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A STUDY OF THE EFFECT OF IMPERFECTIONS IN THE OPTICAL PATH OF THE SNS* TARGET IMAGING SYSTEM USING A MOCK-UP

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Abstract

The Spallation Neutron Source sends a 1 GeV proton beam to a mercury filled target to generate neutrons. The Target Imaging System (TIS) provides an image of this proton beam on the target to help center the beam and determine the peak density. Most of the TIS optical path is installed together with the proton beam window, which is replaced every two to three years. Using the next-to-be-installed proton beam window and a mock-up of the target and the beam pipe to the target, we have studied imperfections in the optical path to estimate their effect on the TIS measurements. In this paper, we show the effect of geometric distortion and light reflections, as well as the difference in the performance of two optical fiber bundles with different resolutions and contrasts.

INTRODUCTION

To produce the neutrons used for materials research, 1 GeV protons hit the stainless-steel target vessel filled with mercury. The Target Imaging System (TIS) helps optimize the target's lifetime by steering the beam to the center of the target's nose cone. The nose cone is coated with aluminum oxide doped with chromia. This layer luminesces when the protons hit, thus producing an image of the beam on the target. The light is collected by an off-axis parabolic mirror at the Proton Beam Window (PBW) and guided by optics and a radiation resistant high purity fused silica fiber bundle to a camera outside the high radiation area, see Fig. 1 and [1-3].

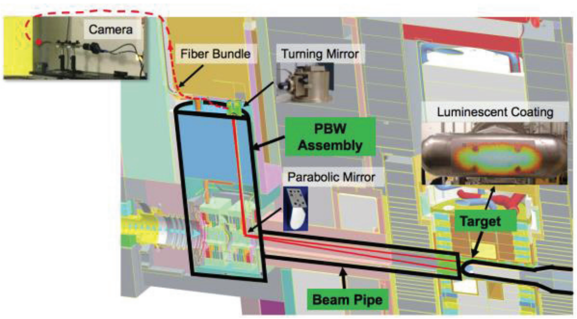

Figure 1: The layout of the TIS.

The TIS calculates the position of the beam to monitor that we are keeping the beam centered within ± 4 mm vertically and ± 6 mm horizontally. The beam can also be steered by equalizing the temperature read-backs from the thermocouples at the PBW. This method requires a symmetric beam halo and a flat orbit.

The TIS also provides estimates for the width of the beam, which is used to calculate the peak density. During operations, we must keep 90% of the beam within a 200 by 70 mm footprint and keep the peak density within certain limits, depending on beam power. A program called the RTBT Wizard (Ring to Target Beam Transferline) uses the beamline optics elements, 4 RTBT wire scanners, and the RTBT harp to predict the width of the beam on the target. The difference between the two width measurements has significantly varied, even more than 30%, with the Wizard usually providing a higher peak density. To be on the safe side, the higher number has been used for operations.

The difference in estimates can be due to the difference in analysis routines, imperfect knowledge of the magnetic fields of the quadrupole magnets, uncertainty in the calculation of the Proton Beam Window's beam scattering effect, widening of the TIS proton image by luminescence due to particles other than protons, a temperature gradient sensitivity in the luminescence across the coating, and imperfections in the TIS optical path. In this paper, we study the effects of imperfections of the optical path, specifically the reflections of light in the beam pipe and the geometric distortion by the optical elements. We will also show what effect the differences in the quality of the optical fiber bundles has on the TIS image.

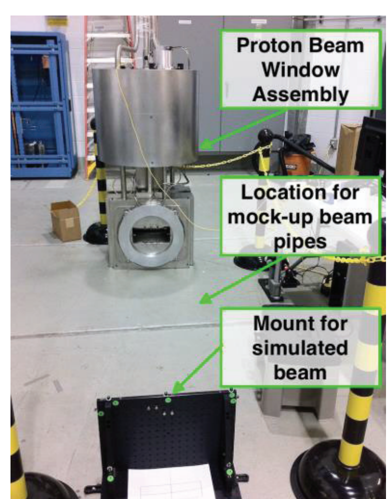

Figure 2: The proton beam window setup.

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MOCK-UP

An optical test bench was available to do testing during the development of the TIS. Now we can only do testing on a new Proton Beam Window (PBW) that is to be installed. The PBW assembly, see Fig. 2, is available before installation in the beam line to install the TIS optical components and, at that time, we can also do our testing. Notice that Fig. 1 accentuates with black borders the elements of the mock-up.

