

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

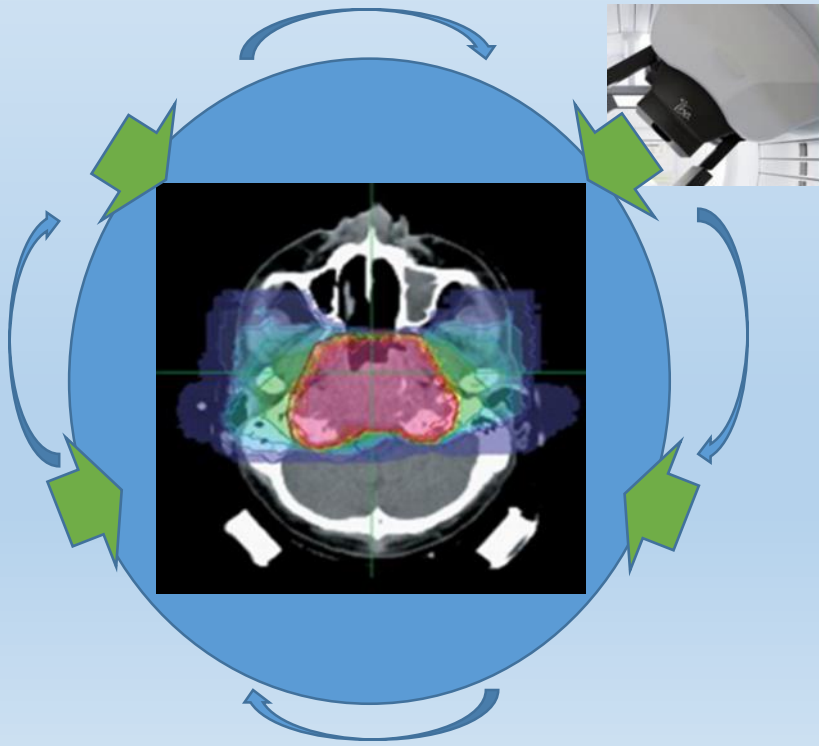
M. Salomé, J. Morse, W. De Nolf
ESRF



L. Abbassi, T. Crozes, JF. Motte

Hadron therapy in cancer treatment

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

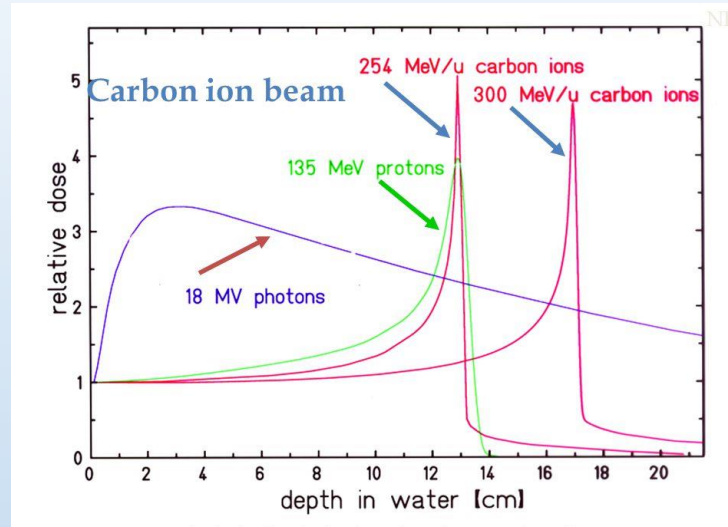


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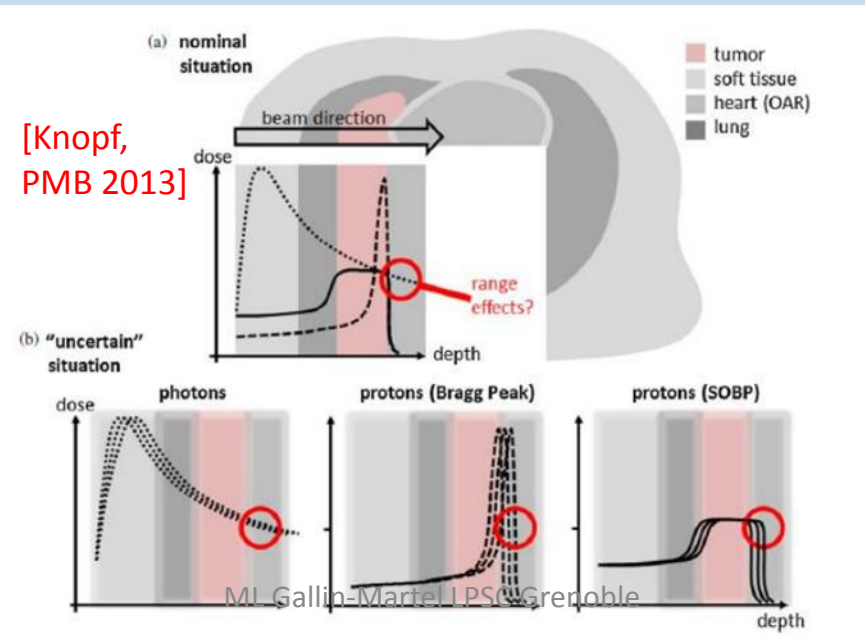
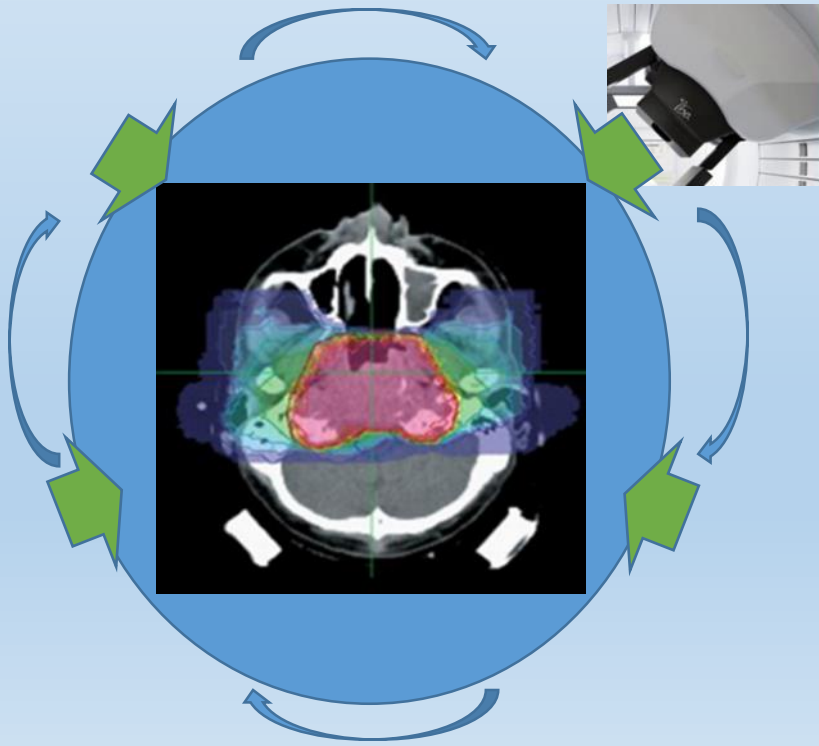
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Dose delivery / incident ionizing particle

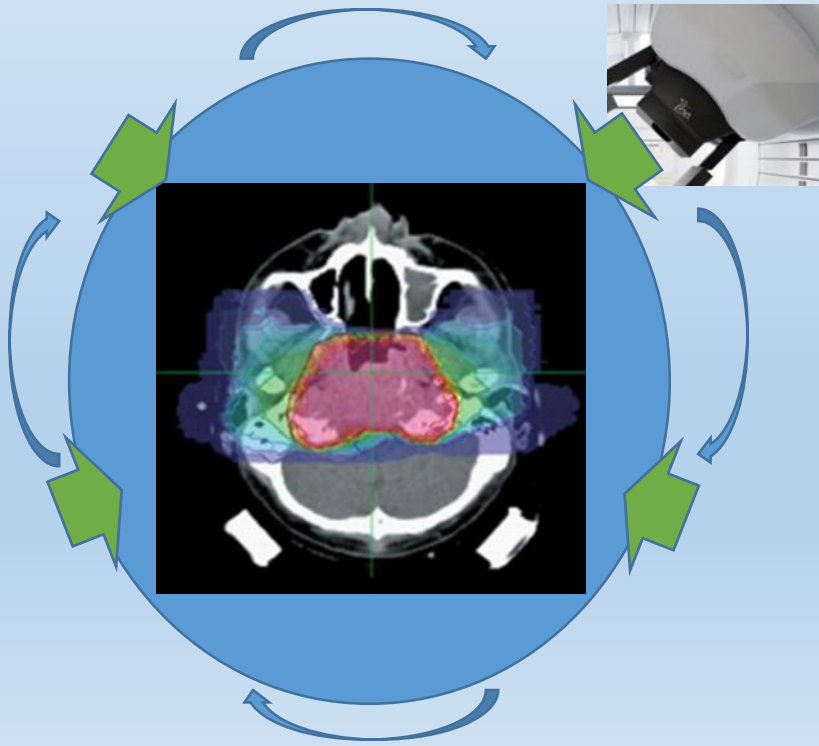


Bragg peak → Ballistic precision

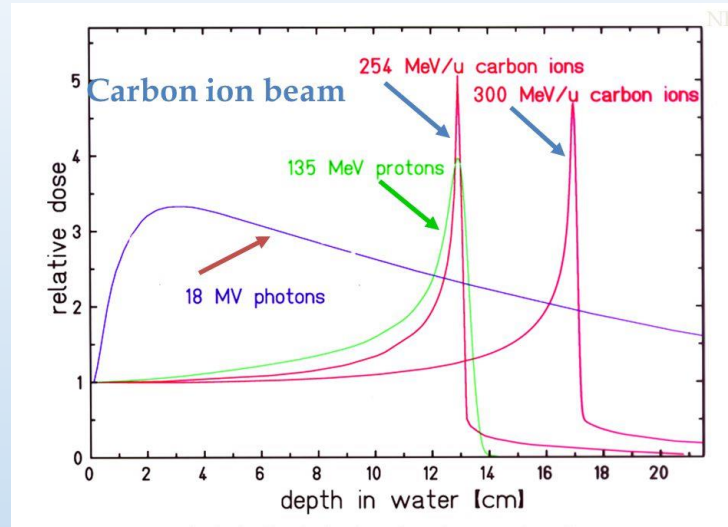


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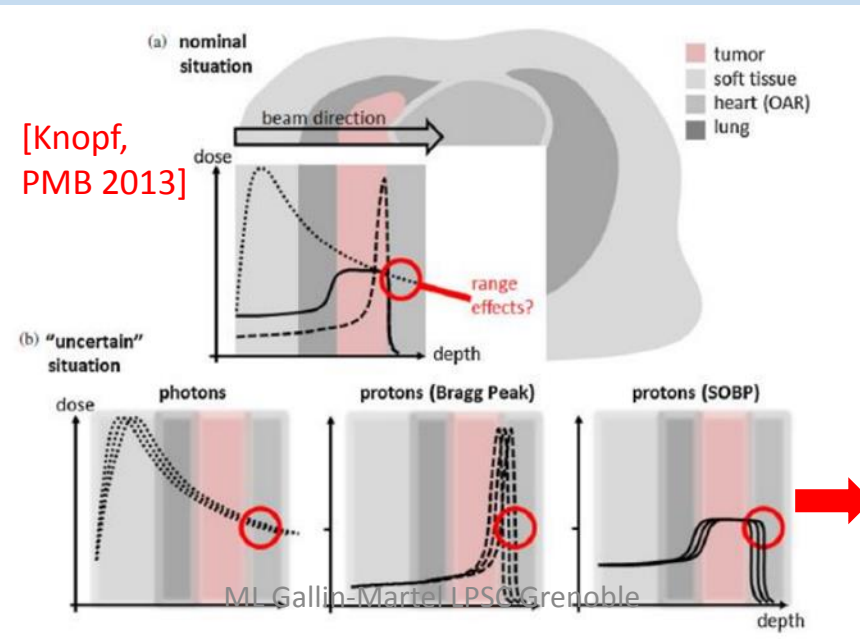
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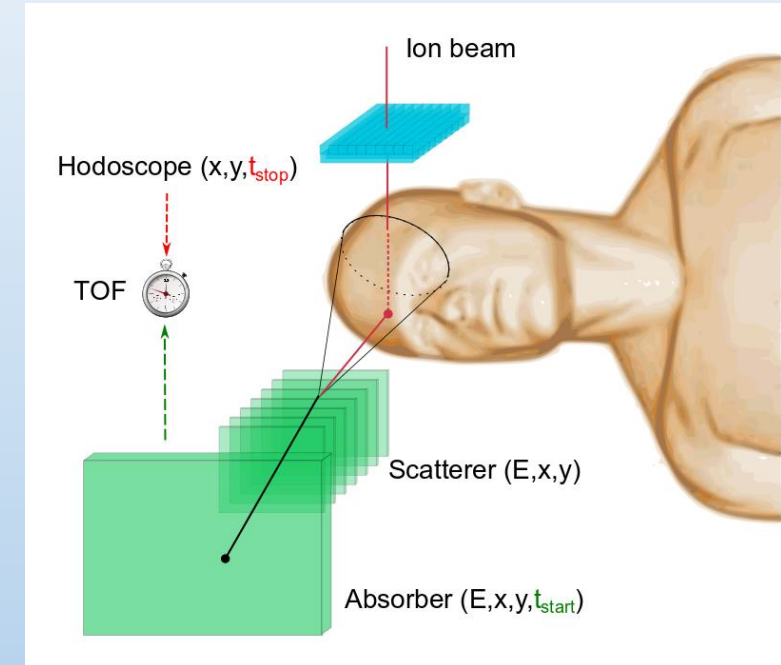


Bragg peak → Ballistic precision



Clarys French collaboration

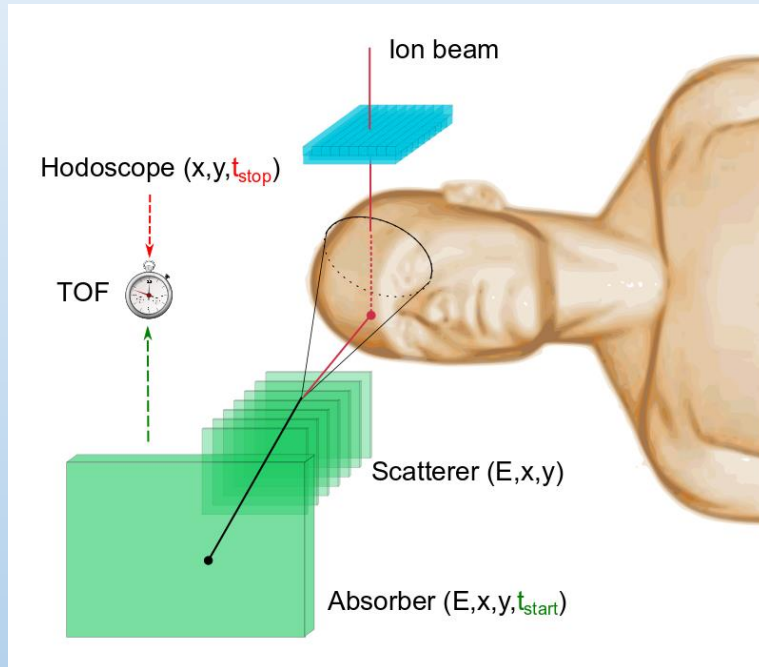
- Time-of-Flight Compton/collimated gamma cameras
- Beam hodoscope



Secondary radiation emission from fragmentation is correlated to ion range

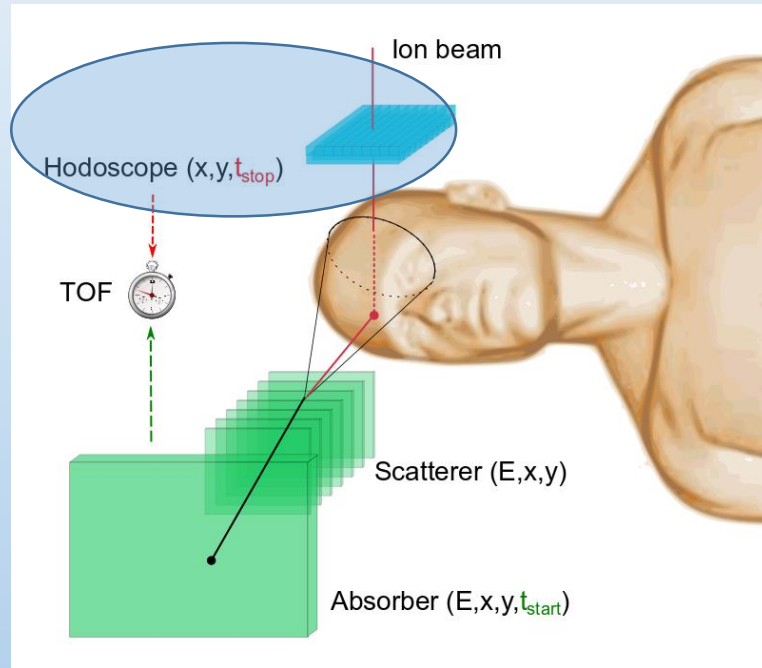
Range uncertainties → Need for online control

Compton camera



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

Compton camera

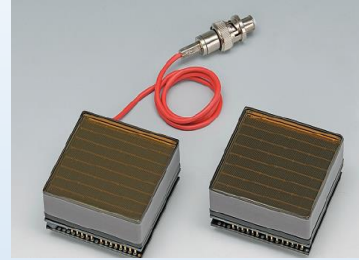


- IN2P3 : 4 laboratories
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Beam tagging hodoscope development : LPSC MoniDiam project

Existing development :

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



Limitations :

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

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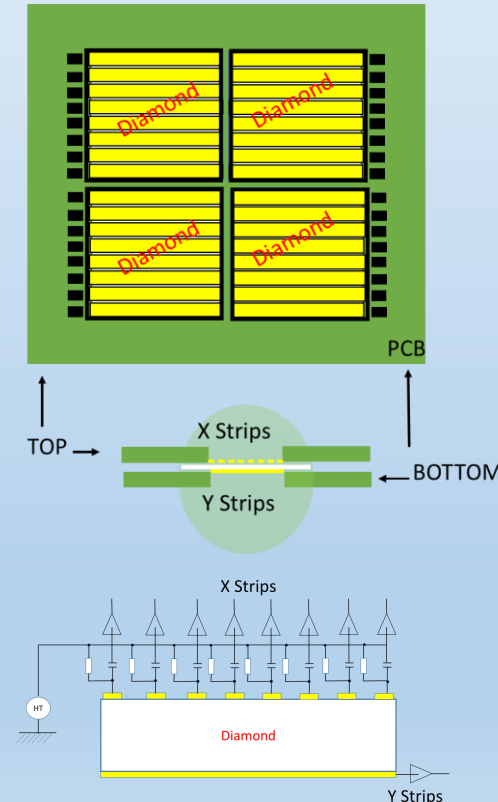


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Foreseen development :

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



Diamond Advantages :

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

Beam tagging hodoscope 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 μ s (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 hodoscope R&D

- Large area poly-crystalline diamond CVD currently on the shelf

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- **Large area poly-crystalline diamond CVD currently on the shelf**
- ❑ Several synthetic CVD grown diamond detectors were tested:
 - ✓ single crystal and polycrystalline from the Element 6 manufacturer
 - ✓ Diamond on iridium heteroepitaxially grown from Audiatec (spin-off Augsburg Univ. Contact M. Schreck)

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❑ **Characterization of the samples** => development of a Labview automated test bench for online **measurement of the diamond leakage current**

Paramètres de mesure

Operateur

Polarisation

Canal

Tension de départ (V)

Pas en tension (V)

Rampe (V/s)

Tension max (V)

Temps entre chaque mesure (s)

Mode de mesure de courant

N (mesures)

Delta t (s)

Prévention claquages

Plafond courant (A)

Temps par itération (s)

STOP

Diamant utilisé

Fabricant

Dimensions (mm²)

Numéro ?

