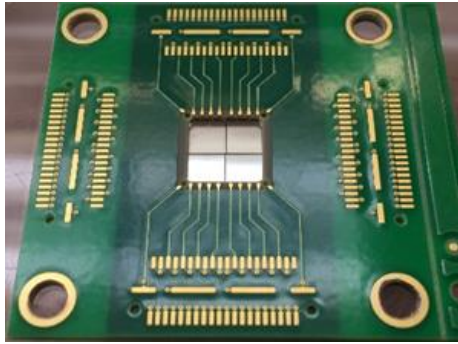


Band Width:	2 GHz
Gain:	40 dB
Impedance:	50 Ω
Dynamic range:	~ +/- 1 V
Power Supply:	12 V / 100 mA

+ for other application :

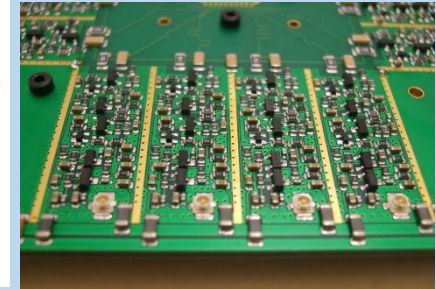
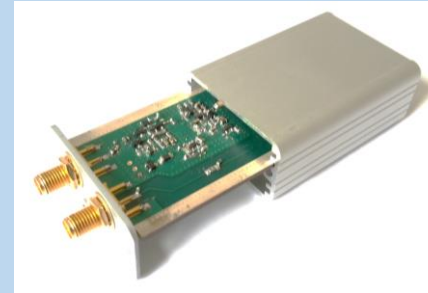
- Charge preamplifier
- Electrometer

Diamond hodoscope Instrumentation



R&T IN2P3 DIAMTECH + ANR DIAMMONI 2020

Fast preamps + QDC in discrete electronics

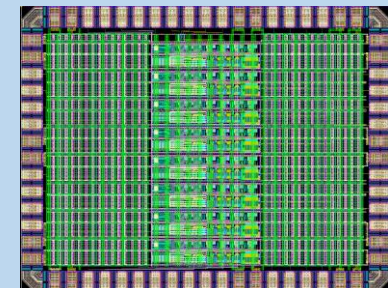
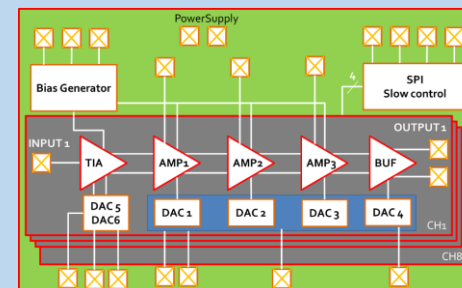


R&T IN2P3 DIAMASIC

LPSC - LPC Caen

ASIC Preamps +TDC+ QDC

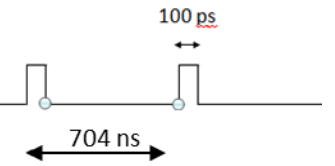
- CMOS 130 nm (CERN)
- Radiation tolerant



Beam tests XBIC @ESRF – 2D current response map

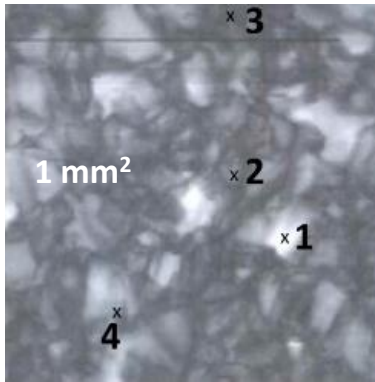
Tests at ESRF with 8.5 keV photons = XBIC source

Xray Beam Induced Current = XBIC

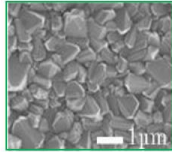


Poly-crystalline E6

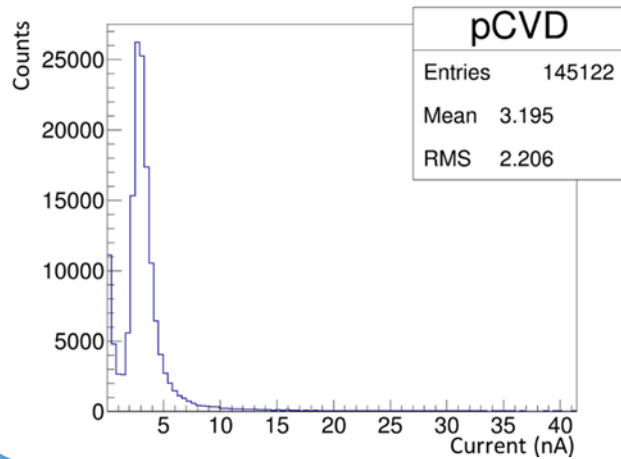
10 x 10 mm² x 500 μm pc-CVD



Polycrystalline (pc-CVD)

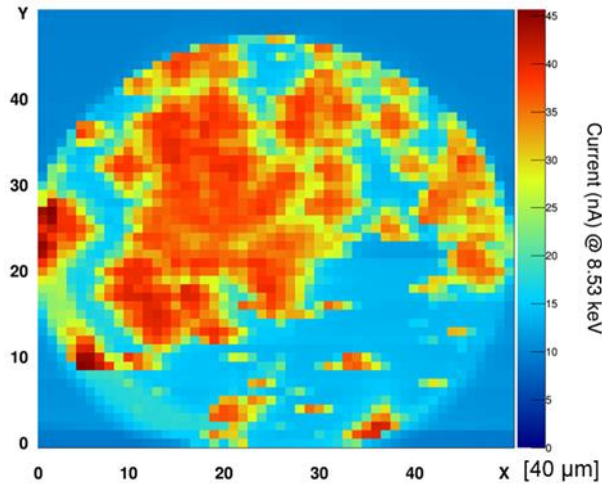


Reflects spatial distribution of grain boundaries

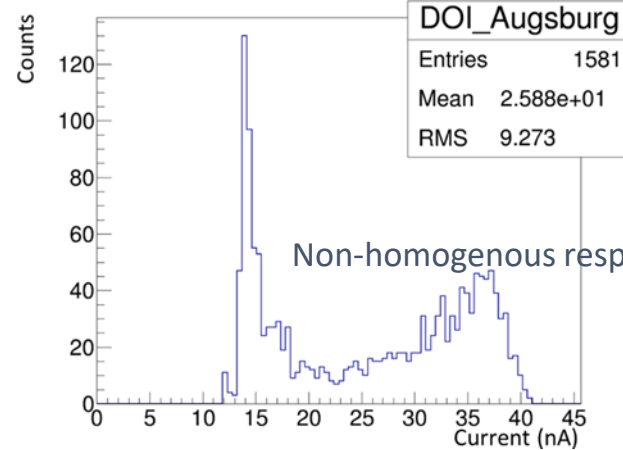
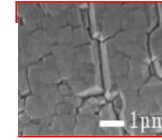


DOI AuDiaTec

5 x 5 mm² x 300 μm DOI-CVD



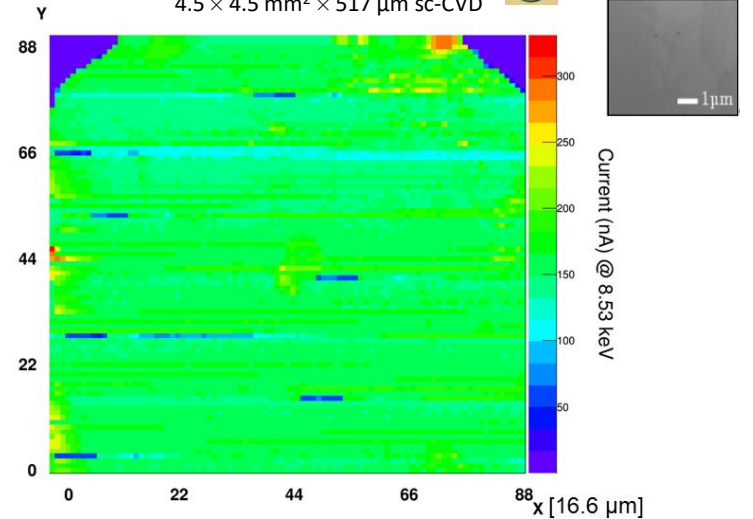
Heteroepitaxy on Iridium substrate (DOI)



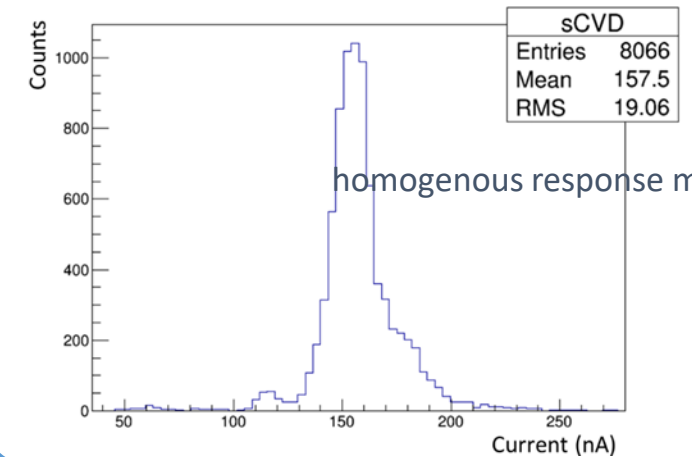
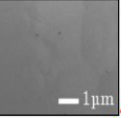
Non-homogenous response map

