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Development of a beam tagging diamond hodoscope for online ion range verification in hadrontherapy

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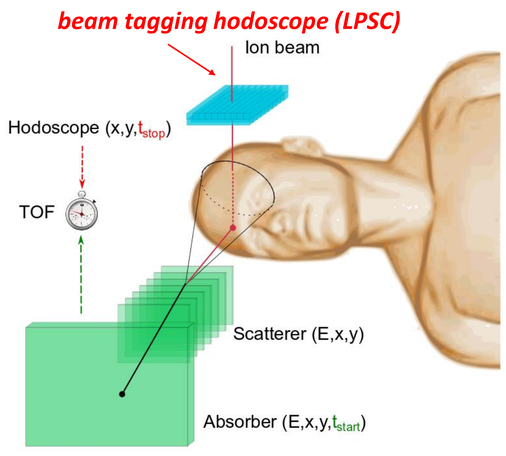
Online ion range control in hadrontherapy

Compared to conventional X-Ray radiotherapy, **hadrontherapy** enables a **highly localized dose deposition (Bragg Peak)**, a **lower entrance dose**, a **better organ at risk protection** and a **better relative biological effectiveness** (carbon ions are mainly concerned) in the targeted volume. The conformation of the dose in depth is obtained by varying the ion beam energy.

These **ballistic properties** allow a powerful tumor targeting but they also lead to a high sensitivity to **ion range uncertainties**. These uncertainties arise from **stopping power evaluation** computed from CT maps, **organ motion** and **patient positioning** during sessions or **morphological changes** along the overall treatment period. As a consequences, **treatment safety margins** are applied (they may approach 1 cm for deep tumors), and beam incidences with distal organs at risk are avoided.

Considering this, in order to reduce margins and optimize the ballistic efficiency, an **online ion range verification** has to be carried out. In this context the **CLaRyS* collaboration** is developing various online ion range verification techniques based on **secondary particles** detection.

Prompt-gamma Imaging is one of these techniques. It relies on the detection of prompt gamma photons emitted by the patient along the ion pathway. Their emission profile is spatially correlated to the ion range so that an online ion range information can be reached. Different gamma detection devices such as **gamma** or **Compton cameras** are developed by CLaRyS. The imaging efficiency of such devices can be improved by **Time-Of-Flight (TOF) discrimination** in coincidence with a **beam tagging hodoscope.** It will provide both position and temporal tagging of incoming ions and will allow a neutron-induced noise rejection. This hodoscope needs to be fast and radiation hard, that led CLaRyS to develop a **diamond** based hodoscope.



The Compton camera project of the CLaRyS collaboration

*CLaRyS : Lyon, Clermont-Ferrand, Marseille and Grenoble (LPSC)

Development of a beam tagging diamond hodoscope

Growth process

Chemical Vapor Deposition (CVD)

Growth in a plasma reactor over a diamond or silicon seed used as substrate

Crystal structures

Single-crystal CVD diamond (sc-CVD) ← **Crystal quality – Charge collection** / **Size – Price -Availability** → **Polycrystalline CVD Diamond (pc-CVD)**

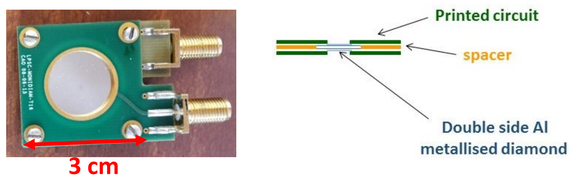
Alternative : **Diamond heteroepixtaxy on Iridium substrate (DoI)**

→ Large samples (> 1cm²) with high charge collection properties **BUT** still R&D

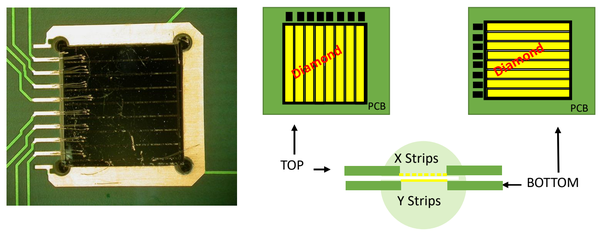
Intrinsic properties

Resistivity	> 10^{13} Ω.m	→	Low leakage currents
e/h pair creation energy	13.1 eV	→	Good Signal-to-Noise Ratio (SNR)
Displacement Energy	43 eV	→	**Radiation hardness**
Charge carrier mobilities	≥ 2000 cm²/V/s	→	**Fast time response**
Atomic number	6	→	**Tissue-equivalent**

Development in instrumentation at LPSC



Diamond detector with full planar metallization used as solid-state ionization chamber for tests



*Double-side stripped diamond demonstrator for the development of a **beam tagging hodoscope***

