Fast timing with diamond detectors for multi-purpose applications

S Curtoni, A Bes, G Bosson, J Collot, D Dauvergne, L Gallin-Martel, M-L Gallin-Martel, A Ghimouz, J-Y Hostachy, A Lacoste, S Marcatili, J-F Muraz, F.E. Rarbi, M Yamouni
LPSC Grenoble

M Fontana, E Testa
IPN Lyon

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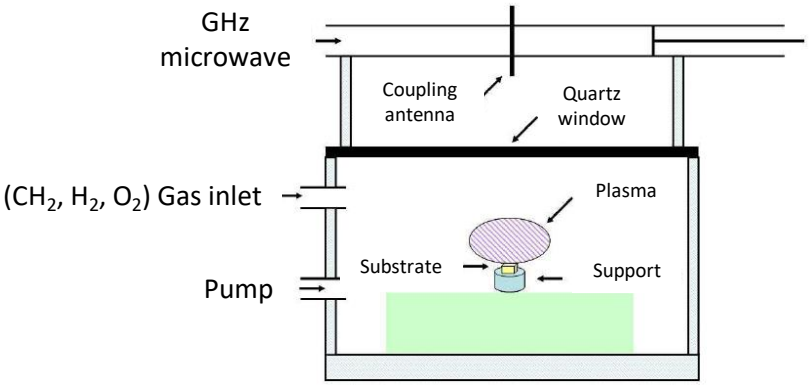
European Synchrotron Radiation Facility (ESRF), Grenoble

L Abbassi, T Crozes, J-F Motte
Néel Institute, Grenoble

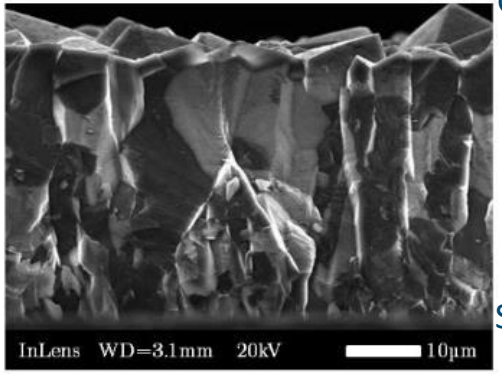
Synthetic diamond as radiation detector

Wide-band gap intrinsic semi-conductor

Growth process : Chemical Vapor Deposition (CVD)



[F Marsolat PhD thesis, CEA-LIST 2013]

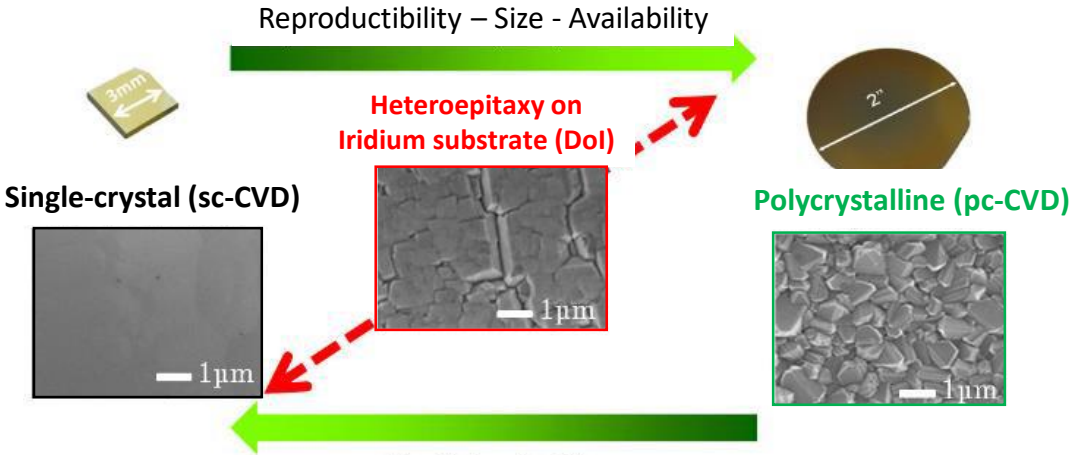


Growth side

Substrate side

[N Vaissière PhD thesis, CEA-LIST 2014]

Crystal structures



[N Vaissière PhD thesis, CEA-LIST 2014]

Outstanding intrinsic properties

Resistivity	> 10^{13} Ω.m	→	**Low leakage currents**
Mean signal (MIP)	36 e^- / µm	→	**Good Signal-to-Noise Ratio**
Band gap	5.5 eV		
Threshold Displacement Energy	43 eV	→	**Radiation hardness**
Electron mobility	2000 $cm^2/V/s$	→	**Fast time response**
Hole mobility	2400 $cm^2/V/s$		
Atomic number	6	→	**Tissue-equivalent**

Various applications

Particle Physics

- **Inner tracking detectors**

Vertex tracking detectors in colliders

→ *withstand ultra-high fluences*

- good thermal conductivity

Nuclear Physics

- **Fission fragment detection**

Fission fragment identification by energy loss, Time-Of-Flight measurements

- good energy resolution
- good SNR

Medical Physics

- **Dosimetry**

- tissue equivalent
- low leakage currents

- **Hodoscope for hadrontherapy**
  - large area
  - *high count rate (100 MHz)*
  - *Good SNR*

In any case: radiation hardness & fast time response required

Various applications

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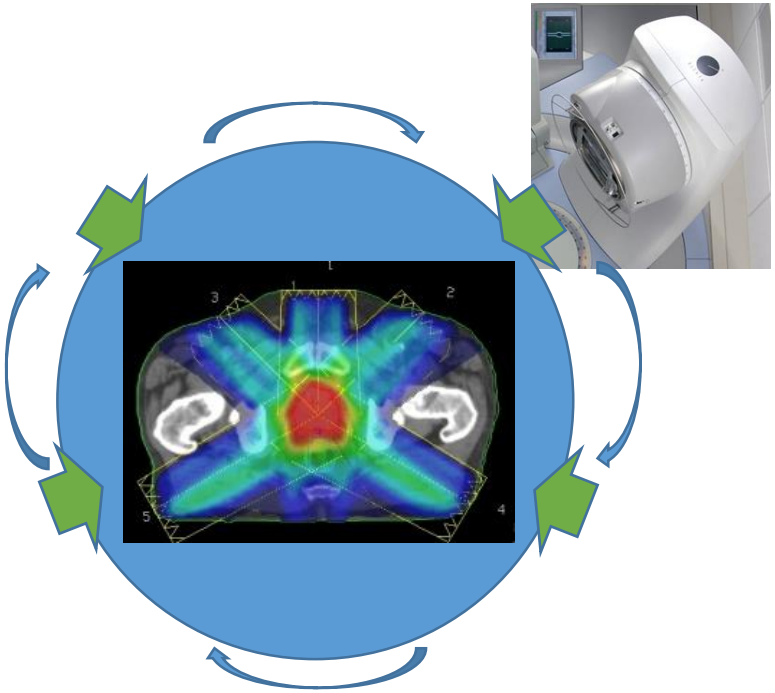
In any case: radiation hardness & fast time response required

Radiotherapy

Treatment of cancer by means of ionising radiations

Conventional X-ray radiotherapy :

Treatment room

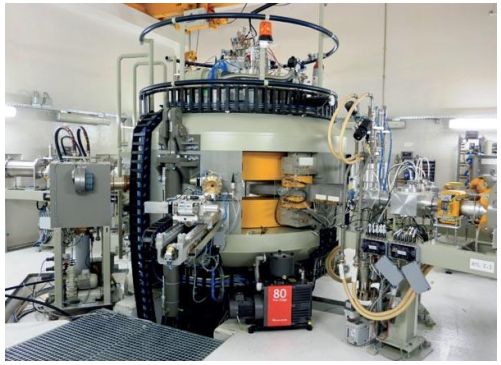


Radiotherapy

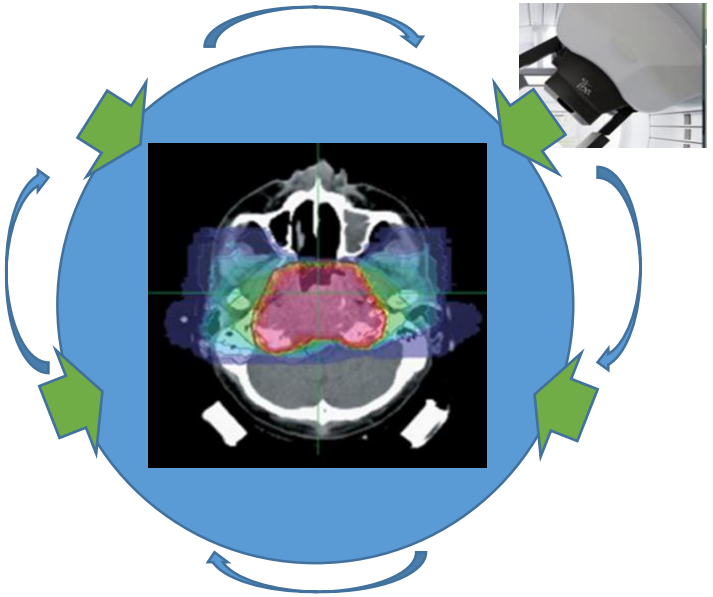
Hadrontherapy:

Proton or light ion beams

Ions production in cyclotron

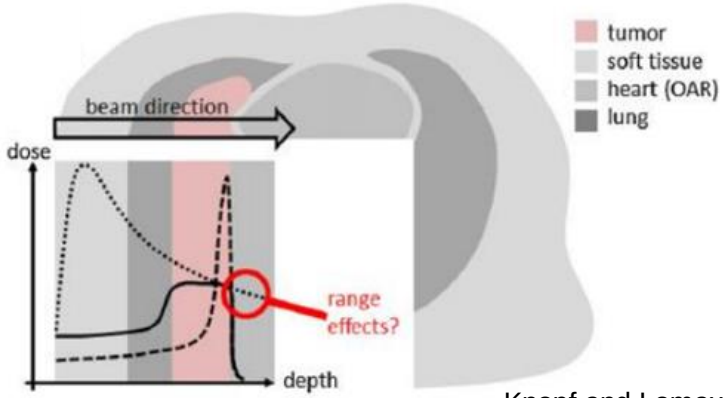


Treatment room

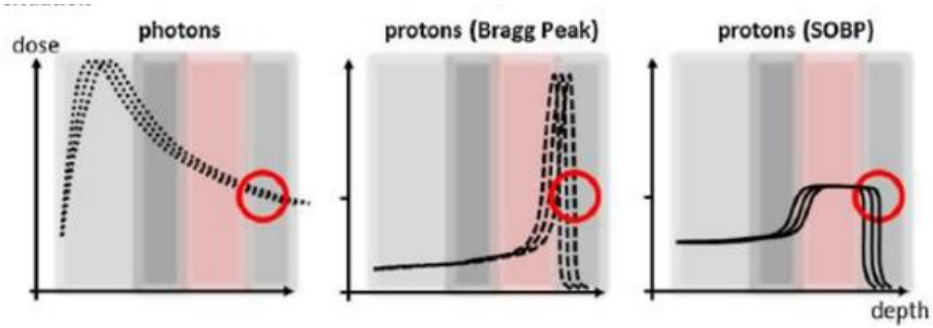


Range uncertainties in hadrontherapy

Ideal dose planification



Effect of change in tissue composition



Knopf and Lomax, Phys. Med. Biol. **58** (2013) R131–R160

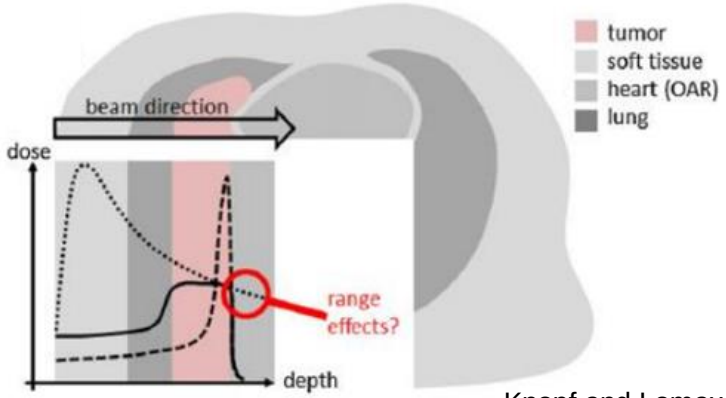
Dose calculation, patient positionning, organ motion, morphological changes

Uncertainties

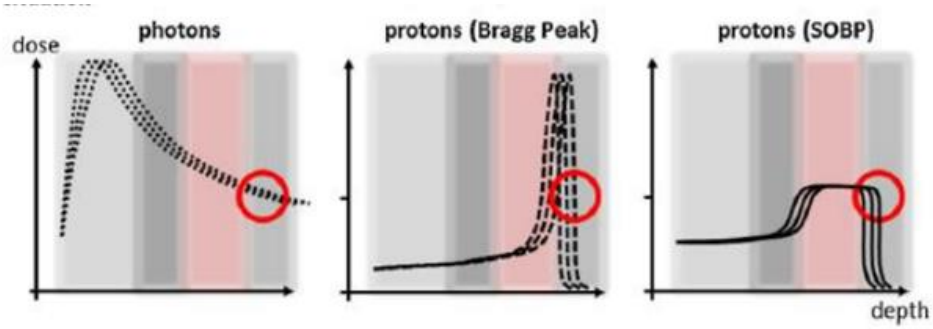
Need for an online ion range control

Range uncertainties in hadrontherapy

Ideal dose planification



Effect of change in tissue composition



Knopf and Lomax, Phys. Med. Biol. **58** (2013) R131–R160

Dose calculation, patient positionning, organ motion, morphological changes → Uncertainties → **Need for an online ion range control**

