

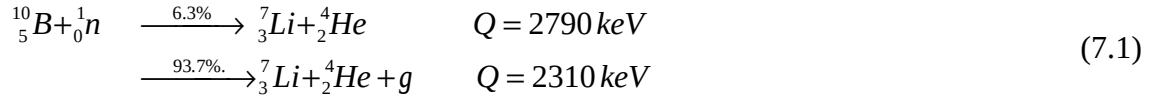
7. Application to Boron Neutron Capture Therapy

7.1 Background to BNCT

Boron neutron capture therapy (BNCT) involves the thermal neutron irradiation of a tumor site that has been selectively sensitized to thermal neutrons via the concentration of boron-10 (B-10) within or near cancer cells [254]. The B-10 is administered by injection of tumor specific boron compounds. Several excellent reviews are available including Barth on general topics [255], Coderre on radiation biology [256], and Zamenhof on microdosimetry in BNCT [257].

BNCT was proposed in 1936 by Locher [258] and the first clinical trials took place at Brookhaven National Laboratory (BNL) in 1951-52 and Massachusetts Institute of Technology (MIT) in 1959-61 [259, 260]. Initial clinical trials were unsuccessful due to normal tissue necrosis attributed to high concentrations of boron in normal brain capillaries and the poor penetration depth of thermal neutron beams. BNCT was resumed in Japan in 1968 using more selective boron compounds. Results were encouraging although they indicated that the survival times of these patients were no better than for those receiving conventional radiotherapy [256, 261]. Recently, several improvements have been made in boron delivery agents and epithermal neutron beam design. Clinical trials were resumed at BNL in 1994 for glioblastoma multiforme (a particularly insidious form of cerebral cancer), at MIT in 1996 for cutaneous and intracerebral melanoma and at the high flux reactor in Petten, Netherlands in 1998 for glioblastoma.

The concept of BNCT is attractive in principle: the thermal neutrons are selective and the range of the fission products limits damage to the cell containing boron. The kinetic energy of thermal neutrons (0.025 eV) is below the threshold for ionization and only inelastic events such as neutron capture produce significant energy deposition. In tissue, hydrogen and nitrogen have significant cross-sections for thermal neutron capture (0.33 and 1.75 barns respectively). They produce 2.2 MeV γ rays and 0.6 MeV protons, respectively. However, provided B-10 concentrations are sufficiently high a large proportion of dose will be due to the capture of thermal neutrons by B-10 with a cross section of 3800 barns. The subsequent nuclear fission process is:



The alpha and lithium reaction products are high LET particles that deposit their energy in ranges of 4.1 and 7.7 μm respectively, comparable to typical mammalian cell dimensions. Information on the energy and ranges of the main BNCT products is provided in section 5.4.

The energy deposition is highly localized in nature and depends strongly on the subcellular spatial deposition of the B-10 nuclei and the subcellular morphology. In addition to the dose due to B-10 neutron capture, many other dose components are present:

1. Protons as recoil products from the interaction of fast and epithermal neutrons with H-1 nuclei and
2. Protons as a product of N-14 neutron capture.
3. Gamma rays arise from H-1 neutron capture and from the neutron source and surrounding materials.

Studying complex radiation environments with such localized energy deposition is accomplished using the tools of experimental and theoretical microdosimetry. In particular, experimental microdosimetry provides techniques for separating varying LET components and measuring dose due to B-10 neutron capture, total dose, beam quality and dose enhancement factors. The separation of LET components using microdosimetric methods is important due to the varying biological effectiveness of these components.

Historically, the primary experimental tool for microdosimetric measurements is the proportional gas counter [11]. Wu [262] first applied a Rossi type proportional counter to BNCT dosimetry. This has been followed by other studies by Maughan [263] and Kota [154, 264].

Wu's experiments used paired TE and TE + boron chambers in the epithermal beam at BNL with some results shown later in section 7.3.2.5. The 2.5 cm diameter TE Rossi proportional counter was built with 50 ppm boron incorporated into the 3 mm thick walls. The same concentration of boron was also incorporated into the gas. The various

dose components of the beam, as described above, may be quantified. Gamma rays and fast protons occur at low LET (2-3 keV), Bragg peak protons at moderate LET (80 keV), heavy recoils and BNCT products at high LET (300 keV). The dual chamber method assists in discriminating the boron dose from other components. Zamenhof writes that such microdosimetric measurements "may contribute to a better understanding of the radiobiology of the B-10 reaction as well as that of the associated background dose components" [257].

However, proportional counter microdosimetry does not accurately reflect the cellular distribution of boron, which is dependent on the delivery agent and subcellular structure. Zamenhof and Solares [81] addressed the issue in the development of high resolution quantitative autoradiography (HRQAR) combined with a novel 2D Monte Carlo simulation. HRQAR uses a 0.8 μm thick film of Lexan as the track detection medium placed in intimate contact with an equally thin tissue sample. Image processing techniques applied to the track detector film identify boron. Their hypothesis is that a full 3D characterization of the cellular architecture and the corresponding B-10 distribution can be mimicked by sectioning a single plane through many cells in the tumor matrix, deriving the boron distribution within this single plane by HRQAR, and performing a 2D Monte Carlo calculation within this plane over many cell sections to obtain the desired microdosimetric parameters. A spatial resolution of 1-2 μm and a sensitivity of 1 ppm boron may be achieved, although the process is very time consuming, taking 8 days for the HRQAR.

Silicon microdosimetry can not achieve the information quality of the autoradiography method although it will offer benefits over the proportional gas counter without the complexity of autoradiography. These benefits include high spatial resolution and the ability to vary the spatial localization of boron to reflect real tissue distributions.

This chapter provides the first reported measurements using boron coated silicon diode arrays as microdosimetric detectors in BNCT. The purpose is to present some preliminary results for this new detector technology. Experiments were performed at BNL, Kyoto University Research Reactor (KUR) and MIT, in chronological order. At BNL, the effects of various boron-coating options on microdosimetric spectra are investigated along with device orientation effects. A U-235 coating is also tested to simulate device behavior in a heavy ion therapy beam. At KUR, the internal p^+ doping

boron was extensively used to simultaneously record microdosimetric spectra and thermal neutron flux measurements. Finally, the experiments at MIT tested the microdosimeter under an epithermal accelerator source.

The subject of tissue equivalence of silicon based microdosimetric measurements in BNCT was discussed in section 5.4. This work demonstrated that under appropriate geometrical scaling (0.63) silicon detectors with well-known geometry will record energy deposition spectra representative of tissue cells of equivalent shape.

7.2 Thermal Neutron Sensitivity of Microdosimeter Construction

A necessary step in establishing the thermal neutron response of the microdosimeter is to examine the device elemental composition and thermal neutron capture cross-section as shown in Table 7.1. A similar table was constructed for the main materials on top of the detector; air and Lucite as shown in Table 7.2. Materials below the detector may be neglected since the silicon substrate is 300 μm thick and ion products from thermal neutron reactions will not have sufficient range to enter the SOI sensitive volume. Within each table, the reactions that produce ion products through (n,p) or (n, α) reactions are highlighted in bold typeface. For each of these reactions, the relative probability of a thermal neutron interaction within the microdosimeter construction was calculated. The probability of an interaction with N atoms is given by the macroscopic cross-section S (in cm^2) for the interaction of thermal neutrons defined as

$$\Sigma = s N \quad (7.2)$$

where s is the thermal neutron cross-section for the element (sometimes called the microscopic cross-section), and N is the number of atoms present. Thus, the count rate R (in counts/s) generated in the detector is given by

$$R = k_r \Sigma \Phi_n \quad (7.3)$$

where Φ_n is the thermal neutron flux (in neutrons/ cm^2/s) and k_r is a correction factor which accounts for the proportion of generated recoil products that reach the sensitive volume and are detected above the microdosimeter noise threshold. Note that given accurate values for k and S (or N), the thermal neutron flux may be accurately derived from count rate measurements using equation (7.3).

The boron-10 within the detector $p+$ region will be used frequently in this work as a thermal neutron detector material. The relative probability of an interaction with a material is calculated as the ratio of the thermal neutron count rate for that material to the count rate for the $p+$ region B-10. For all reactions except the $^{14}\text{N}(n,p)^{14}\text{C}$ reaction we assume that all reactions produce a detectable event (i.e. $k_r = 1$). That is, the relative probability is simply the ratio of macroscopic cross sections. This assumption is a course approximation useful for this preliminary analysis. Later simulations will provide more accurate values of k_r where appropriate. In half of the $^{14}\text{N}(n,p)^{14}\text{C}$ reactions, a 40 keV carbon ion recoil will be ejected in the direction of the sensitive volume. This recoil will generally either not reach the sensitive volume or will have an energy below the noise threshold. Thus $k_r \cong 0.5$ for the $^{14}\text{N}(n,p)^{14}\text{C}$ reaction. Table 7.3 summarizes macroscopic cross-sections for ion product producing components and the corresponding relative probabilities. The following points arise from the comparison shown in Table 7.3:

- The important count rate generating materials are (in order of importance), 1% B-10 in a Lucite coat or cover (optional, if present), B-10 in the $p+$ region, N-14 in air (if present, may not have an air gap above the device), N-14 from the TiN barrier layer.
- The relative number of events due to O-17 (in air, Lucite or oxide) or Ar-36 (in air) reactions are negligible.
- Similarly, the number of thermal neutron reaction events due to B-10 in the substrate is negligible by four orders of magnitude in comparison with B-10 in the $p+$ region.
- The relative number of thermal neutron reaction events due to N-14 in the TiN is quite small, about 6%.
- A 200 μm air gap (with N-14) on top of the detector may produce an appreciable (30%) thermal neutron count rate in comparison with the $p+$ region.
- A 1% B-10 impregnated Lucite cover on top of the detector will produce a thermal neutron count rate up to 1300 times larger than the $p+$ region. This will be an overestimate since $k_r < 1$ for the boron cover.

These findings are useful for understanding the spectra produced by the experiments discussed in the following sections.

Table 7.1. Elements in silicon microdosimeter construction with isotopic abundance, thermal neutron reaction and cross-section. Reactions in bold produce ion products. Reaction data from Mughabghab [265]. Isotopic abundance from Krane (appendix C) [266].

Element	Isotope	Isotopic Abundance (%)	Reaction	Cross-section (barns)	Comments
Boron	$^{10}_5\text{B}$	19.61	$^{10}\text{B}(\text{n},\alpha)^7\text{Li}$	3837	$p+$ doping and substrate doping
	$^{11}_5\text{B}$	80.39	$^{10}\text{B}(\text{n},\gamma)^{12}\text{B}$	5.5×10^{-3}	
Nitrogen	$^{14}_7\text{N}$	99.635	$^{14}\text{N}(\text{n},\text{p})^{14}\text{C}$	1.83	TiN Barrier layer
	$^{15}_7\text{N}$	0.365	$^{14}\text{N}(\text{n},\gamma)^{15}\text{N}$	2.4×10^{-5}	
Oxygen	$^{16}_8\text{O}$	99.759	$^{16}\text{O}(\text{n},\gamma)^{17}\text{N}$	1.9×10^{-4}	Oxide (SiO_2) layer
	$^{17}_8\text{O}$	0.037	$^{17}\text{O}(\text{n},\alpha)^{14}\text{C}$	0.235	
	$^{18}_8\text{O}$	0.204	$^{18}\text{O}(\text{n},\gamma)^{19}\text{N}$	1.6×10^{-4}	
Aluminium	$^{27}_{13}\text{Al}$	100	$^{27}\text{Al}(\text{n},\gamma)^{28}\text{Al}$	0.231	Metal tracks
Silicon	$^{28}_{14}\text{Si}$	92.23	$^{28}\text{Si}(\text{n},\gamma)^{29}\text{Si}$	0.177	Substrate
	$^{29}_{14}\text{Si}$	4.67	$^{29}\text{Si}(\text{n},\gamma)^{30}\text{Si}$	0.101	
	$^{30}_{14}\text{Si}$	3.1	$^{30}\text{Si}(\text{n},\gamma)^{31}\text{Si}$	0.107	
Titanium	$^{46}_{22}\text{Ti}$	8.2	$^{46}\text{Ti}(\text{n},\gamma)^{47}\text{Ti}$	0.59	TiN Barrier layer
	$^{47}_{22}\text{Ti}$	7.4	$^{47}\text{Ti}(\text{n},\gamma)^{48}\text{Ti}$	1.7	
	$^{48}_{22}\text{Ti}$	73.7	$^{48}\text{Ti}(\text{n},\gamma)^{49}\text{Ti}$	7.84	
	$^{49}_{22}\text{Ti}$	5.4	$^{49}\text{Ti}(\text{n},\gamma)^{50}\text{Ti}$	2.2	
	$^{50}_{22}\text{Ti}$	5.2	$^{50}\text{Ti}(\text{n},\gamma)^{51}\text{Ti}$	0.179	
Arsenic	$^{75}_{33}\text{As}$	100	$^{75}\text{As}(\text{n},\gamma)^{76}\text{As}$	4.5	$n+$ doping
Gold	$^{197}_{79}\text{Au}$	100	$^{197}\text{Au}(\text{n},\gamma)^{198}\text{Au}$	98.65	Attaching/wires

Table 7.2. Elements in overlayer materials (air and Lucite (unboronated)) with isotopic abundance, thermal neutron reaction and cross-section. Reactions in bold produce ion products. Reaction data from Mughabghab [265]. Isotopic abundance from Krane (appendix C) [266].