Single-crystal E6

4.5 x 4.5 mm² x 517 μm sc-CVD



Single-crystal (sc-CVD)

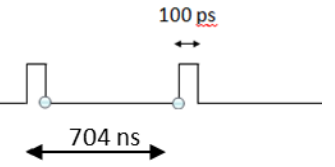


homogenous response map

Beam tests XBIC @ESRF – 2D current response map

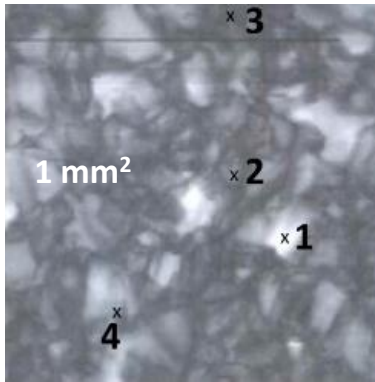
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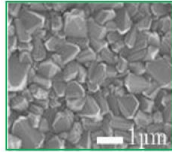


Poly-crystalline E6

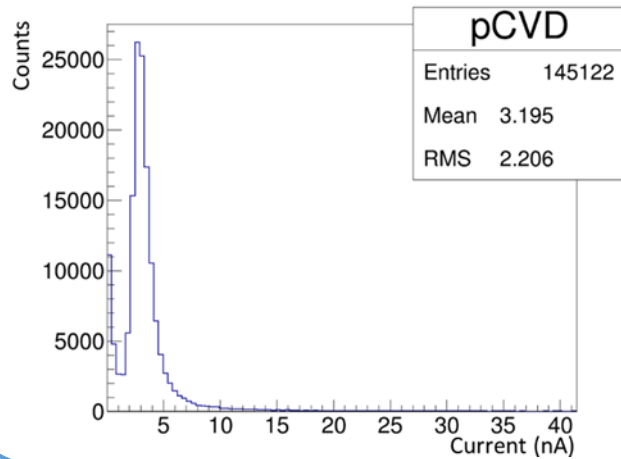
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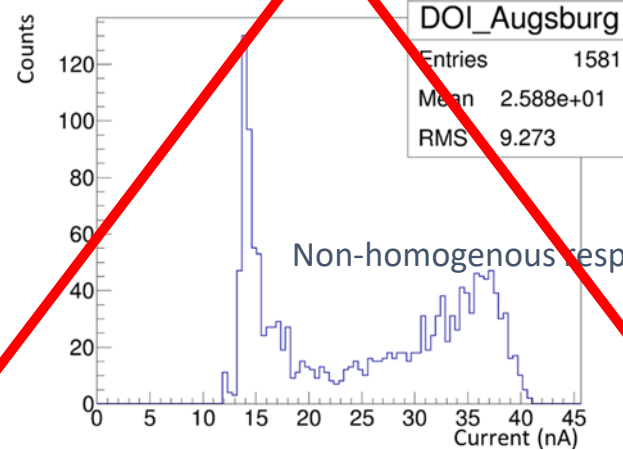
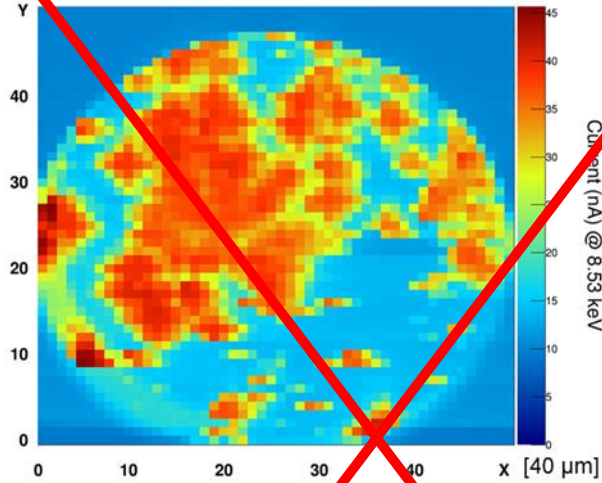


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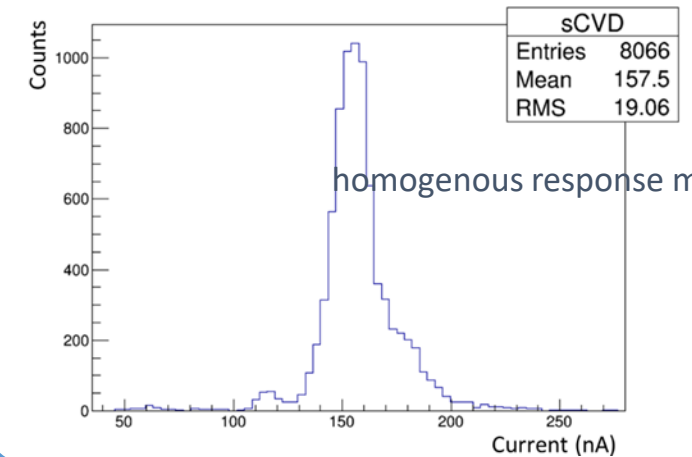
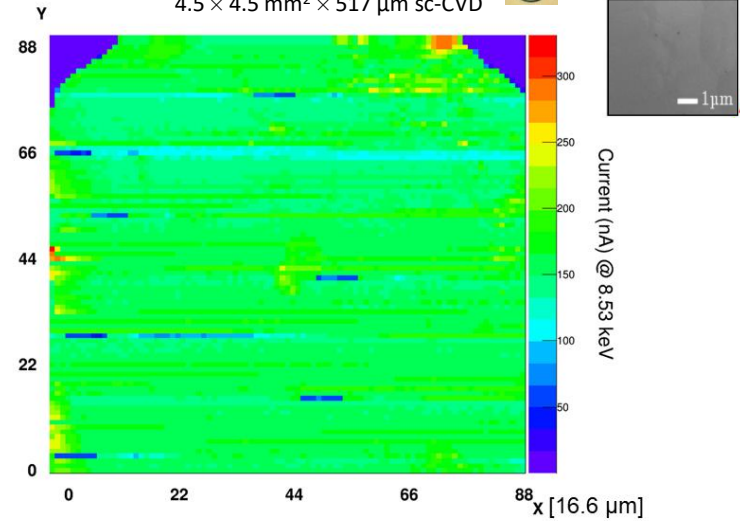
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IDSYNCHRO 2020-2023 (R&T IN2P3 DIAMTECH)

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

Fluence measurement in Micro-beam Radiation Therapy

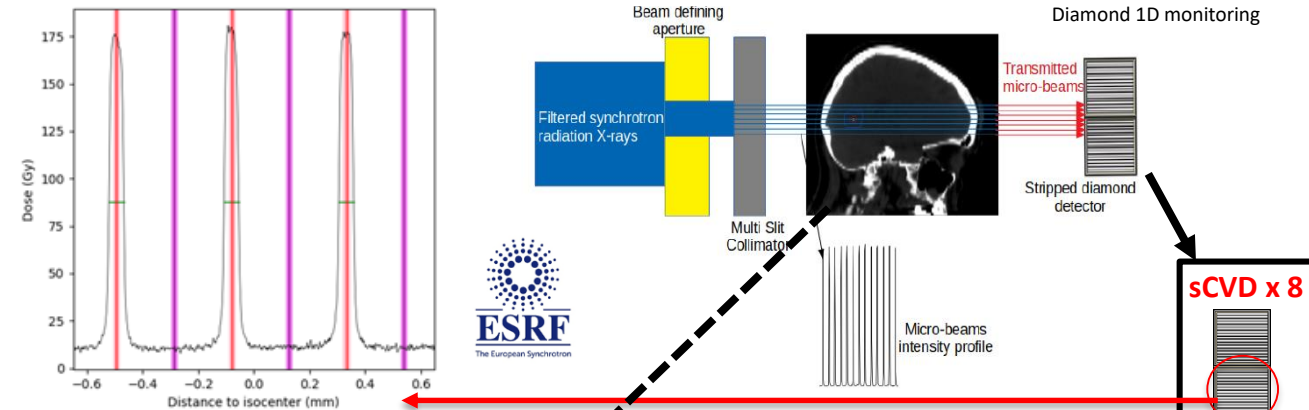
Collaborations :

- LPSC (IN2P3), STROBE (Université Grenoble Alpes INSERM)
- ESRF medical beam line ID17

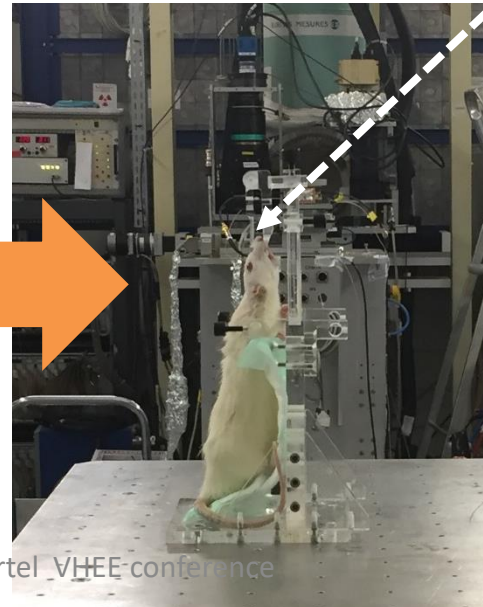
Synchrotron radiation on-line monitoring

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

N. Rosuel PhD thesis (2018-2021)



MRT: 50 μ m
Micro Beam Radiation Therapy

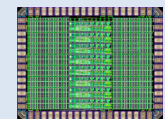
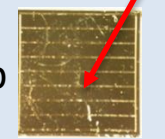