CLaRyS Collaboration

LPSC, IPNL, CPPM, LPC Clermont, CREATIS, LIRIS, CAL

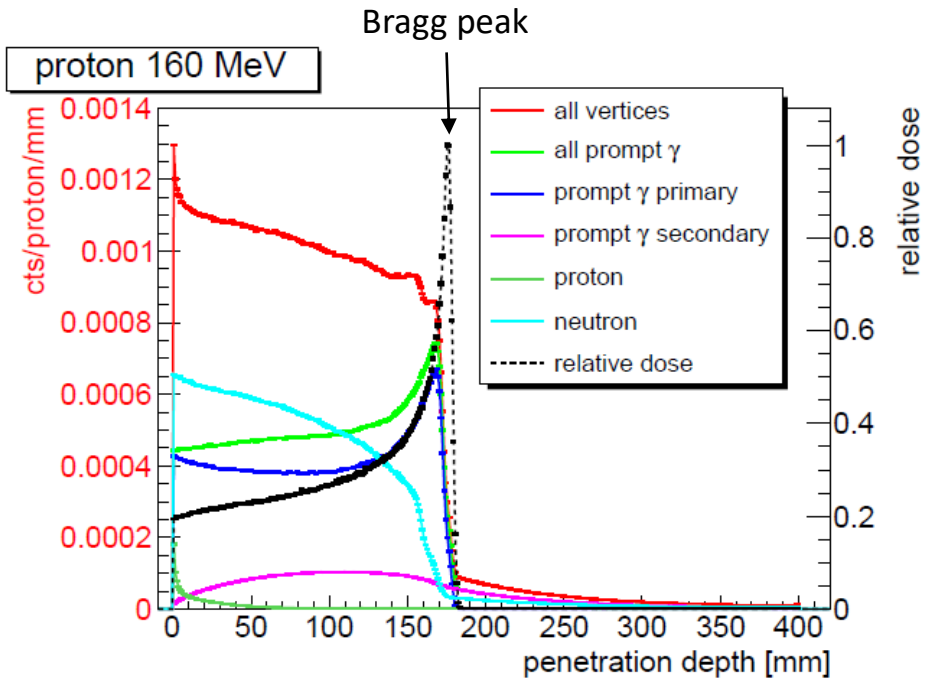
Contrôle en Ligne de l'hAdronthérapie par Rayonnements Secondaires

→ **Develops various approaches of online ion range verification based on detection of secondary particles**

Prompt Gamma Imaging

Imaging of prompt gamma photons emission following inelastic collisions between incident ions and body nuclei

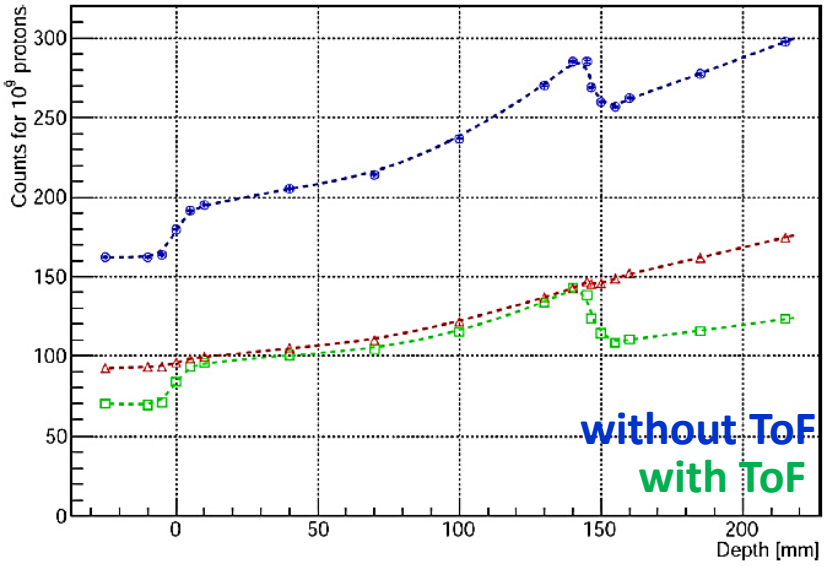
Geant4 simulation (PMMA target)



J Krimmer et al, NIMA RAD-IM 2017

Experiment with 160 MeV protons on a PMMA target

Longitudinal profiles:

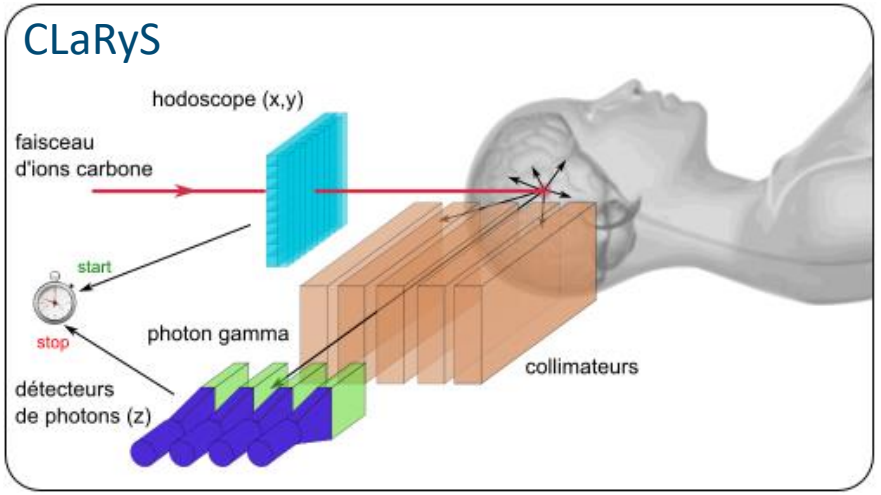


F Roellinghoff et al, Phys. Med. Biol. 2014

Prompt Gamma Imaging

Prompt gamma detection system:

- Compton or multi-slit collimated camera

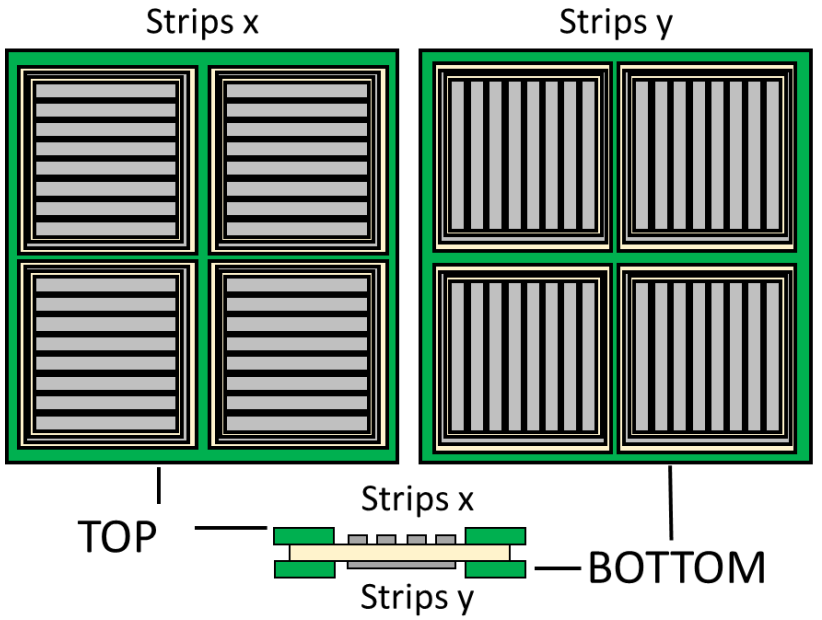


Beam tagging hodoscope : LPSC MoniDiam project

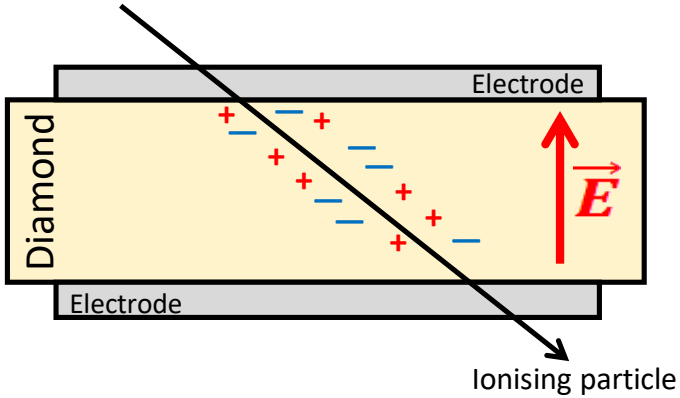
Large area stripped diamond hodoscope

Foreseen features:

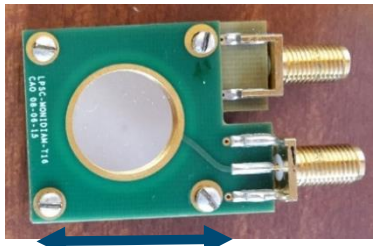
- Time resolution ≈ 100 ps
- Count rate 10 MHz/channel
- Spatial resolution ≈ 1 mm
- Radiation hard



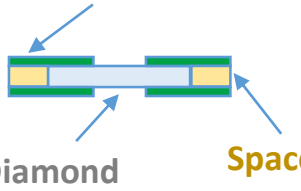
Solid-state ionization chamber



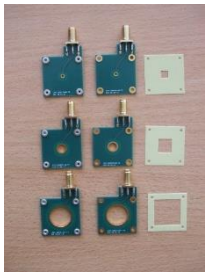
Assembly

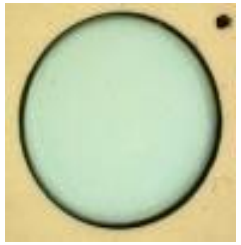


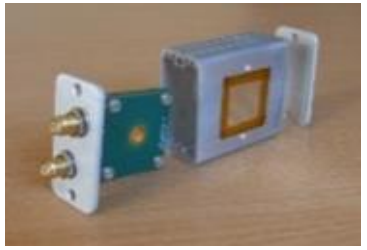
50Ω-adapted Printed Circuit Board



EM Shielding







Readout electronics

Fast current preamplifier by CIVIDEC

Bandwidth:	**2 GHz**
Gain:	**40 dB**
Impedance:	**50 Ω**

Alpha source : ^{241}Am (≈ 5.5 MeV)

