Fast Diamond Detectors for Beam Tagging Applications in Hadrontherapy

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Advantages and pitfalls in hadrontherapy

Nominal situation

Bragg peak

Amaldi and Kraft, Rep Prog Phys 2005
Advantages and pitfalls in hadrontherapy

Nominal situation

Bragg peak

Actual situation

Need for on-line range verification

Amaldi and Kraft, Rep Prog Phys 2005

Knopf et al. PMB 2013
Range monitoring with prompt gammas

Prompt gammas

- Emitted by nuclear de-excitation following NN collisions in the patient
  - nearly isotropic
  - $0 < E_\gamma < 10$ MeV
  - emission within $< 1$ ps

Compton camera CLaRyS (IPNL, CPPM, LPC, LPSC)

Hodoscope:
- Incident ion (bunch) position (reconstruction of the PG emission point)
- Incident ion (bunch) arrival time (TOF)
TOF detection of prompt gammas

Background reduction (increased sensibility)

95 MeV/u $^{12}$C beam on PMMA target
(BaF$_2$ at $d>50$cm from target)

TOF resolution $\sim$ 1 ns required
TOF detection of prompt gammas

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**Background reduction** (increased sensibility)

95 MeV/u $^{12}$C beam on PMMA target
(BaF$_2$ at $d>50$cm from target)

TOF resolution $\sim$ 1 ns required

**Necessary for $^{12}$C treatment**

300 MeV/u $^{12}$C beam on PMMA target

Prompt gamma profiles **WITHOUT TOF**

Prompt gamma profiles **WITH TOF**
TOF detection of prompt gammas

Background reduction (increased sensibility)

95 MeV/u $^{12}$C beam on PMMA target ($\text{BaF}_2$ at $d>50\text{cm}$ from target)

TOF resolution $\sim 1\text{ ns}$ required

Necessary for $^{12}$C treatment

300 MeV/u $^{12}$C beam on PMMA target

Prompt gamma profiles WITHOUT TOF

Prompt gamma profiles WITH TOF

An external detector is necessary for multi-energy treatment (RF varies phase!).
High-resolution TOF detection of prompt gammas

A little bit of kinematics . . .

A 200 MeV proton travels at $\sim c/2$

A 100 ps TOF resolution allows determining the $\gamma$ vertex within 1.5 cm

→ Higher SNR expected
→ No reconstruction needed for Compton imaging (Real Time !)

On-going development at LPSC: diamond-based hodoscope

Specifications:
- Time resolution $\sim 100$ ps
- Count rate $\sim 10$ MHz per channel
- Spatial resolution $\sim 1$ mm
- Radiation resistant

Protontherapy (Cyclotron IBA/C230)
- $\sim 2$ ns bunch every 10 ns
- 200 p/bunch → Bunch tagging

Carbontherapy (Synchrotron)
- $\sim 30$ ns bunch every 200 ns
- 10 ions/bunch → Ion tagging
Characterisation of diamond detectors

Available samples

<table>
<thead>
<tr>
<th>sc-CVD</th>
<th>sc-HPHT</th>
<th>DOI</th>
<th>pc-CVD</th>
</tr>
</thead>
<tbody>
<tr>
<td>E6</td>
<td>NDT</td>
<td>AuDiaTec</td>
<td>E6</td>
</tr>
<tr>
<td>5x5 mm² x 3</td>
<td>5x5 mm² multisector x 1</td>
<td>5x5 mm² x 3</td>
<td>10x10 mm² x 5</td>
</tr>
<tr>
<td>3x2.5 mm² monosector x 1</td>
<td>10x10 mm² x 2</td>
<td></td>
<td>20x20 mm² x 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>II-VI</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10x10 mm² x 1</td>
<td></td>
</tr>
</tbody>
</table>

50 Ω adapted PCBs

EM shielding box

Readout electronics:
(CIVIDEC for single channel custom for multi-channel)
Detector surface analysis with XBIC - single channel diamonds at 500 V

Mimic the interaction of single particles

8.5 keV X-rays
1 \( \mu \)m spot
1500 photons/bunch
Bunch width = 100 ps
E_{dep} \sim 3.3 \text{ MeV max}

