Nuclear Instruments and Methods in Physics Research A 680 (2012) 97–102

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

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

Kyle A. Nelson [a,*], Jeffrey A. Geuther [b], James L. Neihart [a], Todd A. Riedel [a], Ronald A. Rojeski [c], Philip B. Ugorowski [a], Douglas S. McGregor [a]

[a] S.M.A.R.T. Laboratory, Mechanical and Nuclear Engineering, Kansas State University, Manhattan KS 66506, USA
[b] TRIGA Mark II Nuclear Reactor, Mechanical and Nuclear Engineering, Kansas State University, Manhattan KS 66506, USA
[c] Nanometrics, Inc., 1550 Buckeye Drive, Milpitas CA 95035, USA

ARTICLE INFO

Article history:
Received 5 July 2011
Received in revised form
22 February 2012
Accepted 27 February 2012
Available online 6 April 2012

Keywords:
Pockels cell
Reactor pulsing
Radiation detector

ABSTRACT

CdZnTe has previously been shown to operate as an electro-optic radiation detector by utilizing the Pockels effect to measure steady-state nuclear reactor power levels. In the present work, the detector response to reactor power excursion experiments was investigated. Peak power levels during an excursion were predicted to be between 965 MW and 1009 MW using the Fuchs–Nordheim and Fuchs–Hansen models and confirmed with experimental data from the Kansas State University TRIGA Mark II nuclear reactor. The experimental arrangement of the Pockels cell detector includes collimated laser light passing through a transparent birefringent crystal, located between crossed polarizers, and focused upon a photodiode. The birefringent crystal, CdZnTe in this case, is placed in a neutron beam emanating from a nuclear reactor beam port. After obtaining the voltage-dependent Pockels characteristic response curve with a photodiode, neutron measurements were conducted from reactor pulses with the Pockels cell set at the 1/4 and 3/4 wave bias voltages. The detector responses to nuclear reactor pulses were recorded in real-time using data logging electronics, each showing a sharp increase in photodiode current for the 1/4 wave bias, and a sharp decrease in photodiode current for the 3/4 wave bias. The polarizers were readjusted to equal angles in which the maximum light transmission occurred at 0 V bias, thereby, inverting the detector response to reactor pulses. A high sample rate oscilloscope was also used to more accurately measure the FWHM of the pulse from the electro-optic detector, 64 ms, and is compared to the experimentally obtained FWHM of 16.0 ms obtained with the ^{10}B-lined counter.

1. Introduction

The electro-optic (EO) radiation detector, a new category of detector, has the unique ability to detect radiation with no signal processing equipment connected to the sensor [1]. The EO detector utilizes the Pockels effect, which involves the passing of collimated laser light through a transparent birefringent crystal, positioned between crossed polarizers, and focused upon a photodiode. The Pockels cell setup utilizing crossed polarizers, oriented 90° to one another, is referred to here as the 'standard' Pockels cell arrangement. Applying a voltage bias to the crystal will change its refractive index and, therefore, alter the polarization of the light propagating through the second polarizer, also known as the analyzer, and eventually the photodiode current output. Radiation interactions occurring in the crystal will generate free electrical charges, which can perturb the electric field of the crystal and cause a change in the state of polarization. This change in electric field will alter the amount of light transmitted through the analyzer and, consequently, the current (or voltage) output of the photodiode.

The electric field distribution within the Pockels cell is a function of the electrode dimensions. For instance, a voltage placed across an ideal planar device would have equal charge densities of opposite sign upon the contacts; hence the electric field would be constant across the device. However, a Pockels cell with a small dot-shaped contact opposing a large planar contact upon the other surface, having the same number of charges on each contact, would consequently cause the charge density of the small contact to be larger than that of the large contact, and thereby, cause the electric field near the small contact to be much higher than the electric field adjacent the large contact. The effect can be manipulated to enhance the change in photodiode current output from radiation interactions in the Pockels cell crystal by collimating the laser light through the high electric field region of the Pockels cell [1]. The result is a greater change in current output at the photodiode than for a uniform field [1]. The conceptual setup for a 'dot' contact, an optimum anode geometry for electric field enhancement, is shown in Fig. 1. Because CdZnTe was demonstrated as a viable EO detector, mainly due to the

* Corresponding author.
E-mail addresses: nuclearengg@gmail.com, knelson1@ksu.edu (K.A. Nelson).

0168-9002/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.nima.2012.02.048

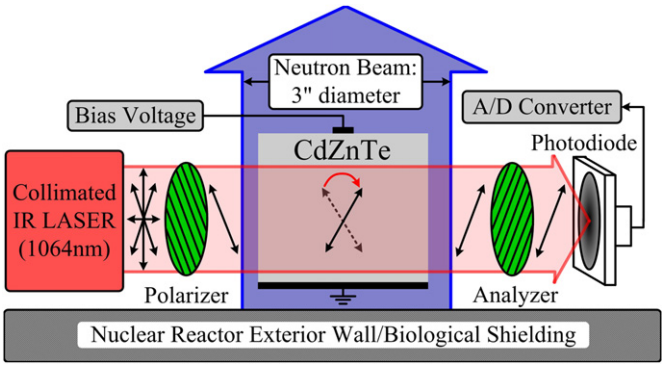

Fig. 1. Depiction of the Pockels cell experimental arrangement in the radial neutron beam.

relatively long free carrier lifetimes (compared to most EO crystals) and the $^{113}Cd(n,\gamma)^{114}Cd$ neutron reaction, the same experimental configuration used for steady neutron monitoring [1] was used for the reactor pulsing measurements.