Type

Référence maison

Référence absolue

Mettallisation

Motif

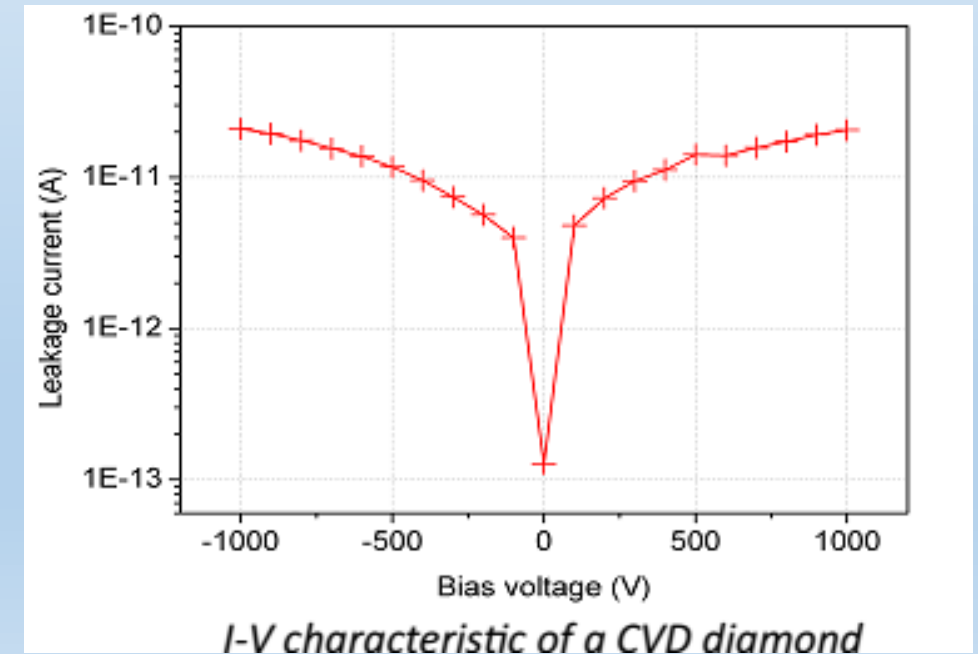
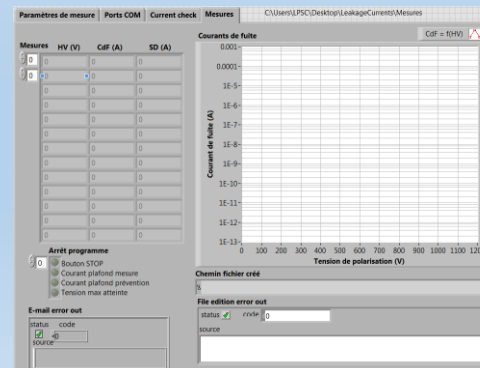
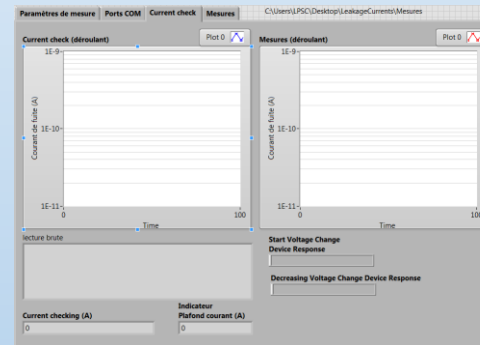
Metal

Sauvegarde données TXT

Choix titre

Titre (si "personnalisé", ne pas spécifier le .txt)

Chemin du fichier créé



Beam tagging hodoscope R&D

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- Metallization performed in Grenoble
 - ❑ aluminium disk-shaped surface up to 2016 at LPSC using the Distributed Microwave Plasmas method

Contact : A. Bess, A. Lacoste



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



Metal contact process

- ✓ Chemical scouring (acids – 100°C)
- ✓ Ultrasound cleaning using Acetone / Isopropanol

Chemical hoods
NANOFAB / Néel Institut



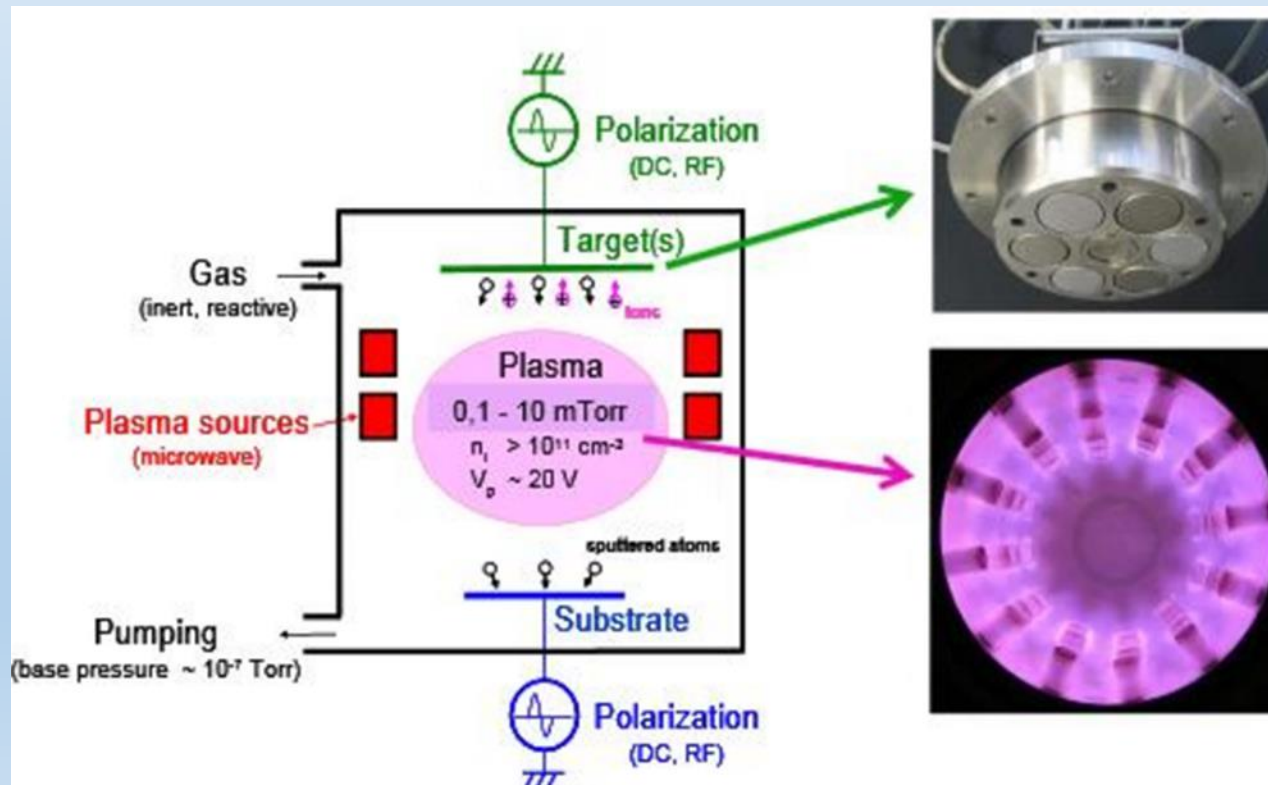
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The crystal surface preparation and metal deposition is performed by a sequential plasma process consisting in two steps of reactive plasma processing followed by plasma-assisted sputtering.

The sensor contact consists of a 50 nm thick aluminum layer deposited both on the growth and the substrate sides.

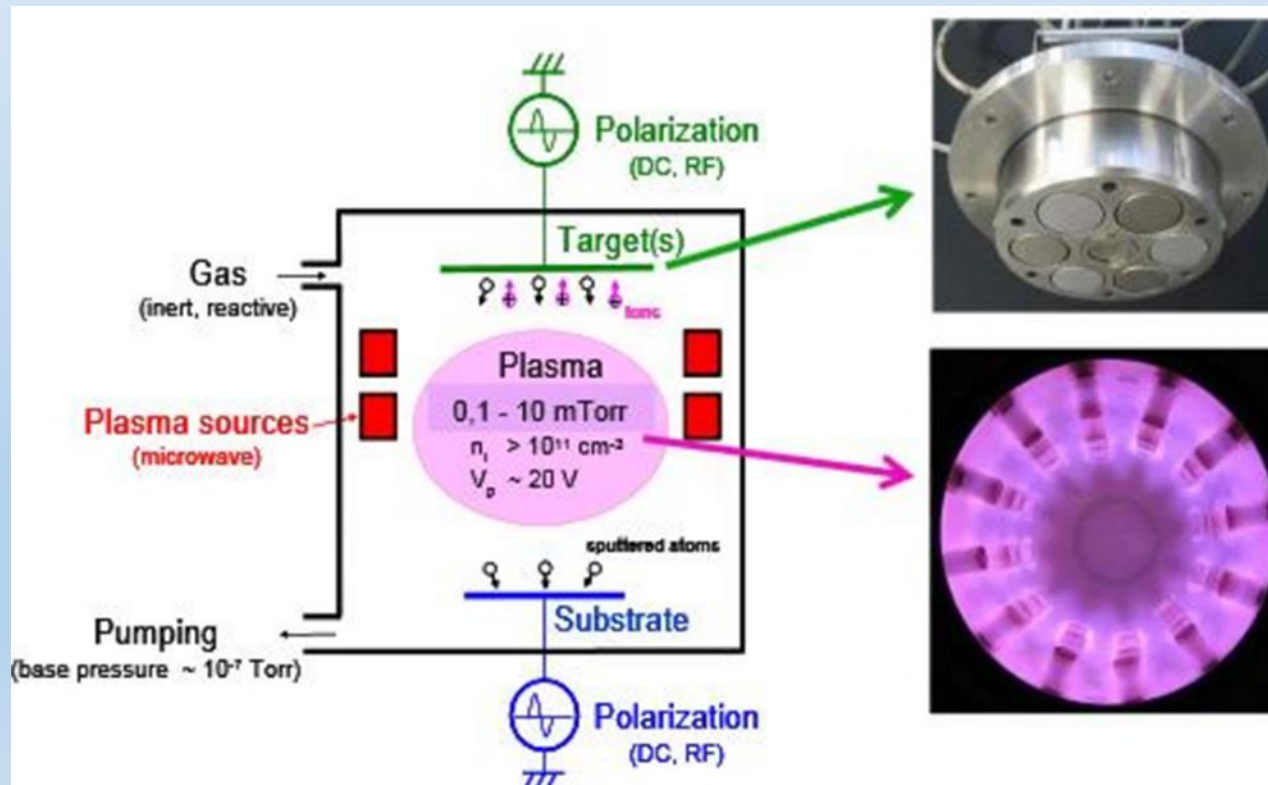
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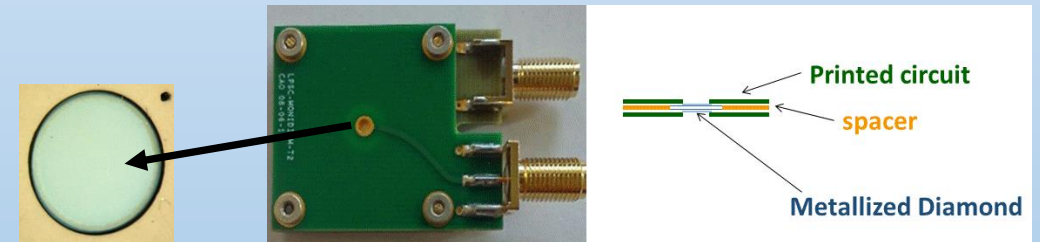
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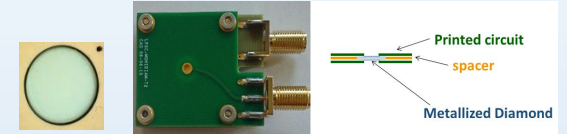
50 Ω adapted detector holder



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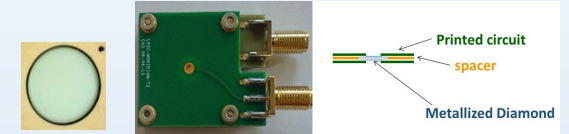
❑ strips metallization in 2017



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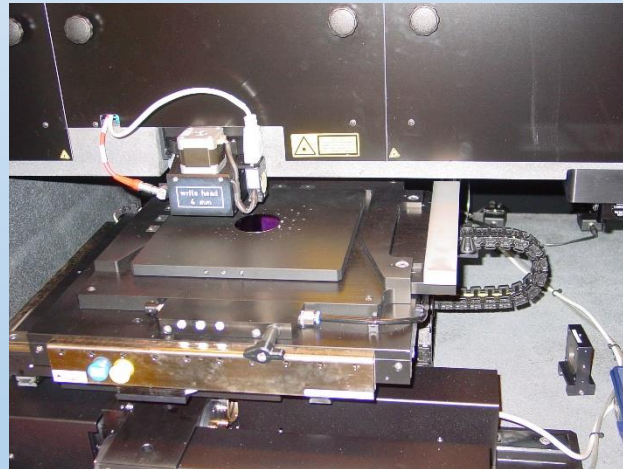
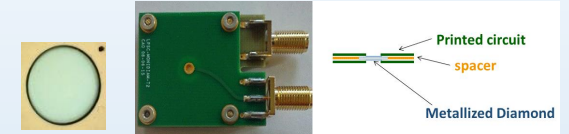
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The **Lift-off** process is used to create the strips

It is a method of creating structures (patterning) of a target material using a sacrificial material (e.g., photoresist).

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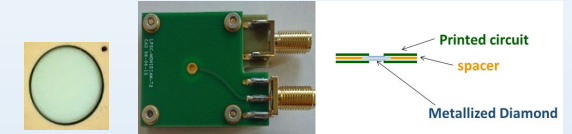
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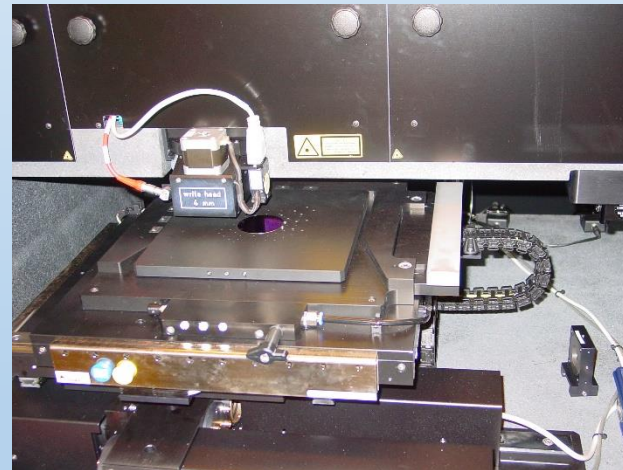
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Four steps are needed :

- ✓ Substrate (squared metallized diamond 100 nm Al layer) is prepared
- ✓ Photoresist is deposited
- ✓ An “inverse pattern” is created => **extreme ultraviolet lithography**
- ✓ The rest of the photoresist is then washed away in a solvent together with parts of the target (target = metallization) material

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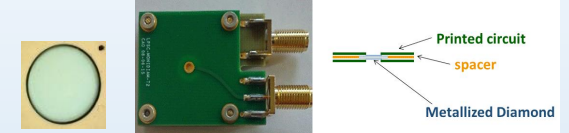
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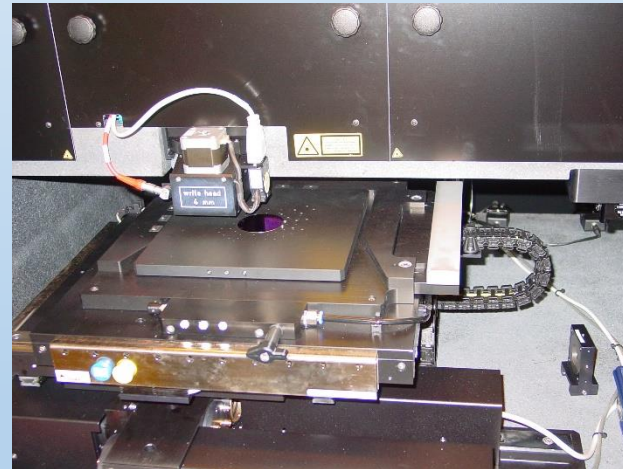
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=> Strips obtained by **ultraviolet lithography** on squared metallized diamond

- ✓ Automatic focus
- ✓ Wave length 405nm
- ✓ Filtre 3% Power 75% Defoc 2200



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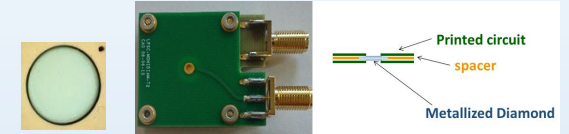
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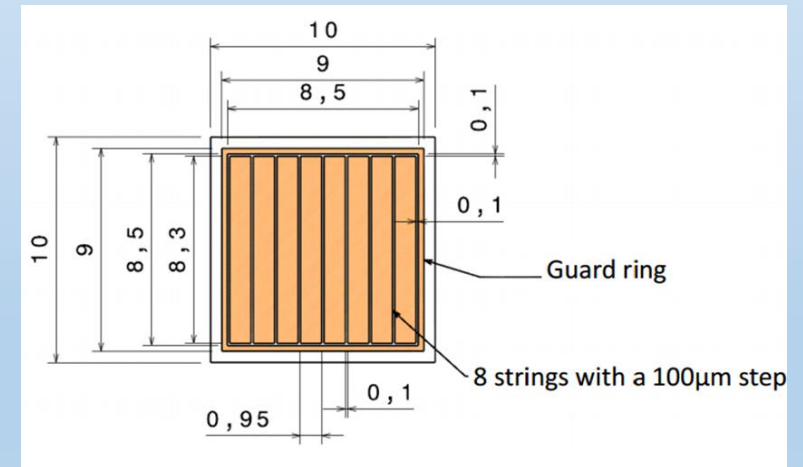
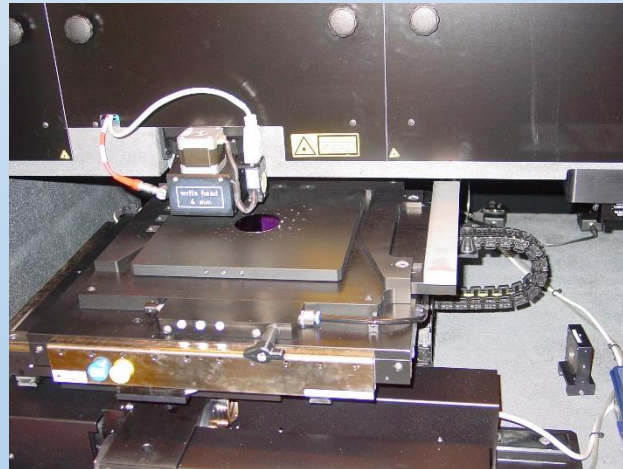
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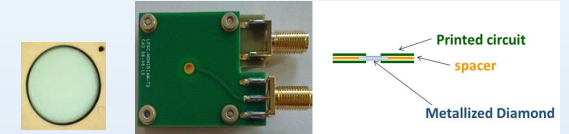
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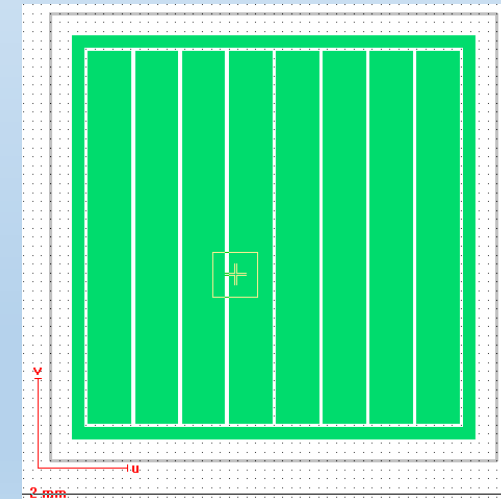
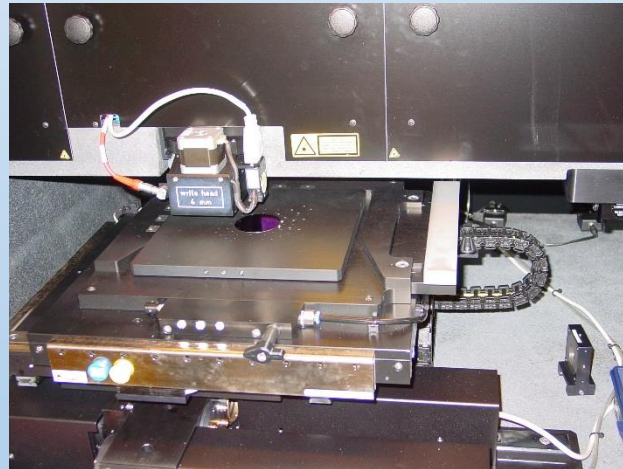
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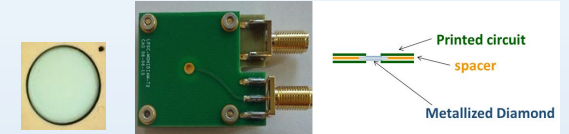
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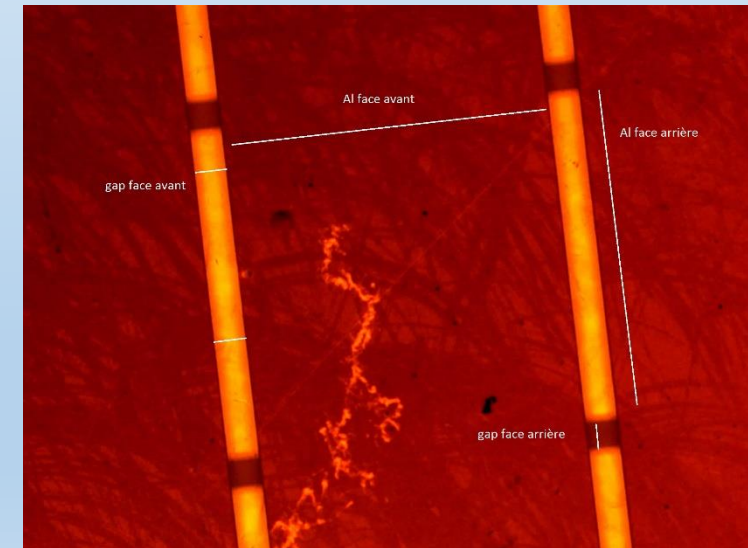
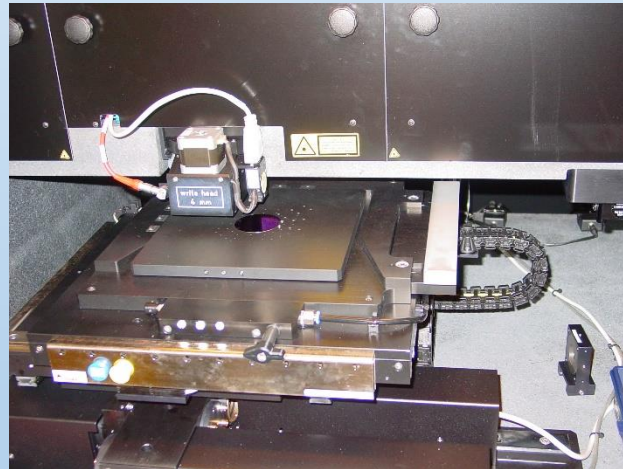
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Lift off

