Large Area Polycrystalline Diamond Detectors for Online Hadron Therapy Beam Tagging Applications

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LPSC Grenoble

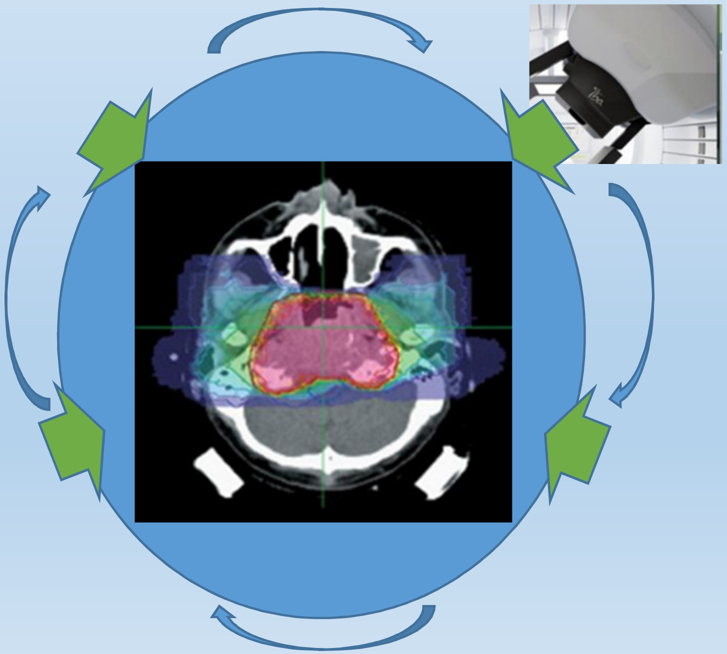
M. Fontana, J. Krimmer, E. Testa

IPN Lyon

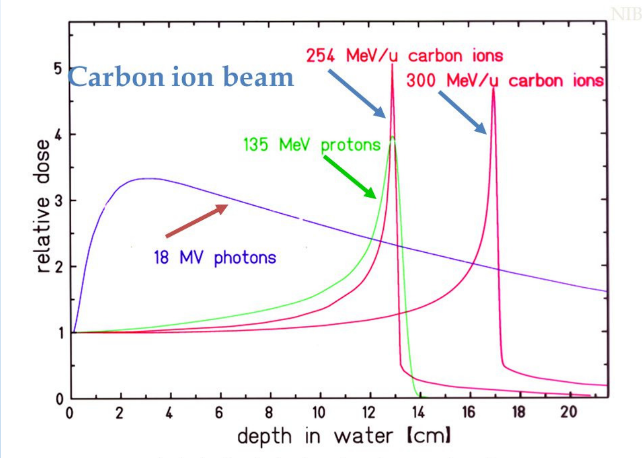
M. Salomé, J. Morse
ESRF

Hadron therapy in cancer treatment

CAL (Centre Antoine Lacassagne) Nice
Cancer treatment using proton beams

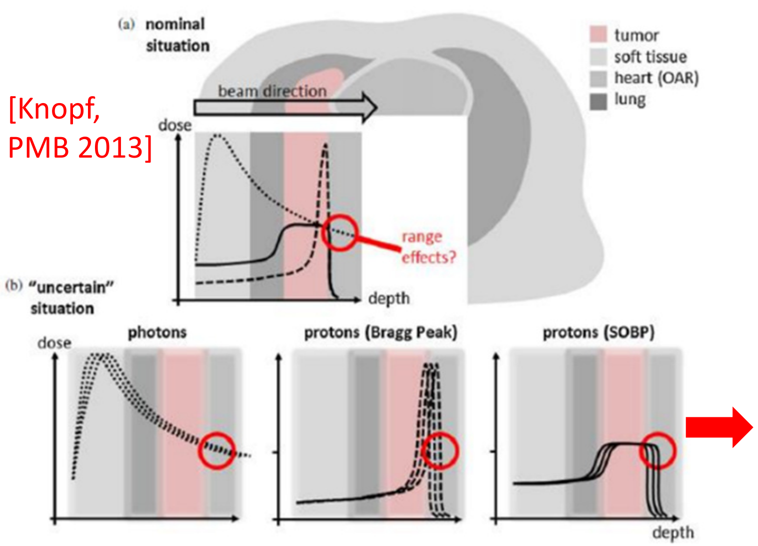


Dose delivery / incident ionizing particle



Bragg peak ➡ Ballistic precision

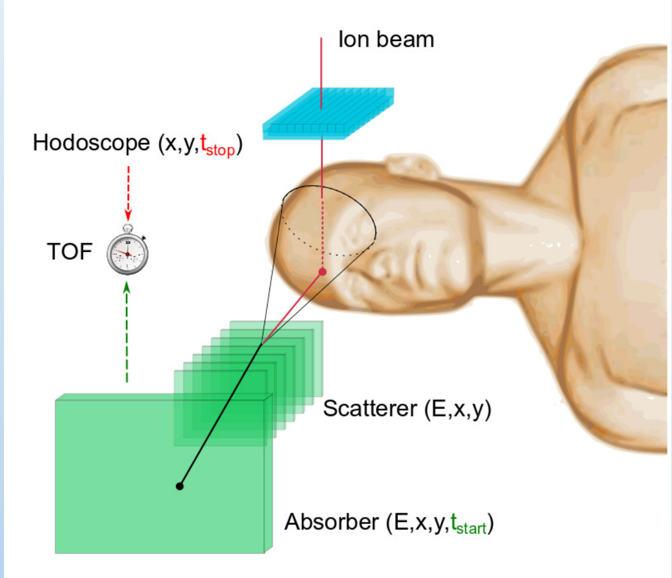
[Knopf, PMB 2013]



ClaRyS French collaboration

- Time-of-Flight Compton/ collimated gamma cameras
- Beam hodosope

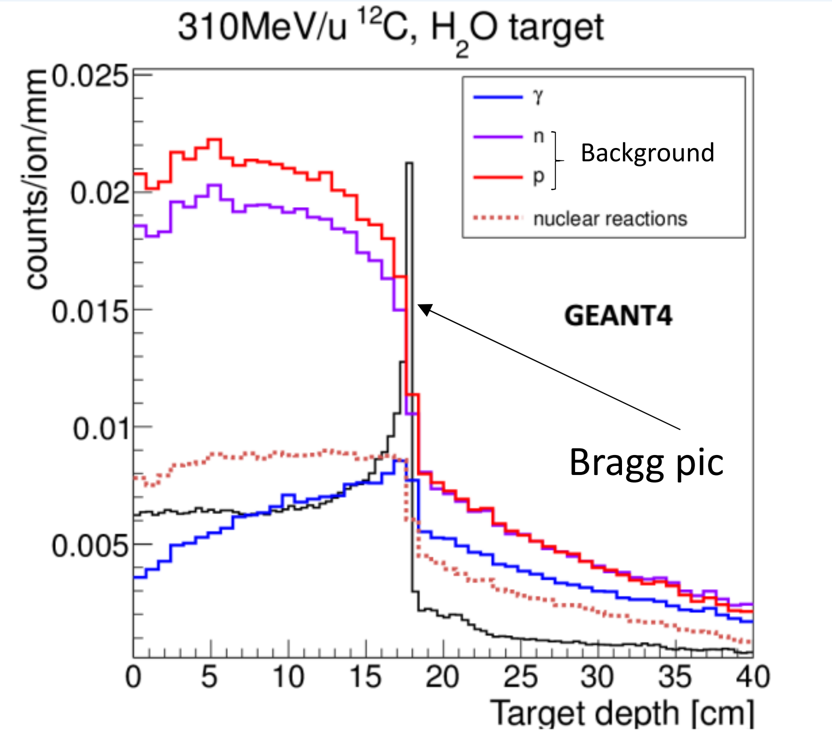
(see GamHadron project M. Pomorski CEA LIST presented at ADAMAS 2012)



Secondary radiation emission from fragmentation is correlated to ion range

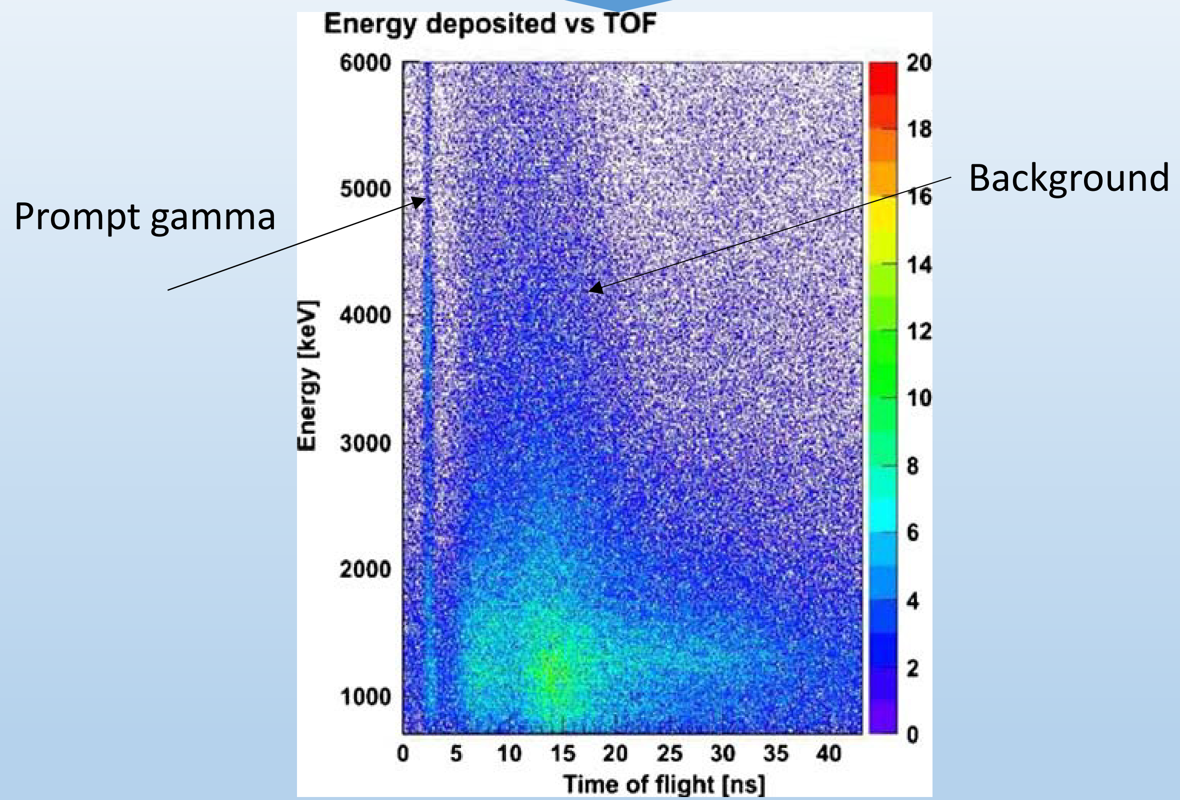
Range uncertainties ➡ Need for online control

Why to develop a beam tagging hodoscope ?