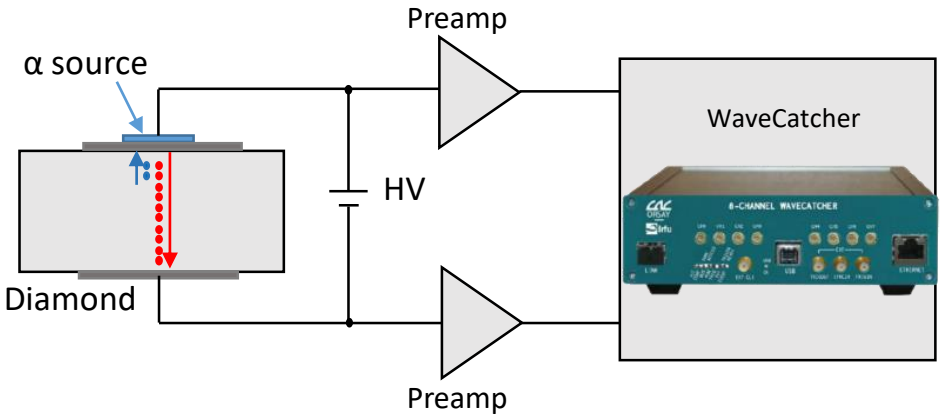
Set-up

α range in diamond ≈ 14 µm

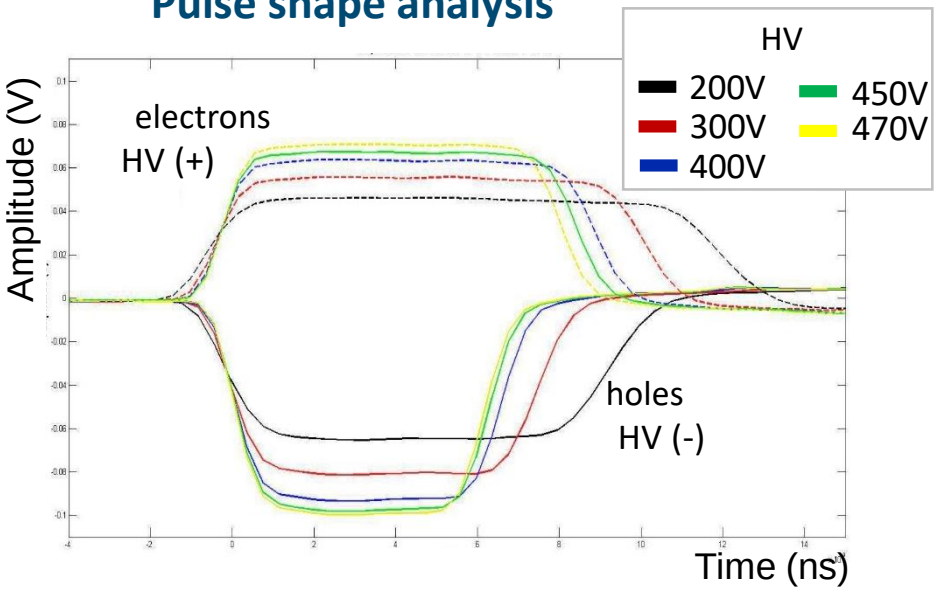
Diamond thickness = 300 – 500 µm

Study of the charge-carriers properties

Readout electronics : 2 CIVIDEC current preamplifiers

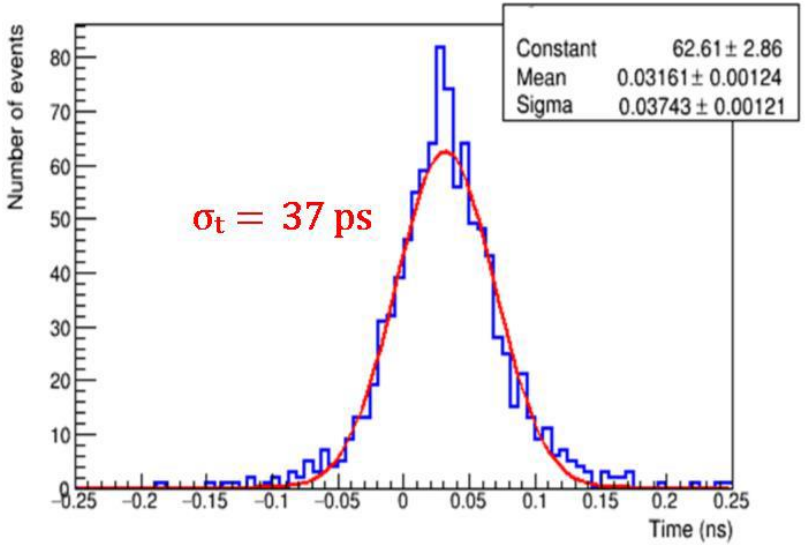


Pulse shape analysis



scCVD sample : 4.5 x 4.5 mm² x 515 µm

Time resolution (offline Constant Fraction Discrimination)



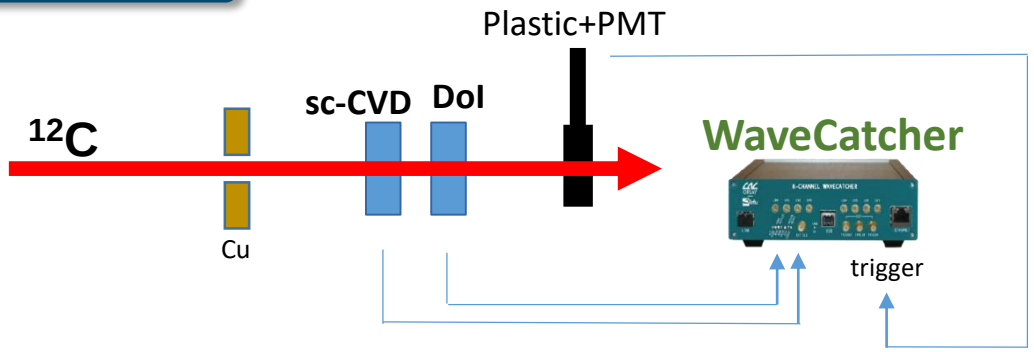
pcCVD sample : 20 x 20 mm² x 500 µm

Tests at GANIL with 95 MeV/u ^{12}C ions

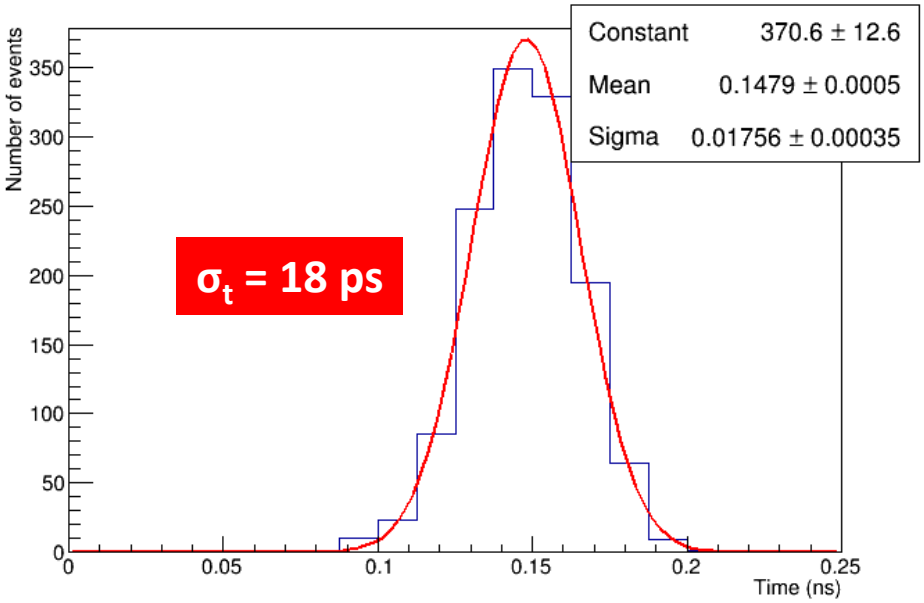
Set-up

sc-CVD : 4.5 x 4.5 mm² x 515 µm
DoI : 5 x 5 mm² x 300 µm

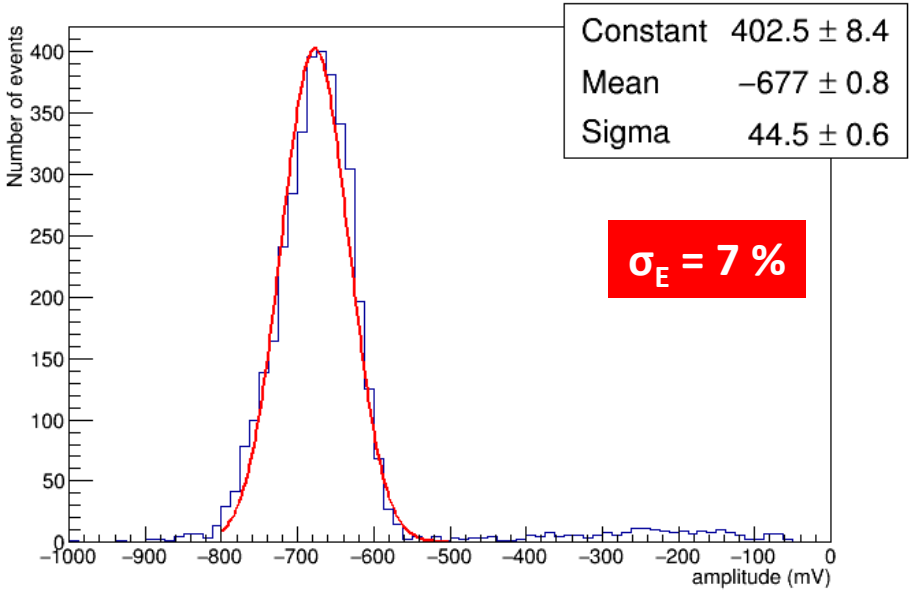
Trigger : Plastic scintillator set after the diamonds



ToF resolution : sc-CVD vs DoI



Energy resolution of the DoI sample

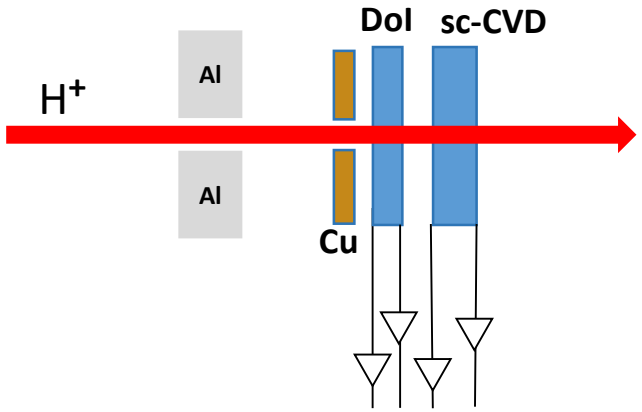


Tests at ARRONAX with 68 MeV protons

Set-up

DoI : 5 x 5 mm² x 300 µm
sc-CVD : 4.5 x 4.5 mm² x 515 µm

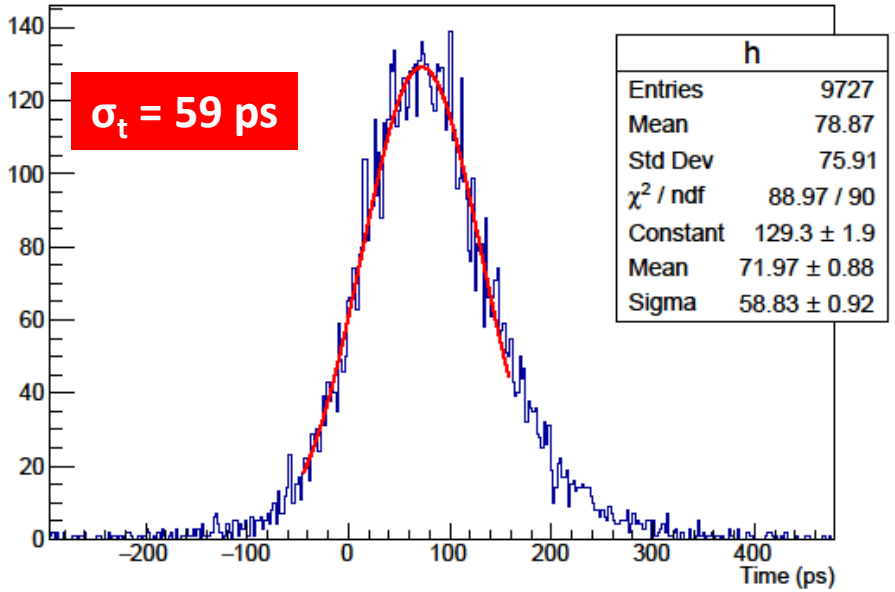
Readout electronics : 4 CIVIDEC current preamplifiers
(Both faces of each diamond)



ToF resolution

Trigger : coincidence between diamonds

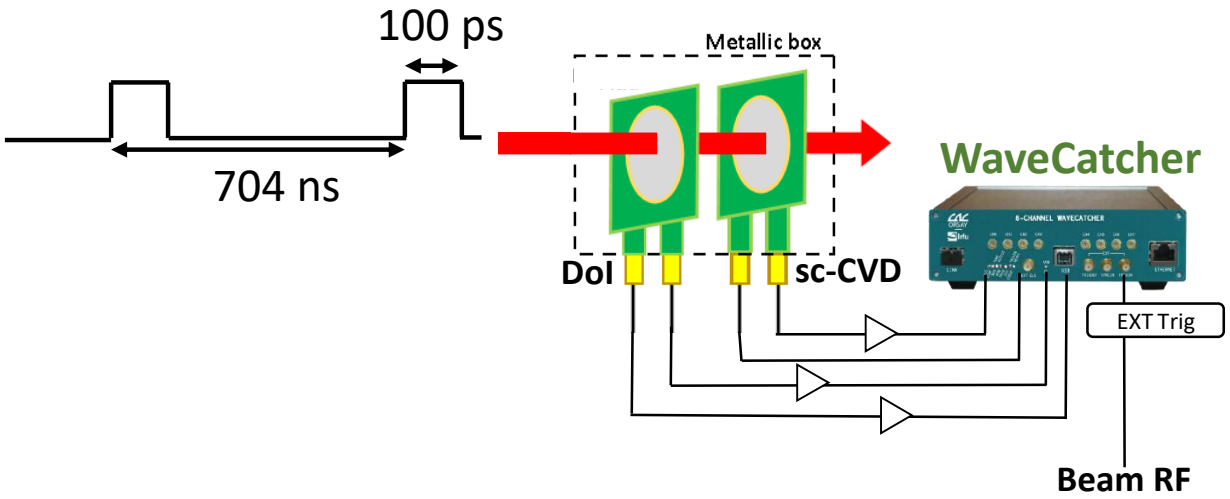
DoI vs sc-CVD (CFD 20%)