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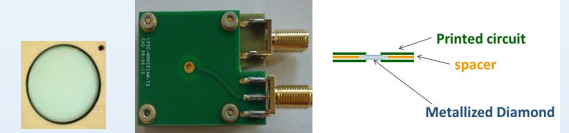
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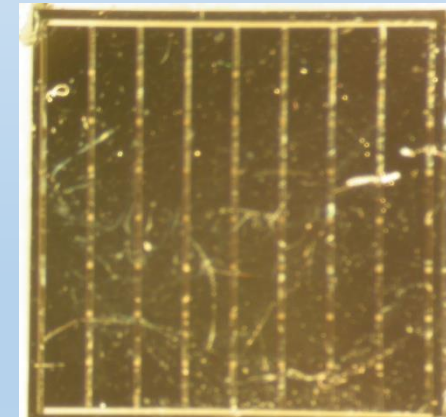
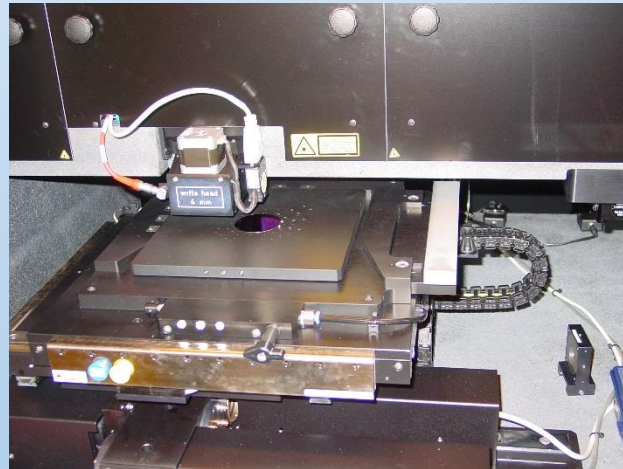
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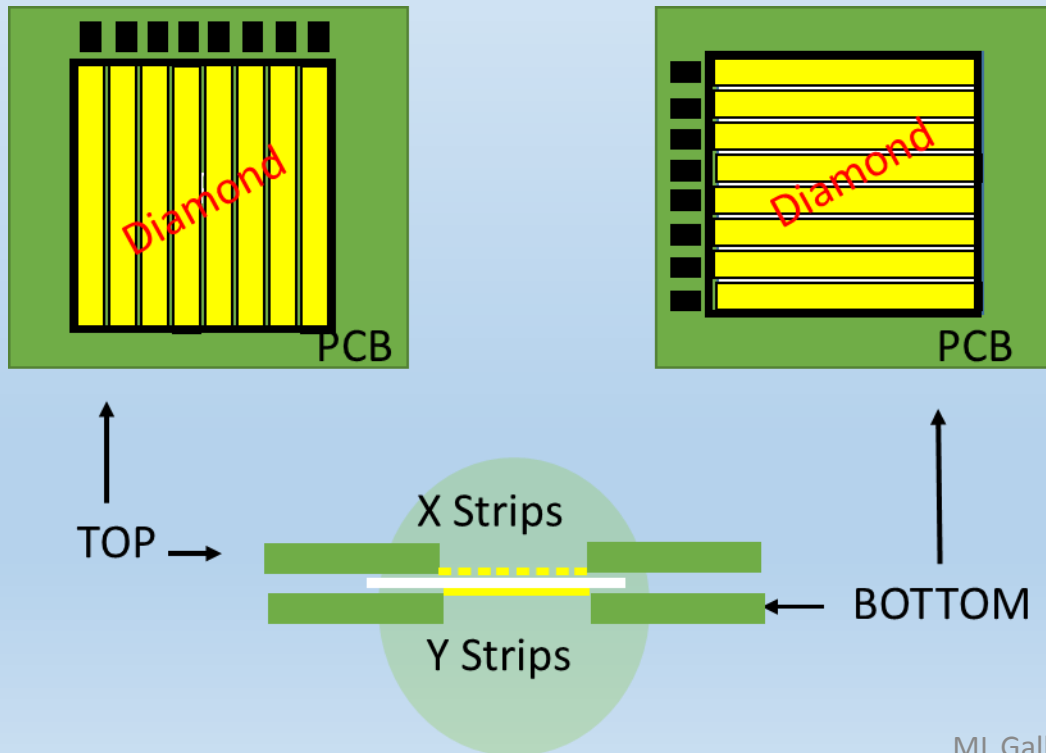
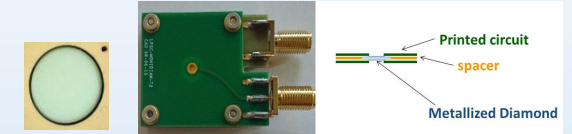
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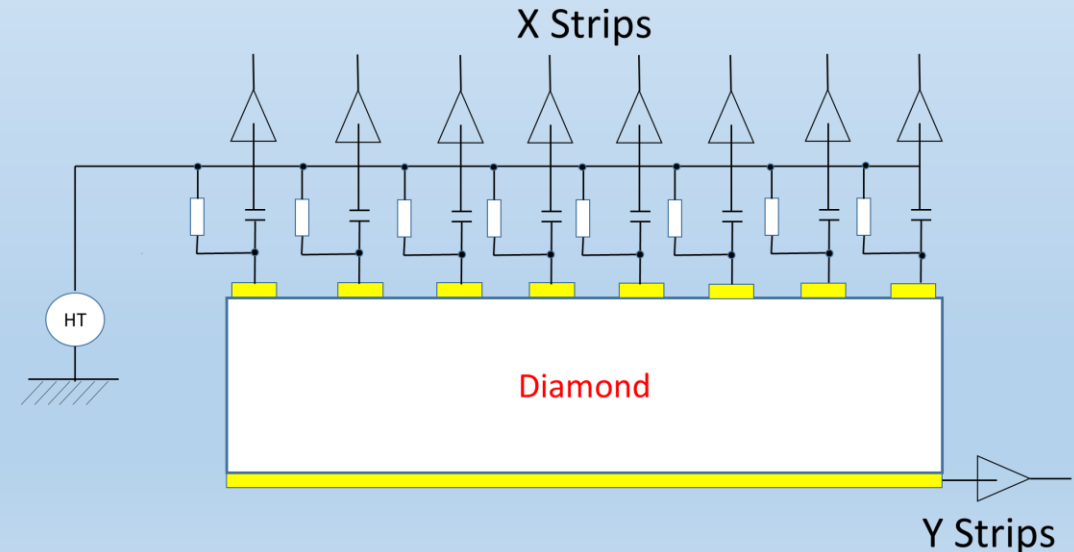
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Fast pre-amplificator developed at LPSC



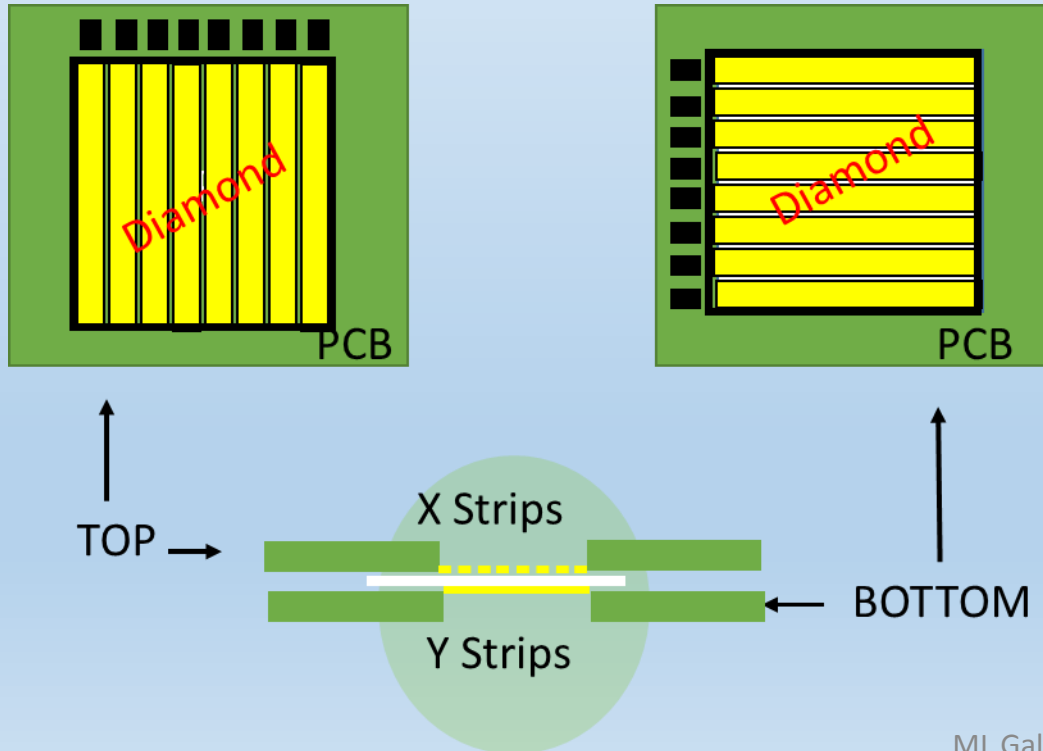
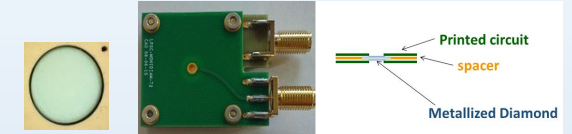
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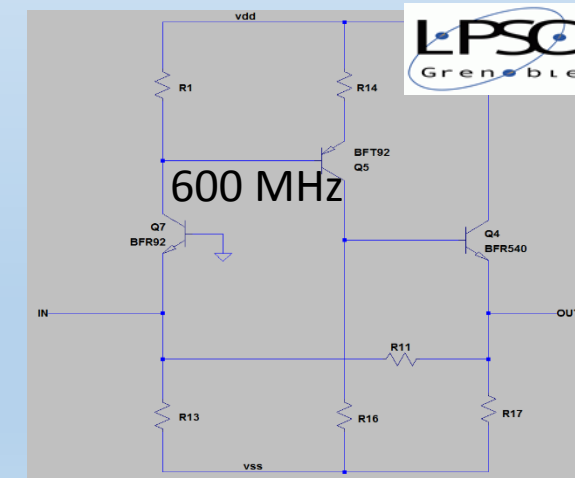
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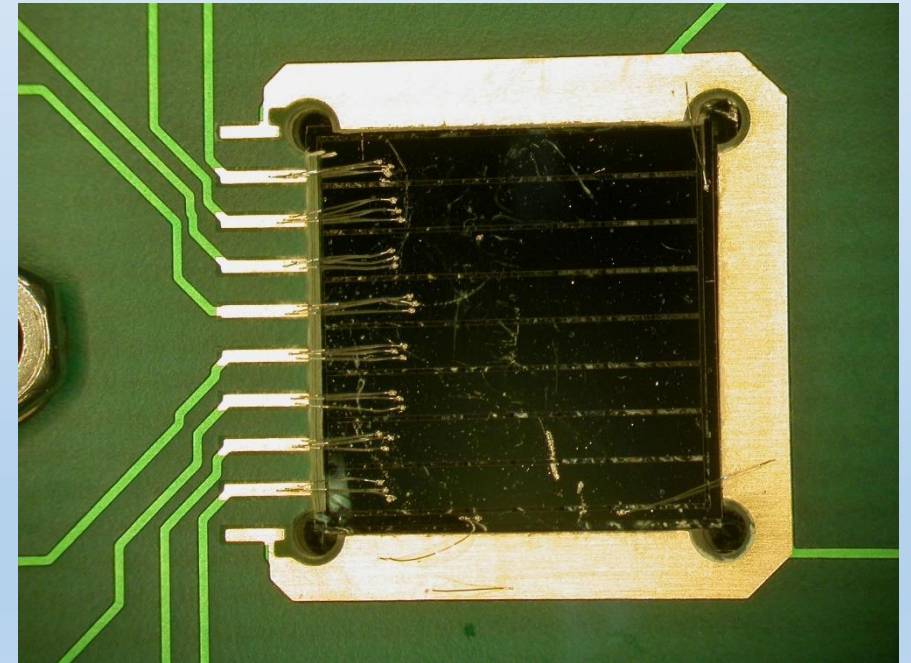
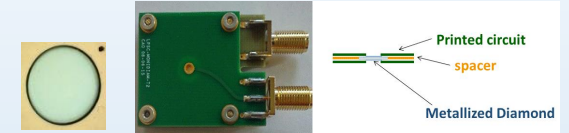
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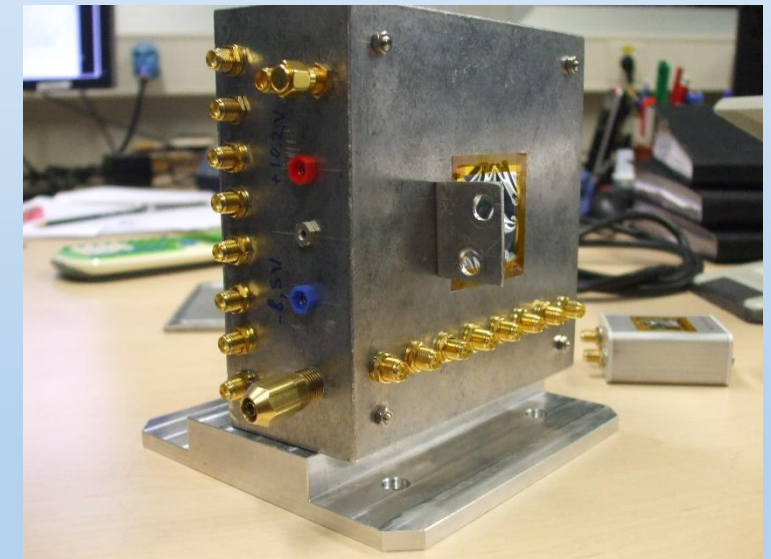
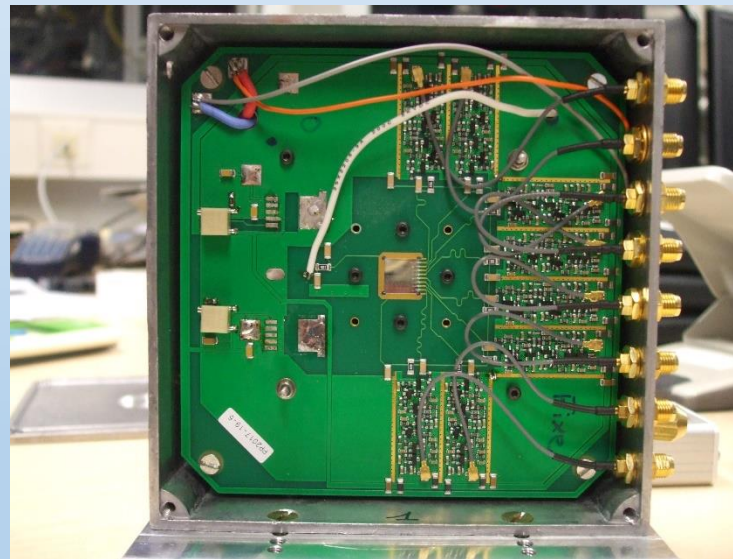
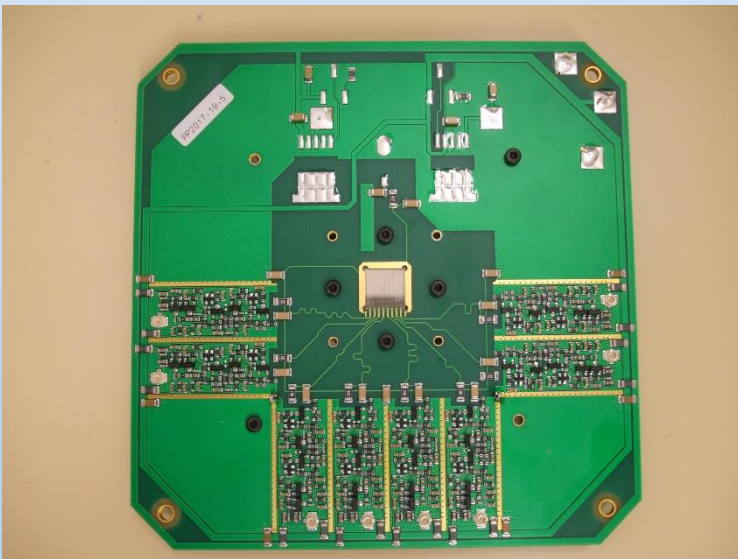
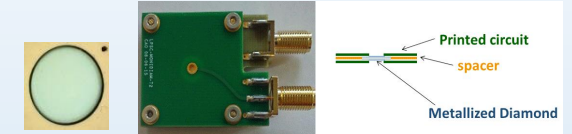
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Bonding of the diamond on the PCB

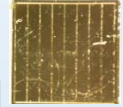
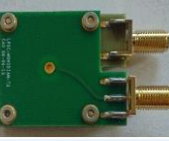
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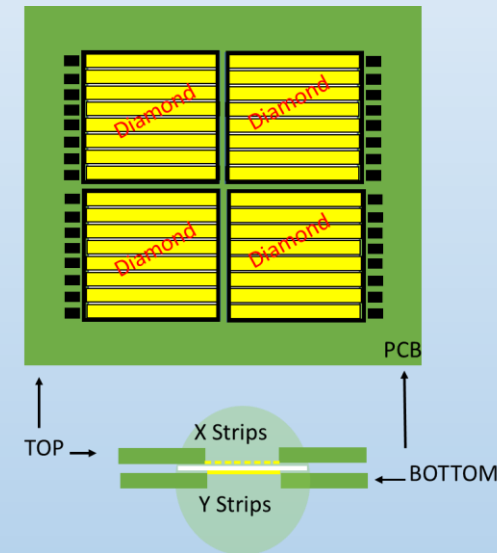
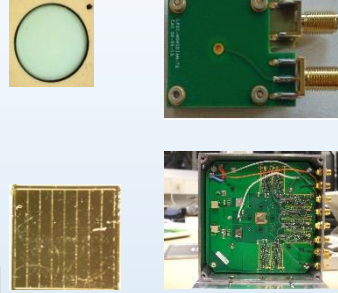
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 - ❑ strips metallization in 2017 at **NANOFAB Neel Institut Grenoble** + integration in the demonstrator socket at LPSC
- **Final detector** : **15 x 15 cm²** mosaic arrangement of stripped sensors => channels >10³



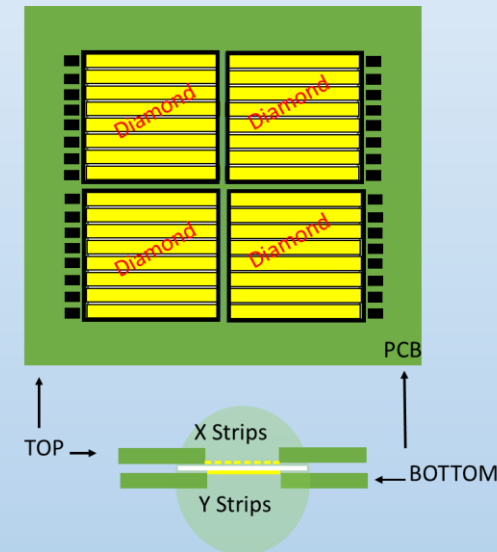
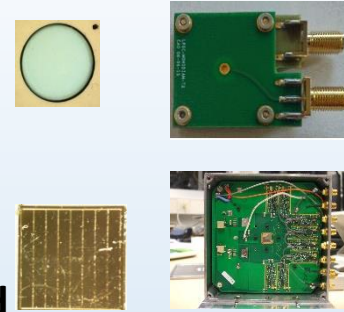
Beam tagging hodoscope R&D

- Large area poly-crystalline diamond CVD currently on the shelf
- Metallization performed in Grenoble
 - ❑ aluminium disk-shaped surface up to 2016 at LPSC using the Distributed Microwave Plasmas method
 - ❑ strips metallization in 2017 at **NANOFAB Neel Institut Grenoble** + integration in the demonstrator socket at LPSC
- Final detector : $15 \times 15 \text{ cm}^2$ mosaic arrangement of stripped sensors \Rightarrow channels $>10^3$
- First prototype in 2019 : 2×2 diamond sensors in a mosaic arrangement



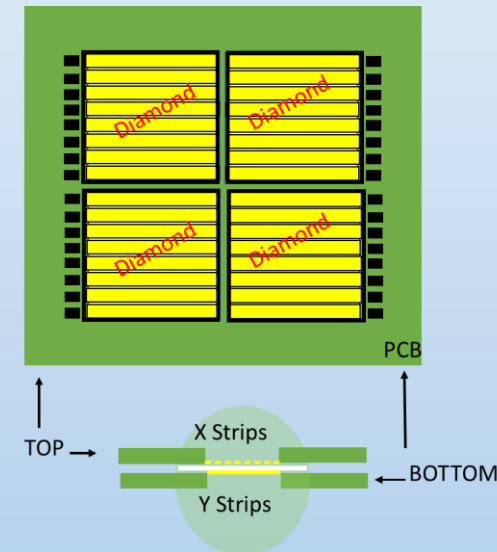
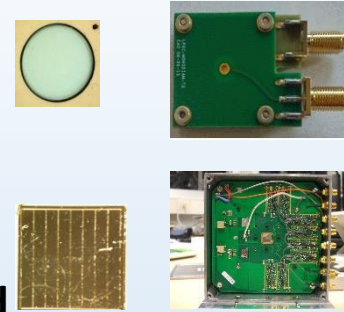
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- Integrated readout electronic (AMS 180 and/or TSMC 130):
 - ❑ Dynamic range: from 7 fC (1 proton of 250 MeV) up to 600 fC (1 carbon ion of 80 MeV/u)
 - ❑ Fast preamplifier 2 GHz / 40 dB
 - ❑ Low walk discriminator
 - ❑ TDC with a resolution $< 100 \text{ ps}$
 - ❑ spectrometry (single crystals are concerned) and charge integration outputs



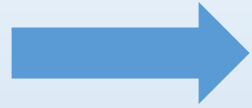
Beam tagging hodoscope R&D

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- Connectics diamond /PCB :
 - ❑ wire bonding
 - ❑etc ...



Diamond R&D at LPSC

Large area diamond single crystal for High Luminosity LHC tracker



Mon◌Diam project, started in 2012



Institut Pluridisciplinaire Hubert Curien => **Characterization**



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



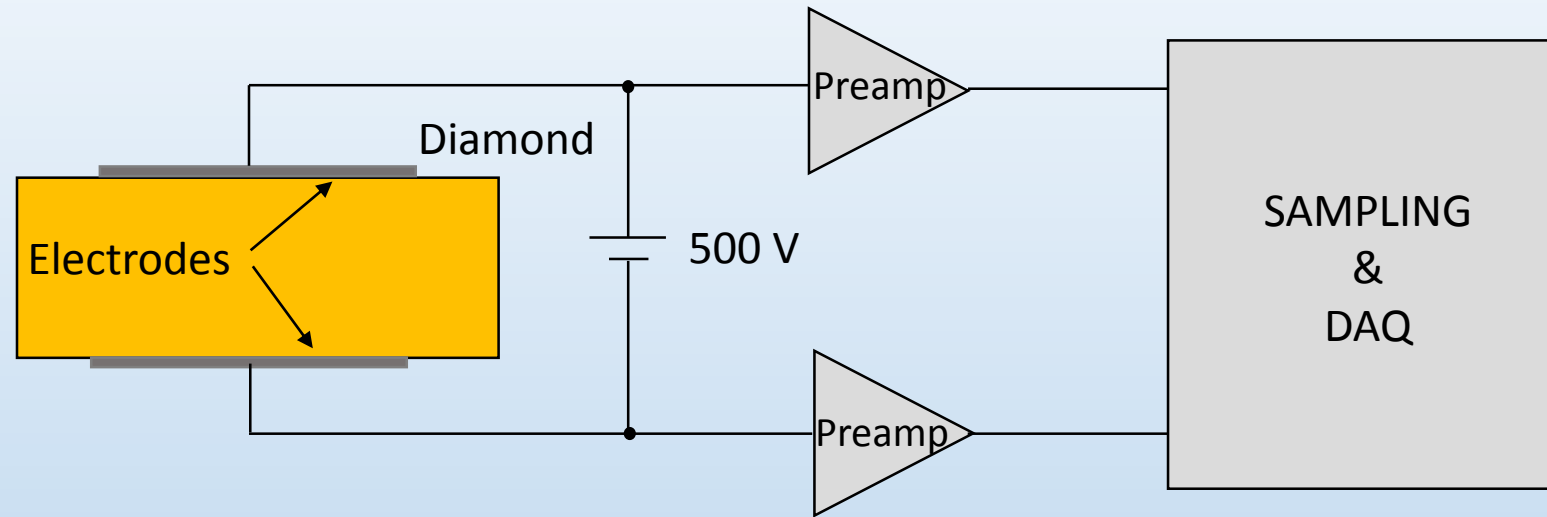
Laboratoire des Sciences des Procédés et des Matériaux => **Growth**



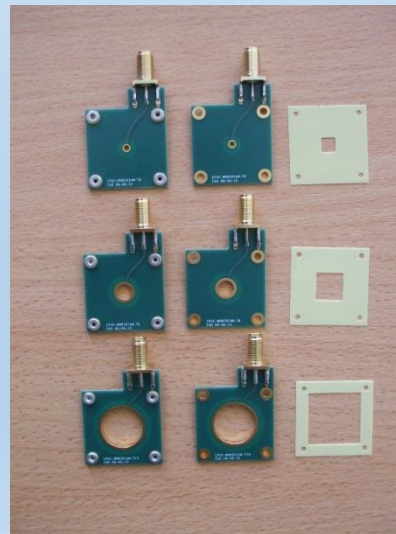
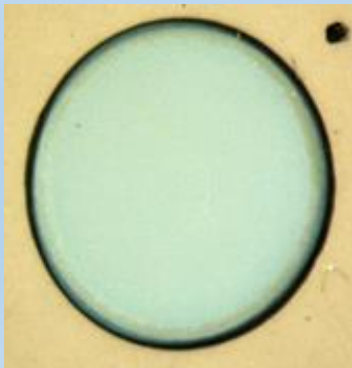
Laboratoire des sciences de l'ingénieur, de l'informatique et l'imagerie => **Functionalization**

