

PAPER • OPEN ACCESS

3D sensitive volume microdosimeter with improved tissue equivalency: charge collection study and its application in ^{12}C ion therapy

To cite this article: B James *et al* 2019 *J. Phys.: Conf. Ser.* **1154** 012012

View the [article online](#) for updates and enhancements.

You may also like

- [The microdosimetric extension in TOPAS: development and comparison with published data](#)
Hongyu Zhu, Yizheng Chen, Wonmo Sung et al.
- [The impact of sensitive volume thickness for silicon on insulator microdosimeters in hadron therapy](#)
D Bolst, S Guatelli, L T Tran et al.
- [Correction factors to convert microdosimetry measurements in silicon to tissue in \$^{12}\text{C}\$ ion therapy](#)
David Bolst, Susanna Guatelli, Linh T Tran et al.



Connect with decision-makers at ECS

Accelerate sales with ECS exhibits, sponsorships, and advertising!

▶ Learn more and engage at the 244th ECS Meeting!

3D sensitive volume microdosimeter with improved tissue equivalency: charge collection study and its application in ^{12}C ion therapy

B James¹, L T Tran¹, D Bolst¹, D Prokopovich², M Reinhard^{1,2}, M Lerch¹, M Petasecca¹, S Guatelli¹, M Povoli³, A Kok³, N Matsufuji⁴, M Jackson^{1,5} and A Rosenfeld¹

¹Centre for Medical Radiation Physics, University of Wollongong

²NSTLI Nuclear Stewardship, Australian Nuclear Science and Technology Organization, Australia

³SINTEF, Norway

⁴National Institutes for Quantum and Radiological Science and Technology, Chiba, Japan

⁵University of New South Wales, Sydney NSW 2052, Australia

E-Mail: anatoly@uow.edu.au

Abstract. This research focuses on the characterisation of a new 3D sensitive volume (SV) microdosimeter covered with polyimide – a material which closely mimics human tissue. The electrical and charge collection properties of the device were investigated and its application in ^{12}C ion therapy were studied. Charge collection studies revealed uniform charge collection and no cross talk between adjacent SVs. To study the microdosimetric response in ^{12}C ion therapy, the new polyimide mushroom microdosimeter were placed at various positions along the central axis of a 290 MeV/u ^{12}C ion spread out Bragg peak (SOBP) at the Heavy Ion Medical Accelerator in Chiba (HIMAC), Japan. From these microdosimetric spectra, dose mean lineal energy ($\overline{y_D}$) and RBE₁₀ results were obtained, with RBE₁₀ increasing from 1.3 at the entrance to 2.7 at the end of the SOBP. The results obtained in this work show that the new generation of mushroom microdosimeters, covered with tissue equivalent polyimide material, are a useful tool for quality assurance in heavy ion therapy applications.

1. Introduction

Particle therapy has many advantages over conventional photon therapy, particularly for treating deep-seated solid tumours due to its greater conformal energy deposition achieved in the form of the Bragg Peak (BP). Successful treatment with heavy ions requires knowledge of the relative biological effectiveness (RBE) of the primary and secondary radiation field. Different methods and approaches are used to calculate the RBE-weighted absorbed dose in heavy ion therapy. The RBE calculated using the microdosimetric approach been reported [1] for a therapeutic ^{12}C beam using a tissue equivalent proportional counter (TEPC). However, the large size of commercial TEPCs can cause the RBE values to be smeared dramatically close to and in the distal part of the BP, which may have significant clinical impact. The Centre for Medical Radiation Physics (CMRP), University of Wollongong, has initiated the concept of silicon microdosimetry to address the shortcomings of the TEPC [2]. In the course of



this research, a new 3D SV microdosimeter covered with a tissue equivalent material in the process of fabrication has been investigated and its application in ^{12}C therapy has been studied.

2. Method

2.1 Detector Structures

The Mushroom microdosimeter structure used in this work is called *trenched planar*, this consists of 3D cylindrical SVs with a planar n+ core produced by ion implantation (planar technology). Each SV is surrounded with a complete p+ doped trench filled with polysilicon (Fig 1b). SEM images of this device's structure show that a complete trench was etched (Fig. 1a) and the trench was filled with polysilicon (showed in Fig. 1b).

The structure is based on an array of 3D cylindrical SVs with diameters of 18 μm or 30 μm , fabricated on a high resistivity p-SOI with a 10 μm thick active layer bonded to a low resistivity supporting wafer and 2 μm silicon oxides in between. The SVs are separated into odd and even arrays. A P-stop layer has been deposited everywhere on both device structures and under the pad to avoid metal-oxide-semiconductor (MOS) build up charge effect under the metal buses [3].

