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Bright Flash Neutron Radiography at the McClellan Nuclear Research Reactor

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Abstract

The University of California, Davis McClellan Nuclear Research Center (MNRC) operates a 2 MW TRIGA™ reactor, which is currently the highest power TRIGA™ reactor in the United States. The Center was originally build by the US Air Force to detect hidden defects in aircraft structures using neutron radiography; the Center can accommodate samples as large as 10.00 m long, 3.65 m high, and weighing up to 2,270 kg.

The MNRC reactor can be pulsed to 350 MW for about 30 ms (FWHM). The combination of a short neutron pulse with a fast microchannel plate based neutron detector enables high-resolution flash neutron radiography to complement conventional neutron radiography

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1. Introduction

The University of California, Davis McClellan Nuclear Research Center (MNRC) operates a 2 MW TRIGA™ reactor, which is currently the highest power TRIGA™ reactor in the United States. The Center was originally build by the US Air Force to detect hidden defects in aircraft structures using neutron radiography; the Center can accommodate samples as large as 10.00 m long, 3.65 m high, and weighing up to 2,270 kg. Two of the four radiography bays are laboratory-size rooms where smaller samples can be inspected using both radiography and tomography. After taking ownership of the reactor in 2000, UCD has transformed the MNRC from an inspection facility for military aircraft into a center for university research making neutron imaging, neutron activation analysis and neutron irradiation capabilities available for a large variety of scientific applications. The capability of thermal neutron radiography to non-destructively reveal certain sample features and characteristics can be complementary to other non-destructive techniques providing unique information about the objects not otherwise available. The high penetration of neutrons through metals compared to X-rays and relatively high attenuation by light elements such as hydrogen can be ex-

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ploited for the study of fuel cells Boillat et al. (2008); Hickner et al. (2008), root growth Carminati et al. (2010), corrosion in reinforced cement Zhang et al. (2010), materials research Beyer et al. (2011) and many other applications. Due to the lower brightness of neutron sources compared to modern synchrotron facilities, acquisition times in neutron radiography is typically measured minutes rather than (sub-)seconds per projection. Although the MNRC reactor is a relatively modest neutron source, it is capable of producing a bright flash of neutron radiation in a 25 ms FWHM pulse with its power peaking above 350 MW in the current reactor core configuration (with complete new fuel peak power can exceed 1000MW). That can be beneficial for applications where relatively brief (i.e., millisecond time scale) processes are to be studied. The short and repetitive neutron pulses at spallation neutron sources offer much less power per pulse and therefore repetitive measurement using multiple pulses is required; this is only acceptable where cyclic processes are being investigated. For applications where only a single neutron flash is required, the MNRC pulse can be a very attractive alternative. Furthermore, the short pulse at MNRC allows flash radiography to be performed with integrating detectors, e.g. imaging plates or film while providing high spatial resolution and covering relatively large areas, which may provide a unique capability not otherwise available. Here we demonstrate the neutron radiography capabilities of the MNRC facility using a high-resolution neutron counting detector based on neutron-sensitive microchannel plates with a Timepix electronic readout. The spatial resolution at continuous operation as well as single pulse flash-radiography with a peak power of >350 MW is demonstrated, together with accurate measurement of the pulse shape or time profile at the sample position.

2. Setup

The measurements presented in this paper were performed at MNRC's Beamport 4, which terminates in one of the four radiography facilities. The detector was installed in the direct neutron beam behind plastic input aperture blocking neutrons outside of detector active area. The beam divergence was defined by the 32 mm aperture installed upstream in the neutron beam, at a distance of 8.6 m from the detector active area, thus providing an L/D ratio of 270. The measured neutron flux at this position is $3\text{x}10^5$ thermal, $1.6\text{x}10^5$ epithermal and $1\text{x}10^4$ fast n/cm^{2}s at a reactor power of 1MW; gamma content of less than 1% was determined using the ASTM beam purity indicator (Active Standard ASTM E2003). The high overall beam purity is due to a 27 cm long sapphire filter installed behind the aperture, which also reduced the count rate[1]. The neutron counting detector used in our measurements contained neutron-sensitive microchannel plates (MCPs) provided by Nova Scientific, coupled with a fast Timepix electronic readout having an active area of 28x28 mm^2. The MCPs converted neutrons into secondary charged particles and ultimately avalanche electrons, with relatively high detection efficiency of up to 40% for thermal neutrons Tremsin et al. (2005, 2011) and with the electron avalanche providing an output pulse of of 10^4-10^5 electrons. The resulting nanosecond output electron pulses were detected by a 2x2 array of Timepix ASICs with 55x55 μm^2 pixels Llopart et al. (2007); Tremsin et al. (2013) which defined the spatial resolution. For the bright flash single pulse measurements, the timing of each registered neutron was detected by the Timepix readout with a free-running clock, although the acquisition can also be synchronized to the reactor pulse by an external trigger fed into the fast readout electronics Tremsin et al. (2013). In the latter case the beam monitor can be used to generate the trigger by sensing the sharp increase of the neutron flux at a particular beamline. The samples in the present experiment were mounted typically at 15 mm distance to the active area of the detector.