Element	Isotope	Isotopic Abundance(%)	Reaction	Cross-section (barns)	Comments
Hydrogen	^1_1H	99.985	$^1\text{H}(\text{n},\gamma)^2\text{H}$	0.33260	53.33 atom% in Lucite
	^2_1H	0.015	$^2\text{H}(\text{n},\gamma)^3\text{H}$	5.19×10^{-4}	
Carbon	$^{12}_6\text{C}$	98.89	$^{12}\text{C}(\text{n},\gamma)^{13}\text{C}$	3.53×10^{-3}	33.33 atom% in Lucite
	$^{13}_6\text{C}$	1.11	$^{13}\text{C}(\text{n},\gamma)^{14}\text{C}$	1.37×10^{-3}	
Nitrogen	$^{14}_7\text{N}$	99.635	$^{14}\text{N}(\text{n},\text{p})^{14}\text{C}$	1.83	75.50 atom% in Air
	$^{15}_7\text{N}$	0.365	$^{14}\text{N}(\text{n},\gamma)^{15}\text{N}$	2.4×10^{-5}	
Oxygen	$^{16}_8\text{O}$	99.759	$^{16}\text{O}(\text{n},\gamma)^{17}\text{O}$	1.9×10^{-4}	23.20 atom% in Air
	$^{17}_8\text{O}$	0.037	$^{17}\text{O}(\text{n},\alpha)^{14}\text{C}$	0.235	13.33 atom% in Lucite
	$^{18}_8\text{O}$	0.204	$^{18}\text{O}(\text{n},\gamma)^{19}\text{O}$	1.6×10^{-4}	
Argon	$^{36}_{18}\text{Ar}$	0.337	$^{36}\text{Ar}(\text{n},\alpha)^{33}\text{S}$	5.5×10^{-3}	1.30 atom% in Air
			$^{36}\text{Ar}(\text{n},\gamma)^{37}\text{Ar}$	5.2	
	$^{38}_{18}\text{Ar}$	0.063	$^{38}\text{Ar}(\text{n},\gamma)^{39}\text{Ar}$	0.8	
	$^{40}_{18}\text{Ar}$	99.60	$^{40}\text{Ar}(\text{n},\gamma)^{41}\text{Ar}$	0.66	

Table 7.3. Relative probability of thermal neutron interaction with selected microdosimeter/overlayer elements. All elements selected produce ion recoil products through (n,p) or (n,α) reactions.

Element/Component	Number Atoms	Micro X-section (10^{-24} cm^2)	Macro X-Section (cm^2)	Relative Prob.	Comments
^{10}B in $p+$ region	2.22×10^{13}	3837	8.52×10^{-8}	1	Area of $p+$ region is 0.022 cm^2 and boron ion implant fluence $1.5 \times 10^{15} \text{ atoms/cm}^2$. Substrate thickness = $2 \mu\text{m}$, area = small diode array (40×120 cells @ $30 \times 30 \mu\text{m}^2$) Lucite thickness = $6.1 \mu\text{m}$ (range of $1470 \text{ keV } \alpha$ recoil) area = small array 0.044 cm^2 TiN thickness = $0.1 \mu\text{m}$, area = 0.011 cm^2 , Density TiN = 5.33 gm/cm^3 . [267] Air thickness = $200 \mu\text{m}$, area = small array 0.044 cm^2 SiO_2 thickness = $2 \mu\text{m}$ ($1 \mu\text{m}$ above and $1 \mu\text{m}$ below SOI), area = small array 0.044 cm^2 Air thickness = $200 \mu\text{m}$, area = small array 0.044 cm^2 Lucite $6.1 \mu\text{m}$ thick. Air thickness = $200 \mu\text{m}$, area = small array 0.044 cm^2
^{10}B in substrate	2.62×10^9	3837	1.01×10^{-11}	10^{-4}	
^{10}B in 1% B Lucite	2.89×10^{16}	3837	1.11×10^{-4}	1300	
^{14}N in TiN	5.57×10^{15}	1.83	1.01×10^{-8}	0.06	
^{14}N in Air	3.31×10^{16}	1.83	6.07×10^{-8}	0.30	
^{17}O in SiO_2	1.47×10^{14}	0.235	3.46×10^{-11}	4×10^{-4}	
^{17}O in Air	3.77×10^{12}	0.235	8.86×10^{-13}	10^{-5}	
^{17}O in Lucite	1.41×10^{14}	0.235	3.31×10^{-11}	4×10^{-4}	
^{36}Ar in Air	1.92×10^{12}	5.5×10^{-3}	1.06×10^{-14}	10^{-7}	

Note 1: See chapter 4 for a device description and Appendix B for additional layout information.

2: Macro X-Section = Micro X-Section $\times$ Number atoms,

Relative probability = Macro X-Section/ Macro X-Section for ^{10}B in $p+$ region

7.3 Experiments at Brookhaven National Laboratory (Boron and U-235 Coating Investigation)

7.3.1 Materials and Methods

7.3.1.1 Description of Brookhaven Medical Research Reactor(BMRR)

The 3 MW BMRR is an adjunct to the Medical Research Center at Brookhaven National Laboratory (BNL). BMRR has three irradiation facilities: an epithermal neutron irradiation facility (ENIF), a thermal neutron irradiation facility, and a broadbeam facility. For this study, we used the ENIF since this beam is used for current clinical trials. A complete description of the facility and collimator design is provided by Liu [268] with a diagram shown in Figure 7.1. In our case, a Lucite cubic phantom was positioned at the irradiation treatment port immediately adjacent to the collimator. The center of the cube was aligned to the center of the collimator. The reactor power used for the experiments was 300 kW for boron coating measurements and 30 kW for the U-235 studies selected at the maximum power allowable without significant pile-up effects observed. The thermal neutron flux at 6.5 cm depth in the Lucite phantom was calculated [268] as 6.29×10^7 n/cm²/s.

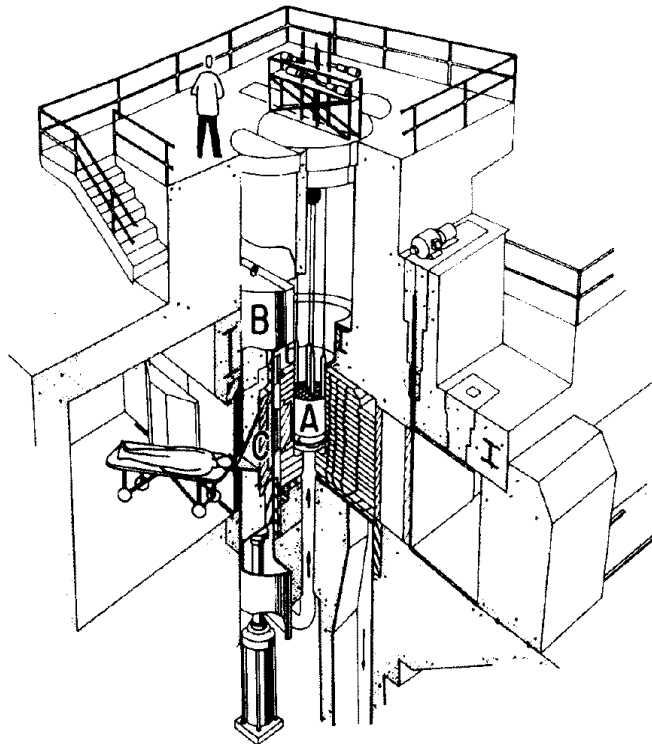


Figure 7.1. Schematic diagram of the epithermal beam and patient irradiation facility at the BMRR. [255] A, core of the reactor; B, moveable shutter; C, epithermal neutron filter. A patient is shown with his head in the neutron beam port. Filters and moderators adjust the energy spectrum to maximize neutrons in the epithermal energy range of ~ 1 eV to 10 keV and minimize those outside this range.

7.3.1.2 Description of probe assembly and device coating (B-10 and U-235)

The microdosimeter probe assembly used was "Probe Assembly #1" fully described previously in section 4.3. The microdosimeter used was a 2 μm SOI device with the small diode size ($10 \times 10 \mu\text{m}^2$ junction) array selected. This device was selected because the sensitive volume was the smallest available. The charge collection characteristics of the device were fully described in section 6.2.4.1. The device was reverse biased at 10V.

Two devices were prepared. One without boron coating and the other with a Lucite coating containing 1% B-10. The boron coating models the biological situation where boron accumulates on the cell surface (e.g. boron attached to monoclonal antibodies) and we are interested in the microdosimetric spectra within the cell nuclei from a two dimensional array of cells. The device overlayer of between 1-1.35 μm (composed of SiO_2 and Al) crudely represents the cytoplasm spacing between the cell nucleus and surface. The coating was developed by dissolving Lucite shavings in dichloroethane. Decaborane was then added to obtain the required concentration of B-10 to an accuracy of $\pm 5\%$. Drops of the solution were then placed onto the circuit and allowed to dry (~ 20 minutes). Note that extreme care should be taken in this process. Dichloroethane is volatile, its fumes are poisonous, and a mixture of decaborane and dichloroethane is known to be shock sensitive.

The minimum coating thickness required is given by the range (7.4 μm) of a 1.78MeV alpha produced by boron neutron capture. Conversely, too large a thickness may attenuate the thermal neutron fluence. Alpha spectroscopy was performed as an indicator of coating thickness. Since a 5.3MeV alpha has a range in Lucite of 31.9 μm , we would expect no charge collected by the device with a coating greater than this thickness. This was observed after 5 coatings.

However, once coated the device cannot be used for non-boron measurements or alpha spectroscopy experiments. A possible solution is to use a detachable boron coated Lucite lid in close proximity to the detector's surface. A thin Lucite lid with a 1% boron coating was constructed for comparison with the direct coating approach. The air gap between the lid and the detector surface was estimated to be between 100-200 μm .

A third Lucite lid was fabricated with a thin film of aluminum backed Uranium-235 glued to the underside of the lid. U-235 has a high thermal neutron fission cross-section

(580 barns). The U-235 nucleus splits in some 40 or so modes following the absorption of a thermal neutron. An average energy of 195 MeV is released in the fission process with a large portion of the energy (162 MeV) carried away by the charged fission fragments. Thus, a U-235 coated lid may be used to test the microdosimeter's performance under simulated heavy ion treatment conditions.

7.3.1.3 Description of phantom

The phantom consists of a sequence of Lucite blocks each $2.5 \times 15 \times 15 \text{ cm}^3$. Using a Lucite nut and bolt, 6 blocks are connected together to form a 15 cm sided cube. A similar Lucite cube has been used at BNL for previous dosimetry and Monte-Carlo studies. One block is designed with a recess for insertion of the microdosimeter probe. Thus, by rearranging the blocks we may move the probe to different positions within the cube. The primary position for measurements in this paper was 6.5 cm depth along the central axis. A 1-meter BNC compatible coaxial cable runs through the probe to connect the microdosimeter to a preamplifier.

7.3.1.4 Microdosimetric measurements

Using the facilities and techniques described in the previous sections microdosimetric spectra were obtained for each coating and lid condition (i.e. boron coating, boron lid and U-235 lid). Experiments were also performed to determine the effect of device orientation on microdosimetric spectra.

The multi-channel analyzer provides a spectrum of the number of events recorded at different energies. The energy deposited by each event is divided by the mean chord length to give the lineal energy (y). To convert to a tissue equivalent microdosimetric spectrum the mean chord length of the silicon device is simply scaled by a factor of $1/0.63$ as described in section 5.4. Furthermore, the mean chord length should be such that the dose mean lineal energy is equivalent to that produced by a spherical proportional counter. The estimation of the mean-chord length was determined using simulation methods, based on these considerations, as described in the following section.

7.3.1.5 Simulation of microdosimetric measurements and MCL estimation

Simulation of the microdosimetric measurements may be performed using the Monte Carlo program developed in section 5.4.2. Such simulations provide increased understanding of experimental spectra and may also be used to estimate mean chord

lengths (MCL) required for lineal energy spectra presentations. The program was modified to take into account the collection efficiency within the sensitive volume. The Monte Carlo program transports an ion along its range in small increments of $Dr = 0.01 \mu\text{m}$. Within the sensitive volume, the energy deposited in Dr is multiplied by the collection efficiency at the current ion position to give the energy collected. The total charge collected E_{col} is simply the sum over all ion positions within the sensitive volume:

$$E_{col} = \sum_{i=1}^{i=n} (E(r_{i+1}) - E(r_i)) C(x_i, y_i)$$

where $r_{i+1} = r_i - \Delta r$, $\Delta r = 0.01 \mu\text{m}$ (7.4)

$$x_1 = x_s, x_{i+1} = x_i + d_x \Delta r, \quad y_1 = y_s, y_{i+1} = y_i + d_y \Delta r,$$

and r_1 is the range of the ion upon entering the SV, $E(r)$ is the energy-range relationship, (x_i, y_i, z_i) is the ion position, (x_s, y_s, z_s) is the first point on entering the SV, (x_n, y_n, z_n) is the last point on exiting the SV or the point at the end of the ion range (whichever comes first), (d_x, d_y, d_z) are the direction cosines of the ion, and $C(x, y)$ is the collection efficiency. The collection efficiency function for the $10 \times 10 \mu\text{m}^2$, $2 \mu\text{m}$ SOI device was estimated in section 6.2.4.1. Note that the collection efficiency is defined in two dimensions and assumed constant in the z direction. The program can also calculate the chord length l as follows:

$$l = \sum_{i=1}^{i=n} \Delta r C(x_i, y_i) \quad (7.5)$$

The mean chord length was calculated for both the boron lid and boronated Lucite coating on top of the $10 \times 10 \mu\text{m}^2$, $2 \mu\text{m}$ SOI device. The dimensions of each of the simulations are shown in Figure 7.2. The entire device of 40×120 diodes was simulated with the collection efficiency for each diode as determined in section 6.2.4.1. Note, that the diode sensitive depth is $2 \mu\text{m}$ in the $n+$, $p+$ regions and $1.82 \mu\text{m}$ elsewhere with the variation due to the LOCOS region consuming silicon. The generation volume, consisting of the boron coating layer, need only extend above the sensitive volume to the maximum range of the generated alpha particles ($7.55 \mu\text{m}$) in Lucite. The overlayer was simplified to consist of the predominant material (SiO_2) with an average thickness calculated as $1.05 \mu\text{m}$. Also note that the simulation assumes negligible nitrogen content in any of the components compared with the high boron

concentration in the Lucite. The simulations will be further discussed in the following results section.

