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 measurements are 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. 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 [2].

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 was constructed to facilitate this task [3].

EMITTANCE MEASUREMENT

Typically, three separate two dimensional phase spaces measurements are combined to create a six dimensional distribution. However, because the un-measured cross-terms are assumed to be zero in this reconstruction, this distribution may not be identical the actual six dimensional distribution. In order to determine true six dimensional distributions, all six degrees of freedom must be directly measured together. The technique proposed here is a generalization of the two dimensional phase space measurement method using slits and a charge collector for the complete six dimensional phase space.

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.

To select 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 due to dispersion. This 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.

The longitudinal measurement is 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 which travel through a RF field and final aperture. See Fig. 1 and [3] for more details. These electrons then hit a detector and are measured as current. This final current measurement reflects 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 shows the full conceptual schematic for the six dimensional measurement.

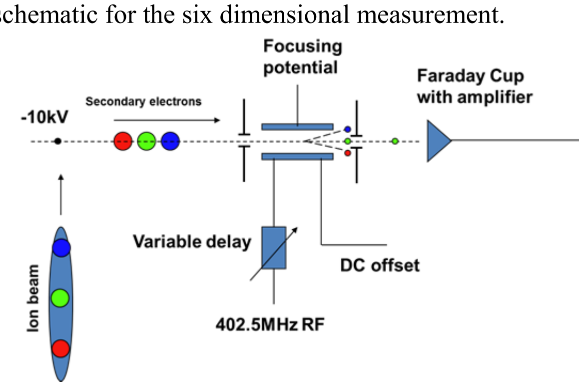

Figure 1: A diagram of the basic plan behind the BSM for measuring the longitudinal distribution in the beam.

After averaging the current over multiple beam shots 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. Figure 3 presents the concept of the full six dimensional measurements below. As the beam travels through slits for select coordinates, a large fraction of particles are 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

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techniques to increase signal strength may be required as the project continues.

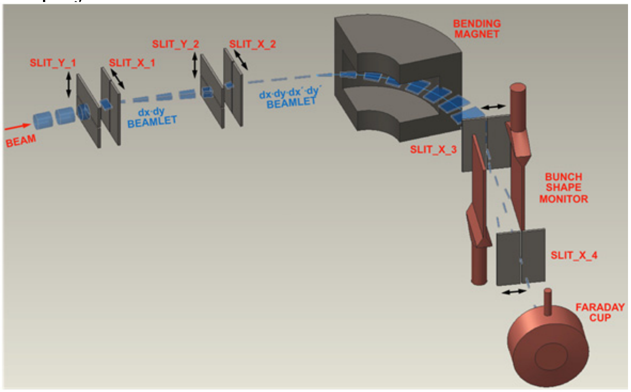

Figure 2: A diagram showing the concept of a full six dimensional emittance scan.

The new Beam Test Facility (BTF) at the Spallation Neutron Source (SNS) houses the experiment [4]. The experiment takes place following an RFQ in the beamline. After the RFQ, there are four 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. These slits all have an aperture width of 200 µm. 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. Specialized scripts based on an Open XAL framework were developed and are used to perform the multidimensional scans [5]. There are plans to add on to the beam line for further beam halo studies [6].

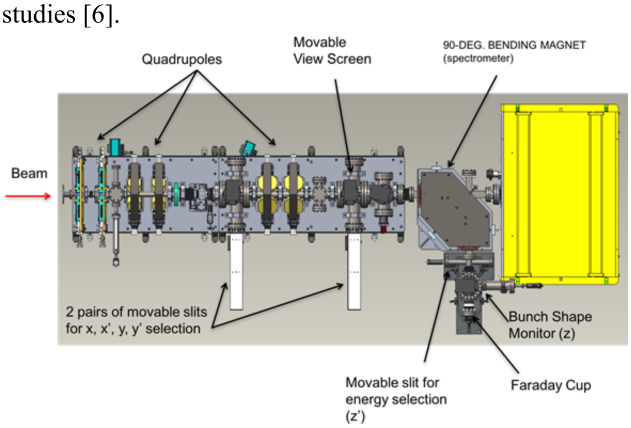

Figure 3: A schematic view of the BTF section where the diagnostics for the six dimensional scan occur.

EARLY RESULTS

Since the BTF officially began operating on September 8th, progress has been made towards a full six dimensional scan. A five dimensional scan of the transverse coordinates along with the energy coordinate has been completed using a luminescent screen at the energy slit location after the bending magnet. Also, a two dimensional scan of the phase and energy spread was performed with the transverse slits positioned at the beam core collecting the first data points of a true six dimensional scan. A first full six dimensional scan is expected to be completed before fall.

Below are some results from past scans. Figure 4 shows a one dimensional scan that used a single slit to measure the horizontal beam distribution and the one dimensional horizontal axis projection from the full five dimensional scan. Note the agreement is very good. Figure 5 is the two dimensional horizontal phase space component of a five dimensional scan measurement. And Figure 6 shows the two dimensional distribution of vertical momentum against horizontal position projected from the same five dimensional scan.

