EXPERIENCE WITH AND STUDIES OF THE SNS* TARGET IMAGING SYSTEM

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Abstract

The Target Imaging System (TIS) shows the size and position of the proton beam by using a luminescent Cr:Al2O3 coating on the SNS target. The proton beam hitting the coating creates light, which is transferred through mirrors and optical fibers to a digital camera outside the high radiation area. The TIS is used during operations to verify that the beam is in the right location and does not exceed the maximum proton beam peak density. This paper describes our operational experience with the TIS and the results of studies on the linearity, uniformity, and luminescence decay of the coating. In the future, tubes with material samples might be placed in front of the target for irradiation studies. The simulations of placing tubes in the front of target coating and the effect on the beam width and position measurements are also discussed.

INTRODUCTION

Spallation Neutron Source

The Spallation Neutron Source (SNS) uses short and intense pulses of neutrons for materials research. These neutron pulses are created through a spallation process by hitting the mercury filled target with 1 GeV protons pulses. The SNS accelerator creates these proton pulses and must steer them to the target within ±4 mm vertically and ±6 mm horizontally of the target center and with a maximum size and peak density to prevent a premature end of life of the target.

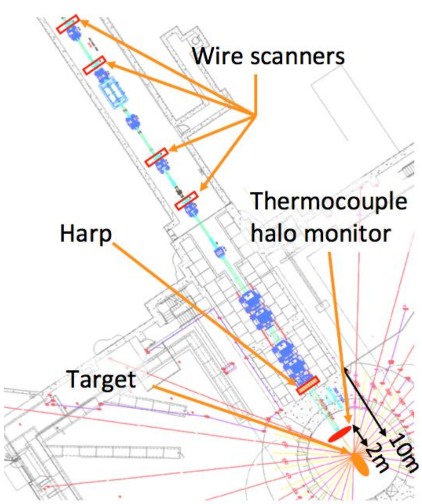

Figure 1: The locations of RTBT instrumentation.

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The Ring to Target Beam Transfer line (RTBT) Wizard program uses wire scanners and harp profiles to calculate the beam size and steering for the initial setup using low power beam. During neutron production with full beam power, the harp still provides profile data to verify the beam profiles but it is approximately 10 meters away and cannot, on its own, fully determine the location of the beam on the target. Thermocouples located at the Proton Beam Window (PBW), are only two meters away from the target, indicate only the halo of the beam. The beam halo is not necessarily symmetric and thus not a good measurement of the profile size or center position of the beam. Figure 1 shows the locations of the instrumentation. The Target Imaging System has been created to deal with these limitations.

Target Imaging System

The TIS measures the position and profile of the beam right on the target nose cone using a luminescent coating. The light produced by the protons hitting the coating is guided using mirrors, lenses, and a rad-hard fiber bundle to a camera outside of the high radiation area [1-5]. Figure 2 shows an example of the acquired image. The coating has fiducial markers that are measured before installation of the target and then used to calibrate the image obtained by the camera. Once calibrated, the TIS can determine the widths, peak density, and center of the beam on the target.

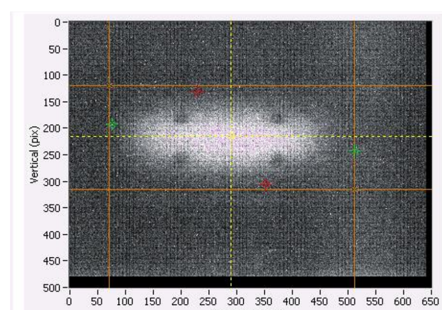

Figure 2: Image of beam on target.