Tests at ID21 X-Ray Microscopy beamline at ESRF

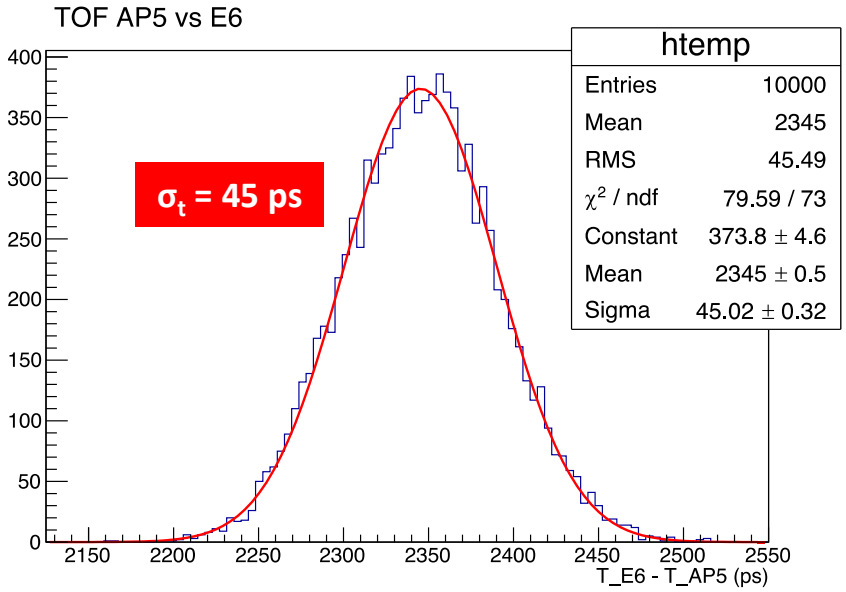
X-Ray micro-beam

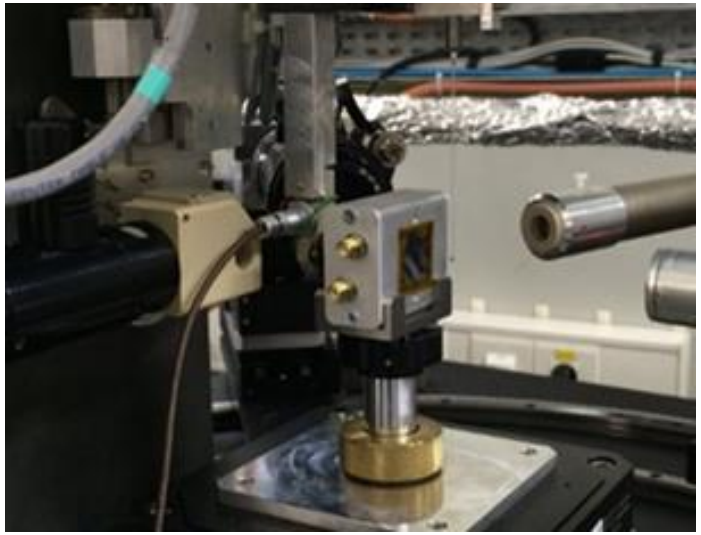
Ø spot : 1 µm
E_{photon} = 8.5 keV
≈ 1500 photons/bunch



DoI : 5 x 5 mm² x 300 µm
sc-CVD : 4.5 x 4.5 mm² x 515 µm

ToF resolution





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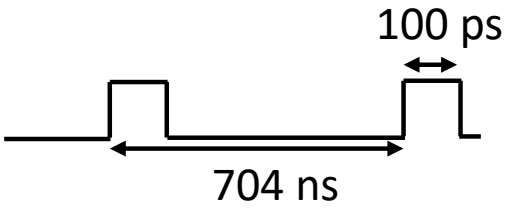
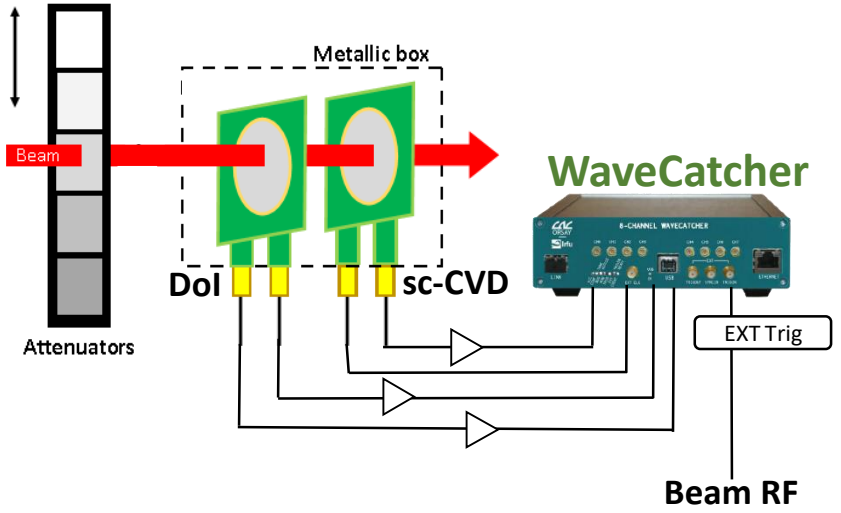
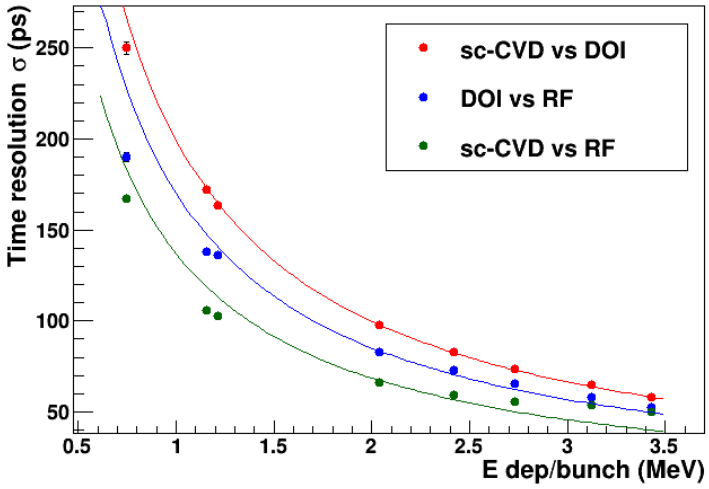




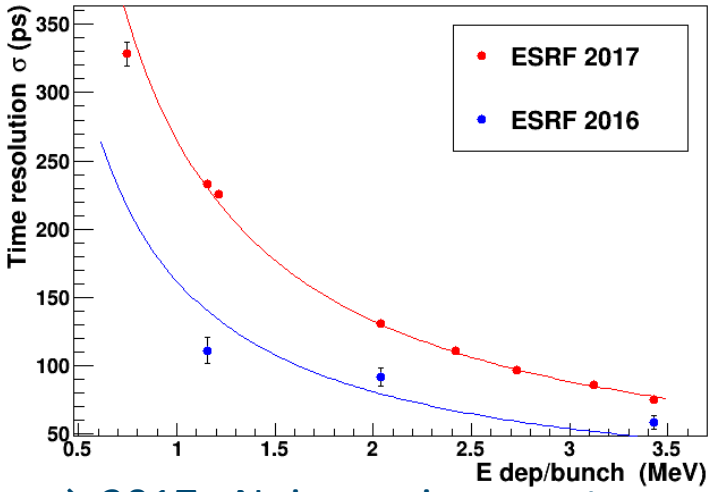
Use of aluminum and titanium attenuators

ToF resolution vs Energy deposit/bunch

Sc-CVD vs DoI vs RF

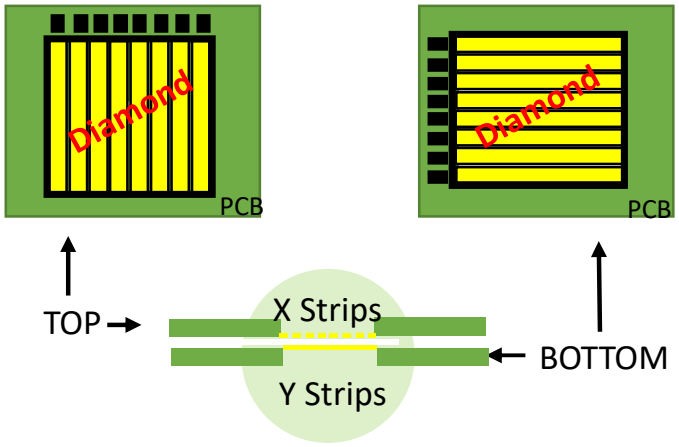


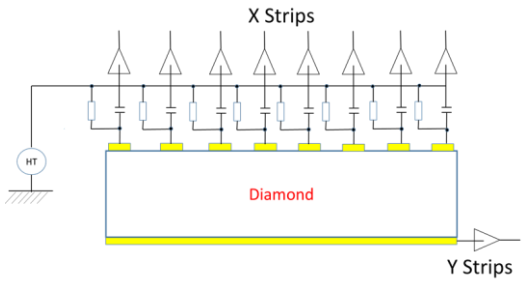
DoI : 2016 vs 2017

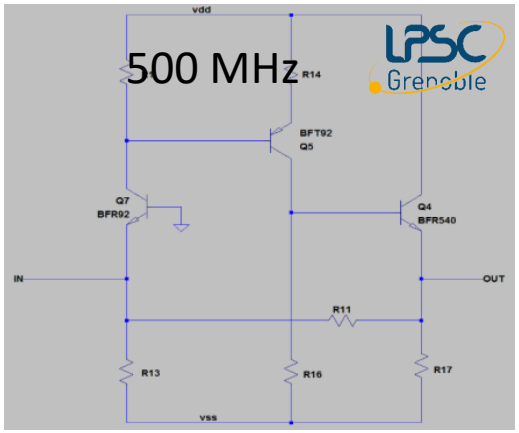


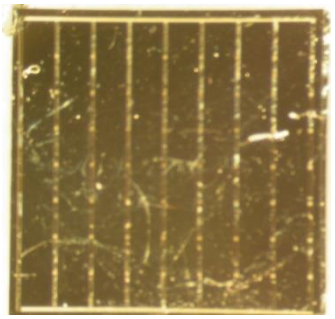
→ 2017 : Noisy environment

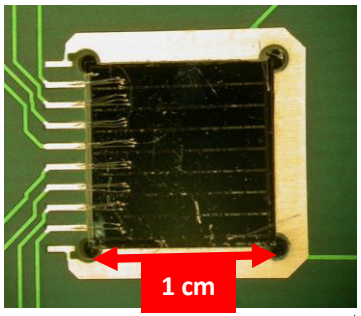
Towards a beam tagging hodoscope : double-side stripped diamond samples

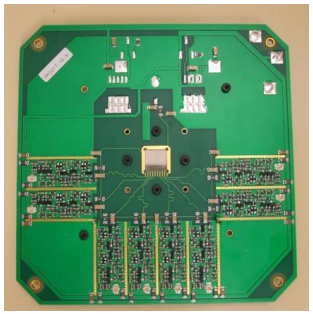


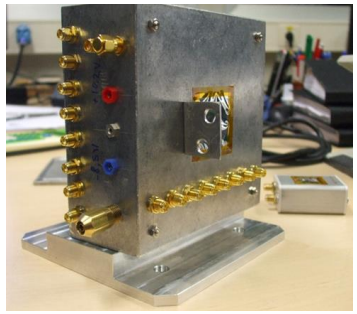












NANOFAB plateform @ Néel Institute Grenoble

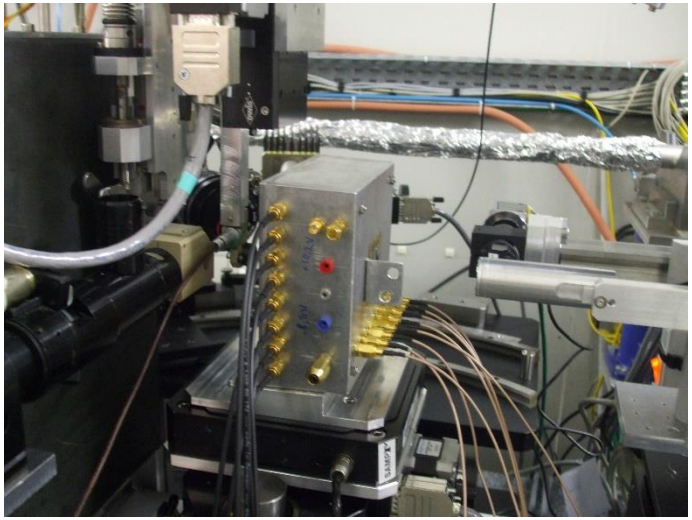
- 100 nm Al deposition by UV lithography
- Wire bonding