Strips on diamond to satisfy MRT beam structure

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

+

elec FE = QDC ASIC LPSC



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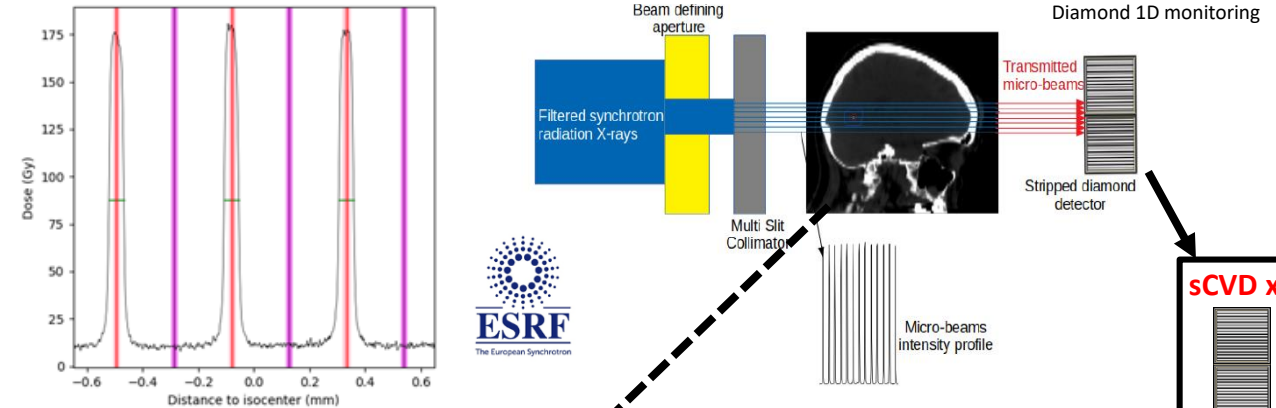
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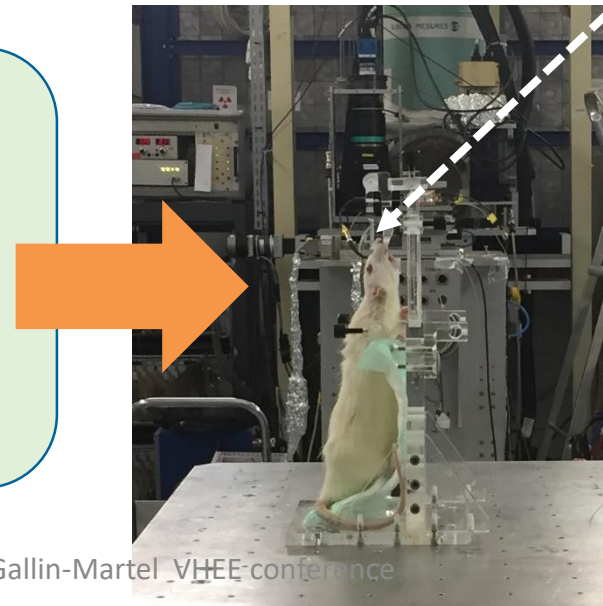
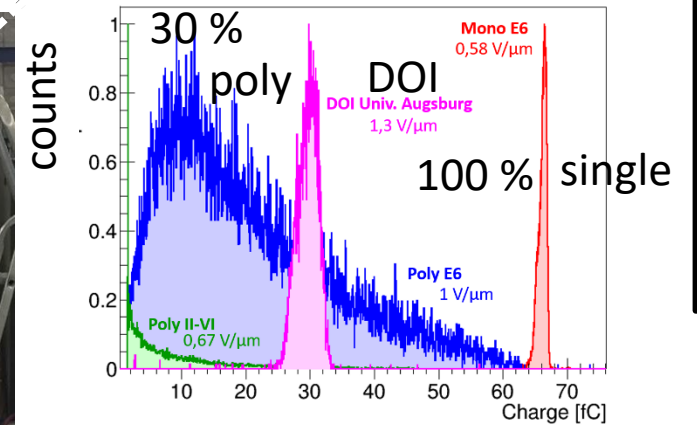
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MRT: 50 μ m
 Micro Beam Radiation Therapy

Why sCVD ?



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

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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

Fluence measurement in Micro-beam Radiation Therapy

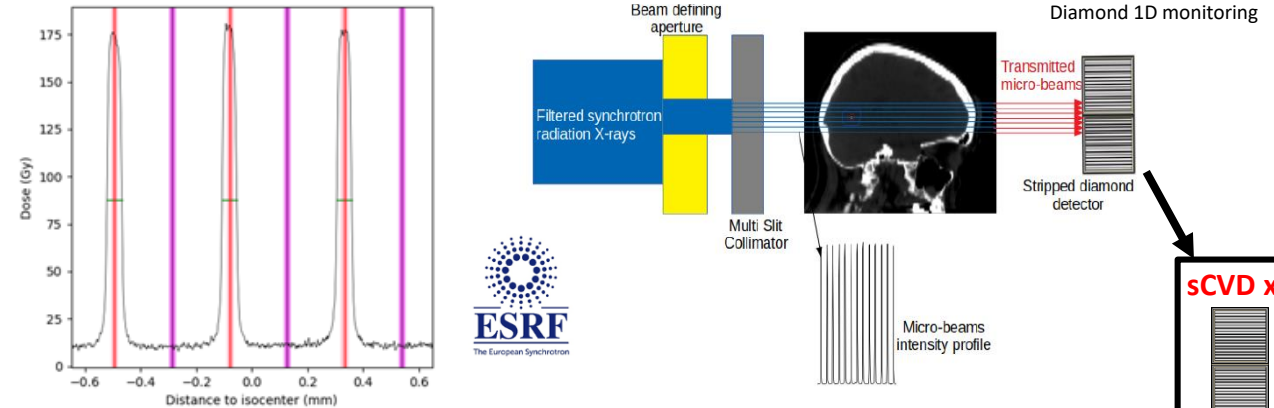
Collaborations :

- LPSC (IN2P3), STROBE (Université Grenoble Alpes INSERM)
- ESRF medical beam line ID17

Synchrotron radiation on-line monitoring

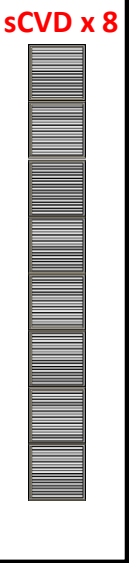
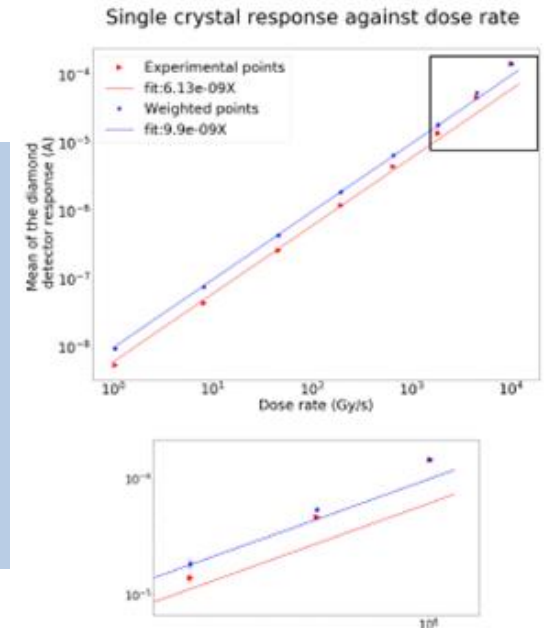
- ➔ X-Rays detection
- ➔ Spatial (micro beams)
- ➔ Huge dynamique (High dose rate)