LIGHT REFLECTIONS

To study the reflections of the light, two beam pipe mock-ups where created, a reflective and a non-reflective version. The inside of reflective mock-up duplicates the geometry of the inside of the beam pipe from the PBW to the target. This mock-up was laser cut from a hard foam material according to the beam pipe drawings. The inside was layered with reflective tape to emulate the shine of the actual beam pipe. The non-reflective mock-up was made from optical blackboard to minimize the reflection and does not follow the internal beam pipe geometry, as the only goal was to shield outside light and minimize reflections. The mock-ups are shown in Fig. 3.

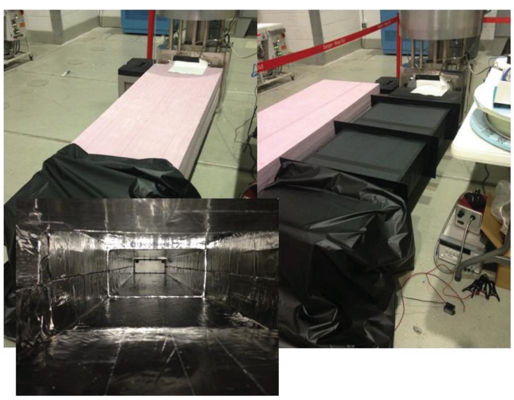

Figure 3: On the left, the laser-cut foam mock-up with the reflective inside, and on the right, the optical black hardboard, non-reflective mock-up.

Simulation of Proton Beam Image

To simulate the beam footprint, we used an electroluminescent sheet as a uniform area light source. In front of it we put a transparency printout of a two-dimensional super-Gaussian to attenuate the light and form a similar light footprint as the proton beam on the target nose, see Fig. 4.

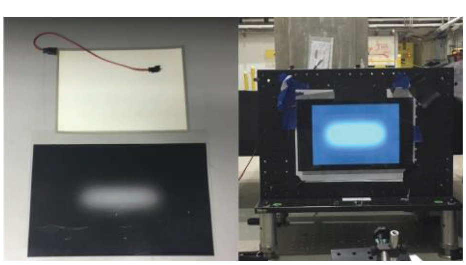

Figure 4: On the left, the electroluminescent sheet with the beam mask, and, on the right, the simulated beam.

Effects of Reflective Light

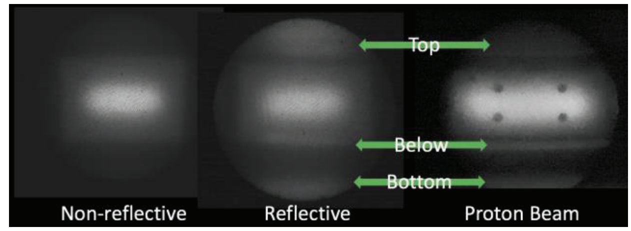

Figure 5: Images of the non-reflective (left) and reflective mock-ups (middle), as well as the actual beam (right).

Using the two mock-ups and the simulated beam image, we can now compare the simulated images with that of the actual proton beam, see Fig. 5. The images have been intensified so that the reflections are easier to see.

We clearly see reflections in the reflective mock-up that do not show up in the non-reflective mock-up. In both the reflective and proton beam images, we have reflections on top, just below the beam spot, and at the bottom. Not visible in these images are very small reflections that can occur on the far left and right.

We now apply the TIS analysis routines to the simulated images to see the effect on the profiles. This is shown in Fig. 6. The top left image shows the reflective mock-up and the bottom left image shows the non-reflective mock-up. Both images are in false colors. On the right, the obtained profiles show for horizontal and vertical, the darker blue and darker red are the reflective cases.

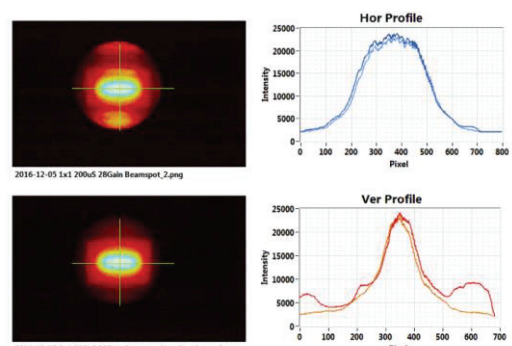

Figure 6: Images and calculated profiles of the non-reflective and reflective mock-up.

The profiles show that there is not much effect on the horizontal profile but a significant effect on the tails of the vertical profile. However, the main TIS analysis program does not extend its analysis to the tails, thus mostly avoiding the effect of this reflection.

We analyzed seven reflective and non-reflective mock-up images, using the standard TIS program, to get an estimate for the effect of the reflections on the real image. The results are shown in Table 1. This shows that the effect on horizontal position is < 0.1 mm and on the vertical position is < 0.5 mm, and that the effect on the peak density is < 3% lowered peak density due to the reflections. The effects of the reflections are more pronounced in the simulated image than in the actual image, see Fig. 7, so we assume that our results are an upper limit of the effect.