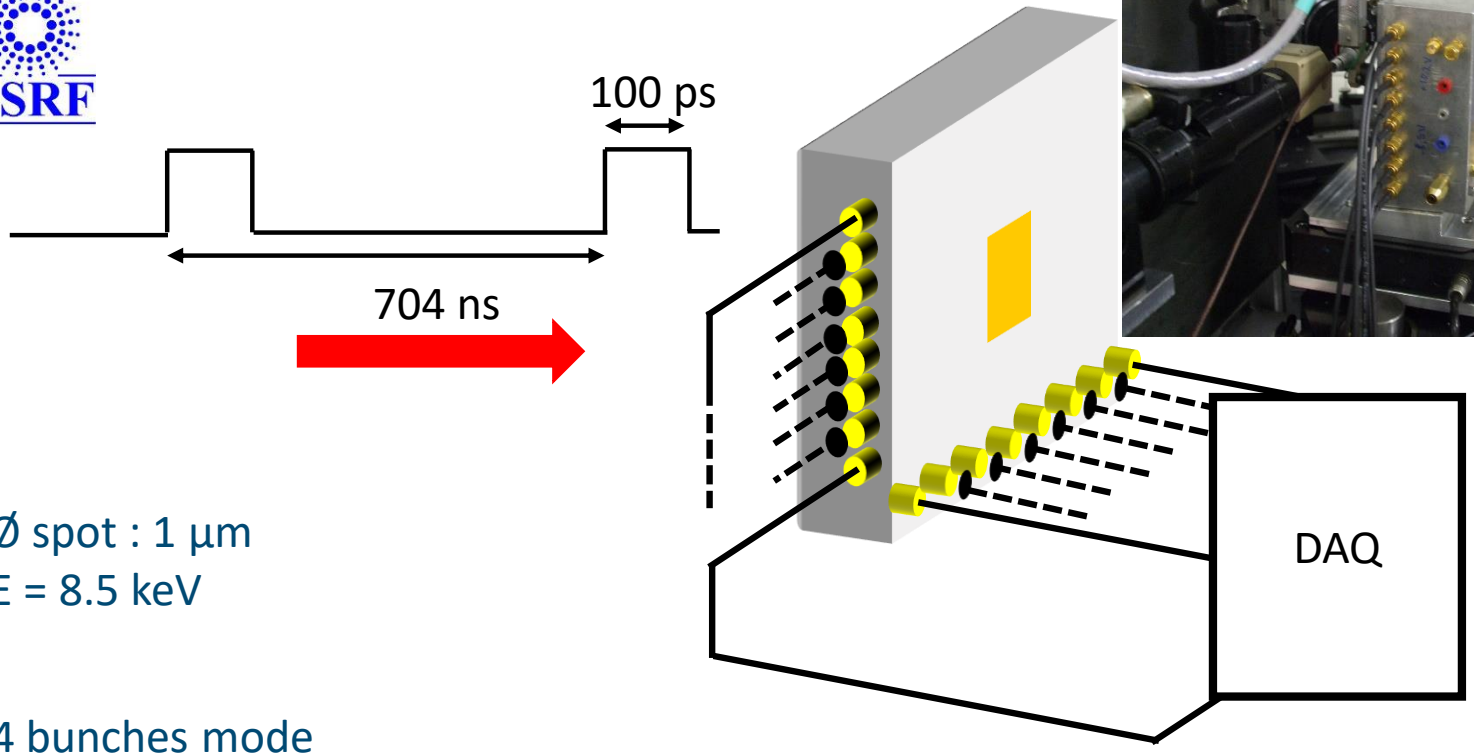
LPSC Grenoble

- Design
- Current preamplifier
- Assembly

Tests at ID21 X-Ray Microscopy beamline at ESRF

The box was positioned with micrometric reproducibility at the sample position of the micro-diffraction end station (in air) of the beamline





Ø spot : 1 µm
E = 8.5 keV

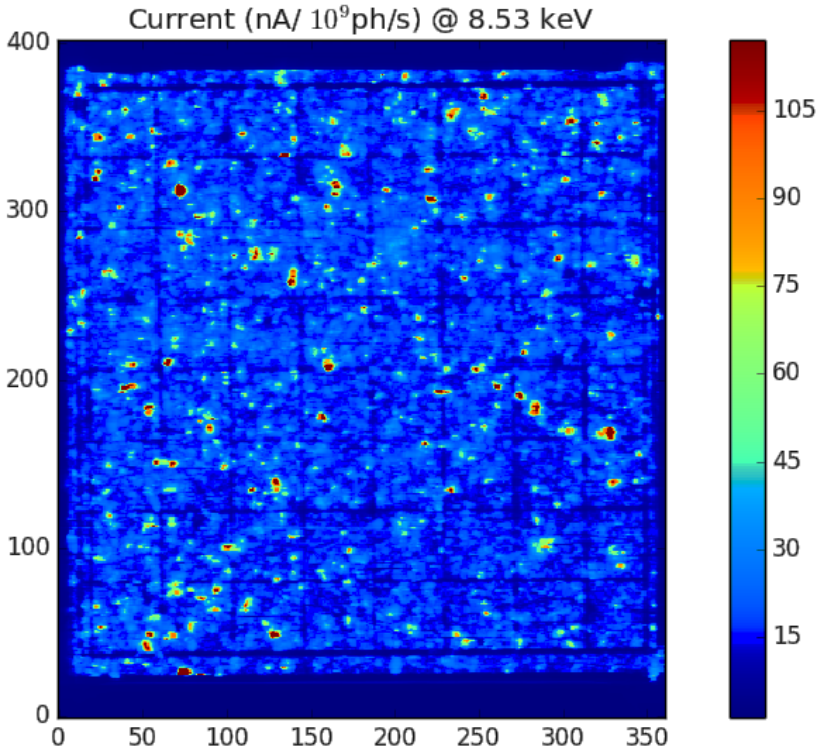
4 bunches mode

≈ 1500 photons/bunch → 4 MeV/bunch deposited in a 300µm-thick detector

X-ray Beam Induced Current technique (X-BIC)

Current mapping

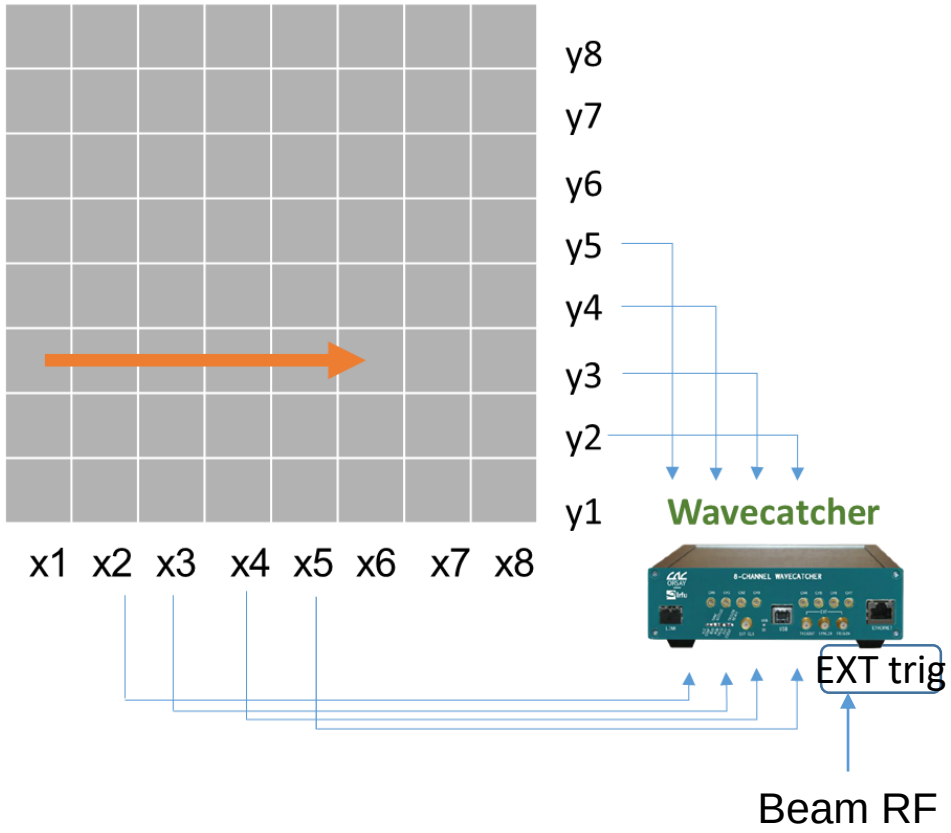
Current integration mode



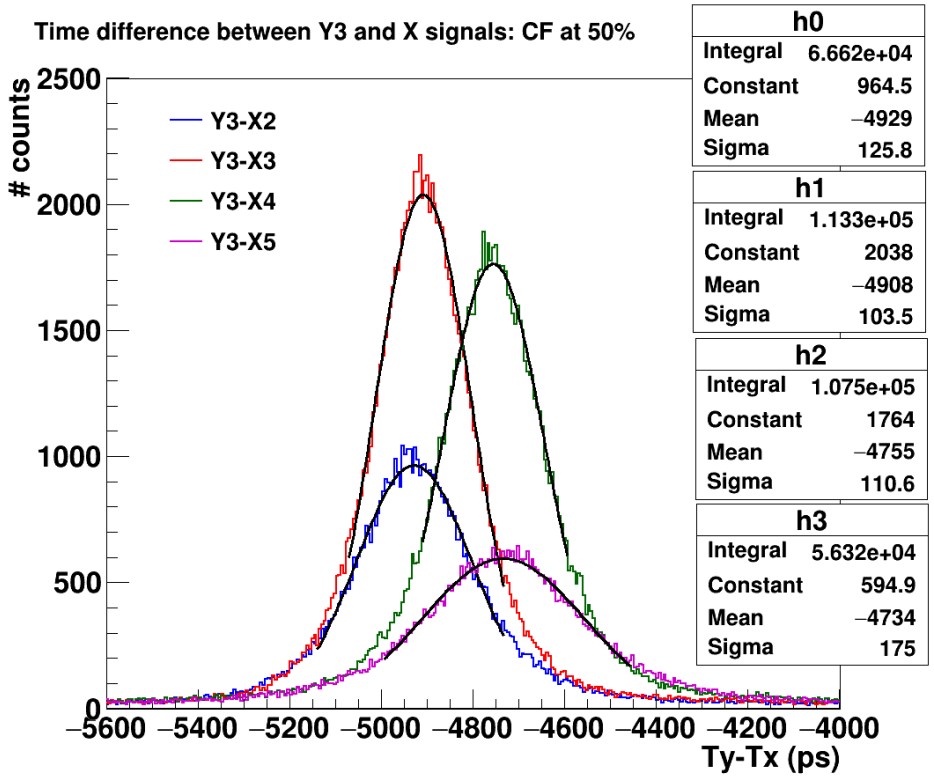
10 x 10 mm² x 300 µm pcCVD sample
Heterogeneous response

TOF-XBIC scanning

Scanning pitch : 100 µm



Tests at ID21 X-Ray Microscopy beamline at ESRF : First results

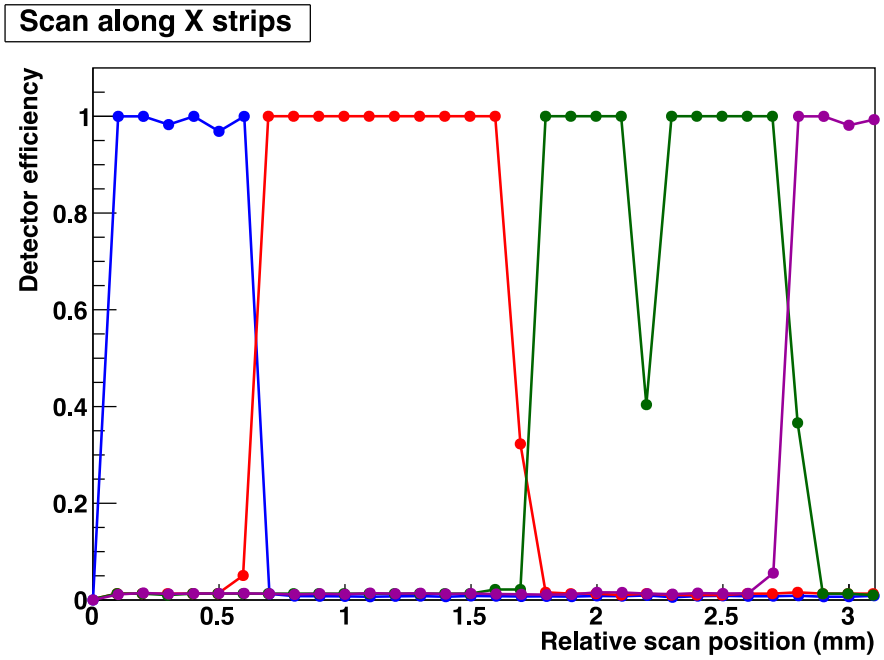


Y3-X2 = 127 ps

Y3-X3 = 103 ps

Y3-X4 = 112 ps

Y3-X5 = 178 ps



Efficiency relative to the RF signal

Conclusions

- Diamond detectors : promising properties for particle tracking:
  → low noise
  → high time resolution
  → radiation hard

→ Time-of-Flight measurements under high radiation fields

- WaveCatcher : timing measurements well under its sampling period (σ_t = 18 ps with ^{12}C ions)

- Development of double-side stripped diamond detectors:

  → 3.2 GHz sampling on 8 strips at the same time

  → First sample exhibits a good time resolution (at the level of 100 ps) on every scan point

→ WaveCatcher is essential in the ongoing characterization of our multi-channel sensors

