The Neutron Radiation Effects Program (NREP) at Indiana University Cyclotron Facility

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***Abstract*— An accelerator-based facility for simulation of neutron-induced single event effects in electronics is under development at Indiana University Cyclotron Facility. The neutron spectrum has been characterized using foil activation techniques and calibrated transistors.**

***Index Terms*—Neutrons, neutron beams, radiation effects**

I. Introduction

An accelerator based neutron source is being developed at Indiana University Cyclotron Facility to facilitate the exploration of neutron induced single event effects (NSEE) in advanced microcircuit technologies. Commercial Off-The-Shelf (COTS) Integrated Circuits (ICs), such as Application-Specific Integrated Circuits (ASICs), Field Programmable Gate-Arrays (FPGAs), and System on a Chip (SoCs) have demonstrated susceptibility to NSEE [1-3].

NSEE effects are a concern for avionics and military applications of electronic devices. Neutrons produced in cosmic ray showers in the atmosphere affect onboard electronics of aircraft while electronic devices for military applications need to be designed to survive the radiation environment generated by nuclear explosions.

The objective of the effort at Indiana University is to develop enabling technologies to produce tailored neutron flux spectra, first free-standing, and finally in conjunction with an ionizing dose rate radiation source. Testing performed to date for NSEE susceptibility has been conducted primarily at reactor based facilities. However, the cost has been quite high due to limited throughput and increased security costs. Security costs are expected to increase in the future. On the other hand, generation of the required neutron environment using an accelerator-based facility has the potential to increase throughput due to rapid cycle rate, and should not have the special security concerns of nuclear reactors. NSEE testing will require control over the peak flux and fluence, as well as the ability to tailor the spectrum [4]. Both atmospheric neutron spectra, as well as enhanced neutron spectra are of interest as a simulator of endo- and exoatmospheric environments.

II. The neutron target

The neutron radiation effects program (NREP) at Indiana University Cyclotron Facility has begun to deliver first neutron beams to users in 2005. Protons are accelerated to 7 MeV by a radio frequency quadrupole (RFQ) followed by a drift tube linac (DTL). The linac runs at a peak beam current of up to ~8 mA, a pulse width of 150 µs, and a repetition rate of 4-30 Hz. Neutrons are produced via Be(p,nx) reactions up to an energy of ~5MeV. At present, NREP uses an existing target/moderator/reflector (TMR) configuration that will eventually be replaced by a TMR configuration optimized for NSEE testing.

The layout of the beamline and target is shown schematically in Fig. 1. The present target is surrounded by a light water reflector that is 50 cm in diameter and 50 cm tall. This reflector is in turn surrounded by a 15cm thick high-

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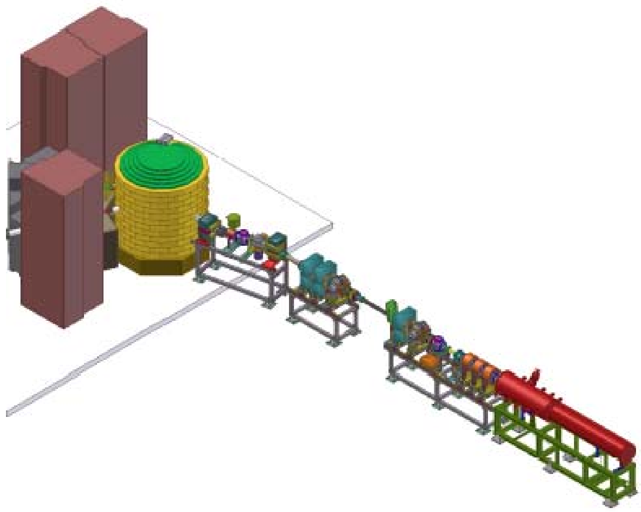

Fig. 1. Overall schematic layout. Shown are the accelerator (right-hand of the picture), the beamline and the TMR (vertical cylinder).

purity lead gamma shield from which it is isolated by a flexible borated material (Thermo 227A) to reduce activation within the lead. The lead layer itself is surrounded by two additional layers of caramel corn bricks (polyethylene beads mixed with borax and epoxy [LWTS]). In our case, the boundary between the two brick layers contains an additional layer of lead to further reduce the gamma field outside the TMR. This lead layer is formed by casting a lead and epoxy combination in the bottom of the molds when forming each of the caramel corn blocks.