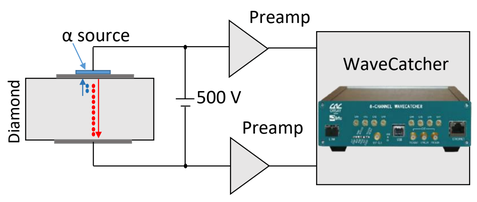
Performances of diamond detectors under various irradiation conditions

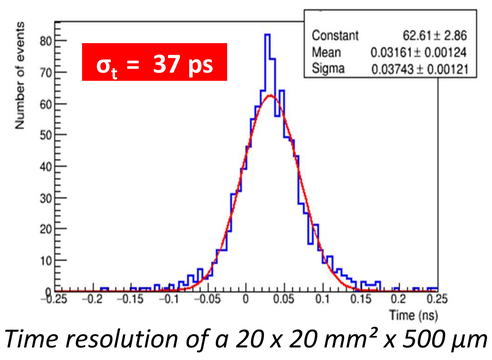
^{241}Am alpha source

Alphas energy ≈ 5.5 MeV

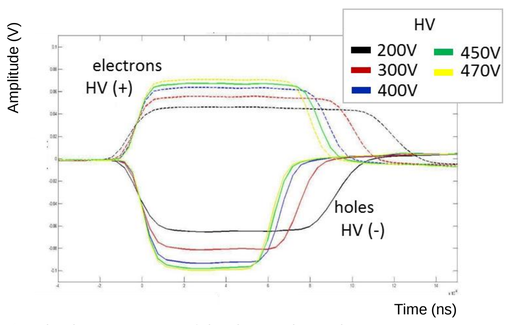
→ Range in diamond ≈ 14 µm << diamond thickness (300µm)

→ Intrinsic time resolution
Charge carriers behaviour analysis





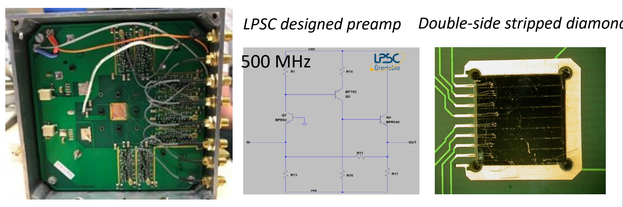
Time resolution of a 20 x 20 mm² x 500 µm pc-CVD diamond (difference of the timing of both surface signals)



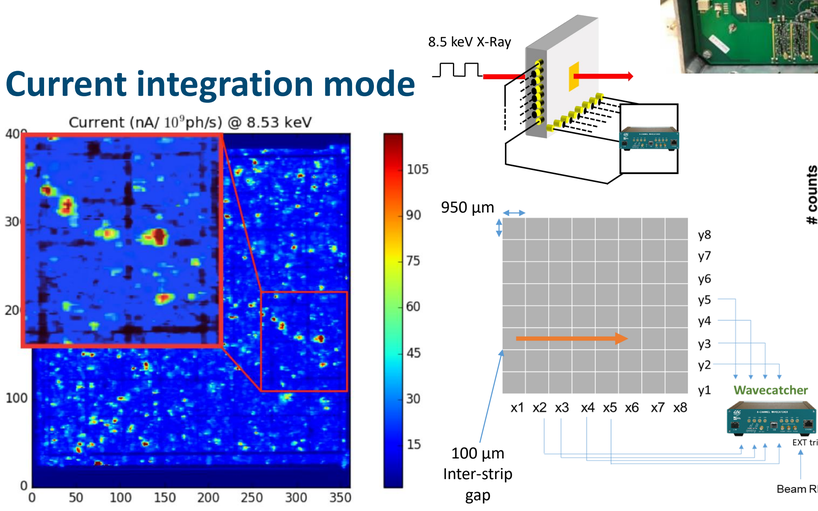
Typical electron and hole pulse shapes measured on a sc-CVD diamond under short-range alpha irradiation at various bias voltages

X-ray pulsed micro beam and double-side stripped samples

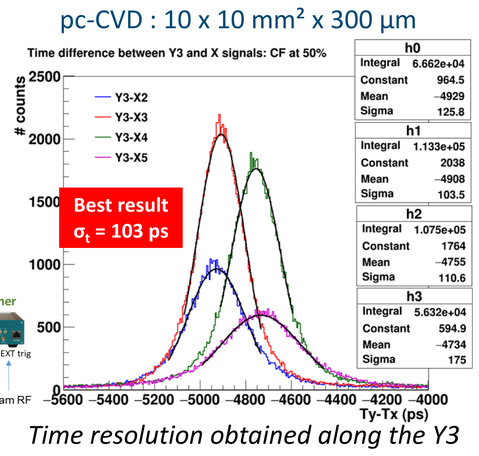
Time response of the first prototypes of double-side stripped diamond detectors with embedded front end electronics designed at LPSC