Thank you for your kind attention

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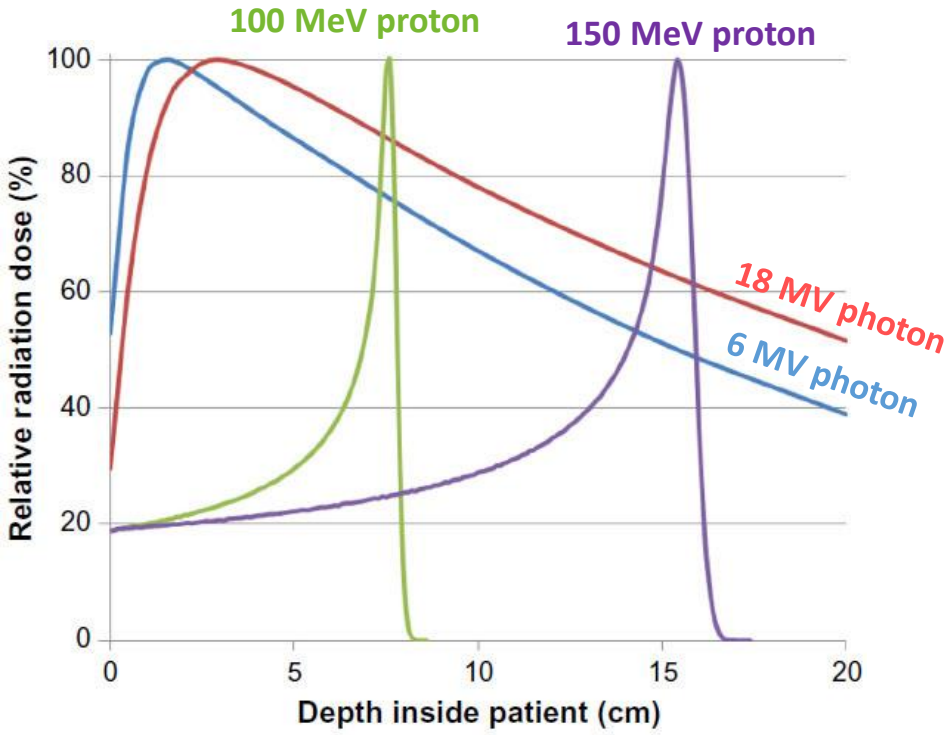
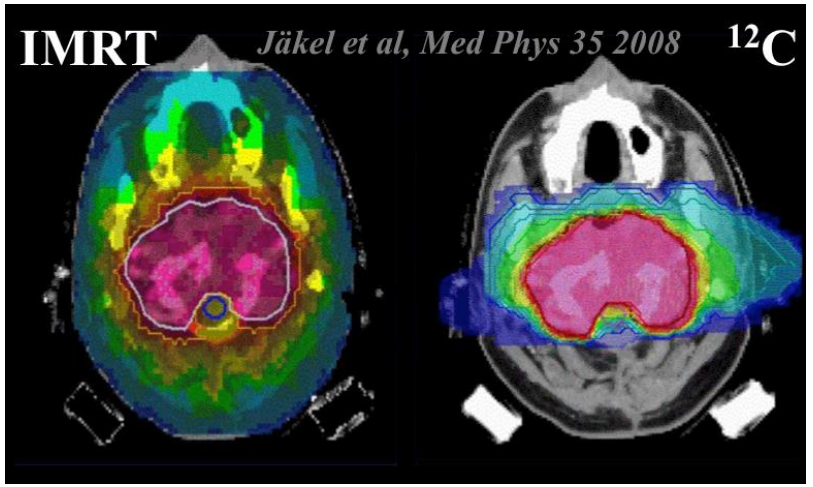
Additional slides

Hadrontherapy

Radiotherapy by means of proton or light ion beams





X-Ray - 12 fields **2 fields**

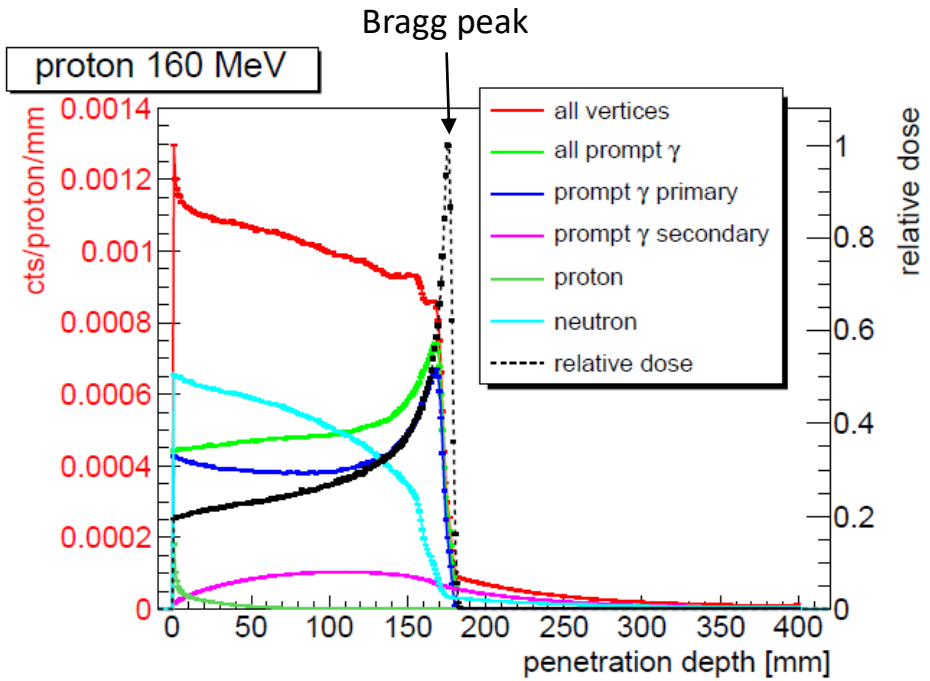
Compared to conventionnal photon radiotherapy

- **Better organ-at-risk protection**
- **Treatment of deep tumors**
- **Ballistic targeting**

Prompt Gamma Imaging

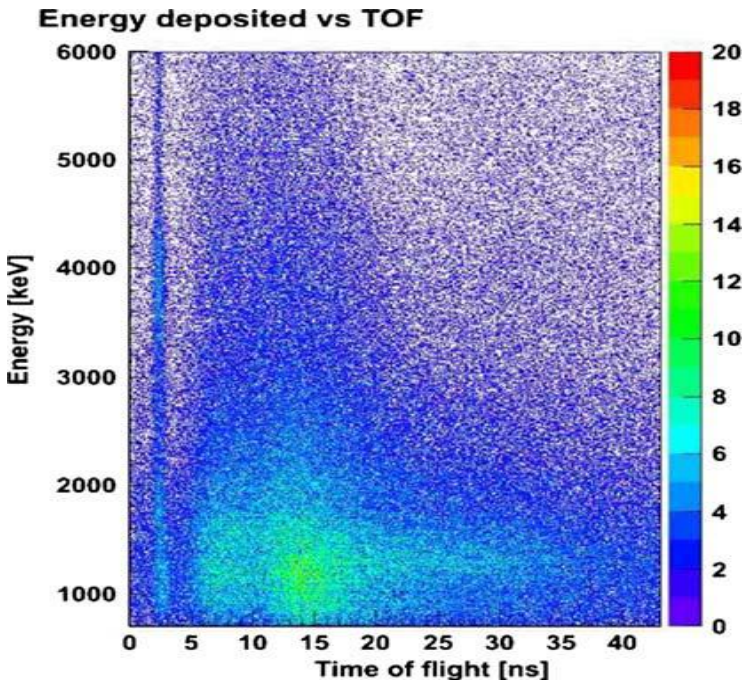
Imaging of prompt gamma photons emission following inelastic collisions between incident ions and body nuclei

Geant4 simulation (PMMA target)



J Krimmer et al, NIMA RAD-IM 2017

Experiment with 95 MeV/u ^{12}C ions on a PMMA target



M. Testa, Rad Env Bio 2010

Prompt Gamma Imaging

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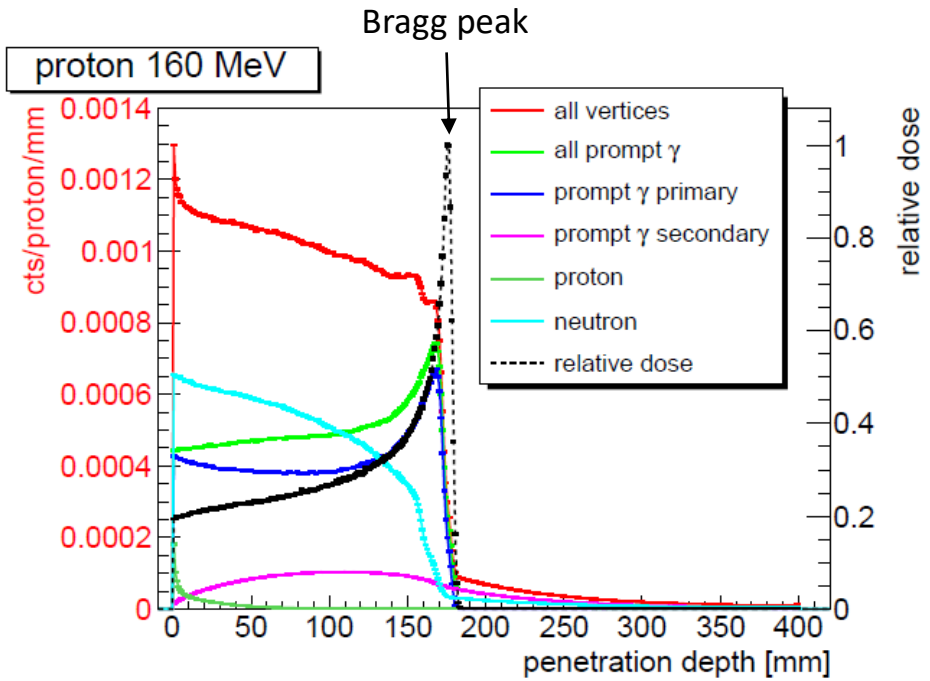
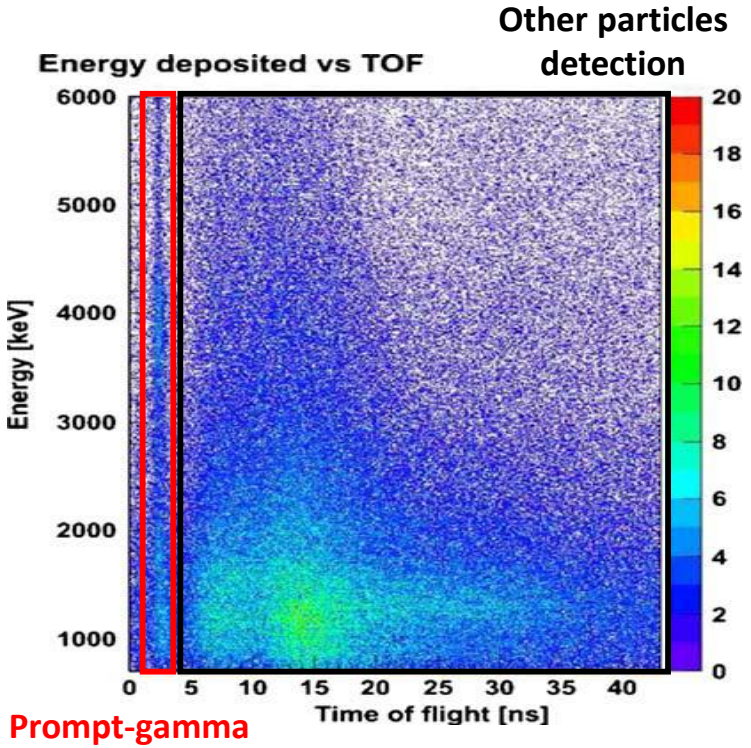


J Krimmer et al, NIMA RAD-IM 2017

Experiment with 95 MeV/u ^{12}C ions on a PMMA target

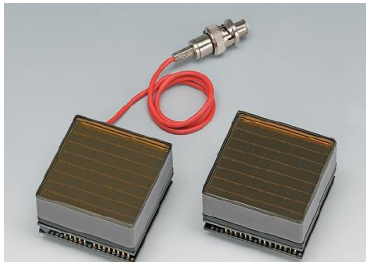


M. Testa, Rad Env Bio 2010

Development of a beam tagging hodoscope

IPNL scintillating fiber hodoscope

- Time resolution ≈ 1 ns
- Count rate < 4 MHz/PMT
- Fiber lifetime under clinical conditions : 1 year

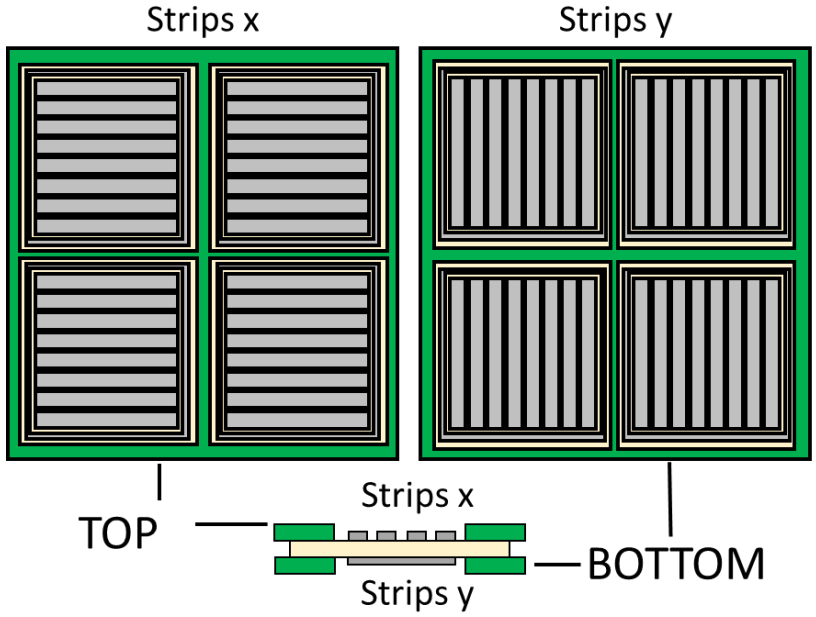


LPSC MoniDiam project

Large area stripped diamond hodoscope

Foreseen features:

- Time resolution ≈ 100 ps
- Count rate 10 MHz/channel
- Spatial resolution ≈ 1 mm
- Radiation hard

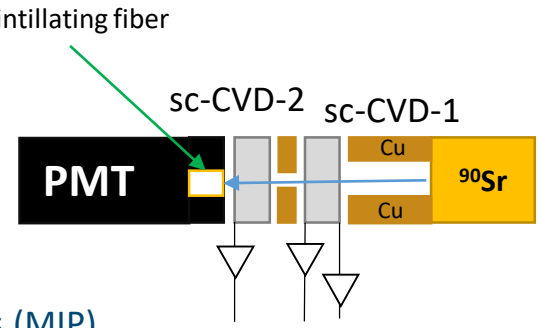


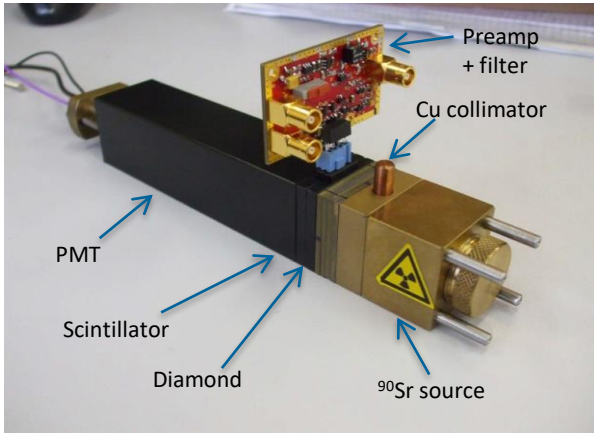
Beta source : ^{90}Sr (E_{max} = 2.28 MeV | MIP)

Set-up

High activity β source : 47 MBq

Both sc-CVDs : 4.5 x 4.5 mm² x 515 µm





PMT → trigerring on high energy electrons (MIP)

Readout electronics : CIVIDEC current preamplifiers

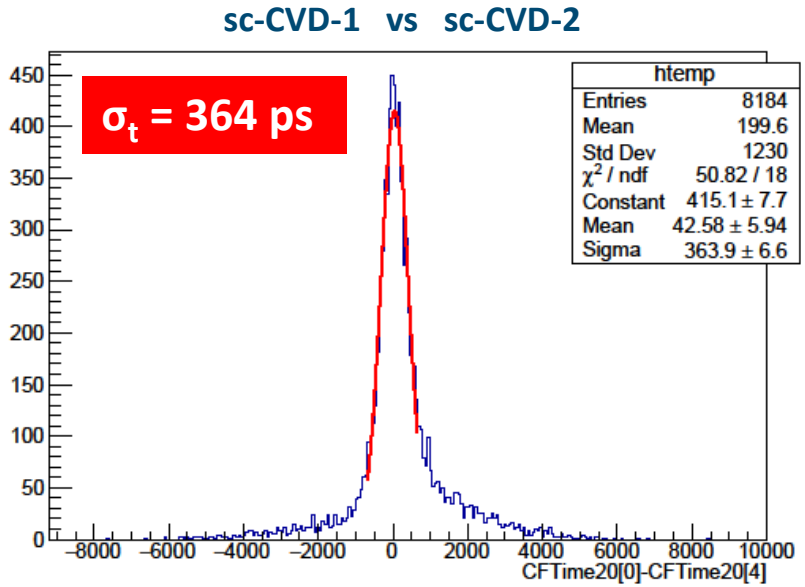
ToF resolution

Using Offline Constant Fraction Discrimination (CFD 20%)

MIP = lowest energy deposit

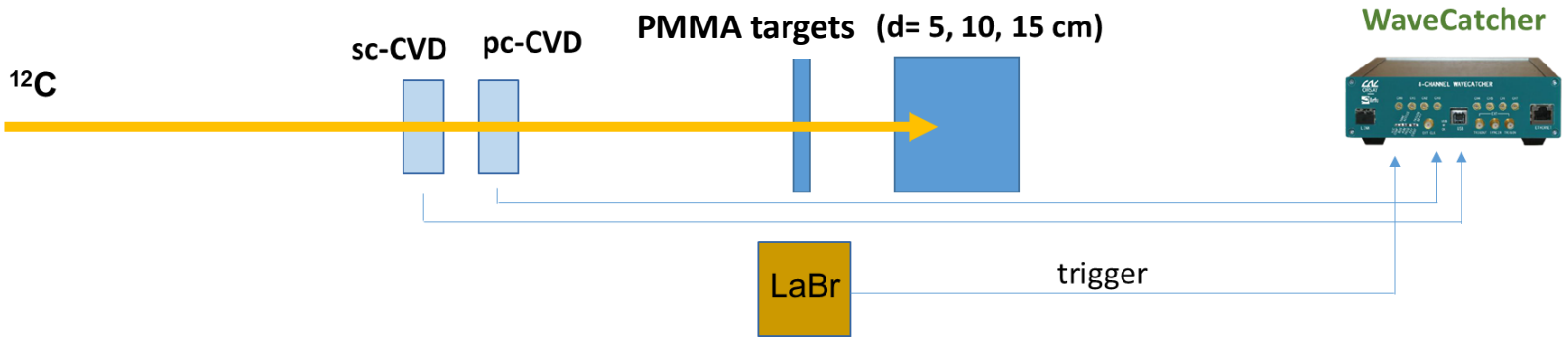
Charge created in a 500µm-thick diamond/MIP:

1.8 fC

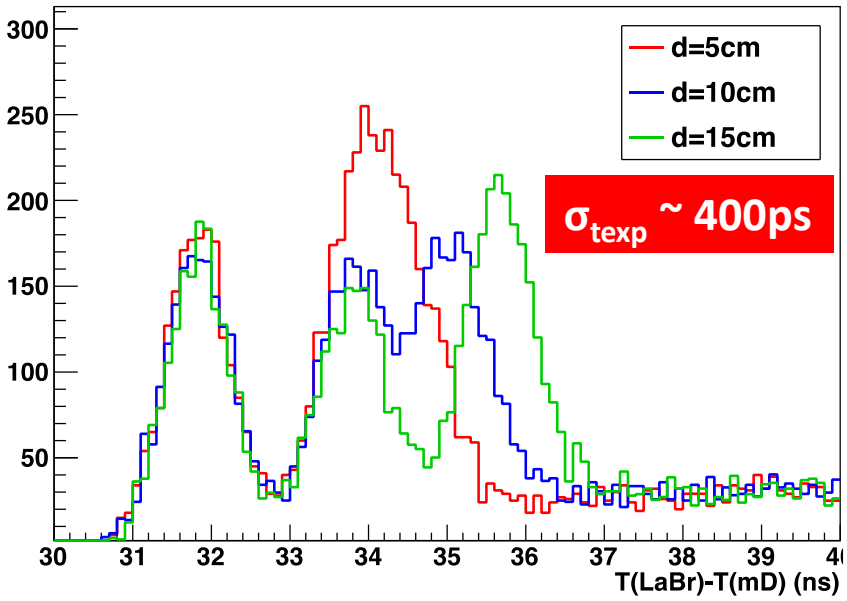


Tests at GANIL with 95 MeV/u ^{12}C ions

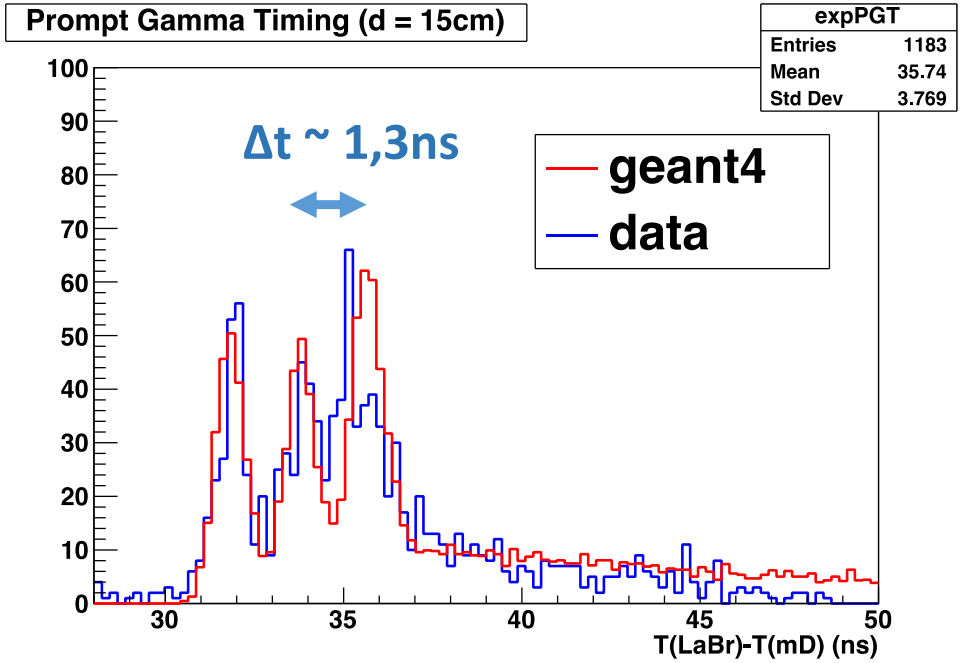
Set-up



G4 simulation: ToF (LaBr vs sc-CVD)



Actual result



Main intrinsic properties of diamond compared to silicon

	Silicon	Diamond
Density [$g.cm^{-3}$]	2.33	3.52
Gap [eV]	1.12	5.48
e^-/h pair creation energy [eV]	3.62	13.1
Mean signal (MIP) [$e^-/\mu m$]	89	36
Resistivity [Ω.m]	10^5-10^6	10^{13}-10^{16}
Electron mobility [$cm^2. V^{-1}.s^{-1}$]	1450	1900
Hole mobility [$cm^2. V^{-1}.s^{-1}$]	505	2300
Thermal conductivity [$W.cm^{-1}. K^{-1}$]	1.48	> 1800
Threshold displacement energy [eV]	25	43
Atomic number	14	6

Energy loss of 68 MeV protons in diamond (SRIM)

TRIM parameters

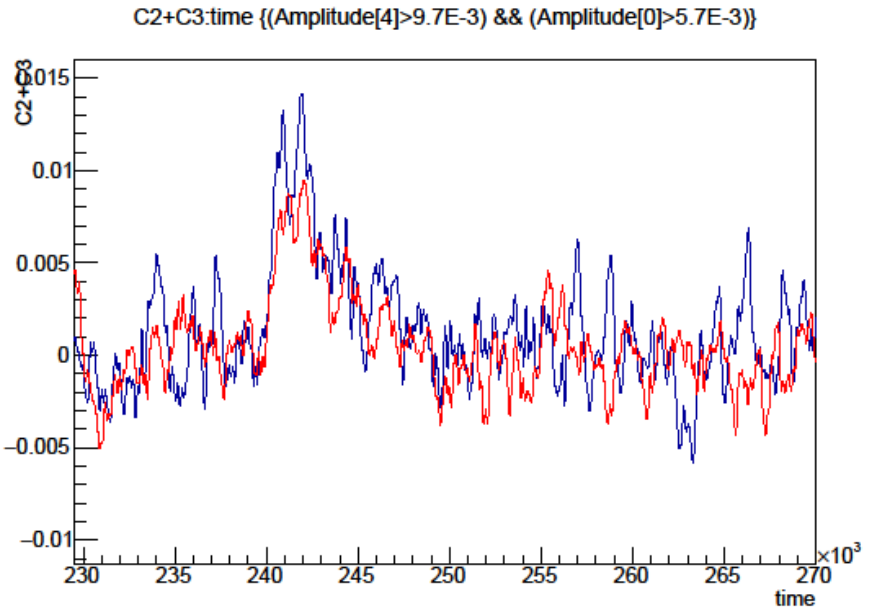
Target layers	Input Elements to Layer
Density = 3.52 g/cm^3 **Width unit = um**	Symbol : C (Name : Carbon) Weight : default for Carbon Damage/disp : 43 eV Damage/Latt : default for Carbon Damage/surf : default for Carbon