N. Rosuel PhD thesis (2018-2021)



MRT: 50 μ m
Micro Beam Radiation Therapy

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



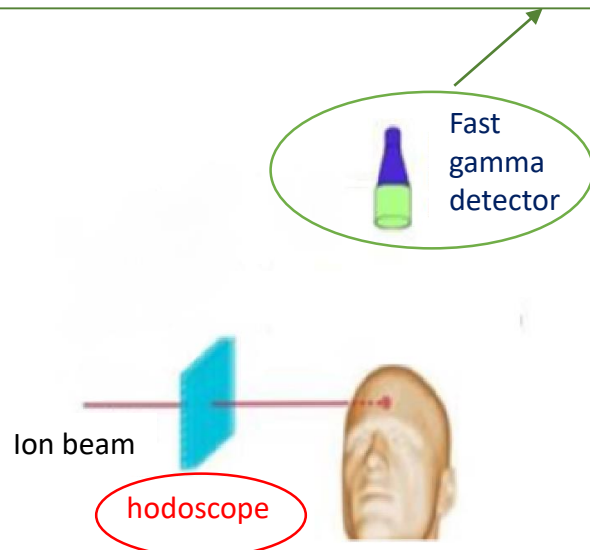
Outlines

- 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

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

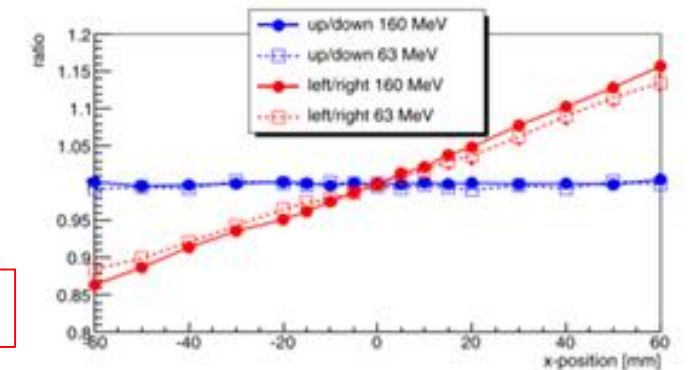
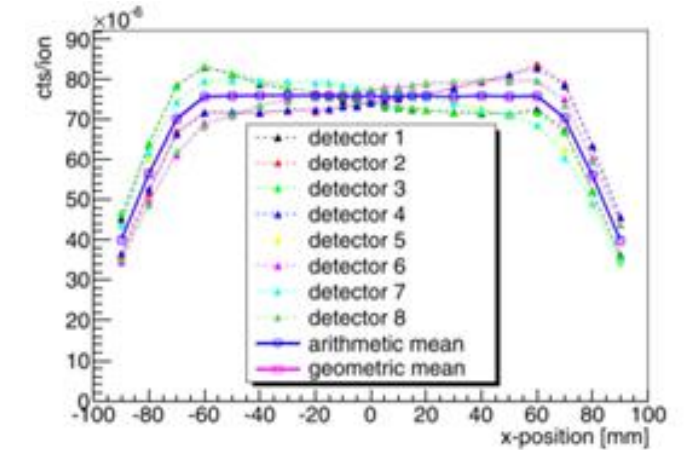
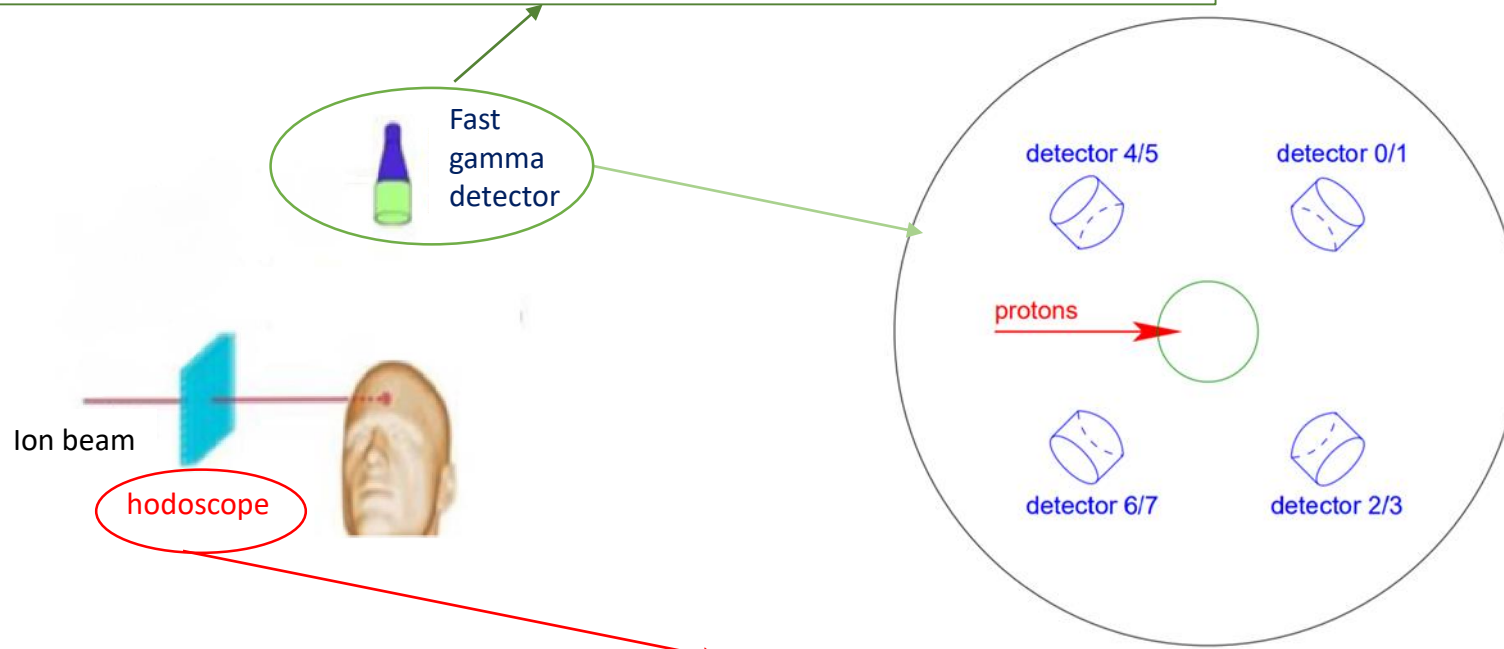


Collaboration LPSC SUBATECH ARRONAX : ANR DIAMMONI + R&T transverse DIAMTECH

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

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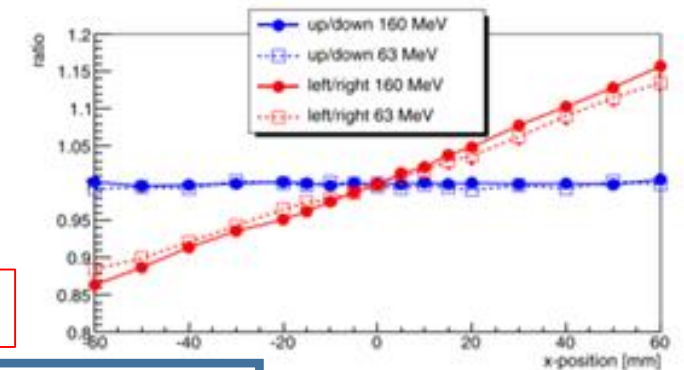
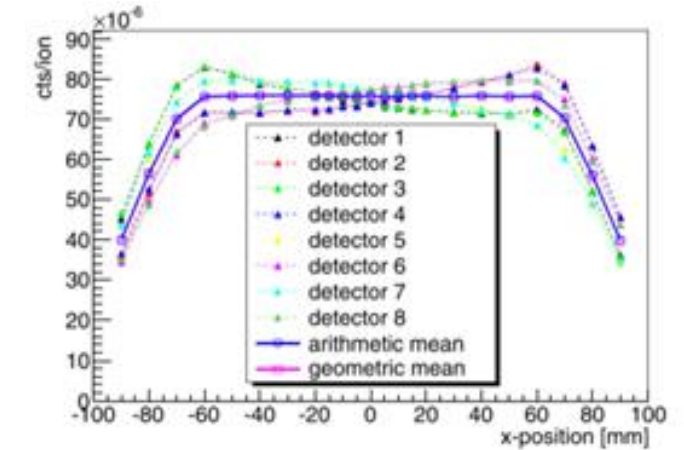
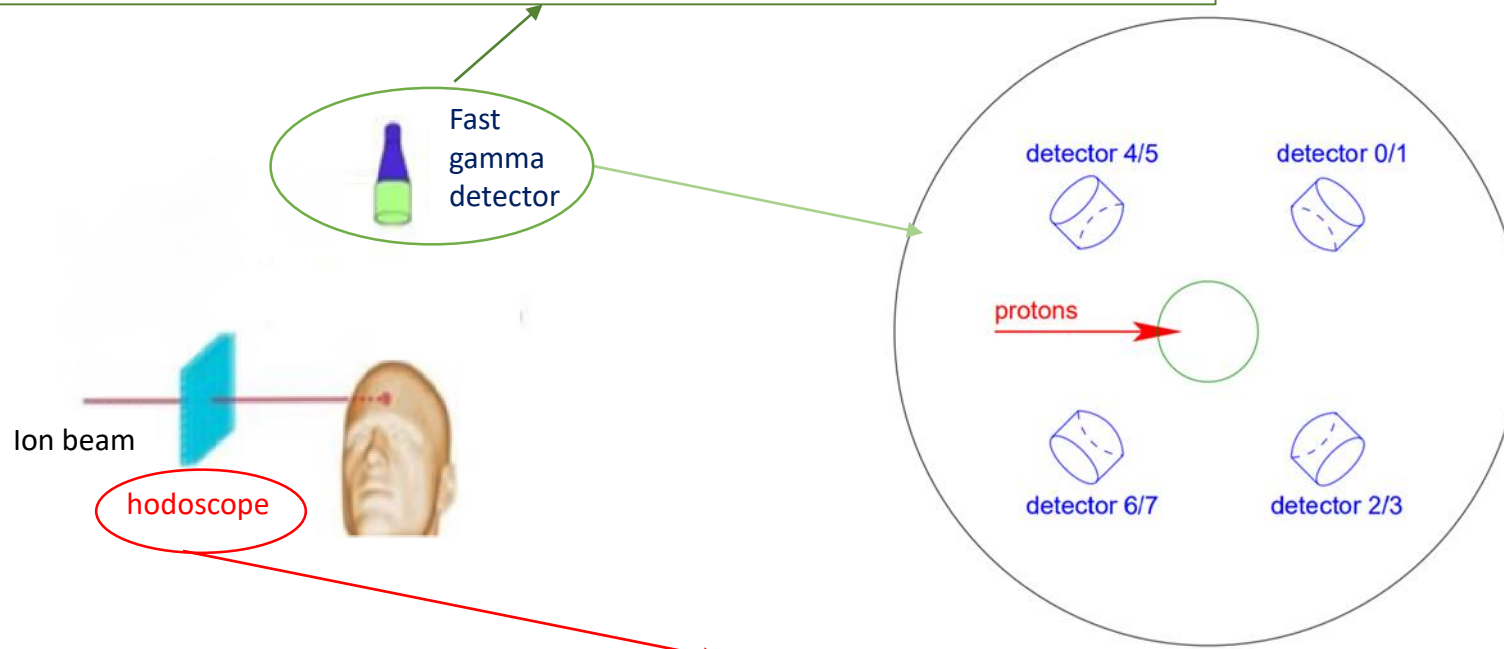
[Krimmer 2017](#)