G. Dedes, PMB 2014

Exp. : 95 MeV/u ^{12}C beam impacting a PMMA target / detector = BaF_2

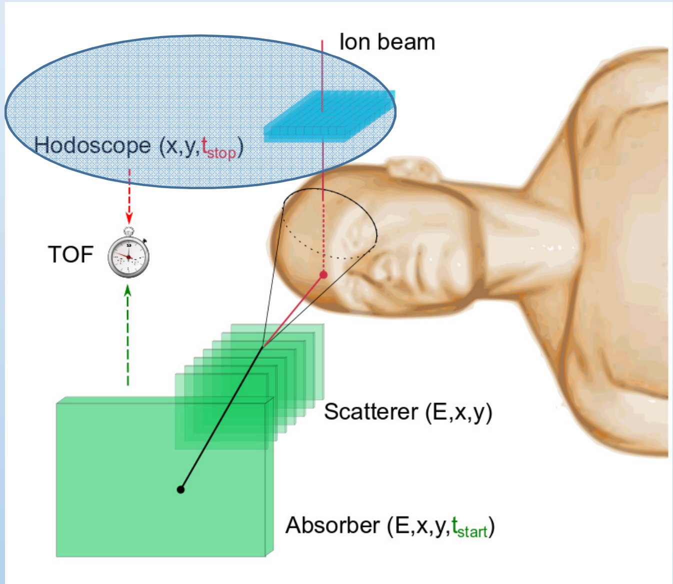


M. Testa, Rad Env Bio 2010

Hodoscope => time of flight measurement at 1 ns to reduce background

ClaRyS French collaboration

Compton camera

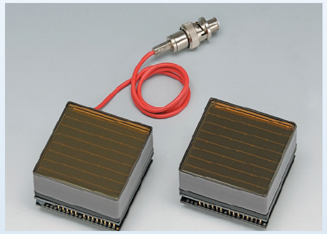


- IN2P3 : 4 laboratories
  - CPPM Marseille
  - IPNL Lyon
  - LPC Clermont Ferrand
  - LPSC Grenoble (MoniDiam project)
- CREATIS Lyon
- LIRIS Lyon
- Centre Antoine Lacassagne Nice

Beam tagging hodoscope development : LPSC MoniDiam project

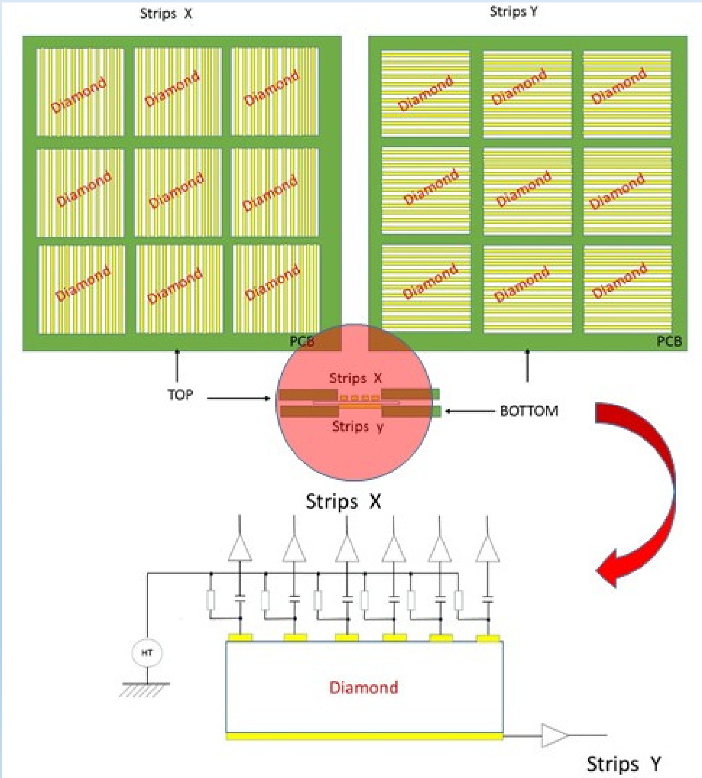
Existing development :

Array of scintillating fibres coupled to multichannel photomultiplier tubes (PMT).



Foreseen development :

MoniDiam project aims to develop a diamond based hodoscope and its dedicated integrated fast read-out electronics



Limitations :

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

Diamond Advantages :

- ❑ Intrinsic radiation hardness
- ❑ Fast signal risetime enables timing precision of a few tens of ps
- ❑ Low noise

Beam tagging hodosope specifications

- **Proton therapy (Cyclotron IBA/C230 Orsay, Dresden…):**
  - Bunch: 1-2 ns
  - HF : 9.4 ns
  - 200 protons/bunch
- **Proton therapy (Synchro-cyclotron Nice S2C2)**
  - Micro-bunch: 7 ns (16 ns)
  - Milli-bunch: 4 µs (1 ms)
  - 10^4 protons/ micro-bunch
- **Carbone therapy (HIT/CNAO):**
  - Bunch: 20-40 ns
  - Bunch interval: 200 ns
  - 10 ions/bunch

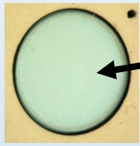
⇒

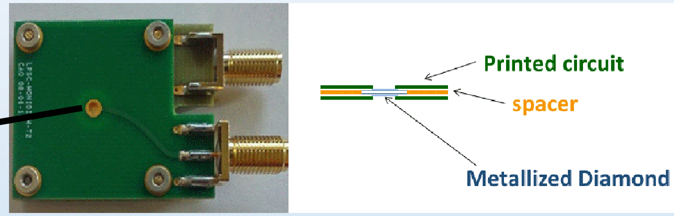
- **Counting rate:**
  - 100 MHz for the whole detector
  - ~10 MHz per channel
- **Time resolution:**
  - At the level of 100 ps
- **Spatial resolution:**
  - 1mm (readout strip)
- **Radiation hardness:**
  - 10^{11} protons/cm²/treatment,
    about 20 treatments a day
    =>10^{14} protons/cm²/year.

Beam tagging hodosope R&D

- **Large area poly-crystalline diamond pc-CVD : 20 x 20 mm² (currently on the shelf)**
- **Metallization performed at LPSC using the <u>Distributed Microwave Plasmas method</u>**
  - ❑ aluminium disk-shaped surface up to 2016
  - ❑ strips metallization foreseen in 2017
  - ❑ thickness optimization (plasma etching)

50 Ω adapted detector holder





A. Lacoste et al., Multi-dipolar plasmas for uniform processing: physics, design and performance, SCi. Technol., 11 pp 407-412, 2002

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- **Metallization performed at LPSC using the Distributed Microwave Plasmas method**
  - ❑ aluminium disk-shaped surface up to 2016
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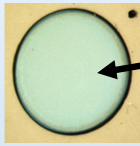
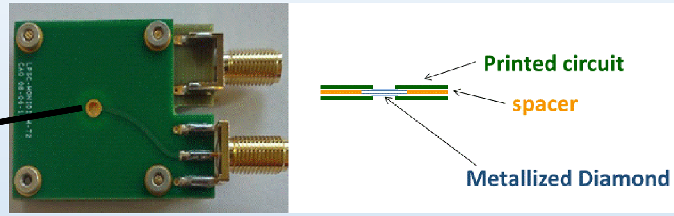
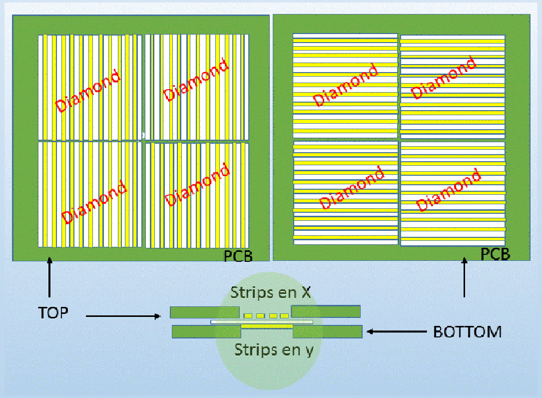
  - ❑ thickness optimization (plasma etching)
- **Final detector : 15 x 15 cm² mosaic arrangement of stripped sensors => channels >10³**
- **First prototype in 2019 : 2 x 2 diamond sensors in a mosaic arrangement**
- **Integrated readout electronic (AMS 180 and/or TSMC 130):**
  - ❑ Dynamic range: from 7 fC (1 proton of 250 MeV) up to 600 fC (1 carbon ion of 80 MeV/u)
  - ❑ Fast preamplifier 2 GHz / 40 dB
  - ❑ Low walk discriminator
  - ❑ TDC with a resolution < 100 ps
  - ❑ spectrometry (single cristals are concerned) and charge integration outputs
- **Connectics diamond /PCB :**
  - ❑ wire bonding
  - ❑ ….etc …

50 Ω adapted detector holder







Diamond R&D at LPSC

Large area diamond single crystal for High Luminosity LHC tracker

→ MonoDiam project, started in 2012

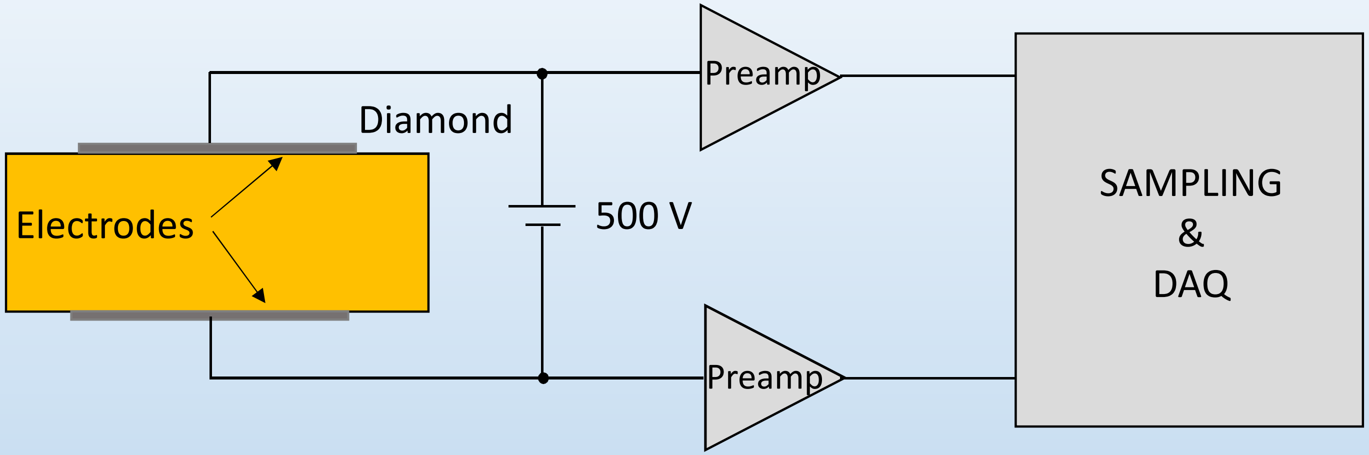
Institut Pluridisciplinaire Hubert Curien => **Characterization**

Laboratoire de Physique Subatomique et de Cosmologie => **Functionalization + characterization**

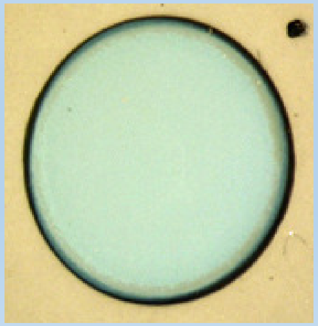
Laboratoire des Sciences des Procédés et des Matériaux => **Growth**

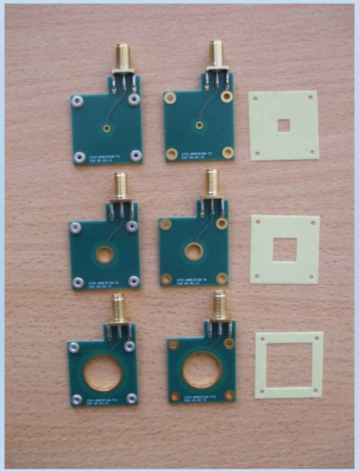
Laboratoire des sciences de l'ingénieur, de l'informatique et l'imagerie => **Functionalization**

Characterization of CVD diamond at LPSC (2015-2016)



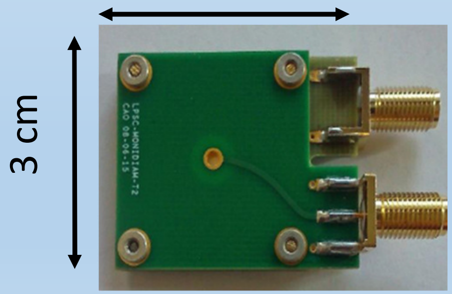
Diamond 0.45 x 0.45 cm^2 x 500 µm sc-CVD E6
Metallization 2 sides
Al 50 nm; ϕ 4 mm





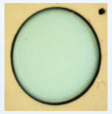
Diamond 0.45 x 0.45 cm^2 x 500 µm sc-CVD E6