2D detector scans at \sim 40 \( \mu \)m steps

5x5 mm\(^2\) x 500 \( \mu \)m sc-CVD from E6

\(< I > = 124 \text{nA}

5x5 mm\(^2\) x 300 \( \mu \)mDOI from AuDiaTec

\( I_{\text{peak}} = 14 \text{nA} \)

Works perfectly despite heterogeneous response
Detector surface analysis with XBIC - stripped diamonds at 300 V

- $I_{\text{peak}} = 4\text{nA}$
- $I_{\text{peak}} = 6\text{nA}$
- $I_{\text{peak}} = 3\text{nA}$

- Current response seems related to surface defects
- DOI and pc-CVD showed the same current response
Detector surface analysis with XBIC - stripped diamonds at 300 V

1x1 cm² x 300 µm DOI from AuDiaTec

1x1 cm² x 300 µm pc-CVD from E6

- $I_{\text{peak}} = 4\text{nA}$
- $I_{\text{peak}} = 6\text{nA}$
- $I_{\text{peak}} = 3\text{nA}$

- current response seems related to surface defects
- DOI and pc-CVD showed the same current response
Diamond detection efficiency

**Triple/double coincidences**
- Beam intensity = 1 pA (< 1p/bunch)
- 1 p signals selected on external detector
- Variable thresholds on DOI and pc-CVD

Detection efficiency:
- = 0.3% – 40% for DOI
- = 75% – 90% for pc-CVD

Low intensity 160 fA
(<< 1 p/pulse)

2 protons

High intensity 25 nA
(5000 p/pulse → attenuated signal)

pc-CVD 1 cm$^2$
DOI 1 cm$^2$
Diamond time resolution - penetrating radiation

**Context**
Development of a beam tagging hodoscope

**Conclusions**
Characterisation of diamond detectors
Characterisation of hodoscope demonstrator

**Characterisation of diamond detectors**

**Single crystal**
- **sc-CVD E6**
  - $0.45 \times 0.45 \text{ cm}^2 \times 518 \text{ } \mu\text{m}$

**Heteropitaxial DOI**
- **DOI Augsburg**
  - $0.5 \times 0.5 \text{ cm}^2 \times 300 \text{ } \mu\text{m}$

**Diamond time resolution - penetrating radiation**

- **95 MeV/u $^{12}$C at GANIL**
  - Edep = 25 MeV in DOI
  - Edep = 44 MeV in sc-CVD
  - $\sigma_t = 18 \text{ ps}$

- **68 MeV protons at ARRONAX**
  - Edep = 1.2 MeV in DOI
  - Edep = 1.8 MeV in sc-CVD
  - $\sigma_t = 60 \text{ ps}$

- **XBIC source at ESRF**
  - Edep = 0.7 – 3.4 MeV in DOI
  - Edep = 0.7 – 3.3 MeV in sc-CVD

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ADAMAS 2018
Characterisation of stripped detectors

NANOFAB Néel Institut Grenoble

LPSC Grenoble
Detector scanning with XBIC source (100µm step - Edep ~3.3 MeV)

Detector scanning with XBIC source (100µm step - Edep ~3.3 MeV)

TOF resolution: X vx Y strips

COG reconstructed X position

Strip detection efficiency
On going development: front-end microelectronics

130 nm CMOS TIA + Fast discriminator

- Radhard technology
- Wide bandwidth, low noise TIA
- 8 channels: V1 submitted Jan. 2018, V2 Nov. 2018

<table>
<thead>
<tr>
<th>TIA Parameters</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>A₀</td>
<td>&gt; 60 dB</td>
</tr>
<tr>
<td>F₋₃dB</td>
<td>1.2 GHz</td>
</tr>
<tr>
<td>Zᵢₙ</td>
<td>20 - 50 Ω</td>
</tr>
<tr>
<td>Vₙ,out (output range)</td>
<td>&lt; 1 mVₚₛₛ</td>
</tr>
<tr>
<td>Input Dynamic range</td>
<td>3 µA - 120 µA</td>
</tr>
<tr>
<td></td>
<td>(non-linearity &lt;1% )</td>
</tr>
</tbody>
</table>
A fast beam tagging hodoscope for range monitoring in hadrontherapy