Characterization of disk shaped diamond

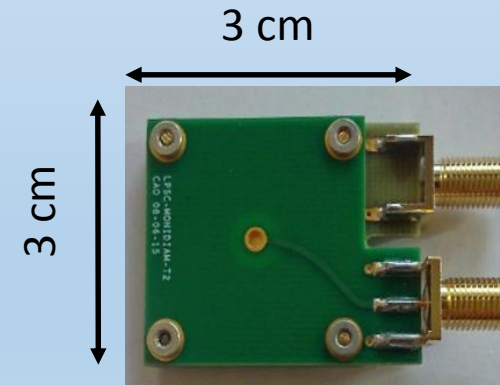
Characterization of CVD diamond at LPSC (2015-2016)



Diamond 0.45 x 0.45 cm² x 500 μ m sc-CVD E6
Metallization 2 sides
Al 50 nm; ϕ 4 mm

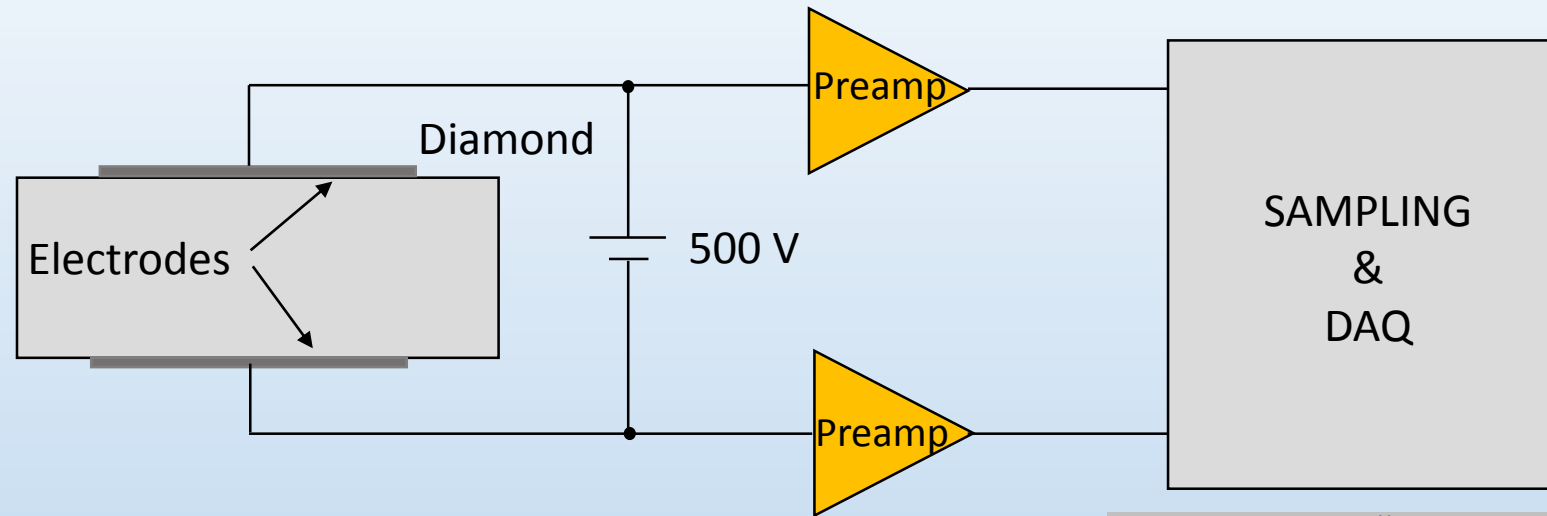
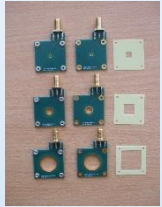
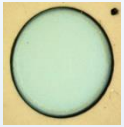


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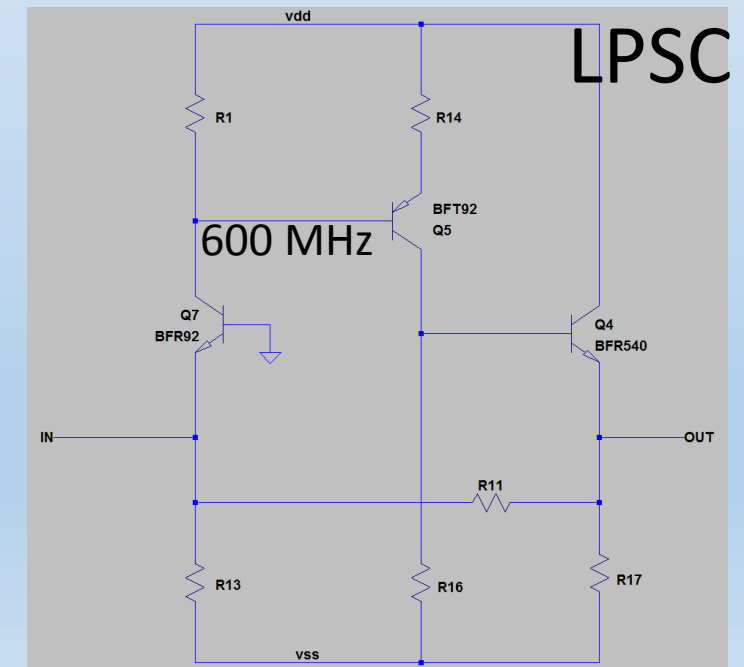


50 Ω adapted detector holder

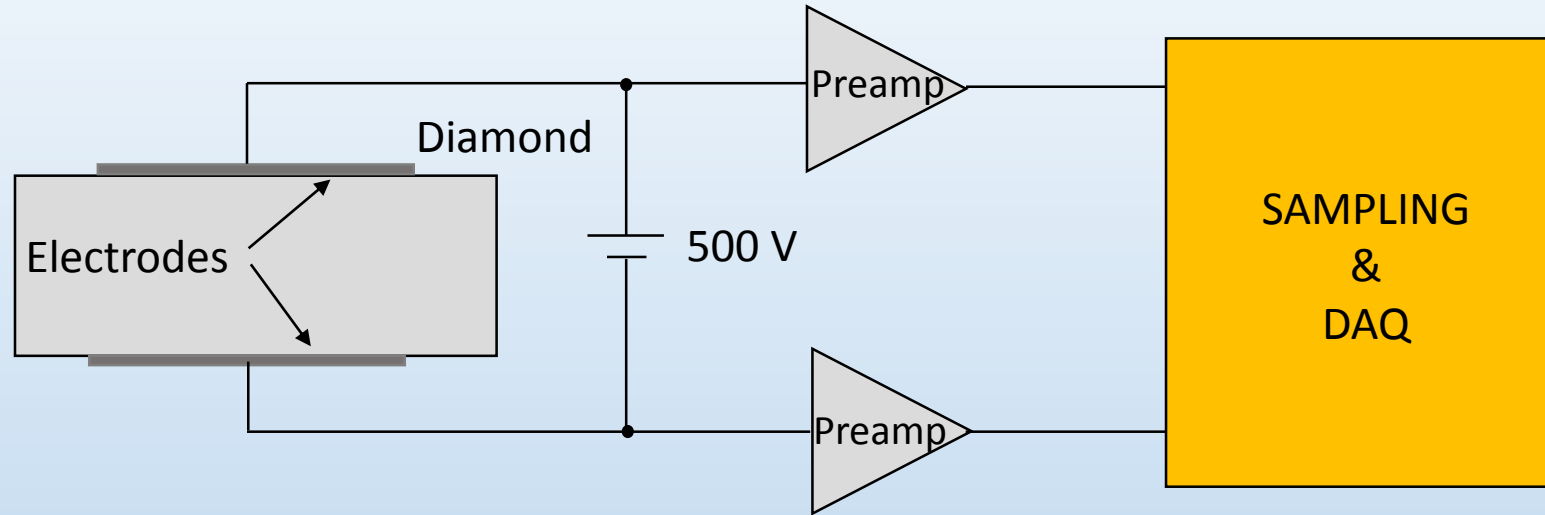
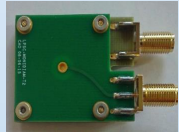
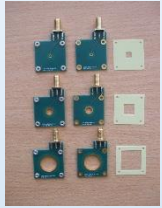
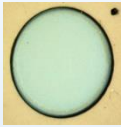
Characterization of CVD diamond at LPSC (2015-2016)



Band Width: 2 GHz
 Gain: 40 dB
 Impedance: 50 Ω
 Dynamic range: $\sim \pm 1$ V
 Power Supply: 12 V / 100 mA



Characterization of CVD diamond at LPSC (2015-2016)



WaveCatcher
500 MHz; 3.2 GS/s



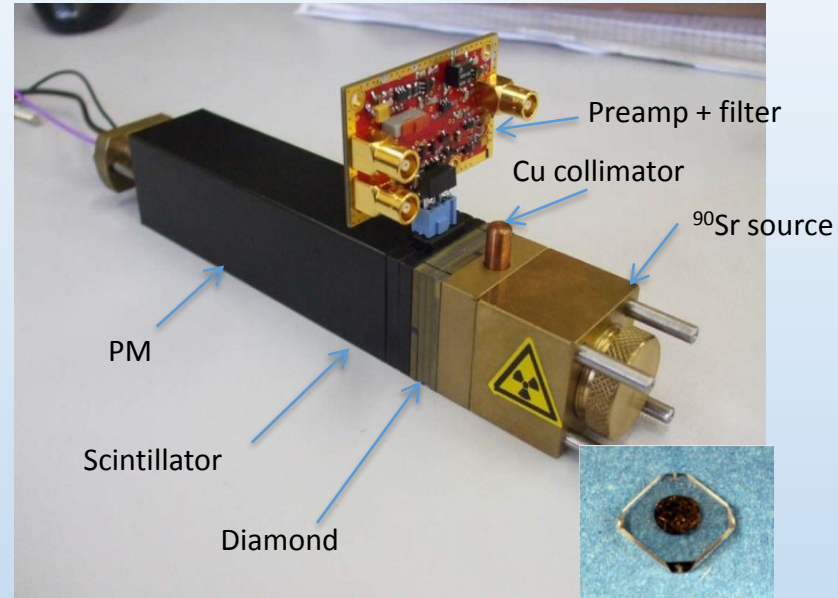
		Unit
SAMLONG ASIC technology	AMS CMOS 0.35μm	
System number of channels	2, 8, 16, 32, 48, 64	
Power consumption	2.5 (2-ch), 15 (8-ch), 23 (16-ch), 100 (64-ch)	W
Sampling depth	1024 / channel	Cells
Sampling speed	0.4 to 3.2	GS/s
Bandwidth	500	MHz
Range (unipolar)	± 1.25 (with full range individual channel 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

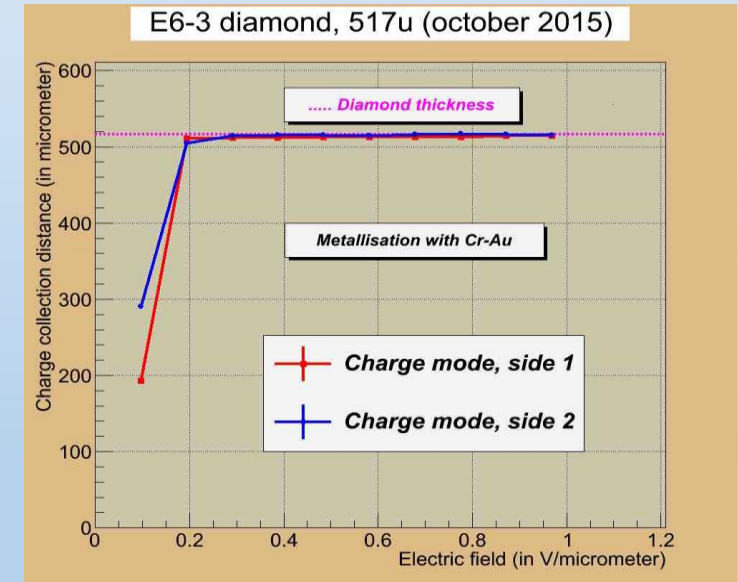
^{90}Sr 74 MBq β source



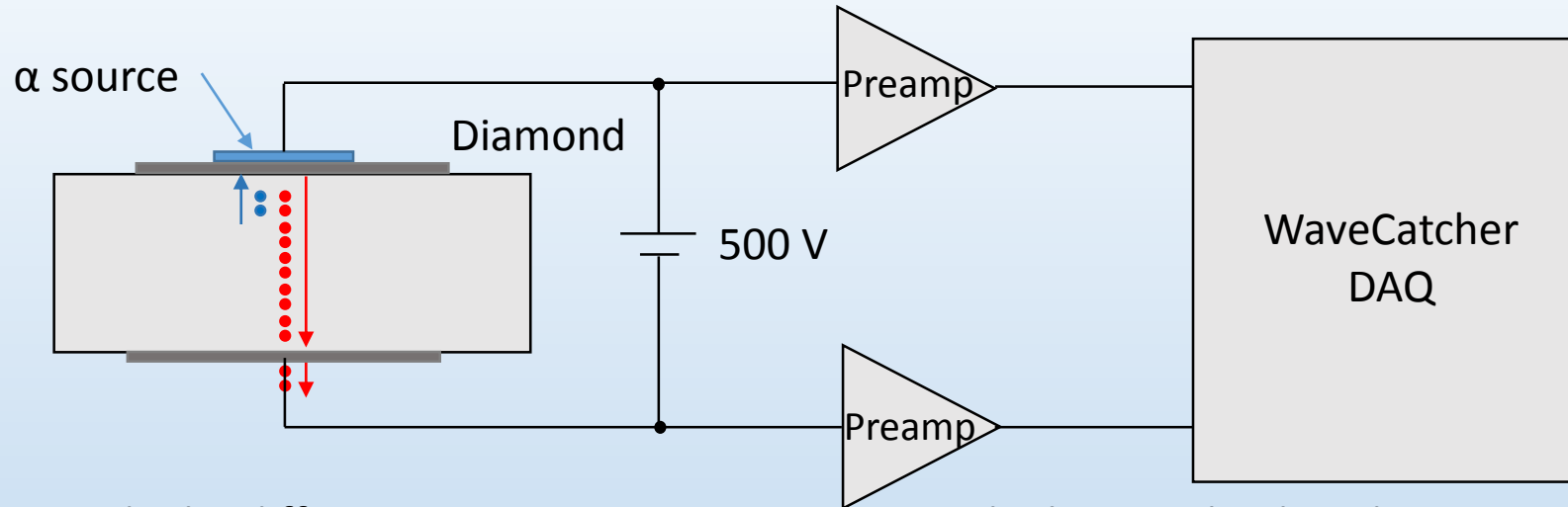
Diamond 4 x 4 mm²

Triggering on high energy electrons (scintillator behind diamond)

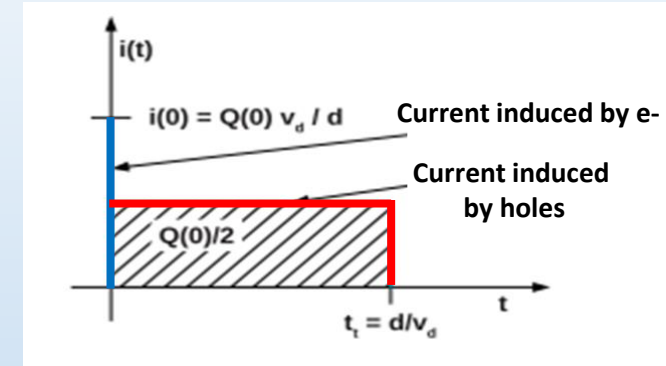
Charge Collection Distance measurement



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



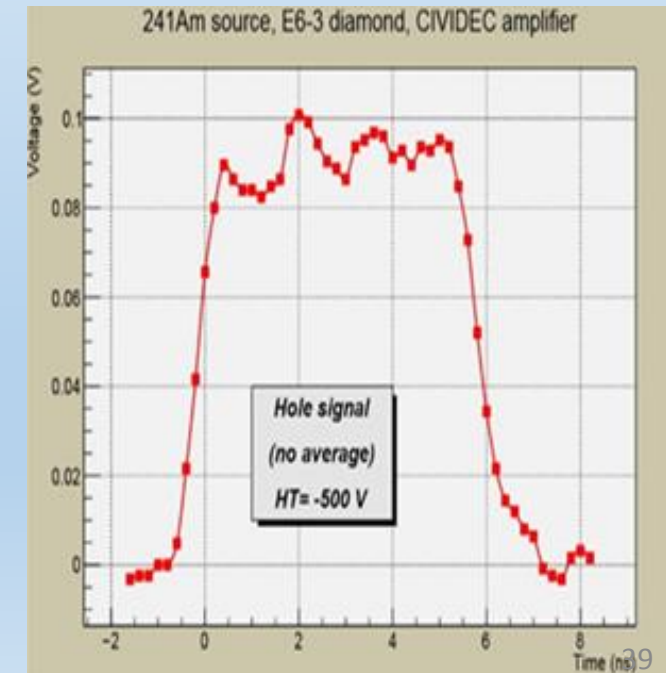
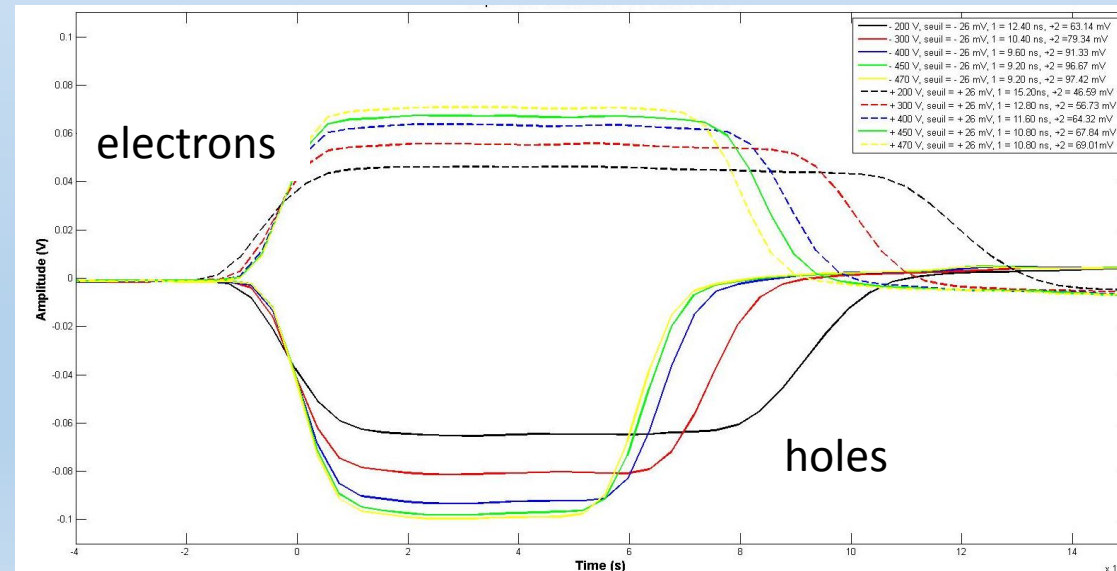
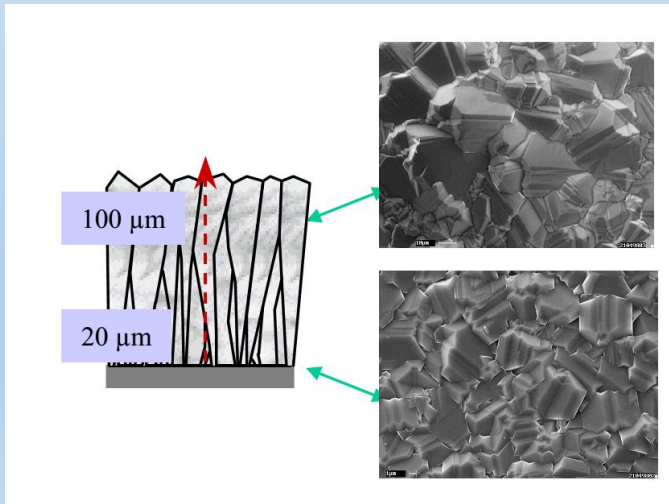
Theoretical Signal