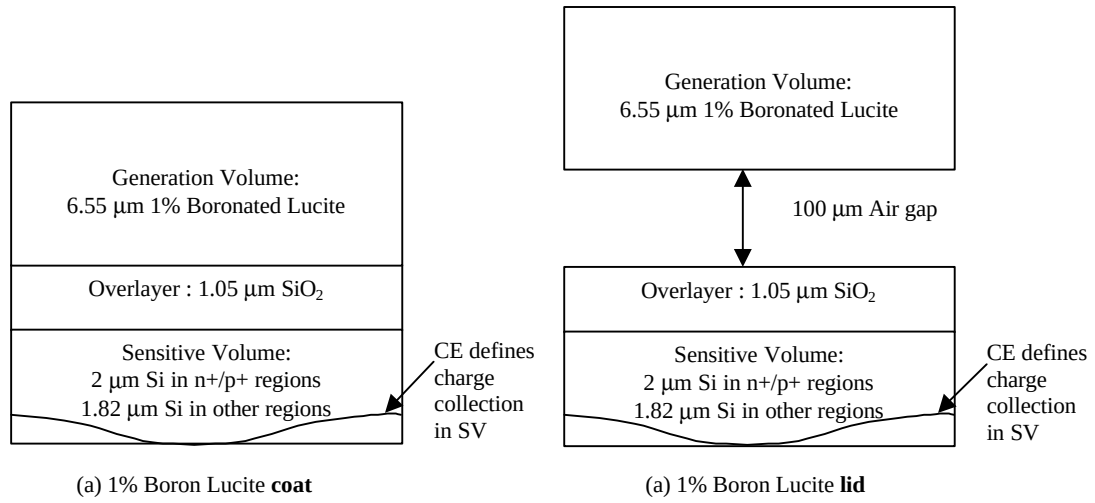


Figure 7.2. Cross-section of boron-coating simulation on top of $10 \times 10 \mu\text{m}^2$, $2 \mu\text{m}$ SOI diode array (40×120 diodes, each cell $30 \times 30 \mu\text{m}^2$). The GV is ($1215 \times 3615 \times 6.55 \mu\text{m}^3$) whilst the SV is ($1200 \times 3600 \mu\text{m}^2$ with a depth of 2 μm in the n^+ , p^+ regions and 1.82 μm elsewhere). The maximum range of 1470 keV alpha particles in Lucite is 7.55 μm . The left side shows the boron coat configuration and the right side shows the boron lid configuration.

The calculated chord length distributions are shown in Figure 7.3. The mean chord length $\bar{l}_{KSi}$ is 1.16 μm for the coat and 1.12 μm for the lid, a value quite low compared to the 2 μm thick sensitive volume. This low value arises from the large number of stoppers due to the short range of the lithium and alpha particles relative to the overlayer and sensitive volume thickness. Two corrections to the MCL are required. Firstly, the MCL should be adjusted so that the dose mean lineal energy is equivalent to that produced by a spherical proportional counter and secondly the tissue equivalent correction is required.

As discussed in detail in chapter 3, the spherical shaped counter is the main reference used in microdosimetric measurements. Therefore, the MCL is corrected to provide a dose mean lineal energy $\bar{y}_d$ that is equivalent to a sphere. Recall from section 3.4, the corrected effective MCL $\bar{l}_{Keff}$ is :

$$\bar{l}_{Keff} = \frac{\bar{l}_{KSi}}{hz} \quad (7.6)$$

where $z = 0.63$ is the TE correction factor discussed in section 5.4, and h is a shape correction factor given by equation (3.37) as:

$$h = \frac{\bar{y}_{d,sphere}}{\bar{y}_{d,K}} \quad (7.7)$$

The dose mean lineal energy for a sphere is $\bar{y}_{d,sphere} = 9/8 L$, where L is the particle LET (assumed constant, see section 3.3.3.1). From the data of Figure 7.3, the dose mean lineal energy for the boron-coated geometry is $\bar{y}_{d,K} = 1.42 L$ giving $h = 0.79$ and for the boron-lid geometry is $\bar{y}_{d,K} = 1.43 L$ giving $h = 0.79$. Thus, the corrected MCL for the boron coating and lid measurements are $\bar{l}_{Keff}(\text{coating}) = 2.32 \mu\text{m}$ and $\bar{l}_{Keff}(\text{lid}) = 2.26 \mu\text{m}$.

The MCL used for displaying measurements made using the U-235 coating use the same MCL as the boron coated device. An accurate MCL is not required for this measurement since the purpose of the experiment was a comparative study of the variation in charge collection spectra with voltage under heavy ion irradiation.

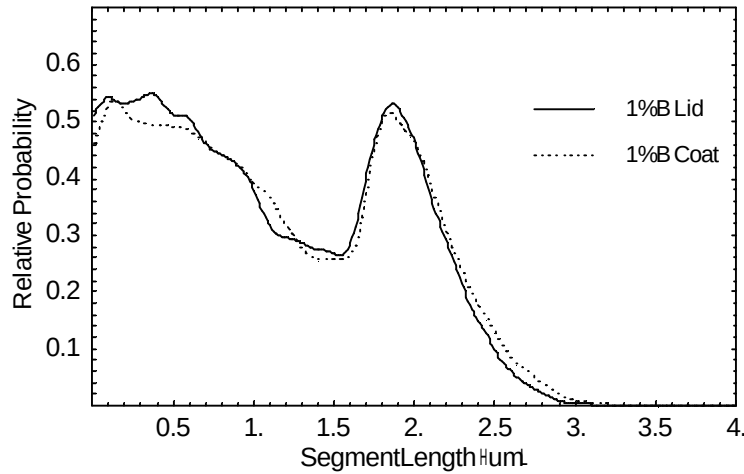


Figure 7.3. Segment length distribution produced by thermal neutron irradiation of a boron/Lucite coating and lid configurations above the $10 \times 10 \mu\text{m}^2$, $2 \mu\text{m}$ SOI diode array. Simulation geometry is depicted in Figure 7.2.

7.3.2 Experimental Results and Discussion

7.3.2.1 Evaluation of boron coating methods

A microdosimetric spectrum was obtained for a device with no boron coating in order to determine the influence of boron used in the construction of the device. Boron is used as the p-type dopant in the p^+ regions of the chip. The spectrum shown in Figure 7.4, and

scaled by a factor of 100 to compare with a boron coated device, indicates the relatively small contribution from boron fission events within the device's p^+ doped region compared to the boron coating. The excellent fast neutron filtering of the epithermal beam is also demonstrated by the small recoil proton component at lower lineal energies.

This spectrum also indicates the validity of ion implanting boron directly into the chip in order to simulate boron deposition in various regions of a cell, an idea recently proposed by Rosenfeld [71]. Such local B-10 concentration variation is not possible with a proportional gas counter. The p^+ region is manufactured by ion implantation of 5×10^{15} boron ions/cm² at an energy of 30 keV and over an area 17% of the total diode area. This gives a B-10 concentration of approximately 1×10^{20} atoms/cm³ or 2000 ppm for 20% isotopic abundance and assuming uniform B-10 distribution within a 0.1 μ m depth region. Concentrations of 50 ppm, which are equivalent to clinically achievable conditions, could easily be obtained by reducing the implant to 1.2×10^{14} boron ions/cm². The distribution of boron through the cell may also be varied by changing the p^+ layout or increasing the substrate boron doping concentration. The latter strategy would require substrate doping of the order of 1.2×10^{19} B-atoms/cm³ to obtain a uniform B-10 concentration of 50 ppm. However, device operation would be severely compromised at such a high concentration due to carrier lifetime and collection efficiency reduction. Note that in the current design thermal neutron interactions with the boron p^+ region will greatly exceed reactions with any of the overlayer constituents (Aluminium, Silicon, Oxygen, Titanium and Nitrogen) or the boron within the bulk silicon (see section 7.4). This is due to the relatively high thermal neutron capture cross-section of boron and a sufficiently large number of ions implanted. The use of the boron p^+ region for thermal neutron studies is investigated in more detail in section 7.4.

A comparison was made of the microdosimetric spectra obtained using direct boron coating versus a detachable boron coated lid. As shown in Figure 7.5, the spectrum for the lid has a comparatively smaller high LET component and a reduced integral count rate. The 100-200 μ m air gap when using the lid accounts for the small reduction in high LET components. The alpha and lithium ions will typically be past their Bragg peak upon entering the sensitive volume since they must pass through the device overlayer structures. Therefore, any additional overlayer will decrease the total energy

deposited. A 100 μm air gap is equivalent to 0.07 μm of SiO_2 , in terms of energy loss of the BNCT ions, which effectively amounts to a 7% thicker overlayer. Thus, the additional energy loss and reduction in mean chord length is relatively small.

Despite the relatively small difference, direct coating of the chip is the preferred method of boron deposition given the attenuation of energy in the air gap and the possible large variation in the air gap distance using the lid method. Based on these observations, the coated device was used for the remainder of the BNL work. The acquisition time for the spectra obtained in Figure 7.4 and Figure 7.5 was only 3 minutes at 300 kW reactor power. The ability of the silicon microdosimeter to function at full reactor power is an additional advantage over the proportional gas counter.

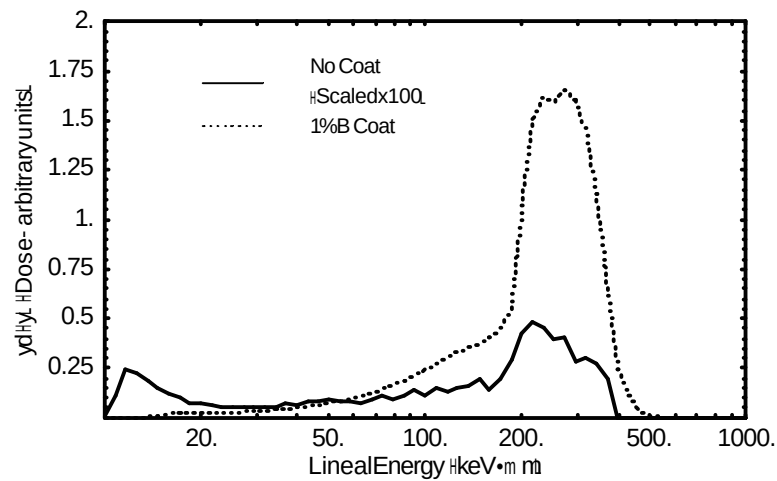


Figure 7.4: Microdosimetric spectra for non-boron coated device compared with boron coating. The spectra were obtained at a depth of 6.5 cm in the Lucite phantom with a reactor power of 300 kW. Note that the no coat spectrum is scaled up by a factor of 100. The peak at 200 keV/ μm in the no coat spectrum arises from boron p^+ -dopant in the device.

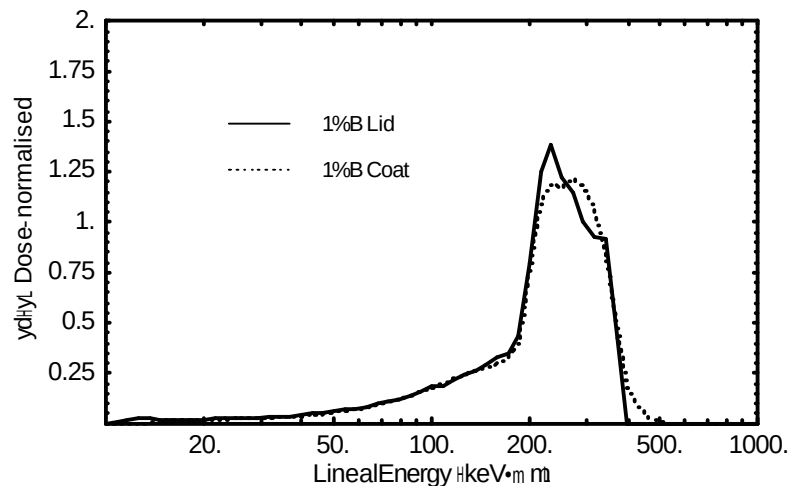


Figure 7.5. Microdosimetric spectra for various coating options. The spectra were obtained at a depth of 6.5 cm in the Lucite phantom with a reactor power of 300 kW.

7.3.2.2 Evaluation of device orientation effects

In order to determine the sensitivity of the device to beam orientation, the Lucite phantom was rotated with the detector positioned in the center of the phantom. The horizontal detector position gave a reduction in integral counts of 6.8% when compared to the vertical (possibly due to a small variation in device depth) with minimal changes in spectral character. Thus, the device is relatively insensitive to orientation. This result is to be expected given the isotropic nature of thermal neutrons.

7.3.2.3 Measurement using U-235 coated diode array

Measurements were performed on the diode array with a small piece of U-235 coated aluminum foil placed on the underside of a Lucite lid. The lid fits onto the recess in the device package, which contains the diode array. The air gap distance between the foil and device is estimated at between 100-200 μm . The fragments produced by the U-235 fission are heavy ions which produce dense plasma tracks in the silicon. Thus, the device must be sufficiently reverse biased to minimize recombination of electron-hole pairs in the plasma track. The purpose of this experiment was to determine the required reverse bias for heavy ions. This provides valuable information for possible future experiments at heavy ion therapy facilities. Figure 7.6 indicates that for voltages greater than 5 volts the difference between spectra is minimal. Therefore, under heavy-ion conditions, the minimum recommended bias voltage is approximately 5 volts, although higher voltages give slightly improved performance. Note that at zero bias recombination significantly reduces the charge collected by the microdosimeter.

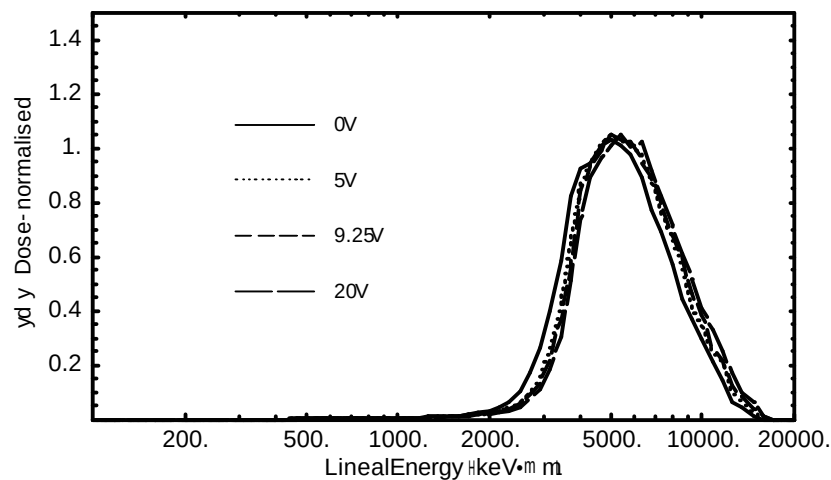


Figure 7.6. Bias dependence of U-235 Covered diode array at a depth of 6.5 cm in Lucite phantom, Reactor Power = 30 kW

7.3.2.4 Comparison with Simulation

The simulations indicate some discrepancies with experimental results as shown in Figure 7.7. The peak at 500 keV in the energy distribution for the coated device is located at 600 keV in the simulation and the simulation has a higher number of low energy events less than 200 keV. Reducing the device overlayer thickness and SOI thickness provides an improved match, although such simulations are not shown here. The simulation shown indicated that 78% of events arise from α -particle interactions with the remainder being lithium ion events. The lithium events contribute to the spectra only for energies less than 300 keV since a significant proportion of the lithium ion energy is absorbed in the overlayer. This is shown in Figure 7.7, where all energies greater than 300 keV are due to α events.