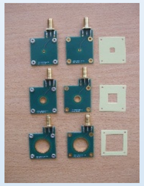
3 cm

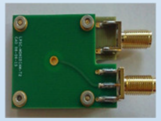


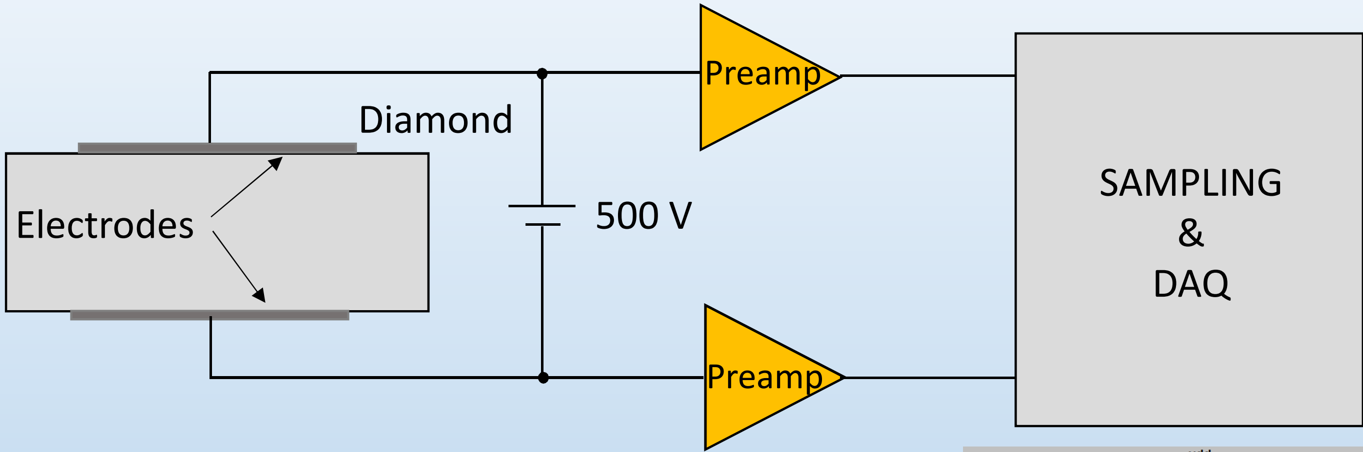
50 Ω adapted detector holder

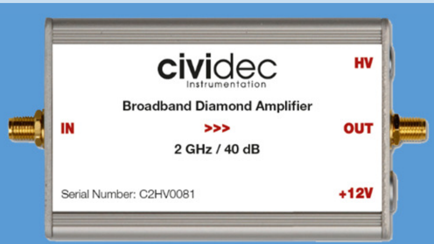
Characterization of CVD diamond at LPSC (2015-2016)



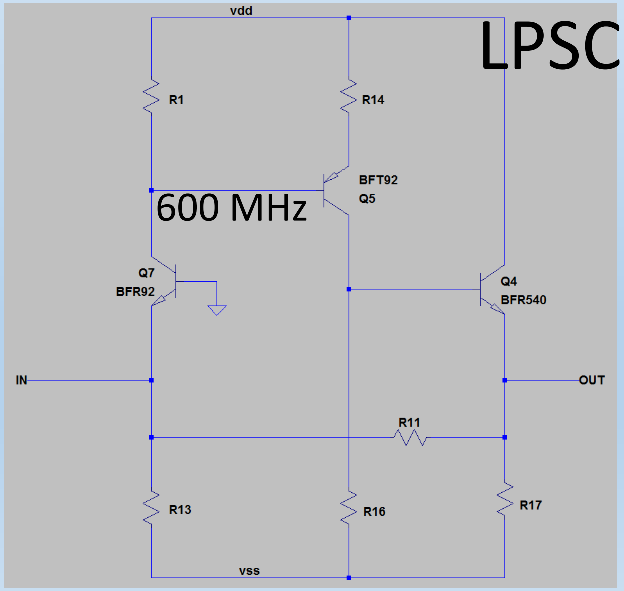




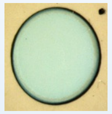


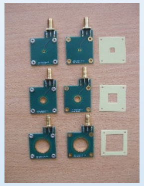


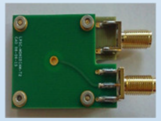
Band Width:	2 GHz
Gain:	40 dB
Impedance:	50 Ω
Dynamic range:	~ +/- 1 V
Power Supply:	12 V / 100 mA

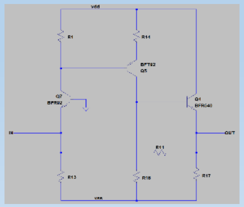


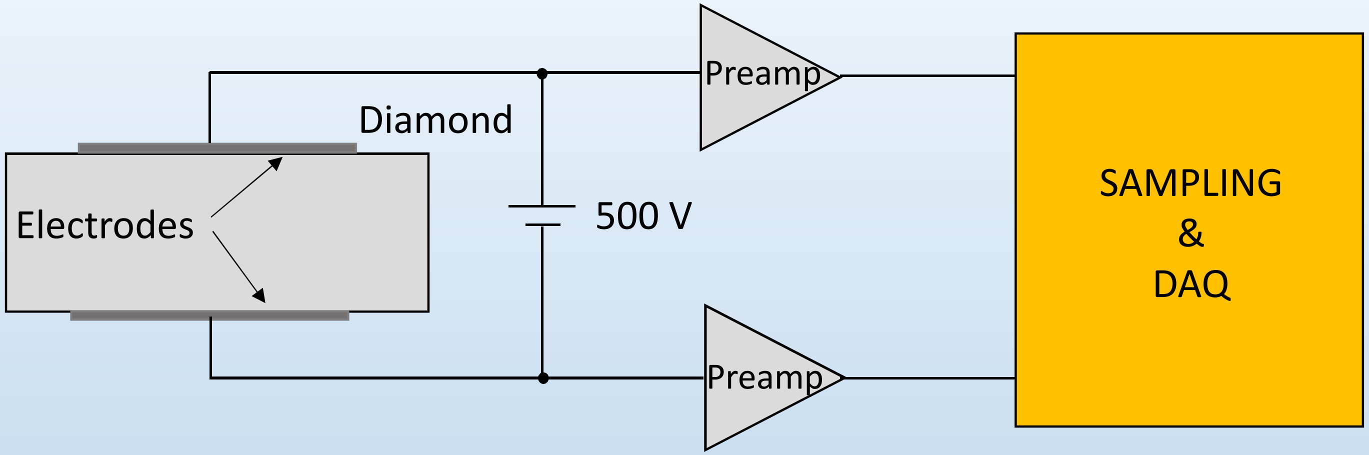
Characterization of CVD diamond at LPSC (2015-2016)











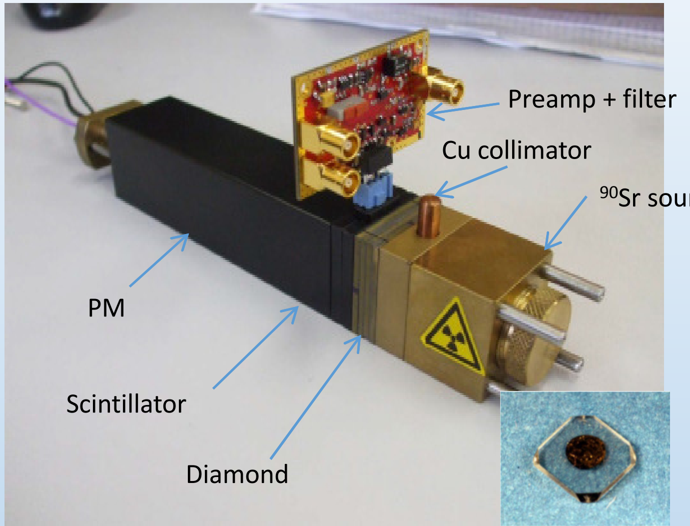
WaveCatcher
500 MHz; 3.2 GS/s

		Unit
SAMLONG ASIC technology	AMS CMOS 0.35µm	
System number of channels	2, 8, 16, 32, 48, 64	
Power consumption	2.5 (2-ch), 15 (8-ch), 23 (16-ch), 100 (64-ch)	W
Sampling depth	1024 / channel	Cells
Sampling speed	0.4 to 3.2	GS/s
Bandwidth	500	MHz
Range (unipolar)	± 1.25 (with full range individual channel offset)	V
ADC resolution	12	bits
Noise	0.75	mV rms
Dynamic range	11.5	bits rms
Readout time	11 to 66 (depends on number of cells read)	µs
Time precision before correction	< 20	ps rms
Time precision after time INL correction	< 5	ps rms

WaveRunner Lecroy
2 GHz; 10 or 20 GS/s

Measurements with a ^{90}Sr source : MonoDiam test bench

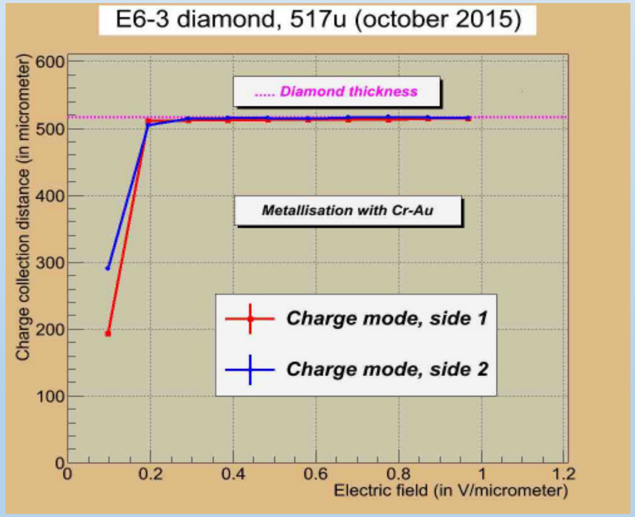
^{90}Sr 74 MBq β source



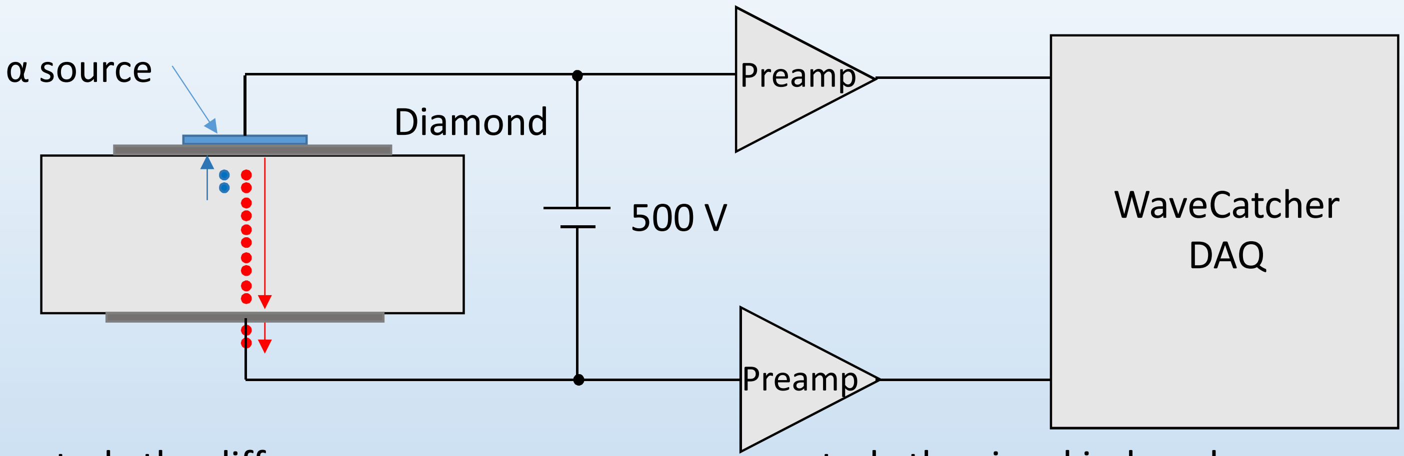
Diamond 4 x 4 mm^2

Triggering on high energy electrons (scintillator behind diamond)

