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TECHNICAL WORKINGS OF THE 6D PHASE MEASUREMENT AT SNS

B. Cathey, A. Aleksandrov, S. Cousineau, A. Zhukov
Oak Ridge National Laboratory, Oak Ridge, TN, USA

Abstract

The Beam Test Facility (BTF) is a functional duplicate of the Spallation Neutron Source (SNS) frontend with a 2.5 MeV beam on which the first six-dimensional phase space measurement has been completed. This presentation will show the technical underpinnings involved in performing the 6D scan with the BTF. The first part will examine the diagnostic setup involving apertures, a screen, and a bunch shape monitor and how the integrated system functions. The next part will cover the scan logic used in the software. The last part will briefly discuss ongoing efforts to analyze 6D measurements and identify correlations.

INTRODUCTION

SNS has completed the first full six-dimensional phase space scan using the Beam Test Facility (BTF) [1]. The BTF, a functional duplicate of the SNS accelerator Front End, produced a pulsed 2.5MeV ion beam with a peak current of up to 50mA, pulse width of 50µs, and maximum repetition rate of 10Hz when using the beam line diagnostics [2]. The test facility began with a H^- ion source followed by a Low Energy Beam Transport (LEBT), a Radio Frequency Quadrupole Accelerator (RFQ), and a Medium Energy Beam Transport (MEBT) where the diagnostics for the 6D scan were located.

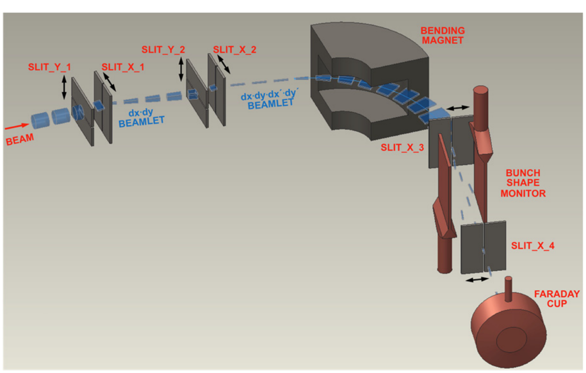

Figure 1: A diagram showing the concept of a full six-dimensional emittance scan.

The concept for the six-dimensional scan is shown in Figure 1. After the beam entered the MEBT, a pair of slits selected the transverse position followed by a second pair of slits selecting the transverse angle. A bending magnet dispersed the beam horizontally based on energy allowing the fifth slit to select the particle energy. Finally, an RF field deflects particles based on their time of arrival, allowing a final slit to select for the particle phase before a Faraday cup measures the charge that passes through all the slits. By moving each slit systematically through the beam over the entire phase space, the particle distribution was measured. This paper will dive into the specifics of different parts of the actual 6D scan.

SCAN HARDWARE

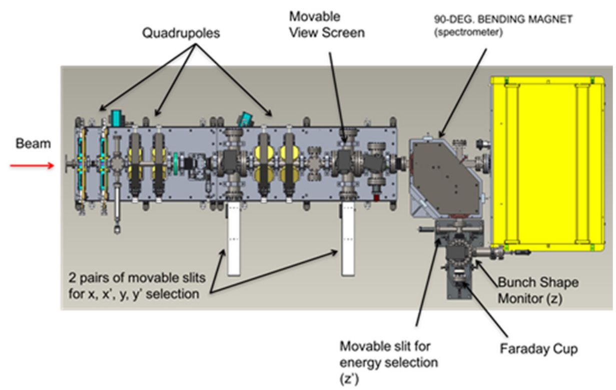

Figure 2: A schematic view of the BTF MEBT which contains the diagnostics for the 6D scan.

Figure 2 shows a schematic for the MEBT. After the RFQ, there are four quadrupole magnets for focusing followed by the first pair of 200µm wide slits, one aligned on the horizontal axis and the other on the vertical. The slits move independently on actuators whose read-back is triggered by the beam pulse. The second pair of 200µm wide slits are 0.94m after the first pair. This aperture size was selected as a balance between signal strength and resolution. While smaller slits increase will increase the resolution, it's important to remember that there are six apertures blocking particles and a smaller gap decreases signal strength exponentially.

Next was the 90° bend using a dipole magnet followed by a fifth aperture 800µm wide and aligned vertically for energy selection. The bending magnet guaranteed any H^+ caused from edge scattering did not disrupt the final charge measurement. The width of the energy slit was chosen as a balance between signal strength and resolution in the longitudinal phase. The energy and phase are highly correlated by the end as there are no rebunchers and a wide slit lacked resolution in both dimensions. The energy slit was not motorized but required manual insertion. Because of this, the dipole current was used to direct different parts of the beam through the energy slit: different dipole currents selected different particle energies.