Note that the lineal energy dose distribution offers a better correspondence than the energy distribution since it involves a higher degree of smoothing and emphasizes high energy events which show a reasonable match.

Deviations between the Monte-Carlo simulation and measurements may be attributable to one or more of the following:

- Variations in overlayer structures are neglected. The overlayer is assumed uniform in thickness and composition. Inclusion of overlayer variations will broaden the spectra, which should improve the correspondence between theory and experiment
- The charge collection model is inadequate. The ions generated by BNCT reactions are close to their Bragg peaks as seen by the figures of section 5.4.1. The collection efficiency was calculated using normally incident 2 MeV alpha particles (LET~250 keV/ μ m) and 5 MeV alpha particles (LET~150 keV/ μ m). Larger peak LETs approaching 350 keV/ μ m are observed for the isotropic BNCT alpha. It is conceivable that recombination losses may be larger in the higher LET particles. Future work should examine the variation, if any, in CE with high LET particles.

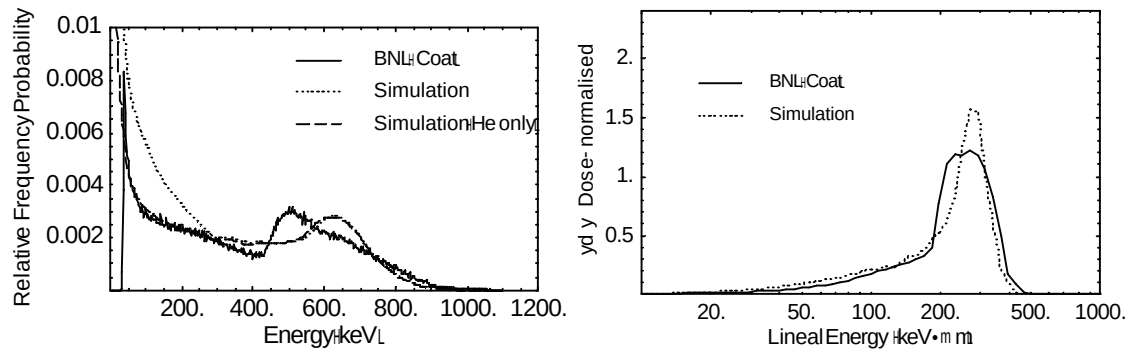


Figure 7.7: Comparison of experimental results (1% B coated diode array (10x10 μ m) at 6.5 cm) with Monte-Carlo Simulation. The left side shows the energy probability distribution and the right side shows the same data presented in standard yd(y) form.

7.3.2.5 Comparison with Proportional Counter Microdosimetric Measurements

Only a few studies have been performed using proportional gas counters to measure BNCT microdosimetric spectra [154, 262-264]. The study performed by Wu [262] is most appropriate for comparison with the diode array since both measurements were performed at BMRR. Wu performed measurements using a 2.5 cm spherical TE proportional gas counter with 50 ppm TE walls and gas. Site diameters of 2 and 6 μ m, corresponding to mean chord lengths of 1.3 and 4 μ m, were simulated by varying gas pressure.

Figure 7.8 provides a comparison of these measurements with the diode array. The spectra show similar peaks although a direct comparison with the diode array is difficult since the pattern of boron deposition differs significantly between detectors. Boron deposition is throughout the entire detector for the proportional counter whilst only on the surface of the diode array. Differences in the spectra may be expected primarily due to different chord-length distributions between a spherical counter geometry and the diode array's RPP type geometry. Wu's device contains boron within the counter so "starters" and "insiders" are included whilst the boron coated diode array measures only "crossers" and "stoppers" (See section 3.1 for terminology definition). Furthermore, the diode array overlayer of 1.05 μ m (on average) separates the boron from the detector. This will reduce somewhat the energy of alpha and lithium ions as well as altering the chord length distribution. Such effects account for the lower lineal energy recorded by the diode array.

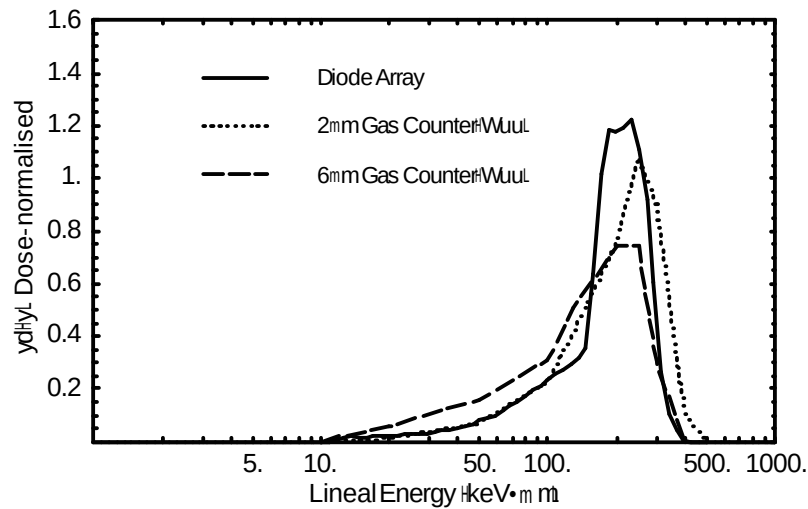


Figure 7.8: Comparison of proportional counter [262] with diode array at BMRR. The mean chord length for the diode array was 2.85 μm .

7.4 Experiments at Kyoto University Research Reactor (*Simultaneous microdosimetry and thermal neutron flux measurements*)

Based on experience gained in the previously discussed experiments, work was performed at the Kyoto University Research Reactor (KUR) principally using the boron p^+ region of the microdosimeter as the thermal neutron sensitive component. Using the p^+ region of the device removes the attenuating effect of the overlayer and presents a boron spatial distribution more nearly representative of possible biological boron distributions. However, the lower boron content makes the device more sensitive to neutron reactions with nitrogen in the TiN and air gaps as indicated in section 7.2. The performance of the p^+ region as a thermal neutron detector and the effect of the air gap will be studied in this section.

7.4.1 Materials and Methods

7.4.1.1 Description of Kyoto University Research Reactor (KUR)

The heavy water thermal neutron facility at KUR utilizes a 5 MW full power reactor. The reactor runs continuously at full power and the beam spectrum and thermal neutron flux are varied using heavy water, Boral and cadmium filters. A complete description of the facility and collimator design is provided by Kobayashi [269, 270] with diagrams shown in Figure 7.9 and Figure 7.10. In order, from the reactor core, the filters consist of an epithermal neutron moderator (80% aluminium plates/20% heavy water, 66 cm total thickness), a neutron energy spectrum shifter (consisting of 3 D_2O tanks, 10, 20 and 30 cm thick), a 30 cm D_2O water shutter, two thermal neutron filters (consisting of

1 mm Boral and 6.4 mm cadmium plates), and an adjustable bismuth layer typically 18.4 cm thick. Various irradiation modes are possible depending on the state of the filter such as open, closed, tank empty or tank full. The irradiation mode is specified by a coding scheme as shown below.

		Collimator Filter (E1=epithelial)				Bismuth (F=18.4 cm)							
		30 cm D ₂ O				20 cm D ₂ O							
		10 cm D ₂ O				30 cm D ₂ O							
		Cadmium Filter				Boral Filter							
		C	B	—	1	1	1	1	—	F	—	E1	All filters in place, D ₂ O tanks full
		O	O	—	0	0	0	0	—	E	—	E1	All filters in open, D ₂ O tanks empty

The presence of the boral or cadmium filter is designated by a "C" or "B", respectively, and the absence by an "O". A full D₂O tank is assigned a "1" and an empty tank a "0". The bismuth filter and collimator filter for all our experiments are in the F-E1 positions corresponding to 18.4 cm of bismuth and the E1 epithermal collimator.

There are three standard irradiation modes at KUR for BNCT:

1. The standard *thermal* neutron irradiation mode, OO-0011-F: tumor seated within a few cm of the surface such as melanoma.
2. The standard *mixed* thermal neutron irradiation mode, OO-0000-F: tumor seated comparatively deeper, from a few cm to almost 5 cm.
3. The standard *epithelial* neutron irradiation mode, CO-0000-F: BNCT for deep-seated tumor without craniotomy.

The mixed mode is the main current treatment mode undergoing clinical trials. The thermal mode has been used in the past and the epithelial mode is planned for future clinical trials. In this study, the mixed and epithelial modes will be used. The thermal neutron flux depth distribution for each mode is provided in section 7.4.2.3.

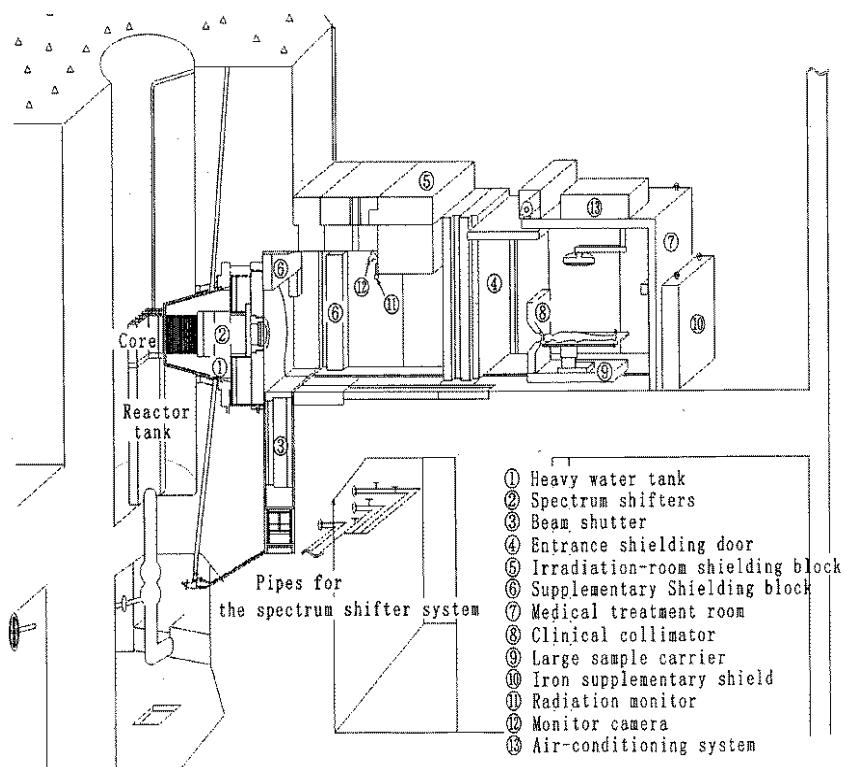


Figure 7.9. General layout of the 5 MW KUR clinical irradiation system [269]

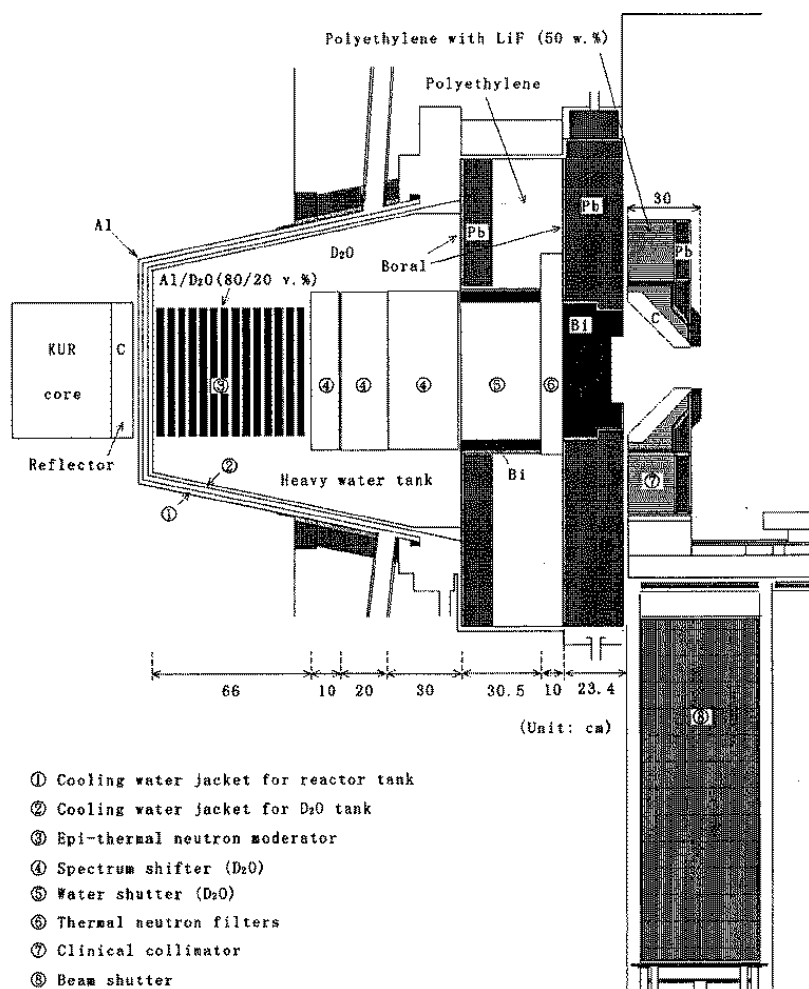


Figure 7.10. Cross-section of epithermal neutron filter construction at KUR

7.4.1.2 Description of probe assembly and phantom

The microdosimeter probe assembly used was "Probe Assembly #1" fully described previously in section 4.3. The microdosimeters used were the 2 and 5 μm SOI devices with the small diode size ($10 \times 10 \mu\text{m}^2$ junction) array selected. For most experiments, the 2 μm device was used and configured in its "raw" state without boronated Lucite coatings or lids. This device was selected because the sensitive volume was the smallest available and offered the best LET or particle type discrimination capability given the short range of the BNCT ion products. The boron doping in the p^+ region is used as the main thermal neutron detection element. In addition, the probe has a 300 μm air gap above the chip compared to 100 μm for the previous experiments at BNL. A comparison of the raw device configurations at BNL and KUR is shown in Figure 7.17. The lid insert used at BNL was not used at KUR (at the time it was, mistakenly, not considered important). The charge collection characteristics of the device were fully described in section 6.2.4.1. The device was reverse biased at 10V.