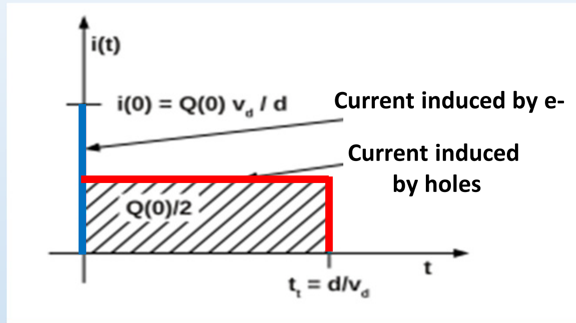
Charge Collection Distance measurement



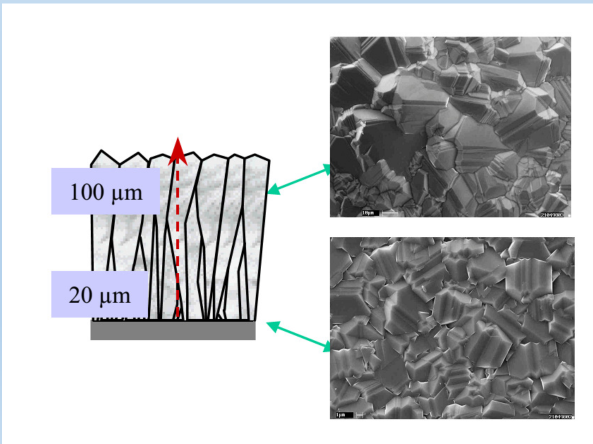
Measurements with ^{241}Am : α source (5.4 MeV)



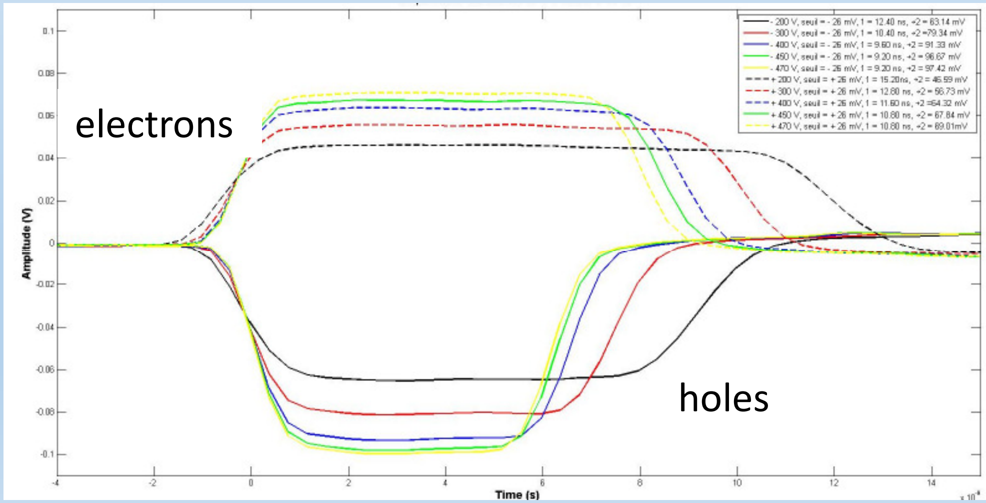
Theoretical Signal



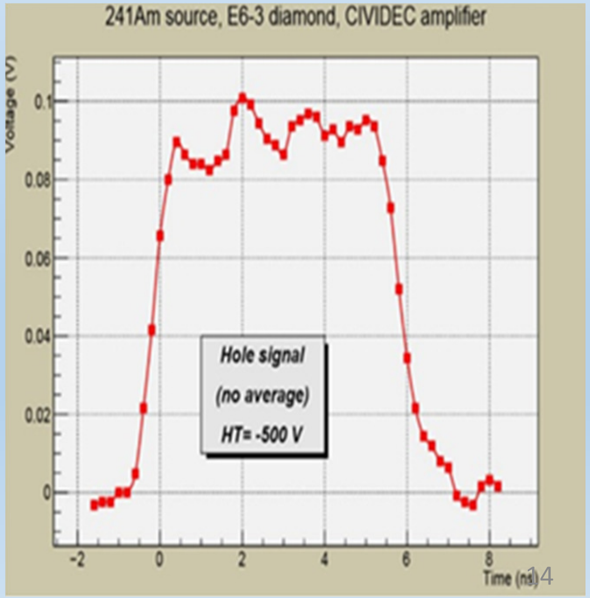
α => study the difference between the growth and substrate sides



α => study the signal induced by electrons / holes

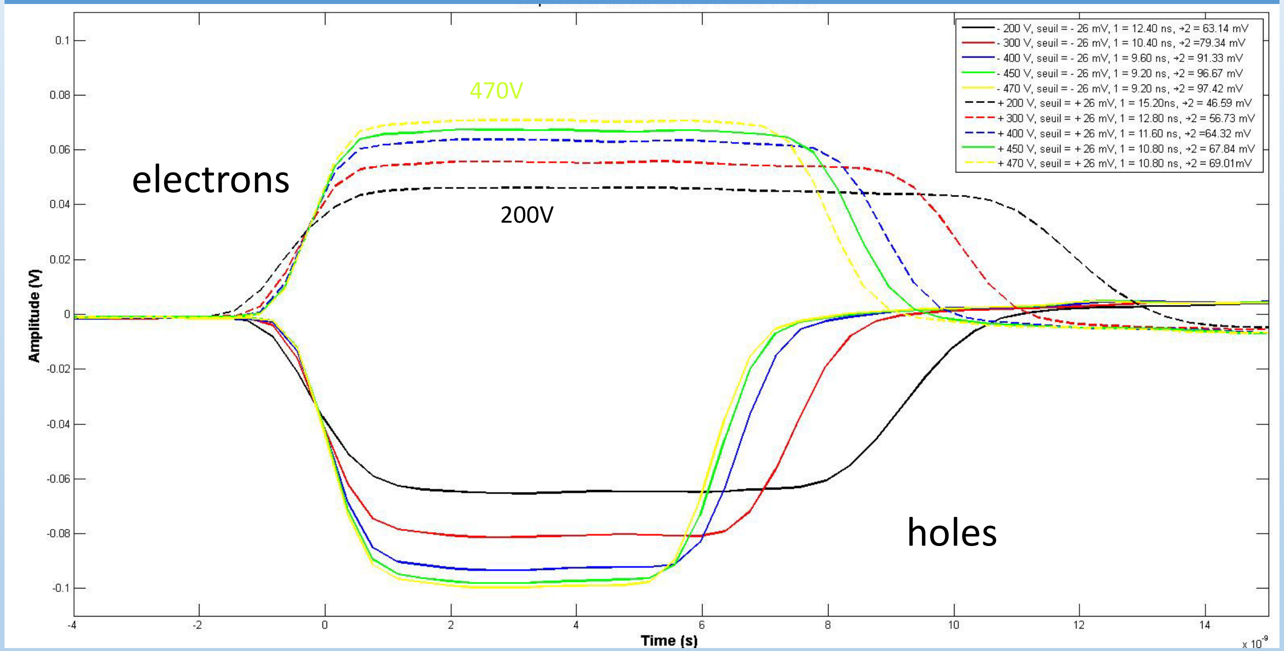


Experimentally measured signal sc-CVD

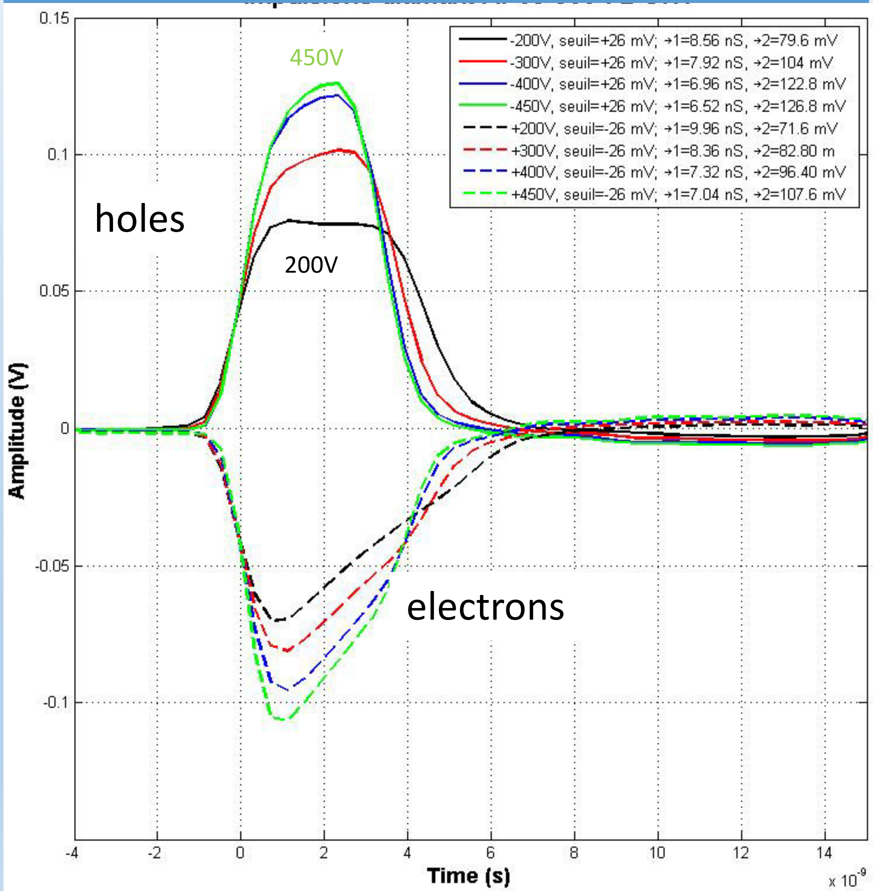


Measurements with ^{241}Am : α source (5.4 MeV)

0.45 x 0.45 cm^2 x 518 µm sc-CVD diamond Element 6



0.5 × 0.5 cm^2 × 300 µm pc-CVD
Augsburg Univ. heteroepitaxially
grown on iridium(courtesy M. Schreck)



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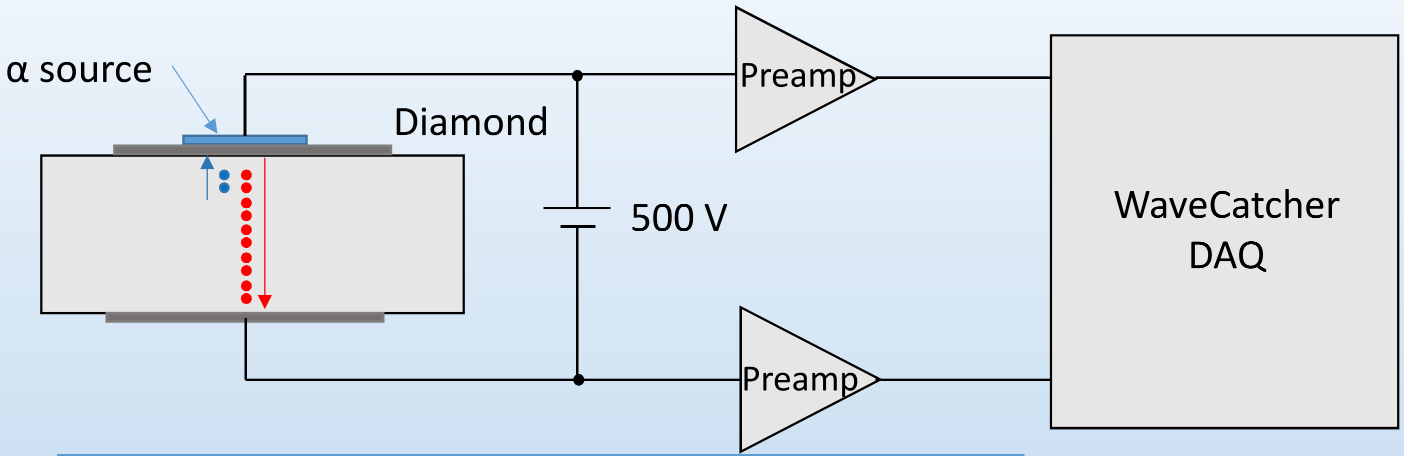