A departure from the initial concept described above was the use of a Beam Shape Monitor (BSM) for the longitudinal phase measurement [3]. Figure 2 shows the BSM occurs after the energy slit. The BSM uses secondary electrons for deflection and charge measurement. This

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change was made because protons are costly to deflect at the necessary time scale. A BSM uses a wire suspended in the beam path with an electric potential. When an H^- hits the wire, secondary electrons are emitted which travel through an RF deflecting field before hitting a scintillating screen. The screen allowed for the entire phase measurement to be made in a single shot reducing the scan time by an exponential power. Because of the weak signal after five slits, it was necessary to use an MCP to increase the signal. After five slits, there was no concern with saturation.

The screen was recorded by a camera which was triggered by the beam pulse. The BSM wire used the same actuators as the first four slits and its position read-back was also triggered by the beam. This improved scan times as it was not necessary to wait for each actuator to stop before collecting a measurement. Scans were conducted while these actuators moved and the data from each element could be brought together for a specific bunch. The BSM wire also measured the vertical angle. Only particles at the wire position emitted electrons for the detector. This meant the wire did not have to chase the beam position after the second slit as different vertical angles would require repositioning the wire. As such, the second vertical slit was not used for the 6D scan.

SCAN TECHNIQUE

In order to cover the full phase space, the scan needed each parameter selector to move one at a time. The term selector is used here to represent the slits, dipole, and wire that select which coordinate in the phase space is being measured at that moment. For a systematic scan, a hierarchy is needed where one selector almost constantly moves and each subsequent selector after that moves less and less. Figure 3 shows the 6D scan scheme. The first slit in the beam path, the horizontal position or *x* slit, received the most energy from the beam. To protect the slit by keeping the energy distributed over its surface, it was the selector in constant motion. After the *x* selector finished a sweep, the *y* selector would move a step, and the *x* selector would sweep backwards to minimize scan time. Once the *y* selector covered its path, the *x'* slit would take a step and the *y* slit would begin traveling backwards and the same pattern would continue. Eventually, all four selectors cover the transverse phase space. Because of correlations between corresponding spatial and momentum parameters, the *x* and *y* selectors would cover different displacements depending on *x'* and *y'* respectively to make sure time wasn't wasted on phase space volumes without beam.

The last selector was the bending magnet used to select the energy, *w*. Because the current read-back was not triggered by the beam like the previous selectors, the scan needed to wait to make sure the dipole current had finished changing before continuing. Therefore, the dipole needed to change its selection the least to minimize the scan time. So once a transverse phase space was measured, the dipole would change, and the transvers space was measured again. This had the added benefit of keeping the dipole current only changing in one direction, not going up and down, which minimized hysteresis errors.

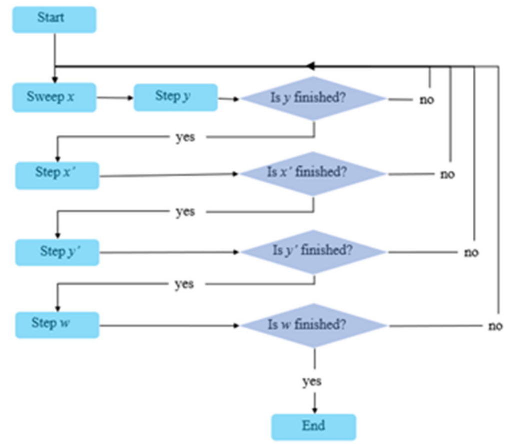

Figure 3: A diagram showing the logic behind the 6D scan.

While the BSM used a camera to measure the particle phase distribution, the BSM could not cover the entire phase of the bunch. Without any rebunchers in the MEBT, the beam was very long when it reached the BSM. However, because the energy is selected first and strongly correlated to the phase, the phase spread reaching the BSM was small enough to measure. Therefore, the BSM central RF phase had to change with the energy to keep the particle distribution in the center of the screen. The *x*, *x'*, and dipole current all determine the energy of the particles reaching the BSM. Ideally, the position of all three would be used to keep the electrons as centered as possible, but the RF phase read-back was not triggered by the beam, like the dipole. This means that the horizontal actuators would have to step and wait for the central phase to adjust each time. However, the dipole current was the largest contributor to energy, so the RF central phase was set to only change linearly with the dipole current. The RF amplitude was set to maximize sensitivity but keep the electrons within the screen area.

