Changing Optical Axis Due To Reactor Operation

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Abstract: During reactor operation, the neutron flux distribution is modified by the reactor control mechanisms, in the case of the reactor at the National Institute of Standards and Technology, this is determined by the angular position of the Cd shim arms and the vertical position of an Al regulation rod. The changing flux distribution results in a change in the optical axis of neutron beams which view a fixed position within the reactor core. The changing optical axis results in two noticeable image artifacts: poor registration between images of a static object taken at different times seen as a change in the position of a sharp edge and a change in the shape of the flatfield intensity. These two effects were measured during the first four days of reactor operation. Both measurements show correlation with the reactor control mechanisms, with combined correlation coefficients during the first two days after reactor startup approaching 1. The change in the edge position is well below the image spatial resolution, and has more uncertainty associated with it. However, the change in the flatfield shape change demonstrates a clear correlation with both shim arm angle and regulation rod position.

Keywords: Neutron radiography; nuclear reactor; nuclear reactor controls;

1. Introduction

A typical assumption made in neutron imaging is that the neutron beam source is stable. At a reactor source this is not strictly the case as the reactor control mechanisms can influence the shape and hence center of the neutron flux. In particular, at the NIST reactor (NBSR), the center of the flux moves a distance of about 2.5 cm over a typical 35 day cycle due to the motion of the Cd shim arms. At the NIST neutron imaging facility, the beam defining aperture is about 4 m from the center of the reactor, meaning that this change corresponds to an angular shift of about 6.25 mrad over the course of a operation cycle. There are two control mechanisms for the NBSR; four cadmium shim arms and an aluminum regulation rod. The shim arms serve both as a poison to shut the reactor down and as a coarse control for where on the fuel rods the fission reaction occurs. The aluminum regulation rod vertically translates to maintain a constant power of 20 MW; while the regulation rod can move either up or down, the average motion is up, with a maximum length of travel of about 30 cm; once the end of travel is reached, the regulation rod drops to the bottom of its travel and the shim arms rotate to expose more of the top section of the fuel rods. The NBSR typical operation is a 10 day shutdown period for refueling and maintenance followed by 35 days of operating at 20 MW. During the first two days of operation, there are relatively rapid changes in the position of the reactor control mechanisms until the ^{135}Xe content reaches equilibrium, with multiple shim arm angle changes occurring. Thereafter, the aluminum regulation rod takes 2 days to 3 days to complete the 30 cm translation. Thus, the typical assumption of a static neutron source is violated, as the reactor core is a dynamic environment.

While these facts are well known, the impact on neutron image formation, to our knowledge, has not been documented. One difficulty is that samples are often dynamic, experiencing temperature changes such as in fuel cells, or being rotated in the case of tomography. Further, the changes are often subtle and for many investigations small in comparison to the Poisson counting statics. Thus, the source of image artifacts can be difficult to ascertain. However, in a recent radiography experiment to the feasibility of neutron radiography for measuring the hydrogen distribution and uptake in thin films, a set of YH samples were imaged with a long exposure time, on order of a day for both the flatfield and sample images. There were four image sets collected: a flat field of the full field of view, 4 YH thin film samples deposited on silicon, a masked flat field, and a masked image of the 4 thin film samples. Comparing the respective flatfields to the sample images, three artifacts were observed: in both sets there was a gradient across each thin film sample, in the full field of view data there was a strong change in the penumbral region (outer edge) of the beam, and in the masked image set it appeared as if the rigidly mounted beam mask was uniformly translated. Shown in Figure 1 are the last two image artifacts, as the gradient is not evident in the grey-scale image. Since the sample did not move, the room temperature was stable to within ±0.5 °C, and the sample had nearly 99 % transmission, these observed artifacts could not be ignored due to sample motion or other sample area systematic effect. There are two possible causes, drifts due to thermal expansion, or a variation in the flux distribution in the NBSR. The detector is mounted directly to the steel shields, and the center of the detector is 106.7 cm (42 inches) above the floor. The linear thermal expansion coefficient of steel is about $1.2\text{x}10^{-5}$ $°C^{-1}$, giving a displacement of the center of about 13 μm per 1°C change. If the changes were due solely to temperature, one would anticipate a diurnal cycle, with a time lag due to thermal mass of the shields and changes only in one direction. However, since the temperature in the imaging facility was stable to within ±0.5 °C and no diurnal cycle was noticed and the shift occurred equally in both directions in from image set shown in Figure 1, it was proposed that the motion of the reactor control mechanisms was the source of these artifacts.