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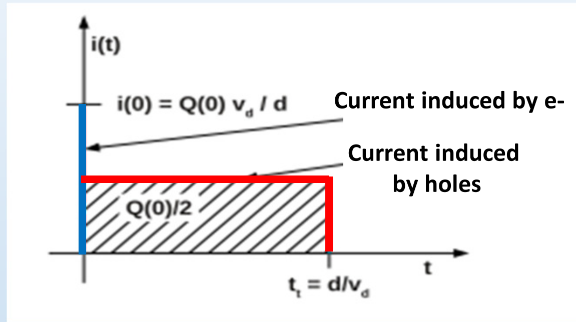

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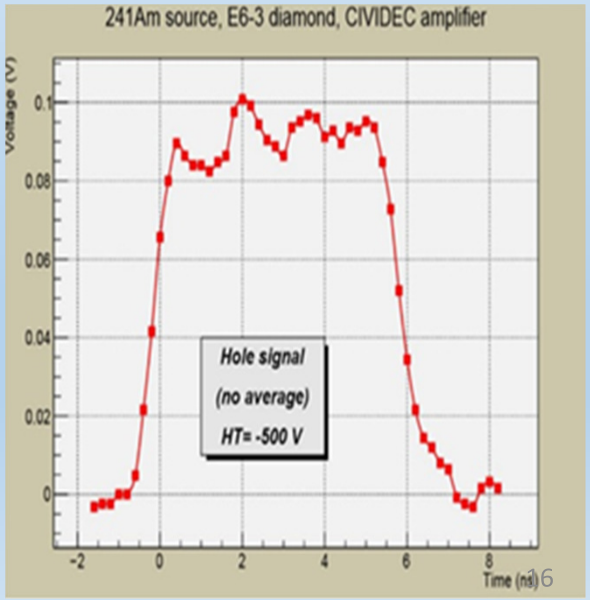
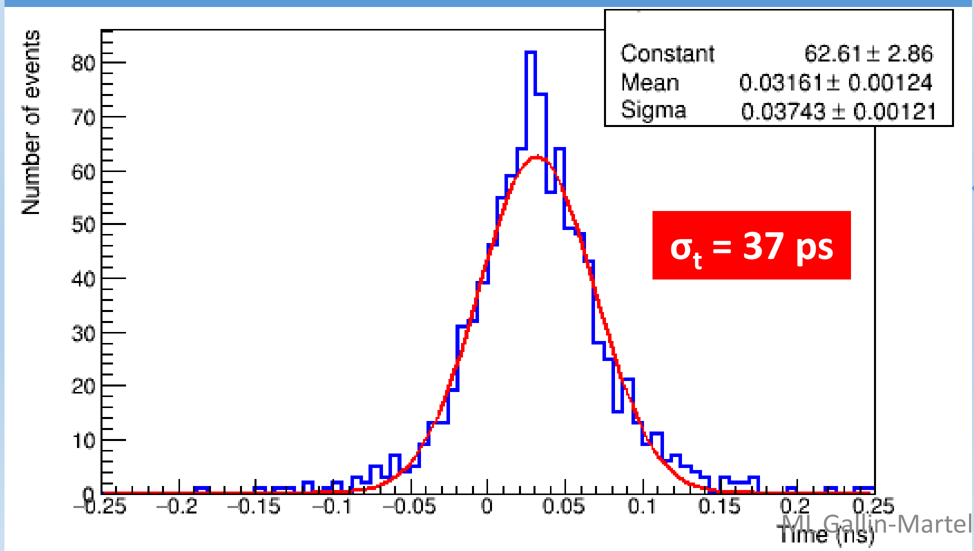


Time resolution pc-CVD 20 x 20 mm^2 x 500 µm E6
Offline Constant Fraction Discriminator method

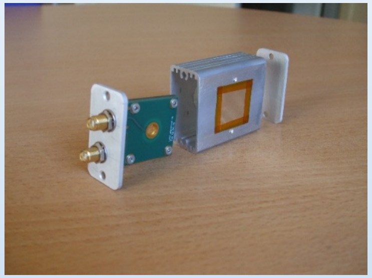


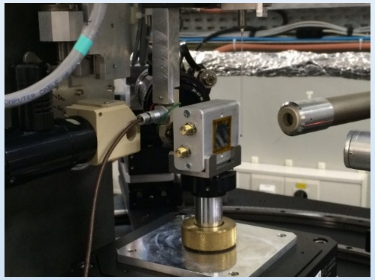
Timing difference of both surface signals

Pulsed beam (8.5 keV ~100 ps) at ESRF ID21 X-ray Microscopy beamline

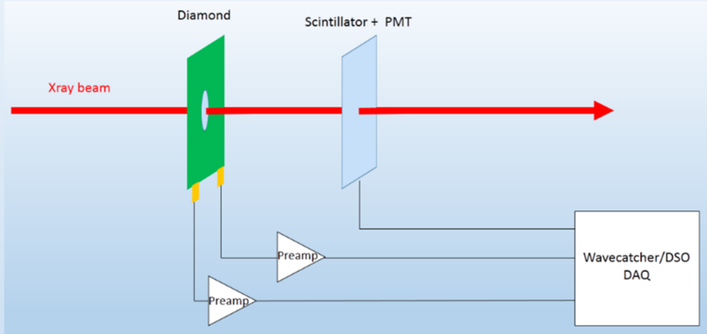
Electromagnetic shielding box

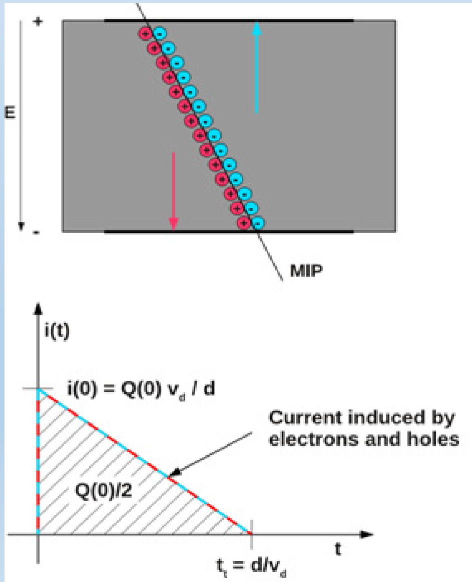
The box was positioned with micrometric reproducibility at the sample position of the micro-diffraction end station (in air) of the ID21 beamline at European Synchrotron Radiation Facility (ESRF) in Grenoble.

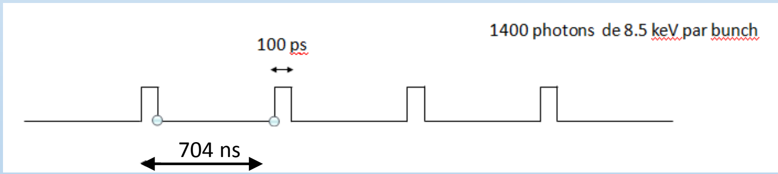




ESRF







A 8.5 keV photon focused micro-beam with a well-defined time structure was used at the ESRF.

As regards energy deposition in the diamond, in the ESRF 4-bunch mode, the ~100 ps duration X-ray pulses, containing a fixed number of photons varying up to ~1400, spaced at 700 ns intervals, mimic the passage of single ionizing particles

Pulsed beam (8.5 keV ~100 ps) at ESRF ID21 X-ray Microscopy beamline

Electromagnetic shielding box

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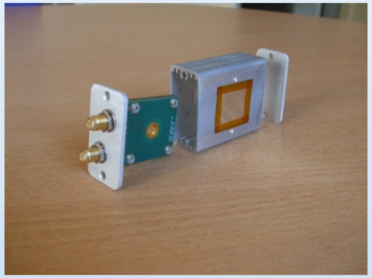
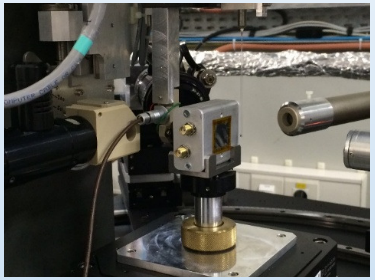
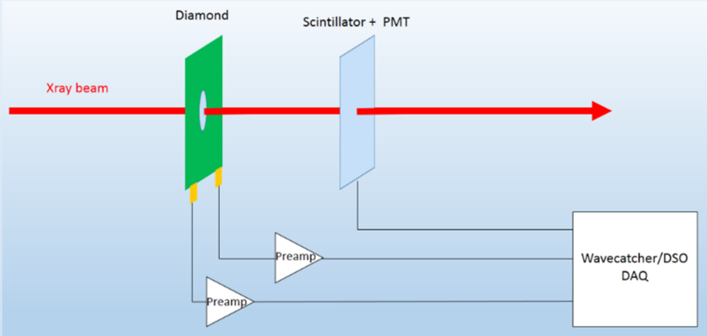
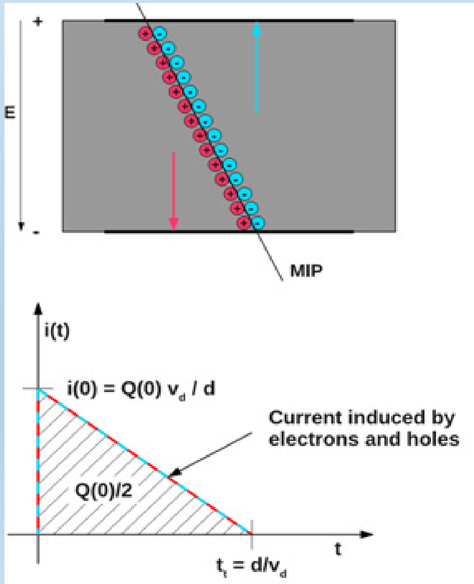
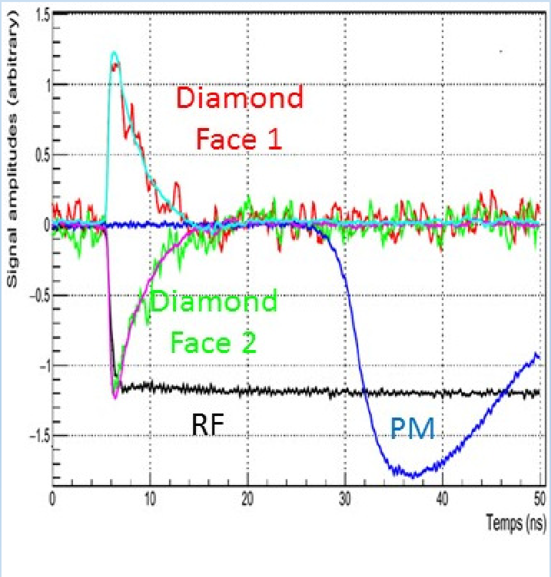