The long scan times required the entire scan to be automated. Specialized scripts based on an Open XAL framework were developed and used to perform the scans [4]. Because the BSM RF deflects only in one dimension, the other dimension could be integrated away to minimize amount of data saved. The resolution of the BSM was about 1°. Each configuration of selectors resulted in a phase plot that needed to be saved. In case of a failure, each measurement was saved as it was collected so that an interrupted scan could continue from where it left off. The script was also smart enough to pause anytime the beam current monitor (BCM) upstream of the first slits showed that the beam had stopped. This kept unnecessary data from taking up space and made sure parts of the phase space were not skipped over.

The scan repetition rate had an average of 2.5Hz. One reason was the size of the data. During lower dimensional scans, memory size was not an issue. It was only when higher dimensions were reached that the script had trouble keeping up with the data size during a scan and need to

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pause. This will be fixed in the future with a more efficient file type to store data. The second reason was the lack of actuator accuracy at faster speeds. When moving, the actuator position read-backs were accurate up to 2.0mm/s. The limiting factor for the 6D scan was the reliable speed of the *x* actuator as it was the selector constantly moving.

The scan took 32 hours and resulted in 5,675,740 points including the points from the BSM screen. Each dimension, other than phase, had a 10 point resolution. Figure 4 shows that the beam current during the 6D scan, measured with the BCM, remained constant for the duration except for a few dropouts. Measurements throughout the year of BTF of operations remained consistent, even between higher and lower dimensional data [5].

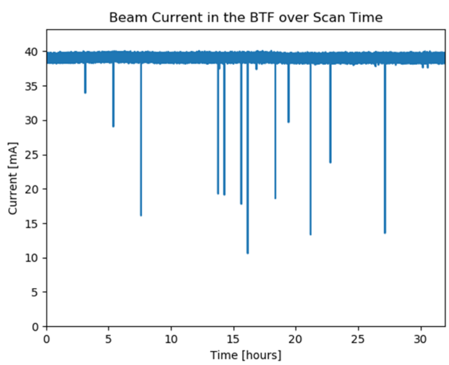

Figure 4: The beam current from the BCM during the 32 hour 6D scan.

DATA ANALYSIS

Data analysis is still developing. While a new correlation has already been seen, a full analysis is more complicated. There is no guaranteed method for finding every correlation between an arbitrary number of parameters. But the first obstacle to finding new correlations is interpolating the distribution. Because the data is so rarified and not regularly gridded due to the offsets from the transverse correlations, it needs to be interpolated to a regular grid. This will allow for quick integration over dimensions to view subsets of the data. However, interpolating so many points in six dimensions has proven complicated.

Custom codes are being written to take advantage of how the data were saved. A linear interpolation method is shown in Fig. 5. The logic is to interpolate one dimension at a time in the order the measurements were made, starting by interpolating over the set of *x* points for each different set of (y, x', y', w). This is done by interpolating the phase plots point by point linearly to determine the phase plot at new regular *x* points. The result is a regular 2D grid for each set of (y, x', y', w) of *x* and phase. This technique continues for each dimension, interpolating point by point for increasing dimensionalities, using the same order as the scan until a regular 6D space is built. Once this has been accomplished, efforts can begin in earnest to find correlations and generate distributions for simulations.

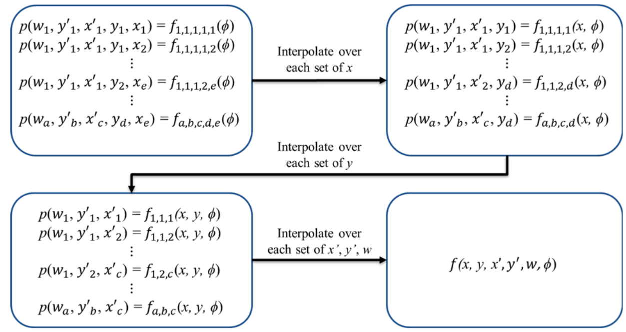

Figure 5: Scheme for proposed 6D interpolation.

While the principle was straight forward, a true six-dimensional scan was a complicated endeavor. Each piece had to work together and cover the entire beam. The largest obstacle in measuring the distribution was the scan time. But improvements to the concept were able to get the final time down to 32 hours. Data analysis is still in progress. While creating a full 6D distribution from the data is the current goal, looking through the data for new correlations will be an ongoing project.

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