PHOTONUCLEAR AND RADIATION EFFECTS TESTING WITH A REFURBISHED 20 MEV MEDICAL ELECTRON LINAC*

T. Webb, W. Beezhold, L. DeVeaux, F. Harmon, J. Petrisko, R. Spaulding, Idaho Accelerator Center, Idaho State University, 1500 Alvin Ricken Dr., Pocatello, ID 83201

R. Assink, Sandia National Laboratories, Dept. 1811 P.O. Box 8500, Albuquerque, NM 87185

Abstract

An S-band 20 MeV electron linear accelerator formerly used for medical applications has been recommissioned to provide a wide range of photonuclear activation studies as well as various radiation effects on biological and microelectronic systems. Four radiation effect applications involving the electron/photon beams are described. Photonuclear activation of a stable isotope of oxygen provides an active means of characterizing polymer degradation. Biological irradiations of microorganisms including bacteria were used to study total dose and dose-rate effects on survivability and the adaptation of these organisms to repeated exposures. Microelectronic devices including bipolar junction transistors (BJTs) and diodes were irradiated to study photocurrent from these devices as a function of peak dose rate with comparisons to computer modeling results. In addition, the 20 MeV linac may easily be converted to a medium energy neutron source which has been used to study neutron damage effects on transistors.

INTRODUCTION

Beginning in summer 2000 the Idaho Accelerator Center (IAC) in Idaho State University based in Pocatello, Idaho began to recommission a CLINAC 20 MeV electron linear accelerator (linac) based on a Varian S-band waveguide. The IAC accelerator was intended for use as a versatile radiation source for a variety of applied physics research and even for limited industrial use [1]. Several proven applications will be described in detail including radiation effects in biological systems and also microelectronic devices using the electron beam directly. The linac is also easily modified to produce high intensity bremsstrahlung photons for photoactivation applications exemplified here with the quantitative detection of trace amounts of a trace isotope of oxygen. In a similar manner the accelerator can act as a neutron generator through the (γ, n) reaction off a high-Z target which has been used to study displacement damage in bipolar junction transistors. In order to support the work in all of these experiments and many more, sample handling, dosimetry, and beam diagnostics are available and well proven.

* The polymer aging, photocurrent, and neutron damage studies were supported by Sandia National Laboratories. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL8500. The radiation biology work was supported by DoD contract DAAD13-03-C-0054.

LINAC FACILITIES

The basic operating characteristics of the linac are described in Table 1. The final electron beam output of the accelerating cavities has an energy spectrum approximately constant from 18-20 MeV with small components both high and lower in energy as seen in Figure 2. The ability to select a particular electron energy is made through either of two bending magnets. Quadrupole focusing magnets may be used to produce a desired beam profile and size through one of the bent 45º (energy analyzed) ports or through the main 0º port (all electron energies). One concern of similarly designed accelerators is assurance of consistent beam parameters (current, pulse shape, beam profile, etc.)

Table 1: IAC 20 MeV linac operating parameters.

Max. Pulse Width:	2 μsec
Repetition Rate:	Single pulse to 60 Hz
Peak Beam Current:	80 mA
Electron Energies:	16 to 22 MeV
Maximum Dose Rate:	~5x10^{10} rad/s
Average Biological Dose Rate on Target	~30 Gy/s

The linac would be useless without the support equipment to provide sample control and irradiation analysis. These systems include among others:

- Gamma ray spectroscopy including HPGe, SiLi solid state detectors as well as NiI scintillators
- ^{3}He and BF_3 proportional counter neutron detectors
- Three dimensional computer-controlled sample transport and translation system
- Tissue equivalent radiochromic dosimeters and calorimeters
- Silicon diode dosimeters for temporal and spatial beam analysis and dosimetry for electronic devices.

Four experiments will be described below exemplifying the capabilities of the 20 MeV linac. It is worth noting that all experiments may be easily performed in a single day owing to the versatility of the accelerator and the associated support equipment and staff.

Photoactivation of ^{18}O

Recent studies of the thermo-oxidative aging of various kind of polymers suggests that the amount of oxygen consumed by the polymer correlates with the mechanical

 0-7803-8859-3/05/$20.00 ©2005 IEEE

properties of the polymer [2]. The rate of oxygen consumption is a useful measure of the aging process. Therefore it is desirable to quantitatively measure the concentration of oxygen in a study of polymer degradation. A particular isotope of oxygen, ^{18}O (stable but only 0.2% of ordinary oxygen), is useful for this study through the reaction ^{18}O (γ,p) ^{17}N with has a reaction threshold of about 16 MeV [3]. The product nucleus is unusual among low-Z nuclei in that it is unstable to neutron emission with a 4.17 second half-life. In fact given a constant photon source, the number of resulting neutrons produced and detected per unit mass is proportional to the original concentration of ^{18}O as can be easily seen from the following equation for the saturation activity A_0 [4]

$$A_0 = N\int \sigma(E)\Phi(E)dE \qquad (1)$$

where *σ(E)* is the (γ,p) cross section, *Φ(E)* is the photon energy spectrum averaged over the irradiated volume, and *N* is the total number of ^{18}O atoms present which is clearly proportional to the concentration times the mass. The bremsstrahlung photons from the linac have been used to irradiate polymer; some representative results are shown in Figure 1.