A cylindrical water head phantom was used as shown in Figure 7.11. The longitudinal axis of the water phantom was aligned with the central axis of the beam and the phantom was placed up against the collimator. The detector was then positioned to intercept the central axis of the beam. A 3D remote controlled actuator system was used to accurately position the microdosimeter ($\pm 2 \text{ mm}$) along the central axis and minimize personnel radiation exposure during measurements.

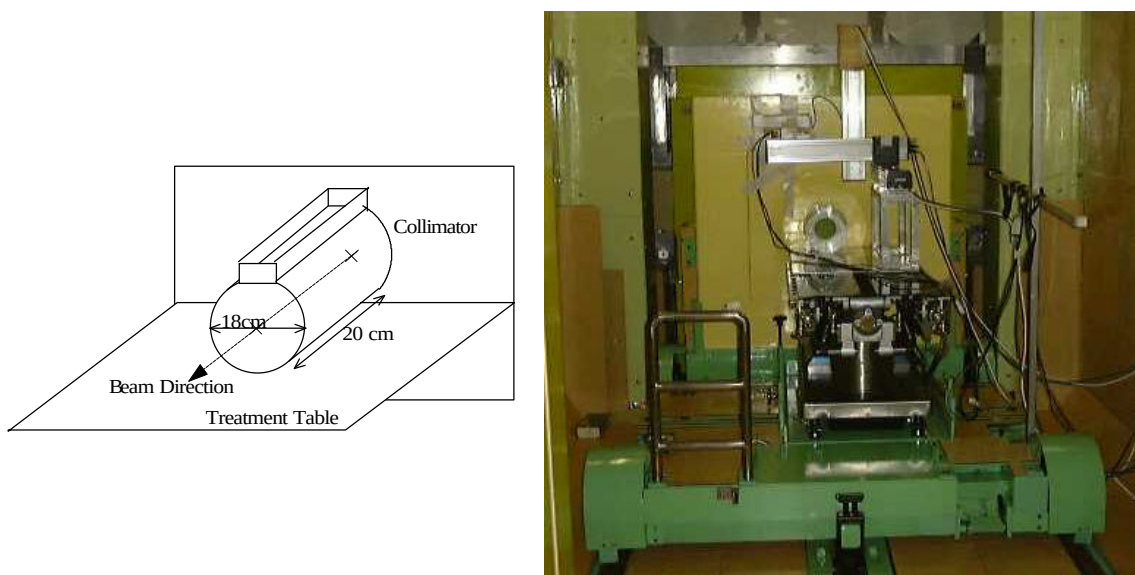


Figure 7.11. Water head phantom used at KUR showing 3D actuator system (above right from phantom) and a rail mounted remote-patient carrier system.

7.4.1.3 Microdosimetric measurements

Microdosimetric measurements were made at distances of 10, 20, 30, 40, 50, 60, 80 and 100 cm from the front face of the phantom. This direction, along the beam axis, will be referred to as the depth direction. The measurements were made for the mixed and epithermal modes with the intention of determining the thermal neutron flux depth distribution. The thermal neutron flux was determined using equation (7.3) with a correction factor k_r determined from simulations as discussed in the results section 7.4.2.3.

In addition, microdosimetric spectra may be compared to determine the relative contribution of various radiation components such as recoil protons from elastic fast neutron scattering. Thus, the principal aim was to examine the capability of the microdosimeter $p+$ region for simultaneously extracting the thermal neutron flux and a microdosimetric spectrum. Most spectra will be presented in energy probability distribution form (i.e. calibrated MCA spectrum). For these measurements, greater spectral character is provided using the energy distribution rather than the standard $y-d(y)$ format.

The ability of the microdosimeter to delineate events of differing LET depends upon a thin sensitive volume. A comparison between the response of the 2 and 5 μm SOI arrays was made at a depth of 20 cm using the mixed irradiation mode.

7.4.1.4 Simulation of microdosimetric measurements and MCL estimation

Monte Carlo simulations of the microdosimetric measurements provide an increased understanding of experimental spectra and may also be used to estimate mean chord lengths (MCL) required for lineal energy spectra presentations. Inspection of Table 7.3 indicates that there are two important regions to consider for the raw SOI device based on the relative probability of interactions.

1. The $p+$ boron doped region: $^{10}\text{B}(n,\alpha)^7\text{Li}$ capture reaction, emitting alpha and lithium recoil products.
2. The nitrogen in the air layer above the device: $^{14}\text{N}(n,p)^{14}\text{C}$ capture reaction, emitting proton and carbon recoil products.

Simulations as per the Monte Carlo method discussed in sections 5.4.2.1 and 7.3.1.5 and 7.3.2.4 were performed for each of these regions as described below.

The p^+ boron doped region simulation:

The GV for the p^+ doping is shown in Figure 7.13. The p^+ ion implantation process uses a mask that overlaps the LOCOS region (see appendix B for device and process details). Therefore, the top of the LOCOS region will receive the same ion implantation as the substrate p^+ region as shown in the cross-section of Figure 7.12. The ion implantation of 30 keV boron produces a typical range in silicon of 0.11 μm and 0.12 μm in SiO_2 . The initial boron profile following ion implantation is spread via diffusion during the annealing phase of device construction. However, the diffusivity of boron in SiO_2 is very much lower than silicon ($3 \times 10^{-19} \text{ cm}^2/\text{s}$ compared to $10^{-15} \text{ cm}^2/\text{s}$ at 900 degC [44]) and there is almost no diffusive spread of the boron in oxide. For simplicity, the gaussian doping profiles typical of ion implantation and subsequent diffusion are approximated in the simulation by the uniform profiles of the RPP shaped GV. The thickness' of the oxide and p^+ region GVs were selected as 0.1 μm and 0.2 μm , respectively (reflecting the differing diffusivity) and the LOCOS thickness is 0.377 μm based on measurements performed by Fujitsu. In addition, the implant "birdsbeak" region associated with the LOCOS oxide growth is not precisely modeled since we represent the implant as a single discrete step from the silicon region to the oxide as shown in Figure 7.13. The final simulation was decomposed using cell symmetry to four GV regions:

$$\begin{aligned} \text{GV} = & \{ \{ \text{Silicon, Cuboid}(\{0,4,-0.2\},\{1,15,0\}) \} \}, \\ & \{ \text{Silicon, Cuboid}(\{0,0,-0.2\},\{4,4,0\}) \}, \\ & \{ \text{Oxide, Cuboid}(\{1,4,0.0885\},\{4,15,0.1885\}) \}, \\ & \{ \text{Oxide, Cuboid}(\{4,4,0.0885\},\{7,7,0.1885\}) \} \end{aligned}$$

where the RPPs or Cuboids are specified by the bottom left $\{x,y,z\}$ and top right vertices. The response of the device to the total GV is calculated by adding together the responses of these GVs weighted (weight factors 2,1,2,1) according to their relative contribution. The SV was defined as the 4 diode cells closest to the GV regions that may receive ion products:

$$\text{SV} = \{ \text{Silicon, Cuboid}(\{-30,-30,-2\},\{30,30,-2 + x_d\}) \}$$

where the diode sensitive depth x_d is 2 μm in the n^+ , p^+ regions and 1.82 μm elsewhere due to the LOCOS region consuming silicon. The collection efficiency within each

diode cell was modeled as given in section 6.2.4.1 and accounted for in the simulation as per equation (7.4). For the simulation, SiO_2 occupies space not defined by the above regions.

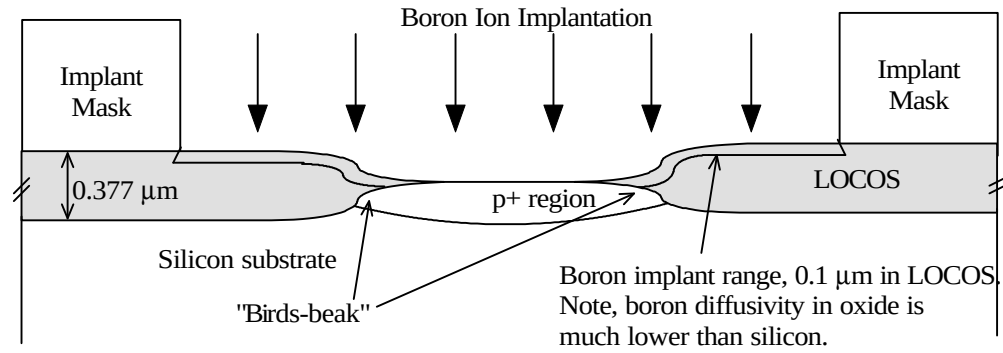


Figure 7.12. Boron ion implantation during device fabrication showing boron deposition in LOCOS (SiO_2) and silicon p^+ region.

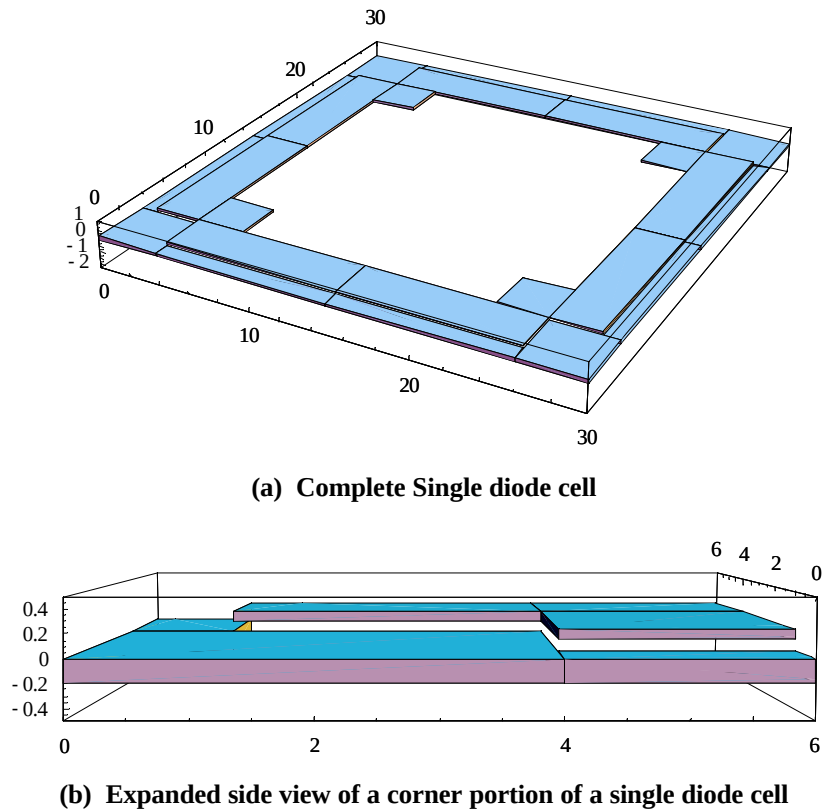


Figure 7.13. Definition of Generation Volume for p^+ doping BNCT simulation. The top inside layer of boron doped material ($0.1 \mu\text{m}$ thick) is within the oxide (due to mask overlap during boron ion implantation) whilst the lower layer ($0.2 \mu\text{m}$ thick) is within the silicon p^+ region.

The mean chord length was calculated for the boron implant BNCT simulation following the same process as for the BNL simulations described in section 7.3.1.5. The chord length distribution is shown in Figure 7.14. The mean chord length $\bar{l}_{Ksi}$ is 2.45 μm , a value higher than for the BNL coating and lid simulations due to the absence of overlayer effects. The correction factor h for obtaining an equivalent dose mean lineal energy to a sphere is 0.96. Therefore, the corrected MCL $\bar{l}_{Keff}(\text{ion implant}) = 4.05 \mu\text{m}$. This MCL will be used in all measurements using the "raw" device as a thermal neutron detector since the boron generated events are of primary interest.

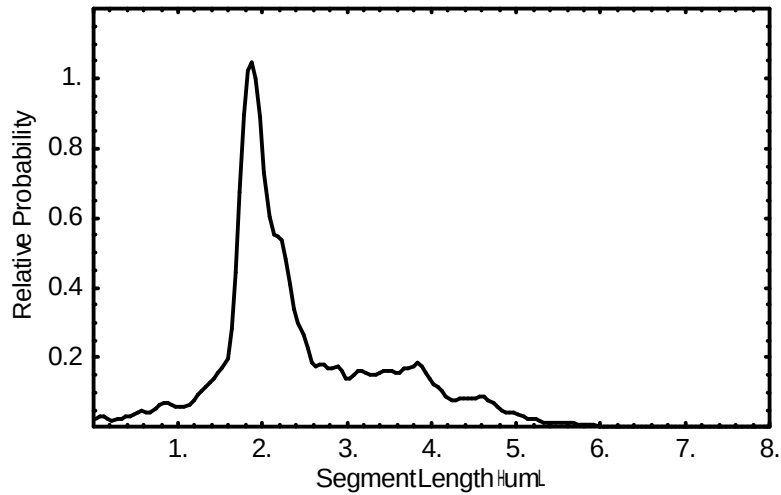


Figure 7.14. Segment length distribution produced by thermal neutron irradiation of the ion implanted region of a $10 \times 10 \mu\text{m}^2$, 2 μm SOI diode array.