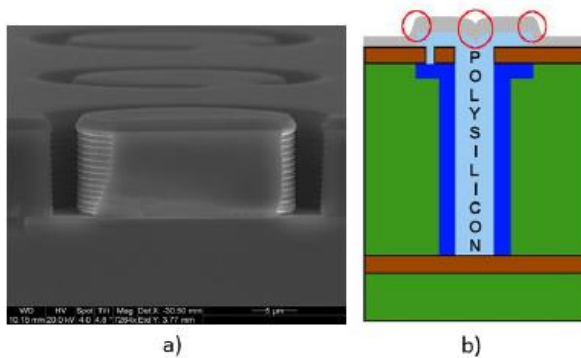


Figure 1. a) SEM image of a trench planar mushroom microdosimeter with a complete trench, b) trench was doped with p+ and filled with polysilicon [3].

The detector utilises the fact that even and odd rows of SVs are read out independently to avoid events in adjacent sensitive volumes being read as a single event in the case of oblique charged particle tracks. The charge collection and response of these detectors has been thoroughly investigated and documented in previous works [3], [4]. The 3D Mushroom microdosimeter was connected to a low noise spectroscopy-based readout circuit, allowing lineal energy measurements as low as 0.15 keV/ μm in tissue [3].

In order to improve the tissue equivalence of the new microdosimeters, they have been covered with a 12 μm layer of polyimide, as seen in Figure 2. While the polyimide layer will serve to improve the tissue equivalence of the microdosimeter, charge collection and uniformity studies were required to understand how the microdosimeter output would be affected by this new layer.

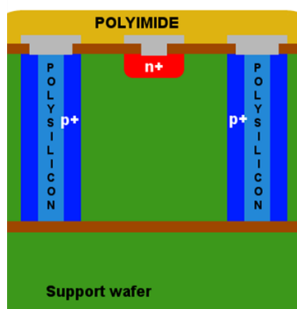


Figure 2. Trenched planar mushroom microdosimeter, where the trench is filled with polysilicon p+ column, then overlaid with the 12 μm polyimide layer.

2.2 Charge Collection Study

The Mushroom microdosimeters was studied using the ion beam induced charge collection technique (IBIC) at the 6 MV accelerator SIRIUS, located at the Centre for Accelerator Science (CAS) facility at ANSTO. This system includes a Confocal Heavy Ion Micro-Probe (CHIMP) which is capable of delivering different types of ions such as Carbon, Helium and Hydrogen ions. This beamline is widely used for analysing and characterising samples using ion beam analysis (IBA) and produces high-current and high brightness ion beams with exceptional energy resolution [5].

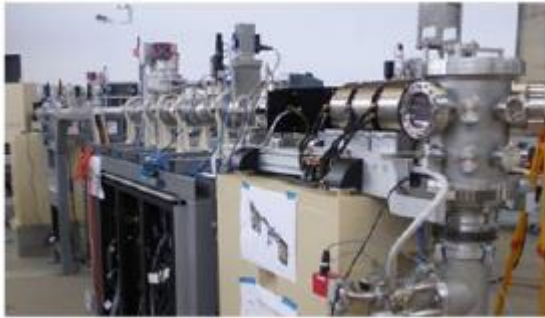


Figure 3. 6 MV accelerator SIRIUS, located at the Centre for Accelerator Science (CAS) facility at ANSTO [5].

The IBIC measurements utilized a microbeam of 5.5 MeV He^{2+} ions which were raster scanned over the surface of the sample. Energy deposited in the microdosimeter was measured using an AMPTEK A250 charge sensitive preamplifier and a Canberra 2025 Shaping Amplifier with 1 μs shaping time. The signal corresponding to the beam's position as well as the charge collection for each event was processed into an event-by-event list mode file. The data was processed into median charge collection image maps for spatial correlation of the energy deposition of the scanned area [3]. The energy calibration was performed using a calibrated pulse generator which was calibrated with a 300 μm thick planar silicon fully depleted PIN diode with 100% Charge Collection Efficiency (CCE) in response to 5.5 MeV He^{2+} ions.