OPERATION

Operators track the results of the TIS during the neutron production runs and adjust the beam trajectory if needed. Figure 3 shows the Target Errant Beam Control screen tracking the center of the beam on the target. The red circles are the individual measurements while the blue circles are the average positions. This shows a peak-to-peak noise of about 1 mm. The bottom part of the figure shows the magnets that can be adjusted to steer the beam if needed. This screen, created by the operators, is always visible in the control room and, in addition to being watched by the operators, also monitored by errant beam

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alarm software. While the TIS is not required for beam operations, it is still treated as a critical system that can only be tolerated to be offline for short time periods of time. During such time the Harp and thermocouple measurements are used to confirm that the beam has not undergone major changes. No beam downtime has been assigned to the TIS, but it has required a restart of the analysis or a reboot of the camera, a few times a year. The system runs mostly without interaction, however the camera's exposure and gain, as well as the analysis fit parameters have to be adjusted during the luminescence decay. The camera has to be replaced about once a year, as it does suffer minor radiation damage since it is located in a (low) radiation area.

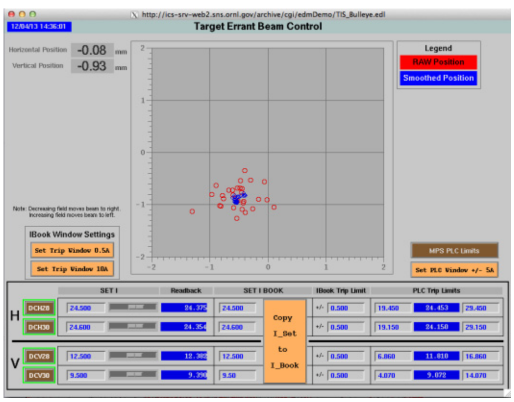

Figure 3: Errant Beam Control Screen.

STUDIES

Position Dependency on Power

Operators noted that during beam power ramping, the TIS reported positions consistently changed by about 1-2 mm in both planes but that the harp reported positions did not change. This points to a problem with the TIS, specifically to a movement of the first mirror pointing at the target. This first mirror is attached to the PBW and the PBW varies in temperature with the beam power. Different calibrations were done at low and high power, confirming that the image alignment does change. This calibration requires human interaction and takes at least 10 minutes each or even days, if we want to analyze thousands of pictures to study trends. New code was written to automatically find the fiducial markers in the images.

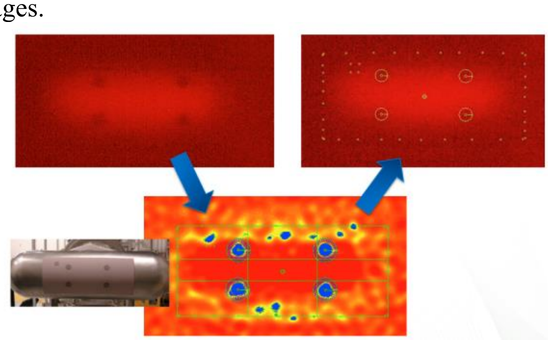

Figure 4: Automatic finding of fiducials.

This process is shown in Figure 4. Algorithms from the LabVIEW Vision toolkit first smooth and enhance the contrast of the original image (top left image) to show the markers more clearly (bottom image) followed by a circular edge finder to determine the center of each fiducial (bottom image). The locations of the fiducials and outlines are then drawn onto the origin image (right top image) and saved to a file. The software can analyze a thousand images within minutes.

To study the dependency of the TIS beam position on beam power, the TIS was set to save an image every second right after a beam outage while the beam power value, the harp and TIS reported positions, and the PBW cooling water temperatures were logged by the SNS Archiver. The data is plotted in Figure 5.

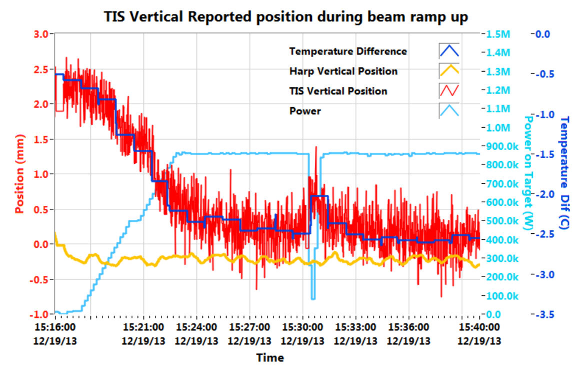

Figure 5: TIS vertical beam position (red).