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

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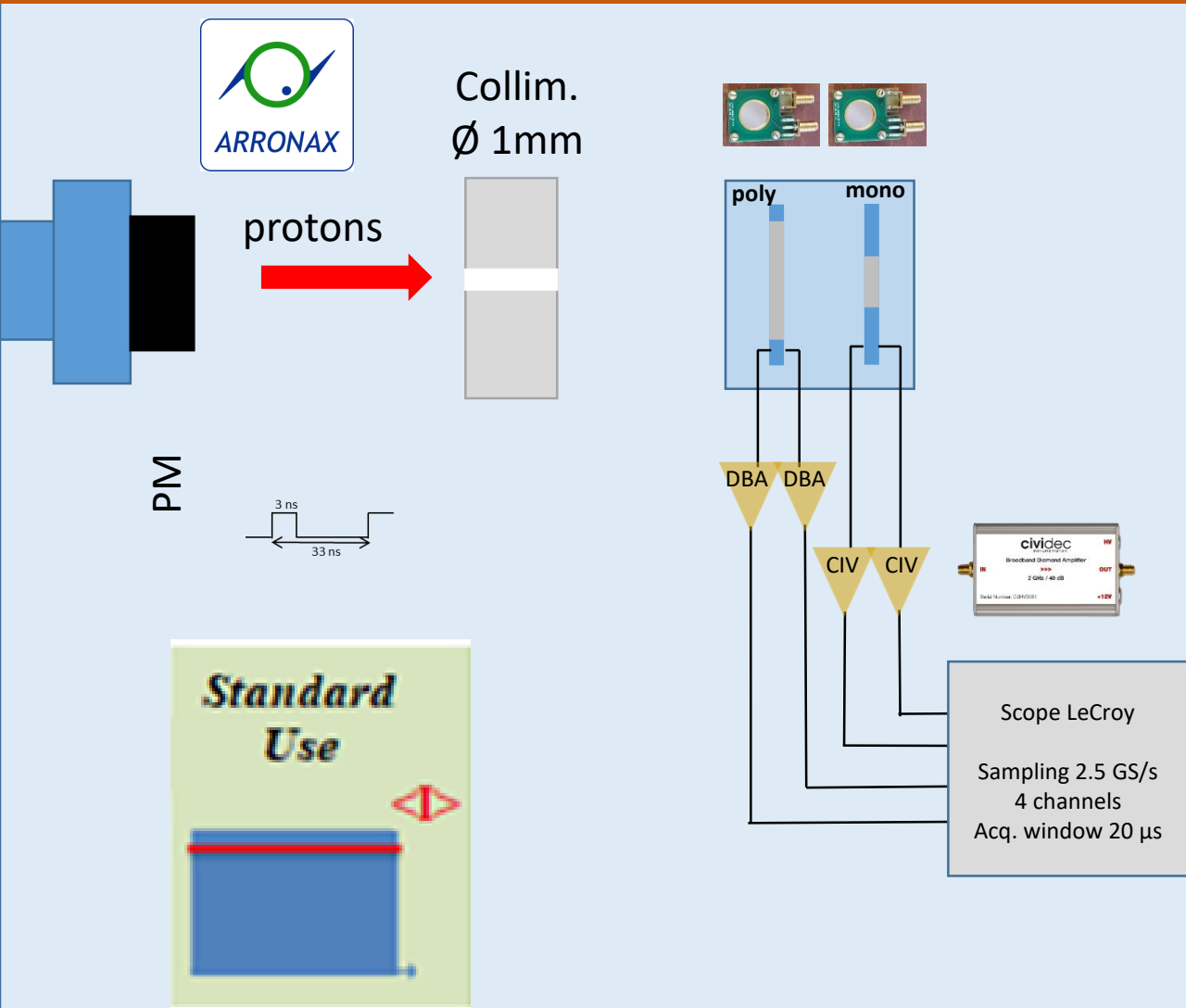


[Krimmer 2017](#)

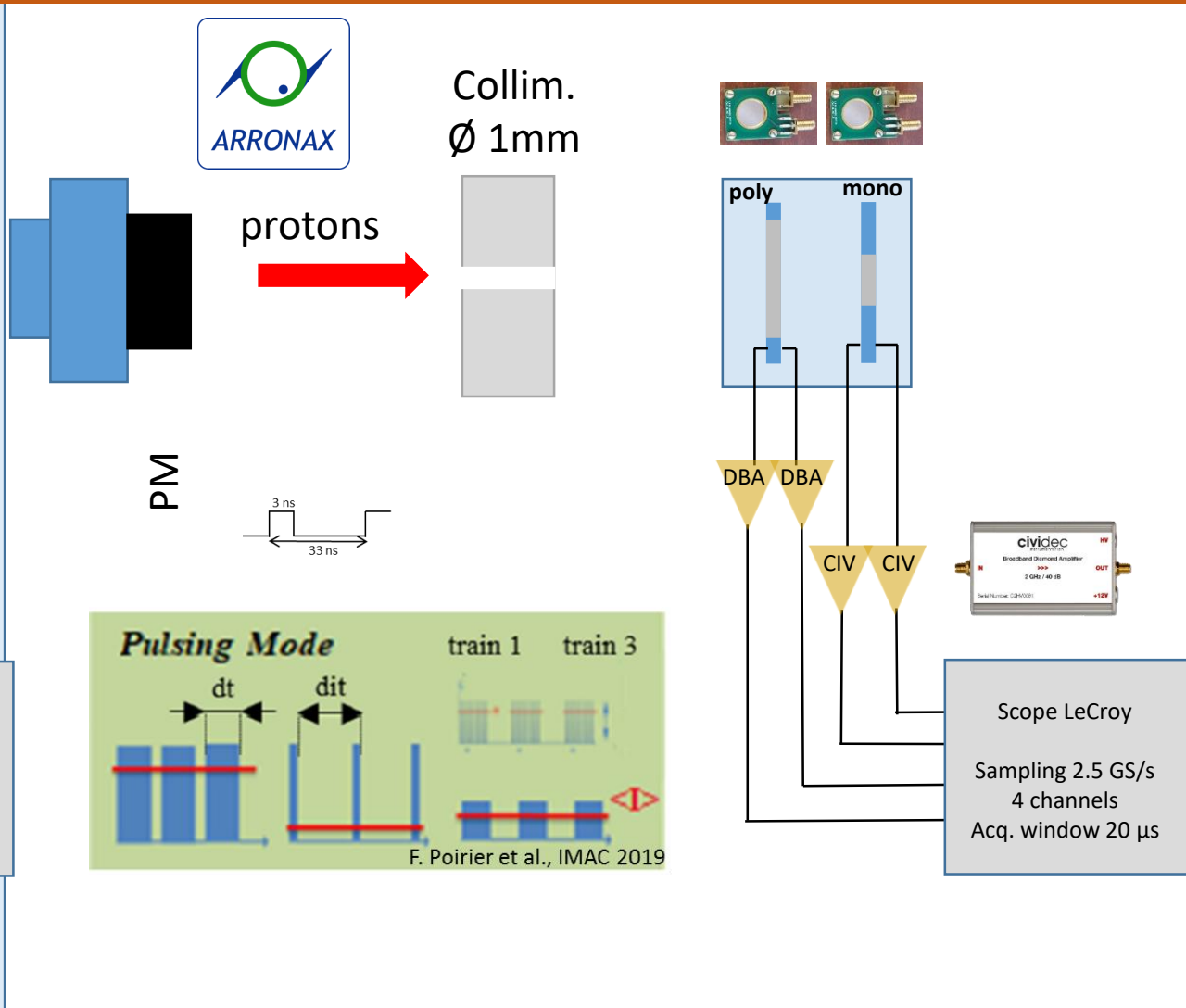
Collaboration LPSC SUBATECH ARRONAX : ANR DIAMMONI + R&T transverse DIAMTECH

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)



Continuous mode



Pulsed mode => Flash Thérapy !

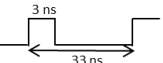
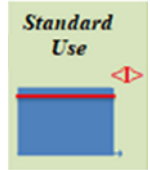
DIAMMONI 2020-2024 (ANR + R&T IN2P3 DIAMTECH)



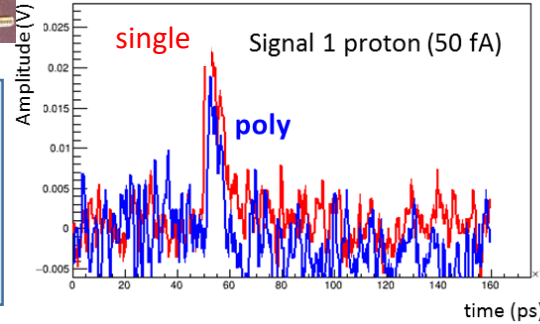
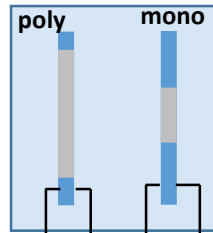
Particle counting vs I_{beam} : preliminary measurement