3. Results

3.1. Spatial resolution and contrast of thermal neutron radiography at MNRC

The spatial resolution and image contrast of the setup was first calibrated while the reactor was operating continuously at 1 MW power. The 2D neutron radiograph of a 250 μm thick gadolinium cross mask is shown in Fig. 1(a). Reasonably high contrast is observed at this image with sharp edges on the scale of 100 μm, see Fig. 1(b). Some

[1] The neutron flux in the other three radiography facilities is of the order of 10^6 n/cm^{2}s and the reactor can be pulsed up to 1000MW with new fuel thus allowing peak fluxes of the order of 10^9 n/cm^{2}s

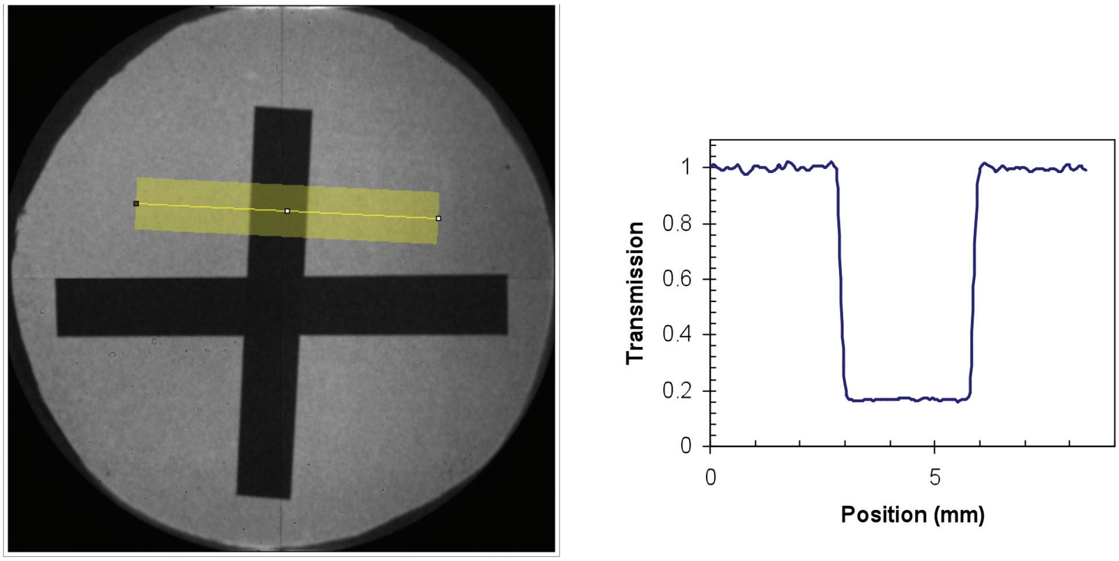

Fig. 1. (a) Thermal neutron radiography of a 250 mm thick ^{nat}Gd mask acquired over 100 s. (b) Cross-section through the radiographic image for the area shown by the dotted rectangle (a). The full width of the edge on each side of the Gd mask is 200 μm. The image is normalized by the open beam image integrated over 300 s.

epithermal neutrons and gamma photons penetrate the Gd mask and are detected by the MCP detector, which has 40% sensitivity to thermal neutrons Tremsin et al. (2005, 2011) and <0.5% sensitivity to gammas Tremsin et al. (2008).

3.2. Single bright neutron pulse

The capability of the MNRC reactor to produce a single bright neutron pulse was characterized for its pulse time profile or shape, as well as the corresponding intensity of the neutron flux at the sample position. A simultaneous measurement of the number of neutrons registered by the detector at the sample position and the reactor power was carried out. The image of a single flash radiograph consists of two sections: an open beam area and an area behind a 25 mm steel bar with about 22% measured transmission, as shown in Fig. 2. The scattering from the environment was negligible compared to the direct neutron flux as seen from the sharpness of the steel edge. The Timepix mode of the MCP detector readout, enabled the measurement of the neutron intensity as a function of time. The profile of the flux behind the steel bar was accurately registered for the entire pulse, as shown in Fig. 3(a). The time profile of the neutron pulse in the open beam area (crosses in Fig. 3(a)), however, was not measured properly for the entire pulse - as the intensity of the incoming neutron flux was almost an order of magnitude higher and the detector can handle only one event per pixel per readout frame. Thus only the rising edge of the pulse intensity was measured correctly. After the 120 ms mark of Fig. 3(a), all the pixels of the detector in the open beam area were already occupied by an event, thus no additional neutrons could be detected before the frame was read out. Good agreement and correlation was noted, between the reactor power and the measured neutron counts at the sample position. That means an increased neutron flux of a factor of 350 can be achieved for a short time, when the reactor is pulsed. The width of the neutron pulse was measured to be 25 ms FWHM. The detector can be run in a mode in which it registers both spatial and timing information for every neutron. This can be very beneficial for post-experiment data analysis, as images corresponding to different phases of the process can be formed from the time-resolved data set. The flexibility of different time binning allows for the compromise or tradeoff between the image statistics and the time bin width: the images with shorter time bin have fewer neutrons, but allows for the studies of faster processes, while increasing the time binning improves the image quality with the penalty of lowering timing resolution. The cool down of the reactor to its normal