The TIS reported vertical position trace (red) shows the change in reported position as the beam is turned on and ramped up in power. The beam power trace (light blue) shows the ramping up of the beam power. Initially, even though the beam pulse has the full charge, the power is very low as there is only one beam pulse per second. The harp reported vertical position (yellow) does not change while the beam is ramping up in power. The difference in temperature of the PBW cooling (dark blue) correlates well with the TIS reported position and shows that the increasing beam power heats the PBW.

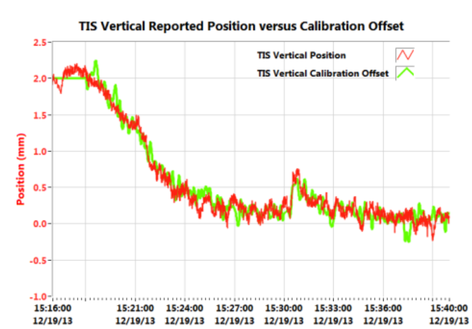

Figure 6: TIS vertical beam position (red) versus the calibration offset (green).

About 1800 images were analyzed to determine the calibration during the beam ramp up. Figure 6 shows the results for the vertical calibration offset. Both the reported vertical beam position and vertical calibration offset are low-pass filtered to show the trends. The curves closely follow each other, including the peak at 15:31, at which time the beam was temporarily interrupted.

These results lead us to conclude that the TIS position variation is due to the mirror moving and given the correlation with the temperature difference curve, that this is most likely due to heat stress.

Luminescence Decay

The selection of the luminescent coating material was based on early studies [2,4] and the brightest material was picked. However, the brightness was found to decay rapidly at production intensities. An initial study in [2,4] roughly shows the decay in luminescence. To further study the decay, and also while preparing to study new coatings, software was created to automatically correct the measured intensity based on camera exposure time, beam intensity, and image background level. The results are plotted in Figure 7 with data from 15 to 27, October 2013. This shows that the luminescence decays very quickly. The decay of the coating is mostly likely due to F-center formation, which saturates within 100-200 MWhrs. Because most of the damage (displacements per atom: dpa) is due to the more uniform backscattered neutrons, up to 85%, the coating decay is also more uniform and within a factor of two edge to center [4].

We plan to use this software tool to determine the different decay behaviors once we have different coating materials on the same target. The coating will be evaluated not only for its luminescence and decay rate, but also for how equally it decays, edge to middle, and when the decay curve flattens in order to end up with a uniform luminescence.

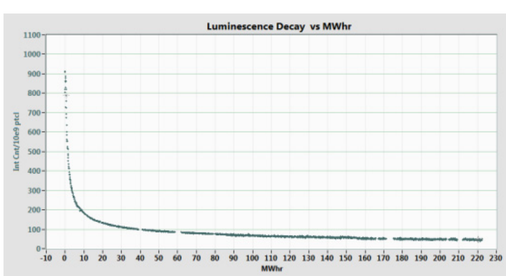

Figure 7: Luminescence decay.

Uniformity Scanning

The accuracy of the TIS estimates of beam position and size also depends on the uniformity of the luminescence across the coating. To study the uniformity, we scan a small pencil beam across the coating and measure the light response. This study has been done before but it has now been automated to speed up the process. A script steers the beam, using up to 10 magnets, while the TIS acquires and saves the images. Because the pencil beam is mostly off-center, it can only be up to approximately 1/300 of the full production beam. This gives very low intensity light that is barely visible by the camera and is affected by noise and light leakage and can only be done with a fresh coating early in the decay curve. The new analysis program first finds the approximate center location of the pencil beam and then positions the projections area around the center. The profiles are calculated by summing the image pixels both vertically and horizontally within the projection areas, as shown in Figure 8, indicated by the light blue boxes. The resulting profiles are shown on the right of the figure. The red traces represent the fits to the large area while the blue traces represent the fits to the narrow boxes and result in a more accurate location and peak intensity estimate.

