

# LARGE DYNAMIC RANGE BEAM PROFILE MEASUREMENTS AT SNS: CHALLENGES AND ACHIEVEMENTS

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## Abstract

Beam profile diagnostics with large dynamic range are an important tool for understanding origin and evolution of the beam halo in accelerators. Typical dynamic range for conventional wire scanners has been in the range of 100. In high power machines like SNS, fractional losses of 1 to 100 part per million are of concern, and therefore a higher dynamic range for profile measurements is desirable. Our near term goal was to achieve a dynamic range of at least  $10^4$  for all profile measurements in the SNS linac and transport lines. We will discuss the present status of this program, challenges, and solutions.

## INTRODUCTION

An uncontrolled loss of a small beam fraction during acceleration in a high intensity linac is the major factor limiting the maximum achievable beam power. The SNS accelerator is approaching its design beam power of 1.4 MeV with typical levels of uncontrolled beam loss within the design limit of 1W/m. This level of beam loss is considered to be acceptable but it still creates a significant activation of the beam line equipment, which affects its lifetime and complicates maintenance. Moreover, the SNS power upgrade plan requires a 50% increase in beam intensity while keeping uncontrolled beam loss at the present level. Understanding the mechanisms of beam loss is a long-standing problem and can provide a path toward increasing beam intensity and residual activation reduction. It is believed that formation of a halo of particles at a large distance from the core is one of the mechanisms. There is not much experimental data available on the halo formation and propagation because of very challenging diagnostic dynamic-range requirements. Typically, a profile measurement system has to have  $10^4 - 10^6$  dynamic range for measuring beam charge distribution well outside the core. It is not that difficult to make a dedicated device for detecting the halo at one selected location, but it will be of limited use for studying origin and dynamics of the halo. It is highly desirable to have as many as possible of such devices distributed along the beam path. In practice, addition of a large number of new sophisticated diagnostics is a significant financial and technical challenge. The SNS accelerator complex has about 50 existing profile measuring stations distributed along the beam path. If their dynamic range could be extended to the desired level of  $10^4 - 10^6$ , they would provide an excellent tool for studying beam halo dynamics and benchmarking computer models. In the following sections we will present our findings on what factors limit the achievable

dynamic range in the different parts of the machine. Simple modifications to the existing wire scanners in the SNS warm linac and high-energy beam transport section allowed increasing the dynamic range to  $10^4$  and above. There are sources of a background signal, not completely understood yet, limiting the dynamic range to about  $10^2 - 10^3$  in the medium-energy beam transport system.

## DYNAMIC RANGE OF THE SNS WIRE SCANNERS

Conventional stepping wire scanners are used for measuring the transverse beam profiles in the normal conducting linac and the transport lines. The original design used an arrangement of 3 wires: vertical, horizontal and diagonal, mounted on a fork, as shown in Figure 1, moving at  $45^\circ$  to the horizontal plane [1].

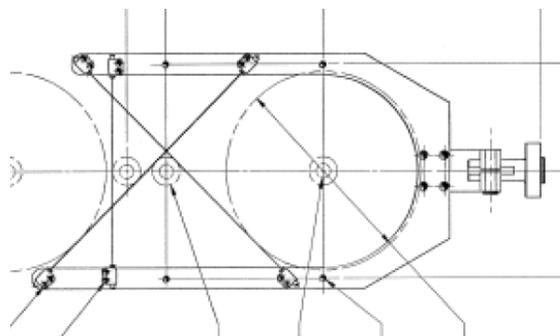


Figure 1: An example of the original 3-wire design of the SNS wire scanner fork.

Carbon wires,  $32 \mu\text{m}$  thick, are used in the MEBT and DTL up to 7.5 MeV;  $100 \mu\text{m}$  thick tungsten wires are used at higher energies. For this selected wire thickness, the proton of  $\text{H}^+$  passes through, and 2 electrons stop in the wire, at all energies. The charge of the collected electrons is measured using a current-to-voltage convertor and 12-bit ADC installed in a service building. The gain of the convertor is switchable in the 1–64 kV/A range to extend the digital dynamic range of the electronics to  $\sim 10^5$ . The achievable analog dynamic range can be estimated using the maximum current to the wire in the beam center, typically  $\sim 2 \text{ mA}$ , and a noise level with no beam, typically  $\sim 20 \text{ nA}$ . The resulting number, of order  $10^5$ , is well matched to the digital dynamic range.

In the original design configuration, the wire scanners delivered reliable profile measurements with a dynamic range of about  $10^2 - 10^3$ , much lower than the above estimate. We found that crosstalk between the diagonal and the horizontal/vertical wires was the major factor

limiting the dynamic range. An example of a typical profile measurement is shown in Figure 2, the vertical profile is plotted in blue, and the horizontal profile is in red. The dynamic range is limited to about 100 by a ghost image overlapping with the real one.