2.3 HIMAC Experiment

To study its performance in ^{12}C therapy, the 3D mushroom microdosimeters were irradiated at the Heavy Ion Medical Accelerator in Chiba (HIMAC), located at the National Institute of Radiological Science (NIRS) in Japan. The facility consists of ion sources, a radio frequency quadrupole linear accelerator (LINAC) for low speed ions and an Alvarez LINAC for medium speed ions as an injector to the two synchrotrons, with maximum energy of 400 MeV/u [4].



Figure 4. Panorama showing the biological sciences beamline at the Heavy Ion Medical Accelerator in Chiba (HIMAC), Japan.

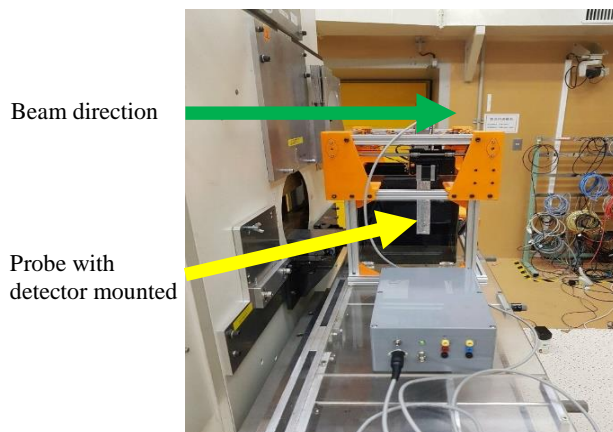


Figure 5. The remote control movable platform holding the detector mounted on the MicroPlus probe, connected to power supply box.

A 60 mm spread out Bragg peak (SOBP) produced with 290 MeV/u ^{12}C ions was used in this experiment. The polyimide mushroom microdosimeters were connected to a low noise spectroscopy-based readout circuit (also called a MicroPlus probe). The probe was then placed in a water tank, Figure 5, and measured at different depths in water along the central axis of the SOBP of the 290 MeV/u ^{12}C ion beam.

3. Results and Discussion

3.1 Charge Collection Study

Figure 6 shows the MCA spectra obtained at 0V and 10V for the Mushroom microdosimeter, using the IBIC technique. It can be seen that at 0V the detector is almost completely depleted, with only a 2% difference in CCE between 0 and 10V. Overall the trenched planar structure has been shown in previous work to have a CCE of 96% [3].

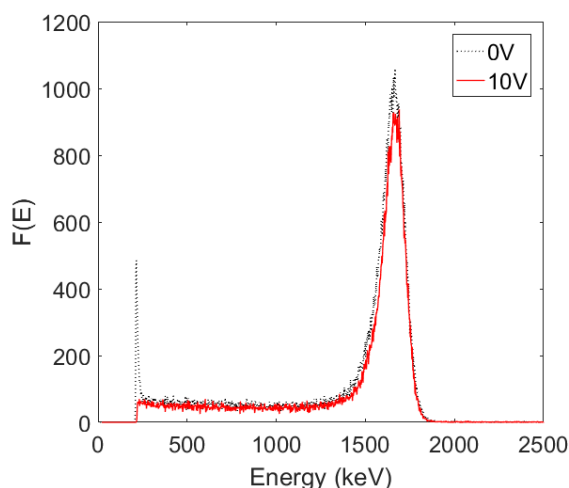


Figure 6. MCA spectra obtained during IBIC for 0V and 10V, for the same scan size of the Mushroom microdosimeter, only even array is connected.

Figure 7 shows the median energy map of multiple sensitive volumes connected in the even arrays. It can be seen that each of the sensitive volumes has very uniform charge collection and well-defined volume shapes. Very low energy charge was observed in narrow region surrounding each SV due to the trench wall doped with p+. Furthermore, no charge collection can be seen within the connecting regions between sensitive volumes, or in the unconnected (odd) array.

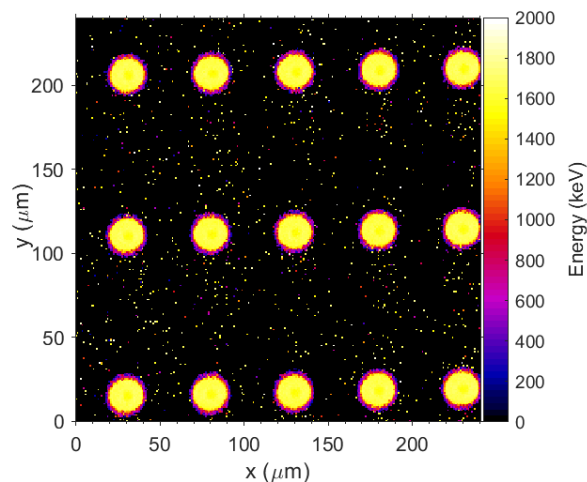


Figure 7. Median energy map of charge collection within three rows of the Mushroom microdosimeter at 10V, only even array is connected.

