# 6D PHASE SPACE MEASUREMENT OF LOW ENERGY, HIGH INTENSITY HADRON BEAM

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*Abstract*

The goal of this project is to demonstrate a method for measuring the full six dimensional phase space of a low energy, high intensity hadron beam. This is done by combining four dimensional emittance measurement techniques along with dispersion measurement and a beam shape monitor to provide the energy and arrival time components. The measurement will be performed on the new Beam Test Facility (BTF) at the Spallation Neutron Source (SNS), a 2.5 MeV functional duplicate of the SNS accelerator front end.

## INTRODUCTION

For high power, high intensity accelerators, beam loss is one of the limiting factors for performance and achievable beam power [1]. Today's state-of-the-art simulation codes provide accurate tracking for the RMS values of the beam through the beam line for many cases, and in principle should also be able to accurately track the beam halo formation and beam loss through the accelerator. However, successful simulation of beam halo and beam loss have yet to be accomplished [2,3,4,5]. As the capabilities of the simulations should be sufficient, the problem may then lie in an incorrect initial assumption, and the most likely candidate is the initial particle distribution, as it is generally approximated [6,7].

In order to determine the initial particle distribution, the beam must be measured over all six independent spatial and momentum parameters in such a way that correlations between parameters can be seen. However, such a scan would be incredibly time consuming and require an accelerator dedicated to the task. As such, no direct full six dimensional measurement of the distribution has ever been performed. The Beam Test Facility at SNS is a small-scale accelerator with available time, which has already been partially designed for this task. The goals of this thesis are two-fold:

1) Complete the design and installation work to allow the full six dimensional measurement
2) Perform the first six dimensional phase space measurement.

The measurement will answer questions that have long persisted about the existence of correlations between the six degrees of freedom and will serve as a full and accurate particle distribution for benchmarking simulations and predicting beam dynamics at the level which relates to beam loss.

## EMITTANCE MEASUREMENT

Current emittance measurement techniques focus on mainly the transverse plane. As of now the most dimensions measured simultaneously are the four within the transvers plane using the "pepper-pot" technique [8]. But this technique is not effective for higher energy beams. It has been shown that the slit and collector method, which works by passing the beam through two apertures of varying position, is an effective technique to measure a two dimensional phase space for a particular axis of a high energy beam.

In the past, three separate two dimensional phase spaces have been combined to create a six dimensional distribution. However, because the un-measured cross-terms are assumed to be zero in this reconstruction, this distribution is not the same as actually measuring all the dimensions together. In order to determine true six dimensional distributions, all six degrees of freedom must be directly measured together. The technique proposed here is the same principle as the above aperture technique but for all six dimensions simultaneously.

The particles will go through a series of five apertures and a Beam Shape Monitor (BSM). Each aperture will allow particles through at the coordinate being measured. By combining two pairs of apertures, one pair being horizontal slits and the other pair vertical slits, the four dimensional transvers phase space can be measured (Fig. 1).

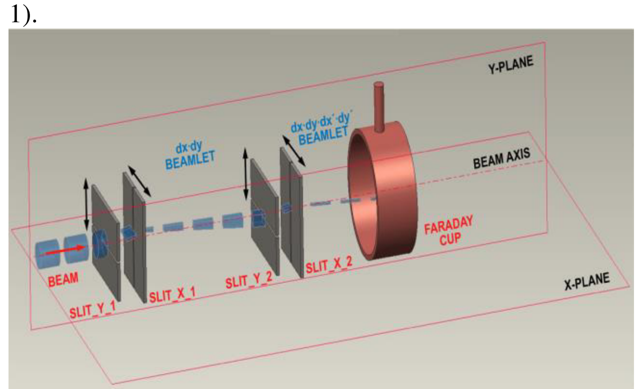


Figure 1: A diagram showing the principle behind a four dimensional scan over the transverse plane.

To find the longitudinal momentum, we use a 90 degree bending magnet. During the turn, the beam spreads as higher momentum and lower momentum particles separate horizontally causing dispersion. This dispersion creates a correlation between the horizontal position and the longitudinal momentum of a particle allowing the selection of particles with certain momentum based on their horizontal position, which is executed using a third movable vertical slit. Because there are no longitudinal control elements, each bunch will expand longitudinally due to the energy spread. Using the bending magnet, each bunch will be separated for measurement as particles with higher energy will have a greater radius in their trajectory than particles with lower energy. Simulations indicate that successive bunches will not overlap and hinder data collection.

