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Nuclear reactor pulse calibration using a CdZnTe electro-optic radiation detector

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ABSTRACT

A CdZnTe electro-optic radiation detector was used to calibrate nuclear reactor pulses. The standard configuration of the Pockels cell has collimated light passing through an optically transparent CdZnTe crystal located between crossed polarizers. The transmitted light was focused onto an IR sensitive photodiode. Calibrations of reactor pulses were performed using the CdZnTe Pockels cell by measuring the change in the photodiode current, repeated 10 times for each set of reactor pulses, set between 1.00 and 2.50 dollars in 0.50 increments of reactivity.

1. Introduction

The electro-optic (EO) radiation detector utilizes the Pockels effect, which involves collimating light through a transparent EO crystal located between crossed polarizers, and subsequently focusing the light onto an IR sensitive photodiode. Applying a voltage bias to the crystal changes the polarization of the light propagating through the Pockels crystal and through the second polarizer (or analyzer), and onto the photodiode. Radiation events occurring in the crystal will generate free charge carriers, which act to perturb the electric field of the crystal, thereby, causing a change in the state of polarization. The effect works to change the amount of light transmitted through the analyzer and consequently the output current of the photodiode. CdZnTe has been shown to be a viable EO detector (Nelson et al., 2010), mainly because of its relatively long electron charge carrier lifetime (as compared to other EO materials) and its large thermal neutron absorption cross section from the isotope ^{113}Cd (Tuli, 1983).

The Kansas State University Triga Mark II nuclear reactor can be used to perform reactor pulsing experiments by withdrawing the three standard control rods to achieve criticality at 10 W, and subsequently ejecting the remaining transient control rod. By ejecting the transient control rod, a rapid upward spike in reactor power is observed peaking at 800 MW of thermal power with a full width half maximum (FWHM) of approximately 20 ms.

The current method for measuring the peak power during a pulse involves calibrating a ^{10}B-lined tube, operated in current mode, at lower steady-state powers and assuming a linear response to predict the maximum power during a pulse. The detector can become saturated at the higher reactivity insertions, and consequently the peak pulse power measurement becomes difficult. One advantage of the EO detector is that the device does not become saturated at high fluxes, as does the ^{10}B-lined tube. Therefore, using data logging equipment, 10 reactor pulses were recorded in real time for each of 7 reactivity insertion settings. The observed changes in photodiode current from the pulses for each reactivity insertion setting were averaged and a variance was calculated. A trend line, or line of best fit, was created to fit the data and an unknown pulse was executed. The trend line was used to predict the reactivity insertion of the unknown pulse.

2. Theoretical considerations

A detailed explanation of the functions and operation of the Pockels cell are found elsewhere (Hossain et al., 2002; Nelson et al., 2010, in review). Because CdZnTe has been previously shown to operate as an EO radiation detector with the standard Pockels cell assembly, (Nelson et al., 2010), the same crystal and setup were used here again. Also previously shown (Nelson et al., in review) is the ability of the CdZnTe EO radiation detector to trace reactor pulses in real time.

The polarization of light changes with electric field and can be controlled by the amount of bias voltage applied to the crystal. A maximum light transmission is reached when the light is rotated

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90°. Applying more bias past the maximum only causes a decrease in intensity at the photodiode. After the bias is increased such that the output intensity returns to the original 0 V setting, the complete characteristic Pockels curve is obtained. The reaction products, when absorbed in the Pockels cell, create ionization charge clouds. At sufficiently high enough interaction rates to cause a measurable change in output intensity, or photodiode current, the ionization rate increases the steady state free carrier concentration to high levels. The application of a bias voltage across the Pockels cell can cause these free charges to drift to their respective electrodes, and by doing so create a smaller internal electric field opposing the externally applied electric field. This perturbation of the electric field will alter the polarization of light passing through the cell. Consequently, the amount of light incident on the photodiode will also change as a result of the perturbation of the electric field. The largest changes in photodiode current occur at the 1/4 and 3/4 wave positions of the Pockels characteristic curve and dictate the optimal operational settings.