Figure 1: Examples of the artifacts due to a changing optical axis when a sample image is normalized by a flat field image. (a) A halo in the penumbral region which is lighter on the left side and dark on the right side, (b) a shift in the edge location in the masked image.

2. Experimental

The flux distribution is affected by both the rotation of the shim arms and the motion of the aluminum regulation rod. The shim arms rotate in increments of about 0.4°, while the regulation rod position is automatically adjusted over a distance of about 30 cm to maintain a constant reactor power. There are thus two cycles, that due to the shim arm position, and that due to the regulation rod. During the first two days of the reactor cycle, the shim arms are moved relatively frequently (every few hours) due to the buildup of ^{135}Xe. Once the concentration of Xenon has reached an equilibrium in the reactor core, the shim arms are moved once every few days. Thus, the beginning of the reactor cycle will demonstrate the greatest changes in the flux distribution, while the air temperature changes over a few hours should be small. In coordination with the reactor operators, the position of the shim arms and regulation rod were recorded once an hour or when moved so as to correlate the movement of the reactor control mechanisms with the above image artifacts. Unfortunately, this meant that there is only coarse information on the regulation rod position due to the slow sample rate.

Shown in Figure 2 is the region of the detector that was used to measure the changes in the optical axis; the edges of the sample mask at positions along the vertical and horizontal directions were tracked, as well as changes in the central portion of the flat field by normalizing later images by the initial image. The measurements were carried out during the first four days after the reactor startup that began on 13 FEB 2009. Images were acquired by a flat panel amorphous silicon detector in direct contact with a ^{6}LiF doped ZnS scintillator, 300 μm in thickness. The pixel pitch of the detector was 127 μm, and the overall spatial resolution is about 250 μm. The L/D for the experiment was about 600, with a neutron fluence rate of about 5×10^6 cm^{-2} s^{-1}. Images were acquired at a rate of 1 Hz, and then 100 were averaged to reduce noise.

Figure 2: Image area used to measure changes in the edge location and flat field shape.

Image acquisition and analysis

Two analyses have been performed. The first was to analyze the position of the edge of the sample mask at a horizontal and vertical location, as indicated in Figure 2. The second was to look at the change in the overall flat field shape with time. The intensity profile along the horizontal and vertical edge of the sample mask was modeled as an error function with a linear dependence to empirically model the observed background in the masked region:

$$x < x_b:\ I(x) = C + m*(x-x_b) + A*(1+\mathrm{erf}\{ (x-x_0) / \sqrt{2}\,\sigma\}) \qquad (1)$$

$$x \geq x_b:\ I(x) = C + A*(1+\mathrm{erf}\{ (x-x_0) / 2^{1/2}\,\sigma\}) \qquad (2)$$

where x_0 is the center of the edge, σ is the standard deviation, A is the amplitude of the error function, *C* is the background, and m and x_b model the linear contribution to the background. The reduced chi-square of the fit was about 1 for all the time series and for both the horizontal and vertical edges. The typical fit uncertainty associated with x_0 was less than 1 μm. The edge position, shim arm angle, and regulation rod position over the entire period with common axes is shown in Figure 3. The time period from start-up to just after the reactor scram on 13 FEB is shown in Figure 2.

The influence of the reactor operation was quantified assuming a linear relationship between the edge shift and the positions of the control mechanisms. The assumption of a linear relationship enables the calculation of the correlation coefficients, defined as the ratio of the covariance between the edge shift and the control mechanism position to the product of the standard deviations of the two populations. The partial correlation coefficients examine the relationship of just one parameter, while the multiple correlation coefficient includes both. The partial and combined correlation coefficients between the edge positions and the shim arm and regulation rod positions for the initial two days before the reactor scram are given in Table 1. As one can see, there is a high degree of correlation, indicating that the observed changes are due to the reactor operation.