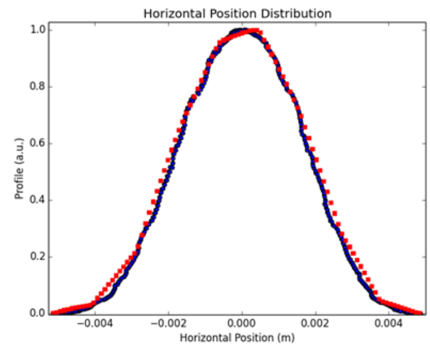

Figure 4: The horizontal beam distribution. Blue is directly measured with a single slit. Red is the projection from a 5D measurement.

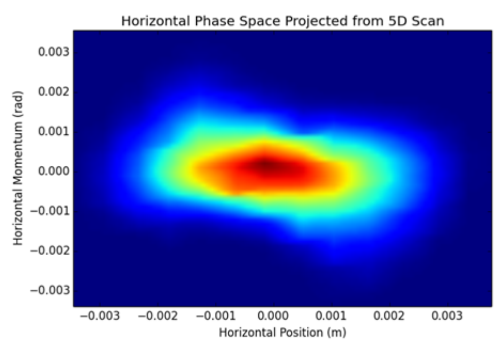

Figure 5: The horizontal phase space from a 5D measurement.

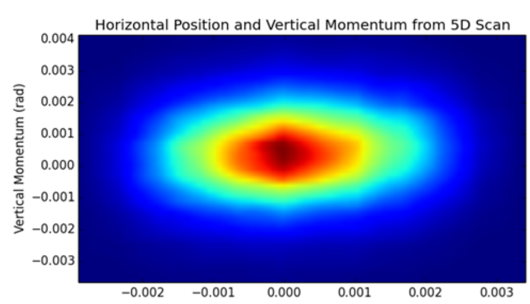

Figure 6: Vertical momentum versus horizontal position distribution from a 5D measurement.

An interesting result from the five dimensional scan is shown below. Figure 7 is a graph of the energy spread for the entire scan projected to a single dimension, showing the expected distribution peaking at the target energy.

Figure 8, in turn, shows the graph of selected energy spreads measured at the beam core. These are individual measurements with the transverse position and vertical momentum all located at the beam center, but with three different horizontal momenta. The blue curve is where the horizontal momentum is zero. Two peaks with a dip at the reference energy are observed. This result was only found at the beam core; the measured distribution was Gaussian as expected farther away from the center.

The final graph gives the first data points of a true six dimensional scan. The transverse slits were all arranged to allow the center of the beam through. The energy slit was fixed to the center of the beam for a given dipole magnet setting. Changing the current in the dipole magnet allowed for a section of the beam with a specific energy to reach the BSM. By measuring the phase distribution for different energies, a graph of the longitudinal phase space could be created. Figure 9 shows the result for the phase space with a defined single horizontal position and momentum, and vertical position and momentum. These are the first 1,960 points in a full six dimensional distribution measurement. The distribution shows the expected linear correlation between energy and phase with the two peaks seen in the five dimensional scan with the same transverse slit locations.

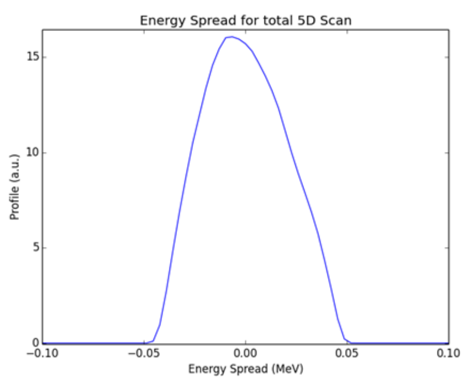

Figure 7: The energy spread from a 5D scan.

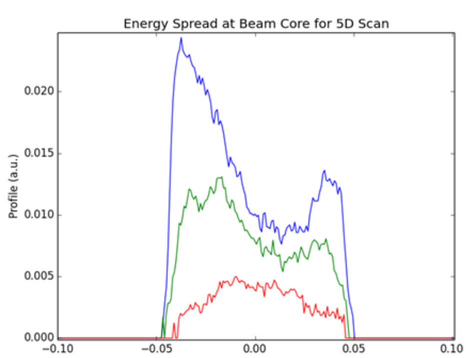

Figure 8: Energy spread from beam core in 5D scan. Blue is with no horizontal momentum. Green and red have horizontal momenta progressively further from zero.

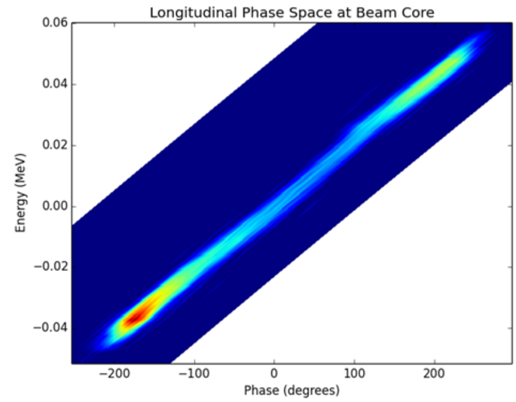

Figure 9: The longitudinal phase space measured at the beam core.

The time required to complete a scan is the largest limiting factor for higher dimensionality scans. This limitation was partially diminished with the use of a luminescent screen in place of the energy slit after the bending magnet for the 5D scan. By removing the energy slit and using a screen in the BSM, there is a possibility that two dimensions can be completely measured simultaneously to significantly reduce scan time. 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 [6].

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