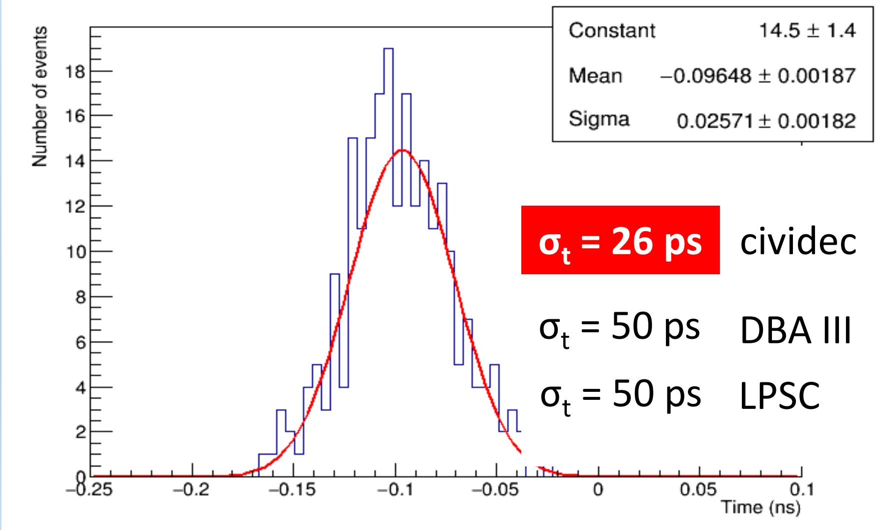








Time resolution sc-CVD 0.45x 0.45 cm^2 x 518 µm E6



σ_t = 26 ps cividec

σ_t = 50 ps DBA III

σ_t = 50 ps LPSC

Pulsed beam (8.5 keV ~100 ps) at ESRF ID21 X-ray Microscopy beamline

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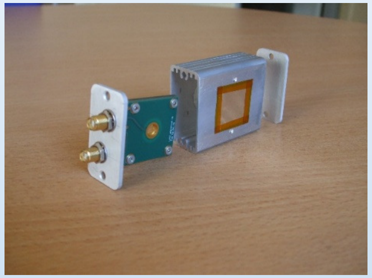
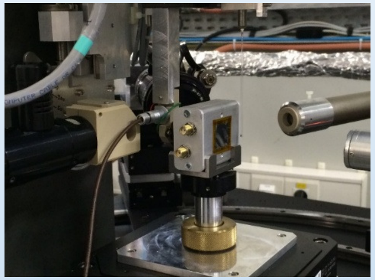
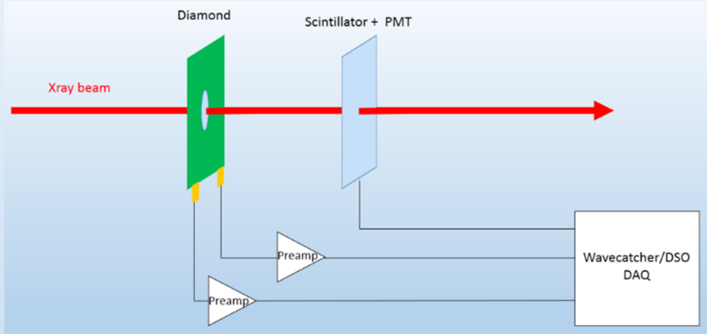
The box was positioned with micrometric reproducibility at the sample position of the micro-diffraction end station (in air) of the ID21 beamline at European Synchrotron Radiation Facility (ESRF) in Grenoble.

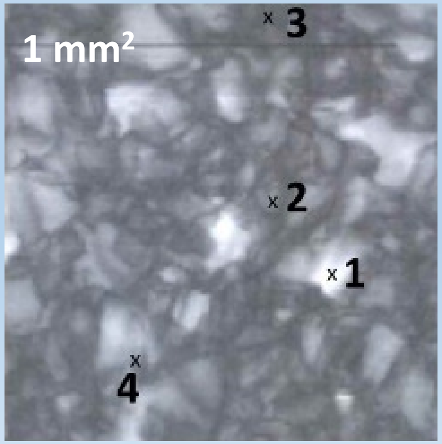


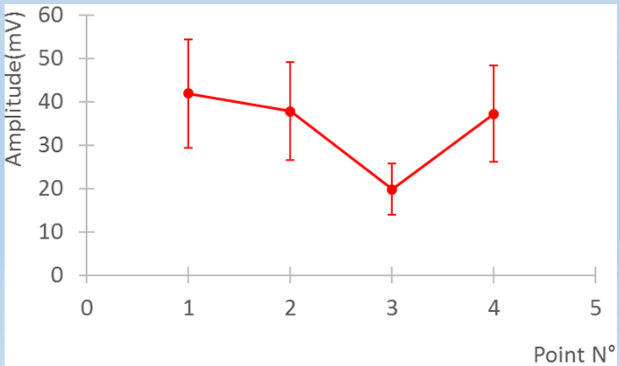




X-Ray analysis on a surface of 1 mm^2

1 x 1 cm^2 x 500 µm pc-CVD Element 6





Diamond surface mapping was performed

The grey scale corresponds to the charge efficiency measured by an electrometer

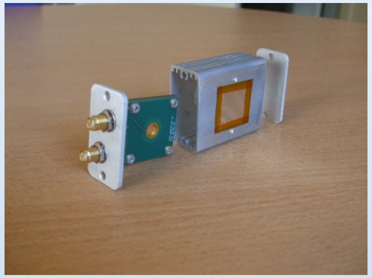
The response of the detector reflects the spatial distribution of the grain boundaries

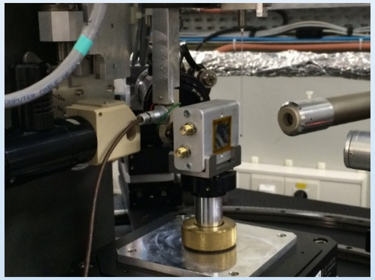
A factor of 2 of difference is observed between the clearest point and the darkest one

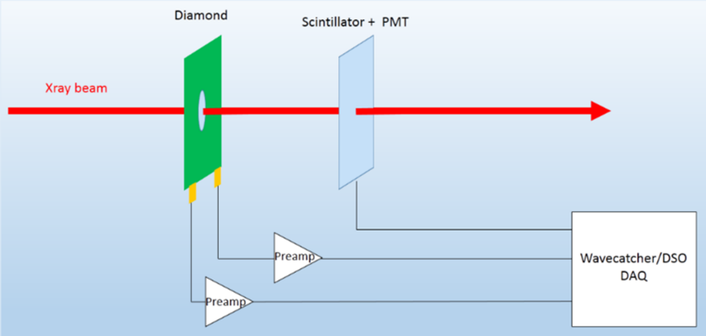
Pulsed beam (8.5 keV ~100 ps) at ESRF ID21 X-ray Microscopy beamline

Electromagnetic shielding box

The box was positioned with micrometric reproducibility at the sample position of the micro-diffraction end station (in air) of the ID21 beamline at European Synchrotron Radiation Facility (ESRF) in Grenoble.

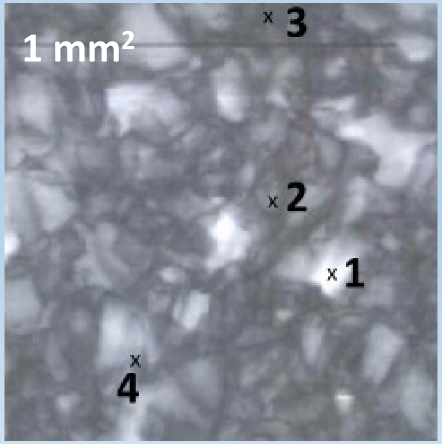


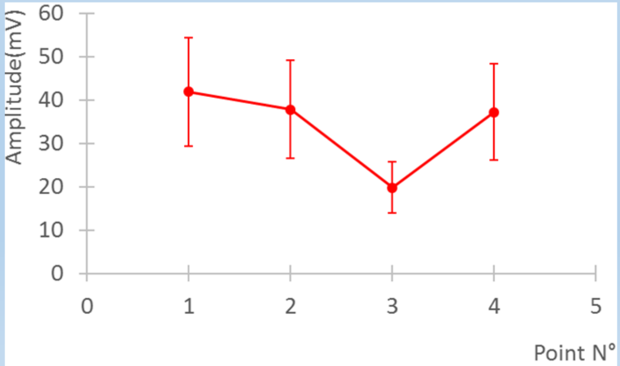




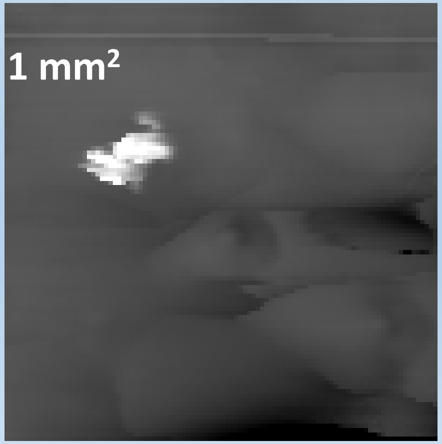
X-Ray analysis on a surface of 1 mm^2

1 x 1 cm^2 x 500 µm pc-CVD Element 6



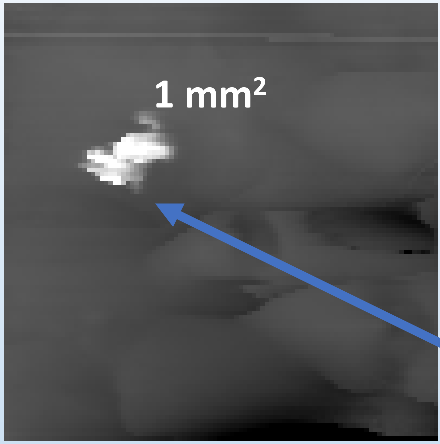


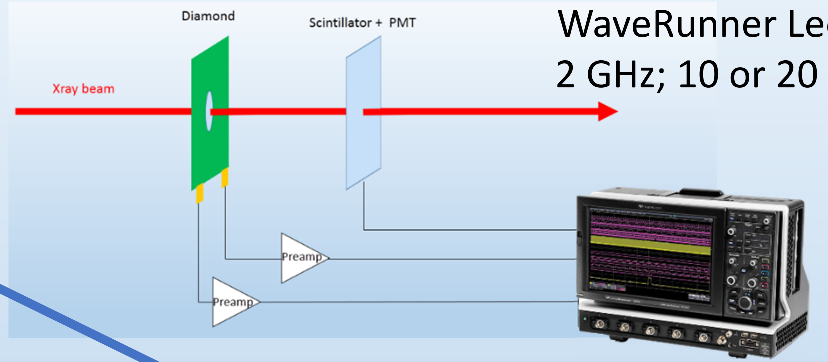
0.5 × 0.5 cm^2 × 300 µm pc-CVD Augsburg University



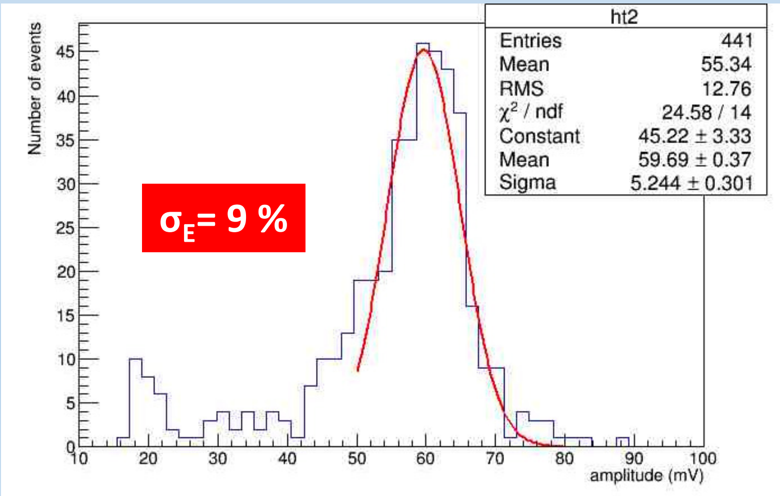
Pulsed beam (8.5 keV ~100 ps) at ESRF ID21 X-ray Microscopy beamline

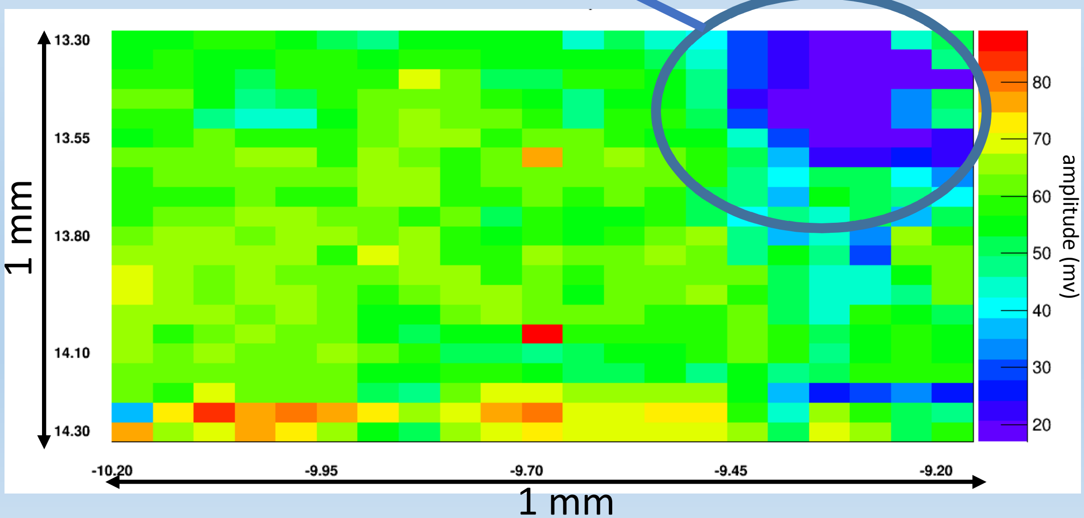
5 × 5 mm² × 300 µm pc-CVD
Augsburg University
heteroepitaxially grown on
iridium





