ADVANCES IN DIAMOND BASED MICRODOSIMETRY FOR HADRONTHERAPY

Michal Pomorski, ADAMAS2018, 13-14 December 2018, Wien
OUTLINE

- Context
  - Fabrication of the diamond microdosimeters
  - Sensors’ characterization under nuclear microbeam probe
    - Sensors’ performance in clinical beam
      - Summary and what’s next
HADRÖN THERAPY

Most of the energy is lost in the Bragg Peak.

- 120 hadron therapy centres worldwide (increasing);
- 3 operating clinical proton therapy centres in France: Orsay, Nice, Caen;
- an intense field of research activity including new methods of treatment ($^{16}$O, $^{14}$N, micro,minibeams, FLASH).
LINEAR ENERGY TRANSFER

SPARSELY ionizing radiation:
  e.g.: X-rays, Gammas

DENSELY ionizing radiation:
  e.g.: Carbon ions

same dose but different LET
thus various biological effectiveness (RBE)
RADIATION QUALITY - MICRODOSIMETRY

‘MICRODOSIMETRY is a methodology that involves the measurement or calculation of stochastic energy deposition distributions in a micron size sensitive volume (SV) within any arbitrary mixed radiation field.’

A concept of solid-state microdosimeter

Lineal Energy

\[ y = \frac{\varepsilon}{\ell} \]

Dose Mean Lineal Energy

\[ \overline{y}D = \int_{0}^{\infty} yD(y)dy \]

micdosimetry ≠ dosimetry at micron scale

- single-particles (low charge),
- ns to µs integration time (10^9 p/cm2),
- pulse-height spectra,
- SV from micro to nano size
  (30 µm cell, 10 µm cell nucleus, > 1 µm DNA size)

- ms integration time
- DC current or charge
- macroscopic (mm) SV size

picture from Si-3DMiMic collaboration
Relative biological efficiency (RBE)

• Biological basis: clinical impact

- Dose/RBE inhomogeneities → LET painting, late effect epidemiology

Dose

LET

Long term effects (necrosis)

Eclipse 5-field standard IMPT

Bio-optimized plan

5-field, Bio-optimized
## Microdosimeters State of the Art

<table>
<thead>
<tr>
<th>Tissue Equivalent Proportional Counter (TEPC):</th>
<th>Silicon Solid-State Microdosimeters (Mushroom):</th>
<th>Diamond Solid-State Microdosimeters:</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="TEPC Image" /></td>
<td><img src="image2" alt="Silicon Mushrooms Image" /></td>
<td><img src="image3" alt="Diamond Image" /></td>
</tr>
<tr>
<td><strong>The ‘Gold Standard’</strong></td>
<td><strong>Compact Device</strong></td>
<td><strong>More Tissue-Equivalent (Z = 6)</strong></td>
</tr>
<tr>
<td>Tissue-Equivalence &amp; Radiation Hardness</td>
<td>Multiple Micro-SVs</td>
<td>Radiation Hardness</td>
</tr>
<tr>
<td>Sensitive (Internal Amplification)</td>
<td>Si - Easy for Microfabrication</td>
<td>No Leakage Current, Fast Drift Velocity for e-h, Low Capacitance</td>
</tr>
<tr>
<td>Maintenance (Gas Flow &amp; High Voltage)</td>
<td>Radiation Hardness ?</td>
<td>High ~13 eV/e-h - Lower Signal</td>
</tr>
<tr>
<td>Low Spatial Resolution</td>
<td>Tissue-Equivalence ? (Correction Factor)</td>
<td>Diamond - 6’ Wafers rather Difficult</td>
</tr>
<tr>
<td>Large size</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Freestanding single crystal diamond membranes (<10 µm) of up to several mms later size

1. Slicing and polishing
2. p+ CVD growth
3. Ar/O deep etching
4. Patterning Ar/O shallow etching/Al

300 – 500 µm
30 – 60 µm
< 10 µm
DIAMOND MEMBRANE MICRODOSIMETER PROTOTYPES

scCVD diamond membrane DIAµDOS p⁺ microdosimeter

SEM Image

SVs down to 25 µm

p⁺-i-m (junction approach)

0V extr. bias, fully depleted

TCAD charge transport simulations ongoing
DIAMOND MEMBRANE MICRODOSIMETER PROTOTYPES

scCVD diamond membrane DIAµDOS guard- ring microdosimeter:

Microscopic Image

Guard ring

Micro-sensitive Volumes (µSVs)

Electrical contacts (Al)

Intrinsic diamond

Few mm

Readout electronics

SVs 50 µm; 10 µm gap

m-i-m (ionization chamber approach)

TCAD simulation

TCAD charge transport simulations ongoing

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PROBING CHARGE TRANSPORT WITH IBIC

IBIC (Ion Beams Induced Current):

- Single ion irradiation (precision: 1 micron)
- Raster scanning + pulse height spectra
- Charge transport maps (µSV definition)
- Well controlled projectile Energy and LET

Perfect tool to test new types of microdosimeters before implementing in clinical conditions (less control)