$\alpha \Rightarrow$ study the difference between the growth and substrate sides

$\alpha \Rightarrow$ study the signal induced by electrons / holes

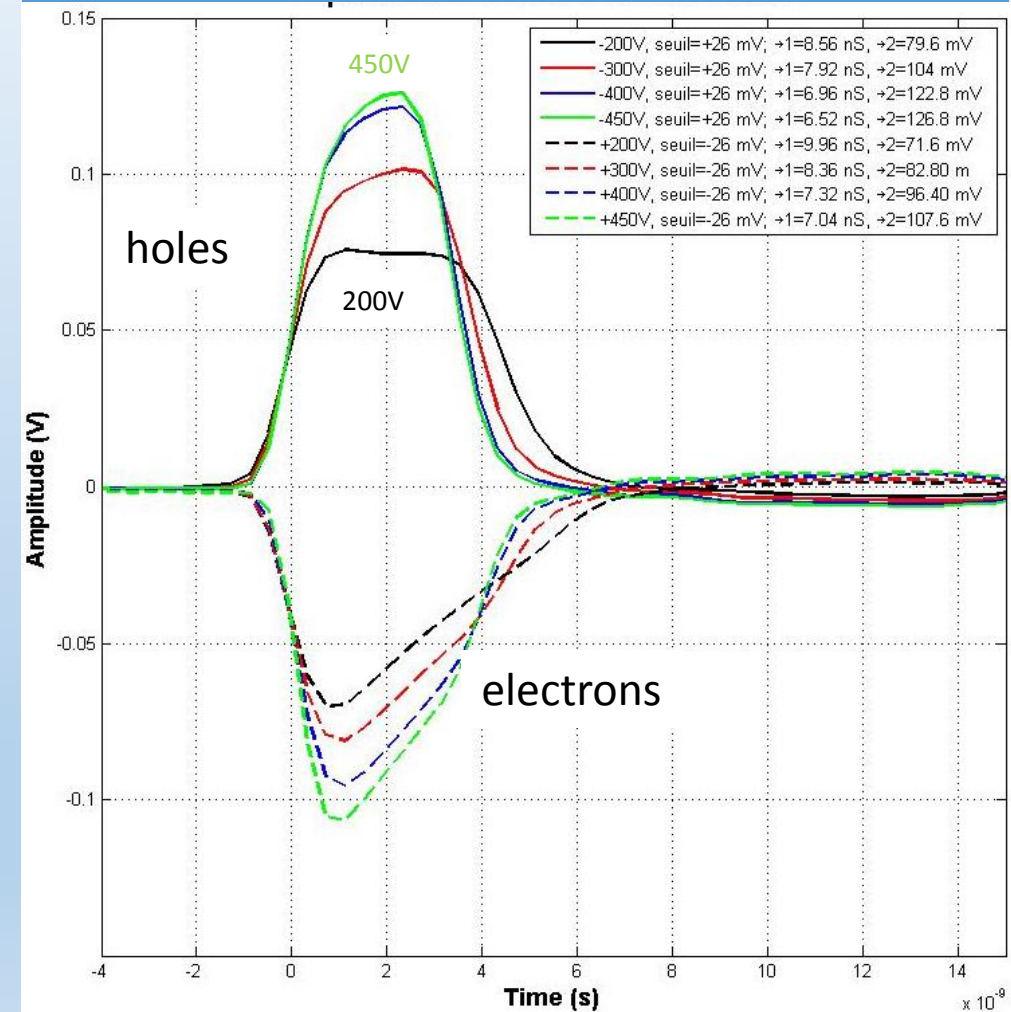
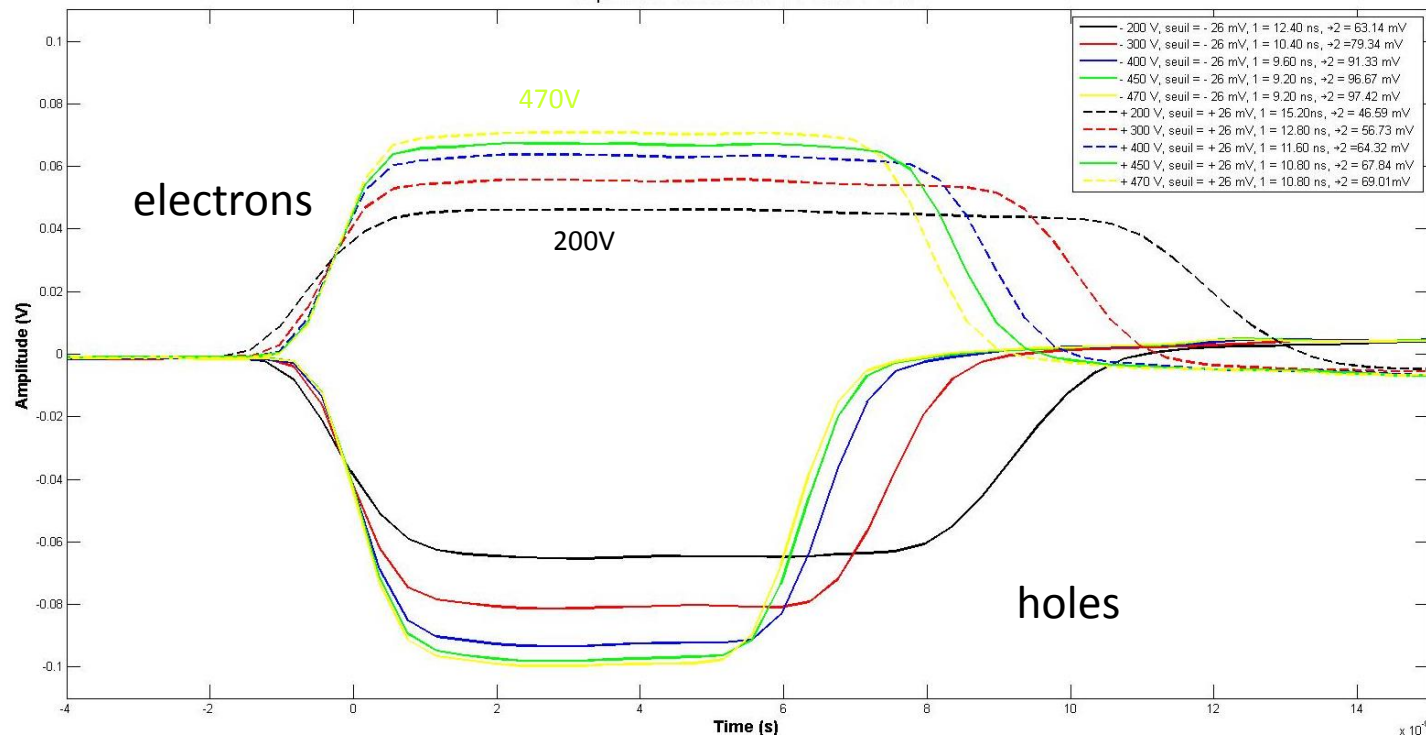
Experimentally measured signal sc-CVD



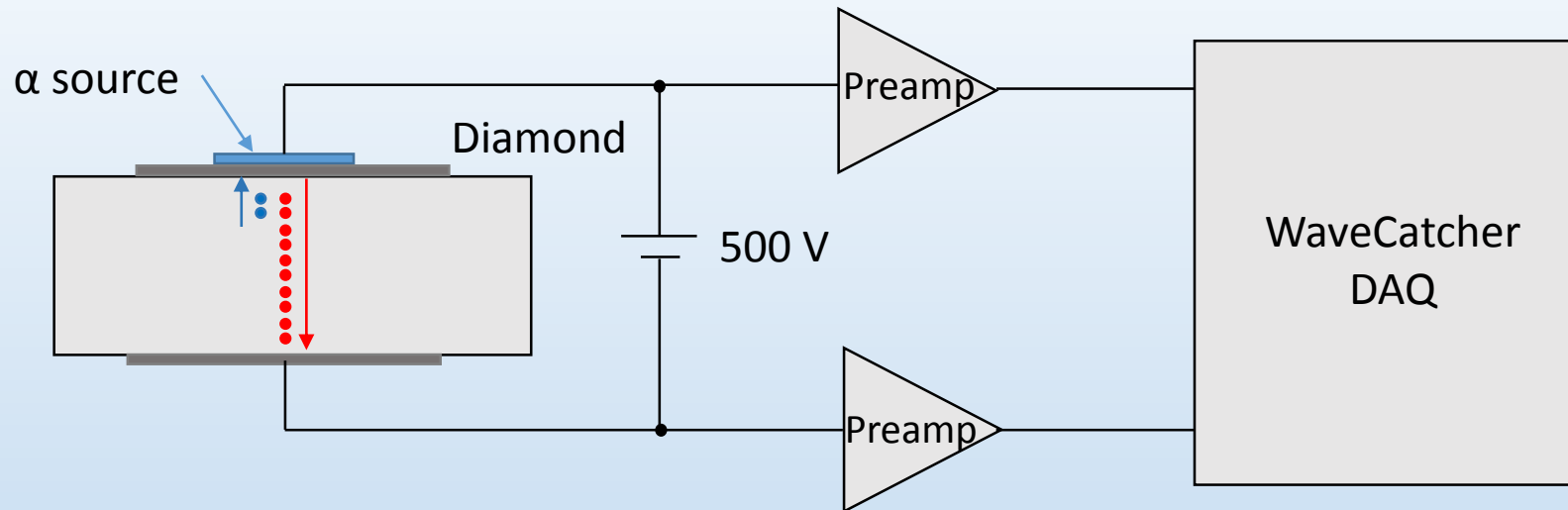
Measurements with ^{241}Am : α source (5.4 MeV)

$0.5 \times 0.5 \text{ cm}^2 \times 300 \text{ }\mu\text{m}$ pc-CVD
Augsburg Univ. heteroepitaxially
grown on iridium(courtesy M. Schreck)

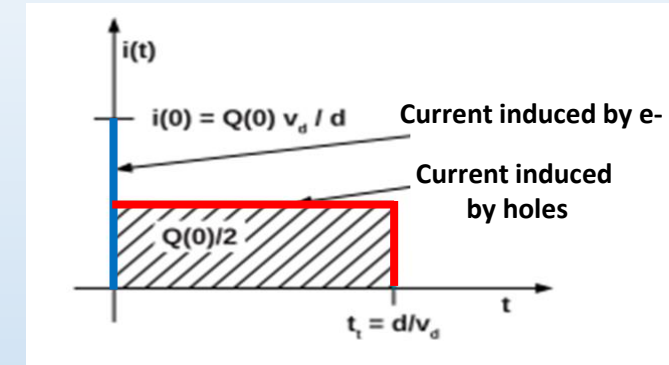
$0.45 \times 0.45 \text{ cm}^2 \times 518 \text{ }\mu\text{m}$ sc-CVD diamond Element 6



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

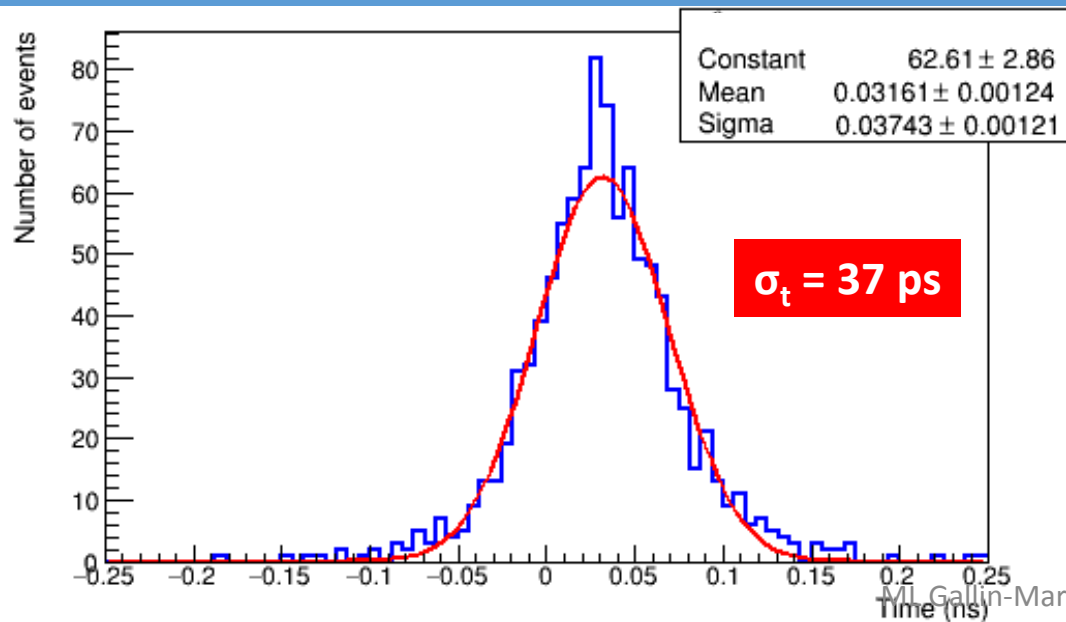


Theoretical Signal

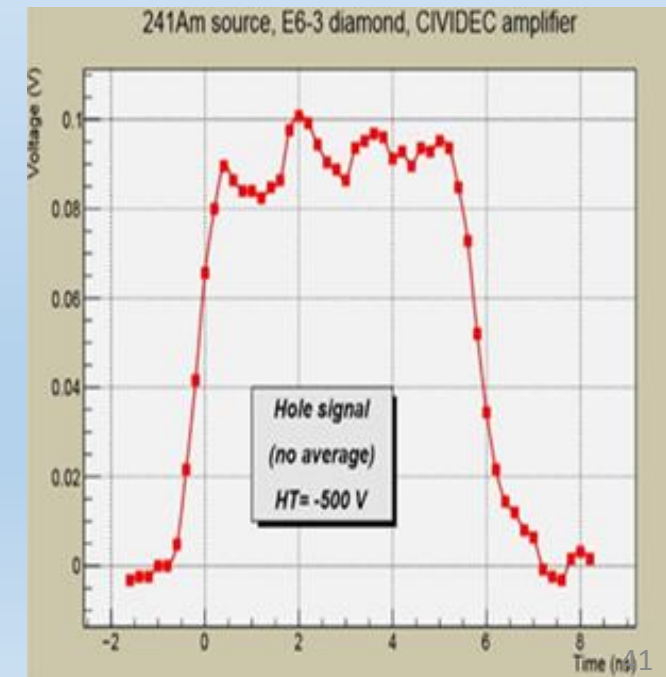


Experimentally measured signal sc-CVD

Time resolution pc-CVD $20 \times 20 \text{ mm}^2 \times 500 \mu\text{m}$ E6
Offline Constant Fraction Discriminator method

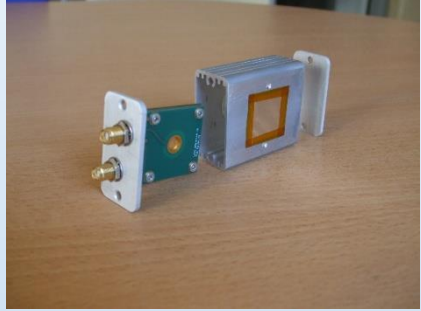


Timing difference
of both surface
signals

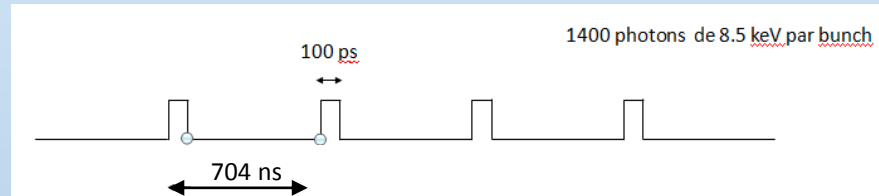
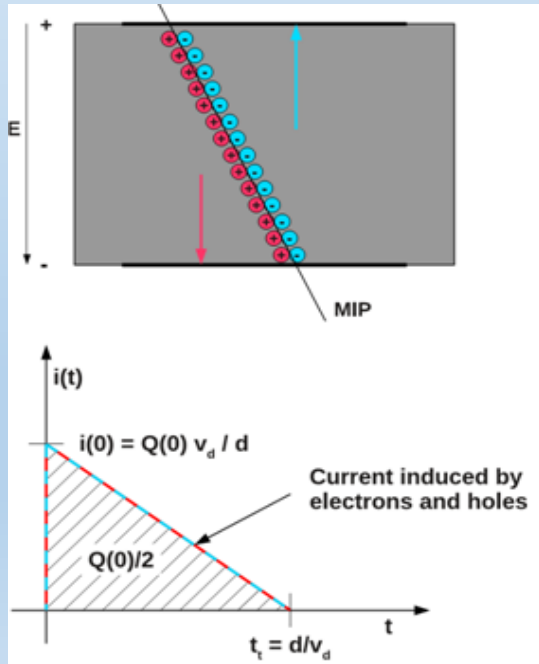
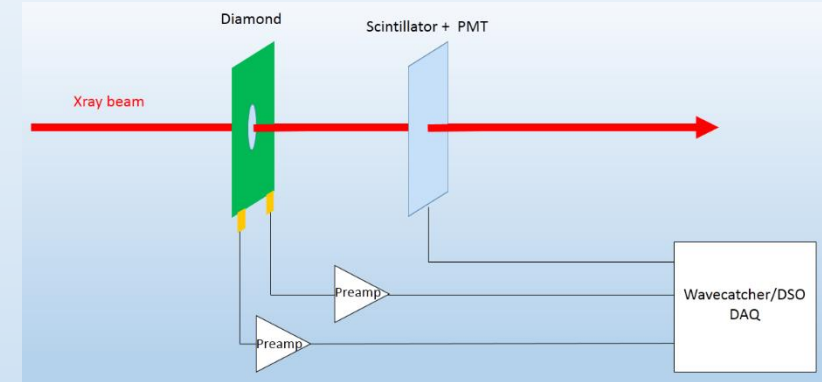
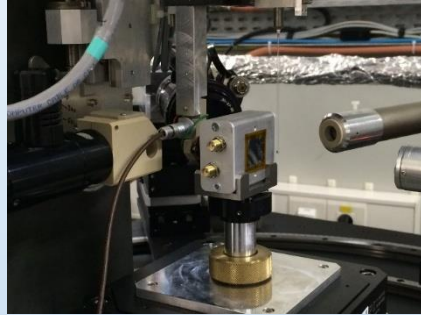


Pulsed beam (8.5 keV ~100 ps) at ESRF ID21 X-ray Microscopy beamline

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.

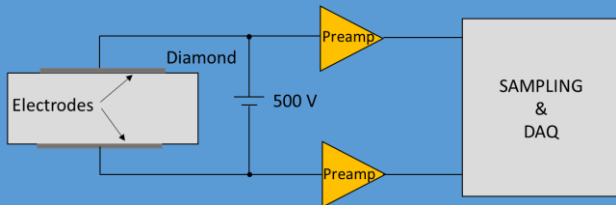
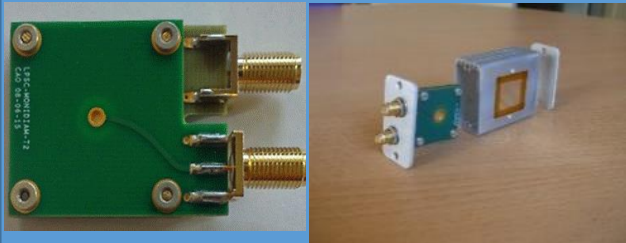


A 8.5 keV photon focused micro-beam with a well-defined time structure was used at the ESRF.

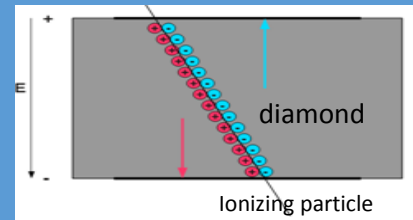
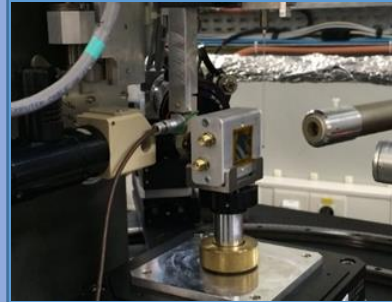
As regards energy deposition in the diamond, in the ESRF 4-bunch mode, the ~100 ps duration X-ray pulses, containing a fixed number of photons varying up to ~1400, spaced at 700 ns intervals, mimic the passage of single ionizing particles

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

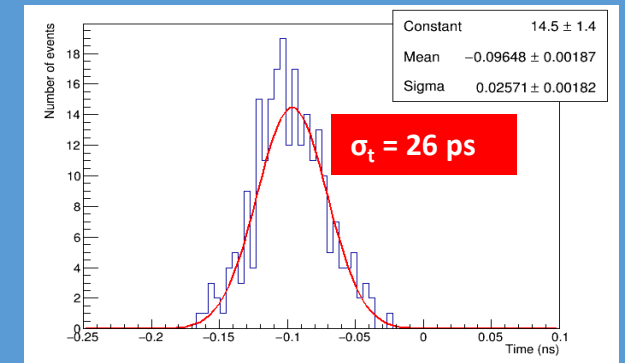
2016 first prototypes tests



ESRF => XBIC (X Beam Induced Current)
Huge interest for our application !



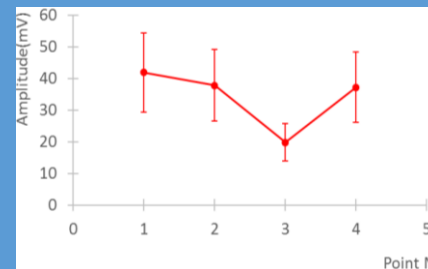
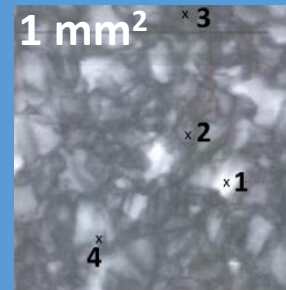
Time resolution (waveform analysis)



sc-CVD 0.45x 0.45 cm² x 518 μm

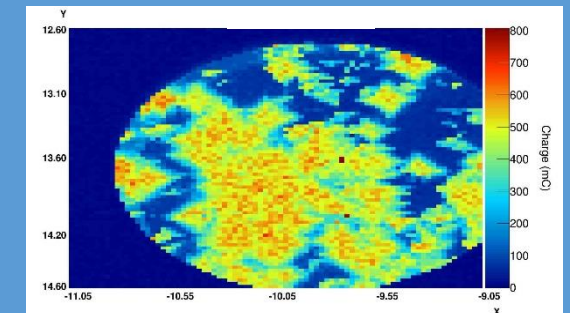
X-Ray analysis the detector surface

Current integration mode



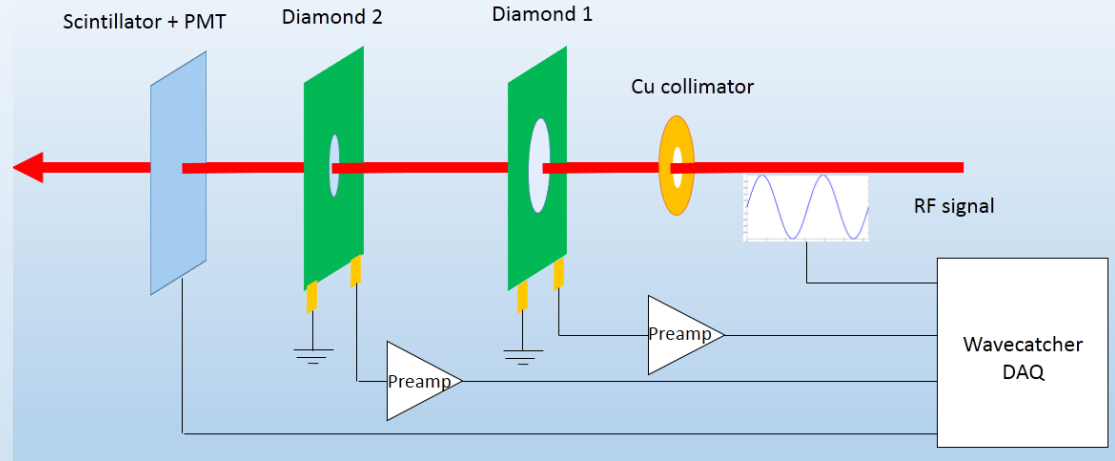
10 x 10 mm² x 500 μm pc-CVD

Waveform amplitude mode

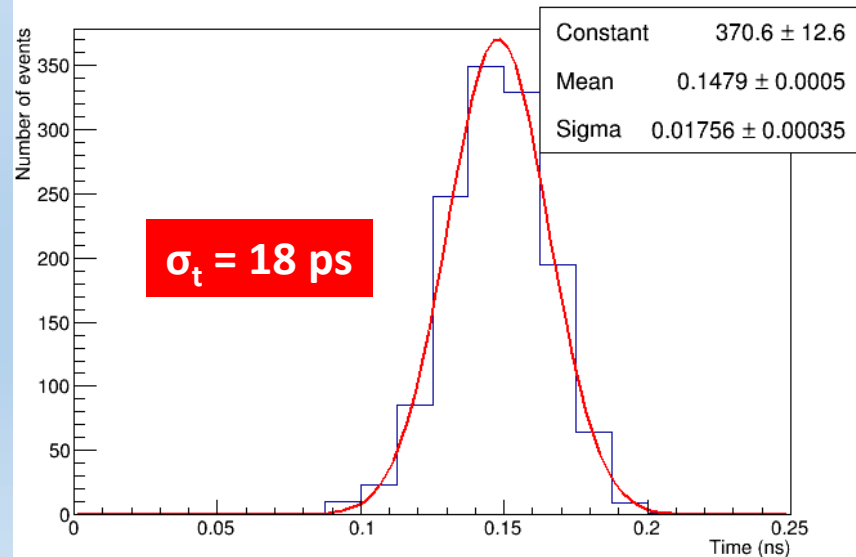


5 × 5 mm² × 300 μm pc-CVD
heteroepitaxially grown on iridium (DOI)

