SINGLE CRYSTAL CVD DIAMOND MEMBRANE MICRODOSIMETERS FOR HADRON THERAPY
INTERESTS FOR MICRODOSIMETRY COMMUNITY

A slide from the opening lecture of MICROS2017 17th International Symposium on Microdosimetry By H.G. Menzel (5th November 2017)

Microdosimetric community seems to be waiting for diamond based sensors!
OUTLINE

1) Introduction

2) Concept and fabrication

3) Charge transport with p, C microbeams
   a. micro SV definition
   b. charge collection efficiency
   c. radiation hardness

4) Preliminary LET for 100 MeV proton beam
HADRON THERAPY

- 120 hadron therapy centres worldwide (increasing);
- 100,000 patients treated;
- Operating clinical proton therapy centres in France: Orsay, Nice, Caen;
- ARCHADE: first carbon therapy centre in France;
- An intense field of research activity including new methods of treatment (mini and microbeams, FLASH).
RADIATION QUALITY

- **RBE** (Relative Biological Effectiveness) of protons is uncertain: limits the efficiency of treatments.

- Strong correlation between a microdosimetric quantity (i.e. spatial distribution of energy deposition by single particle at cellular level) and RBE: LET (linear energy transfer) and biological effects of charged particles in tissues are related.

- Measurement of LET is difficult: today no detector is available in clinical routine.

Simple dosimetry is not enough to assure radiation quality in hadron therapy.
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

microdosimetry ≠ 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)

dosimetry at micron scale
- ms integration time
- DC current or charge
- macroscopic (mm) SV size
MICRODOSIMETRY IN HADRón THERAPY

Tissue Equivalent Proportional Counter (TEPC)

- a ‘gold standard’
- sensitive (internal amplification)
- tissue-equivalence, radiation hard
- size (not really microscopic SV, wall effect)
  - rate issue
  - maintenance (gas flow)

Silicon solid-state microdosimeters

- compact device
- multiple ‘real’ µSVs
- it’s Si - easy for micro-fabrication
  - tissue equivalence (?)
  - radiation hardness (?)

? Can diamond join the advantages of both, and get rid of their pitfalls?
WHY DIAMOND?

Large band-gap (5.5eV) semiconductor

A solid-state ionization chamber
(soon a proportional chamber?)

more tissue equivalent (Z=6) and radiation hard (43 eV)

+ no leakage current and no need for p-n junction
+ fast drift velocity for e-h
+ low capacitance
+ high electrical breakdown (> 1000 V/µm)
+ VIS light and temp. insensitivity

- high ~13 e-h/eV - lower signal
- high density, excitons - pulse height defect
- it’s diamond (for instance pls. forget 6’ wafers)

since 2002 high purity electronic grade CVD diamond available commercially
MICRODOSIMETRY IN HADRON THERAPY

existing diamond microdosimeters prototypes

The idea

5.9 MeV Be microbeam CCE mapping

Real device

Pulse-height spectra

- not uniform CCE
- not resolved spectra

commercial e6 EG scCVD diamond

MICRODOSIMETRY IN HADRON THERAPY

existing diamond microdosimeters prototypes

The idea

4 MeV C microbeam CCE mapping

Real device

Pulse-height spectra @ 0V bias voltage

lab grown scCVD diamond

- problematic to create multiple µSVs

DIAMOND MEMBRANE MICRODOSIMETER CONCEPT

scCVD diamond membrane

30-60 µm

few mm

> 10 µm

Charge transport @ 0V

p-i-m

m-i-m

µSV

ionization

to DAQ

electronic grade diamond bulk

boron-doped diamond thin layer

electrical contacts (metal or carbon based)

p-i-m

m-i-m
DIAMOND MEMBRANE MICRODOSIMETER PROTOTYPES

ElementSix electronic grade single crystal CVD diamond samples

slicing polishing  Ar/O plasma etching  p+ CVD growth  patterning + electrodes

300-500 µm  30-60 µm  >10 µm

300 µm pixels (SV), 6 µm thick scCVD diamond membrane

30, 60 and 120 µm pixels (SV), 4 µm thick scCVD diamond membrane
CHARGE TRANSPORT CHARACTERIZATION – IBIC