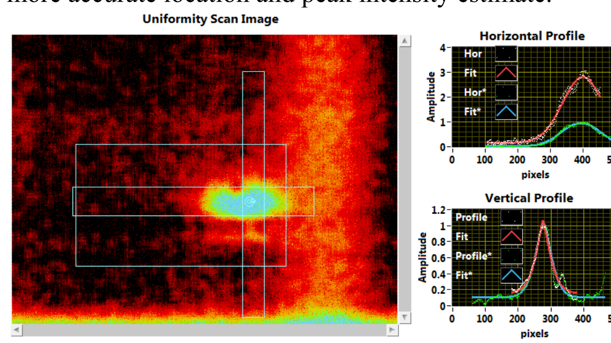

Figure 8: Estimating the pencil beam intensity and position.

The result, intensity versus position (pixel), is shown in the top of Figure 9. There are about 1.8 pixels per mm. The red curve shows that the vertical position is only changing by a few pixels as intended for the horizontal scan. The total variation in intensity is about ±12.5%. However, the noise in the measurement is significant, and, given the low intensities of the light emitted, estimated to contribute about half of that variation. We hope to perform more accurate studies in the future. The bottom half of the figure shows a 3D plot of the scans with the axes representing pixels. The fiducial markers are visible in the plot.

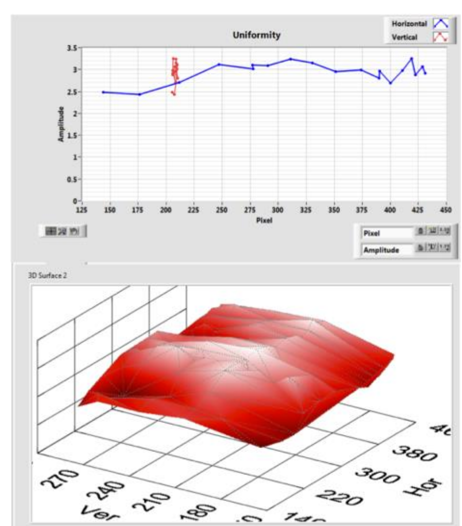

Figure 9: Results of a horizontal scan on top and the overall results on the bottom.

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FMITS Effect on TIS Estimates

A feasibility study is ongoing to build an irradiation facility for fusion materials called the Fusion Material Irradiation Test Facility (FMITS) at SNS [6]. The goal is to study material damage from neutrons such as the impact of He and H transmutation products. The materials to study would be placed inside tubes in front of the target partially blocking the view of the target Imaging System, shown in Figure 10.

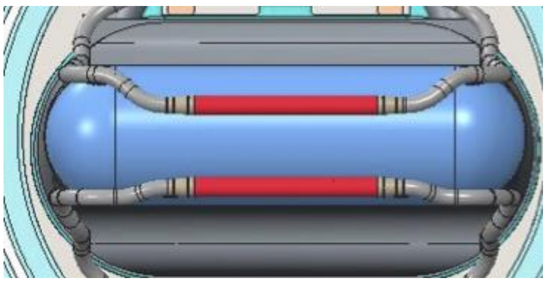

Figure 10: Drawing of the FMITS tubes (red) in front of the target nose cone.

As part of this feasibility study, the effect of the tubes on the TIS is being studied using simulations. To simulate the tubes blocking the light from the coating, the normal TIS program was modified to insert horizontal blackout regions across the image. The tubes can be simulated to be completely black or have partial light to simulate that the tubes have a luminescent coating.

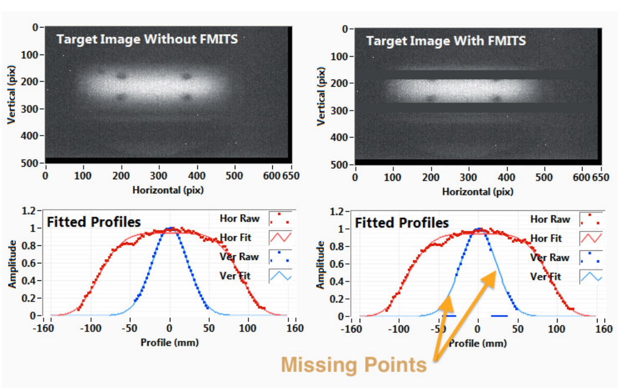

Figure 11: On the left top the typical TIS image and on the right the simulated image with FMITS tubes in front, the bottom shows the resulting profiles.

