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


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Hadron therapy in cancer treatment

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

Dose delivery / incident ionizing particle

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

ClaRyS French collaboration

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

[see GamHadron project  M. Pomorski CEA LIST presented at ADAMAS 2012]

Bragg peak → Ballistic precision

Secondary radiation emission from fragmentation is correlated to ion range

Range uncertainties → Need for online control

[Knopf, PMB 2013]
Why to develop a beam tagging hodoscope?

Exp.: 95 MeV/u $^{12}$C beam impacting a PMMA target / detector $=$ BaF$_2$

Bragg pic

GEANT4

Prompt gamma

Hodoscope $\Rightarrow$ time of flight measurement at 1 ns to reduce background

G. Dedes, PMB 2014

M. Testa, Rad Env Bio 2010

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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 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 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 hodoscope R&D

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

Large area poly-crystalline diamond pc-CVD : 20 x 20 mm² (currently on the shelf)

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 crystals are concerned) and charge integration outputs

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

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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 cm² x 500 µm sc-CVD E6
Metallization 2 sides
Al 50 nm; φ 4 mm

500 V

Diamond 0.45 x 0.45 cm² x 500 µm sc-CVD E6
3 cm

50 Ω adapted detector holder

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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)

WaveRunner Lecroy
2 GHz; 10 or 20 GS/s

WaveCatcher
500 MHz; 3.2 GS/s

Electrodes
Diamond
500 V
Preamp
SAMPLING & DAQ

WaveRunner Lecroy
2 GHz; 10 or 20 GS/s

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

$^{90}\text{Sr}$ 74 MBq β source

Triggering on high energy electrons (scintillator behind diamond)
Measurements with $^{241}$Am: $\alpha$ source (5.4 MeV)

- $\alpha$ source
- Diamond
- Preamp
- 500 V
- WaveCatcher DAQ
- Theoretical Signal

$\alpha$ => study the difference between the growth and substrate sides

$\alpha$ => study the signal induced by electrons / holes

Experimentally measured signal sc-CVD

241Am source, E6-3 diamond, CVIDEC amplifier

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Measurements with $^{241}\text{Am}: \alpha$ source (5.4 MeV)

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

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

ML Gallin-Martel LPSC Grenoble
Measurements with $^{241}\text{Am}$: $\alpha$ source (5.4 MeV)

- **α source**
- Diamond
- Preamp
- WaveCatcher
- DAQ
- 500 V

**Time resolution pc-CVD 20 x 20 mm$^2$ x 500 µm E6**

**Offline Constant Fraction Discriminator method**

**Theoretical Signal**

- Current induced by e-
- Current induced by holes

**Experimentally measured signal sc-CVD**

- Timing difference of both surface signals

**Graphs and Data**

- Constant: $62.61 \pm 2.86$
- Mean: $0.03161 \pm 0.00124$
- Sigma: $0.03743 \pm 0.00121$

- $\sigma_t = 37$ ps

- $241\text{Am}$ source, E6-3 diamond, CIVIDEC amplifier

- ML Gallin-Martel LPSC 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

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.

Electromagnetic shielding box

Time resolution sc-CVD 0.45x 0.45 cm² x 518 µm E6

σᵣ = 26 ps cividec

σᵣ = 50 ps DBA III

σᵣ = 50 ps LPSC

ML Gallin-Martel LPSC Grenoble
Pulsed beam (8.5 keV ~100 ps) at ESRF ID21 X-ray Microscopy beamline

Electromagnetic shielding box

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

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

ML Gallin-Martel LPSC Grenoble
Pulsed beam (8.5 keV ~100 ps) at ESRF ID21 X-ray Microscopy beamline

Electromagnetic shielding box

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

1 x 1 cm$^2$ x 500 µm pc-CVD Element 6

0.5 x 0.5 cm$^2$ x 300 µm pc-CVD Augsburg University

ML Gallin-Martel LPSC Grenoble
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

WaveRunner Lecroy 2 GHz; 10 or 20 GS/s
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

\[ \sigma_E = 9\% \]

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

4.5 x 4.5 mm² x 518 µm sc-CVD diamond Element 6

Signal maximum amplitude distribution measured over the 1.5 x 1.5 mm² surface

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

\[ \sigma_E = 6\% \]
95 MeV/u $^{12}$C beam at GANIL

Time resolution:
- $0.45 \times 0.45 \text{ cm}^2 \times 518 \mu\text{m sc-CVD E6}$
- $0.5 \times 0.5 \text{ cm}^2 \times 300 \mu\text{m pc-CVD Augsburg}$

Energy resolution:
- $0.5 \times 0.5 \text{ cm}^2 \times 300 \mu\text{m pc-CVD Augsburg}$

- $\sigma_t = 18 \text{ ps}$
- $\sigma_E = 7 \%$
95 MeV/u $^{12}$C beam at GANIL

**10 x 10 mm$^2$ x 500 µm pc-CVD E6**

- **1 ion**
  - $\sigma_E = 22\%$

- **2 ions**
  - $\sigma_E = 23\%$

**20 x 20 mm$^2$ x 500 µm pc-CVD E6**

- **1 ion**
  - $\sigma_E = 27\%$

- **2 ions**
  - $\sigma_E = 29\%$
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 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

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.

To learn more:

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.

Contact persons:

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<table>
<thead>
<tr>
<th></th>
<th>NINO</th>
<th>PADI</th>
<th>Expected ASIC</th>
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<tbody>
<tr>
<td><strong>Bandwidth</strong></td>
<td>$\approx 500$MHz</td>
<td>411 MHz</td>
<td>$&gt; 2$GHz</td>
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<tr>
<td><strong>Input Impedance</strong></td>
<td>50 Ω Adjustable</td>
<td>30-160 Ω</td>
<td>$&lt; 30$ Ω - ?</td>
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<tr>
<td><strong>Min. Input-referred Threshold</strong></td>
<td>10fC</td>
<td>25fC</td>
<td>$&lt; 5$fC</td>
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<td>48</td>
<td>$&gt; 40$</td>
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<td>CMOS 180 nm</td>
<td>CMOS 130 nm</td>
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<tr>
<td><strong>Input Signal range</strong></td>
<td>30fC – 2pC</td>
<td></td>
<td>$&lt;5$fC – 600fC (proton ...)</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Diamond</th>
<th>Preamp</th>
<th>HT (V)</th>
<th>Time Resolution RMS (ps)</th>
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<tbody>
<tr>
<td>sc</td>
<td>0.45 x 0.45 cm² x 518 μm</td>
<td>CIVIDEC -500</td>
<td>26.7</td>
</tr>
<tr>
<td>sc</td>
<td>0.45 x 0.45 cm² x 518 μm</td>
<td>CIVIDEC 500</td>
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<td>DBAIII -500</td>
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<tr>
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<td>DBAIII 500</td>
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<td>pc</td>
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<td>pc</td>
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