Large area diamond detectors for fast beam tagging applications in particle therapy

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Motivation (1/5)

Need for in vivo ballistic control in particle therapy

Uncertainty sources:
Dose calculation: Planification (from CT images, RBE), patient positionning, anatomic variations during treatment, moving organs/tumor → Margins

Strategies:
Planification: dual-energy or proton CT, Monte Carlo simulations
Online control: nuclear fragmentation products
  • PET: a posteriori
  • Prompt radiation: gamma, protons (ions heavier than protons)

[Knopf, PMB 2013]
Motivation (2/5)
Time of Flight prompt-gamma imaging with 1D collimated camera

Prompt–γ emission is correlated to ion range

[Roellinghoff PMB 2014]

TOF: reduction of neutron-induced background

➢ Synchronization with beam HF
   Possible with Cyclotron proton beams (IBA-C230)

160 MeV protons in PMMA (Cyclotron)

[Roellinghoff PMB 2014]

However:
   Phase changes with beam energy
   Limitations by bunch length (0.5 – 4 ns)

➢ Ion per ion tagging at $10^7$ - $10^8$ Hz
   Carbon ions from synchrotrons (HIT, CNAO...): Microbunch duration >20 ns
   Synchro-cyclotron proton beams (IBA S2C2): Nanobunch duration ~8 ns ($10^4$ p/bunch)
   TOF ⇒ reduction to 1 proton/bunch necessary
Motivation (3/5)

Spatial resolution issue

- Heterogeneities influence ion range and prompt-gamma yield

95 MeV/u carbon ions in PMMA
2 mm collimation slit

[Pinto Med Phys 2015]

- Gamma imaging: compromise between spatial resolution and efficiency (statistics issue)

Proposed solution by IBA:
Knife-edge camera
(~2 cm spatial resolution)

[Richter, RaOn 2016]

- Ultra-fast timing resolution will improve spatial resolution
Motivation (4/5)

Compton imaging with beam hodoscope

CLaRyS collaboration (IPN Lyon, CPPM Marseille, LPC Clermont, LPSC Grenoble)

Potentially higher detection efficiency than collimated devices

- Beam hodoscope: line-cone intersection

- TOF resolution < 500 ps → real time Compton imaging

[Distance between cone intersections]

RMS = 10 cm

[LeY PhD 2015]
Motivation (5/5)

Prompt-gamma counting solutions

• Prompt-\(\gamma\) timing
  - Average time and shape related to proton range
  - 5mm range shift measurable with single spot
  - Requires high timing resolution (< 1ns)
  - Limitations:
    • Cyclotrons
    • Bunch time spread

• Prompt-\(\gamma\) Peak Integral [Krimmer APL 2017]
  - 2-4 ns time window selection: PG issued from patient
  - Yield depends on energy deposited, beam position

• Both methods would benefit from fast and high-resolution beam-tagging system
Beam tagging hodoscope development: LPSC MoniDiam project (within CLaRyS collaboration)

Existing development (CLaRyS):
Array of scintillating fibres coupled to multichannel photomultiplier tubes (PMT). Fast readout with µTCA acquisition under test.

Foreseen development:
MoniDiam: diamond based hodoscope and its dedicated integrated fast read-out electronics for 100 ps resolution

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

Issues:
- Cost
- Availability of large area

Solution: Assembly of double-side stripped diamond, polycrystalline or DOI

Limitations:
- Radiation hardness
- PMT count rate capability (10^7 cps per PMT)
- Time resolution 500 ps – 1 ns
First tests: single disk-shape metallized diamonds
Diamond detector characterization: test benches at LPSC

**Alpha source** ($^{241}\text{Am} - 5.4 \text{ MeV}$)

- Source $\alpha$
- Diamant
- Preamp
- $500 \text{ V}$
- DAQ

**Beta source** ($^{90}\text{Sr}$)

- Collimateur Cu Source
- Scintillateur PM + filtre
- Preamp + filtre
- Diamant

**Charge collection efficiency (single crystal)**

- $ECC \cong 98\%$
- @ $\pm 500 \text{ V}$

**Data acquisition:**

- Wave catcher 500 MHz
- 3.2 Gs/s, 8 channels

- Wave-runner Lecroy 4GHz
- 40Gs/s

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Beam test at GANIL: 95 MeV/u $^{12}\text{C}$