The Kansas State University (KSU) TRIGA* Mark II nuclear reactor can be "pulsed", by withdrawing the three standard control rods to attain criticality at 10 W and afterwards ejecting the transient control rod. By ejecting the transient control rod pneumatically, a rapid upward spike in reactor power is observed, reaching approximately 1 GW of thermal power with a pulse full width half maximum (FWHM) of approximately 16.0 ms. Using a data recording system, the reactor pulses were measured in real time at the 1/4 and 3/4 wave bias settings of the characteristic Pockels curve for the standard Pockels cell configuration. Afterwards, the measurements were performed with the polarizer and analyzer set to equal angles, instead of the typical 90° orientation. This alternative arrangement, referred to as the "inverted" Pockels cell configuration, causes an inversion of the characteristic Pockels curve, and consequently, causes the maximum light transmission to occur at 0 V bias. Reactor pulsing was repeated at the same bias settings as the standard Pockels cell assembly for the inverted configuration.

2. Theoretical considerations

2.1. Pockels effect

The intensity of transmitted light through a Pockels cell is a function of the applied electric field,

$$I = I_o \sin^2\left(\frac{\pi n_o^3 r d}{\lambda} E\right) \tag{1}$$

where I_0 is the maximum light intensity transmitted through uncrossed polarizers, n_o is the zero bias refractive index, r is the Pockels electro-optic coefficient for the crystal, d is the path length of light transmitted through the crystal, λ is the wavelength of incident light, E is the electric field perpendicular to the optical path and I is the transmitted light [2]. The maximum change of light intensity per unit applied potential can be found by analyzing the second derivative of Eq. (1), which indicates that the largest intensity change occurs at the 1/4 and 3/4 wave positions and optimal operational settings.

^{113}Cd has a thermal neutron capture cross section of 20,000 b with a natural abundance of 12%, [3–5]. The neutron reaction of interest in the present work is [4,6,7],

$$^{113}Cd + n \rightarrow {}^{114}Cd + \gamma_1(558.6\ \text{keV}) + \gamma_2(651.3\ \text{keV}) + \gamma\text{'s}, \tag{2}$$

The reaction products, when absorbed in the Pockels cell, create ionization charge clouds. The application of a bias voltage across the Pockels cell can cause these free charges to drift to their respective electrodes (electrons to the anode, holes to the cathode), and by doing so create a smaller internal electric field opposing the externally applied electric field. This change in the Pockels cell electric field will also alter the polarization of light passing through the cell. Consequently, the amount of light passing through the second polarizer, or analyzer, will also change, which can be detected by a photodiode placed beyond the radiation field.

2.2. Reactor power excursion

The TRIGA Mark II nuclear reactor, designed as a training 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 by Stone, et al. [8]. A majority of the pulse occurs in less than one second; typically the FWHM of the pulse is approximately 20 ms and dependent on the size of the pulse. In general, the FWHM of the pulse decreases as the peak power, or reactivity inserted, increases.

The particular physical attribute of the fuel that allows pulsing to be possible is the prompt negative temperature coefficient of reactivity. The oscillations of the hydrogen atoms in the ZrH fuel matrix, an effect which increases rapidly with fuel temperature, results in the hardening of the neutron energy spectrum and a corresponding decrease in core reactivity [8–12]. The pulses are generated by ejecting a control rod, using air pressure, to rapidly insert >1 \$ of reactivity, causing the reactor to become prompt supercritical. In this state, the reactor power increases rapidly until the rise in fuel temperature causes the hydrogen atoms to oscillate rapidly. This adds sufficient negative reactivity to cause the reactor to become subcritical.

The power during a pulse in a TRIGA reactor can be modeled using either the Fuchs–Nordheim or Fuchs–Hansen models [13–16]. Both the Fuchs–Nordheim and Fuchs–Hansen models are briefly described below and used as theoretical benchmarks for the EO detector experiments and comparisons to TRIGA pulse data. For the Fuchs–Nordheim model, the power as a function of time, $P(t)_{FN}$, is shown in Eq. (3), and the FWHM of the pulse was obtained using Eq. (4). The maximum power, P_{max}, during a pulse can also be calculated using Eq. (5), assuming a constant K. However, the heat capacity, $C_p(t)$, in Eq. (3) uses the change in temperature over time, $T(t)$, to assist in calculating the power in Eq. (3) [see Eqs. (6) and (7)]. This is referred to as the 'modified' Fuchs–Nordheim model whereas the standard Fuchs–Nordheim model uses a ΔT in place of the $T(t)$ [9].

$$P(t)_{FN} = \frac{NC_p(t)\ (\rho_{FN}\beta)^2}{2\alpha l}\ \text{sech}^2\left(\frac{t\rho_{FN}\beta}{2l}\right) \tag{3}$$

$$\text{FWHM}_{FN} = \frac{3.525}{\omega} \tag{4}$$

$$P_{max} = \frac{(\rho_{FN}\beta)^2}{2\alpha K l} \tag{5}$$

$$C_p(t) = 805 + 1.65(T(t) - 25\,^\circ C) \tag{6}$$

$$T(t) = T_o + \frac{\int_0^t P(t)_{FN}\,dt}{C_p} \tag{7}$$

In the above equations, N is the number of fuel elements, β is the effective delayed neutron fraction, C_p is the heat capacity of each fuel element as a function of time shown in Eq. (6), ρ_{FN} is the

* Training, Research, Isotopes, General Atomics.