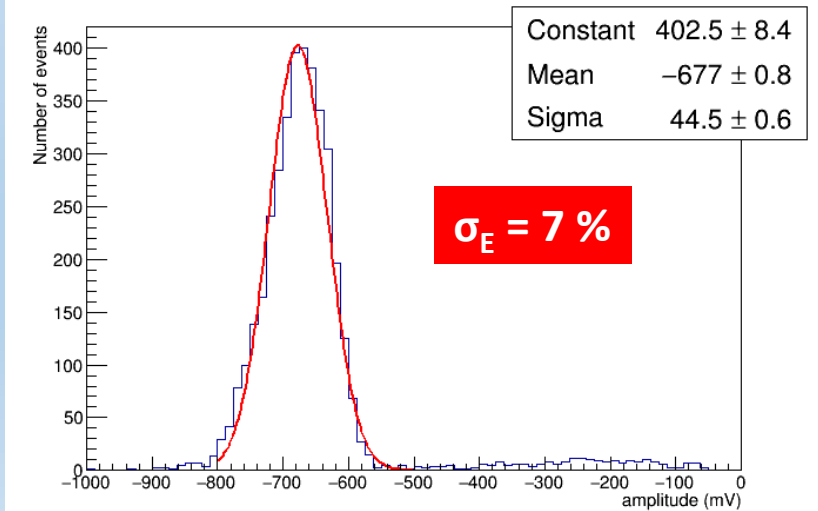
95 MeV/u ^{12}C beam at GANIL



Time resolution
0.45 x 0.45 cm² x 518 μm sc-CVD E6
0.5 x 0.5 cm² x 300 μm pc-CVD Augsburg



Energy resolution
0.5 x 0.5 cm² x 300 μm pc-CVD Augsburg



Characterization of disk shaped diamond

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

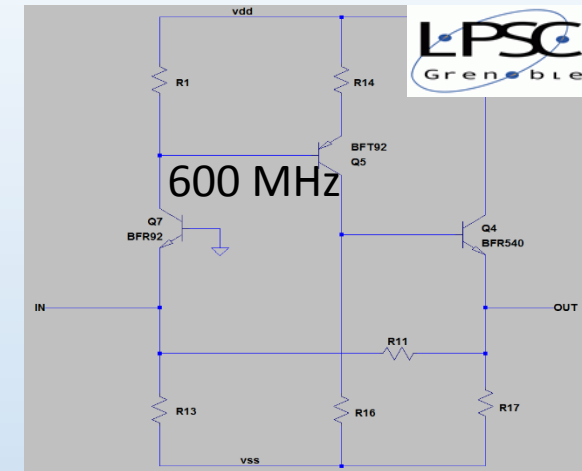
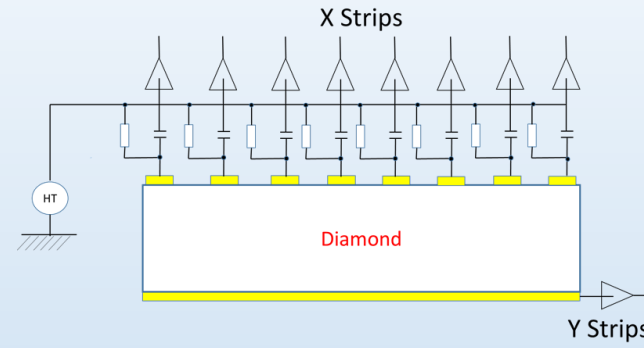
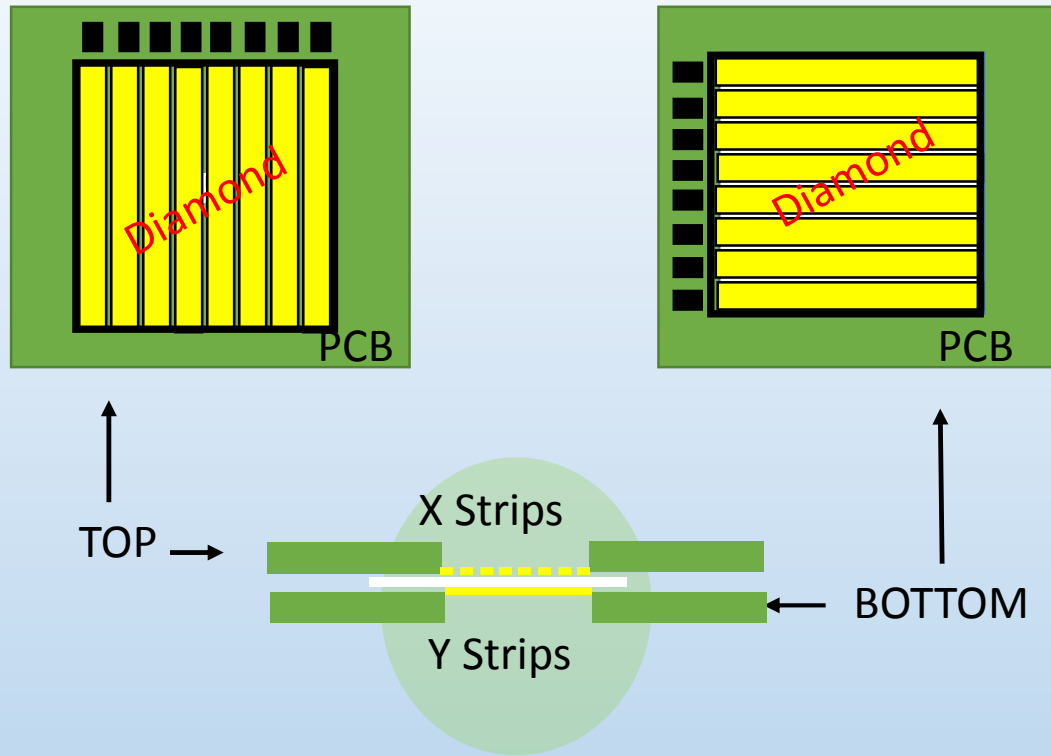
- ❑ a time resolution better than 40 ps,
- ❑ an energy resolution better than 10 %,

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).

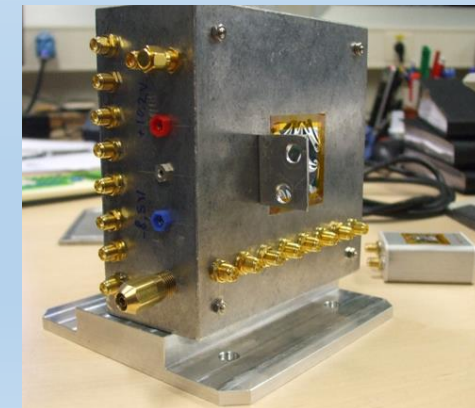
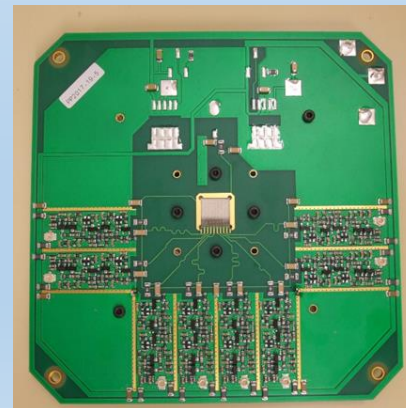
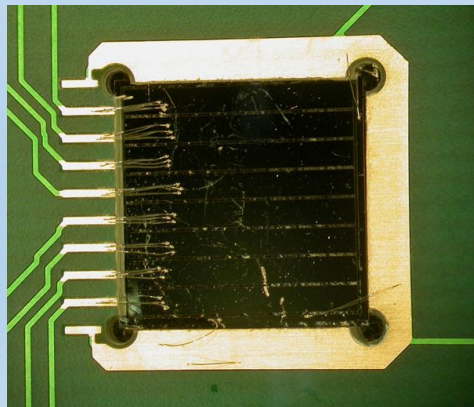
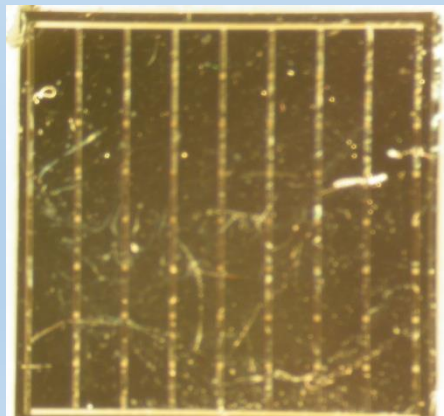
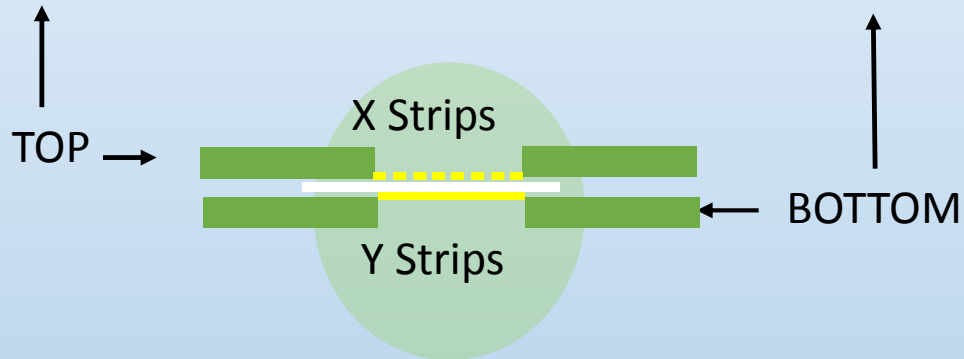
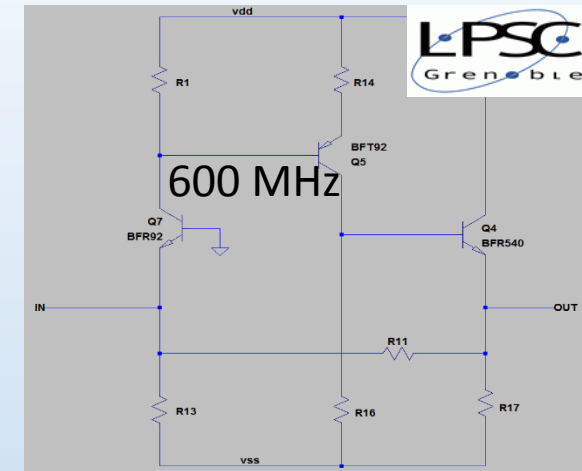
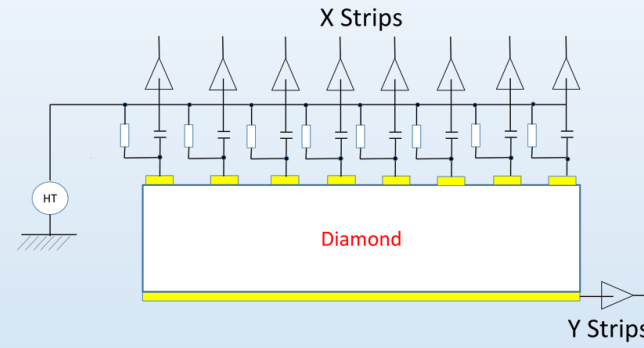
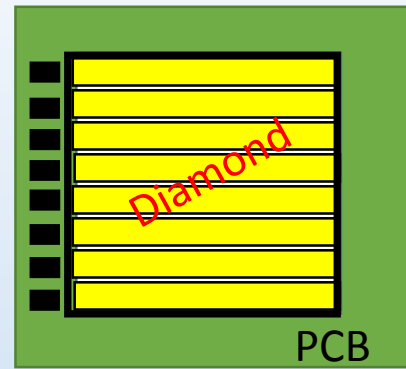
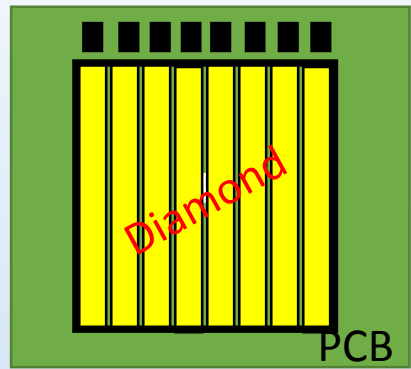
Test benches have been setup at LPSC: alpha, beta sources + wave catcher acquisition

Characterization of double side stripped diamond

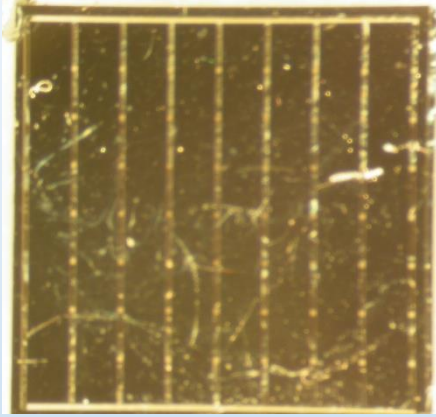
Characterization of CVD diamond at LPSC in 2017



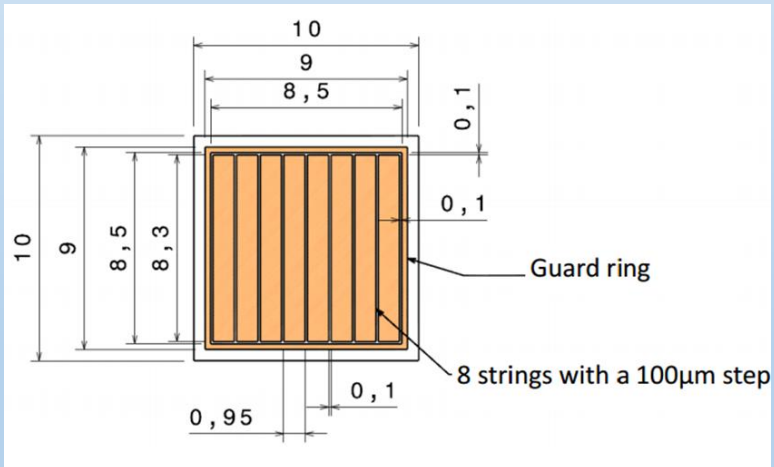
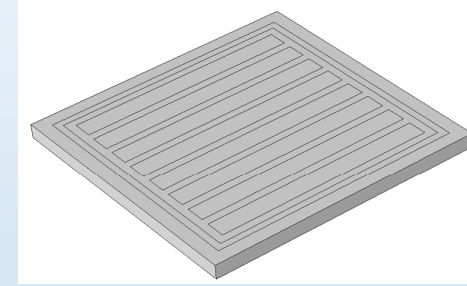
Characterization of CVD diamond at LPSC in 2017



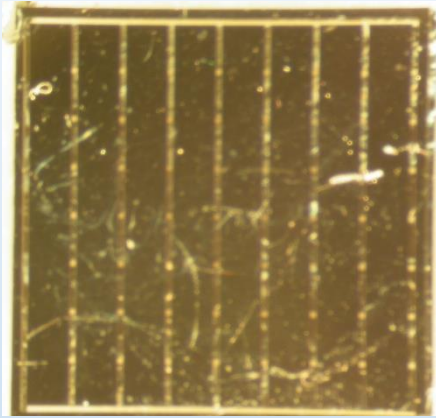
Characterization of CVD diamond at LPSC in 2017



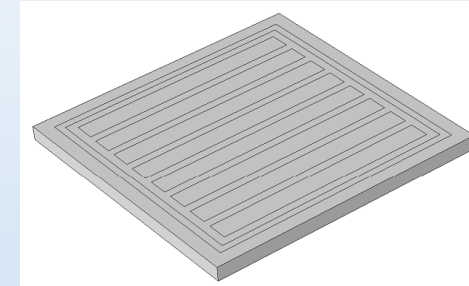
Simulation with © COMSOL Multiphysic 5.3



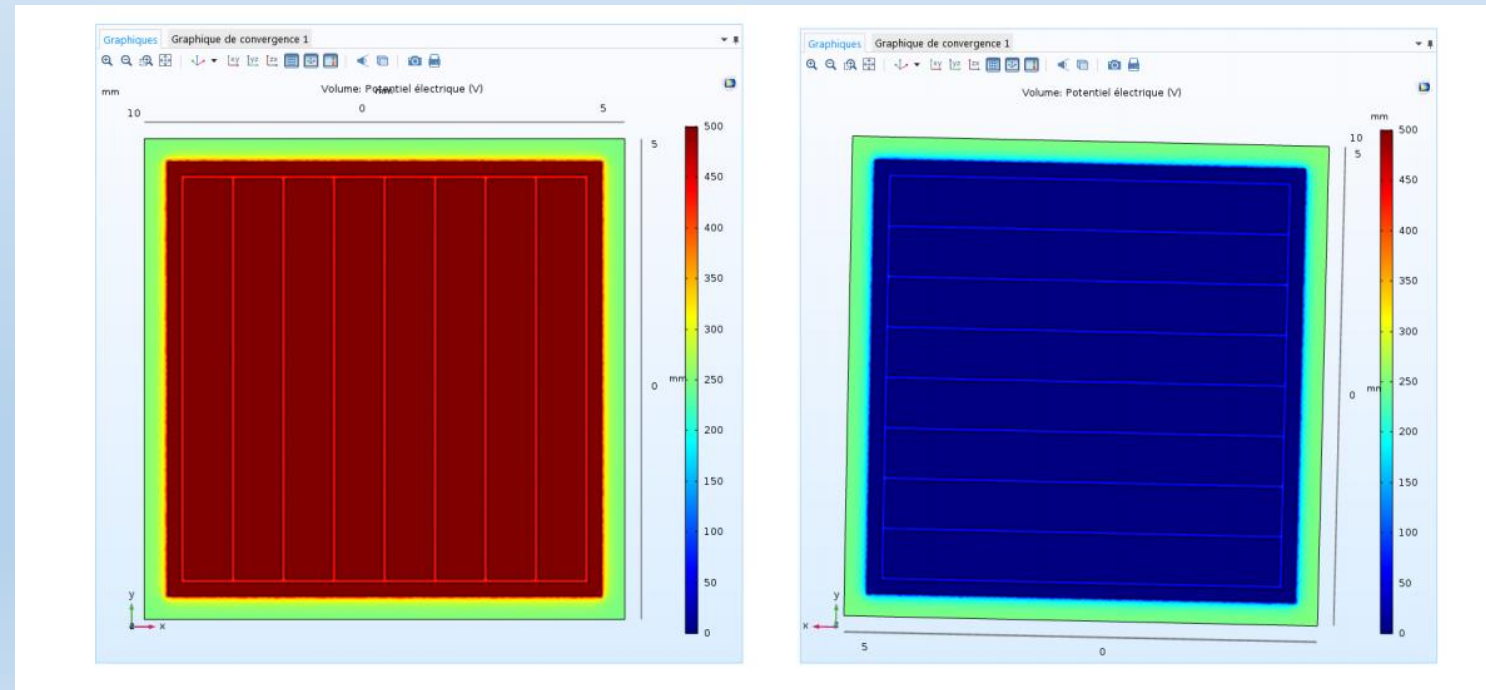
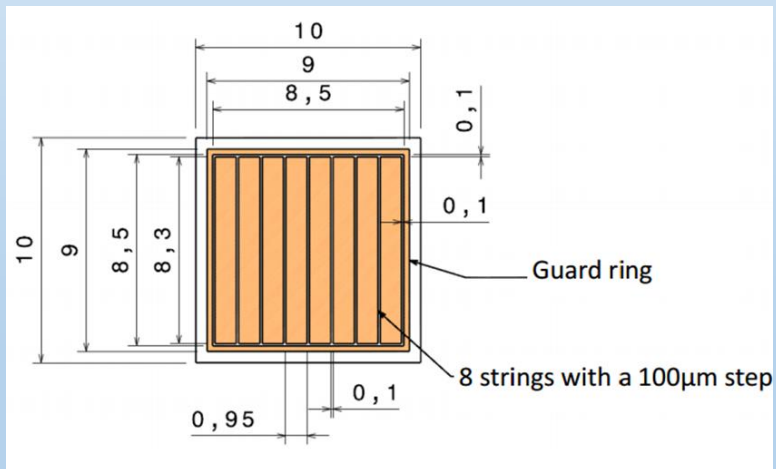
Characterization of CVD diamond at LPSC in 2017



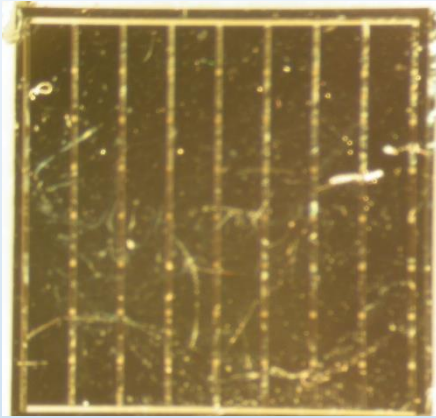
Simulation with © COMSOL Multiphysic 5.3



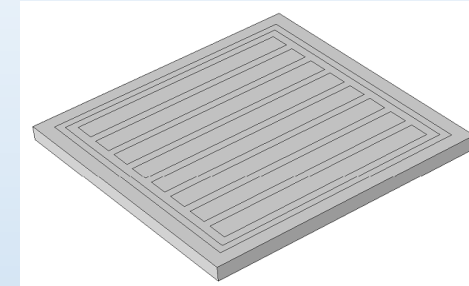
Voltage distribution



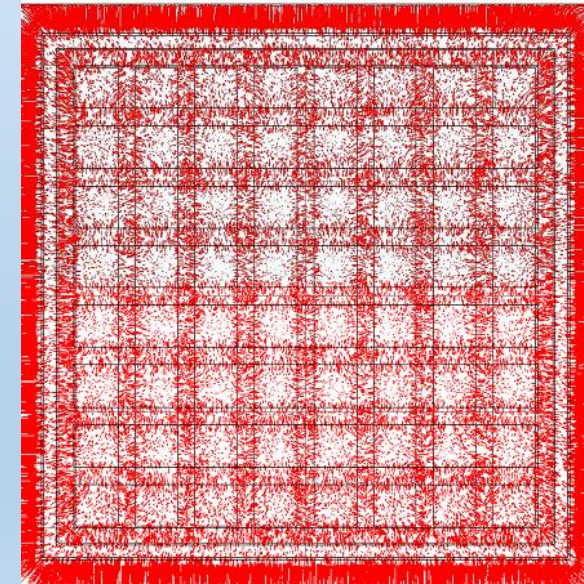
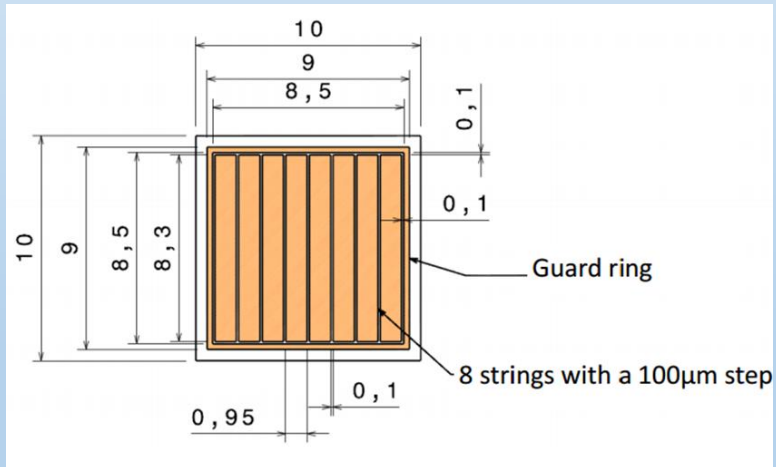
Characterization of CVD diamond at LPSC in 2017