Signal maximum amplitude distribution measured over a 1 mm² surface

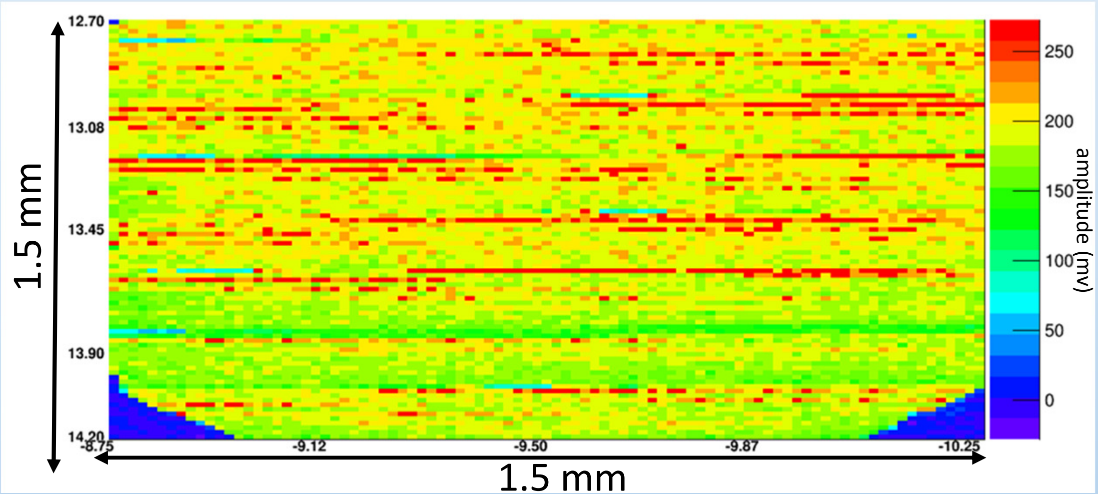


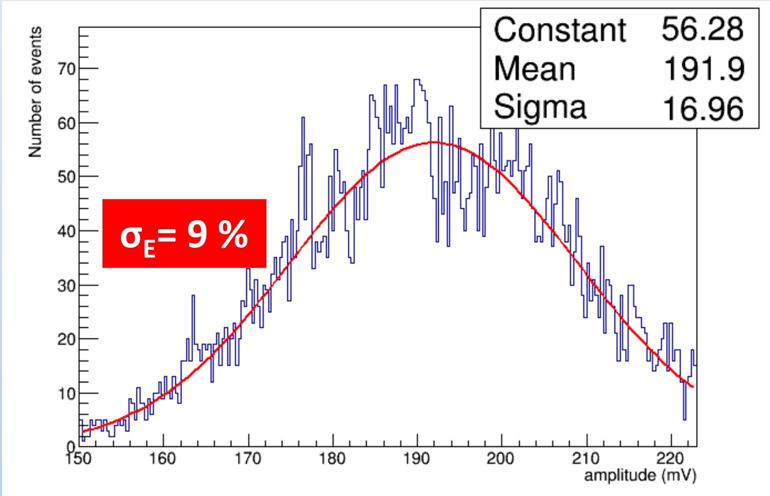


Pulsed beam (8.5 keV ~100 ps) at ESRF ID21 X-ray Microscopy beamline

4.5 x 4.5 mm^2 x 518 µm sc-CVD diamond Element 6

Signal maximum amplitude distribution measured over the 1.5 x 1.5 mm^2 surface

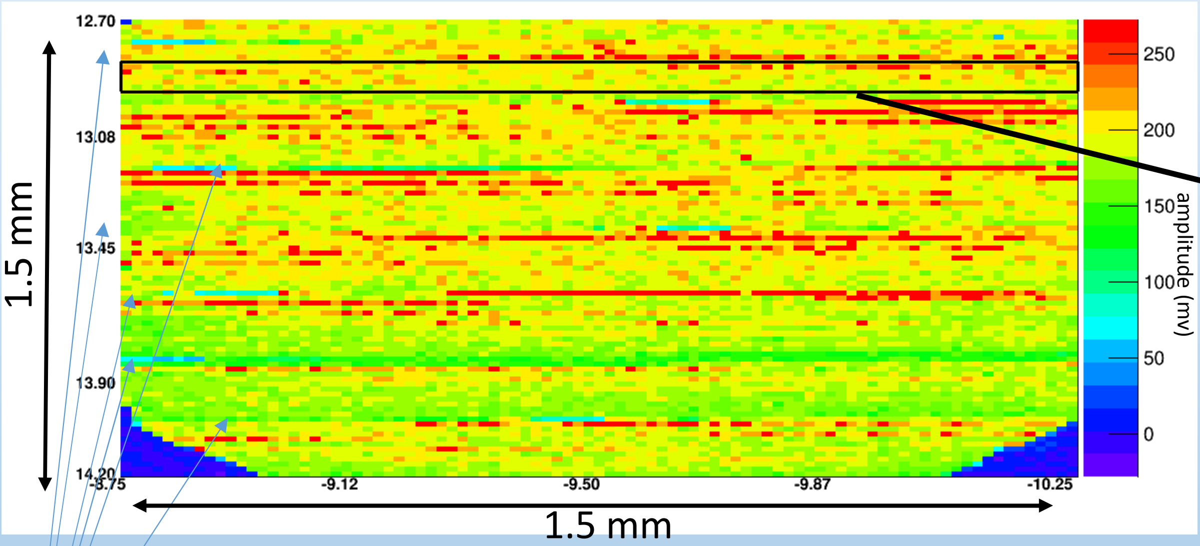


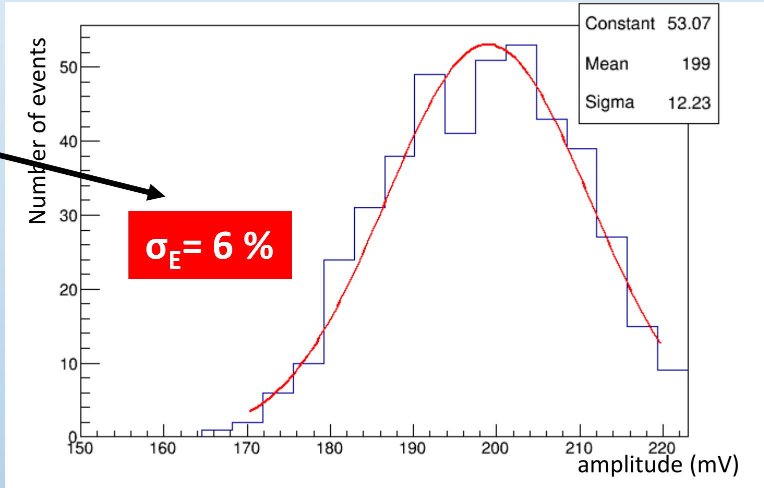


Pulsed beam (8.5 keV ~100 ps) at ESRF ID21 X-ray Microscopy beamline

4.5 x 4.5 mm^2 x 518 µm sc-CVD diamond Element 6

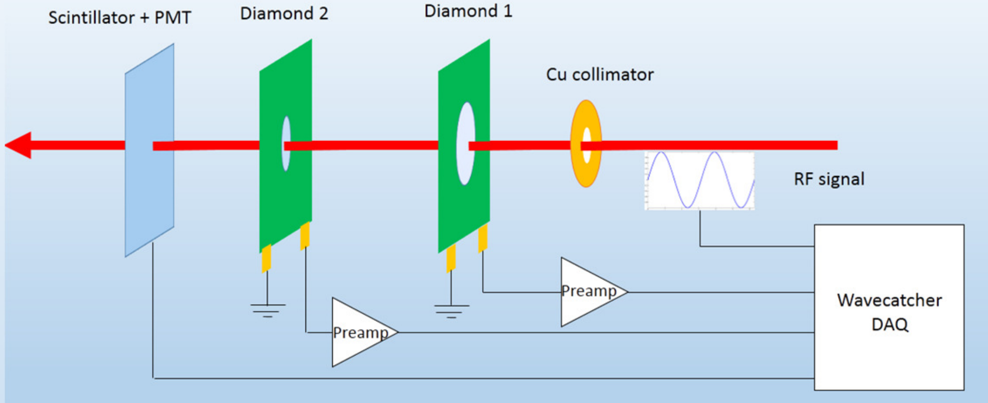
Signal maximum amplitude distribution measured over the 1.5 x 1.5 mm^2 surface



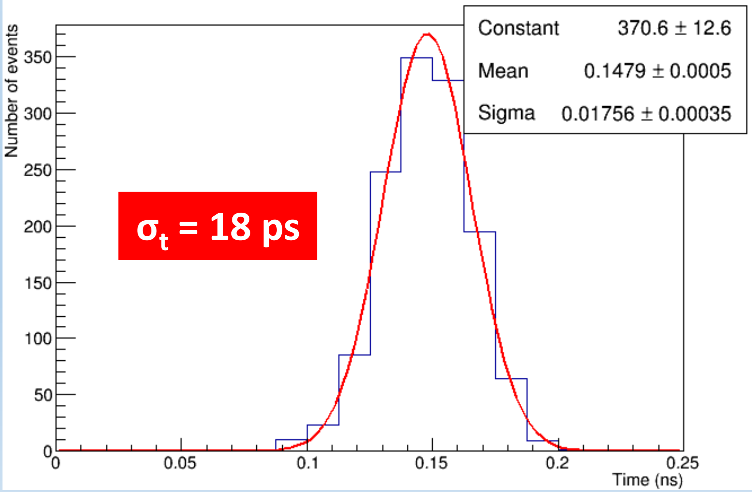


Horizontal lines = beam top-up that occurs every hour …… run = 8 hours of data acquisition

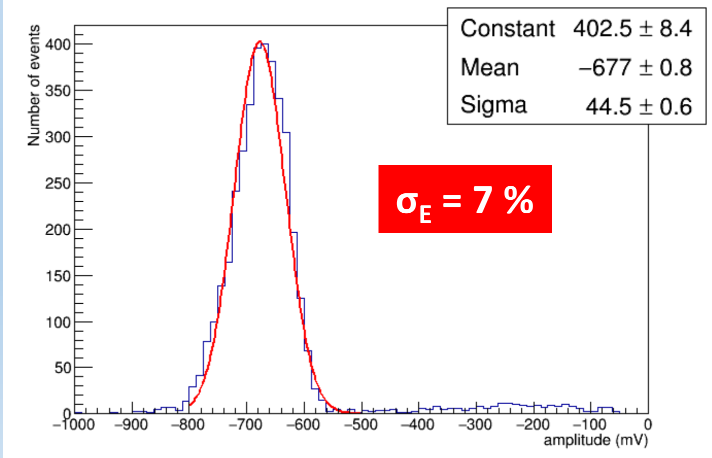
95 MeV/u ^{12}C beam at GANIL



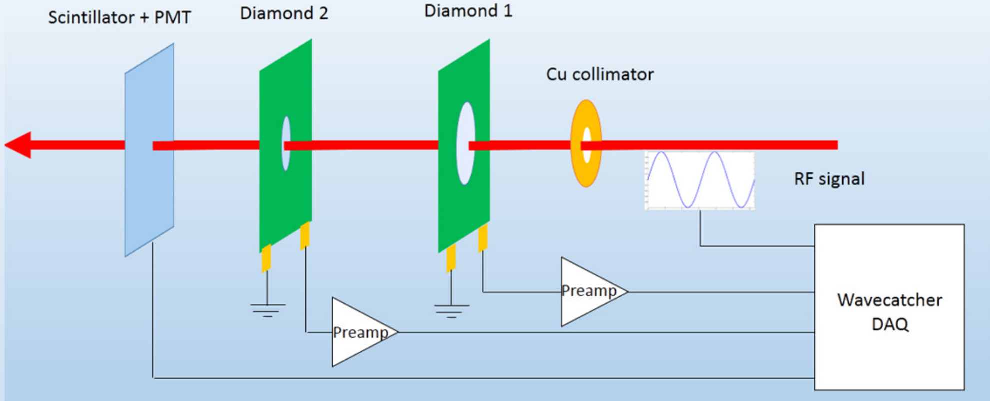
Time resolution
0.45 x 0.45 cm^2 x 518 µm sc-CVD E6
0.5 x 0.5 cm^2 x 300 µm pc-CVD Augsburg