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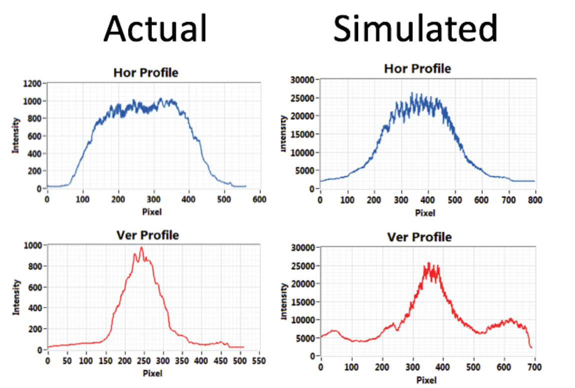

Figure 7: Comparison of actual proton beam profiles, left, versus reflective mock-up profiles, right.

Table 1: Analysis of the Simulated Beam with the Reflective and Non-reflective Mock-ups

Non-reflective	Position mean (mm)	Position STD (mm)	Width mean (mm)	Width STD (mm)
Horizontal	-1.63	0.016	28.7	0.02
Vertical	1.13	0.018	16.6	0.09
Reflective				
Horizontal	-1.69	0.02	28.91	0.02
Vertical	0.72	0.02	17.03	0.09
Difference	**Position (mm)**	**Width**		**Peak density**
Horizontal	+0.06	-0.20%		+3%
Vertical	+0.42	-0.47%		

EFFECT OF OPTICAL DISTORTION

Reference Image for Geometric Correction

To estimate the effect of the optical distortion, we placed a flat sheet of evenly spaced LEDs at the location of our mock-up target. The sheet is shown in Fig. 8. We used a flat surface to mount the sheet and not the curved surface of the target nose cone because the beam is projected onto the target and not wrapped around the target nose cone. We then took an image of the sheet through the TIS optics and used a geometric correction function from the LabVIEW vision toolkit to correct the distortion, see Fig. 9.

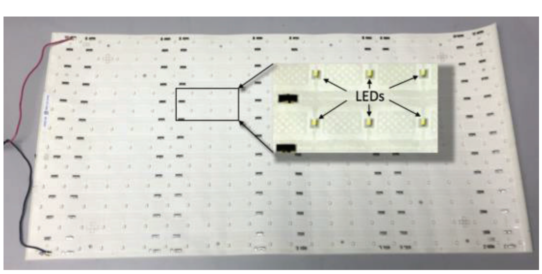

Figure 8: The sheet with evenly spaced LEDs.

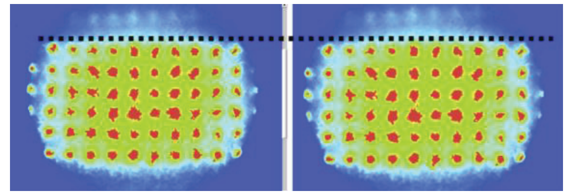

Figure 9: On the left is, in false colors, the original image as seen by the TIS camera, and on the right, the corrected image. The dotted line helps the eye see that a dip on top has been corrected.

Correction Results

When the correction is applied to a simulated image, we find a lowered peak density of about 8.3%. When applied to a production beam image, we find a 6.2% lower peak density. However, we should now recalibrate our image, as the distortion correction affected the scaling, pixels per mm, by about 4%. When this is applied, we see a difference of less than 1.5% in peak density both to a simulated image or a corrected production beam image, see Table 2. This makes the impact of the distortion a minor effect.

Table 2: Effect of the Distortion on the Peak Density

	Horizontal (mm) center	Horizontal (mm) width	Vertical (mm) center	Vertical (mm) width	Peak Density (cnt/px)
Original	0.4	56.0	0.6	28.1	894.7
Corrected	0.2	55.4	0.3	28.0	907.5
Change	-0.2 mm	-1.1%	-0.3 mm	-0.4%	+1.4%

FIBER BUNDLE

The contrast of the fiber bundle is important to the quality of the image of the proton beam. Figure 10 shows images of a pie chart made with different fiber bundles.

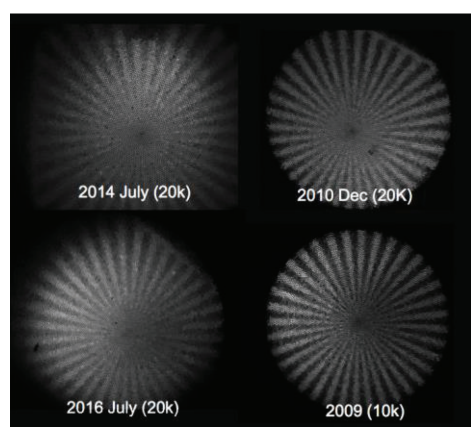

Figure 10: Pie chart images from different fiber bundles.