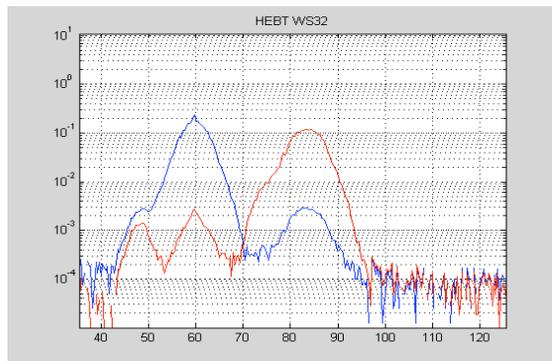


Figure 2: A typical profile measurement done with the 3-wire fork. Blue shows the vertical profile; red, horizontal.

We have not been able to determine with certainty the physical mechanism of the coupling. We found that the real component of the complex coupling impedance is much larger than the imaginary component, so neither capacitive nor inductive coupling plays the important role. This is illustrated by measurements with test and real signals. Figure 3 shows an AC coupling of about 0.4% between the two wires when a test signal (red trace) is injected into one wire and the response is measured on the other (green trace). Signals induced by the beam are drastically different, as shown in Figure 4, where the blue trace shows signal from the wire inserted in the beam, and the yellow trace a signal induced on the other wire. This coupling is mainly DC and its strength, of about 2%, does not depend significantly on the wire-to-wire distance, wire-to-wire voltage up to  $\pm 300$  V, and beam energy from 2.5 to 950 MeV.

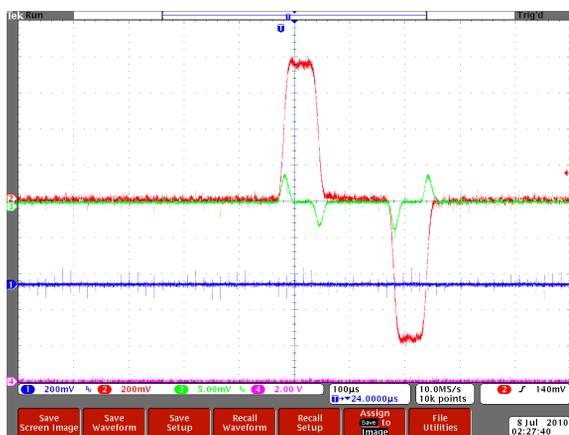


Figure 3: AC coupling between the two wires is measured by injecting a test pulse in one of the wires. The red trace is the signal from the excited wire; the green trace is the signal from the other wire.

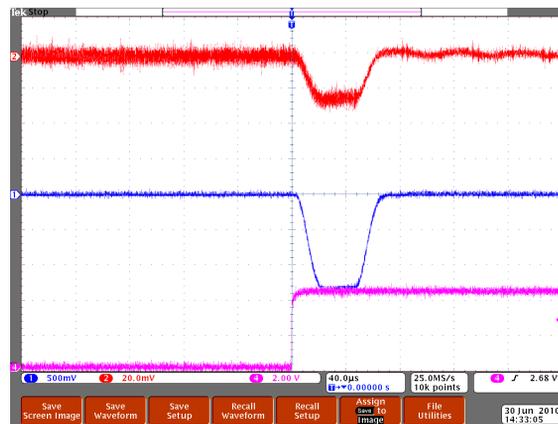


Figure 4: DC coupling between the two wires is measured by inserting one wire in the beam. The blue trace is signal from the excited wire; the red trace is the signal from the other wire.

A plausible explanation, we believe, is scattering of the electrons stripped off the H in the wire. According to a study [2], the fraction of electrons scattered in a tungsten wire and reaching the other wire can be significant.

The dynamic range increased significantly after we removed the diagonal wire and spread the vertical and horizontal wires farther apart. An example of a typical profile measurement after modification is shown in Figure 5; the vertical profile is plotted in blue, and the horizontal profile is in red. The dynamic range increased to about  $10^4$ . The separation of the wires did not change the strength of the coupling, but the ghost image, caused by the coupling, became well separated from the real one.

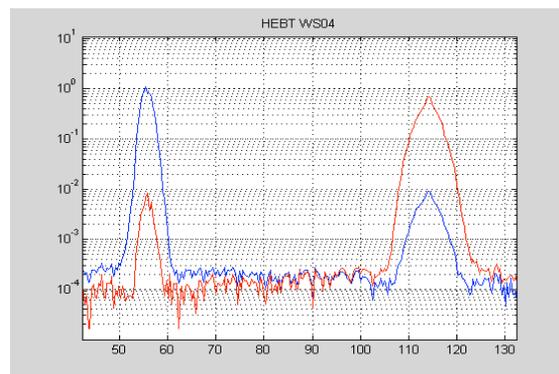


Figure 5: A typical profile measurement with a 2-wire fork. Blue shows the vertical profile; red, horizontal.