The TRIGA Mark II nuclear reactor has the ability to perform reactor power excursion experiments, i.e., reactor pulsing. In other words, the reactor has the ability to release a large amount of fission neutrons and energy over a short period of time. TRIGA reactor pulse experiments and empirical calculations have been performed extensively and reported in the literature (Stone et al., 1959). A typical pulse lasts 20 ms at FWHM. Since the fuel matrix is comprised primarily of ZrH, a prompt negative temperature feedback effect on reactivity occurs due to the oscillations of the hydrogen atoms. The oscillations cause up-scattering of neutrons to occur and therefore lower the probability of neutron absorption, causing a decrease in core reactivity. The ejection of the transient rod causes the reactor to become prompt supercritical until the negative temperature feedback effect on reactivity causes the reactor to become subcritical. The reactivity insertion must be greater than one dollar in order to follow the Fuchs-Nordheim model, as this reactivity corresponds to the threshold of the prompt supercritical state, in which the effect of delayed neutrons on the time response of the reactor becomes negligible (Stone et al., 1959; Simnad, 1980).

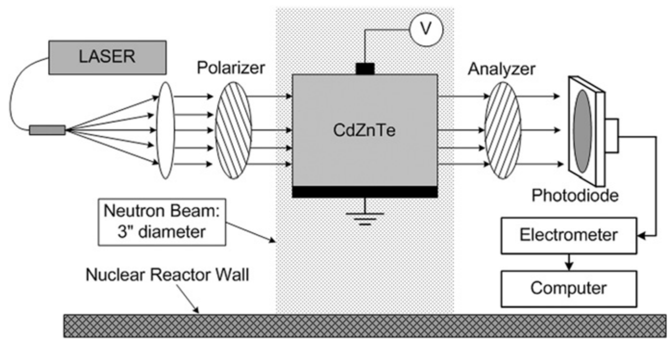

Fig. 1. Conceptual arrangement of a standard Pockels cell setup with a 'dot' contact crystal.

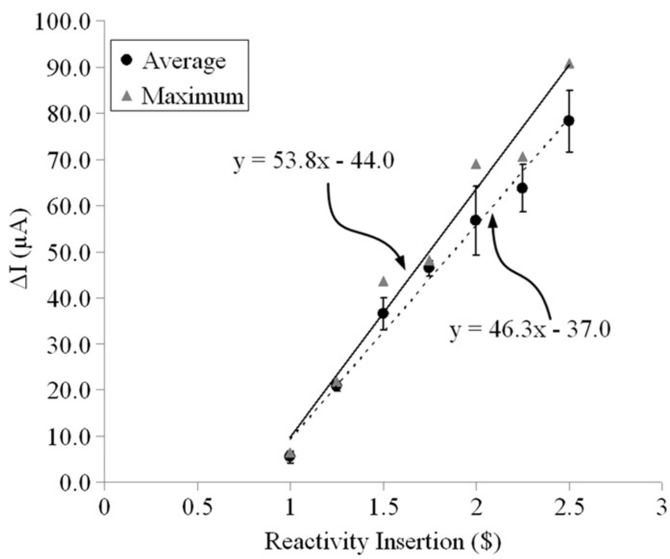

Fig. 2. Plot of the average and maximum changes in photodiode current for seven different reactivity insertion settings.

3. Experimental procedure

A polished $2 \times 10 \times 10$ mm CdZnTe crystal with a 1.5 mm diameter Au anode centered on one of the 10×10 mm faces and a 10×10 mm Au cathode on the opposing face was used as the Pockels cell crystal. The CdZnTe cell was mounted such that the 10×10 mm Au-coated cathode was perpendicular to a 3 in. diameter neutron beam emanating from a radial port at the Kansas State University (KSU) TRIGA Mark II nuclear reactor. Nelson et al. (2010, in review) have recently shown greater detail of the experimental setup, but the conceptual arrangement is shown in Fig. 1. The current at the photodiode was measured using a Keithley 6485 picoameter interfaced with a LabView data recording system sampling one measurement approximately every 10 ms.

The ^{10}B-lined neutron detector was calibrated by plotting the current from the electrometer for 100 kW and 500 kW of the reactor power. A linear fit was made and the data extrapolated to estimate the reactor power during a pulse. For large reactivity insertions the pulse was clipped and the peak power was not measured.

A Pockels cell characteristic curve was obtained by recording the current on the electrometer in 50 V increments, ranging from 0 to 1600 V. This measurement generated the characteristic Pockels curve and assisted in determining the 1/4 wave bias, which was set to 750 V. The new characteristic curve is similar to that previously obtained by Nelson et al. (2010, in review). However, there was some slight drifting in the electronics and the voltage was adjusted slightly to allow 750 μA to be read out on the electrometer prior to each pulse. The KSU TRIGA Mark II nuclear reactor was pulsed 10 times each at reactivity insertions of 1.00, 1.25, 1.50, 1.75, 2.00, 2.25, and 2.50 dollars. In order to insert a specific reactivity with the transient control rod, rod worth curves previously obtained where used to find the ejection position set points. The magnitude of the change in photodiode current from each reactivity insertion setting was averaged and the variance calculated. The data was plotted against the reactivity insertion. Additionally, a single pulse of unknown reactivity was measured with the EO device and the reactivity insertion was estimated from the linear trend lines created by the data sets.