Figure 3: Horizontal and Vertical Edge drift over a four day period, as well as the average shim arm angle and regulation rod position. The BT2 facility was entered around 11:00 on 13 FEB 09, and a heat source (fuel cell) turned on.

There was a large (0.2 mm) change in the horizontal edge position, which is probably a result of this disturbance. The vertical edge at early times tracks well with the shim arm angle. The slow increase thereafter maybe linked to the regulation motion. The horizontal change is greatest in the first few hours of operation, and then is rather steady. The small variations in both edge positions after 14 FEB are possibly due to temperature variations.

Table 1: Partial and combined correlation coefficients of changes in edge location or flat field shape with the shim arm and regulation rod positions.

While there was reasonable correlation between the edge position and the reactor controls, the change in the edge was significantly less than the pixel pitch of the detector. A more robust method was to analyze the ratio of two flat fields separated in time. This ratio showed an approximately linear gradient in both the horizontal and vertical directions (averaging over the appropriate direction within the green box of Figure 2) given by

$$R(x, y, t) = I(x, y, t) / I(x, y, t=0) \approx m_x(t)\, x + m_y(t)\, y. \qquad (3)$$

This gradient is shown in Figure 5, splitting the time in two periods, before and after the reactor scram on 13 FEB. The gradient shows a clear correlation with both the shim arm angle and the regulation rod position, with a combined correlation coefficient of approaching 1.

Figure 5: Horizontal and vertical gradient before (a) and after (b) the reactor scram on 13 FEB 09. The horizontal gradient is strongly influenced by the regulation rod position at later times, while the vertical gradient is influence by the shim arm position.

Conclusions

The reactor control mechanisms result in noticeable changes in the neutron beam optical axis that result in image artifacts which are beyond the control of the experimenter. As a result, high resolution neutron images can show poor registration between images at nominally the same condition, but separated in time, specifically at the NBSR before and after a movement of the shim arms.

As a result, high resolution imaging is only performed at least one day after the initial reactor startup, and multiple reference images are acquired to improve the image registration. It is possible that in the future the change in the flat field can be corrected, but this will require a higher sampling rate of the regulation rod position.

Acknowledgments

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CAPTION LIST

Figure 1: Examples of the artifacts due to a changing optical axis when a sample image is normalized by a flat field image. (a) A halo in the penumbral region which is lighter on the left side and dark on the right side, (b) a shift in the edge location in the masked image.

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Parameter	Regulation Rod	Shim Arm	Combined
Vertical Shift	0.45	0.33	0.52
Horizontal Shift	-0.34	-0.95	0.95
Vertical Gradient	-0.33	-0.85	0.86
Horizontal Gradient	-0.40	-0.95	0.95

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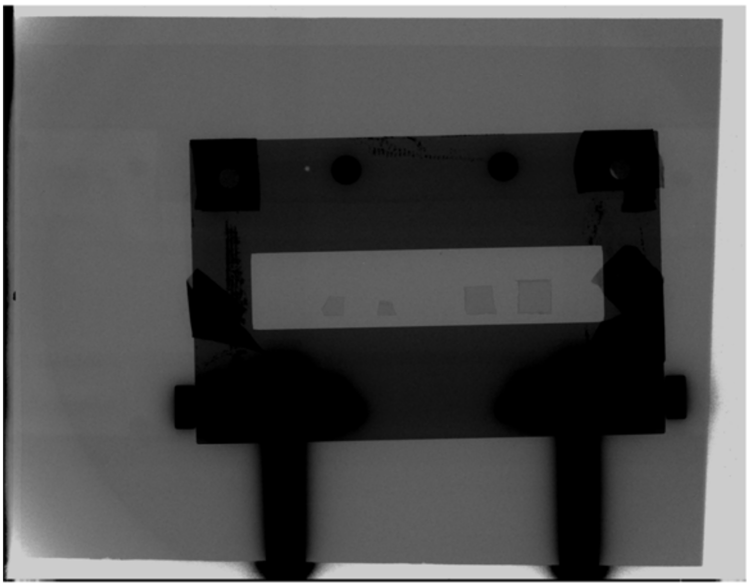
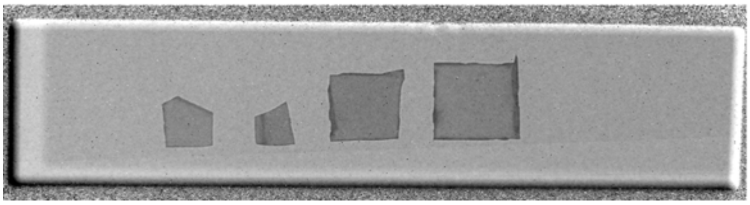