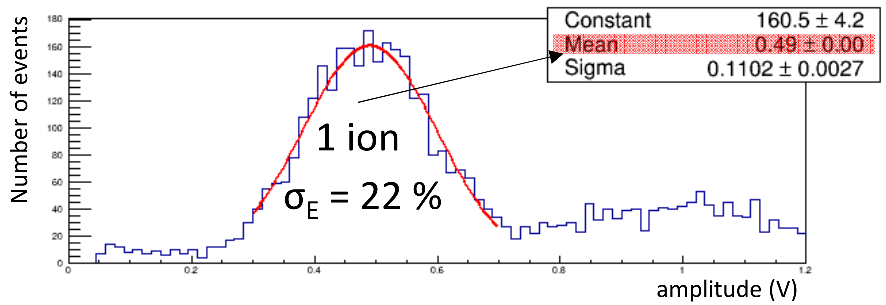
Energy resolution
0.5 x 0.5 cm^2 x 300 µm pc-CVD Augsburg

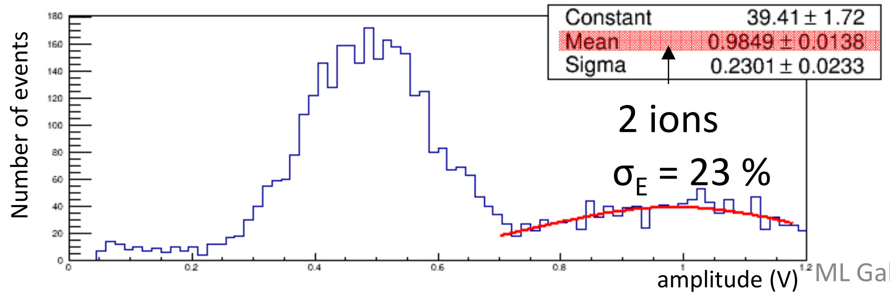


95 MeV/u ^{12}C beam at GANIL

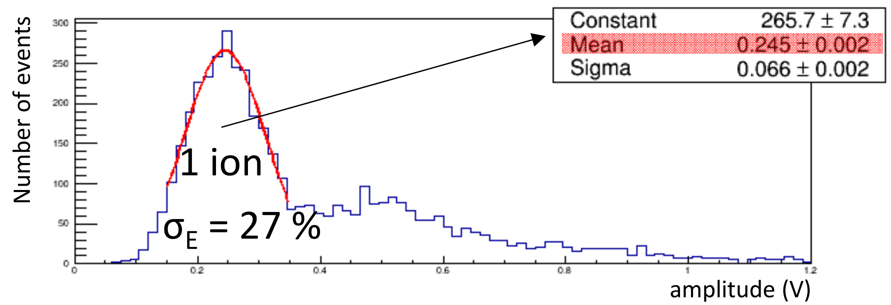


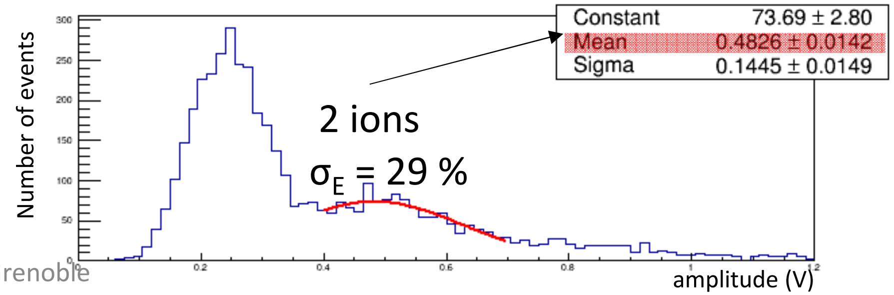
10 x 10 mm^2 x 500 µm pc-CVD E6





20 x 20 mm^2 x 500 µm pc-CVD E6





Conclusion

Synthetic pc-CVD diamond detectors are foreseen for on-line hadrontherapy beam tagging applications.

They will be used as a hodoscope which plays a major role for particle tagging using Time Of Flight both in a gamma camera and Compton camera projects proposed by the CLaRyS French collaboration. Other applications such as proton radiography and secondary proton vertex imaging are also foreseen.

Their radiation hardness, fast response and good signal to noise ratio make diamonds good candidates :

- a time resolution better than 40 ps,
- an energy resolution better than 10 %,

were measured irradiating the whole surface of pc-CVD diamond using various ionizing radiations particles despite the obvious non uniformity of the crystalline structure (ESRF response map).

Test benches have been setup at LPSC: alpha, beta sources + wave catcher acquisition

Ongoing surface characterization using ESRF X-ray microbeams (response map)

Thickness optimization : plasma etching

The final detector will consist of a ~15×15 cm^2 mosaic arrangement of stripped sensors read by a dedicated integrated electronics (~1800 channels) with the following characteristics :

- counting rate per channel : 10 MHz,
- time resolution at the level of few tens of ps,
- spatial resolution at the level of 1 mm.
- dynamic range: from 250 MeV protons to 80 MeV/u carbon

The availability and affordability of very large area diamonds is still an issue for our needs!

Acknowledgement

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).

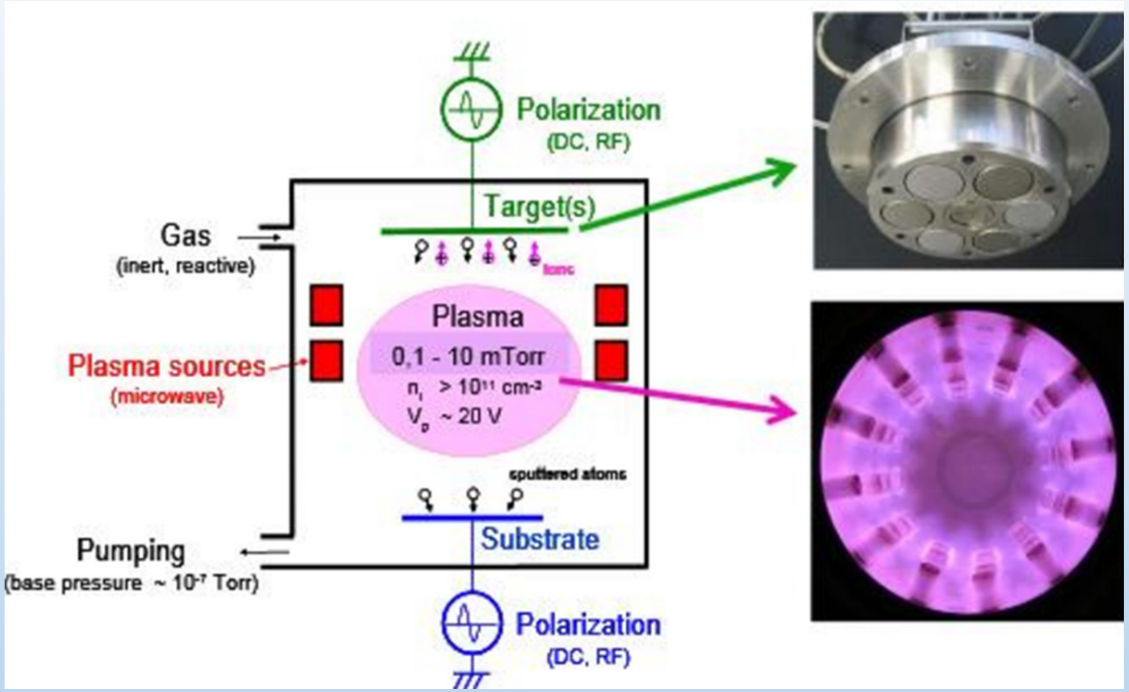
The **CLARA Canceropole** (Oncostarter Project) is thanked.

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

BACKUP

Diamond metallization



The crystal surface preparation and metal deposition is performed by a sequential plasma process consisting in two steps of reactive plasma processing followed by plasma-assisted sputtering

<u>To learn more:</u>

A. Lacoste et al., Multi-dipolar plasmas for uniform processing: physics, design and performance, SCi. Technol., 11 pp 407-412, 2002

WaveCatcher
500 MHz; 3.2 GS/s

		Unit
SAMLONG ASIC technology	AMS CMOS 0.35µm	
System number of channels	2, 8, 16, 32, 48, 64	
Power consumption	2.5 (2-ch), 15 (8-ch), 23 (16-ch), 100 (64-ch)	W
Sampling depth	1024 / channel	Cells
Sampling speed	0.4 to 3.2	GS/s
Bandwidth	500	MHz
Range (unipolar)	± 1.25 (with full range individual channel offset)	V
ADC resolution	12	bits
Noise	0.75	mV rms
Dynamic range	11.5	bits rms
Readout time	11 to 66 (depends on number of cells read)	µs
Time precision before correction	< 20	ps rms
Time precision after time INL correction	< 5	ps rms

It is based on the SAMLONG chip, an analog circular memory of 1024 cells per channel designed in a cheap pure CMOS 0.35µm technology.

The board also offers a lot of functionalities. It houses a USB 12 Mbits/s interface.

D. Breton, E. Delagnes, J. Maalmi – Workshop on timing detectors – Krakow – November 2010

Contact persons :

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Eric Delagnes is with CEA/IRFU, Centre de Saclay, 91191 Saclay, France (telephone: + 33 1 69082252, e-mail: eric.delagnes@cea.fr)

	NINO	PADI	Expected ASIC
Bandwidth	≈ 500MHz	411 MHz	> 2GHz
Input Impedance	50 Ω Adjustable	30-160 Ω	< 30 Ω - ?
Min. Input-referred Threshold	10fC	25fC	< 5fC
Threshold Type		DAC	DAC
Gain (dB)	30	48	> 40
Techno.	CMOS 250 nm	CMOS 180 nm	CMOS 130 nm
Input Signal range	30fC – 2pC		<5fC – 600fC (proton …)

Contact persons :

Laurent Gallin-Martel (laurent.gallinmartel@lpsc.in2p3.fr) Fatah Rarbi(rarbi@lpsc.in2p3.fr) are from LPSC Grenoble France

Pulsed beam (8.5 keV ~100 ps) at ESRF ID21 X-ray Microscopy beamline

Time resolution measured on various diamonds				
	Diamond	**Preamp.**	**HT (V)**	**Time Resolution RMS (ps).**
sc	**0.45 x 0.45 cm² x 518 µm**	CIVIDEC	-500	26,7
sc	**0.45 x 0.45 cm² x 518 µm**	CIVIDEC	500	25,1
sc	**0.45 x 0.45 cm² x 518 µm**	DBAIII	-500	48,84
sc	**0.45 x 0.45 cm² x 518 µm**	DBAIII	500	50,11
sc	**0.45 x 0.45 cm² x 518 µm**	LPSC	-500	53,8
sc	**0.45 x 0.45 cm² x 518 µm**	LPSC	500	48,41
pc	**0.5 x 0.5 cm² x 300 µm**	CIVIDEC	300	49,22
pc	**1 x1 cm² x 500 µm**	CIVIDEC	300	71,94