Three of the bundles have 20,000 fibers and one has 10,000 fibers. The 2010 20,000 fiber bundle was of higher quality, with a contrast of 0.6, but became too expensive due to manufacturing issues. The 2014 bundle was made with a new process, but had a contrast of only 0.4.

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An improvement to this new process was delivered with the 2016 fiber bundle, with a contrast around 0.5. An older fiber bundle, made around 2009, but with only 10,000 fibers, shows a very good contrast, at about 0.7. It is easier to manufacture a bundle with less fibers and the less dense spacing allows for less light leakage among the fibers. The contrast was measured by calculating the modulation between dark and light spots along concentric circles crossing the pie chart segments, see Fig 11.

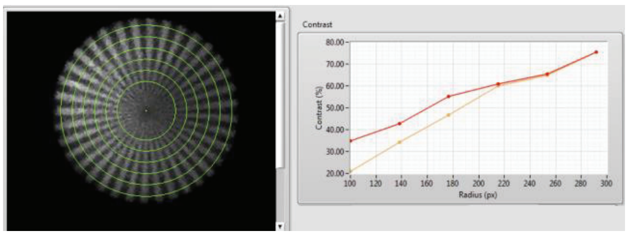

Figure 11: Analysis of the contrast based on a pie chart image through the optical system of the TIS.

We suspect that this difference in contrast is the main impact that lowered the image quality of later TIS installations. One consequence of the lowered contrast is that the image processing software can no longer reliably find the fiducials, and, therefore, the calibration can no longer be automatically done, see Fig. 12. The variation in the positions also increased, from about 1 mm peak-to-peak to about 2 mm. This is still within requirements, and averaging of the results brings the variation back to within 1 mm.

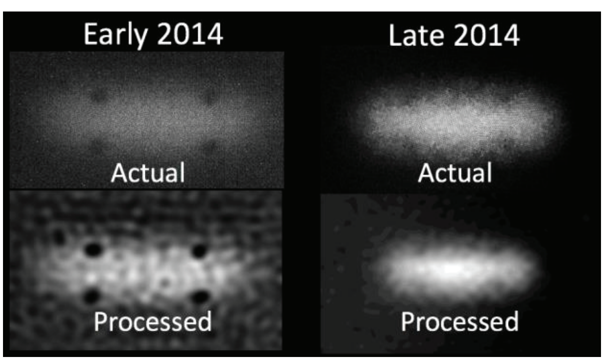

Figure 12: Beam images with the higher contrast bundle on the left and the lower contrast on the right.

MIRROR CORROSION

A water leak developed in the space between the PBW and the target. This water, combined with air and the radiation, caused the aluminum mirror to corrode, see Fig. 13. Note that this figure also shows the thermocouples sticking out from the sides. Unfortunately, the water leak was not fixed as hoped with the next PBW installation and the current mirror is now also corroded.

As it can take up to three years before the PBW will be replaced, we are now left without a functioning TIS and we will have to rely on the RTBT Wizard and the thermocouples for steering and beam width calculations.

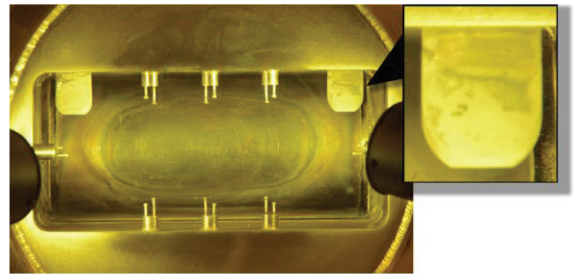

Figure 13: A view of the Proton Beam Window with the corroded mirror.

DISCUSSION

The effect of the reflections and distortions combined is that the TIS calculates at most a 4.4 % lower value for the peak density. More likely, this is less than 3%, given the more intense reflections in the mock-up. This increased intensity is most likely due to using aluminum tape for our reflective material while the inside of the beam pipe is less reflective than that. The combined effects on the position is limited to less than 0.5 mm as the effects go towards cancelling each other out. This means that the studied effects are minor compared to the observed disagreements, and that we must further pursue other possible effects on the TIS calculations.

We plan to compare the different analysis routines using existing data to see if we find a reason for the disagreement between RTBT Wizard and the TIS.

Already, ESS and ORNL have been looking at the luminescence of particles other than the protons on the coating, see [4,5], and experiments are planned.

Given the mirror corrosion problem, from now on we will assume that a water leak can always happen and plan to investigate coatings for the mirror. We plan to use the RaDIATE collaboration, see [6], to expose sample mirrors with different coatings to water and radiation to determine if any coatings are suitable for our environment.

ACKNOWLEDGMENT

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