Measurements reported in this paper have used the existing TMR to obtain experimental data as input to the design of the dedicated NREP TMR.

III. Neutron Flux Measuements

The neutron spectrum inside the moderator cavity has been characterized using foil activation techniques. Measured neutron intensities are compared to MCNPX calculations.

Gold foils and cadmium covered gold foils were used to measure the thermal flux, i.e. neutrons with energies up to 0.550 eV. Nickel foils and sulfur pellets were used to measure the fast neutron flux with energies above 3 MeV. The 2N2222A transistors were used to measure the 1MeV equivalent flux directly according to ASTM-722[5] and ASTM-1855[6]. The gamma dose was measured using thermo luminescent devices (TLDs) and found to be negligible.

The foils and transistors were inserted 100cm deep into the moderator cavity, thus positioning them at a distance of about 8cm from the target. To aid placement of the foils and transistors a 1:1 printout of a position dependent MCNPX calculation was glued to the piece of 10x10 cm^2 piece of cardboard used to hold the items in the neutron beam [Fig.2]. The position dependent MCNPX calculation used to position the foils is folded with the ^{58}Ni(n,p)^{58}Co cross section and thus

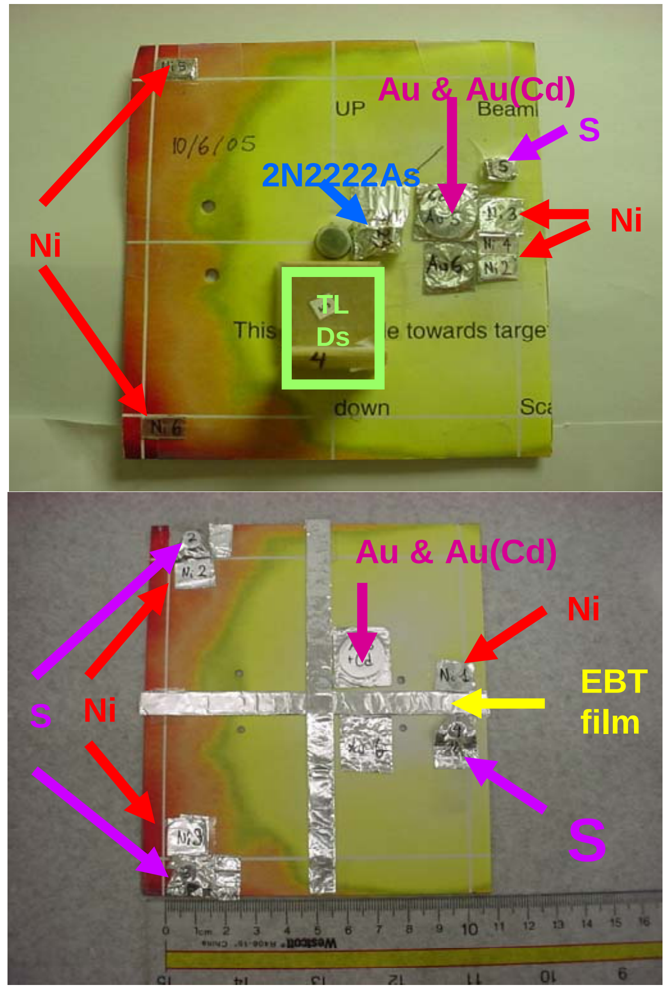

Fig. 2. Location of foils for two irradiations. The colored background is a position dependent MCNPX calculation folded with the ^{58}Ni(n,p)^{58}Co cross section. For details see text.

includes only neutrons with energies above 3 MeV. The left/right asymmetry of the calculated flux is due to the proton beam impinging on the target at a 45^{o} angle. Measurements with both nickel foils and sulfur pellets agree with the calculated position dependence of the fast flux. Sulfur pellets were evaluated both at Sandia laboratory[7] and at IUCF with consistent results.