The longitudinal measurement will be conducted with a Beam Shape Monitor (BSM). The BSM contains a suspended wire with a potential in the beam pipe. When the hadron beam hits the wire, electrons are emitted and repelled from the wire due to the potential on the wire. After passing through an aperture to leave the beam pipe, a deflector, which generates a time varying electric field, is used to easily change the trajectory of the secondary electrons. See Fig. 2. Based on when the electrons enter the field, they will be transversely deflected so that electrons emitted due to particles early in the beam will be deflected differently than electrons emitted do to particles further back. By changing the phase of the electric field, electrons from a chosen longitudinal position in the beam will be not be deflected when they arrive. These electrons then hit a detector and are measured as current. This current is a measure of the number of particles in the beam with the six measurements described above, particles with a specific horizontal, vertical, and longitudinal position and momentum.

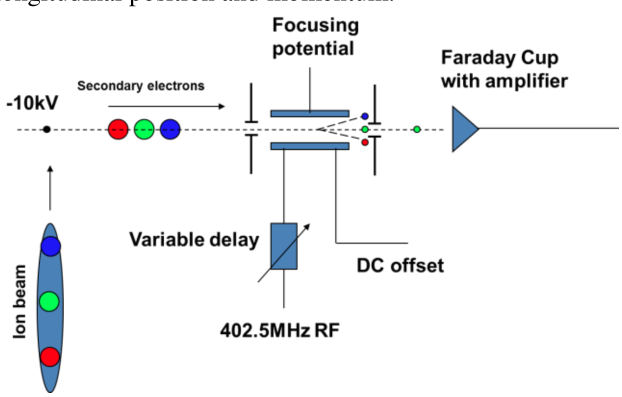


Figure 2: A diagram of the basic plan behind the BSM for measuring the arrival time of hadrons in the beam.

After averaging the current over multiple runs for a specified arrangement of apertures to minimize noise, one aperture is moved to the next position. This continues until all wanted coordinates have been measured. Fig. 3 presents the concept of the full six dimensional measurements below. As the beam travels through slits for select coordinates, there is a large amount of particles lost. By the end, approximately $10^{-7}$ of the particles from the original beam core reach the detector. Faraday cups can detect up to 3σ for our beam, but new techniques to increase signal strength may be required as the project continues. This emittance scan will show if any correlations exist between degrees of freedom commonly thought to be completely independent from each other.

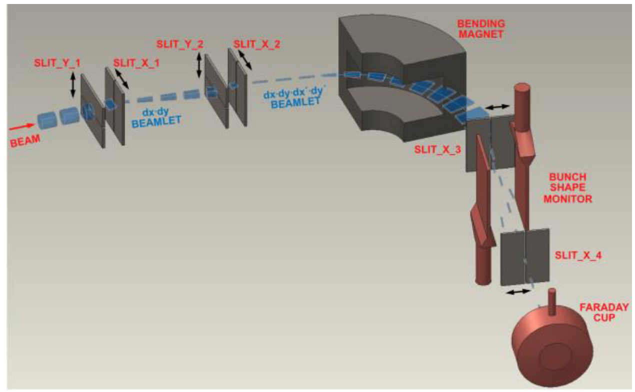


Figure 3: A diagram showing the basic idea behind a full six dimensional emittance scan.

## BEAM TEST FACILITY

A new accelerator called the Beam Test Facility (BTF), a functional duplicate of the first section of the main Spallation Neutron Source (SNS) accelerator has been built at SNS for the purpose of optimizing hardware, testing and commissioning spare Radio Frequency Quadrupoles (RFQs), and performing beam dynamics experiments for high intensity beams [9]. High dimensionality phase space measurements are one of these beam dynamics experiments. The BTF is dedicated specifically for research purposes so it does not need to be shared with users. A schematic of the beam line is shown in Fig. 4.

The beamline starts with hydrogen anions originating from an ion source that produces a beam exactly like the ion source in the main accelerator. It then travels through a RFQ and reaches an energy of 2.5 MeV. Following the RFQ, the beam enters the series of magnets and diagnostics that will be used to measure the phase space. After the RFQ, there are two quadrupole magnets for focusing followed by two moveable slits, one aligned on the horizontal and the other on the vertical. Another pair of quadrupoles is then followed by another two similar slits. Next is the $90^0$ bend using a dipole magnet, followed by a final moveable aperture aligned vertically. The beam line ends at the Beam Shape Monitor. There are plans to add on to the beam line for further beam halo studies.

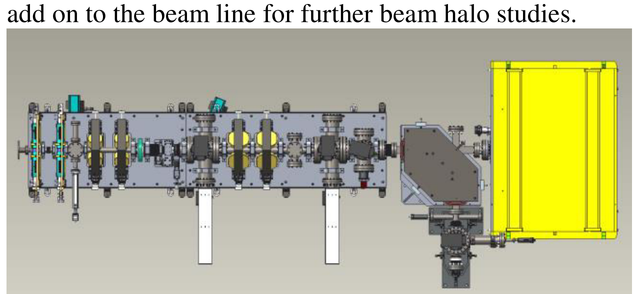

Figure 4: A schematic view of the BTF section where the diagnostics for the six dimensional scan occur.