Figure 11 shows, on the right, such a simulation with the tubes completely black. The tubes are horizontal and don't affect the horizontal profile because that profile is calculated from an area in between the tubes. The vertical profile is affected as the tubes cross through its profile area. A good estimate can still be made of the profile by excluding the points affected and this is shown in the figure's profile plots. The location of the tubes can change depending on the requested exposure ratios to protons and neutrons. The most likely positions have the tubes asymmetrically positioned, as shown in the figure. Because of the asymmetry, the vertical profile still has points on one of the tails, which helps with the accuracy of the estimates.

The results of analyzing many images are shown in Figure 12. Two simulations are done. The first simulation, shown in the top half of the figure, has the tubes in their standard asymmetric locations, where one tube blocks the tail and one tube blocks part of the right side, but not the tail, of the profile. In the second simulation, shown in the bottom half of the figure, the tubes block both tails. The results show that if only one tail is blocked, the estimates in the vertical profile widths differ by about 2-3%, while the noise in the jitter remains about the same. When both tails are blocked, the estimates in the width are still off by about 2-3%, but now the variation in the estimates has doubled. Position variations were found to be less than 0.5 mm, slightly less than the TIS reported position noise. In either case, it shows that the FMITS won't incapacitate the TIS but does degrade the performance by a few percent, though the accuracy remains acceptable.

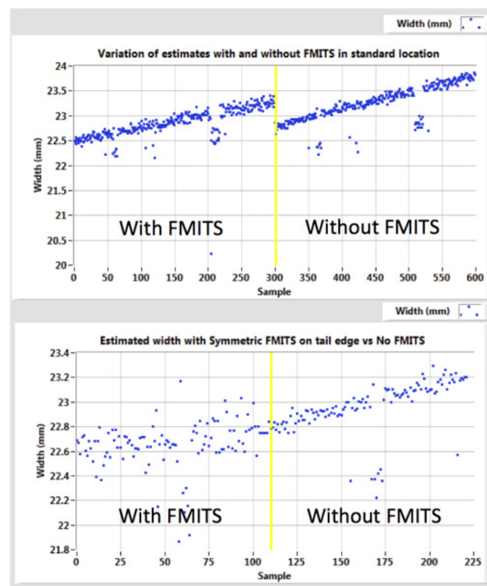

Figure 12: The results of analyzing images with or without the FMITS in different locations.

Simulations in which the FMITS tubes have some coating on the tubes were performed but none of the results of incorporating this light led to acceptable results at this point. Further simulations are planned. An additional problem with using light from the FMITS tubes is that the replacement of the FMITS tubes and target will be done at different times, thus getting coatings at different parts of their luminescence decay curves. We still are considering putting a coating on the FMITS tubes, as a sudden decrease in light can indicate overheating of the tubes. Another issue to resolve is that the tubes can block the fiducial markers. The target coating might have to be designed with additional markers so that a calibration can always be performed.

CONCLUSION

The TIS is an essential tool for day-to-day operations and initial setup of the accelerator. A newly created analysis tool automatically determines the calibration and can potentially be used to automatically correct the mirror movement. The uniformity scan has been automated and sped up by using a script to steer the beam and an analysis program to study the uniformity of the coating. A request for higher power off-centered beam pulses has been approved and we hope to do better scans in the future, although these scans can still only be done early in the decay curve.

The tool to plot the decay curve versus MWhrs on target will help to study future coating materials. The goal is to find a material that has high luminescence throughout its exposure but also changes equally edge to center. Thus an quick saturation in the decay curve could be better than a slow one if that means that the whole of the coating reaches a decayed but uniform response quickly.

Initial studies with the FMITS tubes in front the target nose cone show that the TIS can still function despite the blocked light. Future simulation studies and a mockup of a target nose cone with tubes in front of it with a complete optical path are planned.

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