Collim.
Ø 1mm

protons



PM



DBA DBA

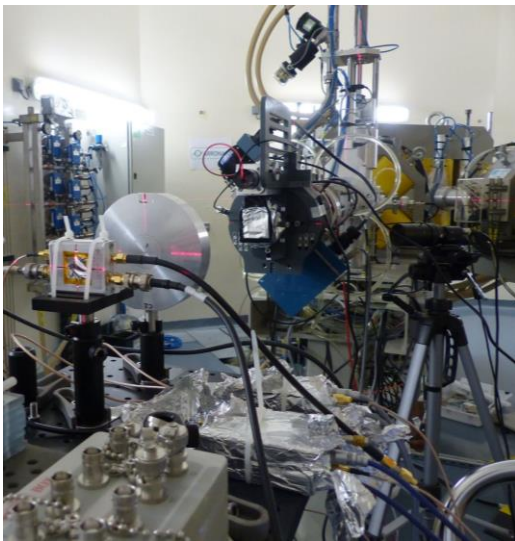
CIV CIV



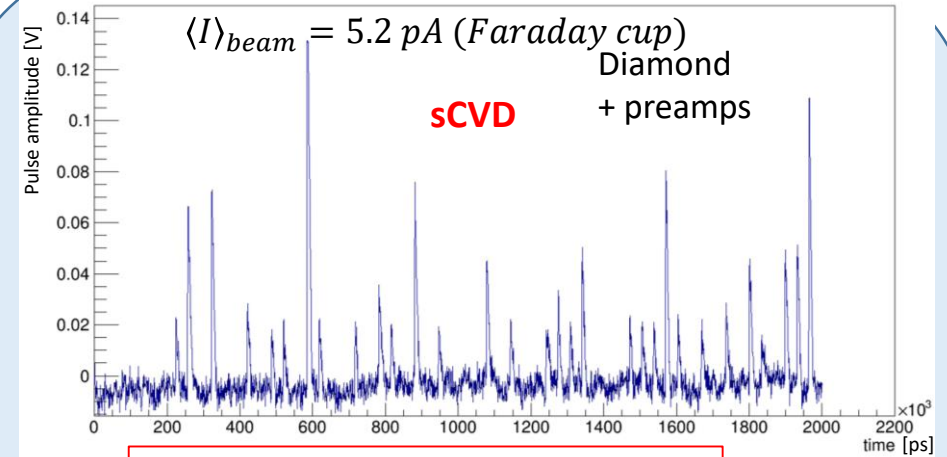
Scope LeCroy

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

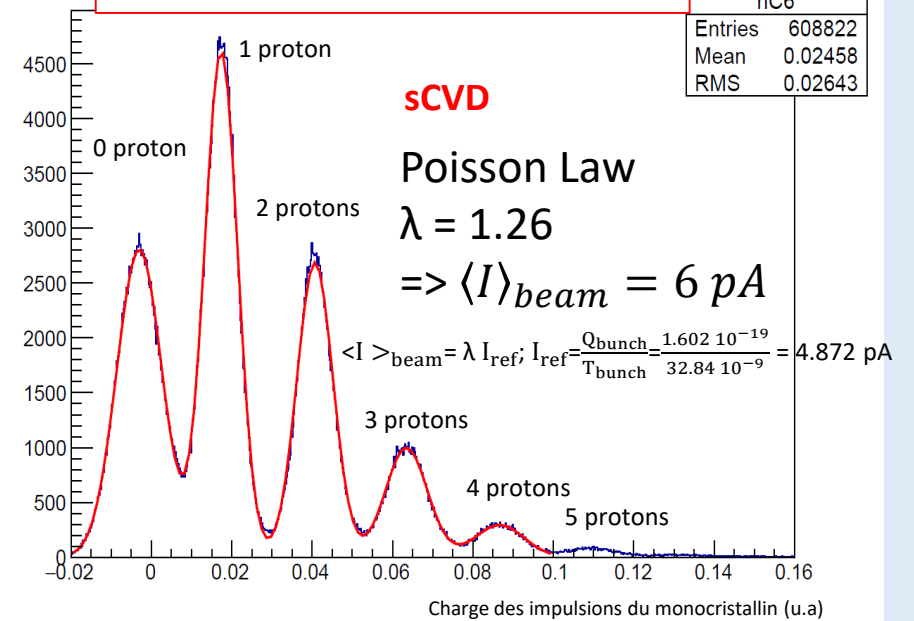
Continuous mode and reduced intensity



5-7 October 2020 IJCLab



Particle counting in bunches



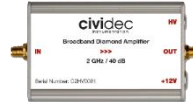
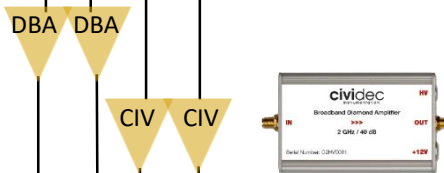
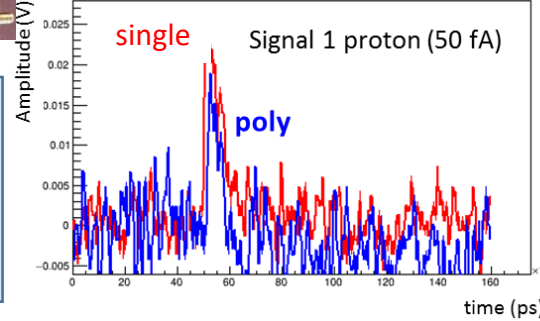
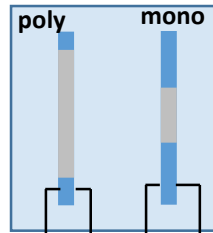
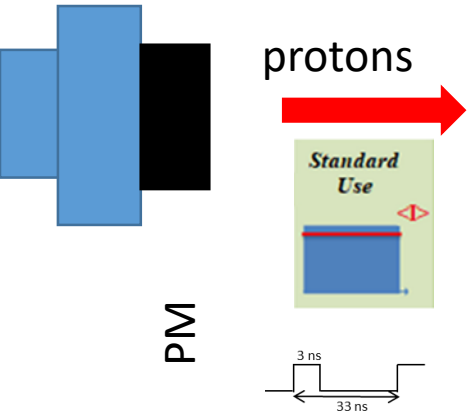
Proton counting in nano pulse

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



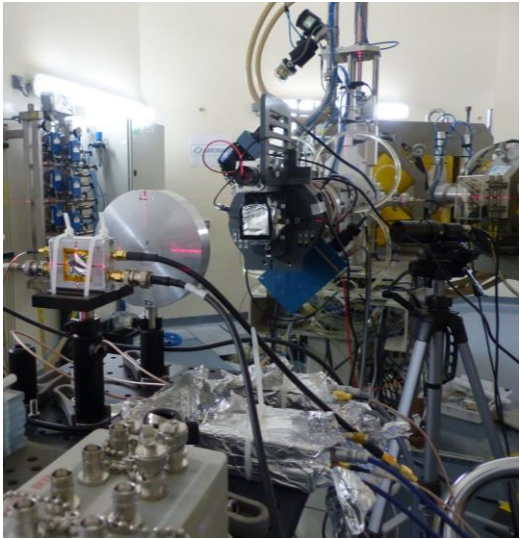
Particle counting vs I_{beam} : preliminary measurement

Collim.
Ø 1mm

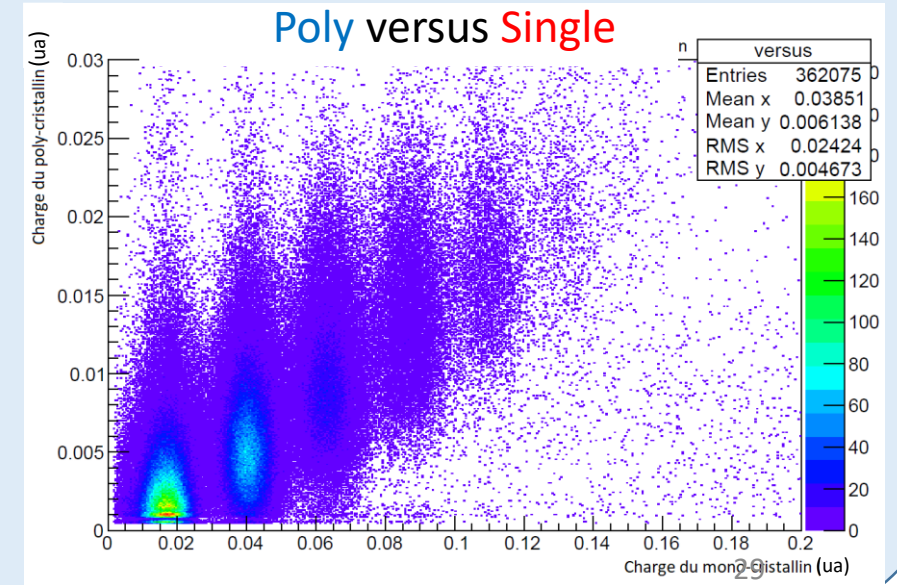
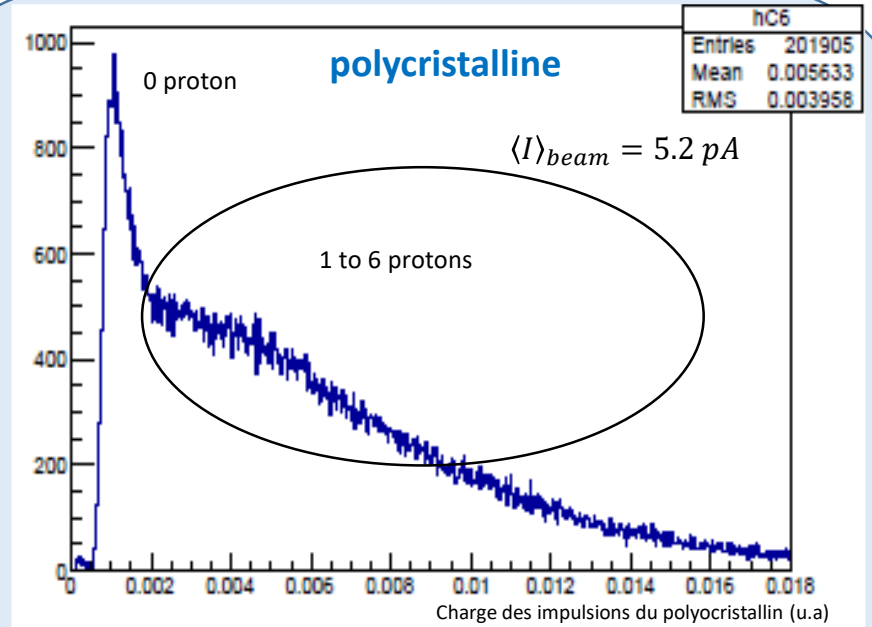


