

BEAM PARAMETER MEASUREMENT AND CONTROL AT THE SNS TARGET*

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Abstract

The spallation neutron production target at the SNS facility is designed for 1.4 MW beam power. Both beam position and profile must be carefully controlled within narrow margins to avoid damage to the target. The position must be within 2 mm of the target center, and 90% of the beam must be within the nominal 70 mm x 200 mm spot size, without exceeding 0.18 A/m² peak beam current density. This is a challenging problem, since most of the diagnostics are more than 9 m upstream of the target, and because the high beam power limits the lifetime of intercepting diagnostics. Our design includes a thermocouple halo monitor approximately 2 m upstream of the target face, and a beam position monitor, an insertable harp profile monitor, and a beam shape monitor approximately 9 m upstream. In this paper we will discuss our strategy to commission the beam delivery system and to meet target requirements during nominal operation.

INTRODUCTION

The beam parameters at the Spallation Neutron Source (SNS) target must be maintained within strict limits. At the nominal beam power of 1.44 MW, the beam position must be kept within ± 2 mm of the target center, 90% of the beam must be within the nominal 70 mm x 200 mm spot size, and the peak beam current density must be kept below 0.18 A/m². At this beam power intercepting beam diagnostics will not survive very long. An additional complication is that most of the beam diagnostics are more than 9 m upstream of the target due to space constraints. The 96 m of beam line leading to the target is perfectly straight, so any sort of optical imaging diagnostics is very difficult to implement.

The baseline set of beam diagnostics originally included an insertable harp, beam position monitors (BPMs), and wire scanners, as shown in Fig. 1. In the last two years we have added additional diagnostics to the design: a thermocouple-based halo monitor about 2-m upstream of the target, an additional BPM just downstream of the harp, and a permanently-inserted bunch shape monitor just upstream of the harp. These additional diagnostics will permit continuous monitoring of the beam size and position, and also provide additional

information that will allow us to more confidently extrapolate the beam position at the target.

During target commissioning, scheduled for April 2006, we will mount a temporary view screen immediately upstream of the target to verify our ability to extrapolate and control the beam parameters at the target.

BEAM DIAGNOSTICS

As shown in Table 1, the three 36-cm diameter BPMs are each expected to provide an absolute position measurement accuracy of ± 2 mm. The last BPM is downstream of the last magnet, and is therefore the only one that can be used to directly extrapolate the beam position on target.

An emittance station comprising four wire scanners 33 to 56 m upstream of the target provides rms emittance and Twiss-parameter measurements that will be used to check the properties of the beam entering the final portion of the beam line upstream of the target.

The harp is the closest profile monitor to the target. It consists of three signal wire planes (horizontal, vertical, and diagonal) [1], and is designed to provide a position measurement absolute accuracy of ± 2 mm. Due to the intense proton beam, the harp signal wires are not expected to survive more than a few months if they are continuously left in the beam. The harp is therefore designed to be insertable, and we expect that it will be used to monitor the beam parameters a few times per day.

The bunch shape monitor is similar to the harp, in that it also consists of wires that intercept the beam, but only the top, bottom, left, and right edges of the beam. Since the wires are in the low-intensity portion of the beam we expect long wire survival times, and this device is therefore designed to be continuously in the beam. The bunch shape monitor will be replaced each time the harp is replaced.

Table 1: Beam diagnostic positions.

Diagnostic	Distance from target face (m)	Absolute position accuracy (mm)
Halo monitor	2.14	$< \pm 2$
BPM	9.25	± 2
Harp	9.52	± 2
Bunch shape monitor	9.64	Not applicable
Wire scanners	33 to 56	Not applicable

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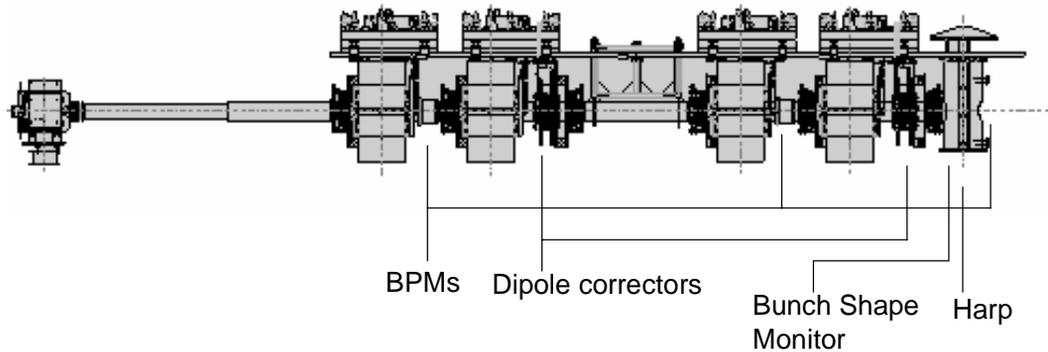


Figure 1: The end of the beam transport upstream of the target.