Several beamtimes @ microbeam facilities:

IBIC (Ion Beams Induced Current):

- Frontal IBIC
- Lateral IBIC

H 2.0 MeV
He 3.0 MeV

12C 16.6 MeV

16O=8MeV/17.5MeV/25MeV
12C 6 MeV/16.6 MeV/24 MeV

covers wide span of LET present in clinics

Analog read-out electronics:

Detector Pre-amplifier Analog Pulse Shaping Peak Detection

few ns

I Q ~ Q_{coll}

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IBIC – GLOBAL RESPONSE P+ @ 0V - 2 MEV P

Raster scan of device @ 0 V

Microscopic Image

* Number of detected ions / pixel

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IBIC – GLOBAL RESPONSE GUARD RING @ 20V

Raster scan of device @ +20 V

Microscopic Image

* Number of detected ions / pixel

micro SVs
Response of DIAμDOS $p^+$ to 2 MeV single proton ion beam

- SEM image of a single µSV
- Median Energy Map
- Normalized energy spectrum
  - Total scan
  - Inside SV
  - ΔE ~ 220 keV

E ~ 0.4 V/µm

Charge Collection Efficiency (CCE)

- 2.0 MeV H
- 16.6 MeV C
- 3.0 MeV He

CCE drop after ions / cm²

- Proton: 100% → 1% after $2.5 \times 10^{13}$
- Carbon: 80% → 12% after $0.6 \times 10^{12}$
- Helium: 90% → 5% after $1.5 \times 10^{10}$

Performance approaching SoA silicon based microdosimeters
IBIC – DETAIL GUARD RING @ 20V

Response of DIAμDOS guard ring to 2 MeV single proton ion beam

Opt. microscope image  Median Energy Map  Normalized energy spectrum

Charge Collection Efficiency (CCE)

Performance approaching SoA silicon based microdosimeters

E > 3 V/\mu m

Ion   CCE @ 0V   Radiation Hardness

Proton 100% 3% after $9.4 \times 10^{12}$

Helium 100%

Applying +/- 20 V to the device resets the radiation damage
Institute Curie, Proton Therapy Center (Orsay, France)

- Proton beamline for intracranial treatments
- 100 MeV p
- 80 mm variable thickness solid-water phantom
- diamond p+ microdosimeter prototypes

Microdosimetry

- Single proton pulse-height measurement in clinical conditions

Dosimetry

- PTW Unidose
  - 'DC' induced charge/current (ms) monitoring, with commercial high precision electrometer used in clinics for dosimetry
SENSORS PERFORMANCE IN CLINICAL PROTON BEAM

Preliminary diamond p+ microdosimeter prototype performance

- works in clinical environment (!)
- no tissue-equivalent packaging…
- no calibration (rather qualitative meas.)
- but trend identical to Si micro. (very promising)
P+ SENSORS PERFORMANCE IN CLINICAL PROTON BEAM

- good agreement with MC GEANT4 simulations
- perfect linearity with dose
- no leakage current (very low noise)

Diamidos microdosimeter can be possibly use simultaneously (monitoring of DC beam induced current with an electrometer)
SUMMARY

- Prototyping and microfabrication
- Ion microprobe characterization
- Encapsulation and integration
- Clinical evaluation + LET
- LET simulation

AND

What's Next

- More prototypes based on p+ and guard ring approach (3D etching, isolation gap) + TCAD simulations and IBIC
- Dedicated PCB's + universal chip carrier mounting of the sensors + encapsulation
- Clinical evaluation of encapsulated devices @TIRO/Lacassagne p Center + LET simulations

Clinical evaluation of encapsulated devices @TIRO/Lacassagne p Center + LET simulations
scCVD Diamond Membrane based Microdosimeter for Hadron Therapy

Izabella A. Zahradnik,* Michal T. Pomorski,* Ludovic De Marzi, Dominique Tromson, Philippe Barberet, Natko Skukan, Philippe Bergonzo, Guillaume Devès, Joël Herault, Wataru Kada, Thierry Pourcher, and Samuel Saada
NATIONAL AND INTERNATIONAL COLLABORATIONS

DIADEM: Diamond membrane based microdosimetric system for radiation quality assurance in hadron therapy
2 years national project; kick-off 26/11/2018

Postdoctoral Scientist

1 year contract asap

The position:

- MC simulations of clinical proton/carbon beams interactions with matter, to benchmark experimental response of the microdosimeter prototypes
- participation in beamtimes for devices testing with clinical beams and particle microbeams at accelerator facilities
- possible participation in fabrication process of the devices (surfaces preparation, thin layer deposition, photolithography, dry plasma etching)

Requirements:

- PhD in physics/medical physics or equivalent
- knowledge of relevant Monte Carlo simulation programs
- knowledge of solid-state particle detectors, associated electronics and signal processing, possibly including some experience at accelerator facilities
- communication verbally and written in English (French would be additional asset)
- knowledge of simple printed circuit boards design and semiconductors simulation software would be an asset
Thank you very much for your kind attention!!!