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Technical Notes

Bright flash neutron radiography capability of the research reactor at the McClellan Nuclear Research Center

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ABSTRACT

The capability to produce a bright, short neutron pulse at the McClellan Nuclear Research Center (MNRC) can be very attractive for some neutron imaging applications. Complementary to conventional thermal neutron radiography conducted at the reactor, operating at the average power of 1 MW, a short pulse of ~25 ms FWHM duration can be produced at MNRC with the peak power exceeding 350 MW. Combination of a fast thermal neutron counting detector with a short neutron pulse at MNRC, enables high-resolution stroboscopic imaging to complement conventional neutron radiography. The results presented in this paper demonstrate the MNRC capabilities for conducting conventional thermal neutron radiography, demonstrating imaging spatial resolution below 100 μm, as well as bright flash neutron radiography with multiple nearly simultaneous events detected with microsecond timing resolution.

1. Introduction

The capability of thermal neutron radiography to reveal certain features and characteristics of various objects non-destructively can be complementary to other non-destructive techniques, and in some cases even provide unique information about the objects not otherwise available. The high penetration of neutrons through metals compared to X-rays, for example, and relatively high attenuation by light elements such as hydrogen can be exploited for the study of fuel cells [1,2], root growth [3], corrosion in reinforced cement [4], materials research [5,6] and many other applications as well. The brightness of modern neutron sources, both continuous and pulsed, lags far behind the intense X-ray fluxes available at synchrotron facilities, thus the acquisition time in neutron radiography is typically measured in seconds to minutes per projection [7]. The MNRC reactor is a relatively modest neutron source, with its average power of 1 MW. However, it is nevertheless capable of producing a bright flash of neutron radiation in a ~25 ms FWHM pulse with its power peaking above 350 MW. 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 can of course be used for such studies, but in that case the power per pulse is much lower, and therefore repetitive measurement using multiple pulses is required. Although the latter may be acceptable where cyclic processes are being investigated, for the applications where only a single neutron flash is required, the MNRC pulse can be a very attractive alternative. Some very bright reactor-based facilities can produce a continuous neutron beam with very high flux [8,9] and therefore stroboscopic imaging can in that case be performed using a detector with very fast shutter capability [10]. However, the short pulse at MNRC allows flash radiography to be performed even with integrating detectors, including imaging plates or films providing high spatial resolution and covering relatively large areas, which may provide a unique capability not otherwise available.

In this paper we demonstrate the thermal neutron radiography capabilities of the MNRC facility measured with a high-resolution neutron counting detector using neutron-sensitive microchannel plates together with a Timepix electronic readout. The spatial resolution of continuous neutron radiography is demonstrated for conventional reactor operation at a power level of 1 MW. Single pulse flash-radiography with a peak power of >350 MW is also demonstrated, together with accurate measurement of the pulse shape or time profile at the sample position.

2. Experimental setup

The measurements presented in this paper were performed at MNRC's Beamport 4, which terminates in one of the four

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(4) radiography facilities. The detector was installed in the direct neutron beam behind plastic input aperture blocking neutrons outside of detector active area, as shown in Fig. 1. During setup the neutron beam is blocked by a large mixed concrete/lead shutter. A lightweight borated plastic shutter, which allows for rapid operation and movement, controls the thermal neutron beam used for radiography. This shutter blocks most of the thermal and cold neutrons, but does not block the gammas and fast/epithermal neutrons emitted by the reactor. Contribution of gammas and fast/epithermal neutrons to the images acquired in the experiments was measured, both with the concrete/lead shutter open and with thermal neutrons blocked by the borated plastic shutter. 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 3×10^5 thermal, 1.6×10^5 epithermal and 1×10^4 fast n/cm^2/s; 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.

An additional smaller aperture of 8 mm was also installed for some measurements, and placed 3.2 m from the sample position resulting in an L/D ratio of 400. This was done to calibrate the effect of beam divergence on the spatial resolution, for those measurements where samples were unable to be placed close to the detector. 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 28×28 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 [11,12] and with the electron avalanche providing an output pulse of $\sim 10^4$–10^5 electrons. The resulting nanosecond output electron pulses were detected by a 2×2 array of Timepix ASICs with 55×55 μm^2 pixels [13,14], 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 [14]. 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, except for the calibration of the effect of beam divergence where samples were mounted at $\sim$115 mm from the active area.

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. 2. Reasonably high contrast is observed at this image with sharp edges on the scale of $\sim$100 μm. Some epithermal neutrons and gamma photons penetrate the Gd mask and are detected by the MCP detector, which has $\sim$40% sensitivity to thermal neutrons [11,12] and <0.5% sensitivity to gammas [15]. If needed in future experiments, the contrast can be further improved by conditioning the epithermal neutron flux with a beryllium filter. The transmission image of an ASTM Neutron Radiographic Sensitivity Indicator (SI) [16] is shown in Fig. 3. The SI consists of a step wedge containing gaps and holes of known dimensions; it is designed to offer a standard reference for traditional film neutron radiography, it cannot be considered as standard for digital radiography, however, because the sensitivity to neutron and gamma radiation is substantially different. Nonetheless, it can still be used to estimate the resolution and contrast of our radiographic setup by providing qualitative information on hole and gap sensitivity in a single unit. The measured

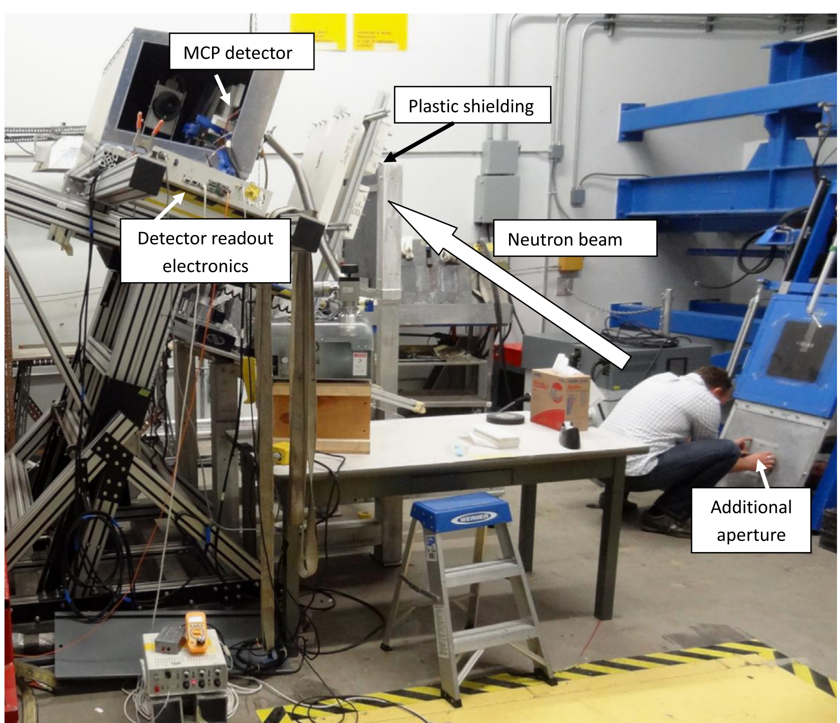

Fig. 1. Photograph of the experimental setup at the beamport 4 with MCP detector installed in the direct neutron beam.