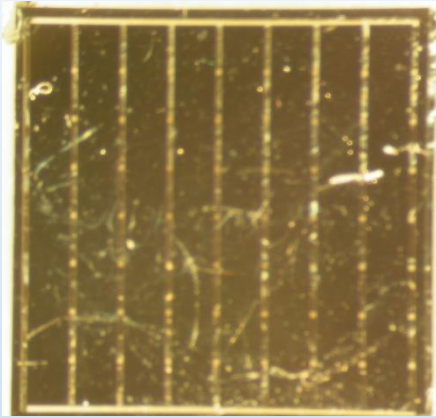
Simulation with © COMSOL Multiphysic 5.3



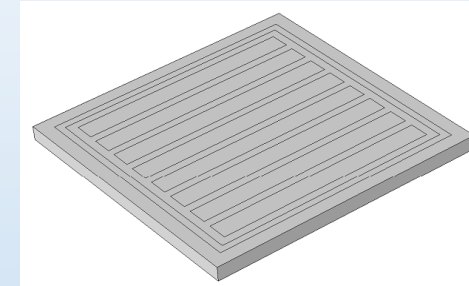
Streamline distribution



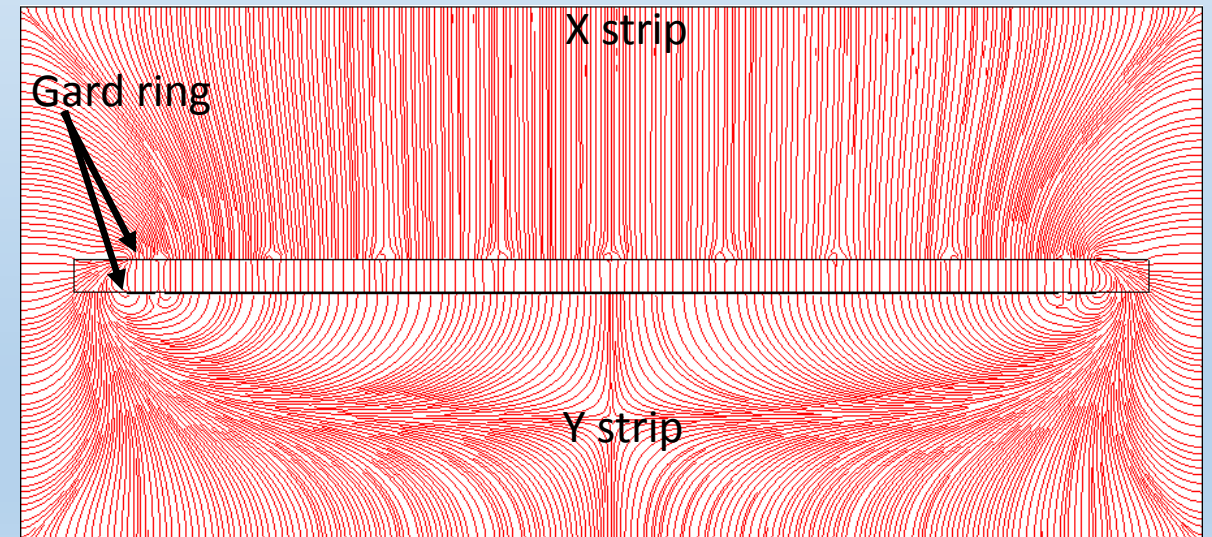
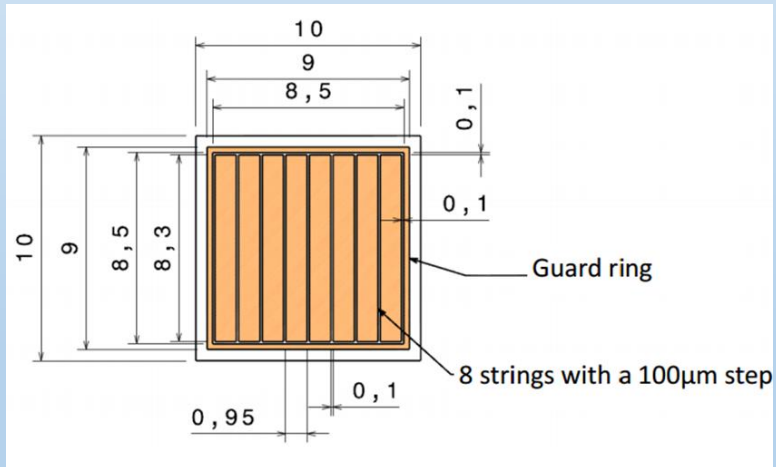
Characterization of CVD diamond at LPSC in 2017



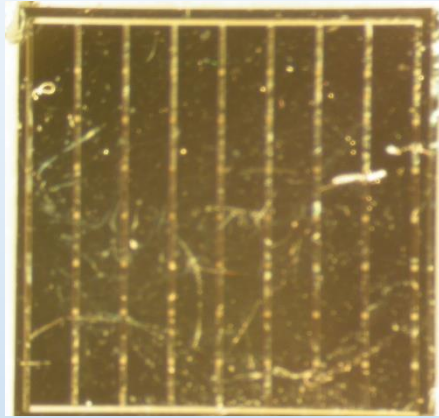
Simulation with © COMSOL Multiphysic 5.3



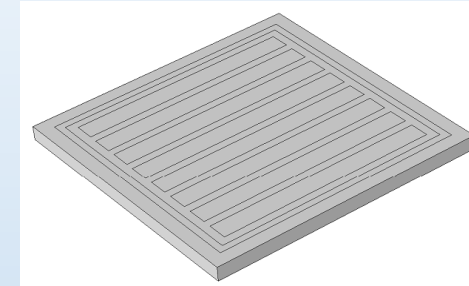
Streamline distribution



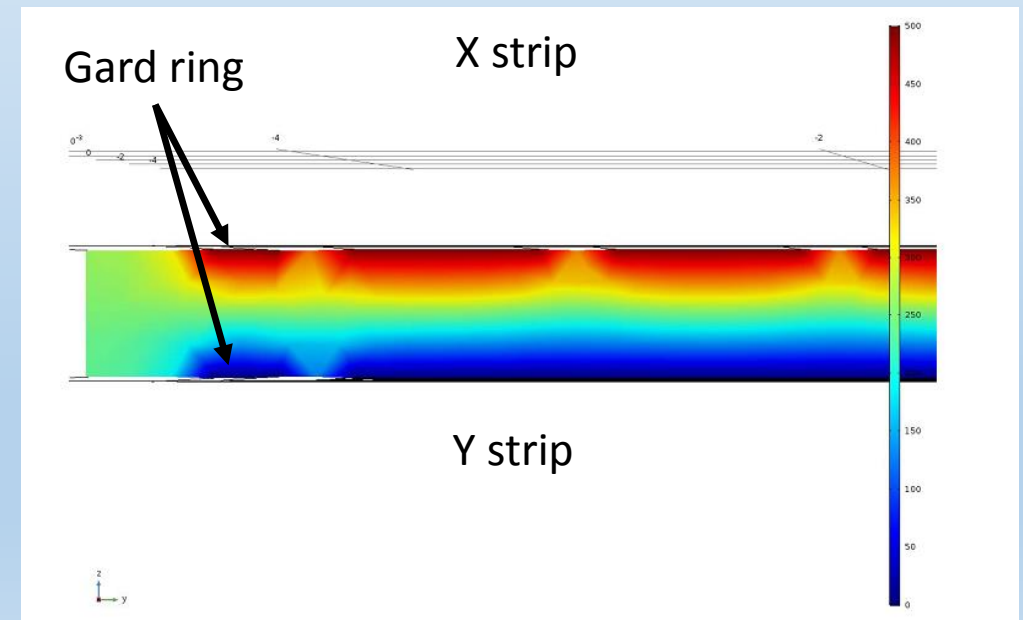
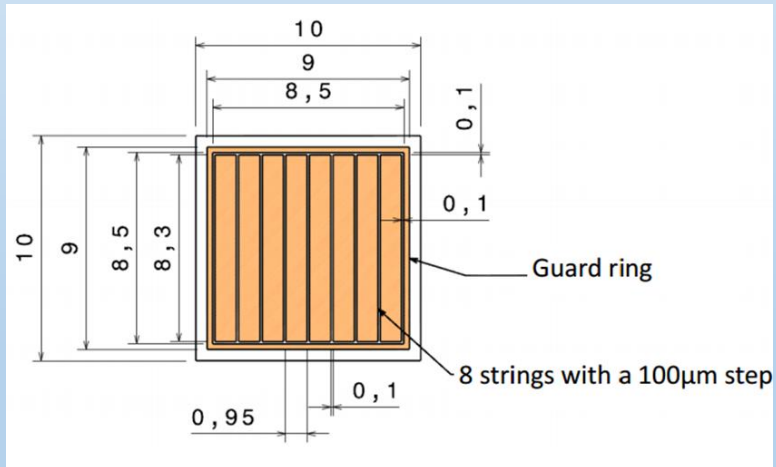
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Simulation with © COMSOL Multiphysic 5.3

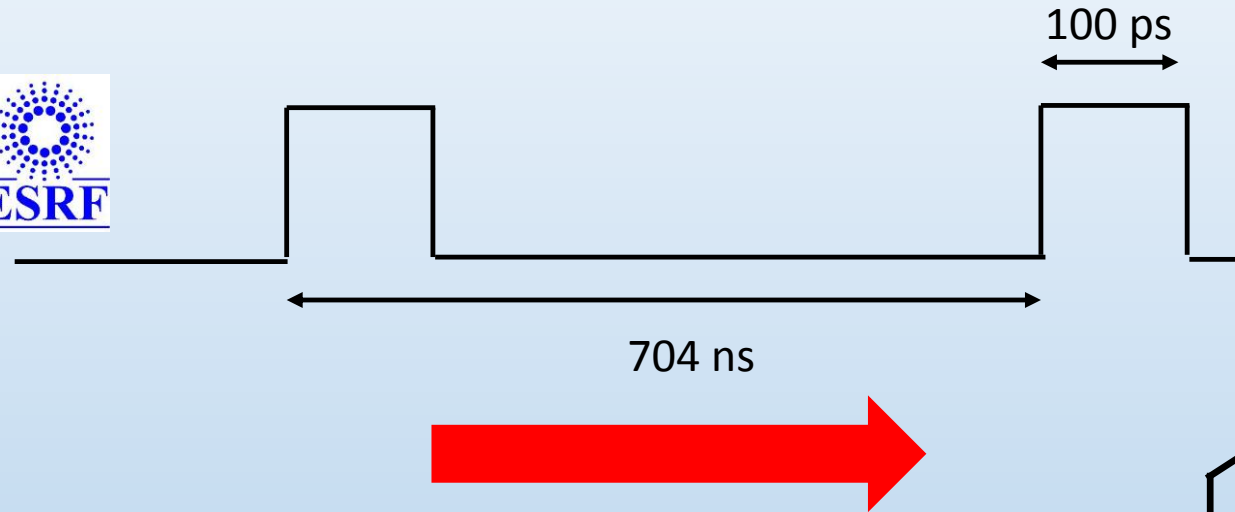


Voltage distribution



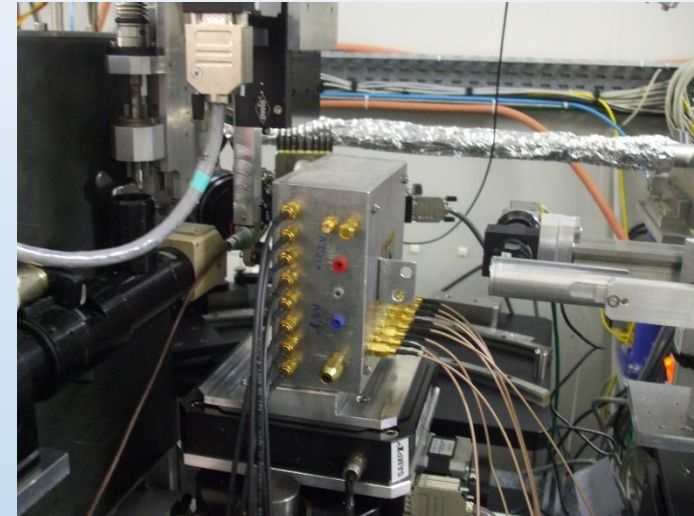
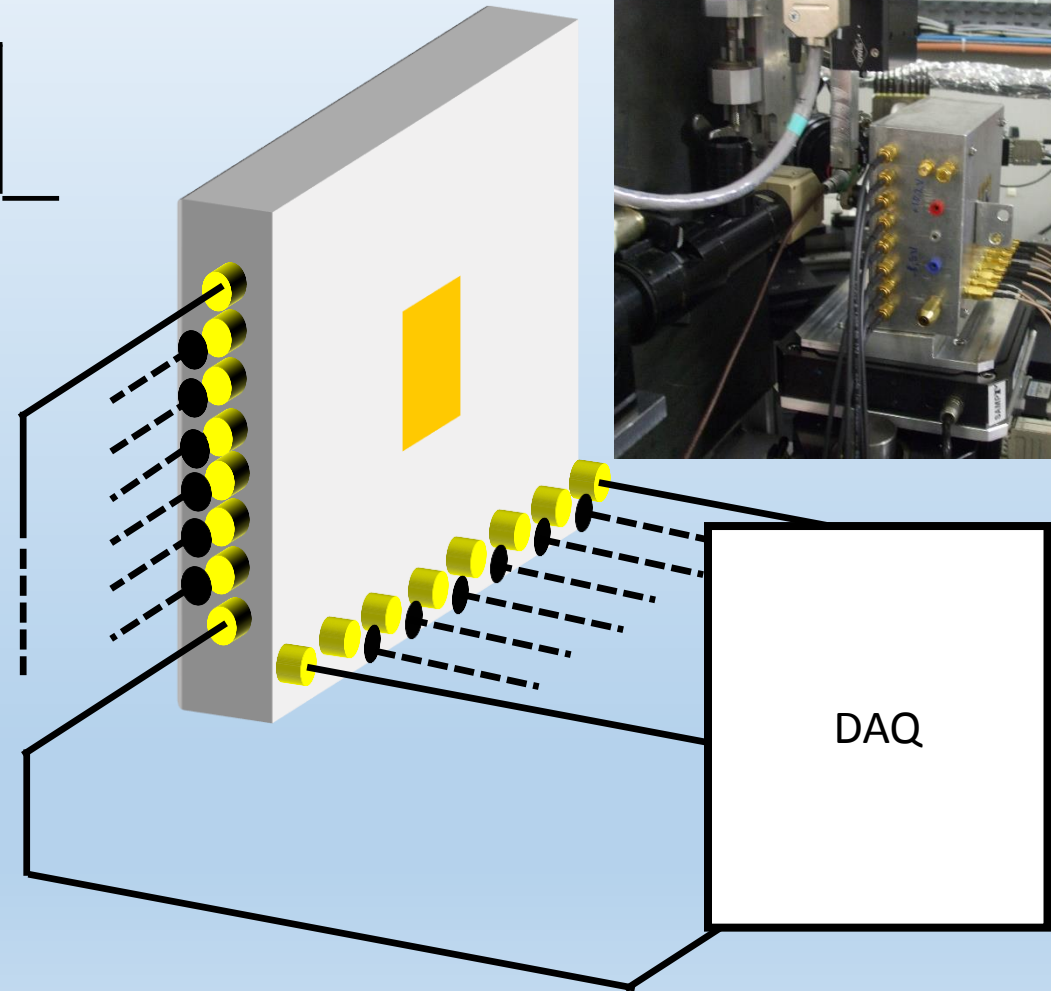
Pulsed beam (8.5 keV ~ 100 ps) at ESRF ID21 X-ray Microscopy beamline

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.



8.5 keV Photon beam in 4 bunches mode

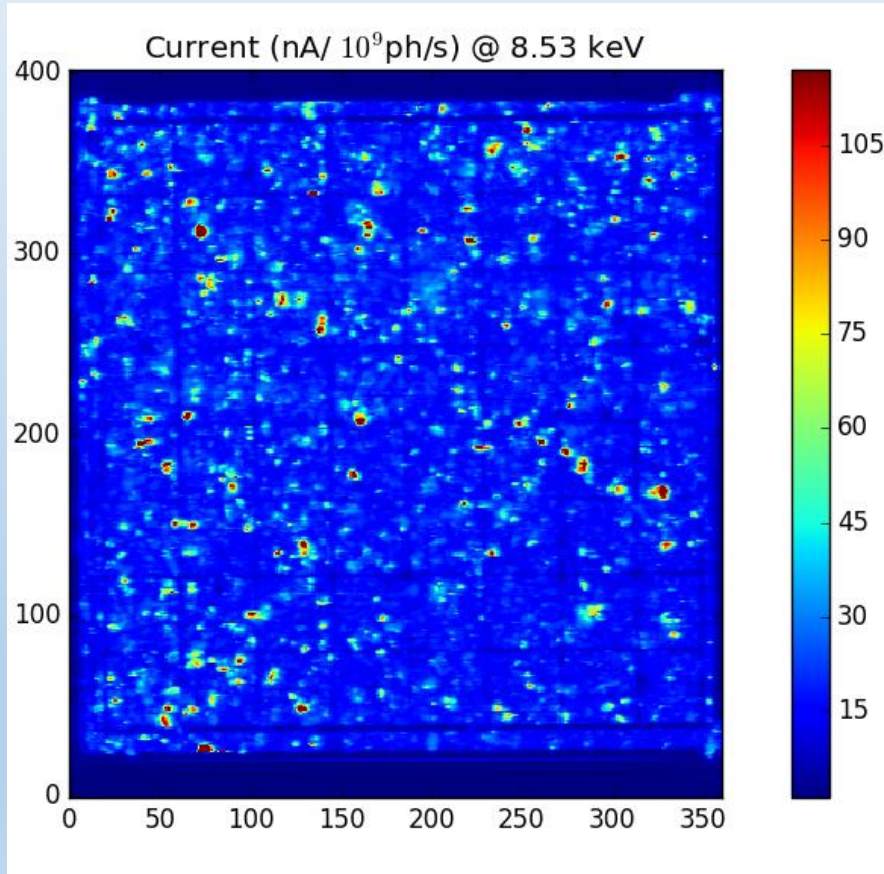
\varnothing spot : $1\ \mu\text{m}$
 ≈ 1400 photons/bunch $\rightarrow 4\ \text{MeV}$ are deposited
in a $300\ \mu\text{m}$ -thick detector