The air gap (nitrogen) simulation:

This simulation is very similar to the BNL coating and lid simulations discussed in section 7.3.1.5. The geometry is described in Figure 7.15. The range of a 590 keV proton in air produced by a capture reaction with nitrogen is 10.42 mm. This exceeds the 10mm side length of the package recess housing the microdosimeter wafer as displayed in Figure 7.17. Therefore, the GV dimensions (in μms) were adjusted to model the entire air gap within the package recess as follows:

$$\text{GV} = \{\text{Air, Cuboid}(\{-6000,-2500,1.05\},\{4000,7500,301.05\})\}$$

The SV was defined as the entire 40×120 array of diode cells with the origin at the bottom left corner of the array:

$$\text{SV} = \{\text{Silicon, Cuboid}(\{0,0,-2\},\{1200,3600,-2 + x_d\})\},$$

where the diode sensitive depth x_d is $2\text{ }\mu\text{m}$ in the n^+ , p^+ regions and $1.82\text{ }\mu\text{m}$ elsewhere due to the LOCOS region consuming silicon. The collection efficiency within each diode cell was modeled as given in section 6.2.4.1 and accounted for in the simulation as per equation (7.4). For the simulation, SiO_2 occupies space not defined by the above regions. The simulations will be further discussed in the following results section.

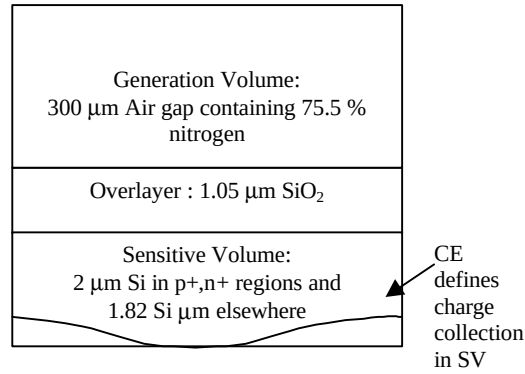


Figure 7.15. Cross-section of nitrogen in air neutron capture simulation on top of $10 \times 10\text{ }\mu\text{m}^2$, $2\text{ }\mu\text{m}$ SOI diode array (40×120 diodes, each cell $30 \times 30\text{ }\mu\text{m}^2$). The GV is ($10000 \times 10000 \times 300\text{ }\mu\text{m}^3$) whilst the SV is ($1200 \times 3600\text{ }\mu\text{m}^2$ with a depth of $2\text{ }\mu\text{m}$ in the n^+ , p^+ regions and $1.82\text{ }\mu\text{m}$ elsewhere). The maximum range of 1010 keV protons in air is 10.42 mm .

7.4.2 Experimental Results and Discussion

7.4.2.1 Comparison BNL and KUR microdosimetric spectrum

A comparison of the energy spectrum obtained at BNL and KUR under similar conditions is shown in Figure 7.16. (BNL: 6.5 cm in Lucite phantom, KUR: 6 cm in water phantom using mixed irradiation mode). The data are normalized by integrating values greater than 450 keV . Above this energy, the spectra are nearly identical. From 80 keV to 450 keV the KUR data exhibits significantly more counts peaking at around 110 keV . This peak is also present in the BNL data although it is much less prominent. Such an energy deposition corresponds to a normally incident 590 keV proton in silicon with an LET of around $60\text{ keV}/\mu\text{m}$. Therefore, the difference in spectra may be due to additional nitrogen present in the KUR experiment. A slightly different lid configuration was used in the two experiments as shown in Figure 7.17. The air-gap above the device was $100\text{ }\mu\text{m}$ at BNL and $300\text{ }\mu\text{m}$ at KUR. The effect of the air-gap was not fully appreciated at the time of the KUR experiments. The following section describes a simulation that confirms the air influence.

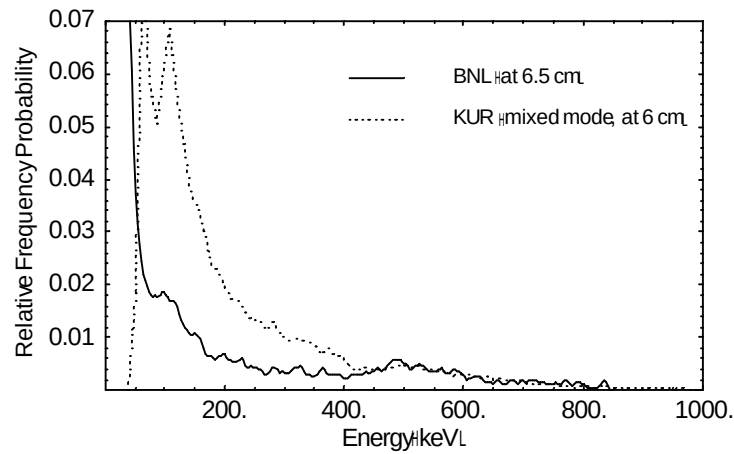


Figure 7.16. Comparison of energy distribution from ion-implanted boron capture reaction at BNL and KUR. An identical microdosimeter was used, $10 \times 10 \mu\text{m}^2$, $2 \mu\text{m}$ SOI diode array. The air gap varied between the two experiments as shown in Figure 7.17. The data is normalized by integrating values $> 450 \text{ keV}$.

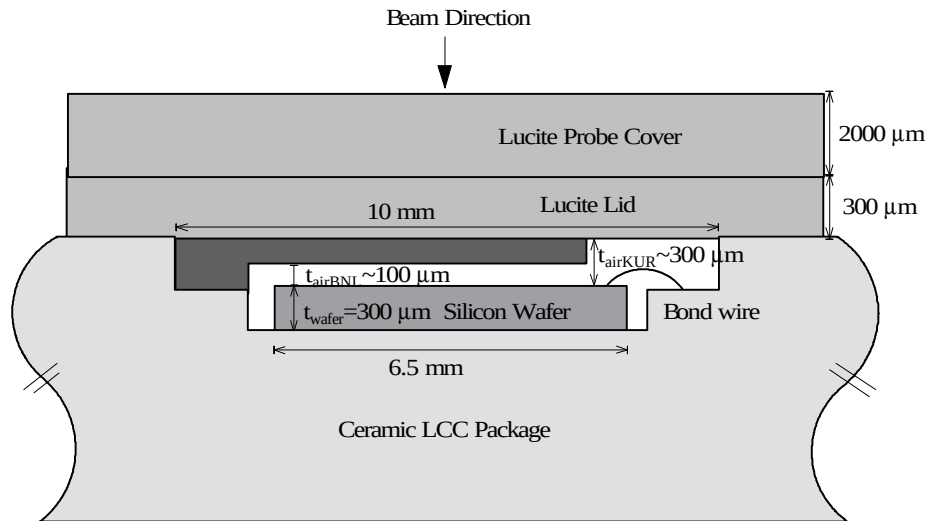


Figure 7.17. Lucite lid configurations for measurements made using the ion implanted boron region of the microdosimeter. The hatched region is a Lucite lid present during the BNL measurements but not present during the KUR measurements. Therefore, $t_{\text{air}} = 100 \mu\text{m}$ BNL and $300 \mu\text{m}$ KUR. The p^+ boron is implanted in the top surface of the silicon wafer ($\sim 0.1\text{-}0.2 \mu\text{m}$ depth). No boron is present in any of the Lucite components in this diagram.

7.4.2.2 Simulation (ion implanted boron and nitrogen in air)

The detector responses to neutron capture reactions with ion implanted boron and nitrogen in the air gap were simulated using the previously described Monte Carlo method.

The p^+ boron doped region simulation:

A comparison of the ion implanted boron simulation with a spectrum from KUR (obtained at 1 cm depth using mixed mode irradiation) is shown in Figure 7.18. The

simulation was normalized to have the same number of counts as the data for energies greater than 450 keV. In this region only counts are expected from the ion implant boron reactions. This spectrum was selected for its high thermal neutron flux and hence excellent acquisition statistics. The simulation correctly predicts the peak at 600 keV but offers a poor match at higher energies. The simulation shows three peaks at 590, 690 and 1120 keV. The lower two peaks are due to lithium ions originating in the silicon p^+ doping for the higher energy (690 keV) and in the silicon dioxide for the lower energy (590 keV). Predominantly (93.7% of the time, equation (7.1)), an 840 keV lithium is generated with a range in silicon of 2.4 μm . Most of the ions originating from the silicon dioxide will intercept the device in the LOCOS region where the thickness is 1.81 μm compared to 2 μm in the p^+ doped region. Furthermore, any additional overlayer reduces the energy deposited since the lithium ion is past the Bragg peak. The two peaks present in the simulation appear as a single peak at 600 keV. The difference may be attributable to the simulation's simplistic modeling including the step approximation to the "birds-beak" region and the uniform distribution of boron.

The higher energy peak of the simulation is due to alpha particles originating from boron within the p^+ region and the silicon dioxide. The alphas have a typical range of 5.1 μm with an initial energy of 1470 keV. The larger range makes the alpha less sensitive to overlayer thickness than the lithium ion. The reason for the discrepancy at high energies, between this simulation peak and experimental results, is not clear. These high energy events (>1000 keV) are due to high angle (60° - 90° , typically 70°) alpha tracks arising from the p^+ silicon substrate region. In heavily doped regions the carrier lifetime is reduced. The collection efficiency function may not correctly model the recombination losses in these regions particularly at high angles. Any electric field present in the substrate due to funneling may possibly increase recombination since drift collection is in a direction which may increase the likelihood of electron-hole pair recombination as shown schematically in Figure 7.19. These effects were not seen in the 2 D simulation presented in section 6.2.2.4. Further 3 D simulations of the 1470 keV alpha at high angles are required. Angled microbeam or broadbeam experiments may also be useful in further characterization of the device collection efficiency.

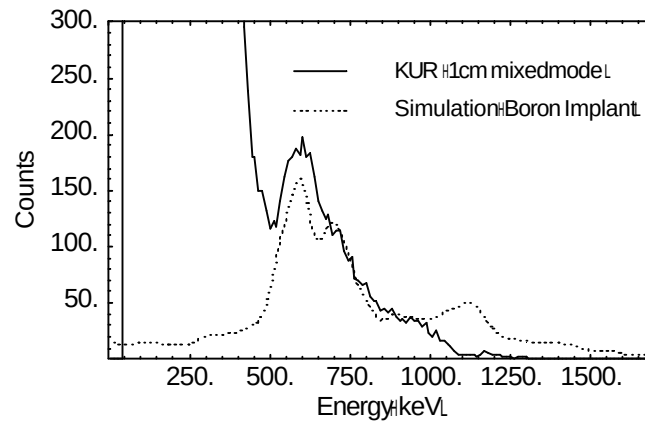


Figure 7.18. Comparison of boron ion implantation simulation with energy spectrum at 1 cm depth, mixed mode irradiation at KUR. The simulation was normalized to provide the same total number of counts greater than 450 keV as the experiment.

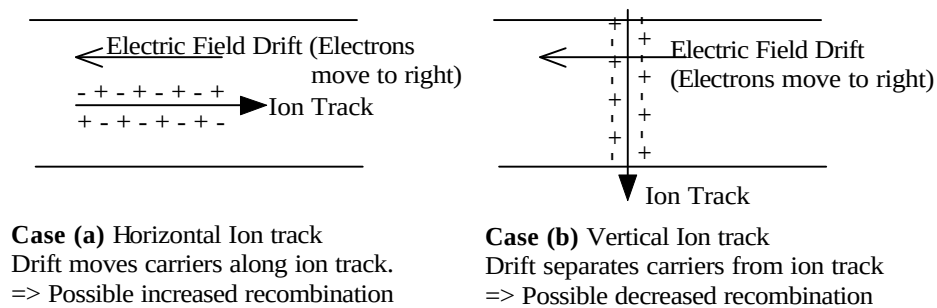


Figure 7.19. Illustration of possible variation in recombination with ion strike direction with respect to electric field.

The air gap (nitrogen) simulation:

The simulations performed in the previous discussion for the boron implanted regions cannot account for the large peak observed at 120 keV in the experimental spectra shown in Figure 7.16. A comparison of the air gap nitrogen simulation with a spectrum from KUR obtained at 1 cm depth using mixed mode irradiation is shown in Figure 7.20. The simulation was normalized to have the same number of counts as the experimental result between 120 and 450 keV. This range was selected due to the small number of counts expected from boron reactions and fast protons. The simulation provides an excellent fit to the observed data for the peak at 120 keV. The fit is not so accurate at higher energies from 300 keV to 450 keV. In this region, events are due to high angle intercepts with chord lengths in the range of 3-4 μm and an average LET of around 100 keV/ μm . The poor fit is most probably due to a combination of two effects: the course modeling of the overlayer as a single thickness oxide layer and, to a lesser extent, the neglect of the TiN layer nitrogen capture reaction. The TiN layer was not simulated since we would expect approximately 7 times fewer counts (see Table 7.4).

Furthermore, the TiN spectrum should be similar to the air gap simulation due to the long range of the protons relative to the device overlayer. Despite some discrepancies, the fit particularly at 120 keV is sufficient to justify the conclusion that the spectral characteristics in the range from 100 to 450 keV are dominated by protons originating from the nitrogen within the air gap and also from the TiN layer.

The rise in counts below 80 keV is due to the contribution of fast proton recoils from neutron interactions. Protons with energies greater than 1 MeV will have an LET less than 50 keV/ μm in silicon. The fast proton energy deposition spectrum displays an exponential shape as higher energy events, requiring high angle events (large chord lengths) and/or high LETs (low energy), are less probable. This spectrum shape will be seen later in fast neutron and fast proton therapy experiments described in chapters 8 and 9. The fast proton content of the microdosimetric spectrum, above the noise level of the detector, may be extracted by subtracting the air-gap simulation from the experimental spectrum. The calculation assumes that the ion-implant boron count rate in this region is negligible which is reasonable given the data displayed in Figure 7.18. The subtraction was performed over the interval from 55 keV to 250 keV with the result shown in Figure 7.20. This demonstrates that the silicon microdosimeter may be used to compare the relative dose contribution of fast protons versus boron neutron capture products since the contributions occur at different parts of the spectra. Minimization of the air gap and TiN thickness would assist in separating the fast proton component of the spectrum.