The last and most-downstream beam diagnostic is the thermocouple halo monitor. It consists of thermocouples inserted into the top, bottom, left, and right edges of the beam. At each thermocouple location there are two thermocouples inserted at slightly different depths into the beam for added reliability and to optimize the measurement for a range of beam sizes. The top and bottom thermocouple probes are 4.2 and 3.75 cm from beam center, and the left and right probes are 11.0 and 11.4 cm from beam center. The halo monitor is designed to center the beam with an absolute accuracy of better than ± 2 mm. The exact accuracy depends on how well the monitor is aligned (see below).

In addition to the above set of permanent diagnostics, we will also temporarily mount a view screen to the spallation target during beam commissioning. The light from the Cr-doped Al_2O_3 screen will be collected by a lens on the end of a fiber optic bundle that extends downstream along the length of the target to a camera 9-m away. The view screen, lens, fiber bundle, and camera will be disposed of after beam commissioning and prior to high intensity operations.

BEAM OPTICS

The beam delivery system upstream of the target consists of four 36-cm aperture quadrupole magnets with rad-hard coils; two dual-plane, rad-hard steering magnets each capable of up to 1.5-mrad beam deflection; and the proton beam vacuum window, which consists of two 2-mm thick, water cooled, semi-cylindrical Inconel sheets. The last quadrupole is 11.59 m upstream of the target face, and the last steering magnet is 1-m downstream of this quadrupole. Particle-tracking simulations have shown that the effects of space charge are negligible in this portion of the facility.

As the beam passes through the proton beam window, the resultant multiple scattering adds a large 6.5-mrad rms contribution to the beam divergence, which causes the horizontal and vertical emittances to grow by about a factor of three (total emittance growth is nine) [2]. However, the window is close enough to the target that the additional angular divergence does not strongly affect

the beam size at the target. Of course some of the scattering interactions result in large deflection angles, which cause approximately 4% of the beam to be lost in the beam flight tube between the window and the target.

BEAM POSITION, SIZE AND SHAPE AT THE TARGET

The thermocouple halo monitor, 2.14-m upstream of the target face, together with the last BPM provides the most accurate and least biased measurement of beam position at the target. Two beam position measurements at distances d_1 and d_2 upstream of the target, with uncorrelated position measurement errors of ϵ_1 and ϵ_2 , will result in an extrapolated beam position y_0 and error ϵ_0 at the target of

$$y_0 = y_1 + d_1 \left(\frac{y_1 - y_2}{d_2 - d_1} \right)$$

$$\epsilon_0^2 = \left(\frac{d_2}{d_2 - d_1} \right)^2 \epsilon_1^2 + \left(\frac{d_1}{d_2 - d_1} \right)^2 \epsilon_2^2$$

For our case, where $d_1 = 2.14$ m and $d_2 = 9.25$ m, the corresponding position errors at the target can be kept within the allowable tolerance of ± 2 mm if the halo thermocouple position measurement error is less than ± 1.5 mm. The harp, when inserted, essentially provides a second measurement of beam position at the last BPM since it is so close to that BPM, and its role in the position measurement at the target is primarily to verify the BPM measurement. The BPMs upstream of the harp cannot be used to determine the beam position at the target without first unfolding the effect of the intervening magnetic fields, and therefore have limited ability to further reduce the error on the target beam position measurement.

The harp, 9.52 m upstream of the target face, and the wire scanners, 33 to 56-m upstream of the target face, provide the best measurements that can be used to extrapolate the beam size and shape at the target. The accuracy in our determination of the beam size and shape

at the target essentially reduces to 1) the error in the measurement at the harp, 2) the error in the beam parameter measurement at the emittance station, and 3) the error in extrapolating beam parameters from the emittance station and the harp to the target face. The error on the rms beam size at the harp has been estimated [1] to be about 5% under ideal conditions, but a more realistic estimate is 10%. The error in a wire scanner rms beam size measurement has also been estimated [1] to be about 10%.