More wire separation requires more actuator travel distance. In some parts of the SNS linac the travel distance could not be increased without a vacuum chamber redesign. At the moment, the cross-talk between the wires limits the dynamic range of the CCL wire scanners to about  $10^4$ . In the MEBT, DTL and HEBT we had sufficient space to separate the wires so that the cross-talk is not the limiting factor.

There are other factors limiting the dynamic range of the wire scans, which are different in the different parts of the machine.

A beam-related background signal dominates in the MEBT (as shown in Figure 6), where we have significant beam loss due to scraping on the collimators and stripping on the residual gas. The exact physical mechanism of this background has yet to be investigated and mitigation measures have yet to be developed.

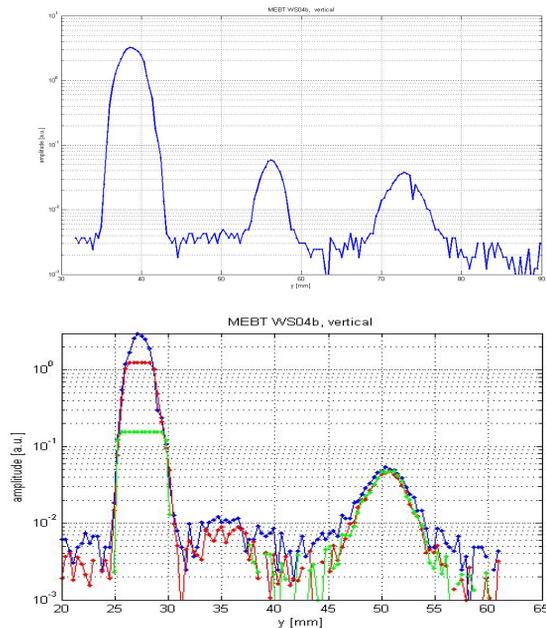


Figure 6: MEBT vertical beam profile measured before (top) and after (bottom) removal of the diagonal wire.

A background signal is also observed in the warm linac, in both DTL and CCL, as illustrated by Figure 7. It does not change when beam is off, but reduces significantly when RF is off in the adjacent cavity. We suspect that a stream of dark current electrons comes out of the end cells of the accelerator structures and is intercepted by the wire. This background can be measured and subtracted from the beam profiles, thus extending the achievable dynamic range, but effectiveness depends on the stability of the background signal.

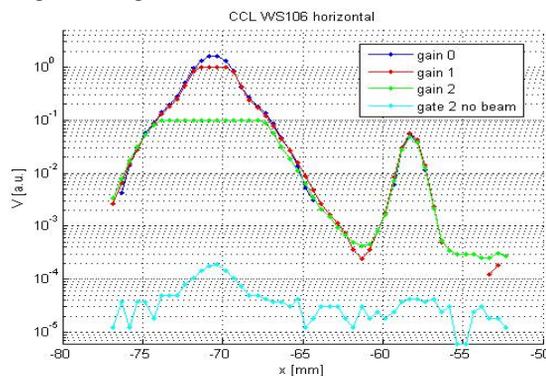


Figure 7: CCL beam profile after removal of the diagonal wire. Blue shows the noise floor with RF and beam off.

A simple sanity check result is shown in Figure 8, where two profiles are shown, measured under identical conditions except that the beam was shifted by ~2 mm in

one case. This test confirms data trustworthiness (note that the ghost image at -100 mm does not pass the test).

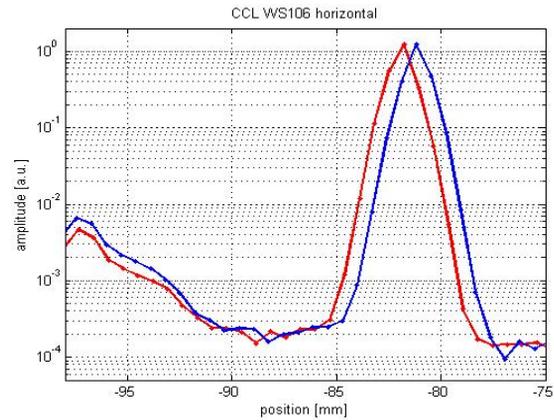


Figure 8: Effect of transverse beam shift on measured beam profile in CCL.

## SUMMARY AND FUTURE PLANS

The SNS wire scanner electronics should be able to provide measurements with a dynamic range of up to  $10^5$ . Other factors, such as wire-to-wire cross-talk and dark current electron background, limit the real operational dynamic range to  $10^2$ - $10^3$ . We demonstrated that simple mitigation measures can extend this range to  $10^4$  in the DTL, CCL and HEBT.

Our near-term goal is to make this level of performance available to users by upgrading the existing software. The new software will include automated gain selection and background subtraction. We expect this to speed up the measurements by a factor of 3 to 4 (currently, 4 scans are required to obtain a single high resolution profile: 3 scans with different gains, and one with no beam for background subtraction).

The next step will be to explore the  $10^5$  level in the HEBT, where the dark current electron background is absent and various electronic interference mitigation measures can be applied, such as differential cable lines, beam averaging, etc.

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