(a)


(b)

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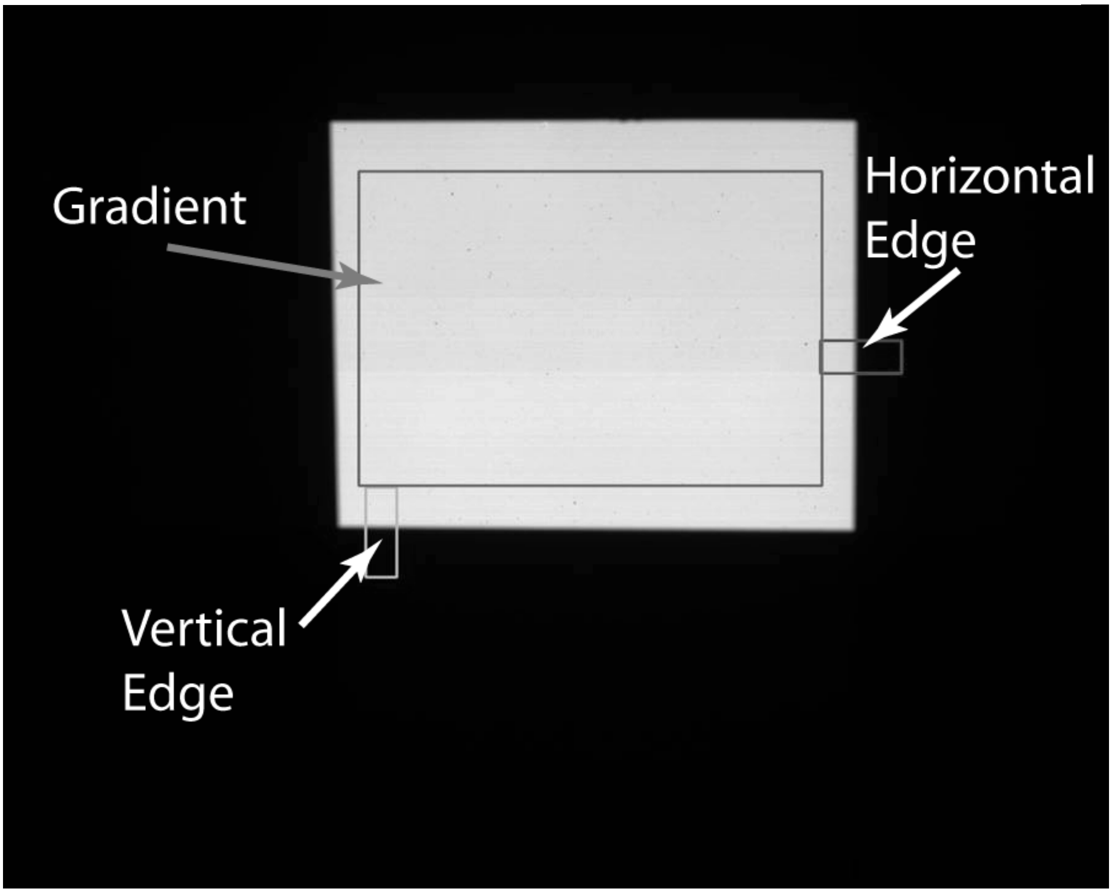

Color:

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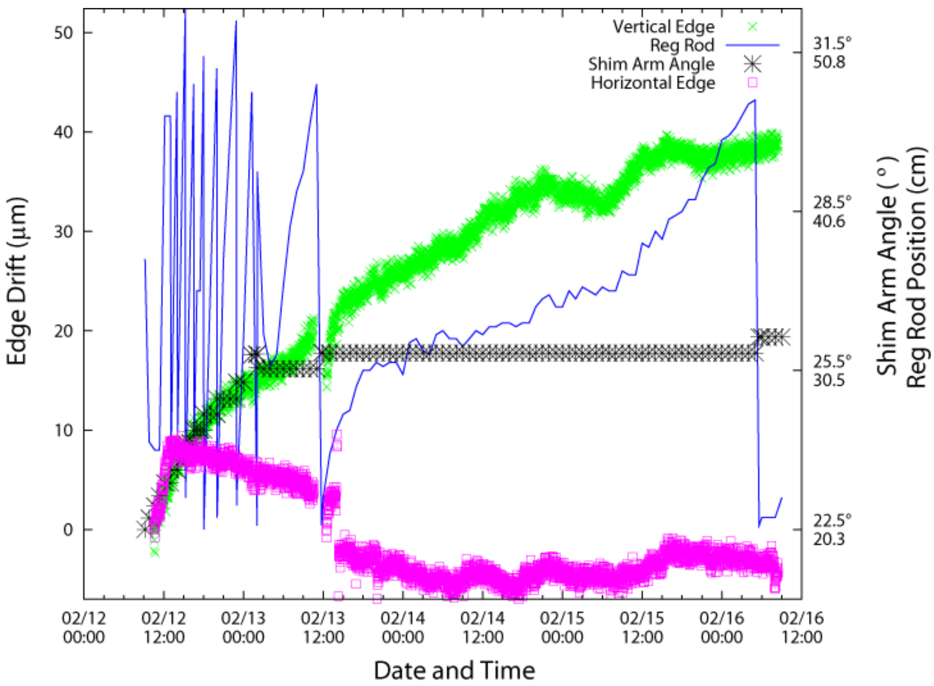

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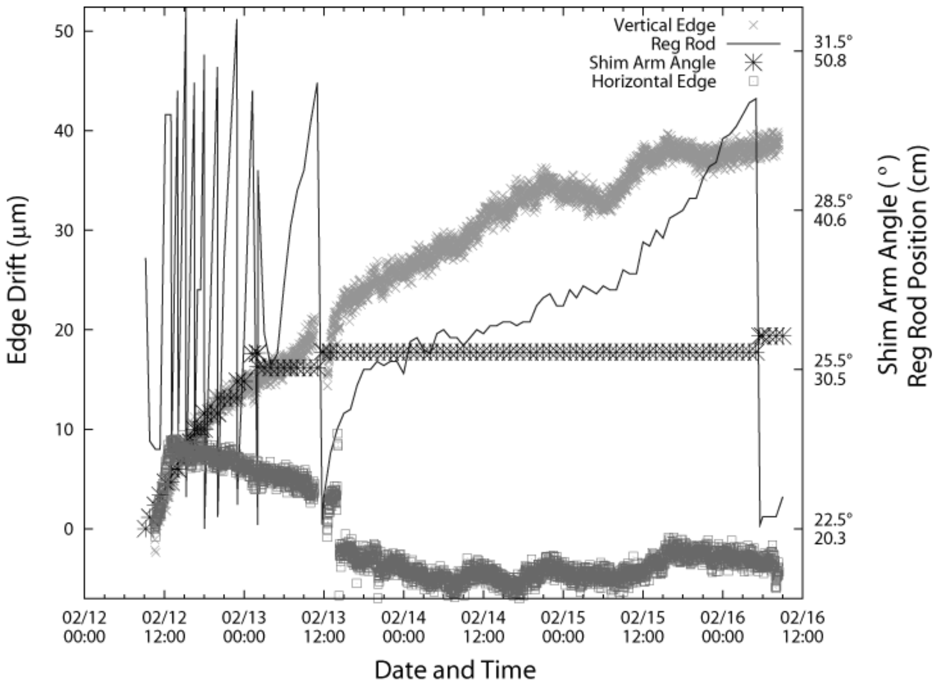
Figure 4: Horizontal and Vertical Edge drift over a four day period, as well as the average shim arm angle and regulation rod position. The BT2 facility was entered around 11:00 on 13 FEB 09, and a heat source (fuel cell) turned on. There was a large (0.2 mm) change in the horizontal edge position, which is probably a result of this disturbance. The vertical edge at early times tracks well with the shim arm angle. The slow increase thereafter maybe linked to the regulation motion. The horizontal change is greatest in the first few hours of operation, and then is rather steady. The small variations in both edge positions after 14 FEB are possibly due to temperature variations.