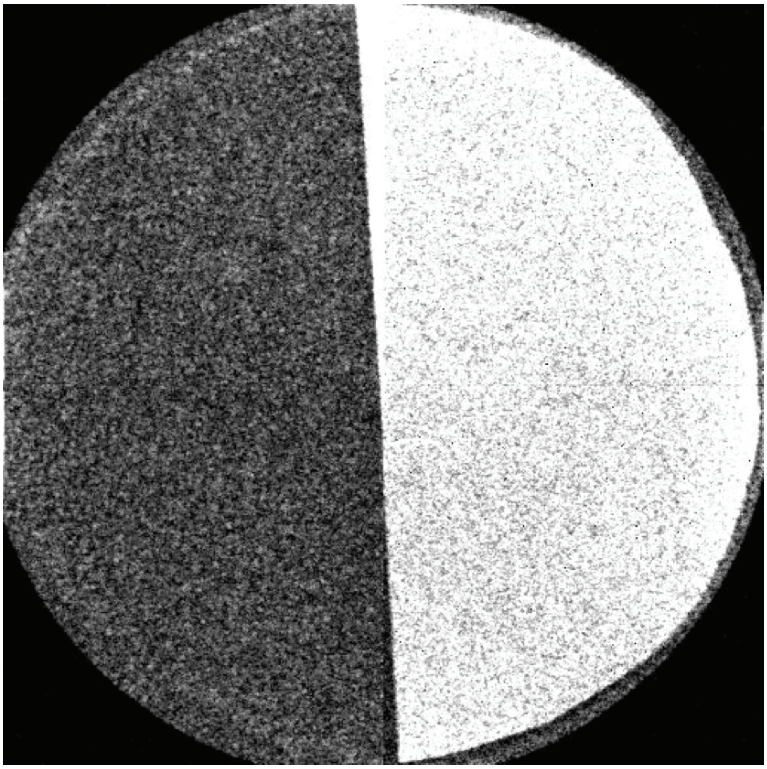

Fig. 2. Image of a 25 mm steel bar acquired over a single bright neutron flash. The transmission of 25 mm steel was measured to be 22%. The peak reactor output reached 354 MW as shown in Fig. 3(a). No correction for multiple scattering was performed in that image, but the sharpness of the edge indicates that the contribution of the scattered neutrons to image blurring is negligible

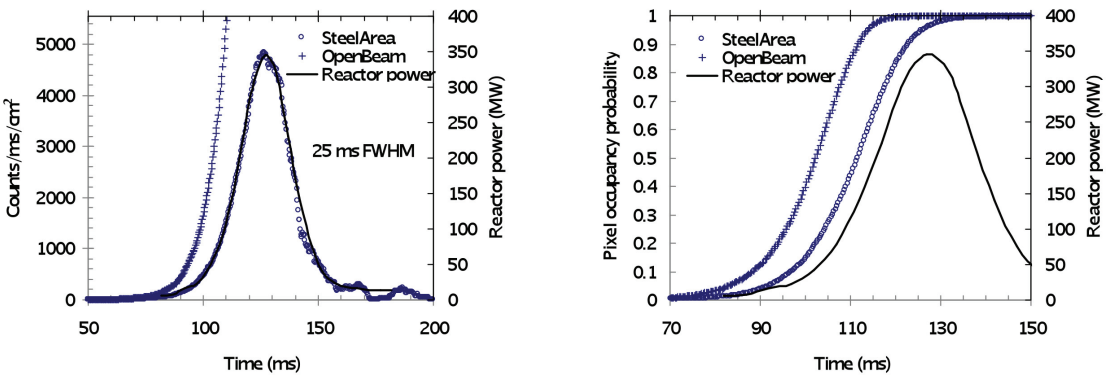

Fig. 3. The time profile of single neutron flash produced by the reactor at MNRC. The number of counts per mm^2 area measured by our detector is shown for two areas: the open beam area of the detector and the area below the 25 mm steel bar.

operational conditions requires about 20-30 minutes, thus limiting the repetition rate for single bright flashes to 2-3 pulses per hour.

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