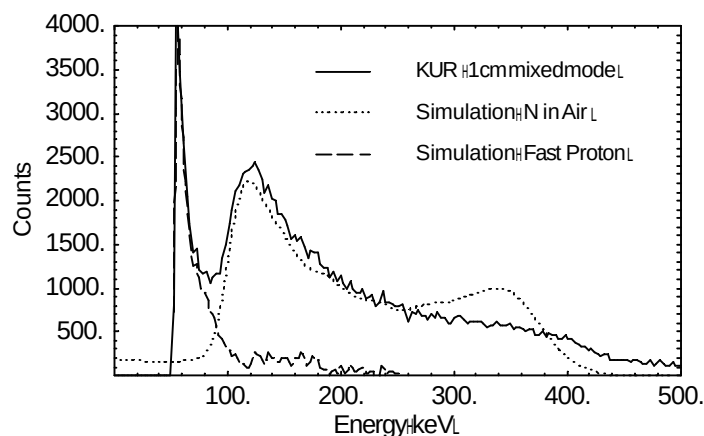


Figure 7.20. Comparison of air gap (nitrogen) simulation with energy spectrum at 1 cm depth, mixed mode irradiation at KUR. The simulation was normalized to provide the same total number of counts within the energy range of 120 to 450 keV as the experiment. The fast proton simulation curve, representing events due to fast neutron generated recoil protons, is calculated by subtracting the air simulation from the experimental data for $E < 250$ keV.

Merged Simulation:

The air gap, ion implant and fast proton components may be added to obtain the spectrum shown in Figure 7.21. Overall, the match between experiment and simulation is reasonable except for the previously noted discrepancies.

The simulation enables calculation of the proportion of generated recoil products that reach the sensitive volume (i.e. k_r in equation (7.3)). Improvements may then be made in estimating the relative probability for thermal neutron detection via the various overlayer and implant elements. Estimates previously provided in Table 7.3 assume a $k_r=1$ whilst Table 7.4 is a revision using values of k_r estimated from simulations. The proportion of nitrogen (mostly from air and TiN) to ion implanted boron counts was expected to be about 0.5. The observed ratio from integration of Figure 7.21 over the appropriate regions was 5.4. This indicates that the amount of boron-10 in the device is lower than expected by a factor of 10.8 or the air gap was considerably larger than expected. The implanted isotopic abundance of boron-10 may not be 19.61% due to beam bending and design features in the ion implantation accelerator. This issue will be further addressed in the following section.

Table 7.4. Relative probability of thermal neutron detection with selected microdosimeter/overlayer elements. This is a revised and improved subset of Table 7.3.

Element/ Component	Number Atoms	Micro X-section ($s \times 10^{-24} \text{ cm}^2$)	Macro X-Section ($S \text{ cm}^2$)	k_r	Relative Prob.	Comments
^{10}B in p^+ region	2.22×10^{13}	3837	8.52×10^{-8}	0.955	1	Area of p^+ region is 0.022 cm^2 and boron ion implant fluence $1.5 \times 10^{15} \text{ atoms/cm}^2$. TiN thickness = $0.1 \mu\text{m}$, area = 0.011 cm^2 , Density TiN = 5.33 gm/cm^3 . [267] Air thickness = $300 \mu\text{m}$, area = $10 \times 10 \text{ mm}$
^{14}N in TiN	5.57×10^{15}	1.83	1.01×10^{-8}	0.5	0.06	
^{14}N in Air	1.15×10^{18}	1.83	2.11×10^{-6}	0.017	0.43	

Note 1: See chapter 4 for a device description and Appendix B for additional layout information.

2: Macro X-Section = Micro X-Section $\times$ Number atoms,

Relative probability = k_r Macro X-Section / (k_r Macro X-Section for ^{10}B in p^+ region)

3: k_r is the proportion of generated recoil products that reach the sensitive volume

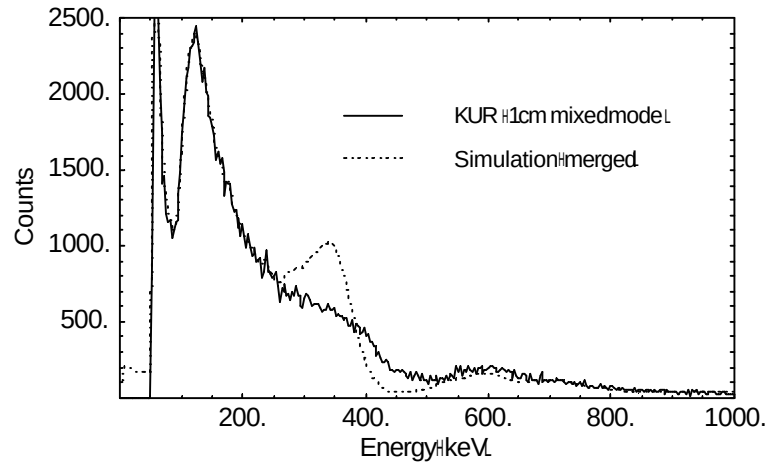


Figure 7.21. Comparison of combined boron ion implantation, nitrogen in air and fast proton simulation data with energy spectrum at 1 cm depth, mixed mode irradiation at KUR. The simulation data from Figure 7.18 and Figure 7.20 has been combined to form this plot.

7.4.2.3 Thermal neutron flux depth profile

The thermal neutron flux variation with depth may be extracted by using the counts generated from the ion-implanted boron-10. In principle, if the exact number of boron-10 atoms is known then the absolute thermal neutron flux may be measured using equation (7.3). However, the implanted isotopic abundance of boron-10 may not be 19.61% due to beam bending and ion selection design features in the ion implantation accelerator. A relative thermal neutron flux profile $F(x)$ was constructed by integrating the energy spectrum $f(E, x)$ at each depth x for E greater than 450 keV and multiplying by a scale factor k . Therefore,

$$\Phi(x) = k \int_{450}^{\infty} f(E, x) dE \quad (7.8)$$

where

$$k = \frac{\Phi(1 \text{ cm})}{\int_{450}^{\infty} f(E, 1 \text{ cm}) dE} \quad (7.9)$$

and $F(1 \text{ cm})$ is the flux calculated by Kobayashi [269] using gold foils (50 μm thick, 3mm diameter) at 1 cm = $3.5 \times 10^9 \text{ n/cm}^2/\text{s}$ (mixed mode) and $4 \times 10^8 \text{ n/cm}^2/\text{s}$ (epithermal mode). The energy spectra were normalized to an acquisition time of 1 second. The calculated value of k was $8.47 \times 10^7 \text{ n/count/cm}^2/\text{s}$. Assuming 19.61% isotropic abundance, we may also estimate the value of k using equation (7.3). That is,

$$k = \frac{m}{k_r \Sigma} \quad (7.10)$$

where m is a factor that accounts for the boron-10 reactions that produce products with an energy deposition less than 450 keV. Both m and k_r may be calculated from the simulation spectrum for the ion implant region $g(E)$ as shown in Figure 7.18. The proportion of capture events that result in an energy deposition k_r is 0.955 and the value of m is given by

$$m = \int_0^\infty g(E) dE / \int_{450}^\infty g(E) dE \quad (7.11)$$

$$= 1.135$$

Using S from Table 7.3, which assumes natural isotopic abundance of boron-10, the value of k was estimated using equation (7.10) as 1.39×10^7 n/count/cm²/s which is about 6 times lower than calculated using equation (7.9). Therefore, the initial assumption of natural isotopic abundance of boron-10 may be incorrect due to the nature of the ion-implantation procedure (magnetic field separation of isotopes). This result is consistent with conclusions derived in the previous section.

Using the k derived from equation (7.9), excellent agreement in the neutron flux profile, between the gold foil measurements by Kobayashi [269] and the microdosimeter, was demonstrated as shown in Figure 7.22. This result demonstrates the feasibility of using the silicon microdosimeter for simultaneous thermal neutron flux measurements and microdosimetry at a high spatial resolution. Note, the deeper penetration of the epithermal beam, although the filtering used in constructing the beam has reduced the thermal neutron flux relative to the thermal beam mode.

The microdosimeter flux measurement error depends on the total counts acquired. The 95% confidence interval on the relative error is approximately given by $3 \sqrt{\text{counts}}/\text{counts}$ (p75 [23]) which leads to a maximum error of 17% at $x = 10$ cm (epithermal mode). In general, the error is within about 10% with improved accuracy simply gained by increasing the acquisition time (currently 5 minutes). The positional accuracy achievable by the probe setup was ± 2 mm limited by bending of the Lucite probes and alignment errors. These errors could readily be improved by redesigning the probe setup since the 3D actuator is capable of sub-millimeter accuracy.

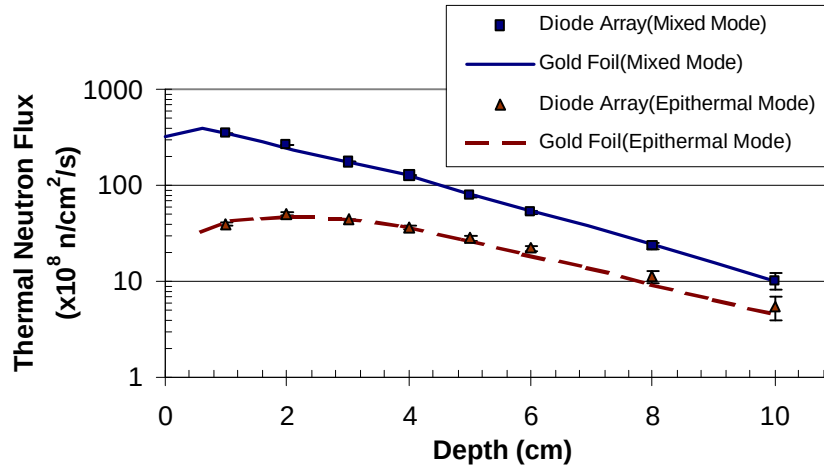


Figure 7.22. Comparison of gold foil and microdosimeter calculated thermal neutron flux profile. The depth profile for the mixed and epithermal irradiation modes are shown.

7.4.2.4 Microdosimetric comparison of irradiation modes

The energy spectrum at various depths in the water phantom is shown in Figure 7.23 for mixed mode irradiation and Figure 7.24 for epithermal mode irradiation. The spectra have been normalized so that the integral counts $> 450 \text{ keV}$ (thermal neutron events) are equal to unity. This presentation highlights differences in the fast proton contribution with energies less than 200 keV . The aim is to demonstrate the utility of the microdosimeter in analyzing the various dose components of the radiation. For the mixed mode irradiation, the proportion of energy deposition events due to fast protons versus thermal neutrons rises with depth. That is, the thermal neutrons reduce with depth at a faster rate than the higher energy neutrons that produce fast recoil protons.

A method of presenting this trend is shown in Figure 7.25. The relative ratio of fast proton events to thermal neutron events at various depths in the water phantom is presented. This was calculated by integrating the counts between 60 and 80 keV and dividing by the integral counts greater than 450 keV . The ratio is normalized to unity at a mixed mode depth $= 1 \text{ cm}$. The features shown in Figure 7.23 and Figure 7.24 are more clearly highlighted. In particular, the epithermal mode shows a higher proportion of fast proton events than the thermal mode; an effect that is expected due to the higher energy of the neutron spectrum. The dip at 2 cm in the epithermal curve is due to the higher thermal neutron flux as shown in Figure 7.22. The relative occurrence of fast proton events at 10 cm is $5\text{-}5.5$ times the occurrence at 1 cm . An improved analysis would consider dose contributions instead of event frequencies using the low noise microdosimeter prototype to obtain as much of the low energy fast proton spectrum as possible.

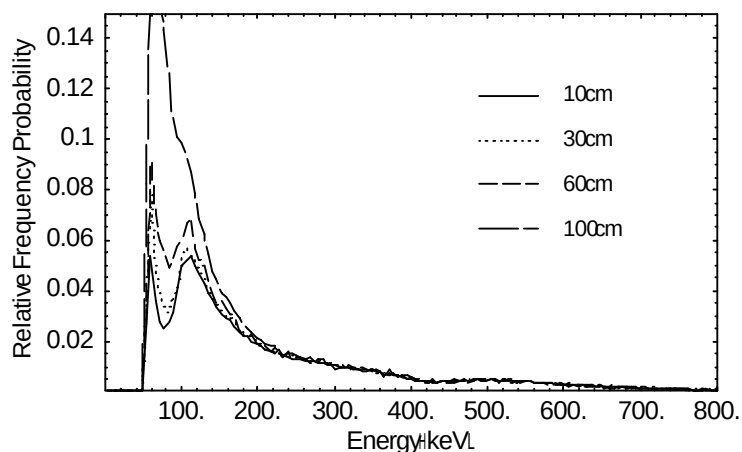


Figure 7.23. Energy spectrum for *mixed mode irradiation* at various depths in the water phantom. Spectra have been normalized so that the integral counts > 450 keV (thermal neutron events) are equal to unity. Differences in the fast proton contribution, $E < 200$ keV, are highlighted.

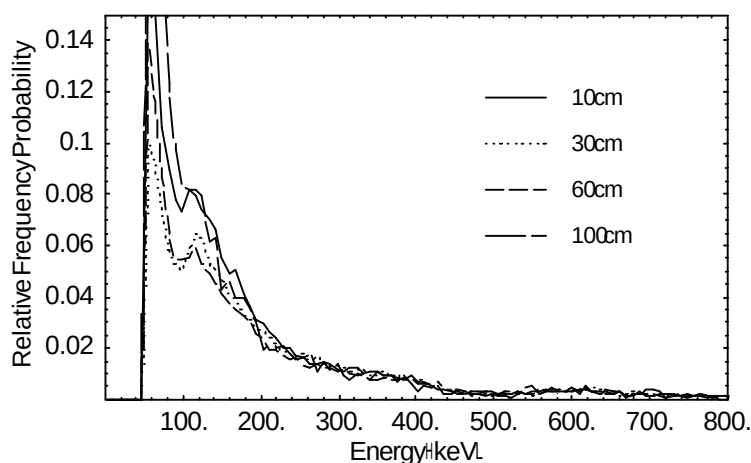


Figure 7.24. Energy spectrum for *epithermal mode irradiation* at various depths in the water phantom. Spectra have been normalized so that the integral counts > 450 keV (thermal neutron events) are equal to unity. Differences in the fast proton contribution, $E < 200$ keV, are highlighted.