Ion Microbeams

2.5 MeV proton
1 µm FWHM

16.6 MeV carbon
~ 1 µm FWHM

CS electronics
- Detector
- Preamplifier
- Analog Pulse Shaping
- Peak Detection

preamp.: Amptek 250 CoolFet
Shaping time.: 500 ns
local DAQ

ΔE + E configuration
- vacuum
- Si PIPS
- membrane

Ion Microbeams

Frontal IBIC
Lateral IBIC

XY Charge

detector efficiency

16.6 MeV C
2.5 MeV p

energy loss [keV/µm]
depth [µm]
IBIC – 2.5 MEV PROTON MICROBEAM

STIM (Si downstream)  
diamond signal @ 0V

*STIM – scanning transmission ion microscopy

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IBIC - 2.5 MEV PROTON MICROBEAM

diamond signal @ 0V

STIM (Si downstream)

pulse-height spectra

*STIM - scanning transmission ion microscopy

ΔE ~250 keV
(~41 keV/µm)

counts normalized to max

100 → 0 % drop ~8 µm
IBIC – 16.6 MEV CARBON MICROBEAM

STIM (Si downstream)

diamond signal @ 0V

*STIM – scanning transmission ion microscopy

60 µm SV

30 µm SV

700 µm

S pulse height [a.u.]

diamond pulse height [a.u.]

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m-i-m ‘parasitic signal’ inverted polarity

Higher signals at the edges $\rightarrow$ strain some areas with zero PH
IBIC – 16.6 MEV CARBON MICROBEAM

diamond signal @ 0V

STIM (Si downstream)

pulse-height spectra

*STIM - scanning transmission ion microscopy
CHARGE COLLECTION EFFICIENCY

~5 MeV α (241Am source)

16.6 MeV C (microbeam)

~100% CCE @ 0V (0.3 V/µm built-in) p, α

~80% CCE @ 0V (0.45 V/µm built-in) C

solution: use of thinner membranes for high LET
i.e. 1.8 V / 1 µm ~100% CCE
High flux C (16.6 MeV) microbeam continuous irradiation of one 30 x 30 μm μSV (all spectra measured @ 0V)

no change: Voc, spectrum shape, peak FWHM, dark current, μSV geometry

even better results expected for thinner membranes (shorter drift path; higher E)
5 MeV α-particles traversing membrane

fast signals (clearly RC limited, 1mm² contacts area)
contact surface optimization \(\rightarrow \ll 1\) ns FWHM + high amplitude
LET MEASUREMENT – 100 MEV PROTON BEAM

Institute Curie Proton therapy Center (Orsay, France)

Proton beamline for intracranial treatments
100 MeV p
80 mm variable thickness solid-water phantom
300 µm SV diamond microdosimeter prototype

Bragg peak (IBA PP05)

Diamond membrane microdosimeter

0 mm
68 mm
78 mm
DIAMOND MEMBRANE MICRODOSIMETER-SUMMARY

scCVD diamond membranes have a great potential for solid-state microdosimetry

- full CCE (p,a) @ 0V, well-defined µSV, ΔE spectra, fast
  - radiation hard (preliminary C data)
  - First LET measurements in clinical p beam (promising)

Issues to be addressed soon:

- µSV geometry optimization: 3D, implantation, thickness homogeneity
  - pulse-height defect for high LET (C)
  - dedicated electronics
- ‘real’ LET measurements (mixed fields)
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!!! Thank you very much for your kind attention !!!
MICRODOSIMETRY IN HADRON THERAPY

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**Challenges:** single particles, pulse-height, low-signals, high rates, radiation damage