Scope LeCroy
Sampling 2.5 GS/s
4 channels
Acq. window 20 µs

Continuous mode and reduced intensity



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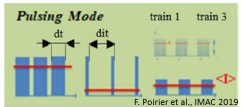
DIAMMONI 2020-2024 (ANR + R&T IN2P3 DIAMTECH)



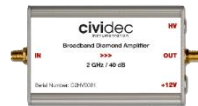
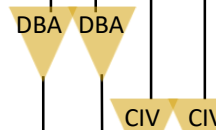
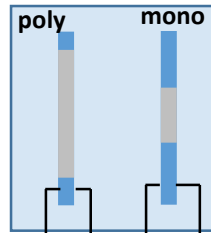
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Collim.
Ø 1mm

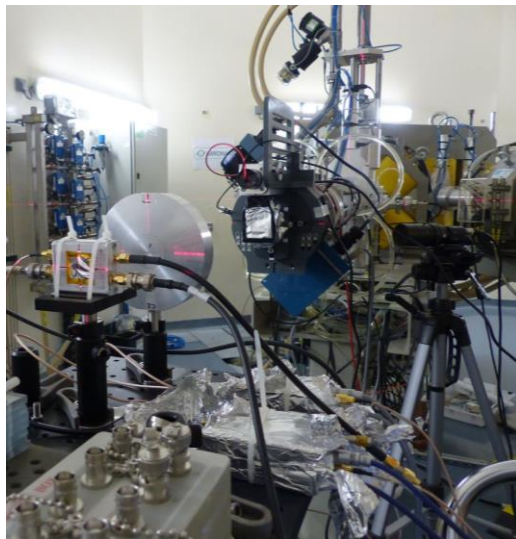
protons



PM

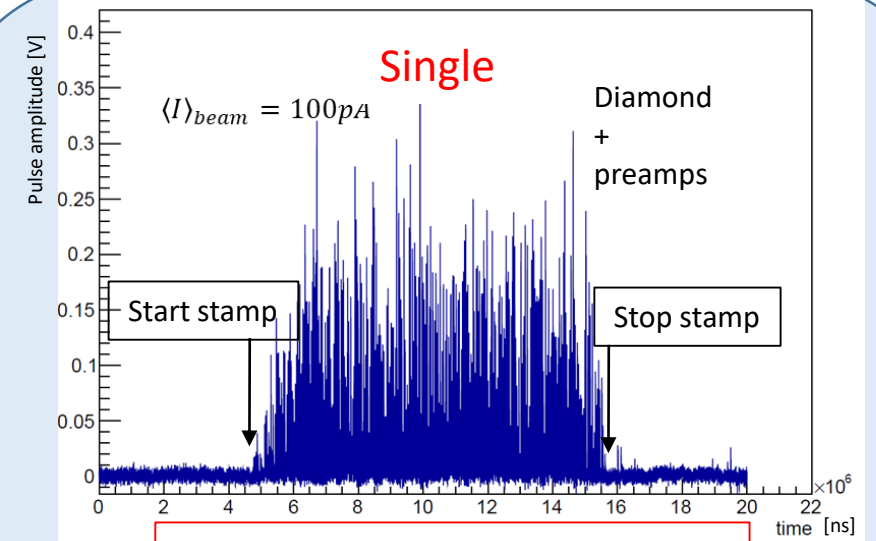


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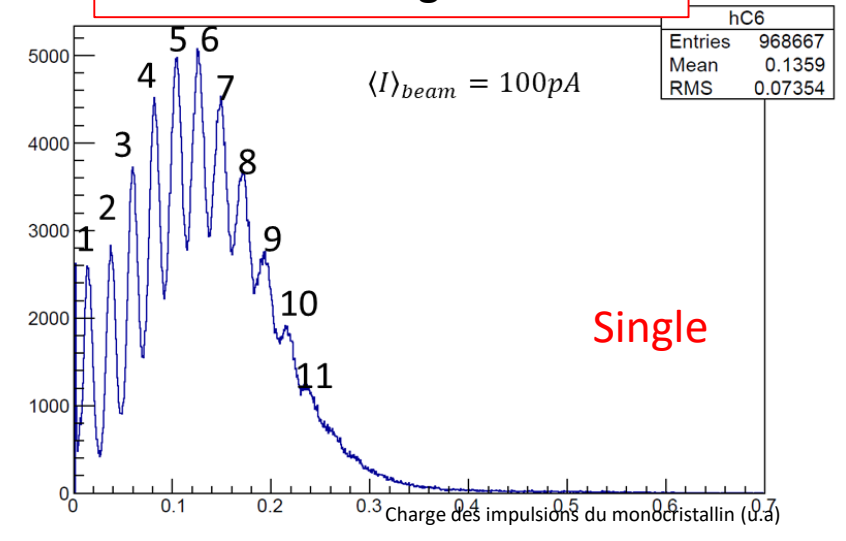


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Pulsed mode and $\langle I \rangle_{beam} = 100 \text{ pA}$



Particle counting in bunches



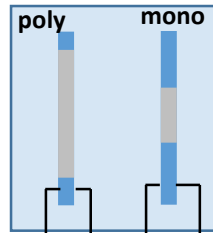
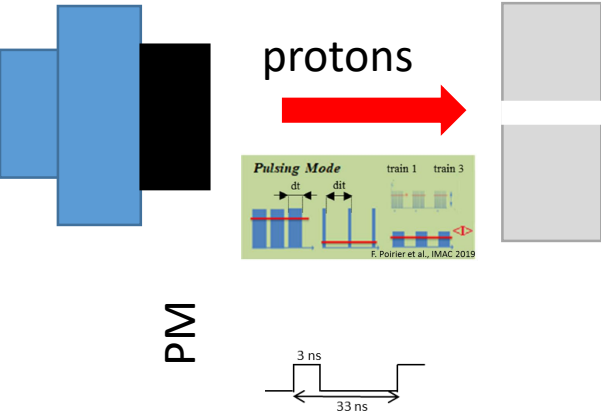
Proton counting in pulses !

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

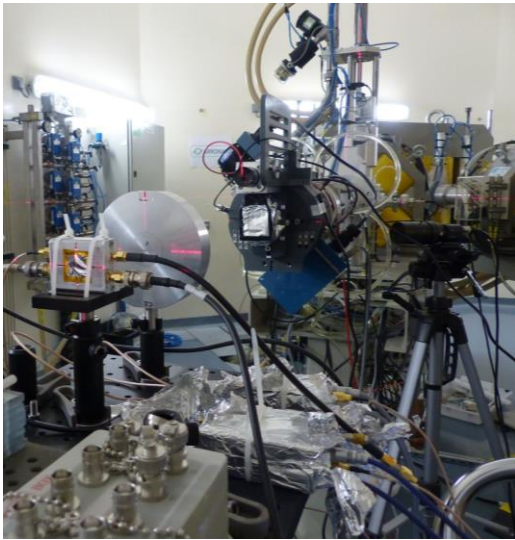


Particle counting vs I_{beam} : preliminary measurement

Collim.
Ø 1mm



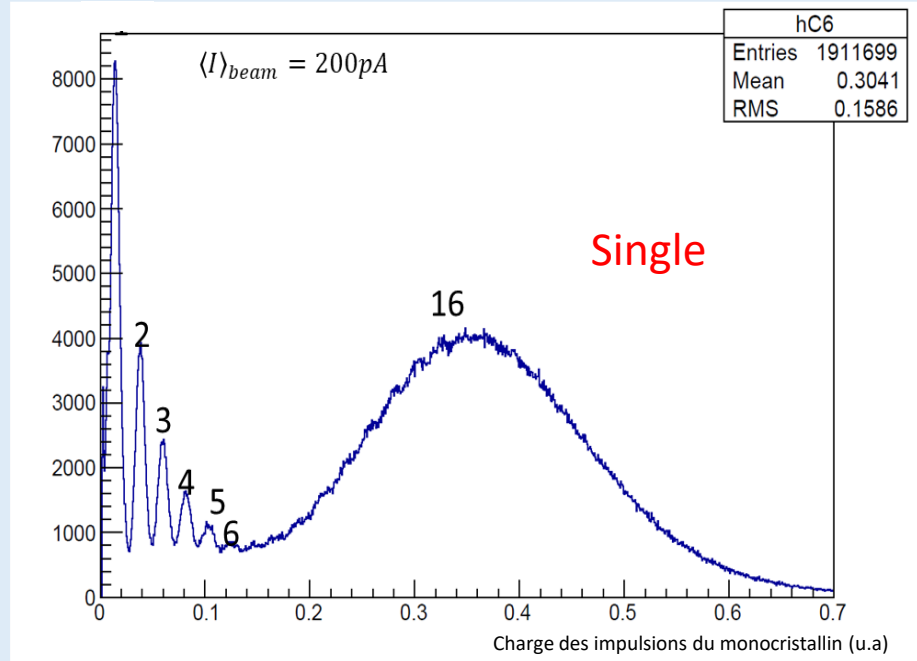
Scope LeCroy
Sampling 2.5 GS/s
4 channels
Acq. window 20 µs