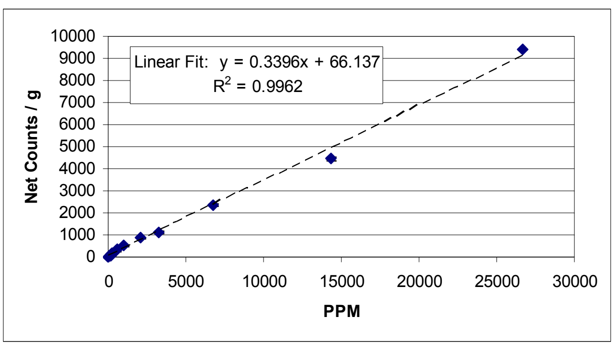

Figure 1: Neutron counts as a function of ^{18}O concentration.

Radiation Biology

Most studies of the effects of radiation on living cells are done using radioactive sources (e.g. Co-60 gamma irradiators). Similar studies may be performed using the 18-20 MeV electron energies at a generally much higher dose rate. The goal was to see what effect dose rate and total dose has on certain single-celled biological entities. One of the frequently tested organisms was *Deinococcus radiodurans* which has been shown to show remarkable radiation-resistance [5]. Figure 2 shows the cell survival fraction for *D. radiodurans* in two different phases of culture growth.

Photocurrent on P-N Junctions

Of particular importance to the hardness and response of electronic circuits in high radiation fields is the dose-rate dependence of the photocurrent of transistors and diodes. Computer modeling codes are available as well as simplified analytic equations to predict these currents in both steady-state and pulsed-radiation environments.

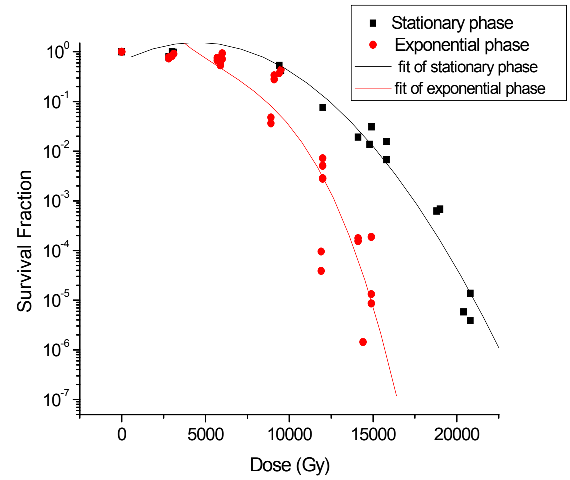

Figure 2: Cell survival as a function of absorbed dose for *D. radiodurans* in two different phases of growth.

The linac is capable of generating instantaneous dose rates of over 1x1010 rad (Si)/s. Figure 3 shows the dose rate dependence of a particular transistor to the electron beam over a wide dose-rate range. The peak voltage (or current) is proportional to the dose rate over a certain range of dose rates. However non-linear behavior is evident in Figure 3 due to a number of possible interesting mechanisms [6]. Also shown are the results of a computer code used to predict the photocurrents. Silicon diodes, especially PIN diodes, may be effective calibrated dosimeters with photocurrent proportional to the dose rate and the total charge collected proportional to the total dose. PIN diodes are regularly used with the 20 MeV linac as beam monitors and dosimeters.

Neutron Irradiation of Transistors

Instead of transient currents from pulsed radiation beams, bipolar junction transistors (BJTs) have been shown to have significant degradation due to sustained neutron fluence [6]. These effects must be well understood in order to predict the response of critical components of electronic circuits in space and around nuclear reactors. The degradation in the common-emitter gain β is quantified by

$$\Delta(\frac{1}{\beta}) = K \bullet \Phi \qquad (2)$$

where *Φ* is the neutron fluence and *K* is the damage constant. The linac was used to study the change in recip-