**Aim:** exploit the ultra-fast coincidence time to detect range variations due to target heterogeneities

- Detector signals sampled with Wavecatcher (3.2 Gs/s)
- Trigger on one gamma detector
Beam test results

Experiment: PG timing spectrum

**PROMPT GAMMA TIMING - LaBr at 120 deg - d = 25 mm - 68 MeV protons**

<table>
<thead>
<tr>
<th>targets</th>
<th>Entries</th>
<th>$\chi^2$ / ndf</th>
<th>$A1$</th>
<th>$m1$</th>
<th>$s1$</th>
<th>$A2$</th>
<th>$m2$</th>
<th>$s2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3009</td>
<td>64.24 / 24</td>
<td>193 ± 7.1</td>
<td>31.1 ± 0.0</td>
<td>0.2443 ± 0.0142</td>
<td>183.2 ± 16.8</td>
<td>31.53 ± 0.01</td>
<td>0.1507 ± 0.0078</td>
</tr>
</tbody>
</table>

$\sigma_t = 111$ ps

Target heterogeneity thickness: measured vs actual value

**MC simulations for sensibility assessment**

G4 simulations with Gaussian smearing - LaBr 120 deg

50% threshold

Measured distribution width
Beam test results

Experiment: PG timing spectrum

Target heterogeneity thickness: measured vs actual value

MC simulations for sensibility assessment

For 1 irradiation spot:
- 4 mm shift detectable at $3\sigma$
- 2 mm shift detectable at $1\sigma$
Diamond dosimeter for micro-beam radiotherapy at ESRF

**MRT: 50 \( \mu \text{m} \) beamlets**

First test September 2018 during animal irradiation

Development of dedicated QDC

Diamond dosimeter for micro-beam radiotherapy at ESRF

**MRT: 50 \( \mu \text{m} \) beamlets**

First test September 2018 during animal irradiation

Development of dedicated QDC
Conclusions and perspectives

- **Main goal**: fast timing for charged particles with large area detectors

- Characterization of the performances of small and medium size detectors with sources, ions, and synchrotron

- Multi-strip detectors: a first prototype of 1 cm² has been developed and tested with discrete electronics

- Experiments proved excellent timing resolution

- **Issue**: Large area diamond with high detection efficiency for protons hardly available

Next steps . . .

- NDT and II-VI diamonds to be tested

- Micro-electronics readout under development
Acknowledgements

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.

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Additional slides
### Beam temporal structure

<table>
<thead>
<tr>
<th></th>
<th>Synchrotron (C230, IBA)</th>
<th>Cyclotron Varian</th>
<th>Synchro-cyclotron (S2C2, IBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>12C Protons</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Typical intensity (ions/s)</strong></td>
<td>$10^7$</td>
<td>$10^9$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$10^8 - 10^{10}$</td>
<td>$\sim 10^{10}$</td>
</tr>
<tr>
<td><strong>Macrostruct.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Period (s)</td>
<td>1 – 10</td>
<td>$\varnothing$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td><strong>Microstruct.</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch width (ns)</td>
<td>20 – 50</td>
<td>1 – 2</td>
<td>0.5</td>
</tr>
<tr>
<td>Period (ns)</td>
<td>100 – 200</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>Ions/bunch</td>
<td>2 – 5</td>
<td>200</td>
<td>2 – 200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4000</td>
</tr>
</tbody>
</table>

- Synchrotron and synchro-cyclotron: low duty cycle, favorable for PET
- Cyclotron: very short pulses, favorable for TOF-PG

- Possibility of a reduced beam intensity at the beginning of the treatment// (tagging of each ion)
TOF resolution with attenuated XBIC source

TOF resolution: DOI vs sc-CVD

- Time resolution degrades as SNR lowers
- Possible to stay below 150 ps $\sigma$ at low deposited energies

Noise level assessment
two beam tests, same irradiation conditions, different detectors

- DOI vs sc-CVD
- DOI vs RF
- sc-CVD vs RF

2017 data

DOI vs DOI

2017 data with wavecatcher

2016 data with LeCroy