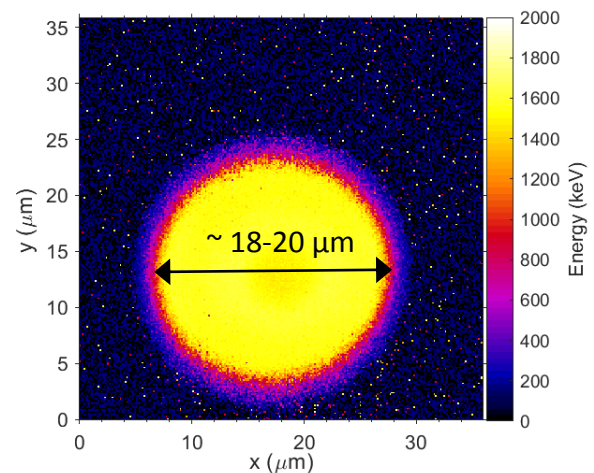


Figure 8. Median energy maps generated using a detector bias of 10V, showing a single SV.

Reducing the IBIC scan size, a single SV can be viewed in Figure 8. This reveals exceptionally uniform CCE within the SV, and a slight reduction of energy deposition was observed in the n+ core region of the SV (approximately 80% CCE compared to the SV). It also confirms that the size of a single SV is $\sim 18\text{-}20\mu\text{m}$.

3.2 Microdosimetric measurements of Carbon ions - HIMAC

Figure 9 shows microdosimetric spectra and \bar{y}_D values obtained at different depths in water, along the central axis of the ^{12}C SOBP. At the entrance, \bar{y}_D is approximately $15\text{ keV}/\mu\text{m}$, as the depth in water increases the microdosimetric spectra obtained shifts to the right, and consequently the lineal energy deposition increases, as the primary beam energy decreases. This leads to higher energy deposition reaching a maximum at the distal part of the SOBP ($\sim 148\text{ mm}$), where the \bar{y}_D measured was $195\text{ keV}/\mu\text{m}$.

The derived RBE_{10} values based on the microdosimetric kinetic model (MKM), obtained in the SOBP are shown in Figure 10. The value of RBE at the entrance was calculated to be from 1.3 and increased to 2.7 at the end of the SOBP. The experimental data obtained with the microdosimeter can be seen to match the TEPC data extremely well in the entrance and at the end of the SOBP. Near the end of the SOBP ($\sim 148\text{ mm}$), the high spatial resolution of the SOI mushroom microdosimeter enables more detailed RBE_{10} measurements to be obtained at the end of the SOBP than the TEPC. The higher experimental values obtained downstream of the SOBP can be attributed to the PMMA sheath, resulting in a different spectra of secondary particles than that observed by the TEPC which were carried out in water.