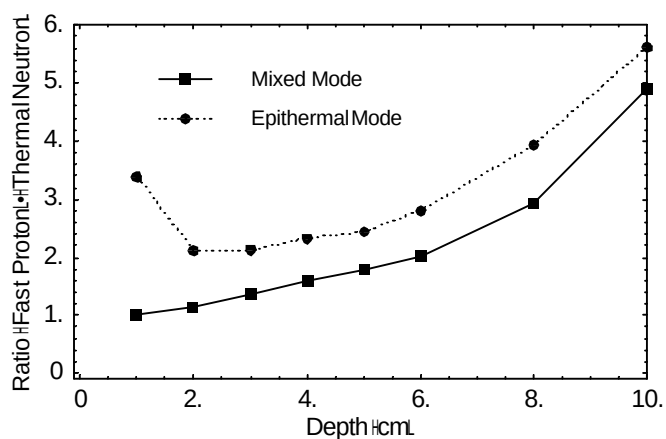


Figure 7.25. Relative ratio of fast proton events to thermal neutron events at various depths in the water phantom. Ratio is normalized to unity at a depth = 1 cm for mixed mode.

7.4.2.5 Comparison sensitive volume depth variation (2 and 5 μm SOI)

A comparison of the lineal energy spectrum for 2 μm SOI and 5 μm SOI devices under mixed mode irradiation at 1 cm depth is shown in Figure 7.26. The mean chord length (MCL) used for the 2 μm SOI device was 4.05 μm as calculated in 7.4.1.4. For the 5 μm SOI device, the MCL was adjusted so that the fast proton edge at 20 $\text{keV}/\mu\text{m}$ matched with the 2 μm SOI lineal energy spectrum. The required MCL was 6.5 μm .

Three main differences are seen in this comparison. Firstly, the 5 μm SOI device is capable of measuring a lower lineal energy due to the larger signal to noise ratio. Secondly, the proton peak, originating from capture reactions with nitrogen, has a higher lineal energy in the 5 μm SOI device. The 590 keV proton with a range in silicon of 7.1 μm is almost always stopped within the 5 μm SOI. Thus, the high LET Bragg peak occurs within the sensitive volume and increases the energy deposition. Lastly, the maximum lineal energy is higher in the 2 μm SOI device. High energy events are due to high angle alpha particles emitted from the ion-implanted boron regions of the device. Thus, the energy deposited by such events will be similar for both devices. However, the lineal energy will be higher for the 2 μm SOI due to its lower MCL.

In summary, the advantage of the 5 μm SOI device is that it has a higher signal to noise ratio. The disadvantage is that it may not discriminate LET as effectively as the smaller SOI device since many particles will be stoppers and not crossers within the sensitive volume. A thin sensitive volume is desirable to maximize the sensitivity to particle LET rather than particle total energy.

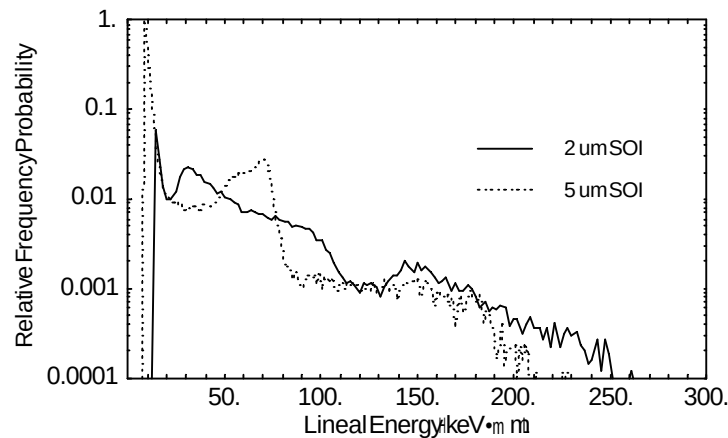


Figure 7.26. Comparison of lineal energy spectrum for 2 μm SOI and 5 μm SOI devices (small diode array $10 \times 10 \mu\text{m}$ junction size) under mixed mode irradiation at 1 cm depth.

7.5 Experiments at Massachusetts Institute of Technology (*Epithermal Neutron Beam Investigation*)

Experiments were carried out at the Massachusetts Institute of Technology (MIT) Laboratory for Accelerator Beam Applications (LABA) to test the performance of the silicon microdosimeter exposed to an accelerator based thermal neutron source. The main aim was to verify the operation of a newly developed low noise silicon microdosimeter (prototype #2 see section 4.4).

7.5.1 Materials and Methods

7.5.1.1 Description of facility

A high current tandem accelerator capable of delivering multi-milliampere proton or deuteron beams at energies up to 4.1 MeV was available at LABA. The beam and target design is orientated towards the development of boron neutron capture synovectomy (BNCS). BNCS is a novel treatment for rheumatoid arthritis which uses the $^{10}\text{B}(\text{n},\alpha)^7\text{Li}$ reaction to ablate the diseased synovial membrane lining the articular joints [271]. The neutron beam requirements differ from BNCT for three main reasons: (i) BNCS has much higher boron-10 concentration levels due to direct administration of boronated compounds into the synovium, (ii) the target synovium tissue is only 1.5-2 cm below the skin and (iii) the joints targeted (knee and fingers) are located far from the body's sensitive organs. The large boron-10 dose per unit incident neutron fluence allows the use of beams with more fast neutron and photon contamination than is acceptable for BNCT, since the beam will be incident on the joint for a much shorter period of time.

Neutrons were generated by bombarding a beryllium target with 1.5 MeV deuterons using the $^9\text{Be}(\text{d},\text{n})^{10}\text{B}$ reaction. The target was located within a 9 cm diameter, 23 cm length, cylindrical D_2O moderator encapsulated in an 18 cm thick graphite reflector. The heavy water reduces the neutron energy, which is initially around 1 MeV, without producing an intense photon flux. The graphite is effective at reflecting neutrons to improve the target dose rate.

7.5.1.2 Microdosimetric setup and measurements

Two microdosimetric probe assemblies were compared in these experiments. The assemblies are designated "Probe Assembly #1" and "Probe Assembly #2" and were both fully described previously in sections 4.3 and 4.4, respectively. The

microdosimeter used was the 2 μm SOI device with the small diode size ($10 \times 10 \mu\text{m}^2$ junction) array selected and configured in its "raw" state without boronated Lucite coatings or lids. This device was selected for comparison with previous measurements and because the sensitive volume was the smallest available and offered the best LET or particle type discrimination capability given the short range of the BNCT ion products. The boron doping in the p^+ region is used as the main thermal neutron detection element. In addition, the probe has a 300 μm air gap above the chip. The charge collection characteristics of the device at the selected reverse bias voltage of 10 V were fully described in section 6.2.4.1.

A water tank with dimensions ($w \times l \times h$) $28.5 \times 28.5 \times 21.5 \text{ cm}^3$ was used as shown in Figure 7.27. For each probe assembly, the detector was placed at a depth of 1.5 cm (from the front face of the phantom) and aligned with the center of the beam axis.

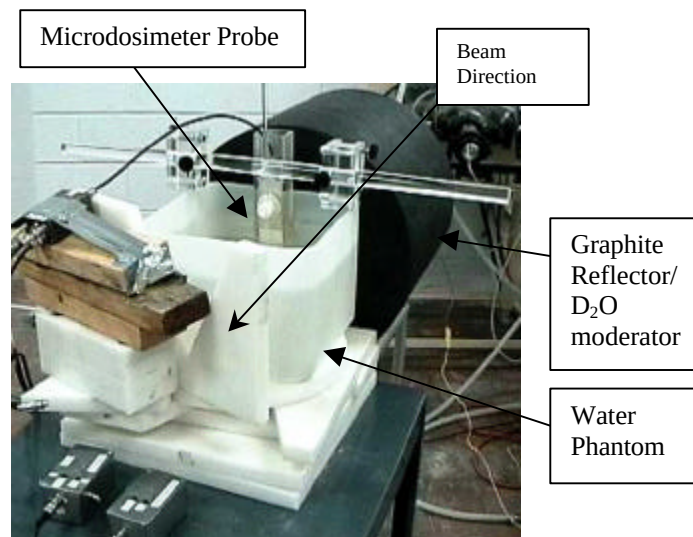


Figure 7.27. Microdosimeter probe and water phantom with the D_2O moderator/graphite reflector at MIT

7.5.2 Experimental Results and Discussion

The lineal energy spectrum in $y-f(y)$ format comparing the performance of Probe Assembly #1 and the improved low noise Probe Assembly #2 is shown in Figure 7.28. The key feature of these spectra is the characteristic exponential distribution below 120 $\text{keV}/\mu\text{m}$ (seen as linear on the linear-log format of Figure 7.28) and attributable to the high fast proton component in the beam. The thermal neutron component ($y > 120 \text{ keV}/\mu\text{m}$) is very small in comparison with the fast proton component in contrast with the BNCT lineal energy spectra shown in Figure 7.26. Longer acquisition times are required to obtain an improved spectra at higher lineal energies. In comparing the

performance of the two probes, the spectra are essentially identical down to a lineal energy of 17 keV/ μm after which the early prototype begins to display increased noise characterized by a departure from the exponential distribution. A similar noise influence occurs for the low noise probe assembly although it occurs at the lower lineal energy of 10 keV/ μm . This improvement in noise performance is consistent with design expectations discussed in section 4.3.

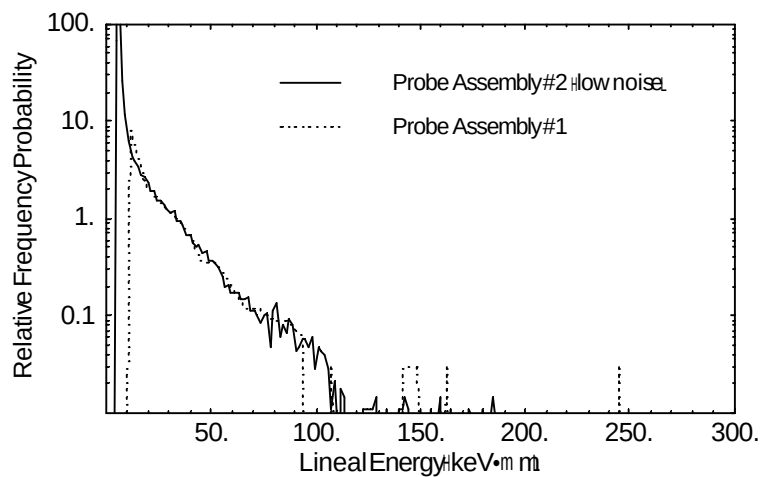


Figure 7.28. Lineal energy spectrum comparing the performance of Probe Assembly #1 and the improved low noise Probe Assembly #2.

7.6 Summary of BNCT Applications

This chapter demonstrates the first application of silicon p-n junction SOI arrays for microdosimetry in radiation oncology and particularly for BNCT. The interaction of thermal neutrons with each of the materials present in the device construction was thoroughly analyzed in section 7.2. The important materials are (in order of thermal neutron sensitivity), B-10 in a 1% Lucite coat or cover (optional, if present), B-10 in the p^+ region, N-14 in air (if present, may not have an air gap above the device), N-14 from the TiN barrier layer.

Experiments at BNL, as presented in section 7.3, were primarily directed at investigating various converter options for the device (Lucite with B-10 and U-235) and for a comparison with a TEPC measurement. Direct coating of the device with 1% B-10 in Lucite did not change electrical characteristics and produced a microdosimetric spectrum similar to the 1% B-10 lid. Discrepancies between these spectra and Monte Carlo simulations were attributable to simplistic overlayer and charge collection modeling. More detailed investigation of charge collection modeling of high LET

particles is encouraged. In addition, preliminary results with the U235 converter suggest that the SOI p-n junction is a promising microdosimeter for heavy ion therapy provided the bias voltage is greater than 5 V to minimize recombination. Measurement of the spectra generated from B-10 deposited within the device p^+ regions demonstrated that typical medical concentrations of B-10 may be introduced in the device design via ion implantation. Such a microdosimeter can be used under full reactor power with any device orientation.

Experiments at KUR, as presented in section 7.4, demonstrated the importance of minimizing the air gap above the device due to the large number of proton events originating from nitrogen thermal neutron reactions. Monte Carlo simulations of this effect were in good agreement with observed experimental spectrum. The ability of the 2 μm SOI microdosimeter to discriminate between fast neutron recoil protons and BNCT products facilitates simultaneous thermal neutron flux measurements and microdosimetry at a high spatial resolution. Excellent agreement in the neutron flux profile, between the gold foil measurements by Kobayashi [269] and the microdosimeter, was demonstrated as shown in Figure 7.22. The number of ion-implanted B-10 atoms within the p^+ region used for these measurements was a factor of 6 lower than expected based on isotope natural abundance suggesting that the ion-implantation process may alter the relative isotope concentrations. If the ion-implanted B-10 proportion is known, accurate absolute thermal neutron flux may be estimated without any need for normalization to a known flux value.

The MCL was calculated using Monte-Carlo methods with values of 2.32 μm (B-10 coat) 2.26 μm (B-10 lid) and 4.05 μm (p^+ ion implant) obtained for the various configurations. The relatively large sensitive volume compared to the range of boron capture products, and its elongated shape along with a sensitivity to the local distribution of boron are responsible for this large variation in MCL. A comparison of the 2 μm and 5 μm SOI devices further highlighted the importance of a small sensitive volume. The advantage of the 5 μm SOI device is that it has a higher signal to noise ratio. The disadvantage is that it may not discriminate LET as effectively as the smaller SOI device since many particles will be stoppers and not crossers within the sensitive volume. A thin sensitive volume is desirable to maximize the sensitivity to particle LET rather than particle total energy.

In response to the failure of traditional microdosimetry to adequately represent realistic tissue architecture and boron distribution, Solares and Zamenhof [81] have developed high-resolution quantitative autoradiography. This technique is difficult and time consuming, although it is currently the most realistic microdosimetric technique available. However, the improvements in traditional microdosimetry possible using silicon diode arrays may help to bridge the gap between proportional counter microdosimetry and the more realistic autoradiography method.