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

X-Ray analysis of the surface of the double side stripped diamond

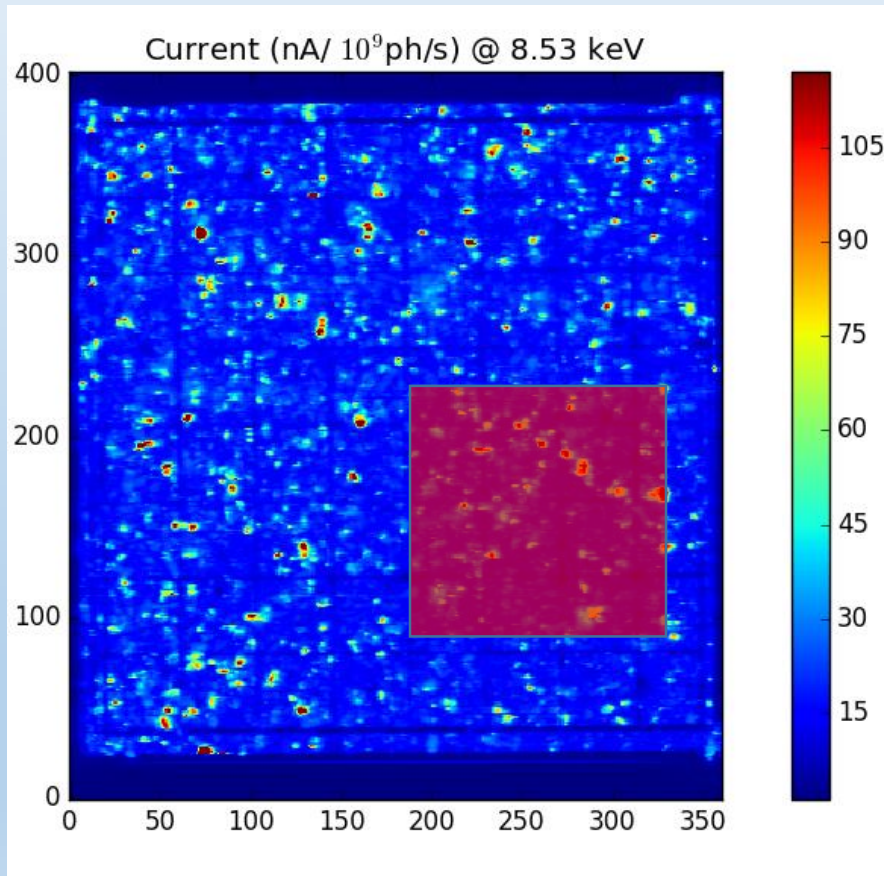
Current integration mode



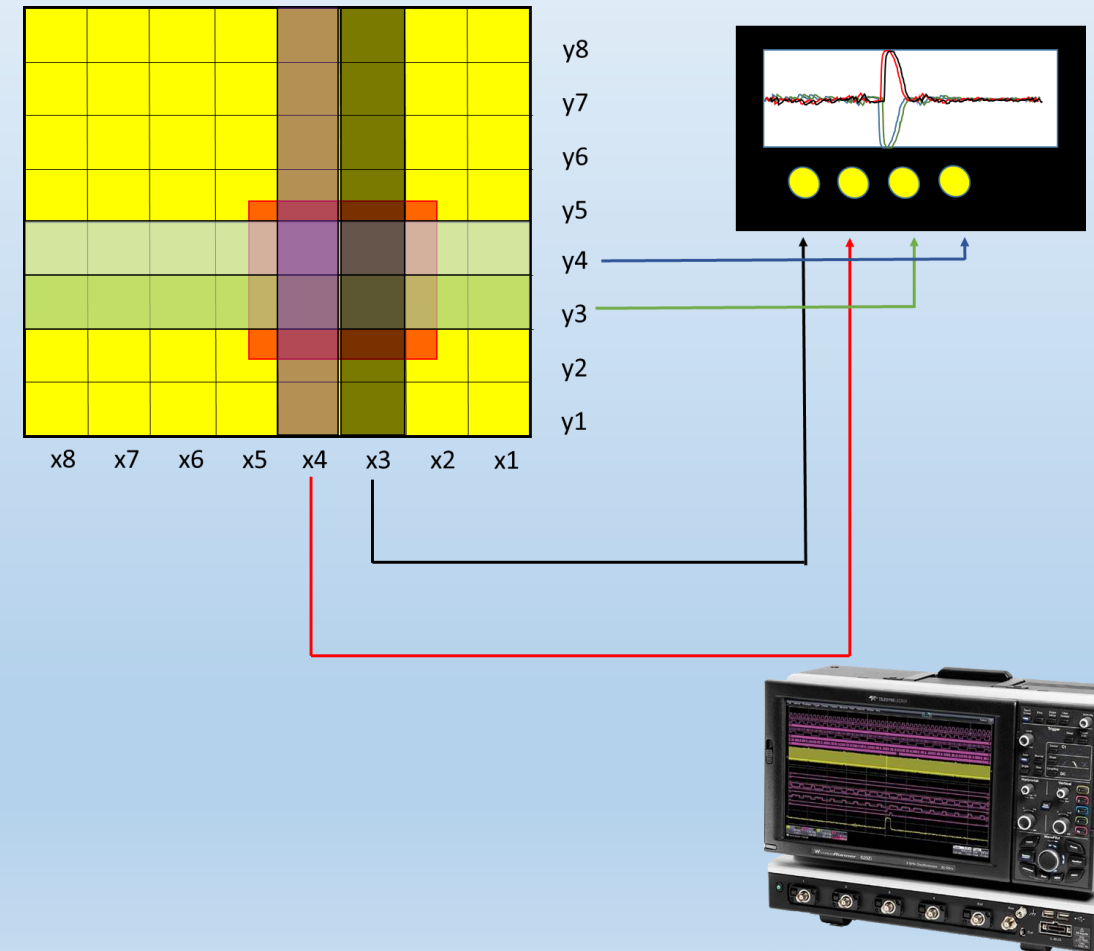
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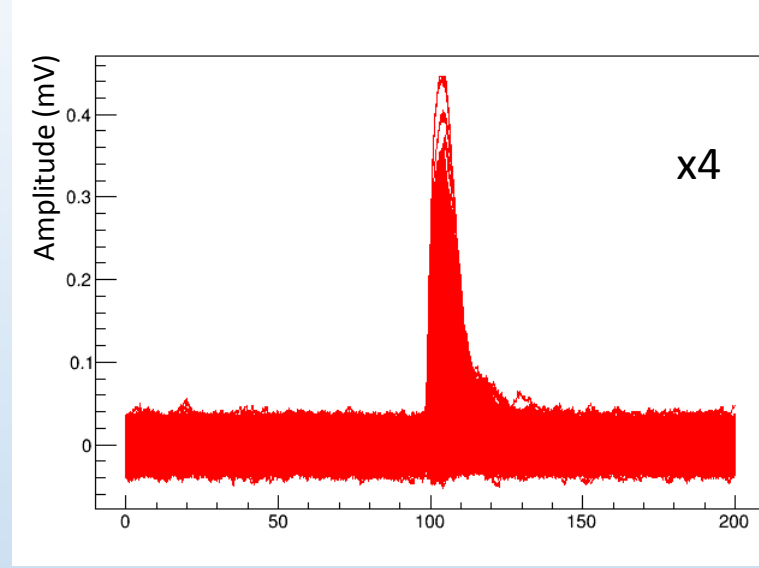
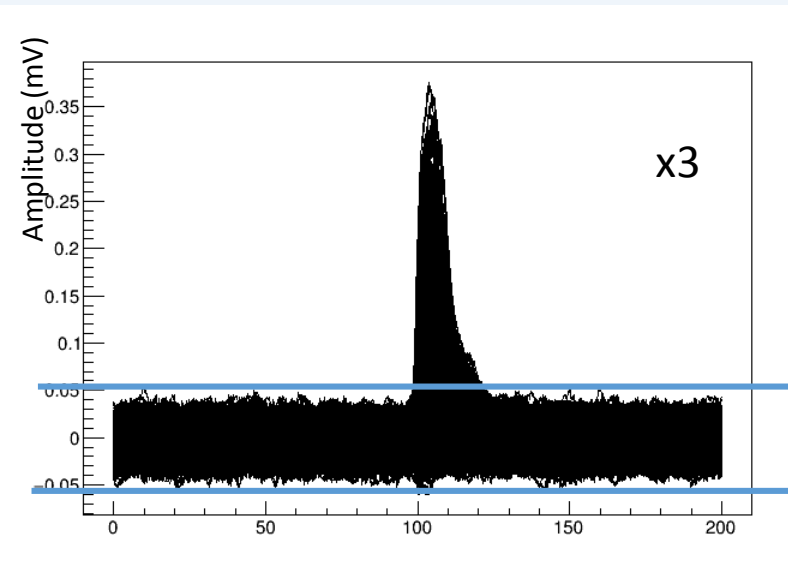
Current integration mode



Waveform amplitude mode



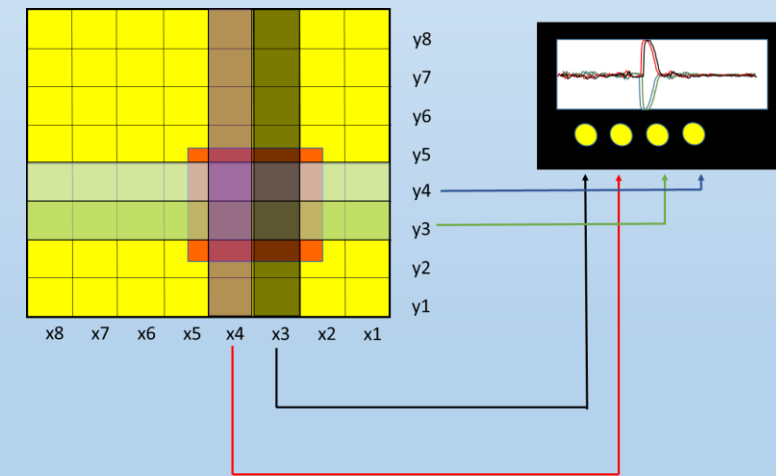
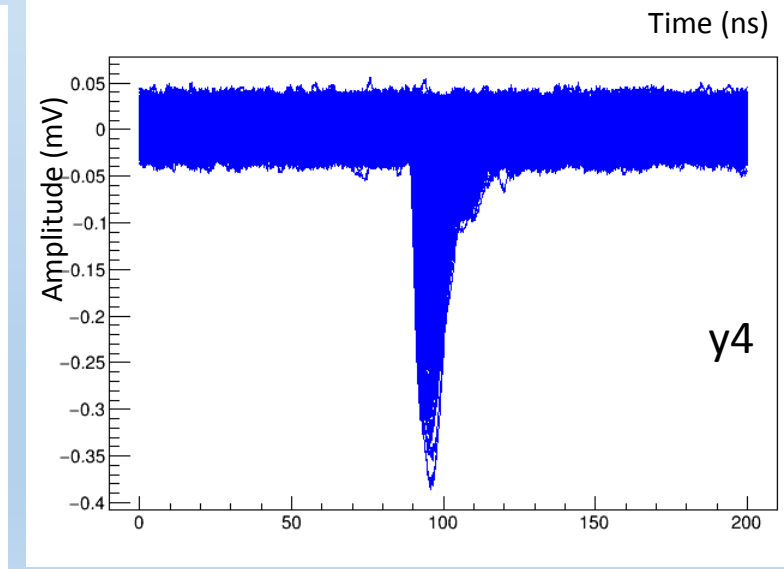
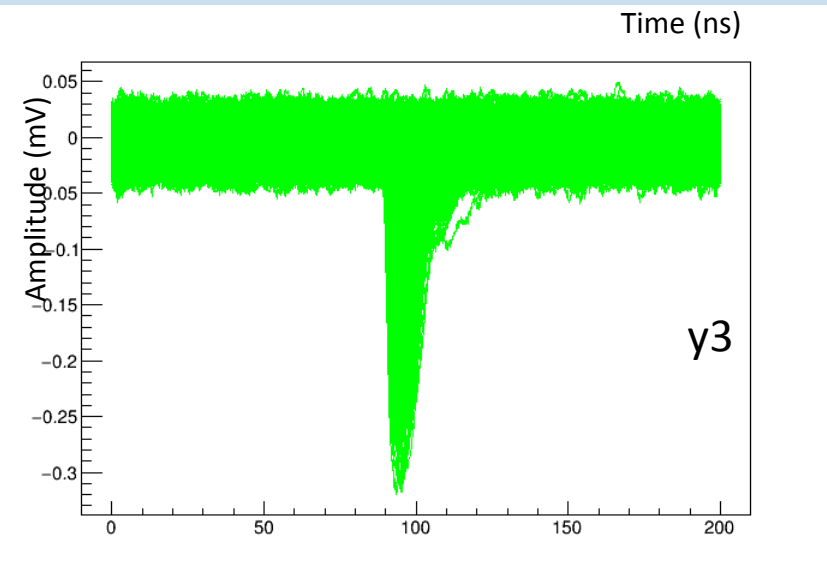
Very preliminary (x,y) barycenter calculation



$$X \text{ strip} = \frac{\text{amplitude}_{\max}(x3) + 2 \times \text{amplitude}_{\max}(x4)}{\text{amplitude}_{\max}(x3) + \text{amplitude}_{\max}(x4)}$$

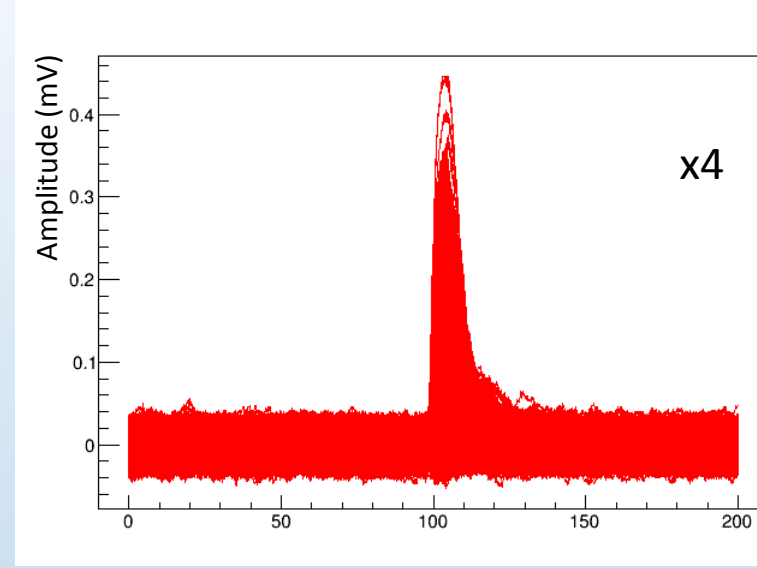
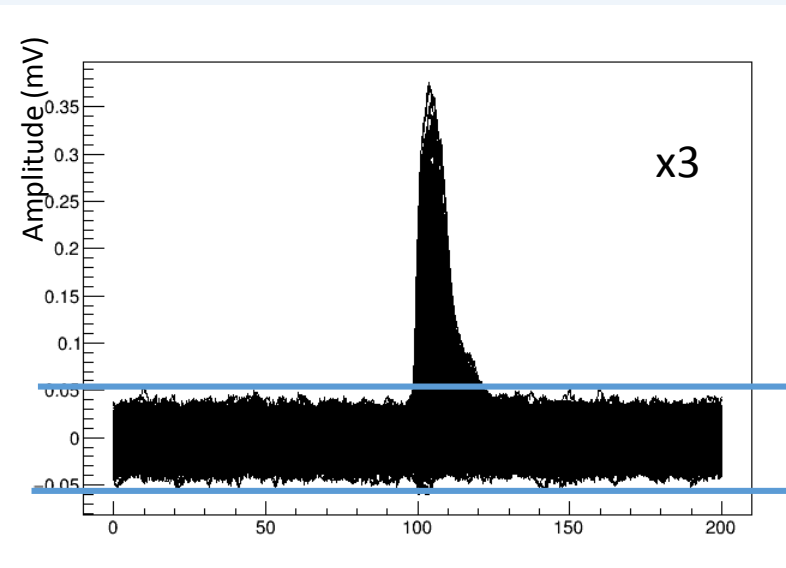
$$Y \text{ strip} = \frac{\text{amplitude}_{\max}(y3) + 2 \times \text{amplitude}_{\max}(y4)}{\text{amplitude}_{\max}(y3) + \text{amplitude}_{\max}(y4)}$$

If amplitude < threshold amplitude = baseline



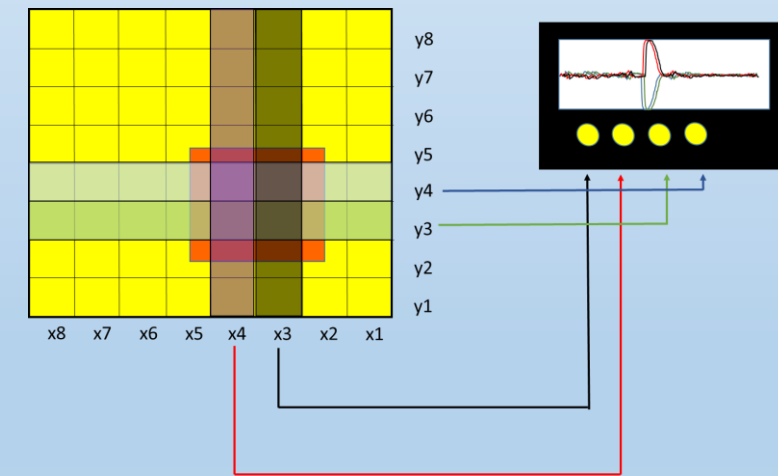
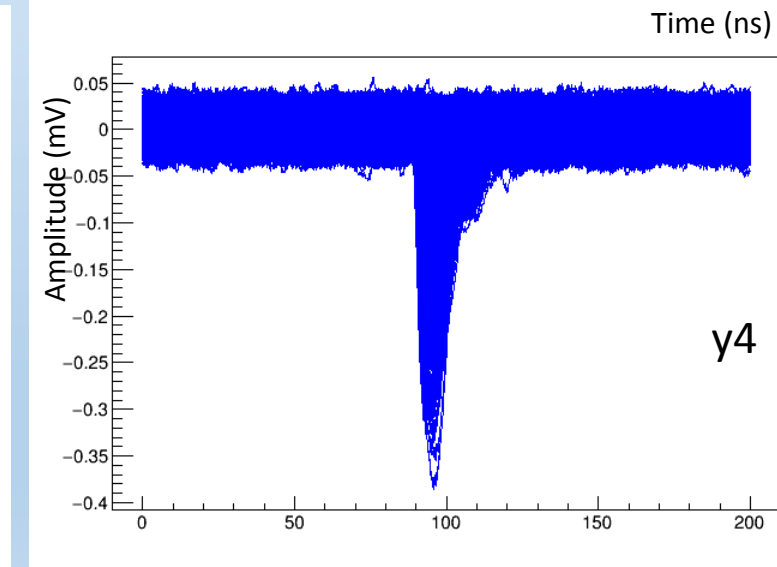
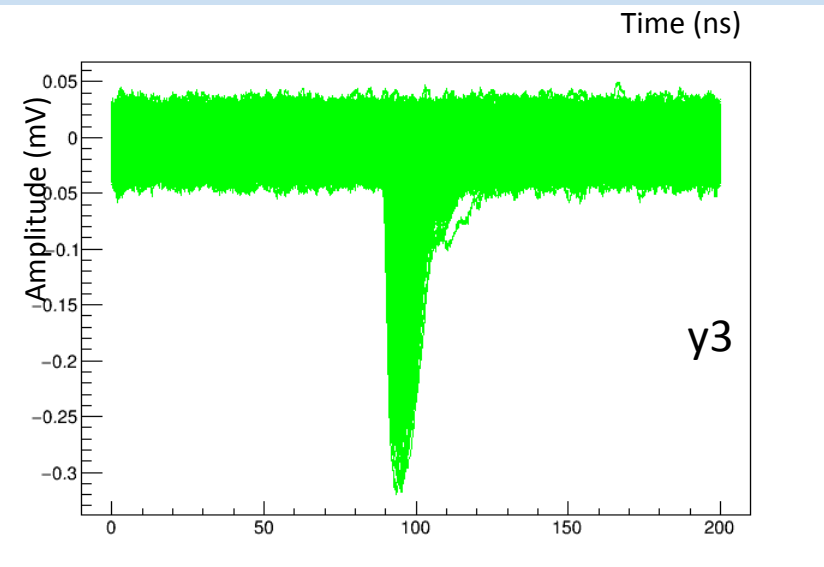
4 channels recording

Very preliminary (x,y) barycenter calculation



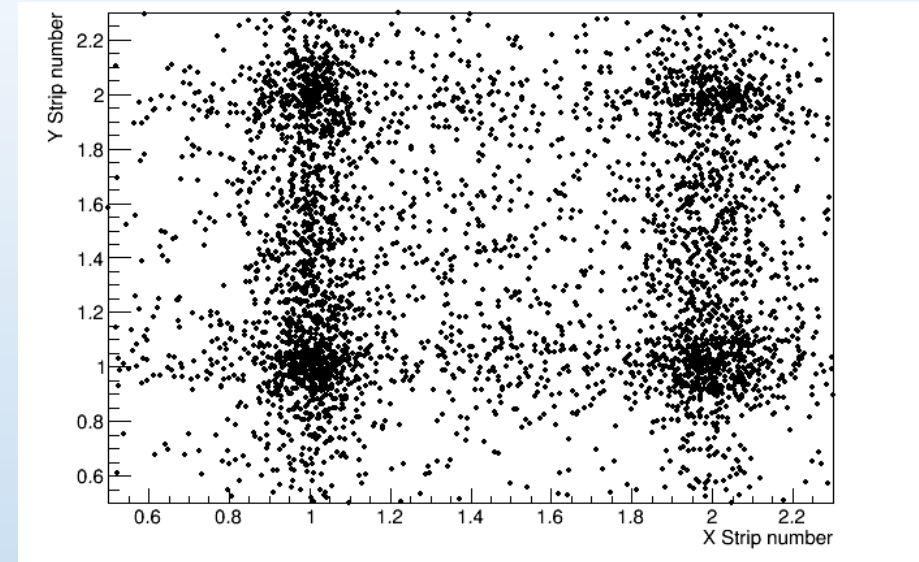
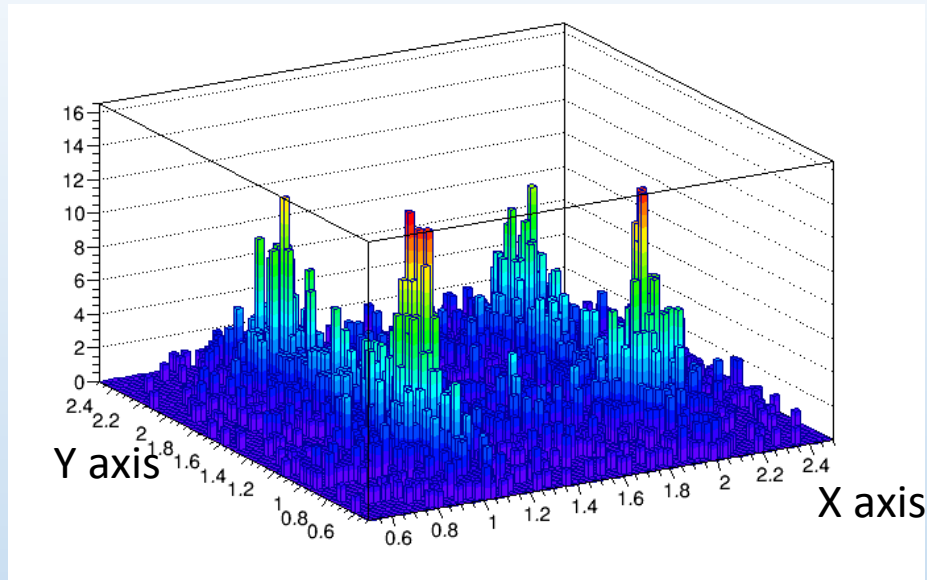
First approach for barycenter calculation

!!! To be refined in a near future !!!

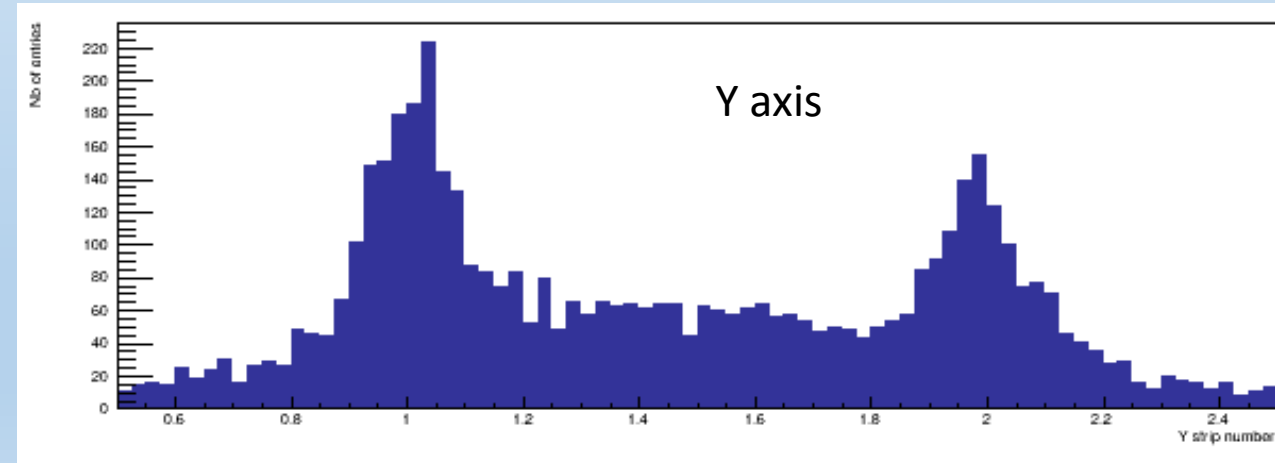
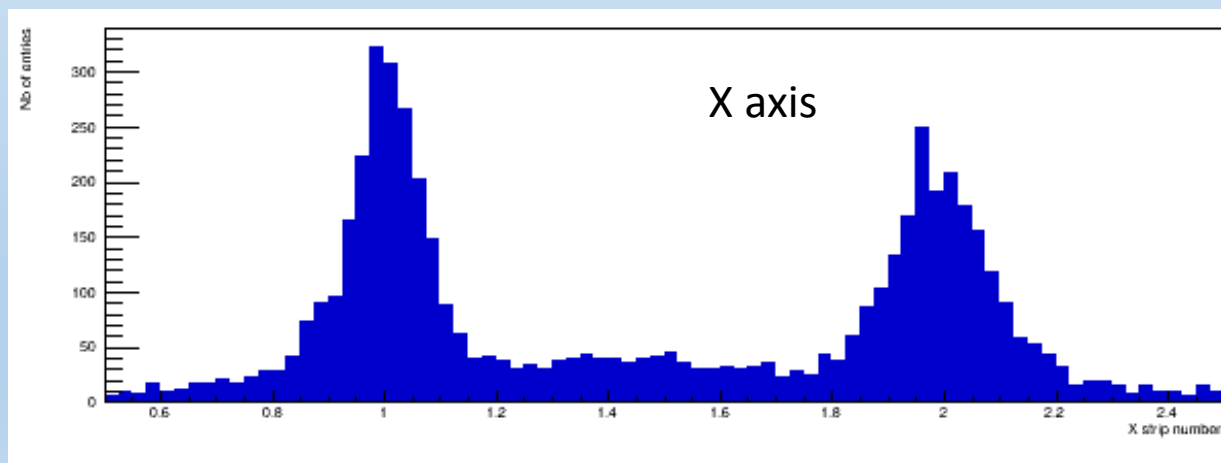


4 channels recording

Very preliminary (x,y) barycenter calculation



Profiles histograms



Characterization of double side stripped diamond

Analysis is still on going More results soon !

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.

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

- ❑ a time resolution better than 40 ps (measured on disk shaped diamond),
- ❑ an energy resolution better than 10 % (measured on disk shaped diamond),

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)

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The final detector will consist of a $\sim 15 \times 15$ cm² 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

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

Acknowledgement



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