4. Experimental results

The plot of the change in photodiode current versus reactivity insertion is shown in Fig. 2. The plot contains both the maximum change in photodiode current and the average of the 10 pulses collected at each reactivity insertion setting. The solid trend line represents the linear best fit of the maximum photodiode change data set, Eq. (1), and the dashed trendline represents the linear best fit of the averaged data set, Eq. (2), where x represents the

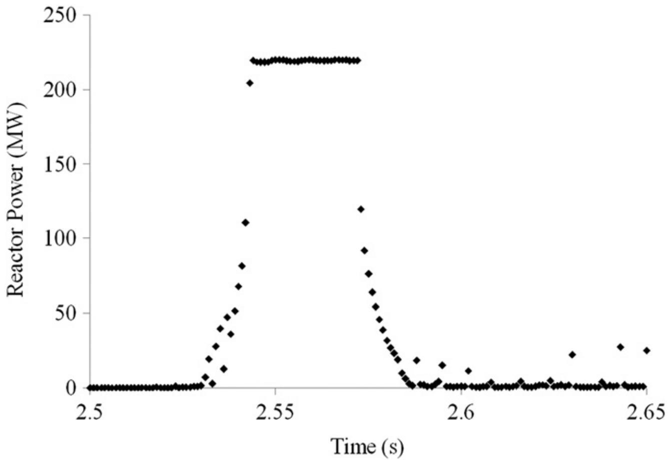

Fig. 3. Response of the ^{10}B-lined neutron detector during a 2.32 dollar pulse.

reactivity insertion in dollars and y is the photodiode current in μA.

$$y = 53.8x - 44.0 \tag{1}$$

$$y = 46.3x - 37.0. \tag{2}$$

The unknown reactivity insertion yielded a change in photodiode current of 85.6 μA, which using Eqs. (1) and (2) yielded a reactivity insertion of 2.41 and 2.64 dollars. The unknown pulse was performed only once and was set to 2.32 dollars based on the reactor rod worth calibration curves. The response of the ^{10}B-lined neutron detector to the unknown pulse is shown in Fig. 3. The EO response to pulsing is shown in greater detail elsewhere (Nelson et al., in review).

5. Discussion

Because the ^{10}B-lined detector became saturated at high reactivity insertions, the accuracy of the measurements conducted with the device are suspect. Additionally, extrapolating low power measurements with a linear fit for the ^{10}B-lined tube to reactor powers almost three orders of magnitude larger may also raise inaccuracies in the peak power measurements. Fig. 3 shows the saturation of the detector beginning at approximately 225 MW, almost 25% of the expected peak power. Because the EO detector does not seem to show any saturation at the large reactivity pulses, it may be a viable alternative to the ^{10}B-lined detector. Additionally, adding a ^{10}B-lined device in or near the reactor core acts as a neutron absorber, thereby, causing flux depression and reducing the reactivity of the core.

The data logging system only records a data point approximately every 10 ms, which is half of the average FWHM of the pulse, 20 ms. The power during a pulse is above 90% of the maximum for less than 10 ms. Therefore, the actual peak maximum may be entirely missed with the current data logging system. This problem appears to be evident in the maximum photodiode change data set as the data points plotted do not form as linear of a data set as the averaged pulse data points.

The unknown pulse was estimated using a linear fit of the two data sets and both trend lines resulted in an overestimation of the actual reactivity insertion value, 2.32 dollars. The unknown pulse was only performed once and the linear fits would be expected to result in an underestimation of the reactivity insertion due to the relatively long time between sampling data points. However, the estimation from the linear fit lines differed by less than 15%. If a data logging system recording a measurement every 10 ns were used, an accurate measurement of the maximum could be conducted. Increasing sample rate is the next logical step.

6. Conclusion

The CdZnTe Pockels cell has been shown to successfully trace and calibrate pulses from the KSU TRIGA Mark II nuclear reactor. This is the first recorded attempt to successfully calibrate reactor pulses of multiple reactivity insertions using an EO radiation detector. The current ^{10}B-lined tube does not always provide an accurate measurement due to the saturation of the device, but the EO detector does not appear to become saturated at high reactivity insertions. Thus the EO device may be a viable replacement detector for reactor pulse monitoring.

Acknowledgments

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