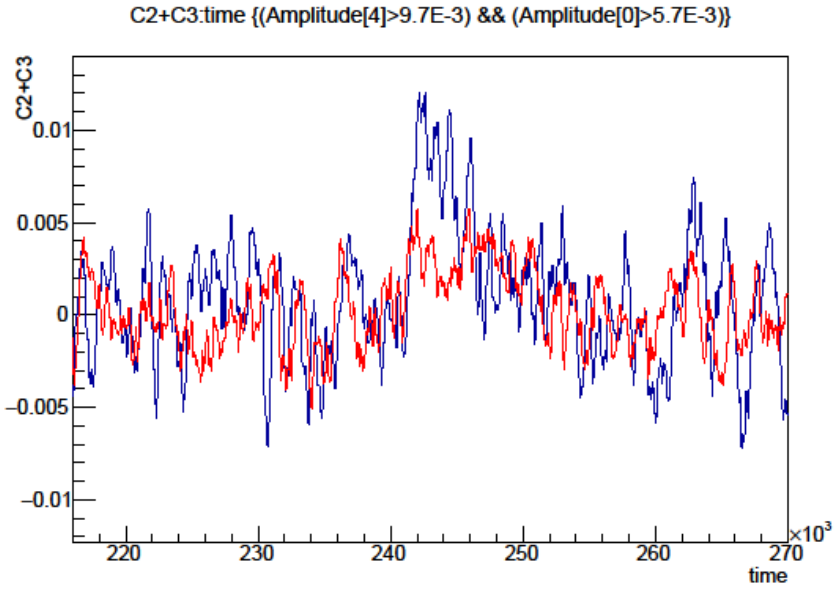
TRIM results with 20k ions

Diamond thickness (µm)	Energy loss (MeV)
300	0.93 ± 0.10
515	1.60 ± 0.13
600 (2 x 300)	1.87 ± 0.14
815 (515 + 300)	2.55 ± 0.16
1030 (2 x 515)	3.24 ± 0.18

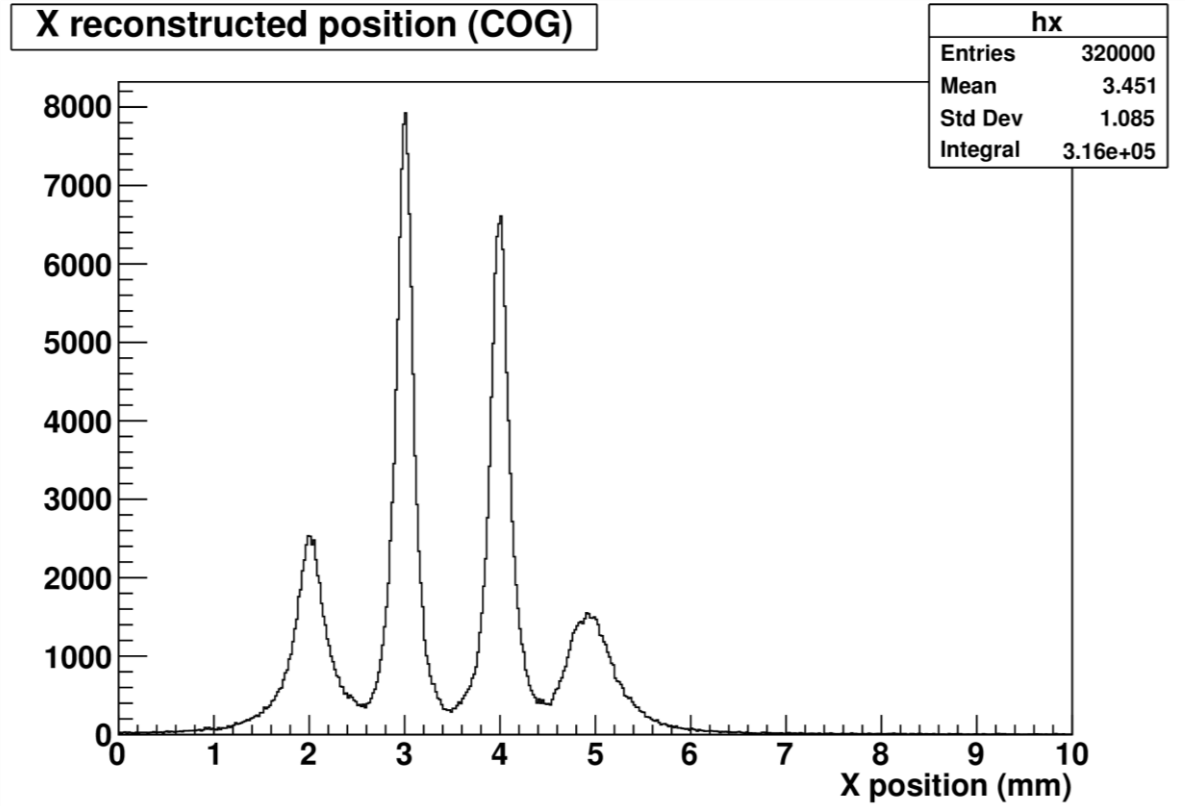
Beta source : ^{90}Sr (E_{max} = 2.28 MeV | MIP)

Typical signals observed

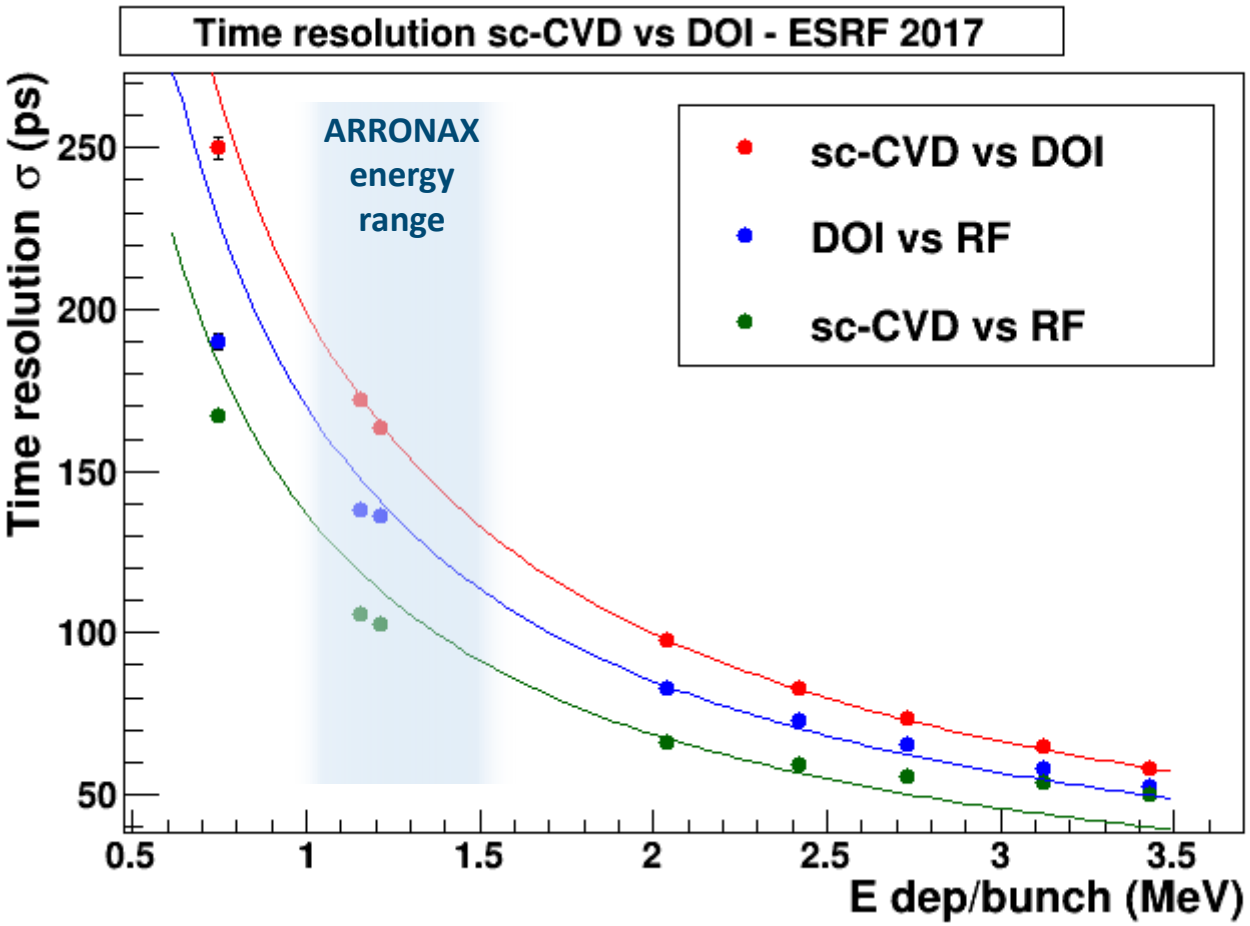


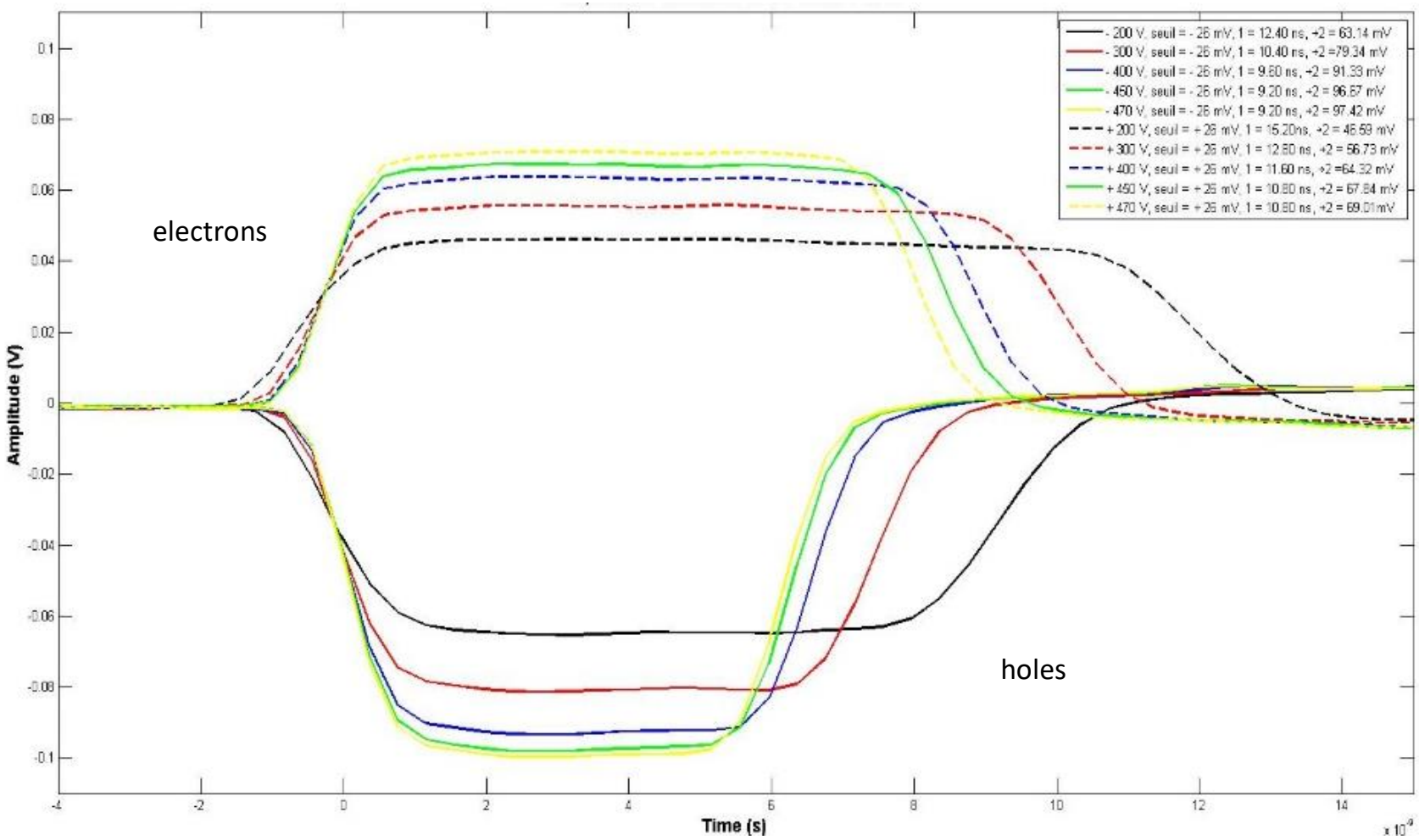


Tests at ID21 X-Ray Microscopy beamline at ESRF : First results



Preamp


Time resolution sc-CVD vs DOI - ESRF 2017
ARRONAX energy range
sc-CVD vs DOI
DOI vs RF
sc-CVD vs RF
Time resolution σ (ps)
250
200
150
100
50
0.5
1
1.5
2
2.5
3
3.5
E dep/bunch (MeV)


- 200 V, seuil = - 26 mV, t1 = 12.40 ns, +2 = 63.14 mV
- 300 V, seuil = - 26 mV, t1 = 10.40 ns, +2 =79.34 mV
- 400 V, seuil = - 26 mV, t1 = 9.60 ns, +2 = 91.33 mV
- 450 V, seuil = - 26 mV, t1 = 9.20 ns, +2 = 96.67 mV
- 470 V, seuil = - 26 mV, t1 = 9.20 ns, +2 = 97.42 mV
+ 200 V, seuil = + 26 mV, t1 = 15.20ns, +2 = 46.59 mV
+ 300 V, seuil = + 26 mV, t1 = 12.60 ns, +2 = 56.73 mV
+ 400 V, seuil = + 26 mV, t1 = 11.60 ns, +2 =64.32 mV
+ 450 V, seuil = + 26 mV, t1 = 10.80 ns, +2 = 67.84 mV
+ 470 V, seuil = + 26 mV, t1 = 10.80 ns, +2 = 69.01mV
electrons
holes
Amplitude (V)
Time (s)
x 10^-9