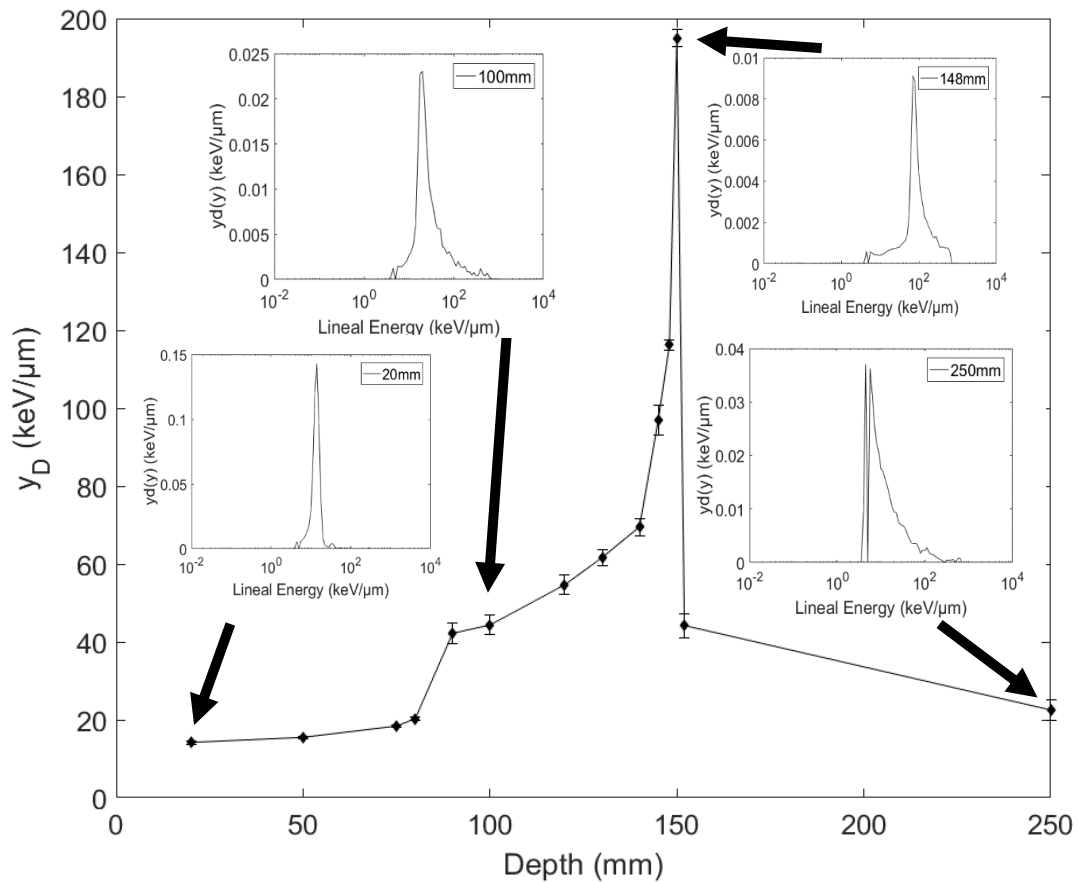


Figure 9. Microdosimetric spectra obtained by Polyimide mushroom microdosimeter in response to 290 MeV/u SOBP ¹²C ions at HIMAC.

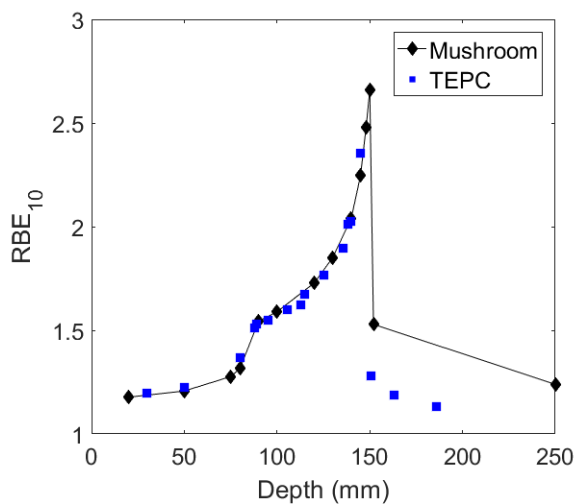


Figure 10. RBE₁₀ distribution obtained by Polyimide mushroom microdosimeter in response to 290 MeV/u SOBP ¹²C ions at HIMAC. Compared with TEPC data taken from Y. Kase [1].

4. Conclusion

The charge collection of a 3D microdosimeter with a polyimide covering has been studied using the IBIC technique and revealed a uniform charge collection with no cross-talk between SVs. A range of microdosimetric measurements were then able to be obtained using the new mushroom microdosimeter. Giving a maximum \bar{y}_D and RBE₁₀ of 195 keV/um and 2.7, respectively. We demonstrated that coating mushroom SVs with polyimide layer in the process of fabrication does not

change electrical parameters and charge collections in SVs. Currently this version of mushroom is only covered with a 12 μm polyimide layer on top of the device, future versions of the mushroom microdosimeter will be fully etched silicon surrounding the sensitive volume and then filled with polyimide, further increasing the tissue equivalence of the device when considering the secondary particle production within the device. These results demonstrate the incremental improvement of the design and manufacturing of silicon microdosimeters with improved tissue equivalency.

5. References

- [1] Kase Y *et al* 2011 *J. Radiat. Res.* **52** 789-96
- [2] Tran L T 2015 *IEEE T. Nucl. Sci.* **62** 504-11
- [3] Tran L T *et al* 2017 *IEEE T. Nucl. Sci.* **65** 467-72
- [4] Tran L T *et al* 2015 *IEEE T. Nucl. Sci.* **62** 3027-33
- [5] Pastuovic Z *et al* 2017 *Nucl. Instrum. Meth. B* **404** 1-8