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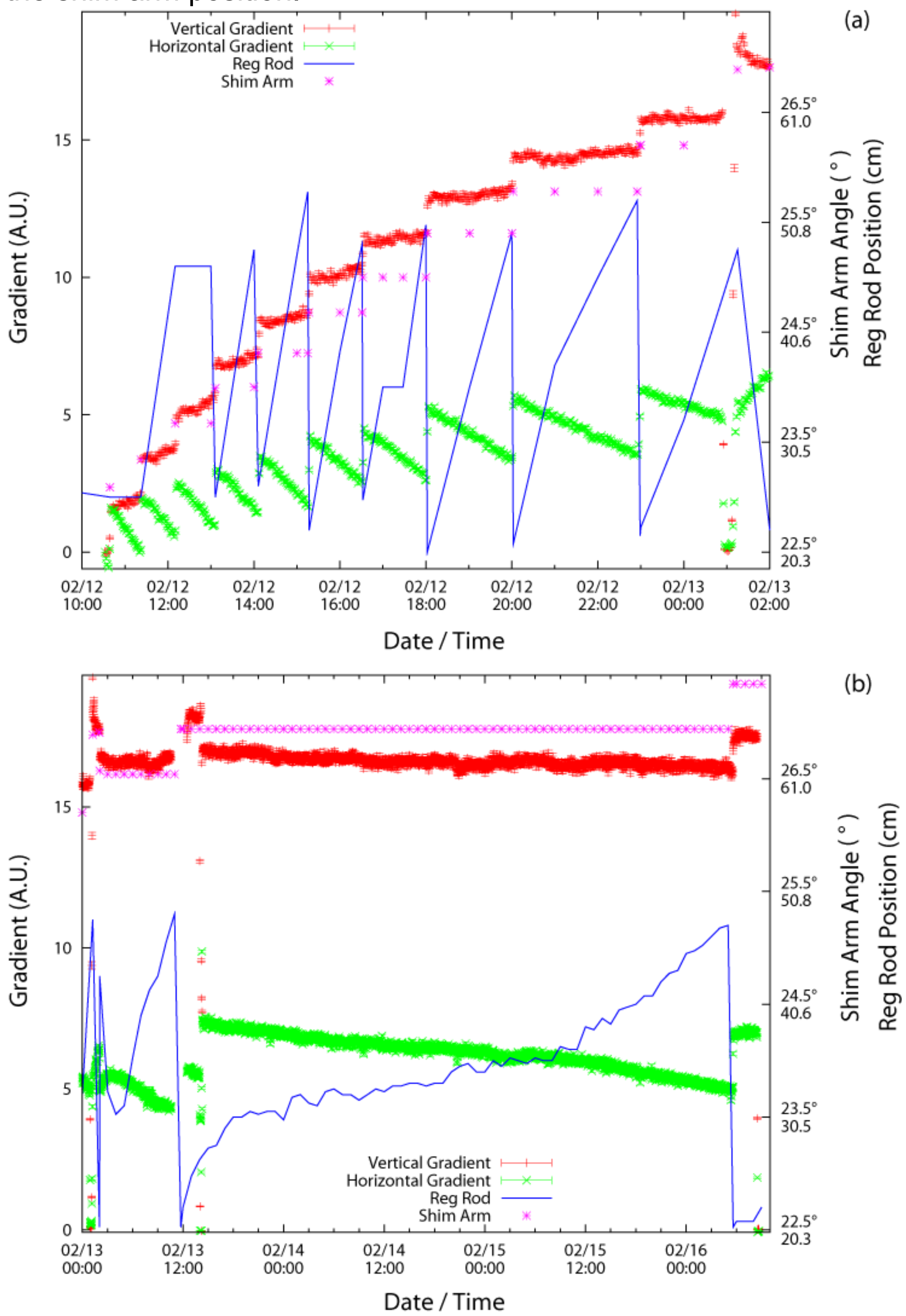

Black and White:

Figure 6: Horizontal and vertical gradient before (a) and after (b) the reactor scram on 13 FEB 09. The horizontal gradient is strongly influenced by the regulation rod position at later times, while the vertical gradient is influence by the shim arm position.