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

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)

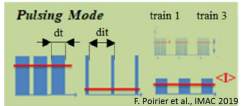


Particle counting vs I_{beam} : preliminary measurement

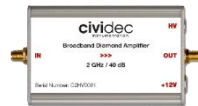
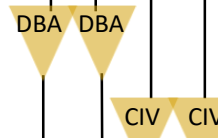
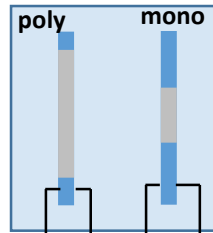
Collim.
Ø 1mm



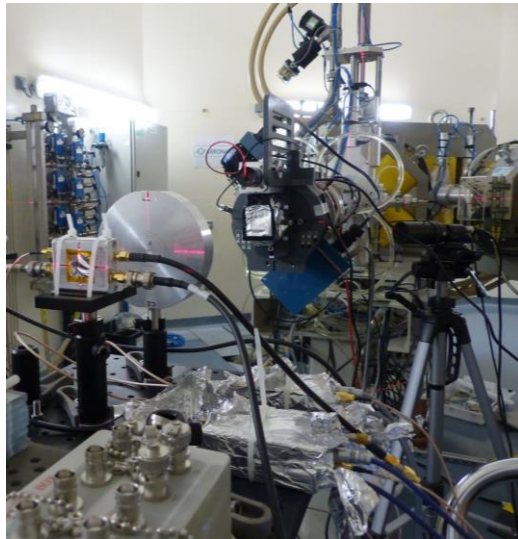
protons



PM



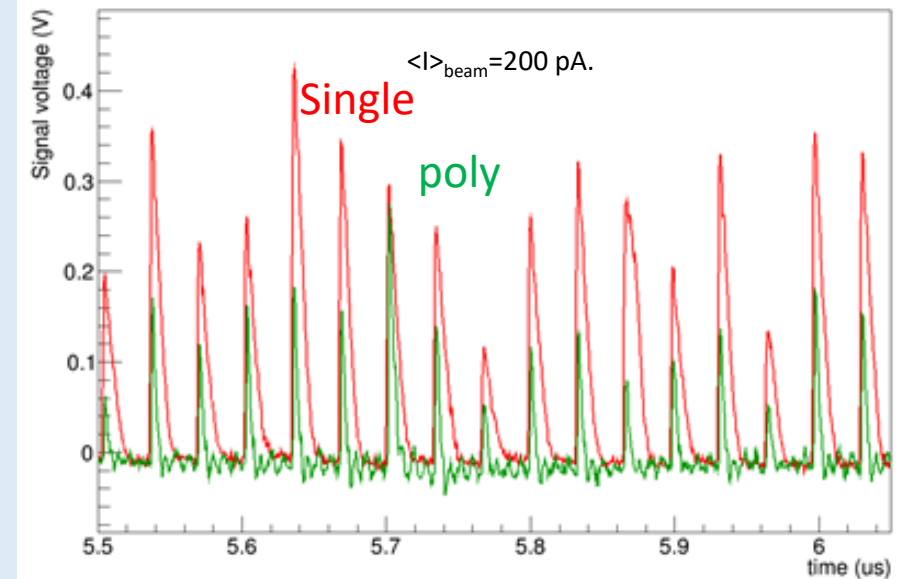
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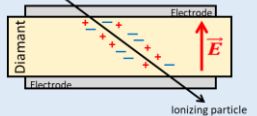
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Pulsed mode and $\langle I \rangle_{beam} = 200 \text{ pA}$

Single vs Poly at higher 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 !

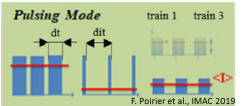
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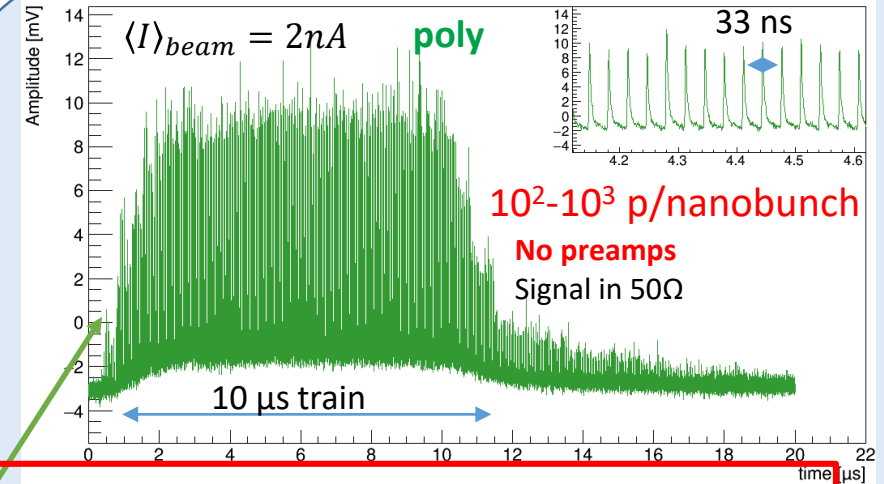
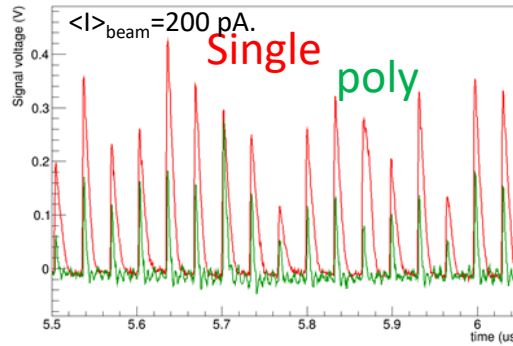
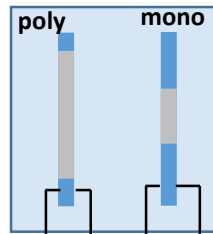
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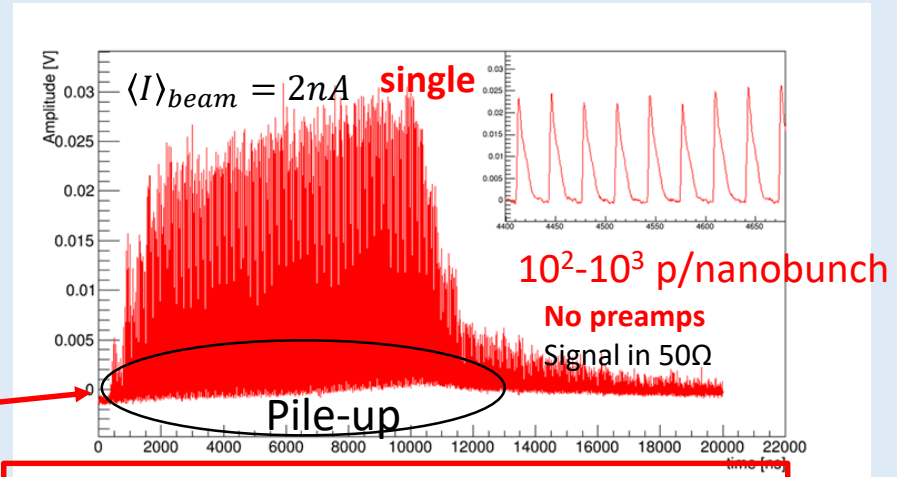
protons



Pulsed mode

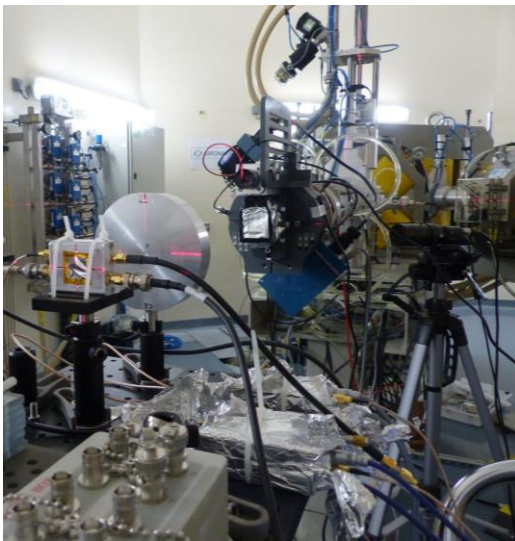


Preliminary results @ 2nA
Flash => $\langle I \rangle_{beam}$ up to μA to be done in Nov. 2020 !



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

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



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- 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 ~ 1 m from the patient).
- => 2020-2024 objectives: design of monitors for CLaRyS-UFT + DIAMTECH-IDSYNCHRO + DIAMTECH-DIAMMONI to perform beam diagnostics and radiotherapies monitoring**

Acknowledgements



ESRF

AGENCE NATIONALE DE LA RECHERCHE

ANR



France
HADRON



UNIA



irfu



saclay

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.

This work was supported by the **Labex PRIMES** (ANR-11-LABX-0063), **FranceHadron** (ANR-11-INBS-0007) and **ANR MONODIAM-HE** (ANR-089520). **ANR DIAMMONI 219725**

The **CLARA** Canceropole (Oncostarter Project) is thanked.

The authors are grateful to **Matthias Schreck** from the Augsburg University for providing the LPSC laboratory with samples of diamond heteroepitaxially grown.

Dominique Breton from the Laboratoire de l'Accélérateur Linéaire and **Eric Delagnes** from CEA Saclay are thanked for their implication in dedicated software development and technical support of the namely "wavecatcher" data acquisition system.