Each quadrupole magnet in the beam line will be mapped to determine the gradient-length product with an accuracy of about 10^{-4} , and the quadrupole power supplies have an absolute accuracy of 200 ppm of the full-scale current. Since the lowest-current quadrupoles run at about 1/3 of the maximum power supply current, the error in the gradient-length product is then less than 600 ppm. Between the emittance station and the harp there are six quadrupole magnets, and each magnet is positioned in the beam transport line with a local coordinate accuracy of better than 0.5 mm. Based on numerous TRANSPORT runs using various magnet strength and magnet position error combinations we find that the errors in emittance and Twiss parameters at the target due to quadrupole strengths and positions are negligible in comparison to the errors caused by the profile measurements.

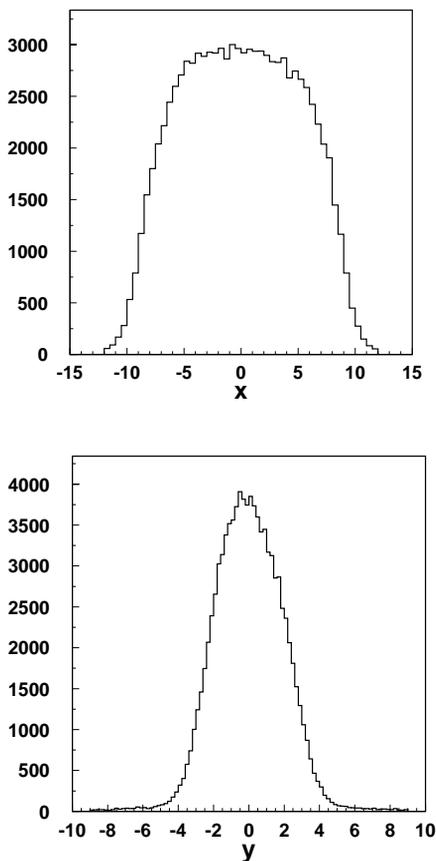


Figure 2: Histograms of horizontal and vertical beam profiles at the target. Plots are relative units vs. position in cm..

To estimate the peak beam density and the beam size at the target, and their errors, we employ a simple linear fitting routine that computes the emittance and Twiss parameters at a given point along a linear beam transport line based upon three or more beam size measurements. From simulated rms beam size measurements assuming 10% errors, the resultant rms beam size at the target can be measured with an accuracy of 7% in the horizontal direction and 9% in the vertical direction. These errors combine to produce an error in the peak density measurement of 11%. The theoretical beam distribution before errors is already at the maximum peak density of 0.18 A/m^2 so the target may have to accept a higher peak density at the expense of a slight decrease in the target lifetime.

The effect of the proton beam vacuum window is primarily seen in the tails of the beam distribution. To determine if we can meet the target requirement for the amount of beam allowed outside the $70 \times 200 \text{ mm}^2$ footprint, we examine beam distributions [2], shown in Fig. 2, from a particle transport model that includes the effects of the vacuum window. Based on the above beam size errors we determined using the linear transport fitting model, we enlarge the full-width half-max (FWHM) of the nominal distribution by 7% (horizontal) and 9% (vertical) and then check the number of particles outside the nominal footprint. Out of 95,000 particles, 10,230, or 11%, lie outside $70 \times 200 \text{ mm}$.

To determine the effect of the beam position error we shift the nominal distribution 2 mm vertically (7% outside the nominal footprint), or horizontally (also 7% outside the nominal footprint), or both (still 7%). If we have both size and position errors, the worst case is 11% outside the nominal footprint, which just barely exceeds the target requirement of 10%. It is impractical to create a smaller beam to stay within the footprint limitations since we are already at the maximum beam density.

To verify the beam delivery system we will mount a temporary view screen to the target face during target commissioning. The beam size and shape at the target will then be directly measured and compared to calculated parameters. We will also individually vary dipole corrector magnets and compare the resultant changes in the beam trajectories to model calculations. We will also vary each quadrupole magnet downstream of the wire scanner emittance station and compare the resultant size and shape variations at the harp and target to model calculations. By the end of the commissioning period we will have thoroughly tested, characterized, and verified the beam transport from the wire scanners to the harp and on to the target, and tested and verified our ability to extrapolate the beam position, size and shape at the target.

REFERENCES

- [1] M. Plum, Beam Instrumentation Workshop, Knoxville, TN, USA, May 3-6, 2004, AIP Conference Proceedings 732.
- [2] Deepak Raparia, BNL, private communication.