$^{12}\text{C}$

Wavecatcher
500MHz, 3.2G/s

Monocry staline:
sc-CVD E6 + DBA III
0.45 x 0.45 cm² x 518 µm

Hetero-epitaxial:
DOI-CVD Audiatec + Cividec C2
0.5 x 0.5 cm² x 300 µm

Deposited energy ~40 MeV

Timing resolution Mono vs DOI

Energy resolution DOI

Timing resolution Mono vs DOI

Energy resolution DOI

$\sigma_t = 18 \text{ ps}$

$\sigma_E = 7%$
Beam test at GANIL: Time of flight measurements

Simulation G4: TOF distribution LaBr vs. sc-CVD E6

\[ \sigma_{\text{exp}} \approx 400\text{ps} \]

\[ \Delta t \approx 1.3\text{ns} \]
Beam test at ESRF: XBIC source at 8.5 keV

Continuous energy deposit (0 to 4 MeV)
- Spot ~ 1 μm
- ~ 1500 photons/bunch
- Bunch width = 100 ps

Timing resolution
- sc-CVD E6
  - 0.45 x 0.45 cm² x 518 μm
  - DOI-CVD Audiatec
  - 0.5 x 0.5 cm² x 300 μm
  - $\sigma = 45$ ps

Current response map
- Poly-crystalline
  - 1 mm²
  - 10 x 10 mm² x 500 μm pc-CVD

DOI
- Non-homogenous response
  - 5 x 5 mm² x 300 μm DOI-CVD
Beam test at ESRF: XBIC source at 8.5 keV

Continuous energy deposit (0 to 4 MeV)

- Spot ~ 1 um
- ~ 1500 photons/bunch
- Bunch width = 100 ps

Although noisy conditions in 2017
100 ps resolution reasonable

Time resolution

DOI vs DOI

TOF resolution: DOI vs sc-CVD

2017 data
Stripped diamond characterization

NANOFAB Neel Institut Grenoble
100 nm Al deposition by UV lithography
Wire bonding

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PCB design
Current preamplifier
Detector assembly

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Beam test at ESRF : XBIC source at 8.5 keV

Surface Analysis

Current-integration mode

Current (nA/10⁷ph/s) @ 8.53 keV

1 x 1 cm² x 300 µm pc-CVD from Element 6

XBIC detecteur scan (100 µm step)

Wavecatcher

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First results

Timing resolution

Best result: $\sigma_t = 103$ ps

Reconstructed position

Detection efficiency
Front-End Electronics: Architecture

- 130nm CMOS TIA + Fast Discriminator
  - Radhard technology
  - Wide bandwidth, Low noise TIA

### TIA Parameters

<table>
<thead>
<tr>
<th>TIA Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_0$</td>
<td>$&gt; 60$ dB</td>
</tr>
<tr>
<td>$F_{-3dB}$</td>
<td>1.2 GHz</td>
</tr>
<tr>
<td>$Z_{in}$</td>
<td>20 – 50 Ω</td>
</tr>
<tr>
<td>$V_{n,\text{out}}$ (output noise)</td>
<td>$&lt; 1$ mV$_{\text{RMS}}$</td>
</tr>
<tr>
<td>Input Dynamic range</td>
<td>$3$ µA – $120$ µA ($&lt;1%$ linearity)</td>
</tr>
</tbody>
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Front-End Electronics: Simulation

- Simulation parameters:
  - Extracted view + Noise tran
  - With bonding wires (2nH): Power supply, ground and input signal
  - Multi-gain discriminator
  - Jitter estimation: from 3 μA to 120 μA input signal

@3 μA input signal

@10 μA input signal
Front-End Electronics: Layout

• 130nm CMOS
  • 8 channels FEE: TIA + Discriminator
  • Will be submitted on December 2017

1.485 x 1.2 mm²
Conclusion

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

- Multi-strip detectors: a first prototype of 1 cm$^2$ has been developed and tested with discrete electronics

- Micro-electronics readout under development (technical collab. with LPC-Caen)

- Framework:
  - Local: ESRF, NEEL:
    - local pole for detector and electronic devices
    - crystal processing and characterization
  - National: LSPM, IPHC, CEA-LIST and CLaRyS collaboration (+CAL-Nice, Arronax...)
  - International: RD42
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