## EARLY RESULTS

The BTS officially began operating on September 8th and has only been available for scans for the last few weeks. The BSM and the 5th aperture have not yet been installed, so scans have been limited to the transverse plane. As of now, only one and two dimensional scans have been conducted in the last few weeks. A four dimensional scan is planned to take place within the month, and a course resolution six dimensional scan by the end of the calendar year.

The one dimensional plots for each aperture show the expected Gaussian distributions. Figure 5 is a graph of the one dimensional scan at the first horizontal slit. Figure 6 shows the phase space plot for the horizontal dimension which gives the expected ellipse. And Fig. 7 depicts what the beam looks like in the transverse spatial plane at the first pair of slits.

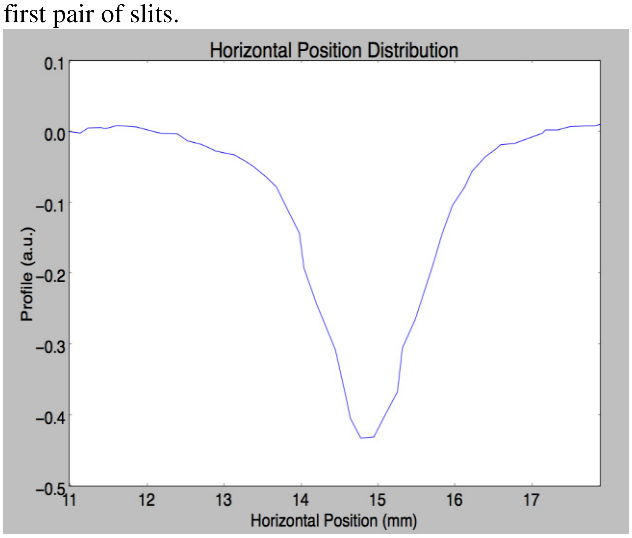


Figure 5: A one dimensional scan across the horizontal axis.

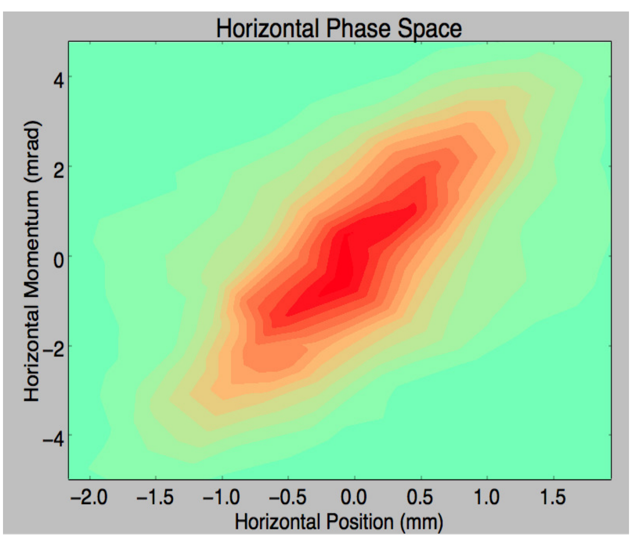


Figure 6: Early measurement of the horizontal phase space distribution.

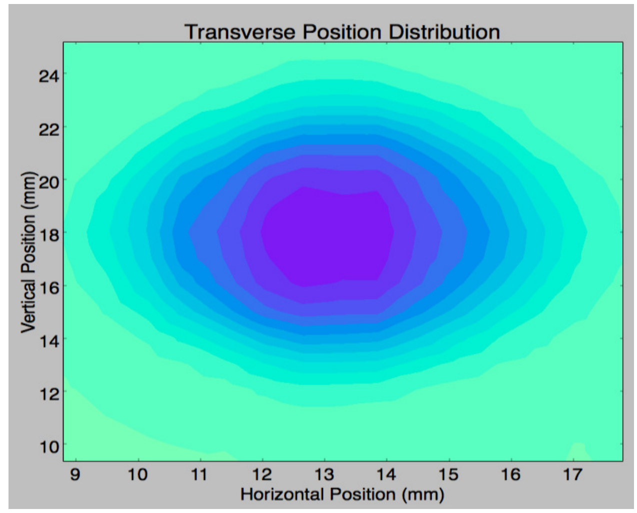


Figure 7: A two dimensional scan over the horizontal and vertical plane.

The current limiting factor in the higher dimensionality scan resolutions will be the time required to complete a full scan. This limitation will be partially diminished with the use of a luminescent screen in the BSM so that two dimensions can be completely measured simultaneously. In the future, after obtaining a six dimensional distribution, we plan to add a FODO line to the end of the BTF with matching and mismatching quadrupoles to study beam halo development and benchmark simulations against the new measured distributions.

## ACKNOWLEDGEMENT

This work has been partially supported by NSF Accelerator Science grant 1535312.

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