Current integration mode



pc-CVD : 10 x 10 mm² x 300 µm

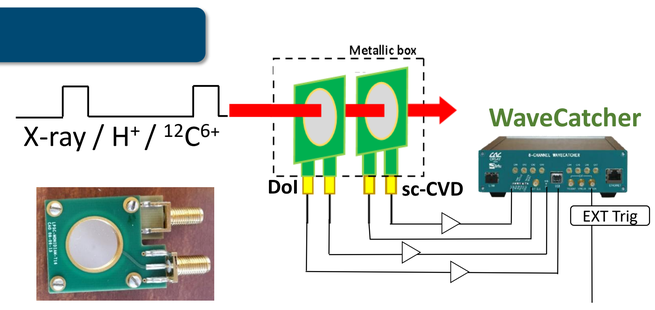


Time resolution obtained along the Y3 horizontal strip of a double-side stripped pc-CVD sample

Pulsed beams

Diamonds: DoI : 5.0 x 5.0 mm² x 300 µm
sc-CVD : 4.5 x 4.5 mm² x 515 µm

Electronics : CIVIDEC current preamplifiers (2GHz, 40dB)



8.5 keV photons (ESRF)

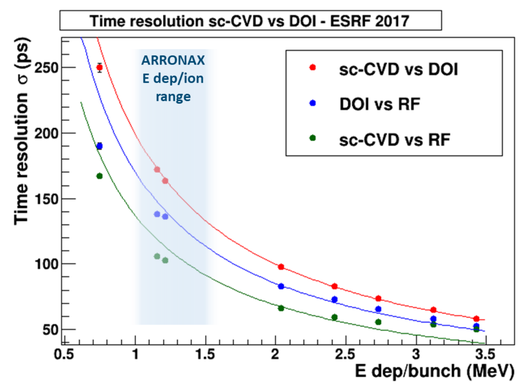
Micro-beam Ø : 1 µm - 1500 photons/bunch
≈ 500 photons absorbed along 300 µm→ almost continuous ionisation with adjustable energy deposited

→Mimicks signal induced by single particles

Trigger : Coincidence on diamonds OR beam RF

Energy deposition/bunch : 3.4 MeV (300 µm)

Use of Al and Ti plates as primary beam attenuators (modifying the energy deposition/bunch)



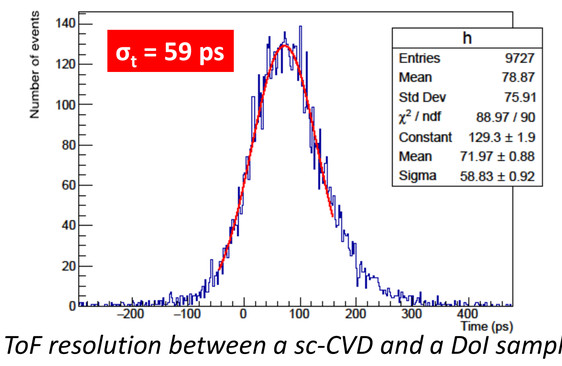
Influence of the energy deposit per bunch on the ToF resolution measured between a DoI, sc-CVD samples and the ESRF beam RF (Fit : Cst/E dep)

68 MeV protons (ARRONAX)

Trigger : Auto-trigger on diamond

Energy deposition/ion (SRIM) :

Thickness	300 µm	515 µm
Energy deposit	0.93 ± 0.10 MeV	1.6 ± 0.13 MeV



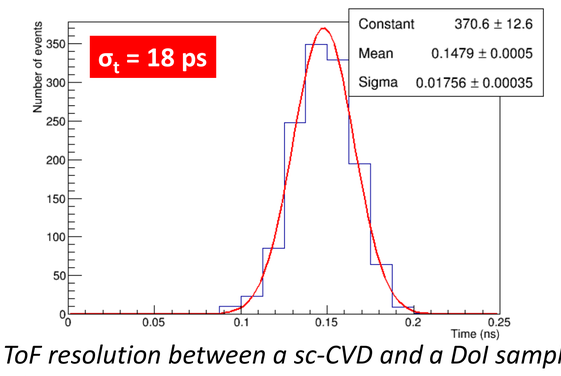
ToF resolution between a sc-CVD and a DoI samples

95 MeV/u ^{12}C ions (GANIL)

Trigger : Plastic scintillator set after the diamonds

Energy deposition/ion (SRIM) :

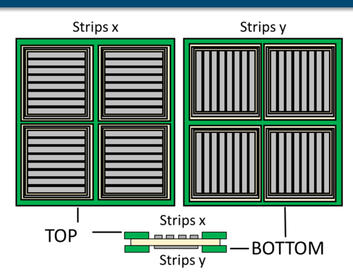
Thickness	300 µm	515 µm
Energy deposit	25 MeV	44 MeV



ToF resolution between a sc-CVD and a DoI samples (Timing difference between detectors in cascade)

Conclusions and perspectives

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. The final detector will consist of a mosaic arrangement of stripped sensors read by a dedicated integrated electronics (~1800 channels) with a counting rate per channel of 10 MHz, a time resolution at the level of few tens of ps, a spatial resolution at the level of 1 mm.



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