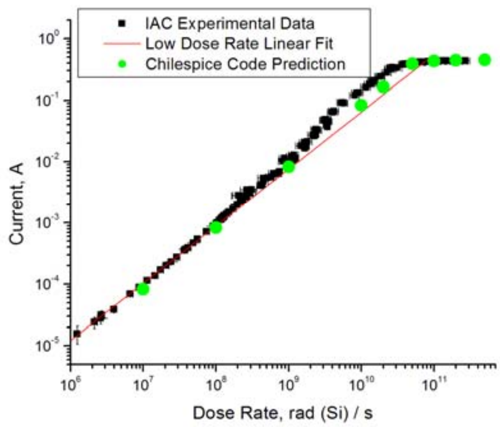

Figure 3: 2N2907 photocurrent versus dose rate with simulated results [7].

rocal gain, Δ(1/β), by hitting the electron beam on a thick tungsten brick generating photoneutrons. The results of the irradiations of a representative BJT is shown in Figure 4. Proper measurement of the damage constant, *K*, requires an annealing procedure to eliminate short-term gain degradation fluctuations. In order to predict the number and energy of neutrons hitting the device, radiation transport code MCNPX was used. The predicted neutron energy spectra is shown in Figure 5. It is standard in radiation effects testing in this kind of experiment to quote an effective neutron fluence to a reference energy (usually 1 MeV) [8].

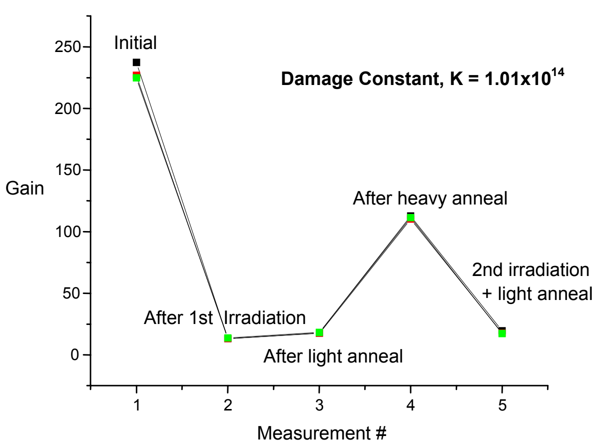

Figure 4: Results of 2N2222 neutron irradiation experiments.

CONCLUSION

We have demonstrated that even a comparatively old and obsolete electron linac originally designed for cancer treatment and similar medical applications still has up-to-date capability for low energy applied physics research. The 20 MeV S-band linac at the Idaho Accelerator Center continues similar studies of the type described above at the present time. The strength of the current system is the versatility in the types of beams, energies, and dose rates available from a single machine.

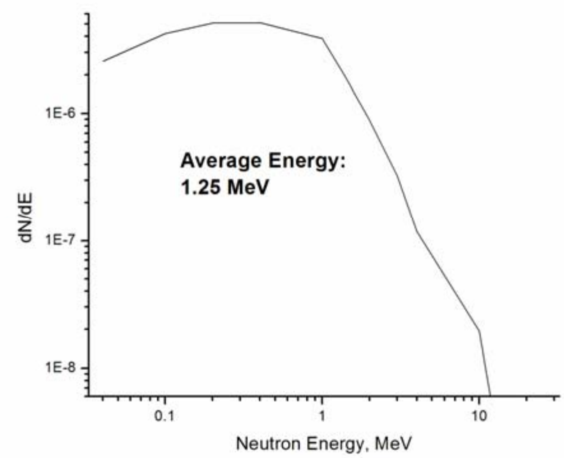

Figure 5: (γ, n) neutron spectrum from tungsten target as calculated with MCNPX.

REFERENCES

[1] For summary of IAC facilities and contact information see http://www.iac.isu.edu/.

[2] J. Wise, K.T. Gillen, and R.L. Clough. Polymer Degradation and Stability 49, 403-418 (1995).

[3] R.B. Firestone, Table of Isotopes, Vol 1, 8th ed. New York: John Wiley & Sons, Inc, 1996.

[4] C. Segabade, H. Weise, and G.J. Lutz. Photon Activation Analysis. New York: Walter de Gruyter, 1988.

[5] J.R. Battista, J. R. AGAINST ALL ODDS: The Survival Strategies of Deinococcus radiodurans. Annual Review of Microbiology 51:203-224 (1997).

[6] G.C. Messenger and M.S. Ash. The Effects of Radiation on Electronic Systems. New York: Van Norstrand Reinhold Company (1986).

[7] D. Dodd et al. Radiation-Induced Prompt Photocurrents in Microelectronics: Physics. Sandia Report, SAND2003-0094, January, 2003.

[8] E722: Standard Practice for Characterizing Neutron Energy Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics. ASTM International (2002).

0-7803-8859-3/05/$20.00 ©2005 IEEE