Neutrons with lower energies are reflected in the moderator and do not exhibit the same position dependence as the fast neutrons. If the silicon damage function from Ref. [5] is folded into the MCNPX calculation, the resulting intensity distribution is flat within ± 7.5cm in x and ± 10 cm in y.

During irradiations, the relative neutron flux was monitored using a low efficiency (nominally η=.001) ^{3}He transmission detector. The ^{3}He detector was mounted in the collimated neutron beam ~130 cm from the target. Also monitored were the gamma and neutron background in the room. Fig. 3 shows the monitor detector counts as a function of time for a 24h long run. The occasional dips in flux are due to trips of either the RFQ or DTL.

In a separate measurement the thermal spectrum was measured using time-of-flight (TOF) techniques. Fig. 4 shows the calculated spectrum together with the TOF measurement.

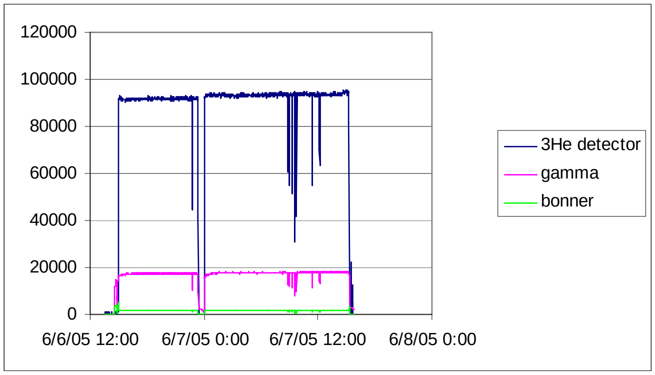

Fig. 3. Monitor detector rates during a 24h irradiation. The gamma detector and the bonner sphere monitor the room background, while the ^{3}He detector monitors the thermal flux from the target.

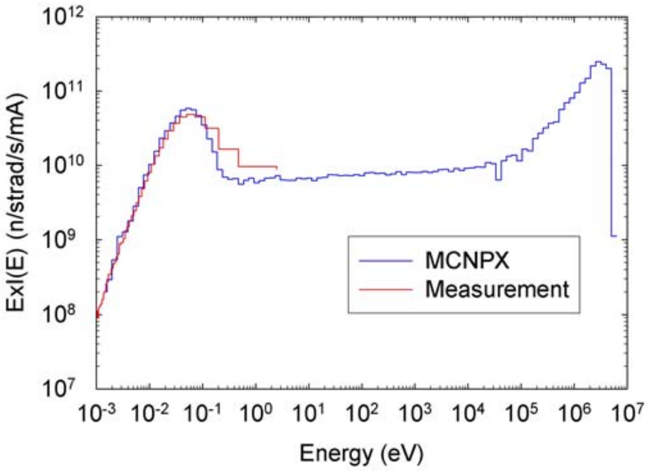

Fig. 4. Comparison of the thermal neutron spectrum with that predicted from an MCNPX calculation. The m measurement was made with a ^{3}He detector positioned 5.7m from the target and normalized to an activation foil measurement

The TOF spectrum was normalized to a Au/Au(Cd) activation.

Overall, the measured flux is 25-45% lower than the calculated flux. Table 1 shows a summary of the measurements made to determine the neutron flux.

TABLE I
MEASURED NEUTRON FLUX

Method	Measured 10^7 n/s/cm^2	MCNP 10^7 n/s/cm^2
Thermal, < 0.55 eV, Au, In, ^{3}He	8.13+/-0.17	11.0
Fast, > ~3 MeV, Ni, S	3.29+/-0.21	5.9
1 MeV equiv., 2N2222A	10.50+/-0.45	18.1

The values are for 7.3 mA peak current, 150 µs pulse width and 30 Hz rep rate.

IV. CONCLUSION

The construction of a dedicated neutron irradiation facility at Indiana University is well under way. The neutron flux of the present production target has been characterized. Beam has been delivered to users.

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